



DOCTORAL THESIS

Demise of the Decapolis

Past and Present Desertification in the Context of Soil Development, Land Use and Climate

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by

Dipl.-Ing. Bernhard Lucke

(born 24.04.1975 in Bielefeld, Germany)

Head of the examination body:

Prof. Dr. rer. nat. Eberhard Schaller

Evaluators:

Prof. Dr.-Ing. Dr. h.c. Michael Schmidt

Prof. Dr. rer. nat. Rupert Bäumler

Prof. Dr. Ziad al-Saad, PhD

Date of the defense:

21.06.2007

Dedication

I dedicate this thesis to four researchers and four books, who were most influential for my work. Gustav Dalman and his *opus magnum* "Arbeit und Sitte in Palästina" provided a real compendium about every detail of daily life in 19th-century Palestine. The title is a little misleading: this book is a real treasure for natural scientists, and Dalman's precise reasoning enlightening. Oliver Rackham and A.T. Grove wrote "The Nature of Mediterranean Europe: An Ecological History". Again the title is a little misleading, since this book contains just everything about desertification in the Mediterranean. Anybody interested in environmental history needs to know it. Last but not least, Arie Issar guided me by his personal example, and his books "Water Shall Flow from the Rock" and "Climate Change – Environment and Civilisation in the Middle East" (together with Mattanyah Zohar) impress with their clarity. "Water Shall Flow from the Rock" was one important reason for the beginning of this present work. May it find mercy in their eyes.

Statutory declaration

I herewith declare that this thesis is the result of my original work carried out at Brandenburg University of Technology Cottbus, Germany, Friedrich-Alexander University Erlangen-Nürnberg, Germany, and Yarmouk University, Irbid, Jordan, within the framework of the doctoral program in Environmental and Resource Management. My research was supervised by Prof. Dr. Michael Schmidt, BTU Cottbus, Prof. Dr. Rupert Bäumler, FAU Erlangen-Nürnberg, and Prof. Dr. Ziad al-Saad, Yarmouk University, Irbid. All the work contained within this text is original except where cited from an additional source. Quotations and other direct or indirect information have been clearly marked and noted. This work has not been submitted previously or to other examination bodies, and is currently unpublished.

Bernhard Lucke

Cottbus, March 23rd, 2007

Abstract

Desertification is seen as a severe threat to Mediterranean ecosystems and the desert fringes. It is assumed that both land use and climate variations can lead to an advance of the desert, and human and natural factors are possibly connected in feedback relationships. It is however unknown how the impact of global warming may look like. In this context, the past might be a key for the future, since a better understanding of historic desertification could allow to better predict what will happen under the current climate change. These questions were investigated in the Decapolis region, an area in the transition zone between the Arabian desert and the Mediterranean climate belt. Several authors postulated that historic desertification was connected with severe degradation of soils, and caused by agricultural mismanagement and deforestation. This idea served as explanation for historic developments like decay and abandonment of cities. However the erosion took place during the last Ice Age and the Younger Dryas. There is no indication that the inanimate landscape changed significantly since the end of the Early Bronze Age. Historic field systems were partially preserved and seem reflected by distinct soil development, indicating that the impact of land use was more complex and less devastating than previously assumed. Human impact on the natural environment seems limited, and certainly not connected with desertification. In this context, northern European misconceptions of how a "natural" landscape should look like may have contributed to negative assessments of traditional agriculture in the Mediterranean. A comparative analysis of soils and colluvia, air photos, historic travel reports, tree rings and climate reconstructions indicates that population growth was behind the flourishing of the region, which took place mostly under favourable climatic conditions. Periods of decline seem triggered by climatic anomalies. As it seems, climate change was previously understood too linearly. Extreme rainfall events can be more devastating than drought, and temperature, wind and rainfall distribution over the year are important as well. Cool and dry periods at the end of the Ice Age were connected with incision and sometimes dramatic erosion. Climatic fluctuations during history may have been connected with pests, famines, plagues and wars which caused dramatic drops of population. The Decapolis region is ecologically sensitive which aggravated the impact of climate variations. Economic recovery took place only when population levels rose again. It is so far unknown how climate will develop under global warming, but it seems very likely that an increasing number of anomalous events would have dramatic impacts on current societies. The key for dealing with global warming seems adaptation to climatic irregularities and fluctuations of the environment.

Zusammenfassung

Desertifikation wird als ernste Bedrohung für mediterrane Ökosysteme und die Wüstengürtel gesehen. Im allgemeinen wird angenommen, dass sowohl menschliche Landnutzung als auch natürliche Klimavariationen zu einem Vorrücken der Wüste beitragen können. Anthropogene und natürliche Faktoren sind dabei möglicherweise in Rückkoppelungen verbunden, jedoch ist noch unklar wie sich globale Erwärmung auswirkt. In diesem Zusammenhang könnte ein besseres Verständnis historischer Desertifikation bessere Vorhersagen ermöglichen. Diese Fragestellung wurde in der Dekapolis-Region in Nordjordanien untersucht, die in der Übergangszone zwischen der arabischen Wüste und dem mediterranen Fruchthland liegt. Eine Reihe von Autoren postulierte, dass dort starke Bodendegradation durch landwirtschaftliches Mißmanagement und Entwaldung verursacht wurde, was als Erklärung für historische Entwicklungen wie die Aufgabe von Städten diente. Die Erosion fand jedoch am Ende der letzten Eiszeit und während der jüngeren Dryas statt. Es gibt keine Hinweise dass die unbelebte Landschaft sich seit dem Ende der frühen Bronzezeit wesentlich geändert hätte. Historische Feldsysteme sind zum Teil erhalten und stehen mit leicht unterschiedlicher Bodenentwicklung in Verbindung, was darauf hinweist dass die Landnutzung weit komplexer und weniger negativ war als bisher angenommen. Der menschliche Eingriff in die Umwelt scheint begrenzt zu sein, und führte sicherlich nicht zu Desertifikation. Eine negative Beurteilung der traditionellen Landwirtschaft im Mittelmeerraum scheint von nordeuropäischen Vorstellungen einer "natürlichen" Landschaft herzuführen. Die vergleichende Untersuchung von Böden, Kolluvien, Luftbildern, historischen Reiseberichten, Baumringen und Klimarekonstruktionen deutet darauf hin, dass Bevölkerungswachstum hinter dem antiken Florieren der Region stand, und vor allem während klimatischen Gunstphasen stattfand. Zeiten des Niedergangs scheinen dagegen mit einer Häufung von Klima-Anomalien verbunden zu sein. Die mögliche negative Wirkung von Klimavariationen wurde bisher eher einseitig in Ernteausfällen durch Trockenheit gesehen. Extreme Niederschläge können jedoch weitaus verheerendere Auswirkungen haben, und Temperatur, Wind und die Verteilung der Niederschläge über das Jahr spielen auch eine wichtige Rolle. Kühle und trockene Perioden am Ende der Eiszeit waren mit Einschneidung der Täler, und zeitweise auch dramatischer Erosion verbunden. Historische Klimafluktuationen könnten ein massenhaftes Auftreten von Schädlingen, Hungersnöte, Seuchen und Kriege ausgelöst haben, die zu einem dramatischen Bevölkerungsrückgang führten und durch die ökologische Sensibilität der Region verschlimmert wurden. Wirtschaftliche Erholung fand erst mit erneutem Bevölkerungswachstum statt. Wenn globale Erwärmung zu einer Zunahme von klimatischen Anomalien führt, könnte dies schwerwiegende Auswirkungen haben.

ملخص

يعتبر التصحر تهديداً شديداً للأنظمة البيئية المتوسطة بالإضافة لأطراف و جوانب الصحراء، و من المفترض أن كلاً من إستعمالات الإنسان للأراضي بالإضافة للتبدلات المناخية الطبيعية يمكن أن تؤدي لتقدم عملية التصحر و تطورها. من المحتمل أن العوامل البشرية و الطبيعية مرتبطة من خلال علاقة أساسية بين الأسباب الرئيسية، و على كل حال ليس من المعلوم ما هو الأثر الممكن و المحتمل على ظاهرة الاحتباس الحراري العالمية، و ضمن هذا السياق فإن الماضي قد يكون المفتاح للمستقبل على أساس الفهم الأفضل للماضي التاريخي للتصحر و الذي يمكن أن يؤدي لتنبؤ أفضل لما يمكن أن يحدث تحت تأثير عملية التبدل المناخي الحالية. هذا السؤال بالتحديد تم البحث عنه في منطقة الإمبراطورية البيزنطية القديمة (ديكابوليس)، التي تمثل منطقة إنتقالية بين بيئة الصحراء العربية و بيئة حزام البحر الأبيض المتوسط، حيث افترض عدد من المؤلفين أن تدهور التربة الذي حصل في الأردن و في الليفانت كان سببه سوء إدارة العمليات الزراعية و إزالة الغابات و هذه الفكرة تم استخدامها لشرح فكرة التطور التاريخي لتراجع المدن و من ثم هجرها. مع العلم أن عمليات الإنجراف الحالية حصلت في و لا توجد أي دلالات تبين أن السمات الأرضية، (Younger Dryas) العصر الجليدي الأخير و في عمليات الجفاف الحديثة و المظهر الطبيعي للأراضي الحالية قد طرأ عليه أي تبدل واضح منذ نهاية العصر البرونزي.

تمت المحافظة على الأنظمة الحقلية التاريخية بشكل جزئي و هي تعكس تطور واضح في التربة مما يؤكد أن تأثير إستعمال الأراضي كان أكثر تعقيداً و أقل إرباكاً و تخريباً مما تم إفتراضه سابقاً. و يبدو التأثير البشري على البيئة الطبيعية محدوداً و غير مرتبط بالتصحر بشكل مؤكد. و ضمن هذا السياق، فإن الافتراض الخطأ من شمال أوربا حول كيف يجب أن يكون المشهد الطبيعي للأراضي يمكن أن يكون قد أدى لسوء تقدير للزراعات التقليدية في حوض المتوسط. إن تطبيقات التحاليل و إعادة تنظيم المناخ تدل على أن النمو tree rings، المقارنة لكل من التربة، الطين، الصور الجوية، تقارير الأسفار التاريخية السكاني هو أساس ازدهار المنطقة و الذي حدث غالباً في ظروف مناخية ملائمة و مفضلة. كما يبدو أن فترات التناقص أو التراجع قد انطلقت نتيجة تبدلات المناخ المفاجئة الغير المتوقعة، و ليس كما هو معروف سابقاً أن تغير المناخ كان يأخذ المنحى الخطي بالتبدل.

إن أحداث الأمطار الغزيرة يمكن أن تكون أكثر تدميراً من الجفاف و الحرارة كما أن الرياح و توزع الهائل المطري على مدار العام يلعب دوراً مهماً أيضاً. كما ارتبطت فترات الجفاف و الرطوبة بشكل بسيط و أدت لعمليات انجراف مأساوية، هذا بالإضافة للتقلبات المناخية التاريخية التي تزامنت إحياناً مع المجاعات، الأوبئة، الكوارث و الحروب التي أدت لتناقص مأساوي في أعداد الناس. إن منطقة ديكابوليس (Decapolis region) منطقة حساسة بيئياً و هذا ما يزيد شدة تأثير التبدلات المناخية، في حين أن عودة العافية الاقتصادية للمنطقة حدثت فقط عند ارتفاع مستويات التعداد السكاني مرة أخرى.

من غير المعلوم، إلى الآن، كيف يمكن للمناخ أن يتطور ضمن ظاهرة الاحتباس الحراري و لكن يبدو من المحتمل كثيراً إن أي زيادة في عدد حالات التغيير المفاجئ سوف تؤدي لتغيير مأساوي و شديد على المجتمعات البشرية.

Terms and abbreviations

AD:	Anno Domini
BC:	Before Christ
EDS:	Energy Dispersive Analytics
FAO:	Food and Agriculture Organisation
GTZ:	Deutsche Gesellschaft für Technische Zusammenarbeit (German Agency for Technical Cooperation)
IRM:	Isothermal Remanent Magnetisation
Latifundia:	Big agricultural holdings
Metropolis:	Very big city in antiquity
OSL:	Optical Stimulated Thermoluminescence
RR:	Redness Rating
SEM:	Scanning Electron microscope
SIRM:	Stable Isothermal Remanent Magnetisation
TEM:	Transmission Electron Microscope
TL:	Thermoluminescence
Wadi:	Arabic word for a valley which is dry during the summer
WRB:	World Reference Base for Soil Resources
WW I:	The first World War
XRD:	X-ray diffraction
XFR:	X-ray fluorescence

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1. Introduction

*Kindliche Anschauungen von Ausländern
haben ohne weiteres Türkenwirtschaft und Araberträgheit verantwortlich gemacht für das,
was Klima und Natur in allen Jahrtausenden hier geschaffen haben,
und dem der Mensch machtlos gegenüberstand.*

Gustav Dalman, "Arbeit und Sitte in Palästina", Band I, 1. Hälfte, p. 209

1.1 A rainy year in Jordan

The winter 1991/92 was very rainy in semi-arid Jordan. This was not only beneficial for agriculture and water supply: it also created huge landslides, hitting the Jordanian water harvesting system unexpectedly. The biggest and most important reservoir, the King-Talal dam in the Zarqa river valley, suffered from vast sediment input from landslides, especially along the Irbid-Amman highway. Approximately 30% of the total sedimentation to the dam during 1980-1997 was deposited in 1991/92 alone (al-Sheriadeh et al., 2000, p. 371, fig. 11), which means this winter with its heavy rainstorms brought as much sediment as ten years of "normal" erosion to the Zarqa river dam. At the same time, Field and Banning counted 290 earth flows and slumps in nearby Wadi Ziqlab (Field and Banning, 1998). If these events would become more frequent, the life span of dams would be much shorter and Jordan's water supply, already now unsustainable due to the pumping of fossil reserves, might become critical. So far, we do not know whether such a development could be triggered by global warming, but if this happens, the impact will be very severe. John Dracup puts it into the following words:

"[...] the possibility of a sudden severe climatic change hangs like a sword of Damocles over arid lands throughout the world. Water systems are built under the single assumption that the means and standard deviations of the annual streamflows will remain stationary [...]. An examination of current hydrologic planning procedures reveals a tendency to deny the potential for climatic change." (Dracup, 1987, p. 217).

Sedimentation in the King-Talal dam was especially significant since a GTZ-funded project for erosion control had just finished constructing field stone walls and terraces in the Zarqa river basin. Whether the effect of the rainstorms would have been even greater if the terraces had not been built cannot be said: but the impact was still impressive enough to raise serious doubts about the performance of such devices. These doubts were further aggravated by the final report of the erosion control project, which had concluded (just before the rainstorms) that the terraces and field stone walls did not fulfill their promises. They were assessed to be a very expensive undertaking – training courses, better education for farmers and more careful use of heavy machinery might have been cheaper and more effective (GTZ, 1991).

Construction of terraces and other devices to control erosion is not only conducted to protect water harvesting systems from sediments, but also as general means to combat desertification, a phenomenon presumably threatening the desert belts and the Mediterranean. But can such devices

really stop the advance of the desert, or will they crumble away once hit by extreme events like the rainstorms in the Zarqa river basin? The failure of this erosion control project might be connected with the comparatively short instrumental climate records which are available up to now. Therefore the look into the past could be a key to better predict what might happen in the future. The present thesis targets past and present desertification: can we learn from the past how to better adapt our land use strategies; and can we use recent experiences to better understand what happened in the past? Let us first consider what desertification means.

1.2 Desertification and climate change: is the past telling the future?

According to UNCCD (1992), desertification is defined as "... land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities", while land degradation means "reduction or loss, in arid, semi-arid and dry sub-humid areas, of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as:

- (i) soil erosion caused by wind and/or water;
- (ii) deterioration of the physical, chemical and biological or economic properties of soil; and
- (iii) long-term loss of natural vegetation".

The focus of activities to combat desertification is usually on preventing soil erosion, as it is assumed to be its ultimate, irreversible outcome. Soil loss does not only mean silting of dams, but also vanishing agriculturally productive land. In this context, desertification is described as feedback process. Overgrazing leads to reduced vegetation, connected with a higher albedo, which is followed by lower net radiation (cooler soil), so there is less convection, less rain, and subsequently less vegetation which aggravates overgrazing (Williams and Balling, 1996). Reduced vegetation also leaves the soil more vulnerable to erosion, so that rainfall may not be absorbed and produce lush green, but instead remove soil, which again has a negative feedback on vegetation growth (fig. 1).

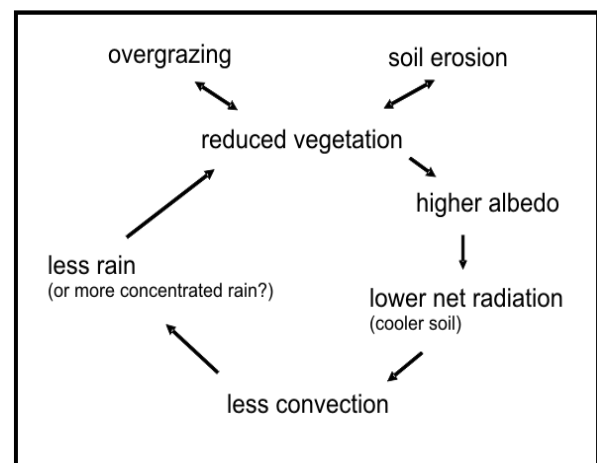


Figure 1: Self-supporting feedback circle of desertification according to Williams and Balling (1996).

However, deserts are not the result of a lack of water vapour in the atmosphere, but of atmospheric circulation on a large scale (some deserts, like the Atacama in Chile, have a lot of moisture in the air but no precipitation). Single factors like the albedo might not be as important as previously assumed: for example, the role of evaporation from the soil could be at least equally relevant (Wurtele, 1987). But it is clear that the land surface, expressed by factors like soil type, vegetation cover, leaf area index or root depth, plays an important role for meteorological processes. The problem is a fluid dynamics one: without proper knowledge about the role of each factor, any attempt to reverse desertification will be uncertain (Wurtele, 1987).

Although desertification has been investigated since the 1960s, it was during the 1990s that major research and development aid projects were launched. Satellite images seemingly showed an expansion of the North African desert belt, almost suggesting that the desert was about to migrate into the Mediterranean fruitland, "knocking at Europe's door" (Hill et al., 2004). The threat seemed imminent: if desertification was not stopped, the vicious feedback-circle might reach dimensions that would be out of control, with dramatic consequences for the environment, economy and politics. Thus money was made available for projects combating desertification, and research to better understand the phenomenon. The outcome was considerable: ranging from fundamental, well-advised criticism (Thomas and Middleton, 1994) to the MEDALUS (Grove and Rackham, 2003, Thornes et al., 1996) and ARCHAEOEDEDES (van der Leeuw and the ARCHAEOEDEDES research team, 2005) research projects which significantly improved our understanding of desertification. In 2007, the desert has still not invaded Europe and public interest fell to lower levels – now terrorism and global warming are the keywords necessary for attention. These might however not be independent from the development which is called desertification, an issue to be discussed in the final chapters of this thesis.

An important point about desertification is that it seemingly already happened in the past. The ruins of once splendid Roman cities in places which are today deserted seem to prove that we are not the first to observe an invasion of sand and rock. Lowdermilk (1944) witnessed how fertile soil in Palestine was eroded and swept into the sea: a development he considered connected with, and aggravated since the Muslim conquest. When he wrote his ideas down, the "dust bowl" had just struck the U.S. agriculture, making clear that extension of farming into desert belts might be unwise if not managed very carefully. Lowdermilk assumed that the Romans and Byzantines knew this problem from long experience and were very careful managers of land and soil, but when the Muslims conquered the area, they brought their herds of goats and sheep, overgrazing, and little understanding of terrace maintenance and soil protection. So they produced the bare, rocky hillslopes visible today, and eroded silt blocking the drainage system, thus creating malaria-infested swamps. As seen in fig. 1, the erosion

might ultimately have changed the climate, rendering any small-scale rehabilitation of the area impossible. So the desert-dwellers brought the desert with them, and it is only foreign initiatives which make a change to the better possible?

Not only erosion might explain the abandonment of once flourishing ancient cities. Archaeologists claim that no environmental change is needed for the demise: political and economic reasons, earthquakes, diseases and other catastrophes might fully suffice (Walmsley, 1992). And natural climate change, not produced by land degradation but creating it, is another thesis that was as simple as popular before the dust bowl (Huntington, 1911). Distinction is difficult to draw: both mismanagement and natural climate change might lead to land degradation, and be connected in feedback relationships. Separating these two is thus a major objective of this thesis.

1.3 The Decapolis region in Northern Jordan

The events in winter 1991/92 made clear that the understanding of erosion in Jordan was still insufficient, and a key to improve it could be the look into the past. Jordan is characterized by numerous ruins of once impressive ancient cities, which might resemble victims of environmental deterioration. If it would be possible to understand their demise in the light of environmental change, this might be a key for assessing current land use strategies and predicting future developments. If ancient land use was unsustainable and contributed to the abandonment, we need to know more precisely when, where and why it created deterioration, and how it looked like exactly. If climate changed already during the past, it would be crucial to understand how this was connected with land use and how its effects on the soil looked like, which might also help to better understand what will happen under global warming. These questions were the beginning of the present work, first conducted as a master thesis with a case study at the site of Abila in Northern Jordan (Lucke, 2002), and now extended to a greater area. The above mentioned questions target, after all, the basics of the phenomenon of desertification: is it a process governed by human action, or merely a natural development?

The Decapolis¹ region in Northern Jordan (fig. 2) was chosen as investigation area, as it provides excellent and unique research opportunities. It includes three different landscapes with distinct

¹ "Decapolis" is a Roman administrative term describing a league of cities that existed in the region during the Roman and Byzantine period. It is applied to delineate the region geographically, as the Roman ruins are the best-known feature of the area. But for the sake of clarity it has to be mentioned that some of these settlements existed since the Early Bronze Age and were part of changing political entities, and some lie in what is today Syria and Israel.

1. Introduction

climates in a small area, but experienced a common history and land use (Walmsley, 1992; Hoffmann and Kerner, 2002). This makes it possible to directly compare an alluvial plain (the Jordan valley), a Mediterranean highland, and a transition area to the Arabian desert – all those characterised by different precipitation and availability of irrigation water (National Atlas of Jordan, 1984). The geological structure is well known (Blackenhorn, 1920; Wolfart, 1967; Bender, 1974; Horowitz, 1979; Peuckert, 1989; Moh'd, 2000) and consists basically of only two source rocks: limestone and basalt, making a comparison of soil development with regard to the source rock promising. The geological layers show little folding and are ordered nearly horizontally (Koeppel, 1930). As well, climate reconstructions are available from speleothems (Bar-Matthews et al., 1998) and the Dead Sea (Bookman et al., 2004, Migowski, 2004), and other proxies such as relic soils (Gvirtzman and Wieder, 2001) and wadi deposits (Moumani et al., 2003). An excellent summary of available data on past climate was compiled by Issar and Zohar (2004).

The ruins of the Decapolis cities are very famous and important places for cultural tourism. Their fame is due to the fact that much of the monumental architecture from the Roman and Byzantine period has been preserved, as it has not been reused in later construction activities (Hoffmann and Kerner, 2002). Rain-fed agriculture in the vicinity formed the economic basis of the Decapolis cities (Fuller, 1987) as well as earlier settlements (Geraty and Herr, 1989). Agriculture in this region must have exceeded subsistence economy and produced a considerable surplus, able to supply food to huge cities (e.g. up to 12.000 individuals

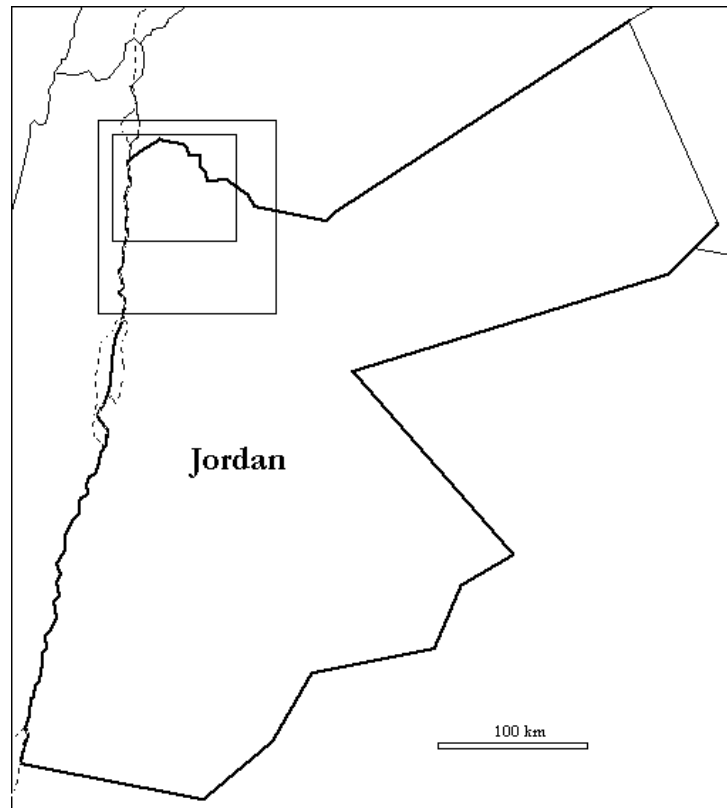


Figure 2: Approximate location of the Decapolis region (big box) and the investigation area (small box).

in Abila) and allowing the construction of impressive buildings (Fuller, 1987, Fahlbusch, 2002). Archaeological excavations indicate that the present land use is very similar to the past: wheat, barley, vegetables and olives are grown on the fields, while orchards exist in wadis which are suited for irrigation. As well, vegetables are irrigated if water from springs or cisterns is available.

Most soils in the investigation area are characterized by red colour (Red Mediterranean Soils or *Terrae Rossae*²). Only sloping areas show mostly greyish-white soils. The origin of *Terrae Rossae* is discussed: Reifenberg (1947), Bronger and Bruhn-Lubin (1997) and Bronger and Sedov (2003) state that *Terrae Rossae* are derived from the underlying rock, and date back to the Pleistocene or earlier. Because limestone produces little residue, it would take a very long time or intensive weathering (high rainfall) to produce the soils visible today. So it is assumed they formed under moister conditions than today, or are very old, or both. The red colour is caused by hematite, a typical mineral of subtropical soils forming under semi-humid and semi-arid conditions (Cornell and Schwertmann, 2003). It was believed that the presence of hematite is an indicator for moist warm climates with a seasonal alteration of precipitation and drought; however Bronger et al. (1984) showed that it could be inherited from pre-weathered minerals which had been deposited with the sedimentary calcareous rocks.

According to Yaalon and Ganor (1973) and Yaalon (1997), the main parent material of *Terrae Rossae* in Israel and Jordan is not the underlying rocks, but aeolian dust, which is brought from the Sahara and Sinai and deposited with precipitation. This input is too slow and steady to be observed in the profile, as the aerosols are mixed with the solum by bio- and peloturbation, but is most significant for soil development. According to Frumkin and Stein (2003), the intensity of aeolian transport and deposition is connected with moisture and vegetation in the Sahara, was interrupted during a moist interval in the Early Holocene, but resumed and is still ongoing. However Jahn (1995) examined circumsaharian soils and found that at humid sites in the Golan heights, only 2-5 % of the soil bulk originated from long-distance aerosol input. Dust additions from local sources were even smaller. But Jahn found 20-40 % dust input in a paleosol of Pliocene age and assumed the same was valid for most Vertisols in the area (Jahn, 1995). According to Issar and Bruins (1983), aeolian input was limited to the last glacial period (100,000 – 10,000 BC). But it might obscure part of the land degradation if it was intense since abandonment of the Decapolis.

The Red Mediterranean Soils in Jordan and Israel are considered to be degraded (Horowitz, 1979). Several authors postulated that historic mismanagement and erosion were responsible for the abandonment of ancient sites (Lowdermilk, 1944; Dregne, 1983; Hillel, 1991), although it was never proven that the erosion is man-made and not natural (Geraty and LaBianca, 1986). In this context, the case study at Abila found slight differences of soil development, which seemingly follow old field borders (Lucke, 2002, Lucke et al., 2005). This would imply that land use did impact soil development, but did not lead to major erosion, since that would have erased the observed differences – an issue which is further investigated with this thesis.

² Singer et al. (1998) suggested that a Terra Rossa is characterized by a pH less than 7 and free of CaCO₃, or otherwise to be called Red Mediterranean Soil (or Rendzina). This is not followed here: Terra Rossa and Red Mediterranean Soil are used as synonyms (see chapter 2.3.4).

2. Methods

*Sometimes one can't see the forest
because of so many trees.*

German saying

2.1 Desertification: complexity

As outlined in chapter 1, desertification is a very complex process governed by several variables which influence each other. It is thus not possible to conclude for the general picture from a single factor alone, and research has to be conducted interdisciplinary. This can well be illustrated by the Argolis in the Peloponnese (Greece), a famous example of interdisciplinary work. The Argive plain is an extremely well investigated area, examined for decades by Tjeerd van Andel and his interdisciplinary research team (Jameson et al., 1994). Focusing on alluvia, Pope and van Andel (1984) identified seven comparatively short periods of sedimentation, which interrupted periods of stability and soil formation. The three earliest instabilities took place during and after the last glacial interval (~330,000 – 30,000 BC). The next period of landscape instability took place during the Early Bronze Age (2500 BC), followed by stability and another brief phase of sedimentation 300 – 50 BC (Pope and van Andel, 1984). After that, landscape remained stable until approximately 1000 AD, followed by a complicated local pattern where erosion continues in some areas until today. This basic situation was confirmed by later investigations, for example by Fuchs et al. (2004) in the nearby Phlious basin. Fuchs et al. (2004) were able to date sediments very precisely using Optical Stimulated Luminescence (OSL), and peaks are coincident with the Neolithic, the Early Bronze Age, the Roman period, and the Ottoman and modern time. In general, an increase in the sedimentation rate could be observed beginning with the introduction of agriculture, and since the classical period, which Fuchs et al. (2004) attributed to more intensive land use connected with population growth. Pope and van Andel (1984) arrived at a similar conclusion: they discussed the impact of eventual climatic variations in comparison with the impact of land use, and summarized that climatic events cannot sufficiently be correlated with the nature and chronology of sediments. Thus land use, especially deforestation, was supposedly the main agent of landscape change.

However, it is very difficult to assign increased erosion to a single cause-and-effect relationship with land use. As Pope and van Andel (1984) point out, not only intensification of agriculture, but also land abandonment might lead to erosion. This is especially true when terraces are not completely abandoned, but used in low intensity without keeping them well maintained: the continued use prevents forest regeneration, while damaged terraces are very prone to gully formation. Also, there is no direct correlation of the Argolis sediment record with the settlement history: Neither the expansion of agriculture during the Late Helladic period is reflected, nor the widespread abandonment during the Dark Age (Protogeometric). As Pope and van Andel (1984) describe it:

"The subsequent long period of landscape stability, lasting through the Classical period, is somewhat of an enigma. Some kind of soil conservation, probably terracing, must have been employed. The evidence for increased runoff and sediment yield in Late Classical to Hellenistic times is consistent with terrace degradation during economic decline, yet the presence of widespread terracing during this period has not been confirmed" (Pope and van Andel, 1984, pp. 302-303).

Butzer (2005) re-evaluated the evidence from the Argolis in the light of a detailed pollen core from lake Lerna, which had been studied by Jahns (1993). According to Jahns (1993), an open, deciduous oak woodland with tracts of maquis and weedy fields was present in the Argolis during 6200 – 5200 BC, reflecting Neolithic land use. This turned to dense forest from 5200 – 3600 BC, which was partially cleared 3500 – 1600 BC. The pollen evidence suggests a fairly modest land use intensity with slowly increasing maquis and olives. It was only during 1600 – 1050 BC that the pollen core shows intensified agriculture for the first time, but tree harvesting seemed still in balance with regrowth, although there might be reduced diversity, perhaps due to selective cutting. The Dark Age 1050 – 800 BC is represented by a short spike of deciduous oak, suggesting only a brief quasi-abandonment followed by large-scale olive cultivation. During 800 – 300 BC, oak declined further, reaching the level of the classic Mediterranean landscape as visible today. But beginning in 300 BC, this landscape began to change again. Evergreen oak increased, followed by pine and deciduous oak, and olive collapsed stepwise until 700 AD – and there is no evidence of a Late Roman agricultural revival, or continuous pastoral pressure. In contrast, the phenomenal expansion of chenopodiaceae suggests extensive deserted farmland. In the 10th century AD, pine invaded at the expense of evergreen oak, suggesting a landscape of subsistence farming in the lowlands, with pine and dwarf juniper in the uplands. Olive cultivation resumed to a major extent only after the Greek independence.

Butzer (2005) suggested the apparent contradictions of the pollen and sediment record might be connected with different technologies and cumulative experience of farmers, so that similar populations might produce different environmental impacts. As well, he stressed the "political economy". This is the societal framework which in conditions of stress (such as oppression, warfare or famine) might turn away from the "good practise" demanded by ancient agricultural writers, in order to maximise short-term benefits necessary for survival. Yet even in this context, it is interesting to note that the Roman and Hellenistic periods are reflected in the pollen core with a sorry state of conservation practise, apparently contrasting the wealth of their monuments and agricultural principles as outlined e.g. by Columella (1972). Butzer (2005) also reviewed the sedimentary evidence again, and found that most of the colluvia might reflect episodes of catastrophic slope failure. The best

2. *Methods*

explanation for these instabilities would be excessive high peak discharge due to heavy rainfall. According to Butzer (2005), they would however not have been so destructive if man had not cleared the slopes and thus paved the way for the floods. Comparing the evidence from the Argolis with a case study in southern Spain, Butzer (2005) showed that there was no linear trend towards degradation, but a complex alternation of landscape changes – and change does not necessarily mean degradation, even if it is irreversible. He concludes that cause-and-effect relationships must be studied inductively: natural and social sciences have to be combined.

It should be emphasized that desertification is not necessarily the invasion of a desert. The Mediterranean and the settled part of Jordan are not countries of bare rock or sand: the Decapolis cities never laid in a desert (although the desert is very close). Desertification does not mean that all the soil is lost: Regarding the example of the Argolis, Jameson et al. (1994) concluded that a maximum of 40-70 cm of plateau soil were eroded since the classical period. This means the physical landscape did not look very different from today. These 40 cm however could make a decisive difference, since a soil's fertility is usually connected with the topsoil and its organic matter. Erosion can be seen as a symptom of land degradation – the real problem is not loss of soil material, but of soil productivity. In this context, nutrient depletion can be a causative factor of soil erosion. When crop removal leads to depletion of N and P in the soil, root growth is reduced, and the soil structure becomes weaker due to less organic matter which means higher susceptibility to erosion. Erosion however might lead to preferred removal of nutrient-bearing topsoil – and again we are in a feedback relationship, the question is only whether nutrient depletion or erosion came first. As well, with nutrients deficiency (like N, P, and K) plant biomass below and above ground is reduced which might further increase the soil's vulnerability. The above described importance of soil fertility is one of the reasons why the final report of the erosion-control project in the Zarqa-river-basin concluded that integrated land management strategies, such as intercropping and periodic cultivation of leguminosae might be more important and effective than the mere construction of soil-retaining devices (GTZ, 1991).

The Roman and Byzantine periods are reflected all over Jordan by small, weathered botsherds from domestic garbage. These are the remains of ancient manure. The Roman agriculturist Columella (1972) provides a detailed description of different kinds of manure, how they have to be collected and treated, and which is best for which crops. In fact, this Roman technology was only re-discovered with the agricultural revolution, when the breeding of livestock in stables, combined with intercropping and systematic appliance of dung, led to a steep increase of productivity already before the introduction of mineral fertilizers (Müller, 1986). As a side effect, the agricultural area in Europe was enlarged by 30% since fallow periods became unnecessary. According to Kron (2004), the Roman agricultural mastership

might be represented by skeletons from the Imperial period being taller and better-nourished, and with evidence that much larger cattle varieties could be bred than during the earlier and later periods. As well, Roman fish farms might have been highly productive, even more productive than comparable farms today, providing a remarkably protein-rich diet (Kron, 2006). In this context, the success of the Roman empire as well as the rapid European development in the 19th century might be closely connected with advances in the agricultural sector.

Details matter: it should be mentioned that livestock during the medieval period – in contrast to the Roman Imperial time – was most important not because of its meat or milk, but because of its dung that fertilized fallow fields in the three-field-rotation system (Müller, 1986). But livestock never played this role in the Islamic world, since beef is not a preferred diet. Pigs could deliver similar services, but pork is not eaten, while the available dung from sheep and goats was usually collected as fuel for fires (replacing the scarce or absent wood). Therefore it might not be necessary to postulate neglect of terraces during the Islamic period. A lack of agricultural skills alone might have made it impossible to maintain the productivity of the land. In this case, desertification as result of land degradation might not necessarily be reflected by huge amounts of eroded soil - the loss of some topsoil might have sufficed to sharply reduce fertility.

2.2 Combining evidence

The review of research in the Argolis makes clear that only a combination of methods can provide further insight into desertification – a more specialised strategy might produce more data, but less understanding. Therefore this thesis applies a combination of methods, which had to be restricted limiting the amount of data, but still provided enough to link the evidence meaningfully:

1. As core method, soils and colluvia were examined, comparing them according to different source rocks, landscape types and precipitations. This should make it possible to identify the main soil forming factors. Relic soils associated with archaeological ruins were used to gather information about ancient soil properties, and to obtain dates for soil development.
2. In cooperation with archaeologists and historians, information about past land use intensity, farming strategies and settlement intensity was gathered.
3. As well, historical sources and studies examining them were reviewed.
4. To get an impression about more recent land use changes, sets of air photos and satellite imagery covering the period 1918 – 2000 were studied.

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5. The vegetation was considered using tree rings, as these provide a terminus post quem for the abandonment of land use structures and additionally deliver information about local climate patterns.
6. Finally the literature about desertification and erosion control projects, including the database of the National Soil Map and Land Use Project of Jordan (NSM&LUP, 1993), was reviewed in order to connect today's evidence with the past and to interpret the data with regard to soil fertility.

The principle of combining evidence was also followed when selecting sites for soil sampling (complemented by the coring of trees and air photo evaluation; see fig. 3 for the distribution of the sampling sites):

- One profile was studied in the Jordan valley: an alluvial plain and sediment trap.
- Colluvium in Wadi Ziqlab, previously studied by Field and Banning (1998) and Maher (2005), was sampled at one profile in cooperation with Lisa Maher in order to complement the available thin section evidence with analyses of bulk soil.
- The Wadi el-Arab, which provides a natural east-west "cut" through the region, was surveyed systematically. It was sampled at several locations, including different soil and colluvia types, seven of which were analysed for thesis.
- One profile and a surface sample were examined from a soil developed on a basalt plateau close to Umm Queis. This is the only examined in-situ basalt soil: due to the very homogeneous distribution of this soil (sharply contrasting with the limestone soils), one profile seemed representative enough.
- Soils around the sites of Abila and Beit Ras in the Mediterranean highland, already studied during my master thesis, were re-examined comparing six in-situ profiles and five colluvia, and compared with some surface samples in a similar environment close to the village Qumeim.
- From the deeper soils further east (towards the desert), one profile from a building pit in the city Irbid was partially analysed; as well as a profile with a paleosol under a basalt flow, close to the village of Amrawah.
- Two surface samples were taken from desert soil close to Queen Alia airport for the sake of comparison. Red paleosols in the steppe and desert were sampled, but not analysed in the framework of this thesis, as its focus is on the agriculturally productive soils.
- Finally, relic mudbrick and soils in and under archaeological ruins were studied in cooperation with archaeologists: at Tell Zera'a (in cooperation with Dieter Vieweger), at Abila (in cooperation with David Chapman), and at Jerash (in cooperation with Alan Walmsley).

2.3 Methods of analysis

2.3.1 Soil analysis

The principle of combining evidence was also followed when selecting the methods of analysis. For soil analysis, a combination of physical and chemical parameters was applied. The importance of combining physical parameters, such as grain size, with chemical properties, such as iron oxides and weathering indexes, has been demonstrated by Bäumler (2001) for soils of different source rocks and climates in the Himalaya, Central Asia and Kamchatka. In addition, a selection of samples was examined for its magnetic properties since Cordova (2000) showed how revealing these analyses can be for Jordanian soils. Also, thin sections of the most important soil and rock types were made and examined with a Scanning Electron Microscope (SEM). And last but not least, OSL-dating was tested with two samples.

In detail, analyses were conducted as follows:

– Sampling:

Soil profiles were opened down to the bedrock, and excavation trenches, gullies, street cuts and building pits studied. For collection of soil samples, freezer bags were filled from a ca. 5 cm thick strip in the middle of the identified layers/horizons. In existing trenches, the outer 5-10 cm were removed to exclude influence from material washed down from above. In the C-horizons, samples were taken from areas which in their optical appearance were not yet altered by weathering. Sampling locations were recorded with a GPS Garmin Geko 201.

– Sample preparation:

The samples were air-dried for 48 hours at 40° C and then sieved by 2 mm. The fraction > 2 mm (skeleton content) was determined and archived, and all further analyses conducted with the fraction < 2 mm.

– Colour:

Colour was determined in the laboratory under standardised light, using the Munsell soil colour chart. Both dry and water-saturated colours were examined, and the Redness Rating (RR) computed with the dry samples according to Hurst (1977). It is calculated according to the formula: $RR = H * \text{Brightness} / \text{Chroma}$, where H is: 5R = 5, 7.5 R = 7.5, 10 R = 10, 2.5 YR = 12.5, 5 YR = 15, 7.5 YR = 17.5, 10 YR = 20 (the index becomes the smaller the redder the soil). For example, 10 YR 8/1 = 160, and 2.5 YR 4/8 = 6,3.

The RR from wet samples led to less stable numbers, and the calculation of RR as proposed by

Buntley and Westin (1965) and modified by Cordova (2000), or Torrent et al. (1980) produced results which were less consistent than the original index of Hurst. Torrent et al. (1983) state that hematite content is most relevant for red soils, since hematite is much stronger colouring than the other iron oxides and will give the soil a red appearance even if present in only low concentrations. They thus based their index calculation on hematite contents. However for the case of the Decapolis region, the index proposed by Hurst (1977) which is based on total pedogenic iron oxides, produced results which much better fitted field observations and soil properties than Torrent et al.'s (1980) index.

It has to be mentioned that even with the help of the Munsell chart, determining soil colour is a subjective undertaking, and errors multiply with calculation of RR. Internal tests showed that different observers can assign different values. But since colours were determined by only one person and under standardised light, at least the tendencies should be reliable. It was decided to examine the colour only after sieving the samples by 2 mm. Its determination proved more difficult and erratic when the soil skeleton was still included, as it could represent a very considerable fraction of the soil. But this is another source of error to keep in mind when using colour for the interpretation of field evidence. The same has to be said about the moisture content, because natural soils are usually not completely dry.

Application of a colour spectrometer (Minolta C300) was considered, but finally not conducted. A more comprehensive study would be needed to evaluate the role of moisture, skeleton, iron oxides, CaCO_3 , light and organic matter for colour.

– pH and electrical conductivity:

The pH was determined with a glass electrode (pH-meter 530 by WTW, with electrode InLab 423 by Mettler-Toledo) in distilled water, with a soil:water solution of 1:2,5. Electrical conductivity was measured with a GMH 3410 conductivity meter by Greisinger electronic in a soil:water solution of 1:5 (according to Schlichting et al., 1995).

– Contents of calcium carbonate and organic matter:

Contents of CaCO_3 and C_{org} were determined using a Leco TrueSpec C/N-analyser. Samples were finely ground and examined in doubles in the C/N-analyser, which delivered the total C- and N-contents. Additionally, ignition loss was determined according to Schlichting et al. (1995): the samples were heated for two hours to 430 °C, which is supposed to eliminate organic matter, but not to expel CO_2 from calcium carbonate (which should start only when reaching 825 °C, see Merck index of chemical drugs, 1996). These samples were then analysed in the C/N-analyser, too,

so that C_{org} could be calculated from the difference after correcting the second C-content by the weight loss caused by ignition. This allows to also calculate the CaCO_3 -content under the assumption that the remaining inorganic carbonates are fixed in form of CaCO_3 (which is indicated by the thin sections and SEM-analyses, as there was no evidence for the presence of dolomite). As long as no dolomite is present, the above described method should be the most precise to determine contents of CaCO_3 and C_{org} in soils.

– Texture:

Particle sizes were analysed after removing CaCO_3 with 10% hydrochloric acid (until no visible reaction occurred any more), since pedogenic calcium carbonate forms complexes and would pretend a much coarser texture than in fact present. Hydrochloric acid (HCl) was washed out again and those samples with $C_{\text{org}} > 2\%$ treated with 30% hydrogen peroxide (H_2O_2) in the warm waterbath ($\sim 50\text{ }^\circ\text{C}$), until no visible reaction occurred any more. This should delete the compounding impact of organic matter. Hydrogen peroxide was evaporated and particle sizes determined after dispersing the samples with sodium hexametaphosphate ($\text{Na}_4\text{P}_2\text{O}_4$), which prevents coagulation of clay particles. Wet sieving determined the sand fraction (according to DIN 19683, 1973), while the smaller particles were analysed with the sedimentation analysis according to Köhn (Schlichting et al., 1995). A problem was encountered when testing the washing of hydrochloric acid only with pH: the sedimentation analysis produced a huge error which turned out to be connected with insufficient removal of chloride-ions, having a coagulating impact as would calcium-ions. Therefore the removal of chlorine was tested with 0,1 M silver nitrate solution (AgNO_3), which immediately precipitates as long as chlorine ions are present. This made it possible to extinguish the errors from the sedimentation analysis. But it also means that the textures published by Lucke et al. (2005) and Schmidt et al. (2006) are skewed towards the silt fraction, due to insufficient washing: in fact clay values are much higher. Since the use of a laser diffraction device does not allow an error calculation, this mistake could not be noted by Lucke and Schmidt. As well, laser diffraction devices might generally underestimate the clay fraction in when applied to natural soils (Konert and Vandenberghe, 1997). Although these authors offered a mathematical solution for this problem, which was applied by Schmidt et al (2006), it seems that all textures of soils in the Decapolis region that were determined with a laser diffraction device can be discarded. Sinowski (1995) systematically compared the methods of texture analysis and found that laser diffraction devices are not generally unreliable, but produce an error which becomes the greater the fine the soil is.

2. Methods

– Bulk density

The bulk density was determined in one case by collecting soil in a container of known volume (film canister), drying for 24 hours at 105 °C, and weighting the soil. Bulk densities of Terrae Rossae were not determined, since the hard lumps would require saran resin impregnation (Brasher et al., 1966), but the expected results did not justify this work-intensive pre-treatment.

– Iron and manganese oxides, aluminium

Pedogenic iron oxides were extracted with sodium dithionite at room temperature according to Holmgren (Schlichting et al., 1995), and the iron, manganese and aluminium contents measured with an atomic absorption spectrometer (M-series by Unicam, thermo-flame-spectrometer). As well, weakly crystallized iron oxides were extracted in the dark using buffered (pH 3.25) oxalate-solution according to Schwertmann (Schlichting et al., 1995). Their iron, manganese and aluminium contents were determined with the atomic absorption spectrometer (AAS), too.

– Total element contents

Total element contents were examined with X-ray fluorescence analysis (XRF), but only a part of the results was available until submission of this thesis. A wavelength-dispersive sequency spectrometer type PW 2400 was used, and samples prepared according to DIN 51001 (2003).

– Magnetic properties

Magnetic properties were examined with the help of Norbert Nowaczyk in the lab of GFZ Potsdam. The bulk susceptibility was determined using a Kappabridge KLY-3S magnetic susceptibility meter (875 Hz), using the sieved but otherwise untreated fine soil < 2 mm in plastic containers. The frequency-dependent magnetic susceptibility was analysed using a Bartington MS2 magnetic susceptibility meter, operating at 460 Hz (low frequency), and 4600 Hz (high frequency). To determine S-ratio and remanence acquisition, samples were magnetised with a 2G Enterprise 660 (0 - 2 T) and a MMPM 10 (2.1 - 10 T) pulse magnetiser. Before magnetisation, samples were stabilised using Araldite A2020 epoxy resin. Remanence was measured in a Molyneux Minispin spinnermagnetometer, with the S-ratio calculated after applying fields of 2 T and -200 mT.

– Thin sections and scanning electron microscopy (SEM)

Thin sections were prepared with the help of Michael Köhler and Gabriele Arnold in the laboratory of GFZ Potsdam, taking advantage of the soil's tendency to form lumps when dry. These lumps could be collected easily and remained stable. After freeze drying the samples were stabilised using Araldite A2020 epoxy resin. The thin sections received a diamond-polishing (in the GFZ Potsdam)

and in one case a lead-antimon polishing (by Andreas Ludwig in the mining museum Bochum). For examination at the SEM with the help of Helga Kemnitz (in the GFZ Potsdam, using a SEM type DSM 962), thin sections were steamed with gold-palladium and in one case with carbonate.

– Optical Stimulated Luminiscence (OSL), and ^{14}C

In contrast to the unreliable Thermoluminiscence (TL), Optical Stimulated Luminiscence (OSL) is an advanced dating method (but which is based on the same principles as TL), which produces very precise results and is excellent for investigating historical periods (see Fuchs et al., 2004). OSL-dating was conducted with the help of Christian Goedicke in the Rathgen-Laboratory in Berlin, again taking advantage of the clay-rich soil's tendency to form lumps. These could be rasped out under red light. Removing the outer 1 cm should delete the impact of exposition to light during sampling. Quartz-based OSL was measured with a Riesø TL-reader DA-12 (Aitken, 1985), with a SAR-protocol according to Murray and Wintle (2000). β -background radiation was calculated from the XRF-values, while α - and γ -background radiation were determined using a gamma-spectrometer type Master 919 (EG&G). Only two OSL-dating analyses were performed in the framework of this thesis, and only with a single sample each, in order to test the methodology. It produced strong signals and very meaningful results, which were counter-checked by ^{14}C -analyses on soil organic matter, charcoal and carbonised olive seeds in the C-AMS laboratory in Erlangen. For investigations like in the Decapolis region, OSL seems to be the best available dating technology.

2.3.2 Air photo analysis

Air and satellite images were examined for field patterns and forest coverage, but only a small part of the collected images was analysed in the framework of this thesis. The aim was to get a basic understanding of how stable the observed field systems are, how they are related to the terrain, and how forest coverage developed. This evidence was connected with descriptions of the area from earlier travel reports. Last but not least, at some places it was tested how distinct soil properties were reflected in the air photos.

2.3.3 Tree ring analysis

In total 20 trees were sampled with a core driller. These included 13 deciduous oaks (*Quercus ithaburensis*), one evergreen oak (*Quercus calliprinus*), one carob tree (*Ceratonia siliqua*), two olives (*Olea europea*), one mulberry (*Morus spec.*), one chestnut (*Kastanea sativa*) and one pine (*Pinus spec.*).

Aim was on the one hand to achieve an age estimate for the natural reforestation in the region which had been reported by travellers of the 19th century. On the other hand, it should be tested how soil properties impacted tree growth, and whether the tree rings would show local variations pointing to different local climatic patterns. Finally, the selection of trees should deliver an indication whether evergreen trees were suited for ring analysis. Rings were measured in the tree ring laboratory of the German Archaeological Institute (DAI) Berlin with the help of Uwe Heussner, who also borrowed me the drills.

2.3.4 Nomenclature and soil classification

Several classification systems were already applied to name soils in the investigation area. For the sake of simplicity, this thesis uses Reifenberg's (1947) and Moormann's (1959) designations as they are the least detailed – I think that more precise classifications might be misleading or reduce the clarity of argumentation. In the future, the recently published World Reference Base for Soil Resources (WRB, 2006) will be applied. But this is outside the scope of this thesis and has been discussed elsewhere (Pietsch and Lucke, submitted). However in order to avoid confusion about soil types due to the use of different classification systems, the main features of names which have already been used are shortly outlined below.

Reifenberg, 1947, and Moormann, 1959:

According to Reifenberg, soils that develop on limestone are *Terrae Calcis*. The red soils of this group, *Terrae Rossae*, are characterised by high clay contents, red colour and neutral to slightly alkaline reaction in the topsoil. They correspond to the Red Mediterranean Soils of Moorman (1959). Softer limestones and marls weather to Mountain Marl Soils, which Reifenberg also calls *Rendzina* (although they can have a different genesis than the *Rendzina* in the German soil classification system). They are characterised by a high content of CaCO_3 (50% and more) and grey colour, and can sometimes hardly be distinguished from the soft source rock. On basalt, soils formed that are similar to *Terrae Rossae*, but Reifenberg calls them *Basalt Soils*. Moormann's (1959) system adds the terms *Yellow Mediterranean Soils* for the soils in transition to the steppe, and *Yellow Soils* for the steppe and desert soils.

The Durham survey (Fisher et al., 1968):

A systematic investigation of soils was initiated by the University of Durham in the 1960s. It basically

referred to Reifenberg's classification, but added several new terms. Brown Limestone Soils were introduced as an intermediate between Terra Rossa and a new group called Grey Limestone Soils. Brown Limestone Soils are characterised by a coarser texture than Terra Rossa and the content of CaCO_3 is higher. The Grey Limestone Soils are an equivalent to what Reifenberg named Mountain Marl Soils. The Durham investigation differentiated Rendzinas from the Grey Limestone Soils: the term Rendzina is used to describe a deeper soil which can be separated from the source rock and is characterised by a light grey to pale brown colour, while the Grey Limestone Soils do not allow to draw a clear border between the soil and soft rock. The term Brown Cherty Soils was applied to substrates which are characterised by a high content of siliceous and cherty facies but have qualities similar to the Brown Limestone Soils. Substrates which were formed out of infill from surrounding crests are called Brown Bench Soils, and are characterised by heavy texture while clay content and red colour intensity increase with depth. On slopes, the Durham survey distinguished Brown Slope Soils (a slope equivalent to Terra Rossa), Grey-White Slope Soils (a slope equivalent to Mountain Marl Soils) and Yellow Brown Slope Soils (Mountain Marls with an admixture of sandstone, but which is not present in investigation area). In the wadis, Alluvial Soils are formed along wadi floors and wadi terraces, and their characteristics depend on the sedimentation history.

The Zarqa river basin soil survey (GTZ, 1986):

The Zarqa river basin project, carried out by GTZ and the Ministry of Agriculture 1986 – 1990, based its soil classification on the physical properties of soils. Only three categories used: Red And Dark Coloured Cracking Clays, Red And Brown Non-Cracking Clays, and Clay Loams With A Surface Crust. From the soil types of the two other surveys mentioned above, the Red And Dark Coloured Cracking Clays would include Terrae Rossae, Basalt Soils, Brown Limestone Soils, Brown Slope Soils, and Brown Bench Soils. The Red And Brown Non-Cracking Clays correspond to the Yellow Brown Slope Soils. The Clay Loams With a Surface Crust include the Mountain Marl Soils, Rendzinas, Grey Limestone Soils, Grey-White Slope Soils and Alluvial Soils.

Soil taxonomy (USDA, 1990), FAO (FAO, 1990) and WRB (WRB, 2006):

The National Soil Survey of Jordan (NSM&LUP, 1993) used U.S. soil taxonomy (USDA, 1990). The variety of soil types identified by soil taxonomy shall not be described here. It may only be summarised that the Red And Dark Coloured Cracking Clays include Vertisols (Chromoxerets), Inceptisols (mainly Xerochepts), and Alfisols (Xeralfs). The Clay Loams With A Surface Crust are described by Inceptisols and Entisols.

While Reifenberg used a genetic approach based on source rock and climate, the Durham survey added the position in the relief as further classification dimension. The Zarqua river basin report based the classification only on colour and texture. With soil taxonomy, the National Soil Survey of Jordan used a completely different system. It creates names by adding certain parts of soil group names or soil designations, referring to the basic properties and genesis of the soil (for example, a Chromo-xerret refers to a chromic (red coloured) soil in xeric (semi-arid) climate with vertic properties (soil mixing due to shrinking and swelling of clay). Thus it is not possible to directly "translate" soil taxonomy to the other classifications, and it is the most difficult system for non-soil-scientists (and therefore not applied here).

The system developed by FAO (1990) is strongly related to the terms used by soil taxonomy, with the difference that soil names are not created, but designations attributed to the main soil group. So for example, the above mentioned Chromoxerret would be called Chromic Vertisol. The FAO-system has now been replaced by the World Reference Base for Soil Resources (WRB, 2006), and terms have largely remained the same although their definition was refined and simplified. For a quick and simplified overview of the soil classifications, see table 1, but which does not claim to be complete.

2.4 Summary of research strategy

As could be seen with the discussion of previous research on desertification, it is not possible to rely on single indicators if cause-and-effect relationships shall be investigated. The discussed possible impacts of land use and climate change are identical: both may significantly alter the landscape. For example, dating colluvia, even if very precise, says nothing about the reasons of sedimentation. In the case of the Argolis, sedimentation maxima coincided with peaks of land use intensity, which led researchers to assume a causal relationship. However, erosion took already place during the Ice Age, and such phases of climatically triggered landscape instability may simply have repeated regardless of man's activities.

In order to distinguish human from natural impacts, the environment has to be studied from different perspectives. Only additional information makes it possible to obtain evidence for inter-relationships. For example, analysis of the soil structure and other properties, compared with different in-situ soils, can allow statements about the character and source of erosion. As could be seen in the Argolis, a pollen core provided a completely new perspective on historic land use.

Research should not only be focused on the past: the comparison with present land use patterns will enable us to understand field systems, whose time of existence can be traced using historic air photos. This may, in turn, be applied to the past and help to better understand the purpose and impact

of land use. Last but not least, comparing present soil fertility with paleosols, and present agriculture with archaeological evidence, will deliver clues whether productivity diminished. Therefore this thesis gathered all available evidence regarding soil development, human activities, vegetation, and climate variations. These are four different narratives, but which can be related to each other using the above mentioned methods, making it possible to identify causal links. In fact, the complexity of desertification requires trans-disciplinary work: just adding evidence from different disciplines does not help much.

Table 1: Overview of soil classifications.

Reifenberg, 1947 and Moorman, 1959	Fisher et al., 1968	GTZ, 1986	USDA, 1990	FAO, 1990, and WRB, 2006
Terra Rossa Red Mediterranean Soil Basalt Soil	Terra Rossa Brown Limestone Soil Brown Slope Soil Brown Cherty Soil Brown Bench Soil	Red And Dark Coloured Cracking Clays	Inceptisol (Xerochrept) Vertisol (Chromoxeret) Alfisol (Xeralf) Entisol (Xerothent)	Cambisol Vertisol (Vertic, Calcic, Chromic, Luvic, Haplic, Cambic) <i>Luvisols were so far not confirmed in Jordan.</i>
Rendzina Mountain Marl	Rendzina Grey Limestones Soil Grey-White Slope Soil Yellow Brown Slope Soil	Clay Loams With a Surface Crust	Inceptisol Entisol Aridisol	Calcisol Leptosol Regosol
Yellow Mediterranean Soil		Red And Brown Non-Cracking Clays	Inceptisol (Calcixerollic Xerochrept)	Cambisol Calcisol
Yellow Soil			Entisol (Torriorthent) Aridisol (Camborthid, Calciorthid)	Calcisol Arenosol
	Alluvial Soil		Entisol (Fluvent)	Fluvisol

3. Detailed description of sampling places

*And I will make Rabbah a pasture for camels,
and the Ammonite cities camps for flocks:
and ye shall know that I am the lord.*

Ezekiel, 25:5

*Put salt on Moab, for she will be laid waste;
her towns will become desolate, with no one to live in them.*

Jeremia, 48:9

*I will also stretch out my hand upon Edom,
and will cut off man and beast from it;
and I will make it desolate.
From Teman to Dedan they shall fall by the sword.*

Ezekiel, 25:13

3. Detailed description of sampling places

The Decapolis region was investigated mostly along the Wadi el-Arab, as it provides a natural east-west "cut" through the region. Figures 3, 4 and 5 show the investigation area, locations of the soil sampling places, and the geology.

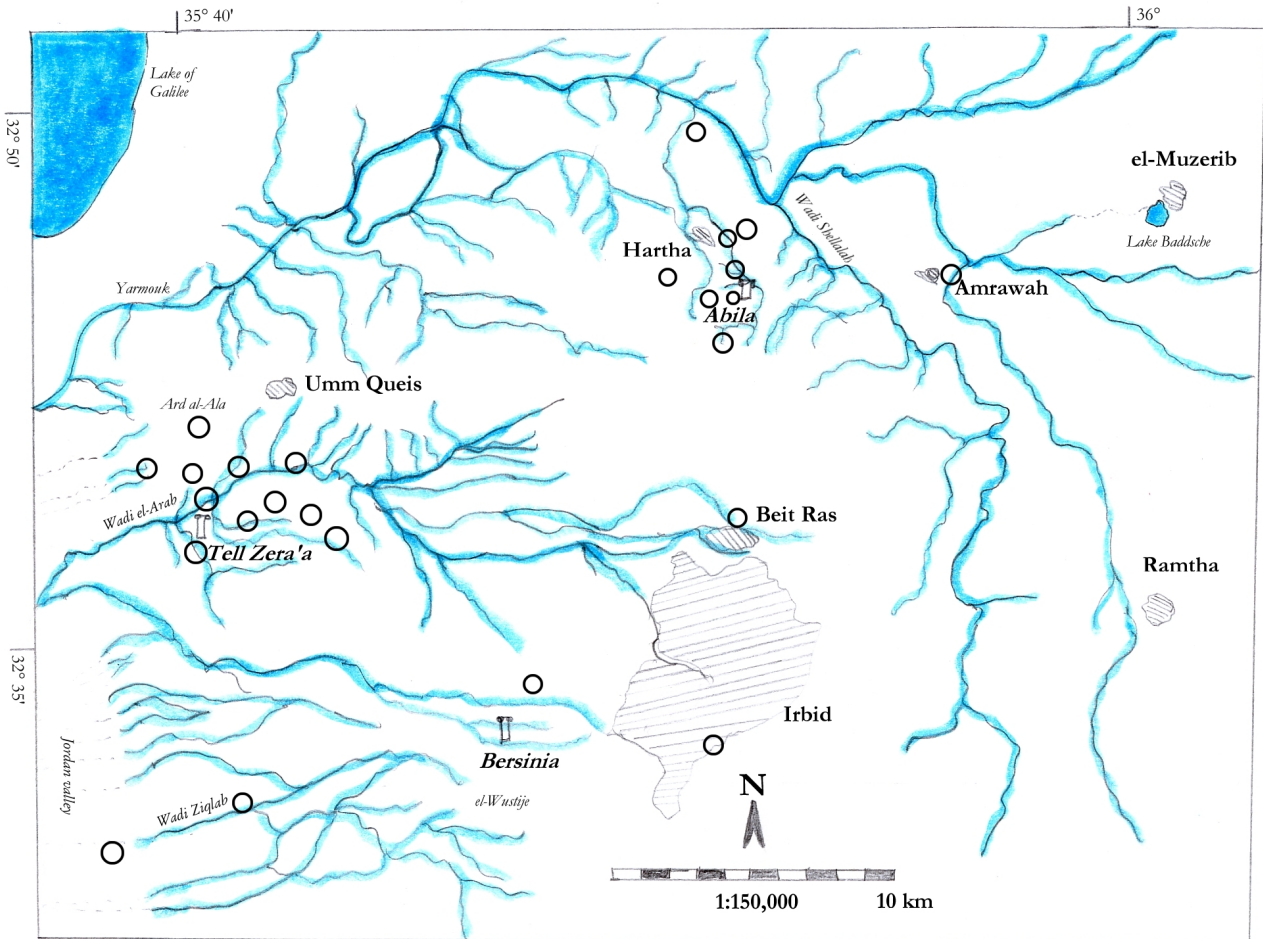


Figure 3: Map showing the most important wadis and sites. Soil sampling places/test sites are marked with circles.

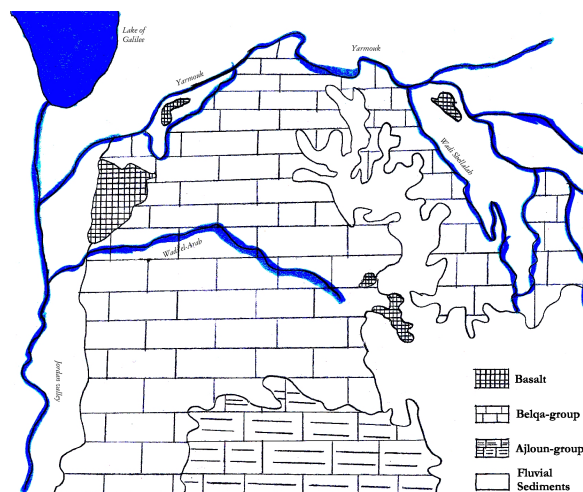


Figure 4: Geological sketch of the region (up to the Yarmouk river), after Bender (1974).

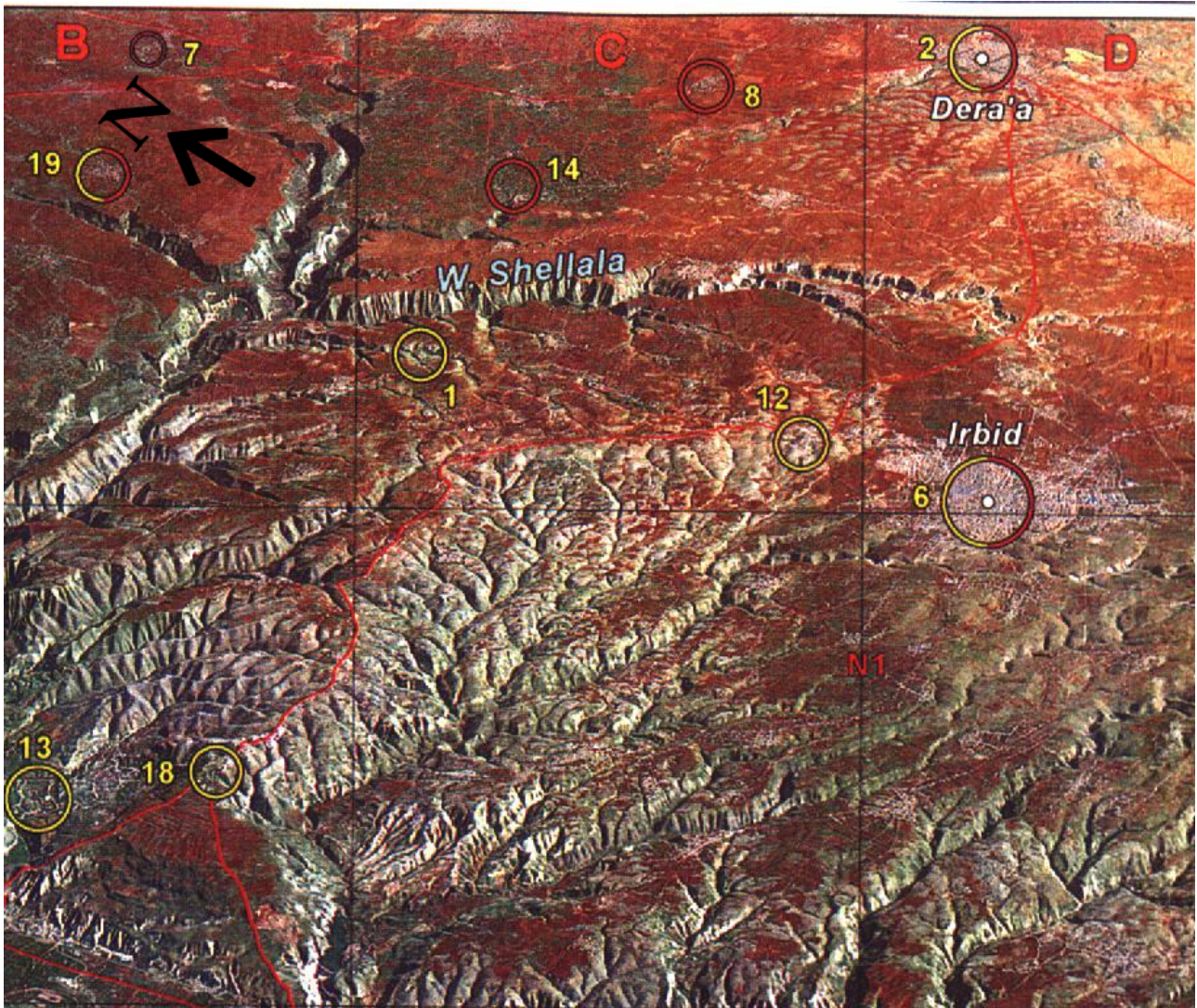


Figure 5: 3-dimensional terrain modelling out of satellite images. The numbers and circles show the locations of archaeological sites: 1 is Abila, 6 Arbela/Irbid, 12 Capitolias/Beit Ras, and 18 Gadara/Umm Queis. From Cleave, 1994, p. 82. ©RØHR productions and C.N.E.S., with permission.

As mentioned in chapter 2, soils should be compared regarding their position in the landscape, the underlying rock and traces of land use. In the tables describing the collection of soil samples, horizons are noted with their depth if a visual distinction was possible or seemed otherwise meaningful (samples were taken from the middle of defined horizons). If the profile was homogeneous, only the sampling depth is noted.

3.1 The Jordan valley

The deepest elevation of all sampled profiles is reached in the alluvial plain of the Jordan valley. A place was selected in front of Tell Arba'in and the delta of Wadi Ziq'lab (N 32° 30' 59.9", EO 35° 35' 37.8", -225 m below sea level). The Jordan rift valley is hot and humid, and characterized by silty, greyish-black soils. Average annual precipitation at the sampled location numbers 250 – 300 mm (National Atlas of Jordan, 1984). The relief is mostly flat or with slight slopes, and the profile lies in the irrigated area between the King-Abdullah-canal and the Jordan river. This site near the ancient tell was selected as it was hoped to find buried surfaces with traces of land use. Excavation did not reach groundwater, but had to be stopped in 250 cm depth due to financial limits and problems with the machinery (although the lower horizons were already moist, which contributed to the machinery problems). But this was enough to expose a reddish horizon in 2 m depth which looked like a paleosol. No archaeological material was discovered, however the profile made clear that sedimentation in the Jordan valley had changed over time. A selection of samples was analysed in the framework of this thesis (marked with bold script, table 2, fig. 6).

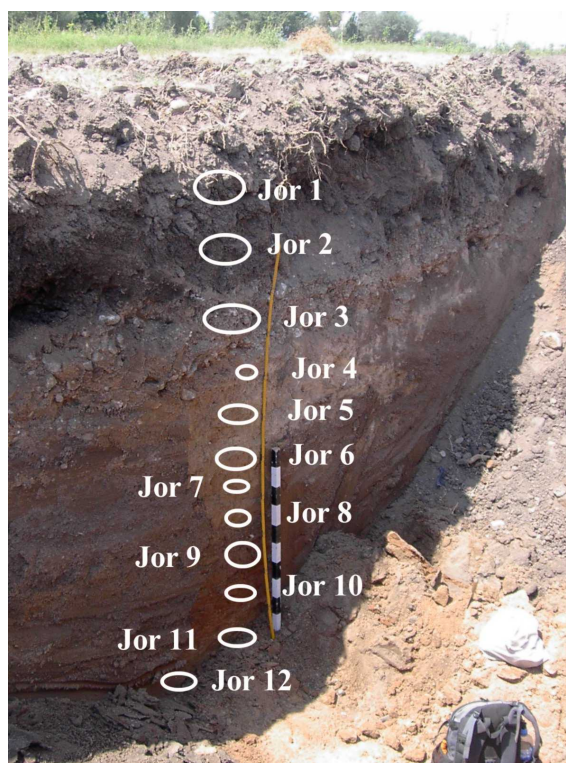


Figure 6: Sampling the Jordan Valley. All photos were taken by the author if not otherwise noted.

Table 2: Samples collected in the Jordan valley.

Sample No.	Depth [cm]	Description/Comment
Jor 1	0-35	Very dark/black horizon, many stones, rounded, partially big
Jor 2	35-70	as above
Jor 3	70-95	Gravel band with grey-brown soil, above mentioned stones concentrated
Jor 4	95-105	Darker yellow, friable structure: older land surface covered by gravel?
Jor 5	105-120	Yellowish soil, small holes (re-dissolved concretions?), sticky
Jor 6	120-140	as above
Jor 7	140-160	Colour becomes darker, turns orange, small holes not present any more, sticky
Jor 8	160-180	as above
Jor 9	180-200	Colour turns red, very sticky, a few stones (the only ones below the gravel band)
Jor 10	200-220	Red, sticky
Jor 11	220-240	Soil turns less sticky, and slightly brighter
Jor 12	240-?	Yellowish, feels sandy, unfortunately only 10 cm exposed

3.2 Wadi Ziqlab

Wadi Ziqlab is a deeply incised valley draining towards the Jordan, parallel to the Wadi el-Arab but much steeper. Chalk and limestone are exposed at the slopes, which show the region's geological structure well. It is part of the limestone plateau (Belqa-group) of mainly Eocene to Upper Cretaceous age, which was uplifted during the Tertiary (Bender, 1974). The calcareous sediments are several 100 m thick and consist of banks of alternating hardness, deposited under shallow marine conditions. The lower part dates to the Upper Cretaceous (Campanian and Maastrichtian) and shows alternating layers of soft chalk and harder limestone (Belqa group B.1-B.3 according to Bender, 1974; or Amman Silicified Limestone and Muwaqqar Chalk Marl according to Mo'hd, 2000). During the Eocene-Pliocene, the Belqa group B.4-B.5 (Bender, 1974) or Umm Rijam formation (Mo'hd, 2000) was deposited, characterised by chalk marl alternating with chalky limestone and chert bands. Quaternary deposits consist of travertine and caliche crusts, as well as clay stone and alluvium in the valley bottom.

Sampling in Wadi Ziqlab could take advantage of ongoing excavations by Lisa Maher and Edward Banning, and samples were taken from the wadi bottom where a Kebaran prehistoric settlement had been located (N 32° 30' 25.7", EO 35° 42' 15.6", 214 m above sea level). Average annual precipitation at this site reaches 300 mm. While the wadi slopes are today covered by greyish-white soils, the excavation trench revealed a red paleosol in 77 cm depth, which was dug out until 152 cm without reaching its bottom. Its surface could be dated to 11,000 BC according to artefacts (pers. comm., Lisa Maher, July 2005). The upper 55 cm of the profile consist of grey colluvium, covering remains of a Byzantine field stone wall on a still red subsoil (table 3, fig. 7).

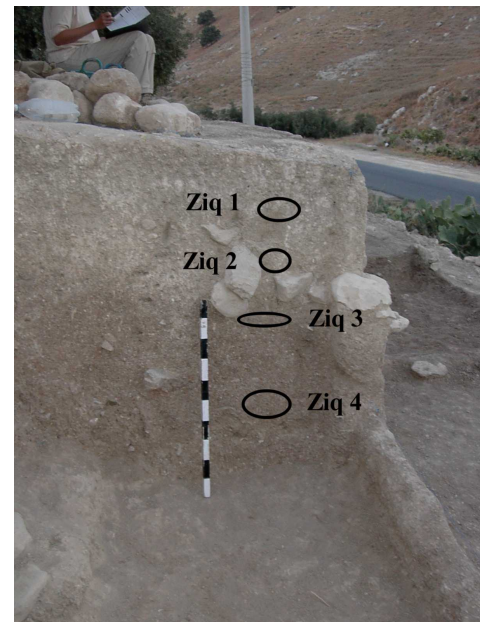


Figure 7: The paleosol in Wadi Ziqlab.

Table 3: Samples collected in Wadi Ziqlab.

Sample No.	Depth [cm]	Description/Comment
Ziq 1	0-20	Upper grey soil
Ziq 2	20-55	Grey soil associated with the remains of a Byzantine field stone wall
Ziq 3	55-77	Reddish soil directly under Byzantine field stone wall
Ziq 4	77-?	Red Paleosol dated to 11,000 BC

3.3 The Wadi el-Arab

Sampling in the Wadi el-Arab focused on the vicinity of Tell Zera'a, which is just in front of a water reservoir. There are numerous springs in the wadi, but most of which are pumped for supply of the city of Irbid, so that the once perennial stream in the wadi has dried up. As well, there are travertines in the wadi and an artesian spring on top of the Tell Zera'a. While the northern slopes of the Wadi el-Arab are very steep and consist of exposed calcareous sediments, the southern slopes are gentle, bearing deeper soils which make them very suitable for cultivation. Due to its abundance of water and easy access, the Wadi el-Arab was an important communication route during prehistoric times. The southern slopes consist of soft white ridges, seemingly representing exposed chalk, with red soils in the depressions (fig. 8). Where the calcareous rocks are harder further upslope, they form natural step-wise ordered terraces (see Koeppel, 1930) covered by thin grey soils. Soil movements are evident on the lower of these terraces, where buried Ah-horizons are clearly visible, and sometimes even still contain roots. Average annual precipitation in the Wadi el-Arab numbers 300 – 400 mm, and it is warm, but not as hot as the Jordan valley.

One profile was opened at the wadi bottom just in front of Tell Zera'a (32° 37' 07.7", EO 35° 30' 28.8", -36 m below sea level). Although outside the old riverbed, it revealed only gravelly grey soil without indication of a different, buried horizon. A soft limestone, probably bedrock, stopped digging in 110 cm depth. Samples were taken as seen in table 4.

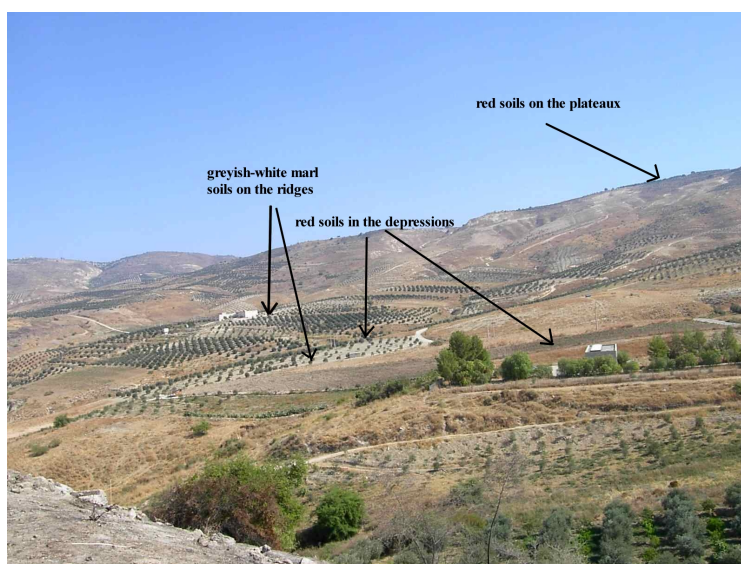


Figure 8: View of the Wadi el-Arab.

Table 4: Samples collected in the Wadi el-Arab, at the foot of Tell Zera'a.

Sample No.	Depth [cm]	Description/Comment
TZ 23	0-20	A lot of gravel
TZ 24	20-35	
TZ 25	35-60	Again a lot of gravel
TZ 26	60-80	
TZ 27	80-110	
TZ 28	110+	Soft limestone

Another profile was opened in one of the red soils in the depressions of the southern slopes, between the white ridges (N 32° 37' 04.5", EO 35° 39' 38.8", -11 m below sea level). Bedrock, again a soft limestone, was reached in 120 cm depth. On the surface, three Roman sherds were discovered. The profile was very homogeneous, although the stone content seemingly slightly increased with depth, and a hard dry crust had formed below the ploughed topsoil. Below the crust, the soil was moist (August 2003). Due to the uniformity of the profile, only one sample (in bold script) was analysed in the lab (table 5).

Table 5: Samples collected from red soil in the depressions of the Wadi el-Arab.

Sample No.	Depth [cm]	Description/Comment
TZ 47	0-20	Ploughed
TZ 48	20-40	Hard crust
TZ 49	40-60	
TZ 50	60-80	
TZ 51	80-100	
TZ 52	100-120	
TZ 53	120+	Soft limestone

In order to check whether the white ridges represented the exposed rock or calcareous material eroded from above (which seemed possible due to the presence of a volcanic bomb in the chalk), a pit was dug into the soft rock (which is so soft that it can be ploughed and cultivated). But since the profile remained homogeneous after 2 m, it was concluded that it is indeed in-situ chalk. Some reddish bands pointed to the presence of pre-weathered iron. As the chalk is cultivated like a soil, and might be added to the surrounding soils by wind or water erosion, one sample (**TZ 54**) was analysed in the laboratory (N 32° 37' 24.1", EO 35° 39' 57.4", -12 m below sea level).

The natural terraces seemed not very promising, as the lower ones collect material from several upslope sources and might additionally have been affected by recent bulldozing. Some profiles showing buried horizons were nevertheless sampled, and one sample (**TZ 73**) analysed in the framework of this thesis, since it seemed "representative" for eroded, mixed grey calcareous material as frequently present in the lower wadi (N 32° 37' 04.4", EO 35° 39' 30.5", -2 m below sea level, fig. 9).

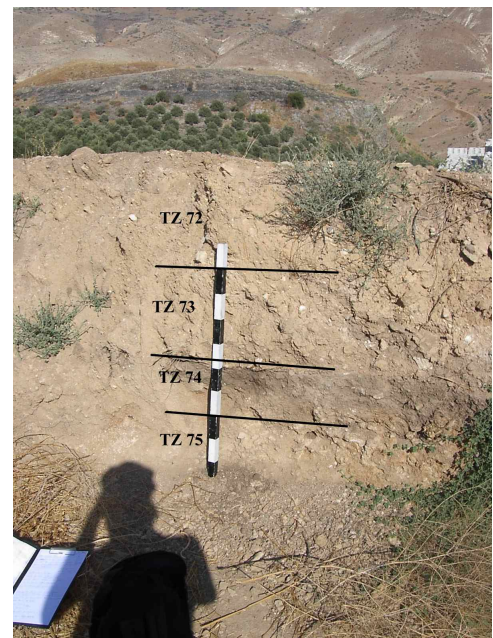


Figure 9: Recent soil movements in the Wadi el-Arab.

3. Detailed description of sampling places

One shallow red soil (30 cm deep) on travertine in the wadi bottom was sampled (**TZ 129**), as well as the underlying rock (TZ 130), but the XRF-analyses of which were not available before submission of this thesis. No coordinates were obtained here, but the travertine lies directly east of Tell Zera'a, below the northern slopes of the Wadi el-Arab. It is an elevated rock, well-visible due to its red soil cover. This might be the Kala es-Sa'a'idi, since it has caves which could be the ones where, according to Schumacher (1886) and Steuernagel (1924, p. 136=A520), the Ottomans buried members of the Sa'a'idi tribe who had harassed the peasants living close to the Wadi el-Arab with frequent raids. Therefore Ottoman forces annihilated the Bedouin tribe with the support of villagers in the mid-19th century and used the caves as mass grave, a story which Schumacher (1886) could verify since he found piles of human bones there.

The higher terraces at the southern slopes are covered by thin grey soils (10-30 cm deep), one of which was sampled (**TZ 65**) as well as the underlying rock (**TZ 66**). The terrace can be found at position N 32° 36' 55.5", EO 35° 39' 25.0", 40 m above sea level. A cistern and some well-hewn stones suggested that a historical building once existed nearby.

Further upslope, a forest of deciduous oak (*Quercus ithaburensis*) and carob (*Ceratonia siliqua*) can be found in the southern Wadi el-Arab (around the village Seidur). Although the trees grow mainly on rocky areas, red soil is present in pockets between the rocks. While some of the trees were cored, a soil sample (**TZ 106**) was taken from one of the pockets at N 32° 36' 55.9", EO 35° 40' 55.9", 289 m

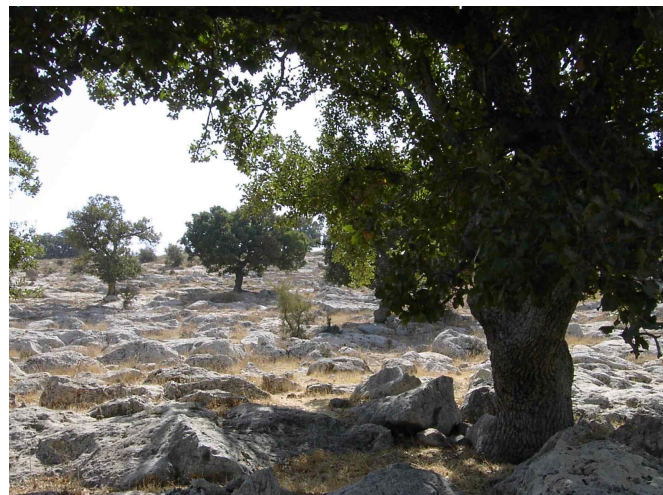


Figure 10: Oak forest in the Wadi el-Arab.

above sea levels (fig. 10). Roman sherds and some hewn stones suggest again ancient activities in this area, and small channels and potholes in the rock make clear that past land use took advantage of the rocky spots. Since cisterns are filled by runoff water, they require the presence of roofs or cleaned, rocky areas.

The northern slopes were mostly too steep to bear soil, but a relic soil of dull colour was found that had been covered by calcareous conglomerate, probably during a landslide. (**TZ 2** – N 32° 38' 42.3", EO 35° 40' 16.7", 90 m above sea level).

3.4 The basalt plateau west of Umm Queis

The basalt plateau west of Umm Queis (in Arabic called *Ard al-Ala*, which means "high land") is a level plain overlooking the Wadi el-Arab and Jordan valley, and covered homogeneously by a deep, dark red soil. This soil developed on top of a basalt flow, which capped the limestone after an eruption in Syria. According to Bender (1974), it is part of the "Yarmouk-basalt" and was deposited in the Middle Pleistocene, around 700,000 years ago. Average annual precipitation in this area reaches 350 mm. A profile was dug out in the approximate centre of the plateau, at N 32° 39' 28.8"; EO 35° 39' 41.8", 322 m above sea level (fig. 11). It showed no distinct horizons and was characterised by deep cracks (up to 70 cm deep). Digging was extremely difficult, and finally bedrock was reached in 170 cm depth. Interestingly, a caliche crust covered the basalt, and few stage I-II secondary carbonates as well as small caliche fragments were visible in the lower 40 cm of the profile. This might indicate the soil dates to the late Pleistocene (Birkeland, 1999). Under the ploughed topsoil, a hard dry crust was observed (August 2003). As well, the profile and soil surface showed numerous small Roman and Byzantine sherds up to a depth of 150 cm in different positions. These suggest a vertic behaviour of the soil, supported by the presence of slickensides. Samples were taken every 20 cm but only three of them (in bold) were analysed in the framework of this thesis, as the profile was very uniform (table 6). For the sake of completeness, another (uniform) exposure of the basalt soil along a street was sampled at the western end of the plateau (UQ 14-17), and one sample analysed (N 32° 38' 11.7", EO 35° 38' 36.7", 221 m above sea level). Last but not least, a surface sample was taken at the southern edge of the basalt plateau, towards the Wadi el-Arab (**TZ 1**, N 32° 39' 04.3" – EO 35° 40' 06.9", 310 m above sea level).

Table 6: Samples collected on the *Ard al-Ala* (the basalt plateau west of Umm Queis).

Sample No.	Depth [cm]	Description/Comment	Sample No.	Depth [cm]	Description/Comment
UQ 9	0-20	Ploughed, hom. red	UQ 14	20	Homogeneously red
UQ 10	20-30	Hard crust	UQ 15	40	As above
UQ 11	30-60	Drought cracks	UQ 16	60	As above
Q 12	60-80	As above	UQ 17	80	As above
UQ 13	80-100	As above			
UQ 18	100-120	As above	TZ 1	surface	Dark red soil
UQ 19	120-140	Few sec. carbonates			
UQ 20	140-160	Some sec. carbonates			
UQ 21	160-170	Some sec. carbonates			
UQ 23	170	Bedrock: caliche			
Basalt UQ	180	Bedrock: basalt			



Figure 11: The basalt plateau west of Umm Queis.

3.5 The Mediterranean highland, Abila, and Capitolas/Beit Ras

Abila is situated approximately 20 km east of the Ard el-Ala and ca. 5 km south of the Yarmouk river (which is today the border to Syria) on a gently sloping plateau of limestone formations, at the crossing point of two small wadis. The highland around Abila gives the impression of a vast, gently undulating plain, covered with red soil of strongly changing properties, and dissected by several wadis. Many wadi slopes are very steep with an angle of about 40 degrees, while a grey and white soil, mixed with gravel and stones, is present in the valleys. There are no artificial terraces or any remains pointing to their existence in the past, but in some areas the rock forms natural terraces. Average annual precipitation at Abila is 400 mm, and the spring Ain Queilbeh was the beginning of a perennial creek, but which is now dry due to pumping for supply of drinking water to the nearby villages.

Thanks to the construction of the unity-dam at the Yarmouk river between Jordan and Syria, the Jordanian military had just dug a street cut at the edge of the limestone plateau north of Abila, towards the Yarmouk river, when an interested German soil scientist arrived by chance (August 2003). This street cut nicely showed the strongly varying soil depth, which seems to be related to the karstic weathering behaviour and changing hardness of the limestone. There is no depth indication on the surface: neither stone content or vegetation, nor soil colour showed any connection with soil depth (an issue to be discussed later in the air photo evaluation). The first sampling of this profile had to be done quickly since it lies in a military restricted area – therefore only seven samples (AB 1-7) were obtained from a 350 cm deep part of the street cut. Later re-sampling with a special permission from the ministry of interior met a partially collapsed profile and faced even more intense time pressure, so only

seven additional samples were obtained from more shallow parts of the street cut (Yar-samples, August 2005). This nevertheless allowed a more detailed study. It seems that several phases of soil development are present. The deepest soil might be a paleosol characterised by slickensides (AB 3-7), that was eroded so that huge boulders from the neighbouring elevated areas were exposed (between Yar 3 and 4). A brighter soil developed on top of these (Yar 3), that was covered by a darker red one but which contains many big stones (Yar 2). The very top consists of a brighter and coarser soil (Yar 1, 1a). The location of this sampling place is (N 32° 42' 54.0", EO 35° 52' 28.8", 381 m above sea level, table 7, fig. 12). Since soil movement processes seemed evident, both ¹⁴C and OSL-dating were applied (sample AB 3) in order to get an impression of the time of erosion and re-deposition. The ¹⁴C-age of soil organic matter was determined as 2320 BP +/- 60 (Erl-N-Jordanien 09/06-3, δ ¹³C -26,3), which means in calendar years 543 – 204 BC (2 Sigma-probability 91,8 %). In 1 Sigma-probability, it has the highest chance between 418 – 355 BC (35,8 %). However due to the presence of roots and other recent organic material, this is only a minimum age. Therefore it is not surprising that the (quartz-based) OSL-dating indicated AB 3 saw light the last time 6880 BC (+- 700, RF2007 Jord AB3). This date that seems more reliable since the quartz grains produced a good signal, even though only one sample could be analysed, and might correspond to the regional "Yarmoukian landslide"-event, which buried various sites in Jordan and the Mediterranean around 6200 BC (Weniger et al., 2005). In the examined profile, archaeological material was not noted, although some stones near the surface might represent remains of an ancient field border.

Table 7: Samples collected from the street cut towards the unity dam (Yarmouk river), at the edge of the high plateau.

Sample No.	Depth [cm]	Description/Comment	Sample No.	Depth [cm]	Description/Comment
AB 1	50	High stone content, remains of ancient field border?	Yar 1	0-30	Brighter topsoil
AB 2	100	As above	Yar 2	30-80	Many big stones, seems to refer to AB 1 and AB 2
AB 3	150	Darker red, slickensides	Yar 3	80-120	Brighter soil, over band of huge stones
AB 4	200	As above	Yar 4	120-160	Darker red soil, slickensides, seems to refer to AB 3 - 7
AB 5	250	As above	Yar 5	160+	Hard limestone
AB 6	300	As above	Yar 1a	0-30	Brighter soil from shallow profile
AB 7	350	As above	Yar Mitte	200	In the deep profile, directly under colour change like at Yar 3/4
AB 8	350+	Soft limestone	Yar Mitte unten	350	Stony layer directly over bedrock

3. Detailed description of sampling places



Figure 12: The profile close to the unity-dam at the Yarmouk river.

In order to take the strongly changing soil properties around Abila into account, a dark red, but stony and very shallow soil (30 cm) was sampled to the north-east of the site (N 32° 40' 50.7", EO 35° 52' 35.8", 471 m above sea level). Samples obtained were **AB 9**, and **AB 10**, a calcareous conglomerate below. Byzantine sherds were visible at the surface.

As well, the area characterized by soil properties seemingly varying along field borders was re-sampled. The texture published by Lucke (2002) and Lucke et al. (2005) had to be corrected, and additional analyses be applied in order to better understand why soil properties changed (N 32° 41' 43.9", EO 35° 51' 15.9", 459 m above sea level, table 8, figs. 13 and 14). As already reported, there was no difference of bedrock or elevation, and both fields showed a lot of material culture (mainly Byzantine sherds). Below the ploughed topsoil a hard crust formed during the summer drought. Bedrock weathered forming the usual pockets, which sometimes appeared darker than the rest of the profile (sampled with AB 1-2 4). The soil of the brighter field was a little bit deeper. The possibility of an ancient field system was supported by the observation that the borders of colour changes seem to be related to very slight elevations. These become visible especially in the early morning and evening, when the sun is low and produces maximum shadowing, and could represent the remains of ancient field borders. Additionally, the pattern of colour changes along field borders was confirmed from a field visit to the Dead Cities close to Aleppo in Syria. There, the ruins of the towns as well as the field borders are still standing, and the soils look similar to those at Abila.

Table 8: Samples collected from the fields showing colour changes around Abila.

Sample No.	Depth [cm]	Description/Comment	Sample No.	Depth [cm]	Description/Comment
AB 1-2 1	10	Plowed	AB 2-2 1	10	Plowed
AB 1-2 2	20	Crust	AB 2-2 2	20	Crust
AB 1-2 3	30		AB 2-2 3	30	
AB 1-2 4	40	dark red soil pocket	AB 2-2 4	40	
AB 1-2 5	40+	Limestone	AB 2-2 5	50	
			AB 2-2 6	50+	Limestone



Figure 13: The slightly darker field 1 close to Abila.



Figure 14: The slightly brighter field 2, divided from field 1 by a small road.

In order to check whether the colour differences could be related to organic matter and cultivation, surface samples were taken from nearby fields where air photos showed that one had been planted with olives some time between 1992 – 2000 (**WQ mit**), while the other one (**WQ ohne**) was seemingly laid fallow since this period. This allows some comparison of short-term influence of tree growth and fallow on soil colour and organic matter. Further comparison with the forest soil at the Wadi el-Arab (TZ 106) should allow some estimates about the impact of long-term tree growth (~200 years) on soils. The fields are located at N 32° 40' 11.1", EO 35° 51' 34.6", 474 m above sea level (fig. 15).

Although all soils close to Abila contain CaCO_3 to some degree, surveys showed that there are also soils in the Mediterranean highland which are CaCO_3 -free. These are present to the southwest, around Deir Abu Sa'id, west of Irbid and around the site of Bersinia. There, the limestone plateau changes its character towards a gently sloping, hilly landscape (probably due to pseudo-injective



Figure 15: With and without olives near Abila.

3. Detailed description of sampling places

folding, according to Neubauer, 1993), and remains of old field systems are well preserved (fig. 16). Sampling was conducted close to the highway from Irbid to Shuna ash-Shamalia. One sample was taken under one of the ridges seemingly representing an old field border (**Feldsys 1**), while another surface sample was taken from the middle of one of the fields (**Feldsys 2**). The sampling place is located close to the village of Qumeim, at N 32° 93' 20.7", EO 35° 47' 37.4", 511 m above sea level, and average annual precipitation numbers around 500 mm.

Three colluvia around Abila were studied in order to get a comparison to the in-situ soil. The first is situated in the northern part of Wadi Queilbeh, where the wadi is steep and narrow. If not filled with gravel, its floor looks like a chessboard of red and white soils, as described by Field and Banning (1998) for



Figure 16: Old field systems close to Qumeim.

Wadi Ziqlab. Landslides might explain this pattern, and a red soil was sampled (**Qo 1**) which laid under a huge limestone block – both had seemingly been deposited with an earth slump (N 32° 42' 05.0", EO 35° 52' 06.6", 290 m above sea level).

The second colluvium is situated very close to the fields sampled with WQ mit and WQ ohne, at a position where the Wadi Queilbeh is broad and gentle, so that sediments should accumulate. This place lies also shortly before the spring Ain Queilbeh, in a part of the wadi that should always have been summer dry (N 32° 40' 18.9", EO 35° 51' 51.0", 432 m above sea level, table 9, fig. 17). The profile was very homogeneous, although the deeper 80 cm appeared darker. This might be a paleosol like in Wadi Ziqlab, or is simply due to increasing moisture. Archaeological material (Byzantine sherds) was abundant at the surface but not noted in the profile. The selection of samples analysed for this thesis is marked in bold.

Table 9: Samples taken from Wadi Queilbeh.

Sample No.	Depth [cm]	Description/Comment
Q 1	5	Homogeneous red soil, some gravel
Q 2	15	As above
Q 3	25	As above
Q 4	35	As above
Q 5	45	As above
Q 6	55	As above
Q 7	65	As above
Q 8	75	As above
Q 9	85	As above
Q 10	95	As above
Q 11	105	A little bit darker – Paleosol?
Q 12	115	As above
Q 13	125	As above
Q 14	135	As above
Q 15	145	As above
Q 16	155	As above
Q 17	165	As above
Q 18	175	As above
Q 19	180+	Soft limestone

The third colluvium is situated directly behind a Roman bridge over the Wadi Queilbeh (N 32° 40' 53.2", EO 35° 52' 16.4", 393 m above sea level, figs. 18 and 19). This bridge had already been noted as promising place since it is a sediment trap with historical context (Lucke, 2002), and could now be sampled thanks to cooperation with the Abila Archaeological Project. Excavations revealed that the bridge was bigger in antiquity, but had partially collapsed. Closer examination



Figure 17: Sampling the lower Wadi Queilbeh.

showed that it consists of three arches, the middle of which is higher. If one crawls beyond it, a height of 180 cm can be measured – therefore Lucke's (2002) estimation that 250 cm of sediment had accumulated since Schumacher's visit in 1888 is wrong. Schumacher unfortunately did not mention where exactly he measured the height of the bridge, or that there are three arches and the middle arch higher (Schumacher, 1889). But one can conclude that Schumacher's height of 11 feet might be much closer to what is visible today if he had crawled under the middle arch. Then about 150 cm have been deposited – and the creek has fallen dry, which might have enhanced deposition since less is flushed out now. The bridge might also have served as a shelter for sheep since dry, which is indicated by the floor structure and might have contributed to the quick silting up.

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Excavations showed that the bridge's vault acted like a sieve. Its southern part (facing the flow of the creek) did partially collapse and shows a disturbed profile, with some differences in the sediments but difficult to excavate and sample due to the presence of many huge boulders. In contrast, the northern profile is well-stratified and free of huge stones, since these were seemingly filtered out by the vault. Additionally, it turned out that the Wadi Queilbeh had seen artificial channeling during the Roman period, so that sediments in the northern profile rested at a 90° channel wall. They indicate very considerable variations of creek flow since construction of the bridge (table 10).



Figure 18: The Roman bridge in Wadi Queilbeh.

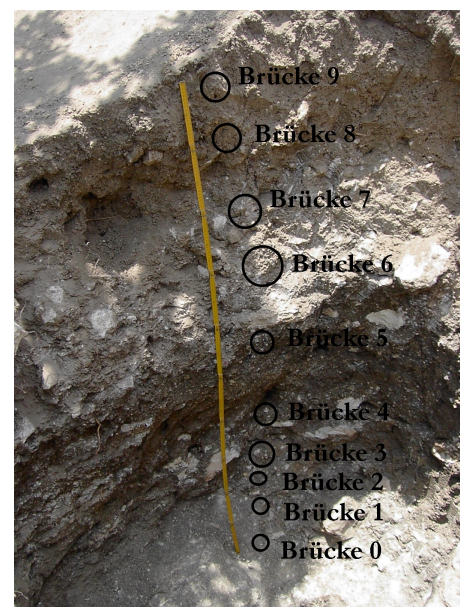


Figure 19: Sampling the Roman bridge.

Table 10: Sampling and horizons behind the Roman bridge in Wadi Queilbeh.

Sample No.	Depth [cm]	Description/Comment
Brücke 9	0-20	Bright brown, loose, ~10% stones
Brücke 8	20-45	Dark greyish-brown, some smaller stones, creek seemingly dry
Brücke 7	45-65	A lot of well-rounded gravel with grayish-brown sediment, quick and strong flow of the creek (probably perennial)
Brücke 6	65-125	Many big, angular stones, mixed with chalk, mortar and stones seemingly collapsed from the bridge, looks like a huge landslide or flash flood, and possibly dry creek
Brücke 5	125-150	Reddish-brown sediment, fine, few stones, clay-rich prismatic structure (seemingly indicating reduced flow of the creek with stagnating water)
Brücke 4	150-158	Reddish-brown sediment, subangular gravel (indicating more turbulent, perhaps alternating transport and intermittent flow)
Brücke 3	158-193	Brown, fine, with bigger stones (20%), not very much water but periodic flooding
Brücke 2	193-203	Gravel band (80% gravel), small and well rounded, indicates perennial, steady good flow of the creek
Brücke 1	203-227	Grey, fine, oxidation-channels along root remains (indicates stagnant water - gley), a few small stones, no running water but muddy conditions in the creek
Brücke 0	227-247	Grey, fine, no coarse material, but ash, charcoal and carbonised olive seeds, could indicate garbage dumped into mud while the city was still intact
Bedrock	?	Bedrock was not reached but seems close, since it appeared at the southern profile in approximately 200 cm depth

The flow of the creek should be directly related to precipitation: according to al-Farajat (1997), the water feeding the springs moves with 1.5 m/hour through the karstic limestone, which means already the winter/summer change leads to strongly alternating water tables. However, the spring Ain Queilbeh was tapped by two water tunnels in antiquity (fig. 20), which should have channelled the greatest part of the available water to the city centre (Fuller, 1987).

The upper, younger tunnel (which seemingly replaced the damaged, older lower tunnel) was part of a huge aqueduct and tunnel network, extending for several 100 km up to the swamps of Dili in Syria, and linking most of the Decapolis cities in a long-range system. Although mentioned in travel reports (Schumacher 1889, 1890, 1897, Wetzstein, 1860), this system was re-discovered and investigated only recently (Döring 2004, 2005). It is a complex enigma



Figure 20: Water tunnel transformed into a cave near Abila.

of its own - my observations led me to the impression that there might have been several phases of construction, and maybe changing water levels (indicated by different water marks). The local tunnels might be older than the big system. According to Fuller (1987), the older tunnel at Abila could date back to the Hellenistic period, while the younger one shows Byzantine inscriptions. It is unclear when the water tunnels went out of use, but it is possible that this happened while Abila was still inhabited, since wells and access points had been orderly closed before the tunnels fell out of use (Fuller, 1987). Later reuse is not very likely – although the younger tunnel saw major repairs at least once, its lower part seems to have been later extended into a subterranean cave complex. This might have been connected with a basilica over these caves (perhaps as a crypt for the church?) and explain why an outlet or castellum aquae is missing. In any case, it is very probable that the water system stopped functioning after the earthquake in 747 AD.

Tapping creek water by the tunnel could be related to the lowest bridge sediments, which indicate moist and muddy conditions, but no running water. The absence of stones points to an intact channel and built-up area. A carbonised olive seed in Brücke 0 was dated by ^{14}C to the Byzantine period: 1480 years BP (+47) (Erl-N-Jordanien 09/06-1, $\delta^{13}\text{C}$ -21,9). This means in calibrated calendar years that the olive seed was carbonized between 436-653 AD (95,4 %-probability, 2 Sigma). In 1 Sigma-probability, the olive seed has the highest chance between 547-622 AD (61,8 %). The

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archaeological context of the bridge was mixed and so far there is no precise dating available, except that medieval sherds could only be found in the upper part of the profile but no clear border could be drawn. This awaits further examination. Also, charcoal is present only in the lowest layers. However, OSL-dating was tested at Brücke 6 and yielded an age of AD 1206 (+- 65, RF2007 Jord Brücke). Schumacher must have measured the middle arch.

Combined with further archaeological evidence, OSL should make it possible to date the sedimentation cycles and relate them to climate reconstructions (e.g. Bar-Matthews et al., 1998, Bookman (Ken-Tor), 2004, Migowski, 2004). For now it can be concluded that significant historic climate variations are most likely reflected at the bridge, preserved due to the fortunate filtering role of this building.

Two other colluvia were studied at the site of Capitolias (today Beit Ras), located approximately 10 km south of Abila in a similar, but steeper landscape. Average annual precipitation there is 500 mm. What is interesting about Beit Ras is one the one hand its recently discovered theatre, which was found only by chance since it had been completely covered by sediments (Karasneh et al., 2002). On the other hand, the town looks like a white spot on air photos (see fig. 5). *Beit Ras* means "house on the crest" and points to the elevated position of the town on a hill overlooking the Mediterranean highland. If erosion took place in the Decapolis region, then here.

The fill of the theatre was already described by Lucke (2002) and Lucke et al. (2005), and now sampled in detail. It consists of 81 layers of rubble and sediments, which had been deposited by water after the outer walls had partially collapsed, and accumulated at the backstage wall (fig. 21). The latter did not collapse since it had been strengthened and supported by towers when the theatre was closed and became part of the city wall. Without reinforcement of this wall, the rubble would probably have scattered over the wadi behind and would today be visible only as perhaps locally increasing skeleton content.

As it seems, every layer represents a sedimentation event related to heavy rainfall, which carried debris and archaeo-



Figure 21: Layered debris in the theatre of Beit Ras.

logical material from the remains of the town into the theatre. The material culture is mixed and ranges from the Roman to the Umayyad period, after which Capitolias was deserted. However, the place was not abandoned while the theatre filled up. Its vaults were still inhabited, and firing places connected with Umayyad domestic pottery could be observed (pers. comm. with Khaled al-Rousan, field supervisor, December 2001). As well, part of the sediments might simply represent garbage that might have been dumped into the theatre while it still was a depression. In any case, the layers represent high-energy mass transport and re-distribution of sediments by water. The remains of firing places from the Umayyad period make clear that the youngest material culture in the fill corresponds to the time when the heavy rainfalls took place. The samples were not further analysed in the framework of this thesis. However, it is interesting to note that such a pattern of quick and intensive sedimentation is not only reported from the Umayyad period: the PPNB site of Ba'ja (close to Petra in southern Jordan) is also covered by huge piles of debris, deposited during a short time (Bienert and Gebel, 2004) and probably connected with strong floods. The debris covering Ba'ja might be related to the already mentioned "Yarmoukian landslide"-event (Weniger et al., 2005), and since a possible upslope source for rubble is missing, the debris in Ba'ja can only represent material from the ruined site itself (pers. comm. with H. Gebel, February 2007). This means that an extremely heavy rainstorm must have flooded the site. Weniger et al. (2005) suggest that such events were more frequent in the whole eastern Mediterranean during the period of the "Yarmoukian landslide"-events, possibly connected with general drought. Although a rubble source is located upslope in the ruins of Beit Ras, the character of material in the theatre indicates a deposition process similar to that in Ba'ja.

The second colluvium investigated at Beit Ras lies in a small wadi at the foot of the hill, surrounded by nearly bare slopes (which show remains of steps, potholes, channels, cisterns and quarrying). Olives are grown there today, and abundant pottery (mainly Byzantine) is visible on the surface. I was not sure which depth to expect: if the wadi is itself subject of re-distribution processes, it might be shallow, and even in Wadi Queilbeh bedrock was reached in only 180 cm. However the red soil proved to be very deep, at least 3 m (fig. 22). The upper 130 cm contained many small stones, which may indicate that this part of the soil is indeed colluvium, while the lower part might be an in-situ soil on a karst pocket. At 110 cm, bigger stones were present, and the



Figure 22: Deep profile at Beit Ras.

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colour seemed to change from a brighter to darker red. Again, this might indicate that a paleosol is present, or only be connected with increasing moisture. Below 130 cm, the soil became more sticky, the stone content was reduced and also the material culture. Archaeological material in fact seemed to be absent after this depth. Starting in 180 cm depth, clay cutans seemed to be present, but no secondary carbonates or Manganese concretions. Reaching 230 cm depth, digging became increasingly difficult since the hole had to be steadily widened to allow handling of the axe, and the clayey soil was most resistant to all attempts of excavations. A *schisch* (long thin iron stab) was used to determine how deep the soil below still was. It was possible to punch it for 70 cm, and it seemed that bedrock did still not appear – the soil was simply too deep and clayey to punch the *schisch* deeper. Therefore I decided to stop the excavation – it might later be resumed with the help of a back hoe. It cannot be said which soil depths are to be expected on this valley, as there are no exposures – I might have caught a pocket related to the karst. However it might also be that erosion and re-deposition were indeed higher at Beit Ras. The location is N 32° 36' 07.1", EO 35° 50' 39.5", 478 m above sea level. Selected samples were analysed for this thesis (in bold, table 11).

Table 11: Sampling and profile description of the Beit Ras colluvium.

Sample No.	Depth [cm]	Description/Comment	
BR 1	5		
BR 2	15		
BR 3	25	Homogeneously red, many small stones, a lot of material culture (mainly Byzantine, but probably mixed – could not be examined thoroughly)	
BR 4	35		
BR 5	45		
BR 6	55		
BR 7	65		
BR 8	75		
BR 9	85		
BR 10	95		
BR 11	105		Band of bigger stones, change to slightly darker red colour
BR Stone	~110		Big representative stone from stone band
BR 12	115		
BR 13	125	Dark red colour, few and smaller stones, little material culture	
BR 14	135		
BR 15	145	No material culture any more	
BR 16	155		
BR 17	165		
BR 18	175		
BR 19	185	Clay cutans at pores? Very few and small stones	
BR 20	195		
BR 21	215		
BR 22	225		
BR 23	235	End of pit, but at least 70 cm deeper	

3.6 The Irbid basin

The next samples were collected from building pits in the city of Irbid (ancient Arbela), located approximately 5 km south of Capitolias/Beit Ras. It is the second biggest city in Jordan and grew very quickly since Jordan's independence. Average annual precipitation is 500 mm. Irbid is situated in a level plain (Irbid-Ramtha basin), which contains some of the most fertile soils of Jordan and is a prime wheat production area. Fluvial limestone gravels and basalt are the source rocks in this basin (Bender, 1974). The plain is not dissected by wadis, and springs and streams are absent. Soils are usually very deep: building pits revealed 4 m and more. The only freshwater source before the introduction of pump systems however was collected rainwater, and Irbid's rapid expansion seems thus closely connected with the introduction of modern pumping technology. While several building pits of soils on the limestone gravel were sampled, only a selection from one profile was analysed in this thesis since the pits revealed more or less similar soils. They show a very clear change of layers: under dark brown soil with slickensides, a horizon of angular stones appears (fig. 23). Below this stone band a brighter reddish-brown soil is present which shows a diffuse transition to the fluvial, cherty limestone conglomerate described by Bender (1974), which Moh'd (2000) attributed to the Amman silicified limestone group. The brighter subsoil shows krotovinas and is not present over the whole sampled building pit: to the southeast (left in the picture) it was seemingly eroded down to the conglomerate, and filled up by dark brown topsoil (which shows nevertheless a level surface). The place is located just in front of the south gate of Yarmouk university: N 32° 31' 53.9"; EO 35° 51' 13.7", 626 m above sea level. Material culture was not noted. The samples selected for analysis are marked in bold (table 12). Another building pit showed massive stage II and III secondary carbonates in the transition zone to the darker soil, but which were not analysed in this thesis. It is however an indication that the colour change is of Pleistocene age (Birkeland, 1999).

There are also some basalt outflows in the Irbid basin, but which could not be sampled. One profile could nevertheless be observed, characterized by a missing change of soil properties like on the limestone gravels. The basalt soil at Irbid looked very similar to the one of the Ard el-Ala, with the difference that the Irbid soil showed stronger slickensides and clay coatings in the subsoil.



Figure 23: Sampling the building pit in Irbid.

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Table 12: Samples taken from the Irbid construction pit.

Sample No.	Depth [cm]	Description/Comment
I 15a	30	Dark brown soil, many roots and few small stones
I 14a	60	As above
I 13a	90	As above
I 12a	110	Soil turns brighter, and a stone band suggests an old land surface
I 11a	155	Brighter brown, slight increase in stone content
I 10a	180	As above
I 9	200	As above
I 8	220	As above
I 7	240	As above
I 6	255	As above
I 05	270	Bright reddish brown, strong colour change under another band of stones
I 04	285	A lot of bigger stones, gravel and much chert
I 03	305	As above
I 02	330	As above
I 01	355	Diffuse transition to cherty limestone gravel below
I 00	370	Gravel sample

Approximately 15 km northeast of Irbid, close to the village of Amrawah, a paleosol developed on limestone and was covered by a basalt flow (N 32° 40' 42.4", EO 35° 56' 31.7", 401 m above sea level, fig. 24). This basalt might be an outcrop of one of the Syrian basalt flows, connected with the



Figure 24: The Amrawah paleosol.

Yarmouk-basalts (700,000 years ago) or one of the Miocene/Pliocene eruptions (23.8 – 1.8 Mio. years, Bender 1974). Since some basalt flows however appeared along rifts during the Quaternary, it could be much younger, too. So far no absolute dates are available. It seems possible that the paleosol was revealed along a crack that opened due to tectonic action since it is very close to the active Yarmouk valley (which is connected with the Jordan rift), and the slopes at the exposure show an angle of nearly 90°. The paleosol under the basalt was excavated until a full section down to the limestone was accessible. It was characterized by a brighter, dull red colour and three bands of secondary carbonates. This soil must already have

been already old when buried, since the two lower bands correspond to stage II secondary carbonates, while the upper one shows a mature stage III. As well, numerous manganese concretions were present, and the soil was very instable, which reminded me to a ferrasol and led to frequent collapses of the profile while digging. A dark red zone directly under the basalt indicated how hematite formed under the heat during deposition of the basalt flow. The basalt is covered again by brown soil of seemingly fluvial origin, in the lower part brighter and with stage I-II CaCO_3 -concretions. There must have been at least two phases of erosion and deposition, which is indicated by the presence of two gravel bands. As well, there might have been tectonic uplift of the area since the gravel bands show a changing inclination and are cut when meeting the present surface. This is reflected by increasing stone content, which is the first time that variations of stone content on the fields can be clearly related to subsoil properties. What is remarkable of this soil is its massiveness, which seems representative for the soils in this area. The buried paleosol is ~375 cm deep, and the brown soil on top of the basalt ~380 cm. The course of events can perhaps be described as follows:

- a basalt flow covered a deeply developed limestone soil with many secondary carbonates
- a bright brown soil was deposited on top of the basalt, again with many secondary carbonates, and the land surface lifted until it was slightly inclining
- this was later leveled by a gravel band (indicating flooding or an erosion event)
- another bright brown soil formed, was leveled again and gravel deposited
- a darker red soil developed, this time without secondary carbonate, and at some time the land's inclination changed again, and erosion cut through the gravel bands
- at some time tectonic movements created cracks in the area, which exposed the paleosol

Interestingly, the exposure shows the final point of basalt deposition – on the other side of the wadi, a brighter subsoil is simply covered by a darker topsoil, but both of the same massive appearance as the soils associated with the basalt flow (fig. 25). Since the brighter soil might be exposed at some points in the investigation area, and perhaps be connected with the brighter subsoil visible in the Irbid area, the colour change was sampled (**AmFw 1** for the darker soil, and **AmFw 3** for the brighter soil) and compared with a selection of samples from the paleosol-profile. The latter was sampled in detail, but only three samples analysed in the framework of this thesis: **Am 1** for the recent,

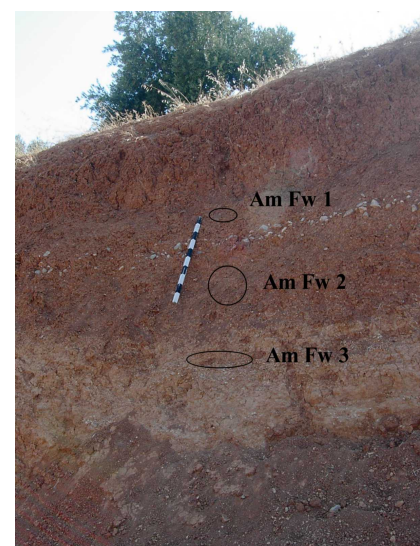


Figure 25: Soil colour change near Amrawah.

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dark brown topsoil over the basalt, **AmO 7** for the bright red soil below the basalt, at a position without manganese concretions and only few secondary carbonates, and **AmO 12** for a lower section of this soil, with some manganese and CaCO₃-concretions, where the soil seemed especially instable. Average annual precipitation at this site is approximately 300 mm.

3.7 Steppe and desert soils

From Irbid and Amrawah it is not far to the steppe and desert – just some 20 km to the east or southeast. Crossing a very short transition zone, which was not investigated further, one arrives on a high, level plateau characterized by yellow, silty soils. These are mostly bare of vegetation, and cut by only few wadis which are very shallow. However massive alluvial gravel fans in depressions indicate that very considerable mass movements took place in the past, and at some locations red paleosols were preserved in pockets which protected them from erosion. One of these paleosols was discovered at the road from Irbid to Mafraq, where it was exposed (and dug away) by a quarry (fig. 26). Interestingly, it showed two phases of red soil development interrupted by phases of aridity, indicated by secondary carbonates forming massive caliche crusts. At the sampled profile, red soil had developed on fine, well-rounded gravel, and been covered by a crust of secondary carbonates. On top of this crust, again fine gravel had been deposited, and another red soil developed. The soil was again covered by a caliche crust, this time extremely hard, and on top of this crust angular gravel with grayish yellow silt had been laid down.

This pattern might point to phases of soil development governed by climatic changes, as described by Khresat and Taimah (1998) and Gvirtzman and Wieder (2001). The desert paleosol was however not analysed in the framework of this thesis, since paleoclimate reconstruction is out of its scope. The paleosols in the desert should however be kept in mind, since they indicate that the Red Mediterranean Soils could have experienced several changes of climate during their genesis (although not as pronounced as in the desert).



Figure 26: Paleosol in the Steppe between Irbid and Mafraq. The photo was taken by R. Bäuml.

For this thesis, only two samples of steppe soil close to Qasr Mshatta and Queen Alia airport were analysed (**Air 1** and **Air 2**, N 31° 44' 16.6", EO 36° 00' 31.2", 735 m above sea level, in order to get a comparison with the Red Mediterranean Soils, and to evaluate the possible role of deflation of steppe soils. Average annual precipitation at Qasr Mshatta is 150 – 200 mm, but which is still enough to farm the area. When the samples were taken (June 2003), wheat was successfully harvested – but this is risk agriculture, which will further be discussed when evaluating the possible impact of drought.

3.8 Ruin soils

As described in chapter 2, soils associated with archaeological ruins were examined in order to compare soil properties with regard to relic soils preserved in the ruins, and historical time frames of soil development on the debris. Samples analysed in this thesis were collected at Tell Zera'a in the Wadi el-Arab (in cooperation with Dieter Vieweger), at Abila (in cooperation with David Chapman), and Jerash (in cooperation with Alan Walmsley). According to Dalman (1942), mudbricks in the 19th century were made by removing larger stones, mixing the soil with dung and chaff, forming the bricks with water, and letting them dry in wooden boxes. It is assumed that this technique also applies to the ancient periods. Regarding the soils on top of the ruins, soil development may have taken place out of the debris, which consists of the limestones occurring in the area.

Tell Zera'a

The excavation of the Gadara-region-project revealed a huge settlement on the Tell Zera'a, which was prominent during the Bronze Age but also settled until the Islamic periods. On the tell, the remains of (air-dried) mudbrick were visible in several trenches excavated in 2003 (N 32° 37' 13.8", EO 35° 39' 19.5", -14 m below sea level). Some larger pieces seemingly belonged together and formed a massive structure at the edge of the



Figure 27: Remnants of Late Bronze Age city wall on Tell Zera'a.

Tell. As it seems, they were part of a Late Bronze Age city wall (fig. 27). While the colour of this structure is mostly reddish-brown, at some places yellowish-white mudbrick remains were visible. So as it seems the mudbricks match the colours of the soils today present in the vicinity: the greyish-white

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material might come from the chalk ridges. Assuming that also the grey, mixed alluvial soil in the valley bottom was also used for the making of mudbricks (which is indicated by Ottoman mudbrick), one can conclude that the colouring of the relic mudbrick walls approximately resembles the relative frequency of soil colour in the closer vicinity of the tell, but with the difference to today's conditions that red seems more prominent in the relic wall. While it was not really possible to distinguish grey mudbrick from the surrounding debris, the good preservation of the other mudbricks indicates quick burial of the wall, and no mixture with the covering debris. Thus red soil might have been used preferentially for making bricks – or was more frequent in the vicinity that today.

Grey mudbrick (**TZ 4**) could be sampled at the remains of some Ottoman houses from 19th century, directly in front of the tell (N 32° 37' 25.0", EO 35° 39' 24.0", 79 m above sea level, fig. 28), which allowed a comparison with regard to the soil's conservation and alteration when used as mudbrick. In the field, the main visible difference between the older and younger mudbrick was only that straw (which is usually added with dung to stabilise the soil) was still visible in the Ottoman wall, while only pores were left in the Bronze Age mudbrick. Red mudbrick from the Late Bronze Age city wall was sampled with **TZ 14**, **TZ 15**, **TZ 16**, and **TZ 16 [II]**. Yellowish-white mudbrick was sampled with **TZ 17**.

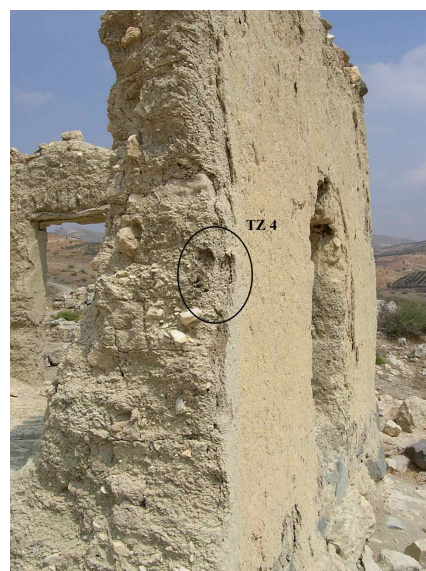


Figure 28: Mudbrick from the Ottoman period in the Wadi el-Arab.

Another interesting feature of the excavation was that the general colour of the debris slightly changed with depth, seemingly not related to moisture since the trenches had dried (August 2003). The upper 10 cm were of dark grey (sample **TZ 6**), seemingly because of high organic matter content (the tell had been farmed before excavation). Below up to ca. 160 cm depth, a bright grey prevailed (sample **TZ 8**), which turned more reddish below 160 cm (sample **TZ 9**). This might support the observation already made with the mudbrick wall, that red soil was more prominent during the Bronze Age - or used preferentially for construction of the tell. The latter seems however not very probable since the grey alluvial soil can also well be used for the making of mudbrick, and the mix in the wall shows that colour seemingly played no role for the design of the Bronze Age town. It is more likely that the soil was used which was most easily accessible, and here a trend towards grey seems evident for the younger periods. It would be worth to more carefully register the kinds of mudbrick and their historical background –

but in the framework of this thesis, only the described samples could be taken.

Abila

Relict mudbrick from Abila had already been investigated in earlier works (Lucke, 2002, Lucke et al., 2005). In the framework of this thesis, only one sample from a Middle Bronze Age mudbrick wall was analysed (sample **Abila relict**). It is located in the deep trench on Tell Abil (area AA, N 32° 40' 57.2", EO 35° 52' 05.5", 430 m above sea level), and was earlier considered to perhaps represent an ancient land surface, conserved in a burrow that was later sealed by plaster (Lucke 2002, Lucke et al., 2005). However, closer examination in cooperation with the Abila Archaeological Project team established that it was only the remains of Middle Bronze Age mudbrick, which was sampled for additional analyses and to re-examine the incorrect texture of earlier works (Lucke, 2002, Lucke et al., 2005).

As well, it should be further investigated to which extent the debris or aeolian deposition contributed to soil development on the ruins. Therefore, the soil cover on Tell Umm el-Amad (area D, N 32° 40' 47.2", EO 35° 53' 04.7", 450 m above sea level) was sampled at positions where erosion could be excluded thanks to remains of



Figure 29: Debris covering the remains of the Umm el-Amad basilica in Abila.

walls surrounding the sampling sites. A thin section of the topsoil was made where huge, well-hewn stones had been covered by grey, silty soil (N 32° 40' 47.7", EO 35° 52' 02.1", 453 m), and the bulk density was measured. Also a profile of debris over a wall of soft limestone was sampled (fig. 29). Samples were taken as shown in table 13.

Table 13: Samples taken from the debris on top of Tell Umm el-Amad, Abila.

Sample No.	Depth [cm]	Description/Comment
AB 4-1	0-5	Roots, plant remains, darker
AB 4-2a	5-15	Bright grey
AB 4-2b	15-23	Bright grey
AB 4-3	23-33	Darker grey band, old surface?
AB 4-4	33+	Well-hewn, weathered limestone (soft enough to be broken by hand)

3. Detailed description of sampling places

Jerash

Sampling at Jerash was conducted since it could take advantage of Alan Walmsley's ongoing excavations, even though Jerash is a little more south and not related to the Wadi el-Arab. But the excavations at Jerash revealed a pattern of debris which reminded me to the Tell Zera'a: it seemed to become more reddish with depth (fig. 30). As it seems, the grey topsoil is associated with huge boulders, which might represent a second phase of collapse and might have been exposed before the grey soil was deposited. This deposition might have been very recent, since the earliest excavations in Jerash in 1928 moved a lot of debris – but it also reminded me to the situation on Tell Umm el-Amad in Abila, where such activities can be excluded.

In air photos from 1918, the area is undisturbed but farmed, just like the other tells. If these loose grey soils at Tell Zera'a, Abila and Jerash are aeolian additions, approximately 20 cm would have been deposited since abandonment of the area. This might not mean much considering the massiveness of some of the agricultural soils, but would point to aeolian activity like on the Chinese Loess Plateau, which is one of the most active regions of dust deposition in the world (see Heller and Liu, 1982). Sampling was conducted as shown in table 14 (N 32° 16' 45.0", EO 35° 53' 27.1", 583 m above sea level).



Figure 30: Soil colour change of debris in Jerash.



Figure 31: Debris under fallen columns in Jerash.

Table 14: Samples taken from the debris on top of the Umayyad mosque, Jerash.

Sample No.	Depth [cm]	Description/Comment
Jer 1	0 – 45	Grey, a lot of huge boulders
Jer 2	45 – 55	Orange, much rubble
Jer 3	55 – 100	Reddish, rubble, might extend deeper

As well, an area was located where, according to Alan Walmsley, the columns of a basilica still laid as they had fallen (supposedly in the earthquake 747 AD). This area had been partially excavated, showing that there is a thin layer of bright debris on a pavement at the bottom. On top of this follows an ash layer, which is covered bright debris again, and then reddish soil, covered by a second ash layer (at least it looks like ash, although it is by far not as massive and pure as the first layer). Now interestingly, the fallen columns rest only on this upper ash layer and are themselves covered by grey debris. This supports Walmsley's (1992) observation that the Decapolis cities were already partially abandoned when the earthquake demolished them. A similar pattern was observed and sampled (but not analysed) at Umm Queis: there fallen the columns also rest on debris, as do the foundations of minor Islamic resettlements (a general pattern at Umm Queis, pers. comm. with Jafar Telfah, field supervisor, August 2003). The place in Jerash had to be sampled at two profiles due to a step-wise excavation (fig. 31). Table 15 shows the collected samples.

Table 15: Samples taken from the debris below the fallen columns in Jerash.

Sample No.	Depth [cm]	Description/Comment
Jer 6a	0-60	Grey debris, fallen columns
Jer 5a	60-70	Ash band, dark grey
Jer 4a	70-120	Reddish soil, profile I
Jer 3a	~120-130	Reddish soil, profile II
Jer 2a	130-165	Bright debris
Jer 1a	165-185	Lower ash band
Jer 0a	185-205	Bright debris covering pavement

3.9 Summary of climate zones

Since the average annual precipitation alone does not define climate zones, these are presented in table 16 for the sampled places according to the Emberger and Koppen classifications (National Atlas of Jordan, 1984).

Table 16: Climatic regions classification of the sampling places.

Climatic regions (Emberger classification)	Sampling places	Climatic regions (Koppen classification)	Sampling places
Arid hot	Jordan valley, Wadi Ziqlab	EA'db4'	Jordan valley
Semi-arid hot	Ard al-Ala, Wadi el-Arab, Tell Zera'a	EB4'da'	Wadi Ziqlab, Ard al-Ala, Wadi el-Arab, Tell Zera'a
Semi-arid warm	Mediterranean high plateau: Abila, Beit Ras, Irbid, Amrawah paleosol	DB3'da'	Mediterranean high plateau: Abila, Beit Ras, Irbid, Amrawah paleosol
Semi-arid mild	Jerash	DB2'da'	Jerash
Arid mild	Steppe paleosol (road from Irbid to Mafraq)	EB2'da'	Steppe paleosol (road from Irbid to Mafraq)
Very arid – mild	Desert soil (Qasr Mshatta)	EB3'da'	Desert soil (Qasr Mshatta)

4. The soil evidence

*But as a mountain falls and crumbles away,
and as rock is moved from its place;
as water wears away stones,
and as torrents wash away the soil of the earth;
so you destroy the hope of man.*

Job 14:18-19

4.1 State of research and interpretation of soil distribution

The detailed description of soils in the investigation area shows strong differences in properties and distribution. It can be summarised that:

- The Jordan valley profile indicates periods of varying sedimentation, and has a gravel horizon pointing to strong erosion. Soil formation shows a tendency to decrease in the younger sediments.
- Colluvia in Wadi Ziqlab show that massive erosion and sedimentation took place in prehistory, and that current soils are much less developed than the paleosols. *Terrae rossae* were covered by *Rendzinas*.
- Soils in the Wadi el-Arab are heterogeneous, but distributed according to the relief.
- The Basalt Soil of the Ard al-Ala is deep and very homogeneous.
- Mediterranean Red Soils around Abila are very heterogeneous, especially regarding depth and colour. Although situated on top of the limestone plateau, the deep profile close to the Yarmouk river indicates that soils were moved and transformed at least twice.
- Most of the investigated *Terrae rossae* contain CaCO_3 , yet those south of the Wadi el-Arab and west of Irbid (in the landscape called *el-Wustije*) are calcium carbonate-free.
- The fluvial limestone gravels around Irbid are covered by very deep Red Mediterranean Soils, with stone bands and a colour change pointing to at least three periods of soil formation. In contrast, a Basalt Soil is very uniform like the one on the Ard el-Ala.
- A brighter red paleosol covered by basalt close to Amrawah might be connected with other bright red soils, as for example in the subsoil of the Irbid basin. At least two fluvial events eroded and redeposited soil on top of the Amrawah basalt.
- Two phases of soil development are visible in a paleosol in the steppe, which were interrupted by periods of increased aridity. Present desert soils are characterised by thin calcareous silts and gravels.
- Ruin soils indicate that red soils might have been more prominent in the past, but that the general picture of soil distribution should not have changed much since the Bronze Age. Since no red soils developed on the debris, one can conclude that weathering intensity and time were not sufficient to produce the red colour, and that the present *Terrae rossae* are old, inherited soils.

As concluded by Schmidt et al. (2006), this pattern clearly points to a dominant role of local factors in soil formation. The deepest soils are located in the east, where wadis are least incised and drainage is

minimal. In this context, long-term erosion seems not so much a matter of average annual rainfall, but relief. Soil variations are strongest on the deeply incised Mediterranean limestone plateau, the level appearance of which seems to be the outcome of considerable soil movement. As indicated by the Yarmouk-profile, one of these movement processes might have taken place around 6880 BC. It is thus younger than the basalt soils, which are characterised by a strongly contrasting uniformity. This illustrates that not only the relief, but also the source rock played an important role for the formation of the soils. The uniformity of the basalt soils might be related to mixing processes that obliterate horizons as visible in the limestone soils, indicated by the drought cracks and slickensides. Even though the deep limestone soils show slickensides, too, their vertic behaviour seems not so pronounced which might be related to different sets of clay minerals.

Soil distribution in the Wadi el-Arab supports the conclusion that soil development took place in a geological time scale. Soil properties are again related to the underlying rocks and relief, with red colluvia in the depressions, exposed chalk ridges, and grey soils covering the natural terraces of harder rocks. The latter might once have carried red soils, as still present on the adjacent high plateaus, but there is so far no reason to attribute their erosion to historical periods. If they had been eroded recently, much more red colluvium should be visible in the Wadi el-Arab (e.g., at the foot of the Tell Zera'a as a sediment obstacle), and not only in depressions between the chalk ridges. Although the lower terraces give evidence of recent soil movements, no red colluvia could be observed there. In this context, the evidence from Wadi Ziqlab merely suggests that the Mediterranean Red Soils were eroded before 11,000 BC.

Earlier studies also recognised such a pattern of soil distribution as natural, representing the erosion climax (Mortensen, 1955, Mensching, 1985, Purschke, 1990). This applies not only to Jordan (Purschke, 1990), but also North Africa (Mensching, 1985) and the Mediterranean in general (Mortensen, 1955). Due to the deeply rooted paradigm of man-made erosion however, it was called "quasi-natural" (quasinatürlich), and Mortensen (1955) defined it as a special research problem to distinguish the man-made erosion from the natural pattern which supposedly obscured man's destructive impact. In the light of additional analyses, it will later be discussed how and whether land degradation in Jordan took place.

Let us turn to Wadi Ziqlab again. Field and Banning (1998), and Maher (2005) describe a complex pattern of colluvial deposits in the Wadi, which are related to landslides and slope collapses. In fact, the valley must have been much flatter and gently sloping during the Early Pleistocene, since substantial archaeological sites from the Paleolithic are present only on the plateau and upper terraces. These show remains of huge sinkholes and slope failures, which indicate how the wadi was incised over

time. As the Jordan rift valley deepened, local base levels dropped and incision was enhanced. Increased aridity at the onset of the last glacial led to dominating erosional processes during the Upper Paleolithic (Maher, 2005). In the valley bottom, the lowest exposed colluvium consist of cobbles overlain by fine sands. The deposition of the earlier reflects flooding events, while the latter indicate a shift from high to low energy transport during the later Early Epipaleolithic (Maher, 2005). By then, a massive red colluvium covered the slopes, and organic remains point to continuing pedogenesis (Maher, 2005). The landscape was stable until the Middle Epipaleolithic, while the valley still had a profile that was shallower and more longitudinal than today, and the main channel was flanked by broad, soil covered terraces (Maher, 2005). With the drying of Lake Lisan some time between 13,000 and 11,000 BC, large-scale erosion and incision resumed, while the base level energy raised again due to the lower levels of the lake. Erosion was again characterised by high energy mass transports since all sites in the younger, brighter colluvium covering the paleosol are associated with angular cobble. Beginning in the Neolithic around 6000 BC, this brighter colluvium was deposited with little post-depositional pedogenesis. In this context, fine alluvial gravels indicate a brief return to fluvial deposition during the Neolithic, perhaps connected with a perennial stream.

Ongoing deposition is evident as all Neolithic sites in Wadi Ziqlab were covered by greyish-yellow soil of strongly varying thickness, and incision continued, too, indicated by the absence of these sites on the lowest wadi terraces (Maher, 2005). Compared with the huge amount of colluvium deposited during the onset of the last glaciation, erosion since the Neolithic seems however small. In average, Byzantine material was only found in the upper 20 cm of the grey colluvium. That most of the younger sediments were also deposited by high intensity mass movement events is indicated by a high density of angular cobbles, and interruption of soil surfaces (Maher, 2005). As well, colluvia vary locally, and were affected by re-deposition. For example, very strong erosion is present in the central part of Wadi Ziqlab, where older terraces are completely missing. As well, Natufian and PPNA sites are apparently missing, which indicates they were removed by massive erosion, which might also explain the sharp colour change to the brighter colluvium (Maher, 2005).

Interestingly, a similar pattern has been reported by Cordova et al. (2005) from the Madaba-Dhiban plateau, south of Amman. This research focused on the vicinity of the site of Khirbet Iskander in the Wadi al-Wala and Wadi at-Thamad. Cordova et al. (2005) dated the plateau soils according to Middle Paleolithic archaeological material. The oldest lithics associated with the Terra Rossa date from the Mousterian, thus indicating that the soils are at least 120,000 years old (Cordova et al., 2005). Since the material was found in the middle of the soil profiles (Nowell et al., 2003), this indicates considerable soil movement or aeolian deposition, because the stratification of the limestone soils points to limited

mixing processes. As well, the distribution of lithics indicates that the Wadi at-Thamad incised by approximately 40 m since the Mousterian, following a pattern which is very similar to Wadi Ziqlab. In the Wadi, the oldest preserved colluvium, the yellowish-brown Dalala soil, was deposited before 17,000 BC. According to Cordova et al. (2005), the Dalala soil could be older, perhaps related to buried soils in the northern Negev which were dated to 26,000 BC (Goodfriend and Magaritz, 1988), and could be connected with loess deposition. Manganese concretions in the Dalala soil may relate it to the buried Amrawah paleosol. This soil as well as part of the plateau soils shows secondary carbonates up to incipient stage III. It is covered by the Thamad terrace, the highest of all aggradational terraces in the Wadi at-Thamad. It accumulated between 17,000 and 6000 BC and shows various horizons of soil development, with loess-like unweathered silts in-between, but which are redder than the Dalala soil (Cordova et al., 2005). A period of landscape stability lasted approximately from 13,000 – 9000 BC, connected with soil formation and incipient clay illuviation. During the Younger Dryas (~9000 – 8000 BC) an abrupt change from silt to angular gravel deposition took place, which was connected with erosion and incision. The erosion of Epipaleolithic-bearing deposits took place all over Jordan roughly between 9000 and 6000 BC, although probably being time-transgressive (Cordova et al., 2005). Another phase of silt deposition in the Wadi at-Thamad followed around 5000 – 3000 BC, creating the Tur al-Abyad terrace which consists of alluvial fill mantled by colluvium. The remains of wells indicate that ground water was accessible from this terrace, which was a fertile floodplain that was well-suited for farming and attracted settlers to Khirbet Iskander. The soil is characterised by comparative richness in organic matter, which might reflect intense land use during the Bronze Age (Cordova et al., 2005). This terrace however was incised in a regional event, probably connected with drought, around 2500 – 2000 BC and might be related to the abandonment of various Early Bronze Age settlements including Khirbet Iskander (which was never resettled). A final phase of colluvial accumulation formed terraces between the Roman and Early Islamic period, which consist of rounded gravel and massive silt units that were again incised and exposed before the 16th century. As in Wadi Ziqlab, landslides are common in Wadi at-Thamad and of such size that they were sometimes nearly mistakenly interpreted as alluvial terraces (Cordova et al., 2005).

The results of these studies are in basic agreement with evidence found by Khresat and Taimah (1998) in Vertisols and desert paleosols. According to these authors, Vertisols in Jordan experienced four episodes of climate change: while humid conditions were present from 40,000 – 20,000 BP, aridity prevailed 20,000 – 13,000 BP. A sub-humid phase took place 13,000 – 7000 BP, after which climate turned arid again.

Gvirtzman and Wieder (2001) found five paleosols formed on sand in the coastal plain of Israel.

4. *The soil evidence*

Red Hamras developed from ~40,000 – 10,500 BC and 8000 – 5500 BC, and a weakly developed Regosol formed 2000 BC – 700 AD. During the Younger Dryas (10,500 – 9500 BC), massive loess deposits covered the oldest Hamra. A wet episode between 9500 – 8500 BC turned the loess material into a dark gray Grumusol, followed by a period of sand dune invasion 8500 – 8000 BC. The following development of red soil was interrupted by sand accumulation ~5500 – 5000 BC, with a short phase of weaker soil development following 4500 – 4000 BC. Again sand deposition prevailed 4000 – 3000 BC, followed by soil development 3000 – 2500 BC, and sand deposition 2500 – 2000 BC. After the last period of relevant soil development, sand was deposited since 700 AD. According to Gvirtzman and Wieder (2001), these periods of soil formation were related to increased moisture, while sand and loess deposition were connected with aridity. Since no gradual transition could be observed between the paleosols, it is concluded that the abrupt end of soil development was connected with sedimentation crossing a threshold that ended soil-forming processes. Some of the red Hamras were seemingly found in offshore boreholes, which confirms their Pleistocene age and formation when the sea level was lower.

Combining the information from these landscape studies with the pattern observed in this thesis, one can conclude that the Red Mediterranean Soils on the plateaus in Jordan are of Upper Pleistocene age or older. Since erosion always leads to some deposition, there is evidence that they were eroded mainly during the late Pleistocene and the Younger Dryas. In this context, it is remarkable that massive historic colluvia as observed at Beit Ras are not present over the whole investigated region. This can be explained in two ways: on the one hand, colluvia deposition was locally different due to the varying relief, and due to the local impact of extreme events. Beit Ras must have been struck by severe rainstorms during the Umayyad period, which did not only fill the theatre, but may also have deposited part of the deep red colluvium in the wadi (the part which contains Byzantine pottery). Compared to places like Abila or Irbid, the rainstorm's impact would have been aggravated at Beit Ras by the relative steep slopes of the site. On the other hand, it is not likely that the occurrence of heavy rainstorms during the Umayyad period was limited to Beit Ras, and in fact the youngest terrace in the Wadi at-Thamad points to similar events on the Madaba-Dhiban plateau during this period. Therefore the non-existence of other historic colluvia of similar size in the studied areas indicates that the landscape is in fact *erosion-resistant*.

It has been claimed that Red Mediterranean Soils are very susceptible to erosion (e.g., by Purschke, 1990), and numerous attempts were undertaken to actually measure erosion with a range of methods. The Zarqa-river-basin project undertook erosion-simulations using sprinklers and runoff-plots (GTZ, 1986). The results ranged from zero to catastrophic erosion, dependent on the handling of

the sprinklers. What could not be taken into account was for example how soil properties changed over the year: different moisture levels are connected with a very different behaviour of the clay-rich Terra Rossa, and all calculations based on time-independent soil properties like texture (usually used in models) are thus questionable. For example, the dry soil forms cracks that have a very important impact on infiltration and can consume runoff water. As well, it matters whether the bedrock has fissures or not which could drain excess water. A water-saturated Terra Rossa however will start creeping, which is hard to track with a runoff plot. Also, extreme precipitation events as the most important agents of erosion are very difficult to measure. Firstly because projects, even if they are conducted under natural conditions, usually do not run long enough to catch one of these events. And secondly even if they did, most sampling devices had to be dug out of meters of colluvium (if they were ever found at the other end of the wadi). These difficulties made Stroosnijder (2005) speak of a crisis in erosion research, and ask whether measuring erosion is possible at all. Many erosion models that are classified as deterministic may in fact have to be called empirical, based on estimates because of the lack of adequate data and measuring techniques. It might be impossible to build a catchment hydrological and erosion model (Stroosnijder, 2005).

Enhanced and very massive erosion plots from concrete were built during the MEDALUS project, and in Mexico in the framework of the RESOLVO project. These were designed to withstand massive deluges while equipped with automatic samplers and rain collectors so that even the effect of the slightest rains would be measured. In Mexico, these devices were built next to gullies of frightening size in Tepetate soils near Morelia (which I visited during an excursion in the framework of the Global-Soil-Change-Conference in Mexico City, March 2005). Tepetate soils have a thin topsoil stabilised by organic matter, and consist of volcanic ash in the subsoil. There is no question that these soils are most vulnerable to erosion: once the topsoil is lost, the ash can be deflated or will harden and immediately form gullies under the impact of water. These might incise dramatically as the hard crust leads to high runoff and the water soon crosses the energy threshold necessary to move soil. But the surprising result of erosion measurements at the Tepetate gullies was that they are basically stable. Rare heavy rainstorms created about 80% of the erosion, while nearly nothing happened under normal precipitation (pers. comm. with Christian Prat, March 2005). Well-managed agriculture was found to be even of advantage, since ploughing can increase infiltration and thus might help to reduce excess water. The gullies near Morelia probably formed during a single extreme precipitation event, possibly a hurricane which struck the area just after the forest had been cleared in the colonial period. But they remained stable since then – which is also indicated by nearby houses still standing (pers. comm. with Christian Prat, March 2005).

If already the Tepetate soils are not so strongly eroded under a similar climate and environment, how is it with Terra Rossa which is much more stable? One might argue that the gullies in the Tepetate would not have formed without deforestation, which was man-made. Yet regarding erosion results from the MEDALUS project, Grove and Rackham (2003) note that not deforestation, but ploughing is more important. One has to add that a Mediterranean forest looks different from a Mexican one, and the possible impact of deforestation will be discussed later. However, evidence from the MEDALUS project supports the conclusion from the Decapolis that erosion is primarily dependent on the geology, and less on the weather, vegetation or human impact. For example, steep and rocky Crete is erosion-resistant, while well-wooded Rhodes with its slighter slopes is strongly affected. Karst and fissures in the Cretan limestone, the softness of Rhodes' marls, and the tendency of Crete's deposits to cement and stabilise make the difference (Grove and Rackham, 2003, p. 284). And even though Cretan farmers were given bulldozers and heavy machinery since 50 years, which led to creating false terraces and moving earth on a scale that was never reached during the whole antiquity, the landscape is not collapsing and dam-builders can still be unmindful of sedimentation. But which can, as the historic colluvia show, be very severe (Grove and Rackham, 2003). In this context, Cerdà (1998) found that there was no hydrological or erosional trend along a climatic gradient in Israel, Crete and Spain, or in other words, that the mean annual rainfall played no role. But temperature might play a role for soil aggregate stability: according to Imeson and Lavee (1998), high temperatures in the Judean mountains were connected with a high concentration of soluble salts and reduced aggregate stability.

The evidence gathered by the MEDALUS project regarding erosion in the Mediterranean has been discussed in all details by Grove and Rackham (2003) and shall not be repeated here. It shall only be mentioned that that the Universal Soil Loss equation failed to predict sheet and gully erosion in the Mediterranean. It seems even worse at predicting total erosion, and leads to values 27-40 times higher than what can be supported by measurements (Grove and Rackham, 2003, p. 263). The possibility of deflation will be discussed with the texture in chapter 4.2.4. Let us summarise that erosion in the Mediterranean is primarily a matter of geology, while phases of quick landscape change seem to be governed by climatic phenomenons. The Decapolis region, and the part of the Mediterranean which is characterised by karst, is erosion resistant. Or, as the National Soil Map and Land Use Project (NSM&LUP, 1993) puts it for the case of Jordan, is in the stable state of completed erosion – which took place during the Ice Age. In this context, the archaeological remains support that few soil was present when the earliest settlements were founded: for example, the Early Bronze Age settlement at Abila was constructed on bedrock. As well, all Dolmen which I observed rest on bedrock, and it does not seem that meters of soil had to be dug away for their construction. Rocky spots were exploited for

water harvesting, quarrying, and viticulture, and show remains from the earliest periods of olive cultivation (cupmarks for pressing olives by hand), indicating that they were there since the earliest agriculture. When Samaria was built in the Iron Age, karst pockets with red soil were built over, indicating that the hill was as rocky as it is today (Reisner et al., 1924). It is likely that settlements were preferably built on rocky spots, since the vertic properties of deep soils would damage the houses. Geraty and Herr (1989), and Dar (1986) found that farmsteads on the Madaba plains and in Samaria were constructed with regard to soil properties, encircling the deepest soils and taking advantage of rocky spots. In this context, already the Mishna mentioned an omnipresent danger that a plough might be damaged by unexpectedly hitting rock under shallow soils in the highland (Dalman, 1932).

From the distribution of soils and colluvia alone we can conclude that general erosion due to historic land use did not take place, a misconception which seems to be connected with northern European ideas about how a "natural" soil or landscape should look like (see a detailed discussion about the imagined erosion in Grove and Rackham, 2003). Land use might locally have enhanced erosion, for example along streets, which on some plains turned into hollow ways and later into gullies (Wilkinson, 2003). Also earthquakes may have played a role, which is well-known since Plato mentioned in his famous account of Atlantis how deep soil on Athens' Acropolis was swept away by a combination of flood and earthquake³ (Plato, Critias III, cited in Grove and Rackham, 2003, p. 288). In Jordan, there is however no evidence for a connection of earthquakes and colluvium deposition. Migowski (2004) analysed sediments in the Dead Sea bearing earthquake signals (seismites), but none seems connected with increased sedimentation. Earthquakes might locally have contributed to slope collapses and sinkholes, but regarding Wadi Ziqlab, Maher (2005) noticed only one rock collapse of Pleistocene age that might have been connected with an earthquake.

Reviewing the evidence from the Dead Sea, it is interesting to note that there are differences of the deposited material. Aragonite precipitated if there was an influx of quickly evaporating freshwater. Clasts were deposited with runoff and consist of chalk, remains of organic matter, and clay minerals. Aragonite and clast are usually ordered in alternating layers, and pairs (varves) represent years (Migowski, 2004). As well, halite and gypsum could be observed and were interpreted to mark warmer and drier conditions with stronger evaporation. Last but not least, sand layers were found which seemingly were connected with aeolian deposition (Migowski, 2004).

The clast layer size is a function of the intensity of floods which carried the sediments to the Dead Sea. This size of the evaporitic layers depends on evaporation intensity and the timing of freshwater influx. To some degree, the layer deposition shows weak clustering which might be

³ Plato's estimate of the deluge's timing, 9000 BC, is surprisingly close to the late Pleistocene erosion phase.

connected with the 11-years sunspot cycle, and the 22-years heliomagnetic cycle (Migowski, 2004). But the solar cycles are seemingly overruled by the impact of general atmospheric circulation patterns. In the Ein Gedi core, the deposition of the so-called "main clastic sequence" 6000-4500 BC is simultaneous with the advent of the pottery Neolithic, and characterised by a sharp rise of sedimentation (Migowski, 2004). Clast layers are associated with significant drops of the lake level, indicating reduced precipitation and sparse vegetation (Migowski et al., 2006). Aragonite layers are mainly absent in the main clastic sequence. This points to a changed pattern of precipitation with summer rains, which might have been connected with monsoons reaching the area. An alternative explanation for the missing aragonite layers would be lower summer temperatures. In any case, the very sharp rise of erosion seems connected with drier conditions, more pronounced floods and reduced vegetation. This pattern repeats, although more erratic, 2100-1500 BC with the "upper clastic sequence" at the end of the Early Bronze Age (Migowski, 2004). It is interesting to note that at both occasions, the changed sedimentation behaviour was connected with sand layers, in the lower core consisting of well-rounded grains seemingly transported through the air (Migowski, 2004). A sedimentation hiatus and fluvial deposition point to a temporary drying of the lake during these periods at the position of the Ein-Gedi core. The sand indicates that periods of climate change might have been connected with very strong storms, which will further be discussed with the thin sections (chapter 4.6).

Archaeologically, the clastic sequences (with a maximum sedimentation around 6000 – 5000 BC) are coincident with gaps in the settlement history, and a switch to nomadic life. In contrast, periods of maximum settlement activity are reflected by the lowest total sedimentation in the Dead Sea (see appendix B in Migowski et al., 2006). If land degradation took place due to human activities, it was local and connected with nutrient depletion, which will be discussed in the light of additional analyses in the following chapters.

Vita-Finzi (1969, 1971) distinguished an "older" and "younger" fill in Mediterranean valleys. These were laid down during periods of sedimentation, while the other times were characterised by incision. His research was initially based on remains of Roman flood farming dams in Libya, which were undercut by incision at the end of the Byzantine period. Although local conditions are always more complex, the general pattern of two aggradation phases seems to apply to the whole Mediterranean and Mexico (Vita-Finzi, 1977). The older fill was deposited approximately from 40,000 – 8000 BC, and the younger fill from 400 – 1800 AD, but deposition moved with latitude from north to south (45°-25°, Vita-Finzi, 1995). It seems therefore that erosion, incision and deposition in the Mediterranean are governed by the general climatic circulation. However, Vita-Finzi (1971) points out that wadi sediments cannot be taken as direct indicator for climate, but only for stream regimes. In this

context, the older fill was deposited by flash floods and mud flows, but the sedimentation of the younger fill mostly remained below the threshold velocity necessary to move larger grains. The younger fill is also characterised by seasonal discharge and selective export of suspension load, yet with a marked depletion of its clay and silt fraction in comparison with the older fill. This was primarily due to a change in stream discharges leading to silt-clay depletion and a steepening of channel gradients (Vita-Finzi, 1971). In the light of the hydrological variability of the affected area, the best explanation is reduced rainfall seasonality. In general, aggradation seems due to a precipitation regime which is less peaked, with respect to both the seasonal distribution and size of rainfalls. Aggradation creates fertile plains, while incision of valley fills impairs an area's grazing resources by destroying the most vegetated areas (Vita-Finzi, 1977).

Bruins (1990) found in this context that stream channel sedimentation in the Negev took place during relatively wet phases (during the Roman period, and from 1200 – 1700 AD, and while incision dominated during dry phases (approximately from 700 – 1200 AD, and from 1700 – today). Rösner (1995) found evidence in wadi terraces in Syria which illustrates how different climatic patterns will lead to different erosion and deposition. Flash floods will first deposit gravel, and only if sustained flow or ponding occur, also fine material will aggrade. Therefore many terraces in Syria show alternating layers of coarse and fine material.

Leopold (1994) found that floodplains will be abandoned and at least partially be destroyed when climate becomes drier. Moist phases in arid and semi-arid areas, even if leading to only slightly enhanced vegetation growth, will bring immediate stabilisation of the landscape. Trends to drier conditions will in contrast lead to incision of valley bottoms. In this context, rainfall in semi-arid areas around the world occurs mainly in form of thunderstorms (Leopold, 1994). The main difference of more humid or arid locations of semi-arid regions is in the character of rainfall, closely related to the number of small rains during a year. Small rains are decisive as they foster vegetation and do not cause great discharges - but the frequency of heavy rains is identical at the above discussed locations (Leopold, 1994). Therefore valley erosion and dry periods are not characterised by a change of annual rainfall, but a change in rainfall intensity. Aggradation occurs in periods of relative humidity. Such periods altered frequently, and erosion is not necessarily contemporaneous in all parts of a drainage basin. Human land use or erosion control devices play no role: check dams in gullies sometimes make things even worse, since erosion is not stopped, but cuts around the dam, making the gully wider (Leopold, 1994).

4.2 Colour, organic matter, CaCO₃, texture, pH and conductivity

In this chapter, the results of soil analyses regarding colour, organic matter, CaCO₃, texture, pH and electrical conductivity are discussed (table 17). These are nearly standard parameters, and applied in most studies.

As already discussed, the colour seems a very prominent and important parameter. Colour changes might reflect different periods and intensities of land use, since they seemingly follow field borders, but it is unclear what causes these differences.

Organic matter is low in soils without winter rest, and thus usually plays no significant role in Mediterranean soils. But it might be relevant for the mentioned soil colour changes on the fields, and provide information about ancient manure and land use intensities.

The texture is a criterion that on the one hand delivers a relative age estimation, since soils should become finer when older. Also, the texture has to be known if the basic behaviour of the soils and suitability for cultivation shall be evaluated.

CaCO₃ delivers an age estimation as well, as it should be leached from limestone-derived soils with increasing age. Also, it has important influence in soil behaviour. For example, the texture will seem coarser when CaCO₃ is present, since it will lead to a coagulation of particles. As well, CaCO₃ affects fertility: if present in huge amounts, it might lead to fixation of plant available phosphorus, but if missing, fertility might be reduced due to a loss of bases in a more acid soil.

The pH delivers information about the chemical "milieu" of the soil, for example about leaching processes and base accumulation. The electrical conductivity allows an assessment of the degree of base accumulation, i.e. soil salinity.

The laboratory analyses are presented in table 17 on the next pages.

Table 17: Colour, organic matter, calcium carbonate, texture, pH, conductivity.

Sample No.	Skeleton – content (%)	Munsell dry	Munsell moist	RR (dry)	C _{org} %	CaCO ₃ %	Clay %	Silt %	Sand %	pH (H ₂ O)	conductivity (μS)	Dating/Age
Jordan valley												
Jor 1	33	7.5 YR 4/1 brownish gray	7.5 YR 2/1 black	70	1.8	51	<i>44</i>	<i>19</i>	<i>37</i>	8.3	124	
Jor 3	61	10 YR 6/3 dull yellow orange	10 YR 3/4 dark brown	40	0.6	64	<i>39</i>	<i>16</i>	<i>45</i>	8.7	120	
Jor 5	3	5 YR 7/4 dull orange	5 YR 5/8 bright reddish brown	26	0.2	61	<i>53</i>	<i>32</i>	<i>15</i>	8.9	140	
Jor 7	1	7.5 YR 7/3 dull orange	5 YR 5/6 bright reddish brown	41	0.3	62	<i>58</i>	<i>23</i>	<i>19</i>	8.9	144	
Jor 10	0	7.5 YR 6/4 dull orange	7.5 YR 4/4 brown	26	0.6	41	<i>67</i>	<i>23</i>	<i>10</i>	8.1	358	
Jor 12	13	7.5 YR 6/6 orange	7.5 YR 5/8 bright brown	18	0.04	65	<i>23</i>	<i>13</i>	<i>64</i>	8.8	120	
Wadi Ziqlab												
Ziq 1	9	7.5 YR 7/2 light brownish gray	7.5 YR 4/6 brown	61	1.4	65	<i>69</i>	<i>21</i>	<i>10</i>	8.2	94	
Ziq 2	5	2.5 Y 8/3 pale yellow	5 YR 5/8 bright reddish brown	n.d.	0.6	63	<i>71</i>	<i>25</i>	<i>4</i>	8.2	118	Post-Byzantine
Ziq 3	24	7.5 YR 6/3 dull brown	7.5 YR 4/6 brown	35	0.8	50	<i>75</i>	<i>22</i>	<i>3</i>	8.3	155	Byzantine
Ziq 4	22	7.5YR 6/3 dull brown	7.5YR 4/4 brown	35	0.9	45	<i>74</i>	<i>22</i>	<i>4</i>	8.1	197	11,000 BC
Wadi el-Arab, colluvium at foot of Tell Zera'a												
TZ 23	28	7.5 YR 5/3 dull brown	7.5 YR 3/3 dark brown	29	1.3	63	<i>54</i>	<i>22</i>	<i>24</i>	8.6	118	
TZ 24	18	7.5 YR 5/3 dull brown	7.5 YR 3/4 dark brown	29	0.6	65	<i>55</i>	<i>18</i>	<i>27</i>	8.7	103	
TZ 25	29	7.5 YR 7/2 light brownish gray	7.5 YR 5/6 bright brown	61	0.4	70	<i>73</i>	<i>17</i>	<i>10</i>	8.4	80	
TZ 26	13	5 YR 8/1 light gray	2.5 Y 4/6 olive brown	120	0.2	72	<i>68</i>	<i>16</i>	<i>16</i>	8.8	94	
TZ 27	18	10 YR 7/2 dull yellow orange	10 YR 4/6 brown	70	0.3	69	<i>54</i>	<i>16</i>	<i>30</i>	8.6	97	

Sample No.	Skeleton – content (%)	Munsell dry	Munsell moist	RR (dry)	C _{org} %	CaCO ₃ %	Clay %	Silt %	Sand %	pH (H ₂ O)	conductivity (μS)	Dating/Age
Wadi el-Arab, red soil in depression												
TZ 50	43	7.5 YR 6/6 dull orange	2.5 YR 3/6 dark reddish brown	18	0.6	58	<i>68</i>	<i>19</i>	<i>13</i>	8.4	84	
Wadi el-Arab, chalk ridge												
TZ 54	1	2.5Y 8/2 light gray	10YR 6/4 dull yellow orange	n.d.	1.0	74	<i>64</i>	<i>25</i>	<i>11</i>	8.3	770	
Wadi el-Arab, terrace on lower southern slope												
TZ 73	43	7.5 YR 7/3 dull orange	7.5 YR 5/4 dull brown	41	0.4	76	<i>40</i>	<i>11</i>	<i>49</i>	8.5	123	
Wadi el-Arab, soil developed on travertine												
TZ 129	8	5 YR 3/6 dark reddish brown	10 R 3/6 dark red	8	0.8	39	<i>67</i>	<i>24</i>	<i>9</i>	8.5	77	
Wadi el-Arab, terrace on upper southern slope												
TZ 65	55	10 YR 5/2 grayish yellow brown	7.5 YR 3/3 dark brown	50	4.0	61	<i>25</i>	<i>11</i>	<i>64</i>	7.8	220	
Wadi el-Arab, forest soil pocket in rocky area												
TZ 106	9	7.5 YR 3/4 dark brown	2.5 YR 2/2 very dark reddish brown	13	3.6	18	<i>69</i>	<i>26</i>	<i>5</i>	8.0	150	
Wadi el-Arab, buried soil on northern slope												
TZ 2	35	5 YR 6/4 dull orange	7.5 YR 4/4 brown	23	0.6	38	<i>70</i>	<i>29</i>	<i>1</i>	7.9	1801	
Basalt plateau Ard al-Ala												
UQ 9	4	7.5 YR 4/4 brown	5 YR 3/6 dark reddish brown	18	1.3	13	<i>89</i>	<i>7</i>	<i>4</i>	8.1	116	
UQ 13	6	7.5 YR 5/3 dull brown	7.5 YR 4/6 brown	29	0.8	15	<i>87</i>	<i>7</i>	<i>6</i>	8.4	145	
UQ 21	1	7.5 YR 4/3 brown	5 YR 3/6 dark reddish brown	23	1.0	13	<i>88</i>	<i>7</i>	<i>5</i>	8.2	165	
Western edge of basalt												
UQ 15	15	5 YR 3/6 dark reddish brown	10 R 3/4 dark red	8	0.9	16	<i>72</i>	<i>21</i>	<i>7</i>	8.7	126	
Southern rim of basalt												
TZ 1	5	5 YR 3/6 dark reddish brown	10 R 3/6 dark red	8	0.7	17	<i>69</i>	<i>23</i>	<i>8</i>	8.4	100	

Sample No.	Skeleton – content (%)	Munsell dry	Munsell moist	RR (dry)	C _{org} %	CaCO ₃ %	Clay %	Silt %	Sand %	pH (H ₂ O)	conductivity (μS)	Dating/Age
Med. plateau, street cut at unity dam, Yarmouk												
AB 1	30	7.5 YR 5/3 dull brown	7.5 YR 3/4 dark brown	29	1.2	44	<i>69</i>	22	9	8.2	160	6880 BC or 386 BC
AB 2	18	7.5 YR 5/3 dull brown	7.5 YR 3/4 dark brown	29	1.0	48	<i>68</i>	21	11	8.1	194	
AB 3	10	5 YR 3/4 dark reddish brown	2.5 YR 3/4 dark reddish brown	11	1.5	32	<i>77</i>	21	2	8.2	129	
AB 4	12	5 YR 4/4 dull reddish brown	2.5 YR 3/4 dark reddish brown	15	0.8	30	<i>77</i>	21	2	8.3	133	
AB 5	10	5 YR 4/4 dull reddish brown	2.5 YR 3/6 dark reddish brown	15	0.5	22	<i>76</i>	23	1	8.4	154	
AB 6	5	7.5 YR 4/4 brown	5 YR 3/6 dark reddish brown	18	0.7	12	<i>77</i>	19	4	8.3	247	
AB 7	2	10 YR 3/4 dark brown	5 YR 3/4 dark reddish brown	15	0.7	11	<i>78</i>	19	3	8.3	236	
Med. plateau, street cut at unity dam, Yarmouk												
Yar 1	27	7.5 YR 5/3 dull brown	5 YR 3/4 dark reddish brown	29	1.3	52	<i>63</i>	22	15	8.1	133	
Yar 2	6	7.5 YR 5/4 dull brown	2.5 YR 3/6 dark reddish brown	13	1.1	46	<i>84</i>	14	2	8.2	125	
Yar 3	30	7.5 YR 5/4 dull brown	2.5 YR 3/6 dark reddish brown	13	0.9	49	<i>75</i>	19	6	8.3	132	
Yar 4	12	10 YR 5/3 dull yellowish brown	5 YR 3/6 dark reddish brown	33	0.9	19	<i>75</i>	24	1	8.2	140	
Med. plateau, street cut at unity dam, Yarmouk												
Yar 1a	27	2.5 YR 6/4 dull orange	2.5 YR 3/6 dark reddish brown	19	1.2	55	<i>65</i>	22	13	8.2	129	
Med. plateau, street cut at unity dam, Yarmouk												
Yar Mitte	25	10 YR 4/4 dark yellowish brown	10 YR 3/4 dark yellowish brown	20	0.4	12	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.3	349	
Yar Mitte unten	17	10 YR 4/4 dark yellowish brown	10 YR 3/4 dark yellowish brown	20	0.3	37	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.9	274	

Sample No.	Skeleton – content (%)	Munsell dry	Munsell moist	RR (dry)	C _{org} %	CaCO ₃ %	Clay %	Silt %	Sand %	pH (H ₂ O)	conductivity (μS)	Dating/Age
Med. plateau, shallow soil on caliche												
AB 9	4	5 YR 3/6 dark reddish brown	2.5 YR 3/6 dark reddish brown	8	1.0	5	75	23	2	8.4	112	
Med. plateau, Abila fields colour change, field 1												
AB 1-2 1	14	2.5 YR 4/6 reddish brown	10 R 3/6 dark red	8	1.5	40	72	23	5	8.1	106	
AB 1-2 2	11	2.5 YR 4/6 reddish brown	10 R 3/6 dark red	8	1.4	36	73	23	4	8.2	101	
AB 1-2 3	15	2.5 YR 4/6 reddish brown	10 R 3/4 dark red	8	0.8	36	69	24	7	8.3	96	
AB 1-2 4	35	7.5 YR 4/4 brown	2.5 YR 3/4 dark reddish brown	18	1.2	23	73	23	4	8.3	83	
Med. plateau, Abila fields colour change, field 2												
AB 2-2 1	17	10 YR 6/4 dull yellow orange	2.5 YR 3/6 dark reddish brown	30	0.9	49	69	25	6	8.2	100	
AB 2-2 2	17	10 YR 6/4 dull yellow orange	5 YR 3/6 dark reddish brown	30	0.7	48	73	23	4	8.3	89	
AB 2-2 3	30	5 YR 5/4 dull reddish brown	5 YR 3/6 dark reddish brown	19	1.0	50	75	23	2	8.3	86	
AB 2-2 4	28	10 YR 6/4 dull yellow orange	2.5 YR 3/6 dark reddish brown	30	0.8	52	74	21	5	8.3	96	
AB 2-2 5	63	2.5 YR 5/4 dull reddish brown	2.5 YR 3/6 dark reddish brown	16	0.6	54	75	21	4	8.3	101	
Med. plateau, fields with olives and fallow, Abila												
WQ mit	20	5 YR 3/6 dark reddish brown	2.5 YR 3/4 dark reddish brown	8	1.8	20	71	22	7	8.0	157	
WQ ohne	28	5 YR 5/4 dull reddish brown	5 YR 3/6 dark reddish brown	19	2.6	34	76	20	4	7.9	182	
Med. plateau, field system remains near Qumeim												
Feldsys 1	8	2.5 YR 3/3 dark reddish brown	10 R 3/3 dark reddish brown	13	1.0	0	68	29	3	7.7	76	
Feldsys 2	40	2.5 YR 3/4 dark reddish brown	10 R 3/4 dark red	9	1.0	1	67	28	5	7.9	125	

Sample No.	Skeleton – content (%)	Munsell dry	Munsell moist	RR (dry)	C _{org} %	CaCO ₃ %	Clay %	Silt %	Sand %	pH (H ₂ O)	conductivity (μS)	Dating/Age
Med. plateau, landslide in Wadi Queilbeh												
Qo 1	1	7.5 YR 6/3 dull brown	7.5 YR 4/4 brown	35	0.8	49	75	21	4	8.2	106	
Med. plateau, colluvium in Wadi Queilbeh												
Q 2	17	5 YR 6/3 dull orange	5 YR 3/6 dark reddish brown	8	1.2	50	74	20	6	7.8	154	
Q 8	25	7.5 YR 6/3 dull brown	7.5 YR 4/4 brown	35	0.7	44	73	23	4	8.0	105	
Q 12	42	7.5 YR 5/4 dull brown	5 YR 3/6 dark reddish brown	22	0.6	37	76	20	4	7.7	114	
Q 18	42	7.5 YR 5/3 dull brown	5 YR 5/3 dark reddish brown	29	0.4	36	74	20	6	8.1	154	
Med. plateau, sediments at Roman bridge, Abila												
Brücke 9	26	2.5 Y 6/2 light brownish gray	2.5 Y 4/2 dark grayish brown	n.d.	0.6	73	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.5	142	
Brücke 8	28	2.5 Y 6/2 light brownish gray	2.5 Y 4/2 dark grayish brown	n.d.	0.4	61	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.4	156	
Brücke 7	20	2.5 Y 6/2 light brownish gray	2.5 Y 4/2 dark grayish brown	n.d.	0.2	58	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.4	175	
Brücke 6	40	2.5 Y 5/2 grayish brown	2.5 Y 4/2 dark grayish brown	n.d.	0.2	73	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.6	138	1206 AD
Brücke 5	4	2.5 Y 6/2 light brownish gray	2.5 Y 4/2 dark grayish brown	n.d.	0.1	45	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.5	165	
Brücke 4	37	2.5 Y 6/2 light brownish gray	2.5 Y 4/2 dark grayish brown	n.d.	0.2	60	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.5	168	
Brücke 3	28	2.5 Y 6/2 light brownish gray	2.5 Y 5/2 grayish brown	n.d.	0.1	51	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.4	156	
Brücke 2	36	2.5 Y 7/2 light gray	2.5 Y 4/2 dark grayish brown	n.d.	0.02	64	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.5	140	
Brücke 1	9	2.5 Y 7/2 light gray	2.5 Y 5/2 grayish brown	n.d.	0.1	58	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.6	267	
Brücke 0	2	2.5 Y 7/2 light gray	2.5 Y 5/2 grayish brown	n.d.	0.1	60	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.6	162	585 AD

Sample No.	Skeleton – content (%)	Munsell dry	Munsell moist	RR (dry)	C _{org} %	CaCO ₃ %	Clay %	Silt %	Sand %	pH (H ₂ O)	conductivity (μS)	Dating/Age
Med. plateau, wadi colluvium near Beit Ras												
BR 2	36	7.5 YR 4/3 brown	7.5 YR 3/3 dark brown	23	1.2	37	75	23	2	8.4	85	Pre-pottery?
BR 10	29	7.5 YR 5/3 dull brown	2.5 YR 3/3 dark reddish brown	29	0.6	26	75	22	3	8.2	101	
BR 14	23	7.5 YR 4/4 brown	5 YR 3/4 dark reddish brown	18	0.3	20	75	23	2	8.0	83	
BR 21	10	5 YR 3/4 dark reddish brown	7.5 YR 3/4 dark brown	11	1.2	8	68	31	1	7.8	116	
Irbid basin, building pit												
I 14a	5	5 YR 3/3 dark reddish brown	5 YR 2/4 very dark reddish brown	15	0.5	3	66	29	5	8.2	92	
I 9	10	7.5 YR 5/3 dull brown	5 YR 3/6 dark reddish brown	29	0.4	11	66	29	5	8.0	180	
I 04	44	10 YR 7/3 dull yellow orange	10 YR 7/6 yellow orange	47	0.1	67	55	3	42	8.4	242	
Colour change Amrawah												
AmFw 1	4	5 YR 5/4 dull reddish brown	2.5 YR 4/8 reddish brown	19	0.4	21	61	36	3	8.7	175	
AmFw 3	5	7.5 YR 6/4 dull orange	7.5 YR 5/8 bright brown	26	0.2	36	56	36	8	9.2	155	
Amrawah, paelosol under basalt												
Am 1	33	7.5 YR 5/3 dull brown	5 YR 3/6 dark reddish brown	29	0.9	13	73	24	3	8.2	165	700,000 - 23.8 Mio.?
AmO 7	10	7.5 YR 6/4 dull orange	7.5 YR 5/8 bright brown	26	0.4	41	64	17	19	8.5	144	
AmO 12	11	7.5 YR 6/4 dull orange	7.5 YR 5/8 bright brown	26	0.6	21	71	23	6	8.4	145	
Desert soils, Qasr Mshatta												
Air 1	1	10 YR 7/4 dull yellow orange	10 YR 4/6 brown	35	1.0	31	46	51	3	8.9	126	
Air 2	12	7.5 YR 7/4 dull orange	10 YR 4/6 brown	30	1.6	22	33	58	9	8.6	165	

Sample No.	Skeleton – content (%)	Munsell dry	Munsell moist	RR (dry)	C _{org} %	CaCO ₃ %	Clay %	Silt %	Sand %	pH (H ₂ O)	conductivity (µS)	Dating/Age
Ruin soils, mudbrick from Ottoman house												
TZ 4	35	5 YR 7/2 light brownish grey	5 YR 5/3 dull reddish brown	53	1.7	61	<i>71</i>	<i>24</i>	<i>5</i>	7.8	1515	19 th century
Ruin soils, relic mudbrick on Tell Zera'a												
TZ 14	11	7.5 YR 6/3 dull brown	5 YR 3/6 dark reddish brown	35	0.6	38	<i>78</i>	<i>20</i>	<i>2</i>	7.7	1905	Late Bronze Age
TZ 15	13	5 YR 6/3 dull orange	5 YR 3/6 dark reddish brown	30	0.8	37	<i>73</i>	<i>24</i>	<i>3</i>	8.1	1130	Late Bronze Age
TZ 16	13	7.5 YR 5/3 dull brown	5 YR 4/4 dull reddish brown	29	0.8	37	<i>50</i>	<i>49</i>	<i>2</i>	8.9	242	Late Bronze Age
TZ 16 (II)	10	7.5 YR 5/4 dull brown	7.5 YR 3/4 dark brown	22	0.4	40	<i>77</i>	<i>22</i>	<i>1</i>	8.7	164	Late Bronze Age
TZ 17	25	10 YR 7/4 dull yellow orange	5 YR 5/8 bright reddish brown	35	0.2	62	<i>69</i>	<i>27</i>	<i>4</i>	9.2	132	Late Bronze Age
Ruin soils, relic mudbrick on Tell Abil												
Abila relict	10	5 YR 5/4 dull reddish brown	2.5 YR 3/6 dark reddish brown	19	0.6	13	<i>68</i>	<i>29</i>	<i>3</i>	8.5	470	Middle Bronze Age
Ruin soils, debris levels on Tell Zera'a												
TZ 6	26	7.5 YR 6/4 brownish gray	7.5 YR 3/1 brownish black	26	3.5	56	<i>60</i>	<i>33</i>	<i>7</i>	7.9	194	Post-Abbasid
TZ 8	18	10 YR 7/1 light gray	7.5 YR 4/4 brown	140	0.5	57	<i>44</i>	<i>27</i>	<i>29</i>	8.9	200	Post-Late Bronze Age
TZ 9	20	5 YR 7/2 light brownish gray	5 YR 4/4 dull reddish brown	53	0.4	56	<i>34</i>	<i>23</i>	<i>43</i>	8.6	2900	Late Bronze Age
Ruin soils, debris on basilica wall, Abila												
AB 4-1	52	5 YR 7/2 light gray	10 YR 4/4 brown	53	1.2	73	<i>48</i>	<i>24</i>	<i>28</i>	8.7	163	
AB 4-2a	10	10 YR 7/3 very pale brown	10 YR 5/4 yellowish brown	47	0.7	81	<i>n.a.</i>	<i>n.a.</i>	<i>n.a.</i>	8.4	126	
AB 4-2b	36	10 YR 8/1 light grey	10 YR 5/3 dull yellowish brown	160	0.4	74	<i>64</i>	<i>22</i>	<i>14</i>	8.3	92	
AB 4-3	23	7.5 YR 7/2 light brownish gray	7.5 YR 3/4 dark brown	61	1.2	72	<i>42</i>	<i>25</i>	<i>33</i>	8.7	103	Post-Byzantine

Sample No.	Skeleton – content (%)	Munsell dry	Munsell moist	RR (dry)	C _{org} %	CaCO ₃ %	Clay %	Silt %	Sand %	pH (H ₂ O)	conductivity (μS)	Dating/Age
Ruin soils, debris on Umayyad mosque, Jerash												
Jer 1	49	7.5 YR 7/2 light brownish gray	7.5 YR 3/4 dark brown	61	1.3	53	52	30	18	8.6	186	
Jer 2	15	7.5 YR 6/3 dull brown	5 YR 3/4 dark reddish brown	35	1.3	52	62	31	7	8.0	548	
Jer 3	24	5 YR 5/3 dull reddish brown	7.5 YR 3/3 dark brown	25	1.8	51	66	23	11	7.8	517	Post-Umayyad
Ruins soils, debris under fallen columns, Jerash												
Jer 6a	38	10 YR 7/3 dull yellow orange	7.5 YR 4/6 brown	47	0.6	55	67	29	4	8.6	89	
Jer 5a	57	7.5 YR 5/2 grayish brown	10 YR 3/2 brownish black	44	1.2	67	48	30	22	8.3	126	747 AD?
Jer 4a	35	5 YR 6/4 dull orange	7.5 YR 4/4 brown	23	0.9	67	64	31	5	8.6	135	
Jer 3a	38	7.5 YR 6/3 dull brown	5 YR 3/6 brownish black	35	1.3	54	64	27	9	8.4	108	
Jer 2a	12	2.5 YR 8/2 light gray	2.5 YR 4/6 olive brown	50	0.5	58	45	40	15	8.6	162	
Jer 1a	18	5 YR 6/2 grayish brown	5 YR 3/1 brownish black	45	1.0	41	17	40	43	8.2	372	
Jer 0a	15	10 YR 6/2 grayish yellow brown	7.5 YR 4/4 brown	60	1.3	47	47	46	7	8.1	560	Post-Byzantine?

4.2.1 Colour

In order to make colour statistically comparable to other results, it has to be translated into numbers. This was done using the redness-rating (RR) according to Hurst (1977), which proved to be the index best representing field observations (see chapter 2.3.1). Lucke (2002) suggested that the slight colour differences on the fields close to Abila (AB 1-2 1 vs. AB 2-2 1) might reflect different cropping patterns or land use intensities, which possibly led to varying contents of organic matter. But this is not the case. There is no trend between RR and C_{org} ($R^2=0.0341$). A high content of organic matter might lend the soil a darker appearance when moist. This could be the reason why the redness rating which was based on the moist samples was less consistent, and

correlated worse with other parameters such as $CaCO_3$ and iron oxides. But there was also no correlation of the degree of darkening (based on a the difference of dry and moist RR) and C_{org} . Samples which were nearly free of organic matter also appeared considerably darker when moist. Here, the kind of organic matter could play a role but which was not investigated further. It might be possible that higher organic matter is visible on air photos at certain times of the year, delaying the drying of soil. Apart from that, it can be summarised that organic matter is not related to colour differences.

Colour did, however, show a correlation to pedogenic iron oxides (fig. 32). As well, colour does correspond to $CaCO_3$, although not as strongly as to iron oxides: enrichment of $CaCO_3$ led to reduced RR ($R^2=0.3503$). Calcium carbonate

led to reduced RR ($R^2=0.3503$). Calcium carbonate

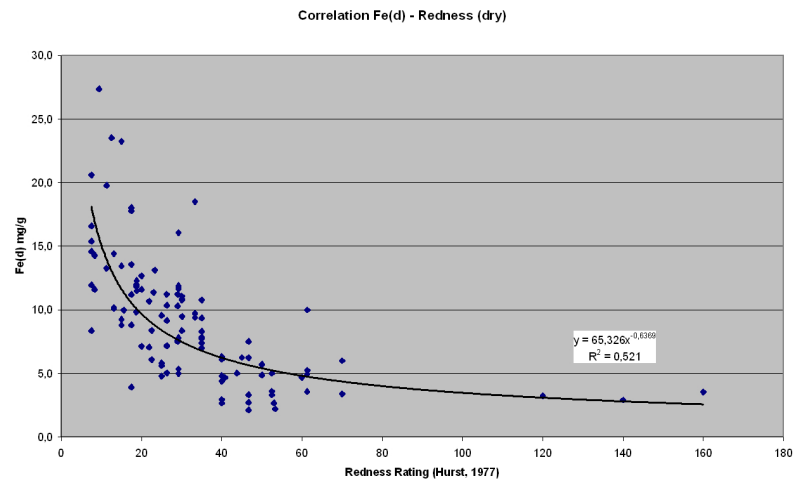


Figure 32: Relationship of pedogenic iron and RR.

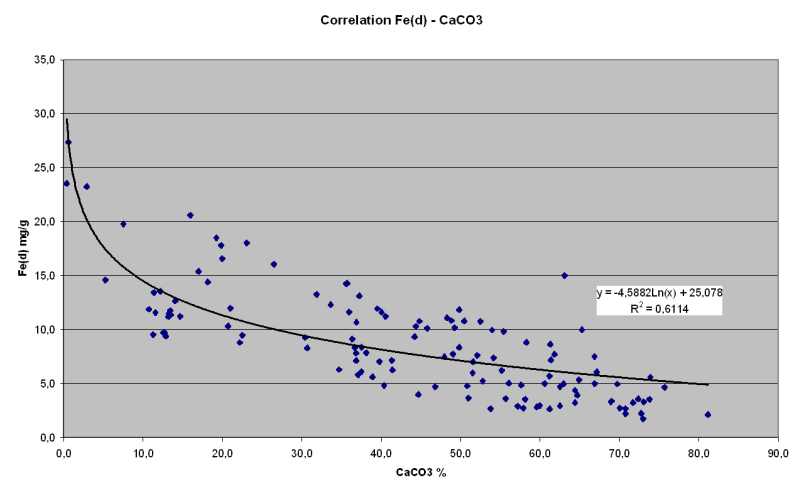


Figure 33: Correlation of $CaCO_3$ -content and Fe_d .

content however corresponds to pedogenic iron oxides, the strongest observed correlation (fig. 33). These results fit field observations, which gave the impression that the colour differences might be related to CaCO_3 (as a white powder) and skeleton contents. In this context, it is interesting to note that the regression follows an exponential function: with decreasing CaCO_3 -content, pedogenic iron oxides and the redness rating rise exponentially. This indicates that the formation of Fe(III)-hydroxides is closely connected with the leaching of CaCO_3 , which releases Fe(II) and possibly also pre-weathered iron oxides. It is however not possible to conduct meaningful correlations of RR and the skeleton content, since the colour was determined in the laboratory after the skeleton had been sieved out. Determination of such a correlation in the field would not make sense, too, as colour determination would be very unreliable without standardised light. So it can only be estimated that the skeleton content, as well as larger stones and boulders, might lend their brighter colour to soils which host them. But it seems that the CaCO_3 content most likely contributes to the colour differences – a relationship which is, to my knowledge, not yet investigated (most studies on colour differences focused on iron oxides, see chapter 4.3.1). In effect, this means the colour changes might be related to varying degrees of soil age and development intensity. To further investigate the matter, an experiment was set up in the geomorphological laboratory in Erlangen. The calcium carbonate-free sample Feldsys 1 was mixed with pure CaCO_3 and with chalk powder from sample TZ 57 (from the chalk profile slightly below TZ 54) in varying degrees of 10, 20, 30, 50 and 70% percent of soil mass. Results are summarised in table 18.

Table 18: Colouring impact of CaCO₃- and chalk additions on sample Feldsys 1.

Sample No.	CaCO ₃ %	Chalk %	Munsell dry	Munsell moist	RR dry	RR moist
<i>Feldsys 1</i>	0	0	7.5 YR 4/4 <i>dark brown</i>	7.5 YR 3/4 <i>dark brown</i>	18	13
Feldsys 1 (1)	10	-	7.5 YR 5/2 brown	7.5 YR 4/2 dark brown	44	35
Feldsys 1 (2)	20	-	7.5 YR 6/2 pinkish gray	7.5 YR 4/4 dark brown	53	18
Feldsys 1 (3)	30	-	7.5 YR 7/2 pinkish gray	7.5 YR 4/4 dark brown	61	18
Feldsys 1 (4)	50	-	7.5 YR 7.5/2 pinkish gray/white	7.5 YR 5/4 brown	66	22
Feldsys 1 (5)	70	-	7.5 YR 8/2 pinkish white	7.5 YR 6/2 pinkish gray	70	53
Feldsys 1 (6)	-	10	10 YR 5/3 brown	10 YR 3/4 dark yellowish brown	33	15
Feldsys 1 (7)	-	20	10 YR 6/3 pale brown	10 YR 4/4 dark yellowish brown	40	20
Feldsys 1 (8)	-	30	10 YR 6.5/3 pale/very pale brown	10 YR 5/4 yellowish brown	43	25
Feldsys 1 (9)	-	50	10 YR 7/2.5 light gray	10 YR 5/4 yellowish brown	56	25
Feldsys 1 (10)	-	70	10 YR 7/2 light gray	10 YR 5/4 yellowish brown	70	25
<i>TZ 57</i>	~ 75%	100	10 YR 8/2 <i>white</i>	10 YR 5.5/4 <i>light yellowish brown</i>	80	28

First one should note the different basic colour of Feldsys 1, which is due to the colour experiment being conducted by another person. Yet the tendencies should again be reliable, and as can be seen, both pure CaCO₃ and chalk have a strong impact on colour. Interestingly, the determined dry redness ratings are very similar, while the colour hues vary considerable. The moist redness shows no clear tendencies as outlined in chapter 2.3.1. As it seems, pure calcium carbonate has only a brightening impact: the hue remains the same, but value and chroma change significantly. In contrast, chalk additions also impacted the hue, which points to the existence to iron oxides (goethite) in the chalk. *However regarding the redness rating, this seems overruled by the brightening effect of CaCO₃.* Both calcium carbonate ($R^2=0.9654$) and chalk additions are negatively correlated with redness rating (fig. 34). As it seems, the colouring impact of calcareous additions is strongest when the concentration is low, which fits the exponential increase of redness with decreasing CaCO₃ determined for the natural samples from the Decapolis region. In can be concluded that calcium carbonate plays an important role for soil colour, which will further be discussed with the iron oxides in chapter 4.3.1.

There is no correlation between colour and texture. Wilkinson et al. (2006) suggested that

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ancient structures visible on satellite images and air photos of the Homs region in Syria are related to changing texture which enhanced or decreased moisture retention capacity. However, since Wilkinson et al. (2006) analysed the texture without removing CaCO_3 , it seems that in fact the coagulating impact of pedogenic calcium carbonate was

studied. Those soils characterised by higher CaCO_3 content might pretend a coarser structure and have a reduced moisture retention. However it seems more likely that CaCO_3 (which was not analysed by Wilkinson et al., 2006) is reflected directly in the satellite images due to its bright colour. As well, darker areas might simply be part of slight depressions which retain moisture longer and accumulate more organic matter – that would be the same principle which makes ancient ditches visible in air photos of northern European soils. In any case, since texture is similar in soils which have different colours (moist and dry) in the Decapolis region, it does not play a role for the colouring.

The deeper profiles further support that soil colour is connected with age and development stage of the soil, which will be discussed in the next paragraphs. For now it can be concluded that *different CaCO_3 -contents* are the most likely explanation for the colour changes of the Abila fields.

4.2.2 Organic matter

Although mostly low, organic matter content seems to well reflect old land surfaces, and is elevated in present surfaces. In the Jordan valley profile, there is an increase in Jor 10 while the horizons above are characterised by very low C_{org} contents. In this context, the small holes might represent the remains of roots and not re-dissolved concretions. If true, this would indicate that the plant cover which once created the holes was not quickly buried after it had died, so the roots were still in the range of micro-organisms who decomposed them. As well, the absence of skeleton content in Jor 10 points to a very stable landscape and few flash floods with little impact. Thus the Jordan valley profile may well reflect dry periods with reduced plant cover, but only few and intense periods of landscape change due to its relative remoteness from gravel and sediment sources. Sample Jor 3 seems to reflect an exceptional

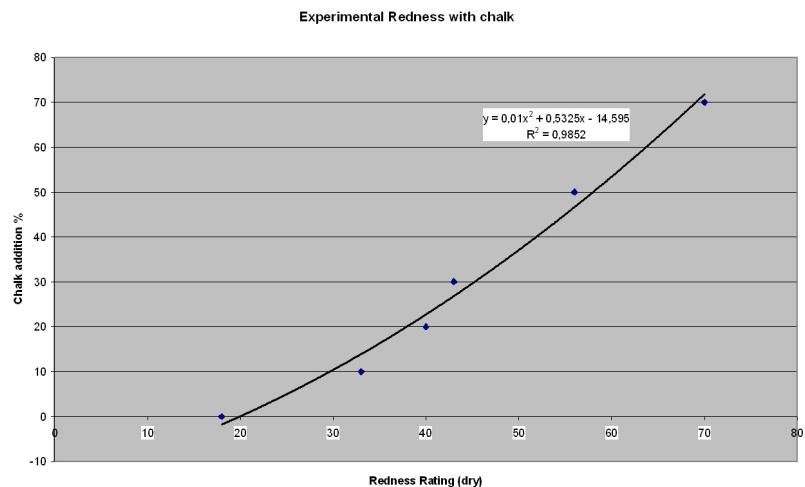


Figure 34: Change of redness under chalk additions.

period of heavy sedimentation, which probably took place on a regional scale. Unfortunately, no date is available so far.

The forest soil (TZ 106) as well as the soil which had been laid fallow (WQ ohne) both show strongly elevated C_{org} -contents. In contrast, olive cultivation (WQ mit) seems not to lead to so strongly increasing organic matter contents. As well, C_{org} increases sharply in AB 3 in the Yarmouk profile, supporting that it is a relic land surface that was covered quickly. A slight increase in AB 6 might confirm the field interpretation that here is another relic land surface. Another paleosol might be present in the Beit Ras wadi colluvium at BR 21, indicated by a sharp rise of organic matter, although not connected with gravel or material culture. This may point to quick soil movements already taking place when the vicinity of was still well-covered by soil. Last but not least, the suspected old surface on the remains of the Umm el-Amad basilica at Abila (AB 4-3) is represented by elevated C_{org} -content, too, which supports that it was later covered by additional debris

Exceptional high organic matter contents were measured on top of the Tell Zera'a (TZ 6) and in the shallow soil on the upper terrace in the Wadi el-Arab (TZ 65). These are even higher than the forest soil and do not fit into context. They might be related to the fertilising impact of garbage in the ruins, or manure since both areas are cultivated. But this seems not a satisfactory explanation as it should be found on the other ruin and cultivation areas, too. I think it is more likely that these values reflect frequent burning of biomass by low-intensity fires which leave a lot of partially carbonised organic matter. Tell Zera'a and some of the upper terraces of the Wadi el-Arab had been burnt every year by farmers when I visited them. These areas are quickly covered by thorny species like *Sarcopoterium spinosum* during spring, which grow preferably on areas characterised by low water retention and bedrock exposure (Ackermann et al., 2004). Since their thorns are really nasty, and as these areas can also be inhabited by poisonous snakes, burning them is a comfortable way to quickly get access again to the spring on the tell, or to make the land available for cultivation and grazing.

It can be concluded that the soil organic matter which accumulates in the area seems relatively persistent, and a good indicator of buried surfaces and land use practices.

4.2.3 Calcium carbonate

Calcium carbonate content shows very clear trends. The first aspect which attracts attention is the decrease of $CaCO_3$ -content in the deep soils and colluvia. The Yarmouk profile (samples AB 1-7) shows decreasing $CaCO_3$ with depth, which supports field observations that the upper part is younger and less developed. While the lowest paleosol has about 10% $CaCO_3$, the middle part has about 20-

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30%, while the upper part deposited after 6880 BC has about 50% CaCO₃. The profile of medium depth which was re-sampled more in detail (samples Yar 1-4) indicates that the general tendency observed with the AB-samples might be attributed to events which led to deposition of new material and thus breaks in the profile. As already suggested by the field evidence, sample Yar 4 seems to correspond to a paleosol also represented by AB 5, which was eroded so that huge stones were exposed on the surface. Then a brighter soil was deposited (Yar 3), and some fluvial activity is indicated by the rising skeleton content. Yar 3 and Yar 4 are very similar, except that Yar 3 shows a sharply increasing CaCO₃-content. I think this can best be explained by an invasion of calcareous dust, and that the much brighter appearance of Yar 3 in the field is related to the sharply rising CaCO₃-content.

It is interesting to note that colour determination in the lab found a higher redness rating for the upper soil than for the underlying paleosol, which opposes the impression from the field. This is interpreted as another indication how unreliable colour examination is, since ideal light and moisture content can hardly be achieved. In context of these difficulties, the observed correlations of colour with CaCO₃ and pedogenic iron oxides seem strong since they are in agreement with field observations.

When carefully re-sampling the street cut, it was noted that a thin band of saprolite was visible over bedrock, and the soil directly above is represented by sample Yar Mitte unten. It is also characterised by strongly raising CaCO₃-content, but not as strongly as at Yar 3. If Yar 3 would represent the eroded subsoil of the neighbouring areas, a gravel band or stones such as in Yar Mitte unten should be visible (which are not represented by the skeleton content, since the sampling had to avoid bigger stones as these did not fit into freezer bags, and would have made it impossible to restrict sampling to a 5 cm-strip). Yar Mitte unten indicates that the lower parts of the soils are derived from the bedrock, and as it seems these horizons were eroded at various, more elevated positions while the rock was covered again by other soil material.

Moved subsoil from the vicinity seems represented by Yar 2 which contains a thick gravel band and has the same calcium carbonate content as Yar 3, indicating that re-calcification affected the whole area before soils were moved again. As suggested by the OSL-date from AB 3, the re-calcification took place before the Younger Dryas. In this context, it would be desirable to more precisely date the layers by obtaining samples directly above and below them.

The trend of re-calcification is also represented by the colluvia in Wadi Queilbeh (Q 2-18) and Beit Ras (BR 2-21). It is however not evident in the sediments behind the Roman bridge (Brücke 0-9). CaCO₃-content there is so high that the sediments can only be derived from the present soils, which indicates that these colluvia were deposited during very different time-scales.

All those soils which do not show red colour are characterised by high calcium carbonate

content of more than 50%. They seem in fact very similar to the chalk sample TZ 54, pointing to the soft rocks along the wadi slopes as dust source, and not the desert soils (Air 1 and 2). A look into the Jordan valley and Wadi Ziqlab indicates that mainly soft, easily erodible chalk from the steep slopes was deposited there, since CaCO₃-contents are very high throughout these profiles. Samples such as Ziq 4 (the Epipaleolithic paleosol) and Jor 10 might represent mixtures of formerly de-calcified Terra Rossa with chalk on the one hand, and ongoing leaching processes due to higher precipitation on the other hand. This is also supported by the colour, which is brighter than the plateau soils. Taking the colluvia together, they point to increasing deposition of calcareous dust or steadily reduced leaching processes since the end of the Ice Age (only sample Jor 1 falls out, but could be explained by leaching as a consequence of well-drained irrigation).

The basalt soil indicates that calcareous dust also affected the Ard al-Ala (samples UQ 9-21). It might also be responsible for the formation of the caliche crust on top of the basalt (that limited aeolian deposition would suffice for the formation of such a crust is outlined by Wang et al., 1994). Since the secondary carbonates in the subsoil reach stage II, this is another indication that dust mobilisation took place during or before the late Pleistocene (Birkeland, 1999), and that the soil is older than that. The very homogeneous distribution of CaCO₃ as well as the other parameters underline the vertic properties of the basalt soil.

The calcareous dust must have come from local sources: how could the missing re-calcification in el-Wustije otherwise be explained? (This pattern is not only indicated by the two analysed samples, but also by extensive field testing.) The local absence of calcium carbonate also indicates that CaCO₃-enrichment due to salt concentration under increasing general dryness can be excluded. The complete leaching of calcium carbonate seems however inherited from a moister climate of the past: according to Yaalon (1997), complete leaching requires 600 – 800 mm annual precipitation. So far, the only likely explanation for the low CaCO₃-contents of Terra Rossa in the Irbid basin and el-Wustije seems the relief. While steep chalky slopes are absent in the Irbid basin, el-Wustije consists of gently sloping hills where chalk exposures are rare or covered by caliche. In this context, it is interesting to note that CaCO₃-levels rise at the rims of the basalt plateau (UQ 15 and TZ 1), which are closer to the possible dust source.

Here man could have played a role by mobilising dust from the chalk by grazing, agriculture, construction works and transport. According to Dalman (1928b), summer traffic during the 19th century released so much dust in Jerusalem that he had to clean his table every hour. Trees and plants on the east side of major routes (due to the prevailing west wind) turned white, as if covered by snow (Dalman, 1928b). This would explain why kissing the feet like mentioned in Isaiah 49:23 was so

humiliating: they were usually covered by dust. However, he also notes that the Terra Rossa is not so easily deflated, an issue to be discussed with the texture in chapter 4.2.4.

Comparing the relic mudbricks with today's soils, one can conclude that CaCO_3 -levels were already high during the Bronze Age. That the additional deposition due to human impact can not have been very severe can already be concluded from the top layer of the Yarmouk-profile (Yar 1a), suggesting that perhaps 10 of 50% calcium carbonate content might be related to human activities during the Holocene. But this was of course locally different and dependent on the presence of a chalk source. On the fields close to Abila, it seems that field 2 received about 10-15% more total CaCO_3 than field 1, which seemingly also caused the colour change. Since this follows field borders, a human influence is clearly indicated. But so far it can only be guessed why lots of chalk were added to field 2. Historic sources have to be consulted in order to find evidence for a manure praxis that would involve chalk deposition. The huge amount of material which would have to be moved to cover a whole field lets attempts of planned soil tilting seem unlikely, and point to slight but steady deposition over centuries of land use. But of course it cannot be ruled out that e.g. a Roman landlord asked some slaves to dump the chalky spoil from a water tunnel onto his field, perhaps to improve the rooting depth for some wines.

Comparing the relic mudbrick on Tell Zera'a with sample TZ 50, it seems that about 20% of the total CaCO_3 in TZ 50 were deposited since the Bronze Age, which might support the impression from the mudbrick wall that soil colours in the vicinity of the Tell shifted towards grey.

It has to be added that the steep, chalky slopes of the Wadi el-Arab would release calcareous dust also without the presence of humans. My personal impression is that blaming a few shepherds and farmers for processes of landscape scale completely overestimates the impact of their daily struggle for survival. That calcareous dust deposition was always present in the area is suggested by the Amrawah paleosols. Although there is no question that these soils are very old, the CaCO_3 -content is even higher than in the modern topsoil. In this context, re-calcification seems nothing new.

It can be summarised that during the Holocene, soils were affected not so much by erosion, but by re-calcification. If humans impacted general soil development, then by releasing calcareous dust.

4.2.4 Texture

Most of the soils are extremely clay-rich. This again confirms field observations: the Terra Rossa forms cracks and huge, very hard lumps when drying, pointing to a strong shrink-swell behaviour connected with a lot of clay. Digging was a major challenge, especially in the basalt soil, and several

axes broke on the way down to bedrock. The wet soils are very sticky and it is impossible to walk with shoes as they become simply too heavy. When Seetzen visited the area in February 1806, he had to walk on field paths because most of the Roman roads were not usable any more. So he was tormented by unpredictably appearing sharp gravel and cold feet, since he had to take his shoes off (Seetzen, 1854, p. 331, "...eine wahre Pönitenz!"). But his suffering is our advantage as we can trace the soil distribution he described, and conclude that things did not change much – we would suffer similarly if walking his route during winter.

While most *Terrae Rossae* show clay contents of 70-80%, the basalt soil of the *Ard al-Ala* has nearly 90%. This is exceptional and supports that the source rock played a role in soil formation. Although data on clay minerals are unfortunately not yet available, Khresat and Taimeh (1998) found that smectite was the dominant clay mineral of their examined basalt vertisols, while smectite and vermiculite were present in the limestone soils. Since smectites have a more pronounced shrink-swell capacity than vermiculites, this might explain the higher clay contents in the basalt soils⁴. According to Fedoroff and Courty (1999), the grinding impact of strong peloturbation will lead to a finer texture over time. In this context, the lower clay values of the basalt plateau rims could simply be connected with a less intense shrink-swell behaviour. But all of the soils should be self-mulching due to the formation of cracks during the summer months. In this context, the limited organic matter seems very important for fertility since it preserves a granular soil structure.

The grey calcareous soils are rich in clay, too. After CaCO_3 has been dissolved by hydrochloric acid (which means that usually more than 50% of the sample's weight were lost), the remains are very clay-rich. The chalk sample TZ 54 indicates that already the rock's residue might consist of more than 60% clay. Clay contents of 80-90% could represent a weathering climax. While weathering processes might initially lead to a quick increase of fine material, texture will change less and less the more strongly the soil is weathered. In the light of the high age of the *Terra Rossa* in Jordan, it is not surprising that the texture is generally very fine. This and the possible presence of pre-weathered clay from the calcareous rocks limit the suitability of texture as an age criterion. It has to be added that deposition of Saharan dust would involve mainly particles of clay-size, too (Singer et al., 1992).

It should be noted that the texture is coarser in the upper part of the deep Yarmouk profile. This could be interpreted as the influence of silty calcareous dust, assuming that material like TZ 54 was deposited. Khresat and Taimeh (1998) investigated whether CaCO_3 was associated with silt or clay, and found that it was increasingly connected with clay particles when soils were stronger developed.

⁴ It should be mentioned that results from Israel are different: according to Gal et al. (1972), the clay minerals in limestone soils are dominated by montmorillonite and kaolinite, which seem inherited from the bedrock.

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This was taken as age indication even if total CaCO_3 -contents were the same. However, these conclusions are not consistent with the *Terrae Rossae* in the Irbid basin and el-Wustije: although these soils have the lowest CaCO_3 -contents, they are – surprisingly – the coarsest red soils. That no analytical error is present is supported by the colluvia in Wadi Queilbeh and Beit Ras. Although CaCO_3 increases in the upper part of the Wadi Queilbeh-colluvium, the clay content remains the same. As well, the paleosol represented by BR 21 is characterised a sudden decrease of clay, showing numbers which resemble the el-Wustije (Feldsys 1 and 2) and Irbid soils, while CaCO_3 -content drops to the lowest value. This could indicate that the soils in the north possibly once looked like in Irbid and el-Wustije until calcareous dust was deposited.

A closer look at the Yarmouk-profile also reveals that the silt content remains the same, while the drop of clay is associated with an increase of sand, probably representing fluvially transported limestone particles. In this context, I am not sure whether an association of CaCO_3 with silt or clay can be measured in the way proposed by Khresat and Taimah (1998). After the samples had been dispersed with sodium hexametaphosphate, the clay and silt fractions were separated and the respective CaCO_3 -contents determined. This works if the tendency of particles to coagulate is constant. However to my knowledge, it is not possible to determine to which degree larger particles are formed by the chemical forcing of CaCO_3 , even if $\text{Na}_4\text{P}_2\text{O}_4$ is added as an opposing agent. The problem of pedogenic calcium carbonate is that it might lead to formation of various, unpredictable conglomerates (Schlichting et al., 1995). Thus analysis of texture without removal of CaCO_3 might produce random results, which is why the general praxis of texture analysis requires the pre-treatment with HCl (see Schlichting et al, 1995).

Texture analysis without this pre-treatment (see Wilkinson et al., 2006), or with insufficient washing of HCl (see Lucke et al., 2005, Schmidt et al., 2006), will suggest a silty structure of 80-90% silt and only 5-15% clay. Such values are in no way consistent with the behaviour and structure of the soil, but which might go unnoticed if not enough time is spent in the field. In this context, one might argue that the infiltration behaviour of the soil cannot be assessed by textures determined after CaCO_3 -removal, since the coagulating impact of CaCO_3 would also play a role. Therefore Lorenz (2006) used texture results determined without any pre-treatment for an infiltration simulation based on the SPAW hydrological model. However, the shrink-swell behaviour expressed by the siliceous clay content should play an even greater role for the infiltration, as it will determine the soil's tendency to form cracks. But no model is so far able to predict the frequency and depth of such cracks.

Field observations suggest that the weakly developed calcareous soils consist mainly of silt, since they are easily deflated and show no cracks when dry. However, these soils also form crusts and lumps. These are however much weaker than those formed by *Terra Rossa*, and probably connected

with CaCO₃-concretions. Decisive for the soils' behaviour should be the form in which CaCO₃ is present. If the microfossils from the calcareous rocks are still intact, pre-treatment with HCl would not make sense and it is safe to assume a silty structure. But when CaCO₃ is finely dispersed, it will lead to randomly coarser texture results. As can be seen by e.g. sample TZ 50, the Red Mediterranean Soils can contain up to 60% CaCO₃ while still showing a clearly clay-dominated behaviour in the field. A border for the right method of analysis is thus impossible to draw, and clarity about the nature of CaCO₃ can only be gained by thin sections (to be discussed later). To summarise, texture analysis in the laboratory can produce meaningful results only if informed by the field evidence.

The question remains why silt contents are elevated in the soils with the lowest contents of calcium carbonate. I have no explanation for this phenomenon and can only guess that the calcareous dust contained a greater amount of pre-weathered clay than the other source rocks. Then the re-calcification would also have meant clay enrichment, except on the basalt soil, which would have been depleted (see TZ 1 and UQ 15). Since the deepest part of the Yarmouk-profile still contains CaCO₃, deposition of calcareous dust there may never have ceased. If true, the rise of CaCO₃ in the upper part of the soils may not so much be connected with increasing dust deposition, but decreasing leaching. This would mean that soil development might reflect a general tendency of increasing aridity, possibly connected with post-glacial warming.

In the light of the texture, the possibility of deflation should be discussed. As Dalman (1928b) already noted, *Terrae Rossae* are not easily deflated. The moist soil is on the one hand not willing to leave one's shoe, and it will be difficult for even a tornado to move it. On the other hand, the dry soil forms huge lumps which are as hard as stone. Additionally, a crust forms which might aggravate water erosion due to higher runoff, but leaves no opportunity for wind. Years of field visits made clear that even very strong winds move no red soil – while the desert soils can already be transported by gentle breezes. The grey calcareous soils seem to have a position in the middle, since a CaCO₃-rich crust protects them against wind.

Let us have a look at the indirect evidence: aeolian activity can be seen in the landscape, which should show soil accumulations in wind-protected areas, and a concentration of gravel and coarse material at wind-exposed sites. But this is clearly not the case. In Jordan, aeolian activity left traces only in the area between Mafraq and the Azraq oasis (Purschke, 1990), and even there no "classical" dunes are present. This by the way indicates that even the desert is not so severely deflated as sometimes assumed: Rösner (1995) showed that a crust and "desert pavement" protect the calcareous silts in the Jordanian and Syrian deserts. While dust emissions are frequent, a general movement and alteration of soils are rare.

This is not to say that deflation of Terra Rossa cannot take place. For example, red dust in Australia was found to consist of kaolinite, which stuck together and formed hard particles of silt size. It represented the remains of deflated, very old red soils (Molinaroli, 1996). Dust in Jordan however looks different, which will be discussed more in detail with the total element analyses. For the case of the Homs region in Syria, Wilkinson et al. (2006) presented a very interesting pattern of soil distribution, and concluded from paleosols under ruins that the soils present in the vicinity today must be degraded. Again the geology seems to have played a dominant role for soil formation, as the best-developed soils are found on fine alluvial gravels, while marls and conglomerates bear only thinner and more calcareous soils. But contrasting today's soils, well developed prismatic red soils with a Bt-horizon can be found under archaeological sites up to the Roman period. Wilkinson et al. (2006) concluded that these are relic Pleistocene soils which were deflated since the Roman period if not protected by the ruins of a site.

Comparing these results with the evidence from Jordan, it seems however not very likely that deflation was the reason of soil degradation. A Bt-horizon (characterised by clay enrichment) has to become very, very dry for a long period before it could become subject of deflation. Ploughing might enhance the deflation, but I wonder why man should have ploughed a completely dry soil. In the light of my visit to the Homs region, I would merely expect that severe flooding from the nearby Orontes river might have affected soil development in the area, and that Bt-horizons might have been obliterated by re-calcification. In this context, it is regrettable that Wilkinson et al. (2006) did not analyse the CaCO₃-content, since the pattern observed in the Homs plain could point to increasing calcareous dust additions during historical periods (although it might not be very different from the Decapolis region: field testing showed that most soils in the area seem to contain at least 10% calcium carbonate, which included one of the paleosols).

The Bt-horizons reported from the Homs region bring us to the question why no argillic horizons are visible in the soils of the Decapolis region. Their age and richness in clay would suggest the presence of clay cutans – however clay illuviation requires complete leaching of CaCO₃. Taimeh (1984) found remains of clay cutans in soils of the Irbid basin and in relic paleosols in the steppe, but which had been destroyed by the later addition of calcareous dust. This supports that re-calcification was indeed a very significant process of Terra Rossa development.

In this context, deflation of Red Mediterranean Soils in Jordan and Syria sounds like another story from the book of man-induced erosion tales. If no gullies or other indications of water erosion are present, one resorts to deflation in order to explain the "degraded" soil structure. Analytical errors which suggest high silt content might contribute to such a misinterpretation. But while water erosion

can be discussed on the basis of a wealth of studies, which could or could not meaningfully measure erosion (see Grove and Rackham, 2003), there are few studies about wind erosion. In fact, measuring wind erosion is one of the most difficult problems of soil science (Blume et al., 1997). Much can be postulated as long as clear data is lacking. The lack of data might however be connected with the difficulty to publish a learned paper on something that did not happen.

Last but not least, the texture should be discussed in the light of the database of the National Soil Map and Land Use Project of Jordan (NSM&LUP, 1993). This project studied whole Jordan with some 42,000 field observations and hundreds of profiles analysed in the laboratory. A basic comparison of data from the NSM&LUP (1993) and soils in the Decapolis was already published by Schmidt et al. (2006), but suffered from analytical constraints concerning the texture. According to the NSM&LUP (1993), soil texture and calcium carbonate content throughout Jordan follow a climatic gradient, and are connected with the source rock. A complete leaching of calcium carbonate was only found where average annual precipitation exceeded 550 mm, and clay contents decrease steadily to the east and south, in accordance with declining precipitation. Buried Red Mediterranean Soils in the steppe and desert areas seem to be related to fossil groundwater (Schmidt et al., 2006). It was also assumed that clay maxima in the subsoil might be related to the levelling influence of land use, that moved less developed soil onto former clay-rich topsoils, creating clay maxima in the B-horizons (Schmidt et al., 2006).

On the basis of the corrected texture values in this thesis, these conclusions can however not be confirmed. On the one hand because the clay maxima in the subsoil disappeared with AgNO_3 -controlled washing of HCl. On the other hand, it has to be mentioned that the NSM&LUP (1993) used a simplified approach for texture analysis, because dissolving CaCO_3 with HCl and subsequent washing is a very time consuming process. Without a large centrifuge, it takes approximately four weeks until Cl^- ions are sufficiently washed out of one sample, since one has to wait until the particles settle at the bottom of the buckets with distilled water (a process which has to be repeated several times). As this could not be handled with the amount of samples studied by the National Soil Map and Land Use Project, the coagulating impact of CaCO_3 was approached mathematically. After determining the texture without HCl-pretreatment, the CaCO_3 -content was subtracted from the total sample weight and the clay content re-calculated on the basis of an empirical formula. This approach however cannot account for the coagulating impact of finely dispersed calcium carbonate, as discussed above for the case of CaCO_3 -association with silt or clay.

For the area investigated in this thesis, a clear correlation between leaching of calcium carbonate and average annual precipitation cannot be drawn. The colluvium at Beit Ras was re-calcified although

situated in a similar climate zone with similar annual precipitation as in Irbid or el-Wustije. As discussed in chapter 4.2.3, the relief seems more relevant, although decreasing leaching during the Holocene might have contributed to the re-calcification. As well, the clay content of *Terrae Rossae* seems not related to the current annual precipitation, but merely to represent a weathering climax that formed under paleoclimates of the Ice Age. But the conclusion that the source rock played an important role is supported: as in the NSM&LUP (1993), the highest clay values are found in basalt soils.

To summarise, the texture of *Terra Rossae* in the Decapolis region is very fine and seemingly represents a weathering climax. It is thus not suited for age estimations and not related to the current annual precipitation. However basaltic source rocks are clearly mirrored by finer texture. It seems very unlikely that the red soils were deflated. While yellow desert and steppe soils are characterised by a silty texture, the true values for the grey soils are hard to determine. They seem to behave like soils which are dominated by silt, but the chalk's residue is very clay-rich. Pre-weathered clay from the calcareous rocks may thus have contributed to the fine texture of the *Terrae rossae*.

In this context, it should be mentioned that the BET-procedure may deliver additional information about the soil structure. This method calculates the specific surface of samples by their nitrogen adsorption. The specific surface is usually strongly correlated to the clay content; however a preliminary test yielded very different results for soils in the Decapolis despite their similar clay values. Sample AB 1-2 2 had a total surface of 36.5 m²/g, and its micropore surface was 4.805 m²/g, sample AB 2-2 2 had a total surface of 21.48 m²/g, and a micropore surface of 3.396 m²/g, and sample *Feldsys* 2 had a total surface of 48.15 m²/g, and a micropore surface: 8.359 m²/g (pers. comm with Rupert Bäumler, March 2007). The results indicate that the better developed soils are characterised by a higher porosity, which might be related to lower contents of primary carbonates. At this moment it is not possible to further interpret the BET-results, but it seems that this method may make it possible to address the impact of CaCO₃-additions which might skew textures due to pre-weathered clay minerals in their residue.

4.2.5 pH and conductivity

In all samples, the pH ranges between 7 and 9, connected with slightly alkaline conditions. This indicates that a semi-arid climate prevailed at all locations and periods, leading to an accumulation of bases and reflected by enrichment in CaCO₃.

Conductivity shows greater variations, although none of the samples is saline. To bear relevance

for crop production, conductivity should be higher than 2 mS. The low values indicate that winter rains always washed salts out, and that irrigation did not lead to salt accumulation. A detailed soil survey in the Jordan valley showed that results from the site sampled in the framework of this thesis are representative for the greatest part of the valley (KfW, 2005). It can be concluded that historical land use did not cause salinity.

It is however interesting to note that conductivity values rise in the paleosols. Samples Jor 10, Ziq 4, Ab 6, AB 7, Yar Mitte and Yar Mitte unten are all characterised by slightly higher conductivity. This might point to an accumulation of bases in clay minerals, or indicate that those soils were exposed to drier conditions before being buried by new material. The undated relic soil on the northern slopes of the Wadi el-Arab (TZ 2) shows the highest conductivity values. It therefore seemingly experienced very dry conditions before being covered by a landslide. Putting these indications together, they might be taken as support for the thesis that landscape instabilities due to extreme precipitation events are connected with or preceded by increased aridity (see chapter 4.1).

The highest conductivity values are present in the chalk and relic mudbricks. Tapwater in Irbid (which is partially pumped from the Wadi el-Arab) has the same conductivity as TZ 54, which is an indication that the groundwater is seeping through the chalk. The very high values in the relic mudbricks point to the use of dung for the making of these bricks, which is confirmed by the 19th century mudbrick sample TZ 4. In this context, the elevated conductivity values of the lower debris in Jerash are remarkable (Jer 2, 3 and 0a). In comparison, the debris levels on the Tell Zera'a show a clear change of conductivity and colour between samples TZ 8 and 9, suggesting that the younger periods used less mudbrick for construction of the town, a change which apparently took place at the end of the late Bronze Age. Soil properties in Jerash however point to the use of mudbrick after or associated with the construction of the Umayyad mosque. This would also explain the darker colour of the lower debris horizons.

4.3 Iron and manganese oxides, and aluminium

The content of pedogenic oxides and hydroxides of iron, manganese, aluminium, and titanium usually rises with increasing weathering intensity and age of soils. In combination with other parameters, it is suited for a characterisation of development stage and relative age of soils. This is especially valid for iron oxides, which has been demonstrated by a number of studies (see Bäumler, 2001, Füllner, 2001, Cornell and Schwertmann, 2003). After dissolution of iron from siliceous minerals (Fe^{2+}), weakly

4. The soil evidence

crystalline oxides are formed, which after time are altered into more stable oxides (Fe^{3+}). Various factors, including pH, temperature, and moisture content of the soil play a role in this process. In the cool, moist climates of the northern hemisphere, usually goethite forms which gives soils a yellow-brown colour. In warm semi-arid regions however the red hematite dominates, which seemingly forms after dehydration of the less stable ferrihydrite (Cornell and Schwertmann, 2003). Well-crystallised iron oxides are very stable, yet a high content of organic matter and reducing conditions under standing water can retard or reverse iron oxidation.

In soil environments, dehydration of ferrihydrite is the only possible way of hematite formation that could be simulated in the laboratory. However, except one case on Hawaii, ferrihydrite in natural environments is associated with goethite, and not hematite (Cornell and Schwertmann, 2003). This phenomenon is explained with ferrihydrite formation being slower than its re-structuring to hematite upon drying of the soil. Another possible way of hematite formation is heating, e.g. under a forest fire. Under increasing organic matter and in damper environments, hematite is however preferentially dissolved and goethite dominates, a process called *xanthization*. It may lead to yellow horizons where higher microbial activity dissolved hematite, but which overly still red subsoils (Cornell and Schwertmann, 2003).

The colour differences observed in the Decapolis region might be connected with changing sets of iron oxides. Soil *toposequences*, characterised by colour variations related to different goethite/hematite ratios, are well-known from the tropics (Cornell and Schwertmann, 2003). Redder soils form on faster drying crests, while more yellowish soils are present in valleys. Singer et al. (1998) describe slight differences in moisture retention of soils in Israel that might already lead to different ratios of iron oxides and thus colour variation. Higher moisture tensions due to faster drying and warming of the soil were supposedly connected with stronger hematite formation – and according to Singer et al (1998), the studied *Terrae rossae* dried faster than the CaCO_3 -rich Rendzinas. In contrast, Foster et al. (2004) discuss that additions of calcium carbonate may promote the reddening of soils, since it leads to coagulation of the particles and thus faster drying. This would oppose the better moisture holding capacity found by Singer et al. (1998) for the Rendzinas.

In this thesis, the content of iron oxides was analysed by two methods: on the one hand by a strongly reducing extraction with sodium dithionite according to Mehra and Jackson (1960) and Holmgren (Schlichting et al., 1995), which captured all pedogenic iron oxides and hydroxides including iron bound in organic complexes. On the other hand, the extraction in the dark with slightly acidic oxalate-solution captured only weakly crystalline iron oxides and hydroxides, including hydroxide-gels like ferrihydrite (Cornell and Schwertmann, 2003). The combination of these two methods allows to

compare the content of weakly crystalline iron oxides (Fe_o) with the total content of pedogenic iron oxides (Fe_d), and thus to evaluate how well crystallised the pedogenic iron is (Fe_o/Fe_d : *activity index*). As well, the comparison of Fe_d with the total iron content (Fe_t) informs about the state of primary iron dissolution (Fe_d/Fe_t : *weathering index*). Another advantage of using ratios is that they are independent from the total contents, which may vary with different parent materials.

The more weathered and older the soil, the higher the Fe_d/Fe_t ratio should become, which is applicable to soil catenas and chronosequences. In contrast, the Fe_o/Fe_d ratio should decrease with stronger weathering, but is not suited for chronosequences. However, it is possible to subtract Fe_o from Fe_d , thus obtaining the amount of well-crystallised iron oxides, which is sometimes better suited for characterisation of soil chronosequences (Fe_{d-o}/Fe_t : *modified weathering index*). Numerous variations of the modified weathering index were developed, for example incorporating the clay content in order to reflect a strong local correlation of Fe_d with clay (Günster, 1999).

As exception, these methods do not work with soils of volcanic ash, since magnetite is dissolved only partially by sodium dithionite, while allophane, imogolite and magnetite are extracted by oxalate (McKeague et al. 1971). This may lead to Fe_o/Fe_d reaching values >1 .

Manganese and aluminium are extracted with sodium dithionite and oxalate, too, but not as well as iron (Bascomb 1968, McKeague et al. 1971). Manganese oxides are less understood than iron oxides, but the same principles of formation should apply. They are more complicated than iron oxides, which is due to their large number and structure which is more complex than that of iron oxides (McKenzie, 1989). Aluminium is non-reducible, but extraction with sodium dithionite may capture the part which is present in iron oxides due to isomorphous replacement of Fe with Al. Oxalate forms complexes with aluminium and extracts Al from hydroxy-layers of clay minerals. Therefore Al_o is usually higher than Al_d . Although no meaningful indices can be formed with Al_o and Al_d , they deliver some additional information about the presence of Al in iron oxides and hydroxy-layers of clay.

Table 19 summarises the the extractable Fe, Mn and Al-contents and the ratios. Since total element contents from XRF-data were only available for part of the samples, calculation of the weathering indices had to be limited to those.

Table 19: Dithionit- (d) and oxalat- (o) extractable iron, manganese and aluminium; total (t) contents of iron and manganese; and ratios.

Sample No.	Fe (d) [mg/g]	Fe (o) [mg/g]	Fe (t) %	Fe (d/t)	$\frac{Fe_d}{(Fe_t/CaCO_3)}$	Fe (o/d)	$\frac{Fe_o}{Fe_d/CaCO_3}$	Mn (d) [mg/g]	Mn (o) [mg/g]	Mn (t) %	Mn (d/t)	$\frac{Mn_d}{(Mn_t/CaCO_3)}$	Al (d) [mg/g]	Al (o) [mg/g]
Jordan valley														
Jor 1	6.0	0.30				0.05	2.6	0.31	0.21				0.18	0.48
Jor 3	4.4	0.55				0.12	8.0	2.86	0.10				0.25	0.42
Jor 5	7.2	0.30				0.04	2.5	0.36	0.28				0.28	0.35
Jor 7	4.7	0.49				0.10	6.5	0.11	0.08				0.31	0.48
Jor 10	11.2	0.72	3.0	0.37	15	0.06	2.6	0.22	0.18	0.039	0.57	23	0.74	0.53
Jor 12	3.9	0.27				0.07	4.4	0.06	0.04				0.25	0.30
Wadi Ziqlab														
Ziq 1	10.0	0.22	6.1	0.16	11	0.02	1.5	0.07	0.02	0.142	0.05	3	0.28	0.25
Ziq 2	15.0	0.39				0.03	1.7	0.03	0.05				0.30	0.63
Ziq 3	10.8	0.27				0.03	1.3	0.13	0.07				0.45	0.63
Ziq 4	10.8	0.18	2.8	0.38	17	0.02	0.8	0.23	0.07	0.036	0.63	28	0.55	0.70
Wadi el-Arab, colluvium at foot of Tell Zera'a														
TZ 23	5.0	0.32				0.06	4.1	0.15	0.08				0.39	0.79
TZ 24	5.3	0.28				0.05	3.4	0.10	0.07				0.34	0.55
TZ 25	5.0	0.14				0.03	2.0	0.01	0.04				0.20	0.25
TZ 26	3.2	0.22				0.07	5.0	0.03	0.02				0.24	0.37
TZ 27	3.4	0.22				0.07	4.5	0.04	0.03				0.22	0.40

Sample No.	Fe (d) [mg/g]	Fe (o) [mg/g]	Fe (t) %	Fe (d/t)	$\frac{Fe_d}{(Fe_t/CaCO_3)}$	$Fe(o/d)$	$\frac{Fe_o}{Fe_d/CaCO_3}$	Mn (d) [mg/g]	Mn (o) [mg/g]	Mn (t) %	Mn (d/t)	$\frac{Mn_d}{(Mn_t/CaCO_3)}$	Al (d) [mg/g]	Al (o) [mg/g]
Wadi el-Arab, red soil in depression														
TZ 50	8.8	0.21	1.5	0.59	34	0.02	1.4	0.22	0.13	0.031	0.72	42	0.45	0.68
Wadi el-Arab, chalk ridge														
TZ 54	5.6	0.15	1.1	0.51	37	0.03	2.0	0.02	0.01	0.012	0.02	14	0.08	0.03
Wadi el-Arab, terrace on lower southern slope														
TZ 73	4.6	0.13				0.03	2.1	0.20	0.10				0.30	0.35
Wadi el-Arab, soil developed on travertine														
TZ 129	11.9	0.24				0.02	0.8	0.43	0.20				0.55	0.85
Wadi el-Arab, terrace on upper southern slope														
TZ 65	5.7	0.70	1.7	0.34	21	0.12	7.5	0.15	0.07	0.036	0.40	25	0.17	0.20
Wadi el-Arab, forest soil pocket in rocky area														
TZ 106	14.4	0.69	4.4	0.33	6	0.05	0.9	0.60	0.38	0.075	0.79	14	0.90	2.30
Wadi el-Arab, buried soil on northern slope														
TZ 2	8.4	0.46				0.05	2.1	0.27	0.16				0.45	0.53
Basalt plateau Ard al-Ala														
UQ 9	11.2	0.76	5.2	0.22	3	0.07	0.9	0.78	0.59	0.094	0.83	11	1.00	1.80
UQ 13	11.2	0.85				0.08	1.1	0.83	0.57				0.95	2.00
UQ 21	11.4	0.81	5.3	0.21	3	0.07	1.0	0.76	0.56	0.093	0.81	11	0.85	2.00
Western edge of basalt														
UQ 15	20.6	0.78				0.04	0.6	0.75	0.43				0.90	1.65

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Sample No.	Fe (d) [mg/g]	Fe (o) [mg/g]	Fe (t) %	Fe (d/t)	$\frac{Fe_d}{(Fe_t/CaCO_3)}$	Fe (o/d)	$\frac{Fe_o}{Fe_d/CaCO_3}$	Mn (d) [mg/g]	Mn (o) [mg/g]	Mn (t) %	Mn (d/t)	$\frac{Mn_d}{(Mn_t/CaCO_3)}$	Al (d) [mg/g]	Al (o) [mg/g]
Southern rim of basalt														
TZ 1	15.4	0.86				0.06	0.9	0.73	0.35				0.90	1.35
Med. plateau, street cut at unity dam, Yarmouk														
AB 1	10.3	0.50	3.2	0.32	14	0.05	2.1	0.43	0.21	0.056	0.76	34	0.56	1.18
AB 2	7.5	0.63				0.08	4.1	0.31	0.20				0.51	1.16
AB 3	13.3	0.56				0.04	1.3	0.59	0.27				0.91	1.62
AB 4	9.3	0.66	4.1	0.23	7	0.07	2.2	0.43	0.31	0.069	0.62	19	0.77	1.46
AB 5	8.8	0.76				0.09	1.9	0.44	0.42				0.87	1.78
AB 6	13.6	0.85				0.06	0.8	0.75	0.52				0.89	2.18
AB 7	13.4	0.90	2.1	0.64	7	0.07	0.8	0.80	0.53	0.037	2.15	24	0.96	2.09
Med. plateau, street cut at unity dam, Yarmouk														
Yar 1	7.6	0.43				0.06	3.0	0.33	0.18				0.33	0.95
Yar 2	10.1	0.40				0.04	1.8	0.41	0.18				0.50	1.10
Yar 3	10.2	0.40				0.04	1.9	0.37	0.18				0.55	1.10
Yar 4	18.5	0.72				0.04	0.8	0.76	0.45				1.10	1.95
Med. plateau, street cut at unity dam, Yarmouk														
Yar 1a	9.8	1.45				0.15	8.2	0.38	0.18				0.45	0.93
Med. plateau, street cut at unity dam, Yarmouk														
Yar Mitte	11.6	0.98				0.08	1.0	0.54	0.51				1.08	2.32
Yar Mitte unten	7.1	0.49				0.07	2.5	0.30	0.28				0.53	1.17

Sample No.	Fe (d) [mg/g]	Fe (o) [mg/g]	Fe (t) %	Fe (d/t)	$\frac{Fe_d}{(Fe_t/CaCO_3)}$	Fe (o/d)	$\frac{Fe_o}{Fe_d/CaCO_3}$	Mn (d) [mg/g]	Mn (o) [mg/g]	Mn (t) %	Mn (d/t)	$\frac{Mn_d}{(Mn_t/CaCO_3)}$	Al (d) [mg/g]	Al (o) [mg/g]
Med. plateau, shallow soil on caliche														
AB 9	14.6	0.87	5.3	0.28	1	0.06	0.3	0.99	0.85	0.124	0.80	4	1.36	2.62
Med. plateau, Abila fields colour change, field 1														
AB 1-2 1	11.6	0.49				0.04	1.7	0.41	0.27				0.74	1.33
AB 1-2 2	14.3	0.40	3.6	0.40	14	0.03	1.0	0.51	0.36	0.069	0.74	26	0.78	1.02
AB 1-2 3	14.3	0.37				0.03	0.9	0.54	0.23				0.73	1.28
AB 1-2 4	18.0	0.57				0.03	0.7	0.64	0.54				1.05	1.34
Med. plateau, Abila fields colour change, field 2														
AB 2-2 1	10.8	0.36				0.03	1.6	0.40	0.29				0.60	1.03
AB 2-2 2	11.1	0.32	2.8	0.40	19	0.03	1.4	0.41	0.29	0.059	0.70	34	0.58	1.02
AB 2-2 3	11.8	0.34				0.03	1.4	0.43	0.20				0.54	0.97
AB 2-2 4	10.8	0.41				0.04	2.0	0.35	0.21				0.80	0.91
AB 2-2 5	10.0	0.27				0.03	1.5	0.32	0.23				0.64	0.68
Med. plateau, fields with olives and fallow, Abila														
WQ mit	16.6	0.51				0.03	0.6	0.88	0.71				1.50	2.15
WQ ohne	12.3	0.55				0.04	1.5	0.65	0.67				1.15	1.70
Med. plateau, field system remains at Qumeim														
Feldsys 1	23.5	0.98				0.04	0.02	1.18	0.72				1.45	1.75
Feldsys 2	27.4	1.02				0.04	0.02	1.37	0.70				1.65	1.75

4. The soil evidence

Sample No.	Fe (d) [mg/g]	Fe (o) [mg/g]	Fe (t) %	Fe (d/t)	$\frac{Fe_d}{(Fe_t/CaCO_3)}$	Fe (o/d)	$\frac{Fe_o}{Fe_d/CaCO_3}$	Mn (d) [mg/g]	Mn (o) [mg/g]	Mn (t) %	Mn (d/t)	$\frac{Mn_d}{(Mn_t/CaCO_3)}$	Al (d) [mg/g]	Al (o) [mg/g]
Med. plateau, landslide in Wadi Queilbeh														
Qo 1	7.7	0.46				0.06	2.9	0.47	0.35				0.50	1.01
Med. plateau, colluvium in Wadi Queilbeh														
Q 2	8.4	0.24	2.8	0.30	15	0.03	1.4	0.45	0.26	0.059	0.77	38	0.67	1.00
Q 8	9.3	0.44				0.05	2.1	0.46	0.33				0.64	0.70
Q 12	10.7	0.33	3.7	0.29	11	0.03	1.1	0.55	0.51	0.069	0.80	30	0.80	1.05
Q 18	11.6	0.39	4.0	0.29	10	0.03	1.2	0.64	0.48	0.075	0.85	30	0.84	0.95
Med. plateau, sediments at Roman bridge, Abila														
Brücke 9	2.2	0.25				0.11	8.2	0.10	0.09				0.17	0.49
Brücke 8	2.6	0.76				0.29	17.6	0.24	0.27				0.17	0.50
Brücke 7	2.7	0.54				0.20	11.5	0.24	0.20				0.21	0.58
Brücke 6	1.7	0.49				0.28	20.6	0.16	0.20				0.18	0.49
Brücke 5	4.0	1.34				0.34	15.0	0.13	0.13				0.23	0.71
Brücke 4	3.0	1.00				0.34	20.3	0.13	0.13				0.24	0.79
Brücke 3	3.7	1.44				0.39	20.1	0.17	0.16				0.23	0.68
Brücke 2	3.2	1.34				0.41	26.7	0.39	0.38				0.28	0.61
Brücke 1	3.5	0.75				0.21	12.3	0.26	0.22				0.29	0.61
Brücke 0	2.8	0.59				0.21	12.4	0.20	0.19				0.30	0.69

Sample No.	Fe (d) [mg/g]	Fe (o) [mg/g]	Fe (t) %	Fe (d/t)	$\frac{Fe_d}{(Fe_t/CaCO_3)}$	$Fe(o/d)$	$\frac{Fe_o}{Fe_d/CaCO_3}$	Mn (d) [mg/g]	Mn (o) [mg/g]	Mn (t) %	Mn (d/t)	$\frac{Mn_d}{(Mn_t/CaCO_3)}$	Al (d) [mg/g]	Al (o) [mg/g]
Med. plateau, wadi colluvium near Beit Ras														
BR 2	13.1	0.43	3.7	0.35	13	0.03	1.2	0.59	0.41	0.070	0.84	31	0.70	1.55
BR 10	16.1	0.60				0.04	1.0	0.72	0.55				1.05	1.75
BR 14	17.8	0.80	5.0	0.36	7	0.04	0.9	0.80	0.47	0.092	0.87	17	1.10	2.00
BR 21	19.8	0.84	5.6	0.35	3	0.04	0.3	0.90	0.71	0.103	0.88	7	1.20	1.85
Irbid basin, building pit														
I 14a	23.2	1.36	5.1	0.46	1	0.06	0.2	2.20	1.50	0.168	1.31	4	1.65	1.85
I 9	11.9	0.62				0.05	0.6	1.23	0.86				1.25	1.00
I 04	7.5	0.21	2.5	0.30	20	0.03	1.9	0.14	0.10	0.022	0.61	41	0.60	0.25
Colour change Amrawah														
AmFw 1	12.0	0.41	4.6	0.26	5	0.03	0.7	0.62	0.37	0.077	0.80	17	0.36	1.05
AmFw 3	9.1	0.31	3.7	0.25	9	0.03	1.2	0.47	0.29	0.065	0.73	26	0.50	0.50
Amrawah, paelosol under basalt														
Am 1	11.8	0.63	1.7	0.69	9	0.05	0.7	0.97	0.58	0.012	8.05	108	1.60	1.08
AmO 7	7.2	0.29	3.4	0.21	9	0.04	1.7	0.29	0.18	0.051	0.56	23	0.45	0.67
AmO 12	10.3	0.32	4.3	0.24	5	0.03	0.6	0.17	0.09	0.044	0.40	8	0.58	0.59
Desert soils, Qasr Mshatta														
Air 1	8.3	0.06				0.01	0.2	0.40	0.26				0.53	1.28
Air 2	9.5	0.07				0.01	0.2	0.45	0.31				1.32	1.32

4. The soil evidence

Sample No.	Fe (d) [mg/g]	Fe (o) [mg/g]	Fe (t) %	Fe (d/t)	$\frac{Fe_d}{(Fe_t/CaCO_3)}$	Fe (o/d)	$\frac{Fe_o}{Fe_d/CaCO_3}$	Mn (d) [mg/g]	Mn (o) [mg/g]	Mn (t) %	Mn (d/t)	$\frac{Mn_d}{(Mn_t/CaCO_3)}$	Al (d) [mg/g]	Al (o) [mg/g]
Ruin soils, mudbrick from Ottoman house														
TZ 4	5.0	0.42				0.08	5.1	0.12	0.06				0.33	0.30
Ruin soils, relic mudbrick on Tell Zera'a														
TZ 14	7.9	0.25	3.2	0.25	9	0.03	1.2	0.21	0.13	0.059	0.36	14	0.30	0.40
TZ 15	8.4	0.26	3.3	0.25	9	0.03	1.1	0.23	0.11	0.058	0.39	14	0.25	0.40
TZ 16	7.8	0.27	3.3	0.24	9	0.03	1.3	0.20	0.11	0.056	0.35	13	0.33	0.42
TZ 16 (II)	7.0	0.25	3.4	0.21	8	0.04	1.4	0.20	0.15	0.057	0.36	14	0.33	0.43
TZ 17	7.7	0.15	2.2	0.35	22	0.02	1.2	0.04	0.04	0.021	0.21	13	0.40	0.23
Ruin soils, rel. mudbrick on Tell Abil														
Abila relikht	11.5	0.58	1.7	0.68	9	0.05	0.7	0.57	0.51	0.031	1.83	24	0.73	1.10
Ruin soils, debris levels Tell Zera'a														
TZ 6	5.0	0.26				0.05	2.9	0.20	0.13				0.30	0.68
TZ 8	2.9	0.31				0.11	6.0	0.10	0.10				0.10	0.80
TZ 9	3.6	0.45				0.13	7.0	0.12	0.11				0.15	1.50
Ruin soils, debris on basilica wall, Abila														
AB 4-1	3.3	0.43				0.13	9.5	0.09	0.04				0.29	0.72
AB 4-2a	2.1	0.12				0.06	4.8	0.07	0.05				0.38	0.45
AB 4-2b	3.5	0.19	1.1	0.32	24	0.06	4.1	0.06	0.04	0.021	0.30	22	0.18	0.35
AB 4-3	3.6	0.29				0.08	5.9	0.11	0.06				0.27	0.55

Sample No.	Fe (d) [mg/g]	Fe (o) [mg/g]	Fe (t) %	Fe (d/t)	$\frac{Fe_d}{(Fe_t/CaCO_3)}$	$Fe(o/d)$	$\frac{Fe_o}{Fe_d/CaCO_3}$	Mn (d) [mg/g]	Mn (o) [mg/g]	Mn (t) %	Mn (d/t)	$\frac{Mn_d}{(Mn_t/CaCO_3)}$	Al (d) [mg/g]	Al (o) [mg/g]
Ruin soils, debris on Umayyad mosque, Jerash														
Jer 1	5.2	1.02				0.19	10.3	0.15	0.09				0.31	0.90
Jer 2	7.0	0.38				0.05	2.8	0.16	0.13				0.39	0.68
Jer 3	4.8	0.36				0.08	3.8	0.13	0.12				0.24	0.42
Ruins soils, debris under fallen columns, Jerash														
Jer 6a	6.2	0.32				0.05	2.8	0.20	0.16				0.35	0.50
Jer 5a	5.0	0.44				0.09	5.9	0.16	0.10				0.30	0.98
Jer 4a	6.1	0.30				0.05	3.3	0.21	0.12				0.25	0.50
Jer 3a	7.4	0.26	5.3	0.14	8	0.04	1.9	0.27	0.14	0.094	0.29	15	0.33	0.29
Jer 2a	4.9	0.25	5.0	0.10	6	0.05	2.9	0.10	0.09	0.101	0.10	6	0.33	0.63
Jer 1a	6.3	0.34				0.05	2.2	0.32	0.11				0.28	6.72
Jer 0a	4.7	0.44				0.09	4.4	0.25	0.15				0.20	0.88

4.3.1 Iron oxides

As it seems, unmodified iron oxide-ratios show a sorry performance for characterisation of age and weathering intensity of soils in the Decapolis region. The weathering index Fe_d/Fe_t is not in agreement with field observations, while the activity index Fe_o/Fe_d does not fulfil expectations, too. Fe_o in general is very low, which indicates good development of the soils: according to Torrent et al. (1980), a Fe_o/Fe_d ratio < 0.1 can be considered as very small. But the low Fe_o -content also means that a modified weathering index Fe_{d-o}/Fe_t does not improve results. As it seems, the total Fe_d content might be better suited for characterisation of soil maturity than the Fe -ratios.

The problem can perhaps best be illustrated and explained with sample TZ 54. Although it represents in-situ chalk in the Wadi el-Arab, the Fe_d/Fe_t ratio is higher than in many old soils. This proves the presence of pre-weathered iron in the sedimentary rocks, which was already indicated by the red bands in the profile. It is not surprising, since iron oxides and clay minerals from river deltas etc. are deposited in shallow marine seas close to the coast, which was the case in the investigation area. This content of pre-weathered, dithionite-extractable iron however could strongly vary throughout the rocks. In this context, the strong negative correlation of Fe_d and $CaCO_3$ indicates that the greater part of calcium carbonate enrichment might not be connected with additions of pre-weathered iron (see chapter 4.2.1).

The expectation from the field is that additions of calcareous dust would reduce maturity of the soils. Therefore the indices were modified by the $CaCO_3$ -content, following Günster's (1999) example who involved clay contents in calculation of the weathering indices (but which does not make sense in the Decapolis region since clay is constantly very high). Although division by calcium carbonate content does not allow distinguishing between those samples where pre-weathered iron from calcareous dust is present, and those where it is not, it refers to the part without $CaCO_3$. This should make it possible to neutralise the impact of calcium carbonate enrichment.

In fact, the index $Fe_d/(Fe_t/CaCO_3)$ corresponds well to field observations (it becomes smaller with increasing age). Therefore also the activity index was modified with calcium carbonate content, which led to values which were much more pronounced although following a similar pattern like the unmodified index. Additionally, it is interesting to note that the unmodified weathering and activity indices show no correlation at all, while the modified indices correlate negatively ($R^2=0.4698$): higher weathered soils have less activity. This is a clear indication that pre-weathered iron in calcareous rocks or dust obscures the evidence from iron oxide-ratios if not addressed in the index calculation.

The modified indices confirm that the Terra rossa of the Irbid basin is by far the oldest and best

weathered soil, which is also expressed by the very high amount of total pedogenic iron. The soils in el-Wustije displays similar values, and although its total iron values are unfortunately lacking, I expect it is likewise developed. As well, the shallow soil on caliche close to Abila (AB 9) seems very old. This was also indicated by thin sections (to be discussed later) and suggests again that the source rock played an important role for soil formation. The caliche under AB 9 is very hard and consists of approximately 97% CaCO₃, so that dissolution should take place only slowly.

In the colluvia in Wadi Queilbeh and Beit Ras, the modified weathering index shows that increasingly less developed material was added as suggested by the field evidence. The index seems not to work well in Wadi Ziqlab, but which might be due to an analytical error in sample Ziq 1 (the sum of total elements is 137%). The Epipaleolithic soil in Wadi Ziqlab (Ziq 4) is developed similarly to the red paleosol in the Jordan valley (Jor 10), the present surface soil of the Yarmouk-profile (AB 1), the fields around Abila (AB 1-2 2 and 2-2 2), and the upper part of the Wadi Queilbeh- and Beit Ras colluvia, which basically confirms field observations. As well, plateau soils that were less affected by re-calcification (AB 4 and AB7, and the basalt soil UQ 9) show lower numbers, pointing to stronger weathering. The Irbid soil seems older than the basalt soil on the Ard al-Ala, which is another indication that the brighter subsoil in the Irbid basin might correspond to the Palesol preserved under the Amrawah basalt. In this context, it is interesting to note that the relic mudbricks on Tell Zera'a (TZ 14-17) and Tell Abil (Abila relik) show values similar to those plateau soils which are less re-calcified. In the Wadi el-Arab, such values are present in the forest soil (TZ 106), but not in the red colluvium (TZ 50) which is closer to the tell. I think this supports the impression from the relic mudbrick wall that red colour was more prominent in the Wadi el-Arab during the Late Bronze Age. Soils in the wadi bottom were since mixed with chalk additions, while the plateau soils were not, or at least less.

The activity index Fe_o/Fe_d seems not so strongly affected by pre-weathered iron, which might be due to the fact that oxalate-extractable iron is generally low. Yet modification with CaCO₃ leads to more pronounced numbers. The modified activity index basically suggests that less weathered soils are richer in CaCO₃. Phases of soil development and increased sedimentation in the Jordan valley seem to be well-reflected by the activity index, and the oldest soils in Irbid and el-Wustije show the lowest numbers. As well, the material deposited at the Roman bridge seems the least mature. The exceptional high values at this location indicate that the Fe_o/Fe_d ratio is not only affected by soil weathering, but also by soil age due to crystallisation of amorphous iron with time (Aniku and Singer, 1990). The field evidence already suggested that sediments at the Roman bridge are by far the youngest sampled material, matched only by the ruin soils.

To which degree the different types of iron oxides impact the colour cannot be discussed, since

the respective contents of hematite and goethite were not analysed. Some indications were achieved from the magnetic studies and will be discussed later, as the question how and whether calcium carbonate affects the water holding capacity.

4.3.2 Manganese oxides

Interestingly, a weathering index formed by the Mn_d/Mn_t ratio performs much better than the unmodified iron index. As it seems, manganese oxides were not bound in the calcareous sediments, or not to the degree of iron oxides. However no weakly crystallised manganese oxides are known that would preferably be extracted by oxalate, which does dissolve already a great part of the oxides. Therefore calculation of an activity index as with iron makes no sense.

Mn_d/Mn_t correlates negatively with $CaCO_3$ (fig. 35). In comparison, there is no correlation between the unmodified iron-weathering index with calcium carbonate ($R^2=0.0432$). There is, however, a good positive correlation of Fe_d/Fe_t to Mn_d/Mn_t ($R^2=0.508$), which seems very similar to the correlation of Mn_d/Mn_t to

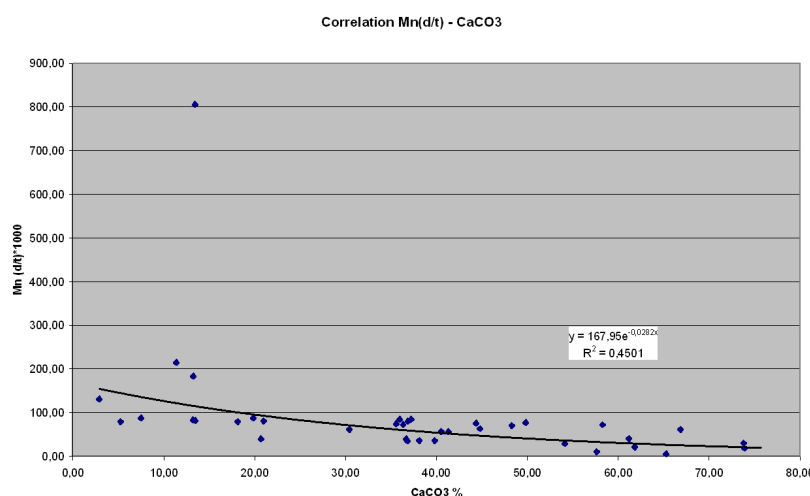


Figure 35: Negative correlation of Mn_d/Mn_t and $CaCO_3$.

$CaCO_3$. In conclusion, it seems that Mn-oxides are less influenced by pre-weathered material in calcareous dust and thus better suited for characterisation of soil age and development than Fe.

However, the Mn-weathering index turns sometimes >1 , which might be connected with analytical errors. Samples AB 7, Am 1 and Abila relikht show total element sums of 88, 83 and 87%, which could be responsible for the impossible values. Mn-contents are very low, so that errors would have a much greater impact than on iron-indices.

The manganese weathering index was also modified with $CaCO_3$, but which produced no meaningful results. In general, the unmodified Mn_d/Mn_t index is very similar to the modified iron-weathering index. The main difference seems the degree to which $CaCO_3$ -enrichment is reflected. This leads to some contradictions in the reflectance of the ruin soils on Tell Zera'a and the wadi colluvium. Apart from that, both indices support the field interpretation.

In my opinion, the modified iron-weathering index is best suited for characterisation of soil development, since the addition of calcareous material should decrease maturity from a genetic point of view. As well, the chosen extraction methods were not optimal for manganese oxides. In this context, the comparatively low Mn_d -values in the Amrawah paleosol might be connected with not all the well-crystallised manganese nodules being captured by sodium dithionite. Manganese-indices seems however a very important additional criterion, and the best for soil age, since they are seemingly not so strongly connected with pre-weathered material in the calcareous rocks and dust. For example, they indicate that the strongly rising $CaCO_3$ -contents in the Wadi Queilbeh and Beit Ras profiles are more connected with calcareous dust (which was already present in the eroded soil), and not with weakly weathered subsoil or chalk from the slopes. If chalky material would have been added to a greater degree, the Mn_d/Mn_t index should be lower, as for example in the Jordan valley, or in Wadi Ziqlab. This might also be the reason why the Mn_d/Mn_t values seemingly contradict the modified iron-weathering index of the relic mudbrick on Tell Zera'a. We can again speculate that these represent a colluvium with greater chalk admixture, but a colour still dominated by hematite, that since turned greyish due to ongoing chalk deposition. Or red soils were mixed with grey wadi colluvium when the mudbricks were made.

Last but not least, it should be mentioned that the formation of manganese oxides is closely connected with seasonal waterlogging in soils where relative high concentrations of iron oxides already exist (McKenzie, 1989). The strongly elevated Mn_d/Mn_t -ratios in the paleosols and plateau soils therefore indicate that these soils once experienced significantly moister conditions than today. Again, the rising $CaCO_3$ -contents in colluvia might not so much be connected with increasing dust deposition, but aridity. In this context, it seems clear that colour differences in the Decapolis region are not so much related to varying hematite/goethite ratios, but to calcium carbonate content. Although Singer et al. (1998) found a slightly higher moisture retention and lower hematite/goethite ratio for the investigated Rendzinas, I would say that in the case of the Decapolis, these difference should be overruled by the colouring effect of $CaCO_3$ -additions (which was not considered by Singer et al., 1998). This is probably also the reason why the redness rating of Hurst (1997) performs best: soil colour in the Decapolis region seems a matter of general soil maturity. Changing hematite/goethite ratios as described by Singer et al. (1998) might not be connected with the very slight differences in moisture holding capacity, but with goethite in the pre-weathered iron of calcareous additions. This would explain why some of the chalky rocks have a yellowish appearance, and why the moisture retention of the soils studied by Singer et al. (1998) is so similar: the "Rendzina" might in fact be a Terra Rossa that was enriched by calcareous material, while a true Rendzina should be characterised by primary, silty calcareous sediments and a lower moisture holding capacity. Therefore it is not surprising that the

redness rating in the Decapolis region correlates best with the Mn_d/Mn_t ratio after removing the impossible values >1 (fig. 36), even better than with Fe_d or the $Fe_d/(Fe_t/CaCO_3)$ -ratio ($R^2=0.4225$). To which degree hematite and goethite contents play a role for colour remains to be determined.

4.3.3 Aluminium

Although no meaningful indices can be calculated with Al, its extractable contents correspond well to the soil maturity estimates. The level of Fe-Al replacement depends on Al-activity in the soil solution, which is connected with the concentration (or deposition) of Al, pH, and moisture (Cornell and Schwertmann, 2003). Higher levels of extractable Al in the paleosols may therefore have recorded stronger pedogenesis, which is supported by a close positive relation of Fe_d - and Al_d -values ($R^2=0.7114$). While Al_o is usually higher than Al_d , they follow the same tendency and show a strong positive correlation ($R^2=0.7489$). Al_d corresponds positively to the Mn_d/Mn_t ratio (fig. 37), which indicates that formation of Mn_d and Al_d are related. It again points to moister conditions in the past, because aluminium and other metals can be fixed in Mn-oxides under periodic waterlogging. Al_d correlates positively with the modified iron-weathering index ($R^2=0.3916$), but not as strongly as with Mn_d/Mn_t . There is no correspondence of Al to the unmodified Fe_d/Fe_t -index.

Al_d represents isomorphous replacement of Fe in iron oxides and can reach a maximum of 33% in goethite, and 16% in hematite (Cornell and Schwertmann, 2003). In the

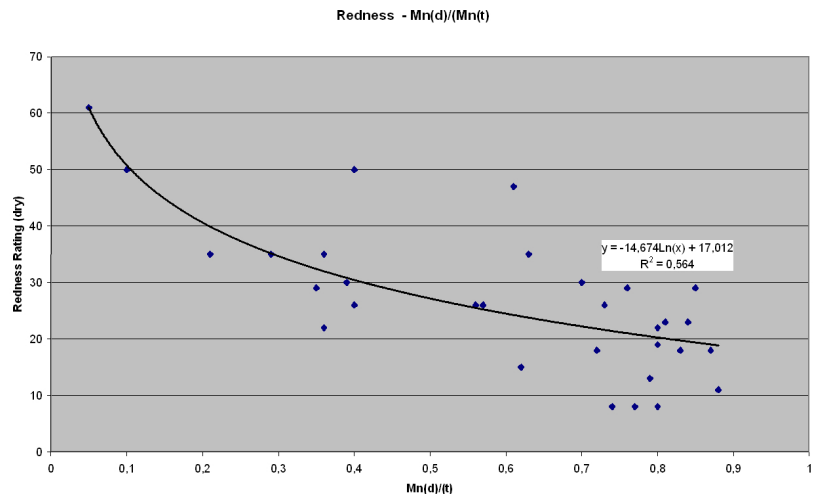


Figure 36: Positive correlation of Mn_d/Mn_t and Redness.

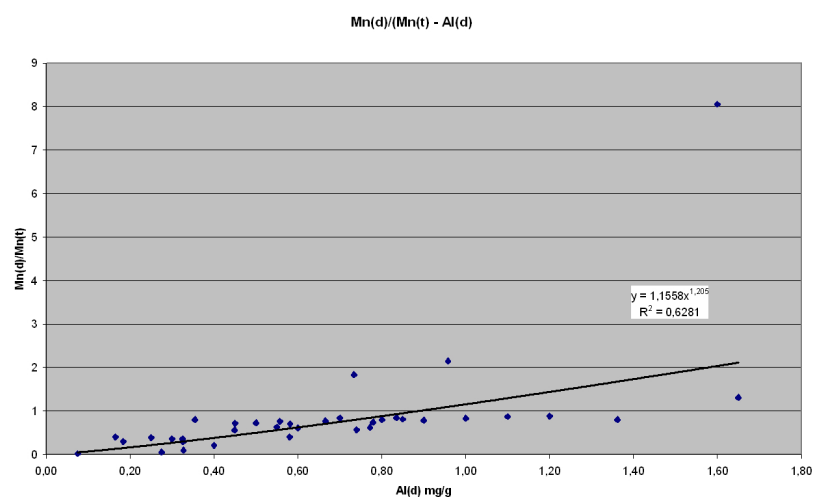


Figure 37: Positive correlation of Mn_d/Mn_t and Al_d .

investigated soils, it ranges between 1% in the weakly developed soils and 7-10% in the older ones. Thus the extractable Aluminium contents confirm the previous conclusions, and allow to add some lines of interpretation. As already suspected in the field, the soil pocket AB 1-2 4 below the fields near Abila shows an increase of both extractable iron (from 14.3 to 18 mg/g) and aluminium (from 0.73 to 1.05 mg/g). Its values are similar to the best developed soil in the deepest part of the Yarmouk-profile and support the conclusion that this type of soil was once more widespread in the area, but since eroded or altered by deposition of new material. Regarding the discussed maturity of the relic mudbrick on Tell Zera'a, the Al-values behave similarly to manganese oxides, and point to a similar conclusion: that red soil was mixed with chalky material. A massive increase of Al_o in Jer 1a seems to be connected with the ash in this layer.

While Al_d corresponds a little bit better with Mn_d/Mn_t than Al_o, it is vice-versa with Fe_d/(Fe_t/CaCO₃). Why isomorphous Fe-replacement in iron oxides or Al accumulation in clay hydroxy-layers correlates stronger in each case cannot be said. In any case, it seems safe to assume that content of pedogenic oxides, colour, and soil maturity in the Decapolis region are connected - and related to calcium carbonate additions.

4.4 Total element contents and soil parent materials

Total element contents were analysed for soils and the underlying rocks in order to assess to which degree the rocks constitute the soil parent material. The complete values are given in the appendix. Based on these analyses, several ratios were calculated: Ti/Zr, Ba/Sr, and a base accumulation index $(\text{SiO}_2 + \text{TiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 + \text{MnO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O})/\text{CaO}$.

Titanium and zirconium are very stable elements supposed to accumulate in soils. Compared with the parent material, the total content of both elements may change due to mass transports, but the *ratio* should remain similar as long as no foreign soil is added. Ti migration is only known from podzols, or a general presence of strong organic acids, or from clay illuviation (Milnes and Fitzpatrick, 1989). The first two can be ruled out for the Decapolis region, while argillic horizons were not observed, but might have been destroyed by re-calcification. No element is completely stable in soils, but the Ti/Zr ratio seems the best available index for assessment of inheritance.

The barium/strontium relationship is a weathering index based on the comparison of a stable with an unstable element. Compared with the parent material, increased weathering of the soil should lead to depletion of the less stable elements, and accumulation of the more stable ones (Retallack,

4. The soil evidence

2001). Weathering indices are problematic in areas with a negative water balance such as Jordan, since the frequent drying of soils may lead to accumulation of cations which are otherwise quickly washed out (for example, Ca^{2+} precipitates in form of secondary carbonates). Nevertheless the Ba/Sr-index was determined since these elements seem to behave as required: compared to the source rock, Ba is enriched in all soils, and Sr depleted without exception.

A surprising feature of soils in the Decapolis region was that most cations are enriched in comparison to the underlying rocks. Therefore also a base-accumulation-index was calculated involving all ions that show frequent enrichment, divided by calcium which alone is depleted in all soils (and usually coupled with strontium). These indices are given in table 20. For the rocks, also the possible CaCO_3 -contents are given as determined by XRF and the C/N analyser. The true contents must be between or below these values, since the XRF also captures Ca from other primary minerals, while the C/N-analyser might overestimate CaCO_3 due to organic matter in the sedimentary rocks (which was not ignited). As well, density of the rocks was estimated according to their water displacement. Based on this, the CaCO_3 -content from the C/N-analyser, and a medium soil density estimate from the literature (1.6 g/cm^3 , Purschke, 1990), it was calculated how many meters of rock dissolution would produce one meter of soil. This number is also given in the table, as well as a subjective rock hardness description.

Table 20: Ti/Zr, Ba/Sr, base accumulation index, and rock residue estimate. Rocks are marked with (R).

Sample No.	Ti/Zr	Ba/Sr	Base-accumulation index	$\text{CaCO}_3\%$ (C/N)	$\text{CaCO}_3\%$ (XRF)	density (g/cm^3)	hardness	m rock for 1 m soil
Jordan valley								
Jor 10	20	0.67	2.19					
Wadi Ziqlab								
Ziq 1	25	2.14	8.05					
Ziq 4	41	0.40	1.36					
Wadi el-Arab								
TZ 50	27	0.48	0.64					
TZ 54 (chalk)	23	0.31	0.33					
TZ 65	25	0.63	1.02					
TZ 66 (R)	18	0.34	0.10	96.7	92.8	2.1	hard	11-23
TZ 106	29	3.66	5.18					
Ard al-Ala								
UQ 9	33	3.00	6.85					
UQ 21	32	2.92	7.33					
UQ 23 (caliche)	8	0.15	0.04	98.3	96.3	2.2	very hard	(20-44)
Basalt UQ (R)	80	0.86	6.72	11.8	22	0.8	hard	?

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Sample No.	Ti/Zr	Ba/Sr	Base-accumulation index	CaCO ₃ % (C/N)	CaCO ₃ % (XRF)	density (g/cm ³)	hardness	m rock for 1 m soil
Med. highland								
AB 1	30	1.65	1.72					
AB 4	30	2.07	2.92					
AB 7	24	0.46	1.19					
Ab 8 (R)	11	0.06	0.16	84.2	89.7	1.8	very soft	6-9
Yar 5 (R)	9	0.15	0.06	99.2	95.5	2.3	hard	15-82
AB 9	26	4.21	13.47					
AB 10 (R)	14	0.22	0.13	96.7	91.9	2.5	hard	8-19
AB 1-2 2	27	1.26	2.21					
AB 1-2 5 (R)	10	0.23	0.05	99.2	96	2.2	soft	18-86
AB 2-2 2	27	0.88	1.41					
AB 2-2 6 (R)	12	0.26	0.08	98.3	94.3	3	soft	9-32
Q 2	27	0.75	1.42					
Q 12	28	1.31	2.36					
Q 18	27	1.34	2.65					
Q 19 (R)	9	0.26	0.05	93.3	96	2.1	soft	11-19
BR 2	28	1.40	2.28					
BR 14	28	2.64	6.35					
BR 21	27	3.08	10.20					
Irbid basin								
I 14a	23	3.45	29.58					
I 4	40	0.74	0.70					
I 00 (R)	16	12.67	37.05	13.4	4.6	2.1	very hard	(1)
Amrawah								
AM Fw 1	26	1.59	5.00					
Am Fw 3	26	1.11	2.76					
Am 1	27	0.18	0.55					
Basalt Amrawah (R)	68	1.33	10.62	9.1	14.5	2.8	hard	?
AmO 7	27	1.42	1.99					
AmO 12	26	1.49	4.71					
AmO 20 (R)	12	0.27	0.13	97.5	91.4	4.1	very hard	5-16
Ruin soils								
TZ 14	30	1.11	2.08					
TZ 15	29	0.98	2.15					
TZ 16	29	1.03	2.15					
TZ 16 (II)	29	1.15	2.23					
TZ 17	28	1.24	0.87					
Abila relik	23	0.34	1.10					
AB 4-2b	25	0.70	0.37					
AB 4-4 (R)	27	1.41	1.97	95.8	43.3	1.5	soft	2-26
Jer 3a	31	2.19	7.63					
Jer 2a	27	2.66	8.06					

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The different Ti/Zr-ratios point to changing parent materials, and little relation between rocks and soils. Looking at the total element contents, one notes an important difference between the basalt and limestone soils. In the first one, most elements in the soil are slightly depleted in comparison with the underlying basalt. In the latter ones, all elements except Ca, Sr and U are enriched. This is an apparent contradiction, making clear that there must have been different genesis periods, and/or additions of foreign material. The distribution of CaCO₃-contents (see chapter 4.2.3) would point to local dust sources, and in fact the Ti/Zr ratio of the chalk sample TZ 54 is much closer to the limestone soils than the underlying rocks. However, even compared with TZ 54 most soils must have experienced additions of Ti-rich material, while the basalt soil was depleted in Ti but enriched in Zr.

I think this confusing pattern can be explained with the absolute element contents and the type of material that was added. The additions must have contained less titanium than the basalt, but more than the limestones - thus this element was depleted in the basalt soil, but enriched in the limestone soils. Since zirconium is present only in very low concentrations in the rocks (even in the basalt), it was enriched everywhere. As mentioned above, zirconium accumulation could also be connected with soil age, and it is hard to say whether enrichment was mainly a matter of weathering or dust addition. In this context, it is interesting to note that the supposedly oldest soils like in the Irbid basin, or in the deeper Wadi Queilbeh- and Beit Ras-colluvia, are most enriched in Zr. The same is true for TiO₂, Ba, SiO₂ and Al₂O₃, which should also accumulate with age. But what does not fit into this pattern, especially considering the supposed increased moisture and weathering during formation of these paleosols, is that MgO, Na₂O and K₂O are also accumulated, and only CaO depleted. Enrichment of Na₂O and MgO points to foreign salt sources, e.g. from the Dead Sea, or salinity due to a negative water balance – but which can be ruled out in the light of the low conductivity values.

Manganese oxides incorporate Li, Na, K, Ba, Al and Fe, and some additionally have a "tunnel-structure" which hosts foreign cations and water (McKenzie, 1989). Therefore base accumulation might be connected with the formation of manganese oxides. To examine this possibility, a "Mn-fixation index" $(Al_2O_3 + Fe_2O_3 + MgO + CaO + Na_2O + K_2O) / MnO$ was calculated, which was plotted against the Mn_d/Mn_t ratio. But no correlation could be observed. This did not change when correlating the index to the Mn_d-content, or simply computing a cation sum without division by MnO, or removing Al, Fe or CaO from the index. A correlation was only obtained between the total cation sum and the Mn_d-content, but it was negative: a higher cation sum corresponded to lower Mn_d-values, which should be connected with the relationship between higher Mn_d/Mn_t-ratios and lower CaCO₃-contents. Therefore the cation accumulations cannot be explained with fixation in Mn-oxides. The slight variations of heavy metals concentration, especially Co, might however be connected with Mn-oxides since they strongly

absorb heavy metals (McKenzie, 1989).

While local dust sources (like TZ 54) can explain the enrichment in CaCO_3 and to some part other cation additions, it is unlikely that they are connected with the accumulation of SiO_2 . The only sample which points into this direction is Ziq 1, but which is considered unreliable due to an element sum of 137%. Enrichment in SiO_2 might be connected with the weathering of silica-rich sedimentary rocks such as I00 from the Amman silicified limestone in the Irbid basin, but which does not explain the higher Al_2O_3 -values and cation accumulation. Compared to the bedrock, SiO_2 -enrichment by the ten- to thirtyfold as in most limestone soils is unlikely to stem from weathering, and cannot be connected with calcareous dust: the oldest soils with the lowest CaCO_3 -contents show the strongest silica enrichment. Therefore long-range desert dust deposition as postulated by Yaalon and Ganor (1973) must have taken place. That dust deposition can be intense was already observed by Hanauer (1893), who observed a muddy rainstorm connected with an easterly wind in Jerusalem, which was so strong that it silted up the canals.

The very clay-rich texture of soils in the Decapolis region seems to speak against such dust additions, since aeolian deposits like in the Negev or on the Chinese loess plateau usually consist of silt. As well, it seems evident from the distribution of soils in the landscape that the source rocks played a role in soil formation. However, the dust which is transported from the Sahara consists mostly of clay. And clay minerals would bring exactly the kind of enrichment which is observed: aluminium phyllosilicates with variable amounts of iron, magnesium, alkali metals, alkaline earths and other cations.

Glaciers and deserts are the world's dust sources. According to Yaalon and Ganor (1979), the desert dust transported to Israel originates from alluvial deposits in mountain valleys of the Sahara, Sinai, and Negev, ultimately coming from old lake beds and weathered minerals from the mountains. Junge (1979) suggested that the fine dust is produced by crystalline breakage of saltating grains. According to Jahn (1995), the particles should become finer the farther they are transported, which would explain why silt is deposited in the Negev, but clay in the Decapolis. According to Ganor and Foner (1996), total dustfall in Israel is composed of a uniform local background with superimposed pulses of desert dust storms. However, only 1-7% of the transported dust is deposited (Yaalon and Ganor, 1979). According to Ganor and Foner (1996), the clay mineral assemblage varies according to the origin of the storm trajectories, and follows a gradient: dustfall is highest over the Negev, and reduced moving north.

According to Israelevitch et al. (2006), there is a permanently existing reservoir of dust in the atmosphere over northern Africa. This dust reserve can be transported as soon as the appropriate

synoptic conditions arise, even if there is no primary dust mobilisation. Dust transport to the eastern Mediterranean is connected with the Sharaf depressions, and thus occurs mainly during May and October (Kubilay et al., 2000). High dust deposition rates require the co-existence of dust and rain, and are highly variable in space and time: 30% of the annual mineral dust deposition in 1992 occurred during two dust storms in May (Kubilay et al., 2000). The presence of dust also has an important impact on the likeliness of rain, since it leads to an drop concentration around the particles, accelerating the growth of clouds (Levin and Ganor, 1996) and increasing the potential to produce rain (Israelevitch et al., 2006). Very recent research however indicates that fine aerosols as produced by air pollution can prevent the formation of clouds and reduce rain (Rosenfeld et al., 2007). Precipitation is inhibited as water vapor condenses on the pollution particles and creates a cloud containing a large number of drops that are so small that they float with the air and are slow to coalesce into raindrops or to freeze into sleet and snowflakes. This translates into a net loss of precipitation when the "lifetime" of the cloud is shorter than the time necessary for it to release its water, as happens when clouds form as they ascend across a ridge and then descend and evaporate downwind (Rosenfeld et al., 2007).

Regarding the composition of dust currently deposited in Israel, Yaalon and Ganor (1979) found that it was characterised by SiO₂, Fe, Al and to a lesser degree by Na and K. Its mineralogical composition in the clay-mineral free fraction was 35-45% quartz, 30-40% calcite, 10-20% dolomite, 5-10% feldspar, 2% halite and less than 1% gypsum. Clay minerals were characterised by montmorillonite and mixed layer minerals, followed by kaolinite, illite and palygorskite. Molinaroli (1996) found that smectite is a mineralogical marker for the presence of Saharan dust in the eastern Mediterranean, while palygorskite is a marker in the western Mediterranean.

Singer et al. (1992) installed dust traps on Mount Karmel and examined the dust deposition in Israel from 1989 – 1992. Most trapped particles were smaller than 10 µm, and many smaller than 5 µm. But closer examination revealed that dust particles could in fact be divided into two even smaller groups: those that were smaller than 2 µm, but clung at those larger than 3 µm, forming composite-particles. Quartz was the dominant mineral, followed by carbonates (calcite + dolomite), and some halite and gypsum. As well, feldspars and clay minerals (kaolinite, palygorskite and illite) were present. The ionic composition was described as a mixture of distinctly marine origin (Na⁺, Cl⁻, Mg²⁺), and continental origin (Ca²⁺). Dolomite was considered to be connected with particles of marine origin, as SO₄²⁻, which led to wetfall in the acid range. Continental dustfall, which was associated with dust storms, was however alkaline. The formation of gypsum and halite was attributed to phytomineralogenesis on the needles of pine trees, under which the dust traps had been installed (Singer et al., 1992). Kaolinite was the most abundant clay mineral in the samples studied by Singer et al. (1992).

The presence of palygorskite had been suggested by X-ray diffraction (XRD), but could not be confirmed by Transmission Electron Microscope (TEM).

The mineralogy of current dust depositions as described by Singer et al (1992) seems not fully in agreement with the evidence from the Decapolis: the content of clay minerals is too low. Here it is important to note that Ganor (1975) found that dust settling without rain has less than 20% clay, while pluvio-aeolian dust contains 50-60% clay. If clay mineral deposition was connected with higher precipitation in the past, this would not only fit to the XRF-data from the Decapolis paleosols, but also explain the clay-rich texture of the paleosols in the coastal plain of Israel (Issar and Bruins, 1983). In this context, Issar and Bruins (1983) found an isotopic anomaly of fossil water in the Negev. According to Issar et al. (1987), this paleowater was depleted in ^{18}O and deuterium, but enriched in sulphates. This is explained with a southward migration of the latitudinal climatic belts, namely the westerlies, during the Ice Age, which was probably connected with a high pressure area over glaciated Europe. So the Negev enjoyed a more humid climate while depressions entered Israel over Cyrenaica and northern Africa, and not as today over Cyprus. Saline marshes in Egypt, probably much larger than today due to the regression of the sea, released salts rich in sulphates. Connected with the higher precipitation, these led not only to the sulphate-anomaly in the fossil water, but also created fossil calcic gypsum layers in the subsoil of Negev loesses (where gypsum crusts are not formed today). The depletion in ^{18}O may also point to summer rains. It is interesting to note that today's rainstorms are characterised by a NaCl- CaCO_3 composition, while only in a few cases CaSO_4 is the major salt, always connected with continental west-southwest trajectories of rainstorms (Issar and Bruins, 1983).

While the composition of the Negev loess is similar to dust coming today from the deserts of northern Africa, alternating layers of clay and silt overly Early Pleistocene sandy deposits (Issar and Bruins, 1983). The uppermost loess blanket (50 cm of 11 m), presumably laid down during the Holocene, has a low clay content of 25%. Therefore Issar and Bruins (1983) conclude that extent and character of aeolian deposition have changed since the end of the Ice Age. Dating of soils and paleowaters indicates that depositional processes were active mainly 100,000 – 10,000 BP.

The average annual dust deposition measured by Singer et al. (1992) was 6 g/m^2 , which would mean that 6 mm soil are accumulated in 1000 years (if a mean density of 1 g/cm^3 is assumed). If this deposition rate was constant since the basalt flow covered the Umm Queis plateau 700,000 years ago, it would have led to deposition of approximately 4,20 m soil. Taking the Mousterian artifacts as the oldest dated evidence for existence of the plateau soils, one arrives at ca. 72 cm dust accumulation since then. According to Gvirtzman and Wieder (2001), dust sedimentation during the Younger Dryas was elevated by the factor 100, since they found an average growth of 0,7 mm/year for the paleosols in the

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coastal plain of Israel. These authors also arrive at different average annual rates of present dust deposition: 22-39 mm in 1000 years are assumed for the Mediterranean climate zone, and 34-83 mm for the desert belt. According to Gvirtzman and Wieder (2001), some of the red paleosols are today exposed at the surface and must have incorporated the aeolian additions. Only where deposition was very fast, and perhaps connected with fluvial sedimentation, it led to a break in soil genesis and thus the alternating layers of the coastal hamra-kurkar soils. Applying this model to the Decapolis region, it seems that the Yarmouk profile represents such breaks of soil genesis, although they were not as sharp as in the coastal plain of Israel. In comparison, the soils of el-Wustije and the Irbid basin seemingly never saw an interruption of soil genesis. An exception is the brighter subsoil of the Irbid basin, but which might in fact be strongly weathered rock as indicated by the Ti/Zr ratio. The Amrawah-palesol shows a different Ti/Zr characterisation, and points to unchanged soil parent materials for a long time. Since its intense manganese concretions are missing in all other examined soils, it might not have a counterpart, or experienced unique conditions of waterlogging, or the concretions were re-dissolved e.g. in the recent soils at Amrawah with a colour change like in the paleosol (AmFw 1 and AmFw 3). In fact, this colour change cannot be explained on the basis of present data, and is worth to be investigated further.

In the light of the high age of soils in the Decapolis, it seems well possible that long-range aeolian deposition played an important role in their formation, even if was as low as measured by Singer et al. (1992) and limited to the period found by Issar and Bruins (1983). The diminishing enrichments of clay minerals in the younger soils indicate that Issar and Bruin's (1983) model is valid for the Decapolis. Such long time periods however should also mean that weathering and soil formation out of the bedrock take place.

In summary, soils in the Decapolis region seem to have formed out of three main parent materials: the source rocks, long-range dust transport from the Sahara, and local, chalky dust emissions. The role of the source rock is clearly indicated by the element contents of the basalt soil. As well, long-range dust transport from the Sahara led to deposition of clay, which seems connected with higher precipitation, and was much more intense during the Pleistocene. This would explain why cations are most enriched in the paleosols, but CaCO₃ is most leached, and why clay values are so high. Precipitation and long-range clay deposition were reduced during the Holocene, reflected by rising CaCO₃-contents and connected with local emissions. As well, the youngest ruin soils resemble the elemental composition of chalk and show no indicators of clay deposition any more. That dust transport (and also local deflation) was very limited in the area during historical periods can well be shown with the "Dead Cities" in northern Syria, close to Aleppo. These settlements were abandoned at

the end of the Byzantine period and are largely intact. Water collectors had been installed at every possible location in the towns because rain was the only water supply. Fig. 38 shows that these cleaned rocky areas are still clean. It can be concluded that aeolian activity in the area was very limited or absent in the last 1400 years, and that most of the soil covering the ruins of the Decapolis in Jordan stems probably from the debris of collapsing buildings.



Figure 38: Water collection basin in Serjilla (Dead Cities, Syria).

It is worth to review the base accumulation index and Ba/Sr ratio. They show a strong positive correlation ($R^2=0.7544$), which is not surprising since Sr is usually bound to CaCO_3 and washed out simultaneously. Ba seems to be connected with the enrichment of the other cations, which points to deposition together with clay minerals. Ba however might also come from local sources, or be elevated by high concentrations in the respective rock, indicated by relatively high Ba-contents of samples like TZ 54 or the limestone AB 4-4. In this context, it is interesting to note that the Ba/Sr ratio shows a weak negative correlation to CaCO_3 -content ($R^2=0.3116$). Assuming that CaCO_3 is connected with local dust emissions, this indicates that local dust sources play a minor role for Ba-enrichment. This negative correlation to CaCO_3 is even stronger with the base accumulation index ($R^2=0.4681$), and again follows an exponential function. It makes clear that the great majority of clay minerals does not come from local dust sources.

Considering whether the Ba/Sr ratio or the base accumulation index represent soil age or weathering, one finds no correlation of with the Mn_d/Mn_t -index. As well, there is no considerable correlation with the unmodified Fe_d/Fe_t index ($R^2=0.2146$). The base accumulation index however shows a strong negative relation to the modified iron weathering index ($R^2=0.7185$). The positive correlation to the Ba/Sr ratio is also strong ($R^2=0.6391$). This might be connected with the negative correlation of these indices to the CaCO_3 -content, which is included in the $\text{Fe}_d/(\text{Fe}_t/\text{CaCO}_3)$ ratio. Yet, since the indices correspond stronger to the modified iron weathering index, this points to long-range aeolian deposits playing a role for total and pedogenic iron contents. This confirms the conclusions from the pedogenic oxides (chapter 4.3): the modified iron weathering index performs best for characterisation of maturity of the soil, as it may also reflect pre-weathered iron deposited with clay

minerals from long-range dust transport. Manganese oxides however seem not so much affected by local or distant dust, and thus to stand best for soil age. In contrast, the base accumulation index, and to some degree the Ba/Sr index, seem to be connected with the presence of long-range dust deposition in the soil.

Let us finally consider the degree to which the source rock could have contributed to soil development. The working hypothesis from the field was that varying soil depth, or at least the karst structure of the bedrock, might be connected with varying hardness and CaCO₃-content. Since Ca²⁺ is washed out and CO₂ evaporates according to the "residual theory" (Reifenberg, 1947), only the non-calcareous residue of the rock should remain in the soil (such as clay minerals and iron oxides). The CaCO₃-estimates indicate that most of the limestones are very pure and contain 95-99% CaCO₃. Their chemical similarity implies that variations of the CaCO₃-content or other soil properties are unlikely to be connected with the source rocks. The chalk however seems to contain considerably more residue (see TZ 54, with only 74% CaCO₃), which might explain why Ti/Zr contents in the younger soils are so close to the chalk. As well, the deeper part of the Yarmouk-profile (AB 8) is characterised by a lower CaCO₃ content of 84%, and is very soft, which might explain why a pocket formed there.

However, a rough calculation of the amount of limestone dissolution necessary for the production of one meter of soil shows that 5-86 m of limestone would have to be dissolved. In the light of these huge amounts, it seems unlikely that the limestone contributed significantly to soil development, even if soil production follows a "humped" function and is increased in shallow soils (Wilkinson and Humphreys, 2005). Therefore Yaalon (1997) considered *Terrae Rossae* to be purely allochthonous soils formed by dust. As well, the sharp boundary between a *Terra Rossa* and the underlying rock is often taken as indication of their foreign origin. But it would contradict field observations in the Decapolis: the limestone soils seem clearly related to the bedrock and its varying hardness and purity, and partially show saprolite (see chapter 3), which is widely reported from *Terrae Rossae* around the world (Foster et al., 2004).

An explanation for the role of the rocks can be given by *isovolumetric replacement*. According to Merino (2006), weathering of limestone and other rocks does not only take place in form of dissolution and loss of the host mineral. Instead, authigenic clay minerals forming the *Terra Rossa* grow in a super-saturated gel, called metasomatic front. In this front, the clay's main elements Fe, Al, and Si are supplied by dissolved dust, while newly forming clay crystals replace calcite by *pressure*, via the stress they generate in the host mineral. In fact, the transition from *Terra Rossa* to limestone might not be "sharp": Enrique Merino presented thin sections showing the metasomatic front and partial replacement of calcite by clay at the 2005 annual meeting of the Geological Society of America in Salt

Lake City⁵, and at the World Soil Conference 2006 in Philadelphia. Interestingly, the forms of microfossils in the presented Bloomington limestone were preserved as "shadows" in the newly formed clay before being destroyed by its shrink-swell behaviour. This resembles tropical laterites where the matrix of the host rock is still visible (Merino and Dewers, 1998, Nahon and Merino, 1997).

That diagenetic rock displacement can be controlled by the "force of crystallisation" (now renamed into "induced stress") was already shown by Maliva and Siever (1988). Fletcher and Merino (2001) studied the process in in the laboratory and found that guest minerals completely strange to the host can be formed, e.g. silex in limestone which is completely silica-free. The host mineral may either dissolve to accommodate growth of the guest mineral, or precipitate and form a pressure shadow. The driving force for isovolumetric replacement is a sufficient supersaturation for the new mineral in the pore fluids of the rock (pers. comm. with Enrique Merino, January 2007). This applies not only to Terra Rossa, but to any other rock replacements, and with a slightly different mechanism also to the formation of secondary carbonates in the soils (Wang et al., 1994). Since the volume of the host mineral matrix is not changed, now one meter of limestone produces one meter of Terra Rossa which perfectly fits to the pattern in the Decapolis region.

If the volume-adjusted replacement of limestone by clay is described by a mass-balance, it produces acid. This acid was visible in Merino's thin sections of the Bloomington soil, producing a bleached zone in front of the clay-calcite replacement. So the H⁺ from the replacement leaches and dissolves calcite ahead, leading to voids just in front of the reaction zone. The acids create bulges which act as traps for more acid, thus leading to a "fingered" weathering structure. According to Merino (2006), this is how karst forms, and explains why Terra Rossa and karst are associated: the latter is the product of the former. For the case of the Decapolis region, I suppose that softer parts of the limestones dissolve more easily under the acids, which is why soil depth and karst pockets are related to varying hardness. Terra Rossa can thus be seen as a "metasomatic claystone" with lateritic and pedogenetic transforms. Merino (2006) concludes that Terra rossa is a unique laterite, and that none of its major elements comes from its parent limestone. I would however think that the the combined process of clay mineral growth and calcite dissolution by acids will also free pre-weathered clays and iron oxides, as proposed by Bronger et al. (1984). These authors showed that Terra Rossa is related to the limestone residue. We can conclude that isovolumetric replacement might explain the depth and distribution pattern of the soils, as well as their association with karst. Their mineralogical properties however seem related to pre-weathered clay minerals and iron from the limestone residue, local chalk emissions, and long-range dust transport from the Sahara. The present study does however not allow to

⁵ His presentation can be viewed online at: http://gsa.confex.com/gsa/2005AM/finalprogram/abstract_90146.htm.

present any numbers describing the degree to which each factor contributed to soil development. This could only be achieved if the rock residue, the timing of the replacement process, and the intensity and kind of dust deposition would be determined in detail.

Many researchers believe that aeolian deposits are responsible for up to 80% of the Terra Rossa's volume (pers. comm. with Mordechai Stein, April 2004). I do, however, not share this view and think that dust additions only provided a subordinate part of the total soil mass. In the context of isovolumetric replacement, long-range dust additions may be unnecessary for explaining the divergent element compositions of soils and source rocks, since chemically completely strange guest minerals can grow in the host rock. Thus the enrichment in bases could be the result of clay minerals growth, and their decrease simply be related to local chalk additions. These would lower the share of clay elements in the XRF-record while still showing a clayey texture, as CaCO_3 has to be removed for grain size analysis.

4.5 Soil magnetism

Cordova (2000) found that some of the colluvia at the Madaba-Dhiban plateau were characterised by elevated magnetic susceptibility, which indicated that Terra Rossa was mixed with less developed sediments. He concluded that Red Mediterranean Soils had once extended into the steppe and desert fringes, and, according to C^{14} -dates and archaeological material, were eroded mainly at the end of the Pleistocene or beginning of the Holocene (Cordova, 2000). Apart from his study, to my knowledge no soil magnetic analyses were conducted in Jordan. Since Cordova's results showed that magnetics might provide important additional insight, the methodology was applied to a selection of samples.

Contrasts of magnetic properties can be used to define horizons in sedimentary deposits that would otherwise appear uniform, and to map structures that have otherwise disappeared (Becker, 1998). This is especially useful for archaeological research. For example, slight differences of the subsoil's magnetic properties allowed to draw a virtual "street map" of Pi-Ramesse in Egypt, a city that has completely perished. As well, it was possible to locate Troy's Late Bronze Age defensive moat and to confirm the existence of a large town as described by Homer in the *Ilias* (Becker, 1998). The magnetic contrasts are on the one hand visible due to enrichment of magnetic minerals like magnetite and maghemite in ash and mudbricks, or, like in Pi-Ramesse, due to their depletion in sterile Nile mud and sand (LeBorge-effect). On the other hand, the remains of postholes and wood are also characterised by magnetic enhancement, which is attributed to bacterial activity during the

decomposition of organic matter (Faßbinder et al., 1990).

The basic criterion of soil magnetism is the magnetic susceptibility κ (referring to the soil volume) and the specific susceptibility χ (referring to the soil mass). It quantifies the ease with which a material can be magnetised in a weak field, and reflects the sum of its magnetic properties (dia-, para-, superpara-, ferro-, antiferri- and ferrimagnetism). As well, the frequency-dependent susceptibility is measured. It refers to the smallest (superparamagnetic) minerals. Due to their small size, these particles have thermal vibrations at room temperature, and do not acquire a stable remanent magnetisation (see below). They show however alignment in the presence of external magnetic fields, and make the greatest contribution to the total low-frequency susceptibility κ_{lf} in comparison with other minerals (Thompson and Oldfield, 1986). In contrast, their contribution to the high-frequency susceptibility κ_{hf} is significantly lower, because the magnetisation of small grains becomes "blocked". This is due to a viscous effect of high-frequency fields on grains lying close to the superparamagnetic particle size border (Thompson and Oldfield, 1986). Biogenous magnetic particles are mostly of superparamagnetic size, reaching ~ 30 nm (Faßbinder et al., 1990), and pedogenesis in general is connected with enrichment of small grains < 100 nm (Evans and Heller, 2003). Therefore the ratio $(\kappa_{lf-hf}/\kappa_{lf}) \cdot 100$ gives a percentage-estimation of the biogenous share of magnetic minerals. In soils, it may reach 0-24% (Thompson and Oldfield, 1986). In the examined soils, it varied between 4 and 11%, which matches the range found by Cordova (2000) at the Madaba-Dhiban plateau. According to Evans and Heller (2003), a ratio of 11% indicates a considerable presence of pedogenic magnetite.

Magnetic particles which were exposed to a strong field partially keep their alignment (remanence). The maximum remanence is called saturation isothermal remanent magnetisation (SIRM), which is determined in a field of 2 T. Division by the magnetic susceptibility can be used as rough estimate of magnetic grain sizes: smaller particles will have lower SIRM/ κ ratios. Superparamagnetic particles have distinctively high susceptibilities, and low SIRM/ κ ratios since they acquire no remanence at room temperature, while larger multidomain grains and mixtures of single-domain and superparamagnetic grains have similar higher SIRM/ κ ratios (Thompson and Oldfield, 1986).

Magnetic minerals show a different likeliness to acquire remanence, and to lose it in a reverse field. The coercivity describes the strength of the reverse magnetic field necessary to delete remanence. Here, the S-ratio provides a measure of the relative amount of high-coercivity (hard) to low-coercivity (soft) magnetic minerals in a sample that acquired remanence in a 2 T field (Evans and Heller, 2003). It provides a fair estimate of the contribution of (hard) antiferromagnetic hematite (goethite acquires remanence only in fields > 2 T) to (soft) ferrimagnetic minerals (magnetite and maghemite).

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The S-ratio was calculated according to the formula: $\frac{1}{2} * \left(1 - \frac{IRM_{-0.2T}}{SIRM_{2T}} \right)$

Magnetite and maghemite contribute stronger to remanence than hematite and goethite: the factor is approximately 1:100. Also, magnetite and maghemite (which are usually associated and characterised by similar magnetic properties) completely reverse their magnetic orientation in a field of -200 mT, while hematite does not change its remanence in such a weak field. To give some examples, pure magnetite would acquire an $IRM_{-0.2T}$ which is identical with the $SIRM_{2T}$, but negative, so the S-ratio would be 1. With pure hematite, the $IRM_{-0.2T}$ divided by $SIRM_{2T}$ is again 1, but positive, so the S-ratio would be 0. With 50% magnetite and hematite (1:1), the $IRM_{-0.2T}$ would be -99, and the $SIRM_{2T}$ would be 101, with a resulting S-ratio of 0.99009. In the studied Jordanian soils, the S-ratio is between 0.95 and 0.90 for the well-developed soils, indicating a magnetite:hematite ratio of 1:5 to 1:10. In the less developed sediments and chalk, this ratio rises to 1:40 and 1:100.

Finally, the remanence acquisition behaviour allows estimation of the relative abundance of magnetite, hematite, and goethite. While magnetite quickly reaches saturation remanence in fields of up to 200 mT, hematite saturates in fields of 100 mT – 2 T, while goethite acquires remanence only in fields between 2 and 10 T. Step-wise magnetisation and remanence measurement allows therefore to describe which minerals carry the magnetic signal. The results of the magnetic analyses of soils from the Decapolis region are summarised in table 21.

Table 21: Magnetic properties of selected samples.

Sample No.	Magnetic susceptibility χ	Weight (kg)	Magnetic susceptibility χ (1/kg) *E-3	SIRM	S-ratio	SIRM/ χ	χ_{lf} (460 Hz) *E-6	χ_{hf} (4600 Hz) *E-6	$(\chi_{lf-hf}/\chi_{lf}) *100$
Jordan valley									
Jor 1	9.40E-004	0.006712	140	4.427	0.93572	4.711	892.08	808.82	9.33
Jor 3	5.11E-004	0.006789	75.32	2.598	0.93129	5.082	484.83	438.69	9.52
Jor 5	7.87E-004	0.006513	120.84	3.928	0.94343	4.991	749.66	681.59	9.08
Jor 7	5.35E-004	0.006593	81.2	2.795	0.93520	5.221	483.17	438.10	9.33
Jor 10	1.46E-003	0.006834	214.13	7.553	0.93265	5.162	1394.17	1266.31	9.17
Jor 12	4.52E-004	0.007604	59.46	2.456	0.92631	5.432	433.15	392.02	9.49
Wadi Ziqlab									
Ziq 1	2.06E-004	0.005693	36.13	0.891	0.92106	4.332	187.1	172.25	7.94
Ziq 2	2.94E-004	0.005915	49.68	1.069	0.92365	3.640	272.91	247.51	9.31
Ziq 3	1.44E-003	0.006711	214.52	4.871	0.94009	3.383	1360.57	1220.57	10.29
Ziq 4	1.74E-003	0.006028	287.82	6.071	0.94762	3.499	1633.55	1467.21	10.18

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Sample No.	Magnetic susceptibility χ	Weight (kg)	Magnetic susceptibility χ (1/kg) *E-3	SIRM	S-ratio	SIRM/ χ	χ_{lf} (460 Hz) *E-6	χ_{hf} (4600 Hz) *E-6	(χ_{lf-hf}/χ_{lf}) *100
Wadi el-Arab									
TZ 23	1.25E-003	0.006942	180.16	5.986	0.93832	4.786	1197.03	1074.39	10.25
TZ 24	8.53E-004	0.006412	133.03	3.988	0.93665	4.675	815.19	730.19	10.43
TZ 25	5.28E-004	0.006477	81.47	2.629	0.92959	4.981	503.53	453.35	9.96
TZ 26	2.84E-004	0.006490	43.68	1.308	0.90167	4.615	264.09	239.27	9.40
TZ 27	4.14E-004	0.006951	59.49	1.897	0.91108	4.587	392.77	354.96	9.63
TZ 50	1.68E-003	0.006102	275.05	7.354	0.94341	4.382	1591.26	1420.33	10.74
TZ 54	8.12E-005	0.005129	15.83	0.330	0.49499	4.060	70.67	64.56	8.65
TZ 106	3.17E-003	0.006276	504.83	13.854	0.94386	4.373	2994.42	2683.21	10.39
Ard al-Ala									
UQ 9	1.62E-003	0.006631	244.94	15.352	0.93816	9.452	1551.08	1466.23	5.47
Med. highland									
AB 1	1.35E-003	0.006753	200.31	8.265	0.94605	6.110	1285.05	1178.08	8.32
AB 3	1.70E-003	0.006473	261.86	10.048	0.93978	5.928	1623.79	1484.44	8.58
AB 6	2.40E-003	0.006839	351.17	14.144	0.94026	5.889	2300.02	2107.30	8.38
AB 1-2 1	1.33E-003	0.005989	222.3	7.274	0.93174	5.464	1224.21	1106.13	9.64
AB 2-2 1	1.17E-003	0.006026	194.96	6.995	0.93091	5.954	1120.91	1009.61	9.93
Feldsys 2	2.15E-003	0.007285	294.9	9.392	0.94254	4.372	2007.40	1804.31	10.12
Q 2	9.71E-004	0.006662	145.68	5.013	0.92041	5.166	878.96	799.43	9.05
Q 8	1.23E-003	0.007009	174.89	6.368	0.92291	5.195	1174.45	1066.05	9.23
Q 12	1.50E-003	0.006352	236.38	7.943	0.93545	5.290	1418.37	1287.68	9.21
Q 18	1.25E-003	0.005926	210.51	6.347	0.92070	5.088	1177.42	1067.47	9.34
Brücke9	5.27E-004	0.007014	75.15	3.445	0.93989	6.537	492.87	451.21	8.45
Brücke8	3.91E-004	0.006042	64.69	3.059	0.92708	7.828	368.77	346.43	6.06
Brücke7	3.87E-004	0.005951	65	3.060	0.92381	7.910	367.71	345.66	6.00
Brücke6	3.84E-004	0.006465	59.35	3.223	0.94389	8.401	347.15	325.95	6.11
Brücke5	5.07E-004	0.006595	76.8	4.423	0.92114	8.732	484.80	459.79	5.16
Brücke4	5.43E-004	0.006995	77.65	4.696	0.72390	8.646	491.20	462.41	5.86
Brücke3	6.32E-004	0.008164	77.45	5.144	0.92470	8.135	601.65	567.20	5.73
Brücke2	4.41E-004	0.006541	67.45	3.794	0.94531	8.600	414.71	383.65	7.49
Brücke1	5.13E-004	0.006777	75.72	3.908	0.93228	7.616	488.87	455.72	6.78
Brücke0	4.78E-004	0.006004	79.67	3.834	0.93804	8.014	449.42	418.19	6.95
BR 2	2.28E-003	0.006226	365.67	10.624	0.94014	4.666	2134.45	1905.58	10.72
BR 10	2.71E-003	0.005841	463.96	12.728	0.94352	4.697	2557.98	2281.85	10.79
BR 14	3.34E-003	0.006356	525.75	15.590	0.94138	4.665	3173.66	2834.42	10.69
BR 21	3.52E-003	0.006066	580.83	16.513	0.94296	4.687	3348.99	2991.97	10.66
Amrawah									
Am 1	1.95E-003	0.006297	309.67	11.319	0.93423	5.804	1876.46	1720.27	8.32
Am O 7	9.49E-004	0.006531	145.36	5.147	0.92100	5.421	922.89	887.18	3.87
Am O 12	9.90E-004	0.006835	144.79	8.522	0.92113	8.611	962.75	922.65	4.16
Desert soil									
Air 1	7.85E-004	0.006479	121.19	5.888	0.92383	7.499	765.97	733.40	4.25

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Sample No.	Magnetic susceptibility χ	Weight (kg)	Magnetic susceptibility χ (1/kg) *E-3	SIRM	S-ratio	SIRM/ χ	χ_{lf} (460 Hz) *E-6	χ_{hf} (4600 Hz) *E-6	(χ_{lf-hf}/χ_{lf}) *100
Ruin soils									
TZ 14	2.17E-003	0.006534	331.60	11.907	0.91589	5.496	2042.15	1852.09	9.31
TZ 15	2.18E-003	0.006036	360.34	9.537	0.94750	4.385	2056.56	1846.42	10.22
TZ 16	2.07E-003	0.006202	334.03	9.416	0.94764	4.545	1975.31	1773.63	10.21
TZ 16 (II)	2.27E-003	0.006136	369.95	9.911	0.94663	4.366	2163.23	1942.44	10.21
TZ 17	3.71E-004	0.006721	55.15	2.098	0.89993	5.659	349.58	328.75	5.96
Abila relikt	1.35E-003	0.005934	227.66	8.295	0.92028	6.140	1288.47	1181.12	8.33
TZ 6	8.60E-004	0.005821	147.74	4.488	0.94328	5.219	810.90	737.36	9.07
TZ 8	9.53E-004	0.005839	163.24	6.500	0.94643	6.820	1019.21	933.05	8.45
TZ 9	1.32E-003	0.005923	222.86	5.007	0.94854	3.793	883.48	800.84	9.35
AB4 – 2b	5.26E-004	0.005702	92.22	2.815	0.93047	5.353	496.57	449.3	9.52
Jer 6a	9.97E-004	0.005903	168.87	4.982	0.92606	4.998	944.82	862.41	8.72
Jer 5a	1.10E-003	0.005885	186.15	4.135	0.91973	3.775	764.27	699.51	8.47
Jer 4a	8.05E-004	0.005807	138.60	3.848	0.93423	4.781	735.81	669.56	9.00
Jer 3a	7.25E-004	0.005845	124.09	3.902	0.91437	5.380	681.87	623.46	8.57
Jer 2a	5.31E-004	0.005530	95.96	2.556	0.90593	4.816	487.16	442.7	9.13
Jer 1a	3.02E-003	0.004203	719.33	14.064	0.93539	4.652	2730.69	2465.46	9.71
Jer 0a	7.74E-004	0.005527	140.04	7.485	0.94700	9.670	1220.55	1104.89	9.48

As can be seen, the best developed soils show the highest specific susceptibility χ . For example, the Jordan valley profile shows susceptibilities which mirror the field impression of alternating periods of soil development. The total susceptibility seems related to absolute soil development intensity, and, like expected from field observations, is most pronounced in Jer 10. The Jordan valley data indicate that the magnetic susceptibility is in fact the best parameter to assess soil development intensity. As discussed in the previous chapters, texture, calcium carbonate content and iron oxides show similar tendencies, but are more difficult to interpret due to the presence of chalk admixtures. But how can the higher susceptibilities be explained? "Magnetic enhancement" is common in topsoils (Thompson and Oldfield, 1986) and could be attributed to a variety of reasons (see Evans and Heller, 2003):

1. Atmospheric fallout of ash or other deposition of magnetite-bearing material.
2. Natural fires that caused thermal transformation of weakly magnetic iron oxides (especially hydroxides) to magnetite or maghemite in the presence of organic matter (Cornell and Schwertmann, 2003).
3. Inorganic formation of ultra-fine grained magnetites by oxidation of Fe^{2+} to ferrihydrite and magnetite at room temperature and near-neutral pH, due to transfer of electrons from decomposing organic matter under highly variable redox conditions and strongly changing soil moisture (Maher and Taylor, 1988).

4. Bacterial metabolism producing extracellular ultrafine magnetite grains under anaerobic conditions in periodically waterlogged soils, or intracellular magnetosome formation by magnetotactic bacteria under more oxygenated conditions in topsoils (Faßbinder et al., 1990).
5. Weathering of iron-bearing minerals due to wetting and drying cycles with ferrihydrite formation under presence of organic matter. Iron-reducing bacteria utilize ferrihydrite as terminal electron acceptor in their fermentation mechanism, so that partial dehydration and reduction of ferrihydrite to magnetite will take place in the presence of excess Fe^{2+} . Magnetite might later be oxidised to maghemite (Dearing et al., 1996).

All possible processes except addition of foreign material are connected with organic matter, and – apart from fires – with release of Fe^{2+} and ferrihydrite formation. The last point seems the most important for soils of the Decapolis region, as it is essentially the same process that leads to rubefication. According to Cornell and Schwertmann (2003), maghemites are widespread in subtropical soils because of the frequent occurrence of vegetation fires in these latitudes. Magnetic enhancement due to heating under presence of organic matter would be associated with corundum ($\alpha\text{-Al}_2\text{O}_3$), which is a product of Al-compounds exposed to high temperatures. Heating would also lead to hematite formation, which is shown by fire places in northern Europe where hematite is otherwise absent. Since ferrihydrite and hematite have rarely been observed together, Weng et al. (2006) thought the fire idea a step further. They postulate that red soils are the result of vast fires, possibly associated with the impact of meteorites, but that the red colour was later lost due to xanthization in moist climates with lots of organic matter.

Although the presence of corundum could not be investigated, the evidence available from the top of Tell Zera'a (sample TZ 6) does not suggest an important contribution of fires to magnetic enhancement or red soil colour in the investigation area. A forest fire might produce higher temperatures than the frequent burning of thistles and maquis on the tell. However I think that iron weathering under drying and wetting cycles, and in association with organic matter, fits so well to conditions in the Decapolis region that it is not necessary to look for another explanation for magnetic enhancement. In the case of paleosols on the Chinese loess plateau, pedogenesis led to enrichment of magnetite to 0.17% of the total soil mass – compared to 0.021% of geogenic primary grains in the loess (Evans and Heller, 2003). But this tiny enrichment led to an increase of the magnetic susceptibility by 400%, which illustrates the relevance of magnetite for susceptibility. Much more hematite is present in the loess (~1%), but as discussed above, would be significant for the magnetic properties only if magnetite and maghemite are missing. The smallness of pedogenic magnetites in the Chinese loess is

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indicated by the remanence acquisition behaviour, because differences are only visible in fields up to 100 mT – another clear indication for a pedogenic origin of magnetic enhancement.

Hydrolysis and dissolution of Fe^{2+} , as well as the presence of organic matter, are closely connected with precipitation. The production of new magnetite and maghemite during pedogenesis may thus semi-quantitatively reflect precipitation. In fact, Heller et al. (1993) and Maher et al. (1994) used susceptibility and ^{10}Be -content for reconstructions of

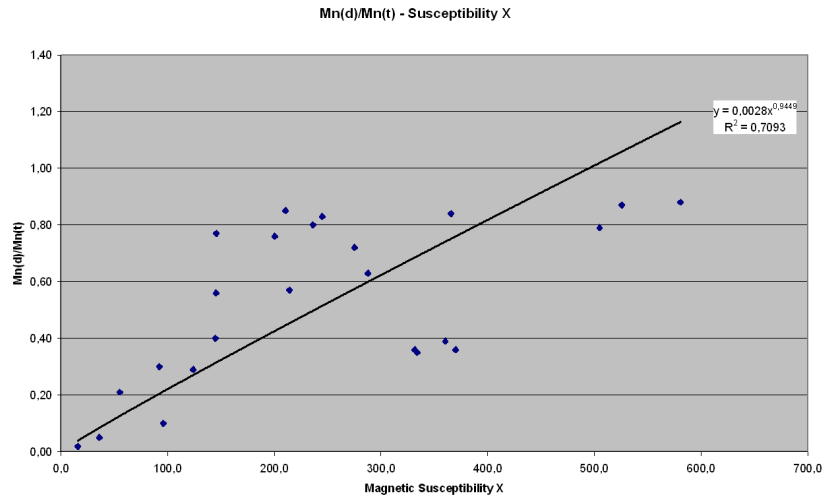


Figure 39: Positive correlation of Mn_d/Mn_t and Susceptibility.

paleorainfall on the Chinese loess plateau. In the case of the Decapolis region, it is very remarkable that from all investigated soil parameters, the Mn_d/Mn_t -ratio shows the strongest positive correlation to the specific susceptibility χ (after removing the impossible Mn_d/Mn_t values >1 , fig. 39). Manganese has no relation to magnetic properties, but the Mn_d/Mn_t ratio seemed the best indicator for soil age (see chapter 4.3.2). This indicates that the high susceptibilities of the paleosols are inherited from moister periods of stronger pedogenesis and vegetation cover. The correlation to manganese oxides lets not only process 5 (weathering of iron), but also processes 3 and 4 (organic and inorganic magnetite formation) seem possible, as they are connected with periodic waterlogging which might be related to high extractable manganese.

The next strongest correlation of the specific susceptibility χ is negative to calcium carbonate content (fig. 40). Increasing calcium carbonate contents are always associated with diminishing susceptibilities. As sample TZ 54 illustrates, the chalk is characterised by a very low

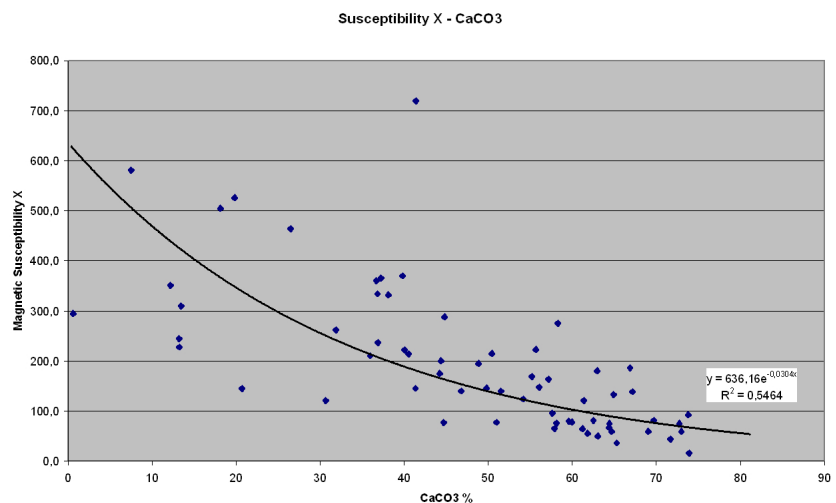


Figure 40: Negative correlation of Susceptibility and CaCO_3 .

susceptibility, low remanence, and a S-ratio which points to a magnetite:hematite ratio of 1:100. Since its SIRM/ χ is small, and the ratio $(\chi_{lf-hf}/\chi_{lf}) * 100$ is relatively high, it seems however that the chalk's weak magnetisation is mainly carried by small magnetite and maghemite grains. It probably formed with some weak pedogenesis in connection with the agricultural activities on the chalk, which are also indicated by the high phosphorus content. It would be interesting to compare this sample with some deeper sections of the chalk, since magnetite could also be inherited from iron oxide deposition during sedimentation of the rock.

In all samples, susceptibility shows only a weak correlation positive to pedogenic iron Fe_d ($R^2=0.3953$). The positive correlation to Al_d ($R^2=0.4297$) and Al_o ($R^2=0.5478$) is better. The susceptibility's positive relation to the modified iron weathering index is even worse ($R^2=0.2994$), and there is no connection with the unmodified Fe_d/Fe_t index. As well, there is no correspondence to the base accumulation index or texture. Since susceptibility is connected with iron-bearing minerals (Evans and Heller, 2003), this missing relationship might come as surprise – but in the case of the soils in the Decapolis region, it only confirms the impressions from the iron oxide analysis (chapter 4.3). Varying inheritance of pre-weathered iron from the sedimentary rocks, as well as deposition of foreign iron-bearing clay minerals, skew the relation of iron minerals to susceptibility. As well, magnetite is only partially extracted by sodium dithionite (McKeague et al. 1971).

The magnetic analyses very clearly support the conclusions from the previous chapters: pedogenesis was stronger in the paleosols, and soil maturity reduced by local chalk additions. A role of the source rock is also indicated. The basalt soil UQ 9 shows a medium susceptibility, with a medium S-ratio of 0.93816 which points to a magnetite:hematite ratio of approximately 1:7. It has however one of the highest SIRM and SIRM/ χ , and the second smallest $(\chi_{lf-hf}/\chi_{lf}) * 100$ (after the desert soil). This points to large multidomain magnetite grains as carrier of the magnetisation, which are inherited from the basalt.

In contrast, sample Feldsys 2 has a $(\chi_{lf-hf}/\chi_{lf}) * 100$ twice as high, a SIRM/ χ of less than half, and magnetite/hematite ratio of approximately 1:6. Magnetic properties of Feldsys 2 seem to a much larger extent characterised by pedogenic magnetic minerals. Since this soil is situated in a similar relief as UQ 9, its higher susceptibility and pedogenic magnetite could be attributed to the slightly elevated precipitation, if this applies to the Pleistocene paleoclimate as well. It could however also be taken as indication that the limestone soil is older than the basalt soil.

The absolute susceptibilities seem related to the relief: depressions are characterised by the highest susceptibilities in the subsoil, and a strong decrease in the upper parts. As it seems, depressions on the one hand gathered water and magnetic minerals from slope wash when pedogenesis was more

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intense in the area, and were probably also characterised by more abundant vegetation and organic matter. With increasing aridity however, the valleys saw increased sedimentation of weakly magnetic chalk and calcareous dust. Therefore the susceptibility of the plateau soils is today higher than that of some wadi soils, and all upper soil horizons in the wadis are magnetically depleted. The exceptional high susceptibility of the Beit Ras colluvium might be explained with the steep slopes and the fact that most of them are covered with caliche, which would reduce the share of weakly developed chalk while providing maximum slope wash of magnetically enhanced topsoil.

Although it is not possible to correlate susceptibility to total iron or titanium contents, there are some interesting tendencies inside single profiles. As can be seen in figs. 41 and 42), total iron and titanium contents show very similar distributions and trends with regard to susceptibility. This points to the

presence of titanomagnetite (Fe_2TiO_4 – one or more iron atoms in magnetite (Fe_3O_4) are replaced by a Ti atom). Titanomagnetites mostly occur as residual primary grains in soils, and point to the presence of volcanic material (Milnes and Fitzpatrick, 1989, Evans and Heller, 2003). Their contribution to the magnetic susceptibility is however lower than that of magnetite, due to different magnetic moments of Fe^{2+} in the crystal structures (Milnes and Fitzpatrick, 1989). Under the assumption that all titanium is bound in titanomagnetite (which is of course very unlikely, but delivers a reference for the relative abundance of the element), the maximum amount of iron bound in titanomagnetite was calculated. The surprising result – despite the strong variations of absolute Fe_t - and Ti-contents – was that the *relative* amount showed little

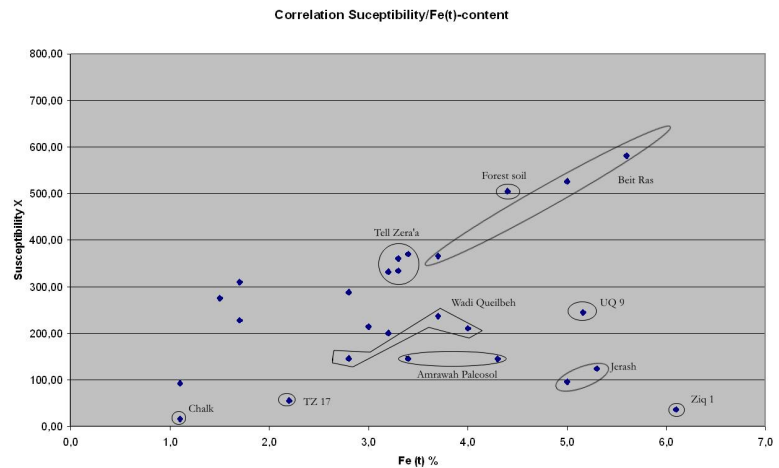


Figure 41: Pattern of total iron contents in relation to susceptibility.

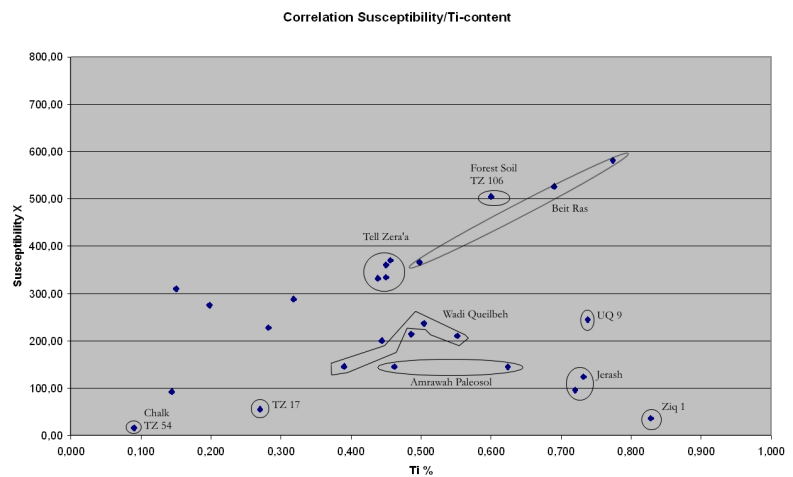


Figure 42: Pattern of titanium contents in relation to susceptibility.

variation. Most samples were characterised by 27-29% of maximum titanomagnetite contribution to total iron content. It was slightly elevated to 32-33% in the supposedly oldest paleosols (AB 9 and AB 7), and in the Jordan valley paleosol (Jor 10), and strongly elevated to 37% in the Irbid soil. The chalk sample TZ 54, the Wadi Ziqlab paleosol Ziq 4, and the subsoil in the Irbid basin fell out with values of 20%. Chalk additions might be the reason why the relic mudbrick and soils in the bottom of the Wadi-el Arab and Wadi Ziqlab had slightly reduced values of 25%.

Titanomagnetite grains of fine to medium sand size were detected in most soils with the scanning electron microscope (see chapter 4.6). While they are expected in the basalt soil, their presence in the limestone plateau soils is more difficult to explain. It could be connected with strong storms that were able to carry grains of this size over greater distances – which would also explain their homogeneous distribution. This points to a uniform *relative* contribution of primary magnetic minerals to susceptibility, and supports that the observed differences are mainly due to distinct pedogenesis intensities. In the Yarmouk-profile (AB 1-3), the decreasing susceptibility in the upper horizons is associated with rising SIRM/ χ -values, which might be connected with an increasing contribution of primary magnetite grains (deposited during storms?) to susceptibility.

Apart from the gravel content, magnetic properties seem best suited to examine the otherwise fairly unstructured sediments of Abila's Roman bridge. They show low susceptibilities with little variation. The low levels might be due to the reducing influence of water from the perennial stream which was flowing there until the advent of modern pumping. As well, the field evidence suggested that Brücke 0 and 1 might have been affected by standing water and thus reduction of iron oxides and reduced susceptibilities. These sediments are however very similar to the rest of the profile, and to other wadi sediments like in the upper part of Wadi Ziqlab or at the foot of Tell Zera'a. I interpret this similarity as a negligible role of the creek for iron oxide morphology of the bridge-sediments. It points to very little pedogenesis since construction of the Roman bridge, especially in comparison with the wadi paleosols like in the nearby Wadi Queilbeh profile. The slight highs of susceptibility at the bridge seem connected with periods of reduced water flow in the creek (Brücke 0, 1, 3-5), characterised by deposition of clay-rich material under partially standing water. Brücke 9 is also characterised by slightly elevated susceptibility, which indicates that pedogenic processes are active since the falling dry of the creek. Periods of good water flow, such as Brücke 2 and 7, are in contrast connected with lower susceptibilities, which indicates little sedimentation. The lowest susceptibility is present in the landslide of Brücke 6, which in its properties is closest to the chalk. The other magnetic parameters of the bridge sediments show too little variation to be of significance for interpretation. Only the S-ratio of Brücke 4 might indicate an increase of hematite in the magnetic minerals, but which has no equivalent in other

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soil samples and cannot be interpreted with regard to changed sedimentation processes. All in all, deposits at the Roman bridge seem to consist of a random composition of material in the vicinity, which might be due to deposition during flash floods. But the sediment which seems to resemble strongest erosion (Brücke 6) has the lowest susceptibility. One can conclude that erosion of Terra Rossa since construction of the Roman bridge was very low, if at all present. The deposited material seems best represented by soft chalk and Rendzinas from the valley's slopes. In comparison, strongly elevated susceptibilities in the clastic layers of the Dead Sea sediments (Migowski, 2004) might be connected with considerable amounts of Red Mediterranean soils eroded during the Yarmoukian landslides 6000-4500 BC, and at the end of the Early Bronze Age 2100-1500 BC.

Last but not least, a selection of samples was magnetised in steps and their remanence measured. The resulting pattern of remanence acquisition delivers indications for the contribution of magnetite, hematite and goethite to the magnetic properties of the soils, since magnetite acquires saturation remanence in fields of up to 200 mT, hematite in fields of approximately 200 mT to 2 T, and goethite only in strong fields of 2-10 T (fig. 43). This can however not directly be related to susceptibility, since

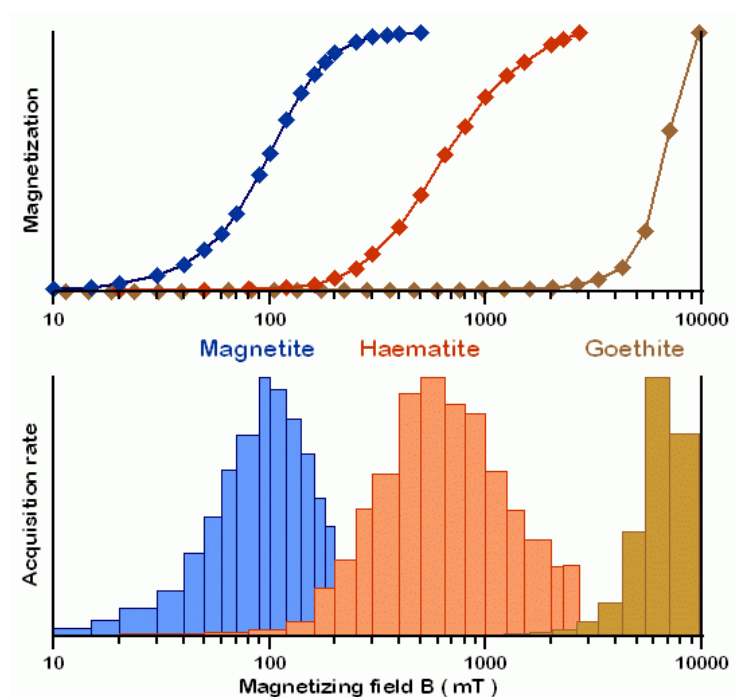


Figure 43: Typical remanence acquisition of magnetite, hematite, and goethite. From: <http://www.gfz-potsdam.de/pb3/pg33/facilities/pulsemagnetizers/index.html>, by N. Nowaczyk, with permission.

superparamagnetic particles do not acquire remanence at room temperature. Nevertheless, magnetite dominates the remanence behaviour of all samples, and as discussed above, may come from both pedogenic processes and primary minerals (fig. 44). The latter should be present in all soils as indicated by the presence of titanomagnetite. As already suspected (see chapters 4.2 and 4.3), goethite is present in the chalk sample T'Z 54. Its contribution to the total magnetisation is small – but as it seems nearly as high as the contribution of hematite. As well, the samples Brücke 4, Air 1, BR 14 and to some extent UQ 9 show some remanence acquisition by goethite. In contrast, the relevance of goethite in sample Feldsys 2 is lower. This is taken as support for the earlier conclusion that chalk and calcareous dust

deposition locally affected soils, which is connected with the CaCO_3 -content – and Feldsys 2 is not only CaCO_3 -free, but also characterised by the smallest relevance of goethite for remanence acquisition.

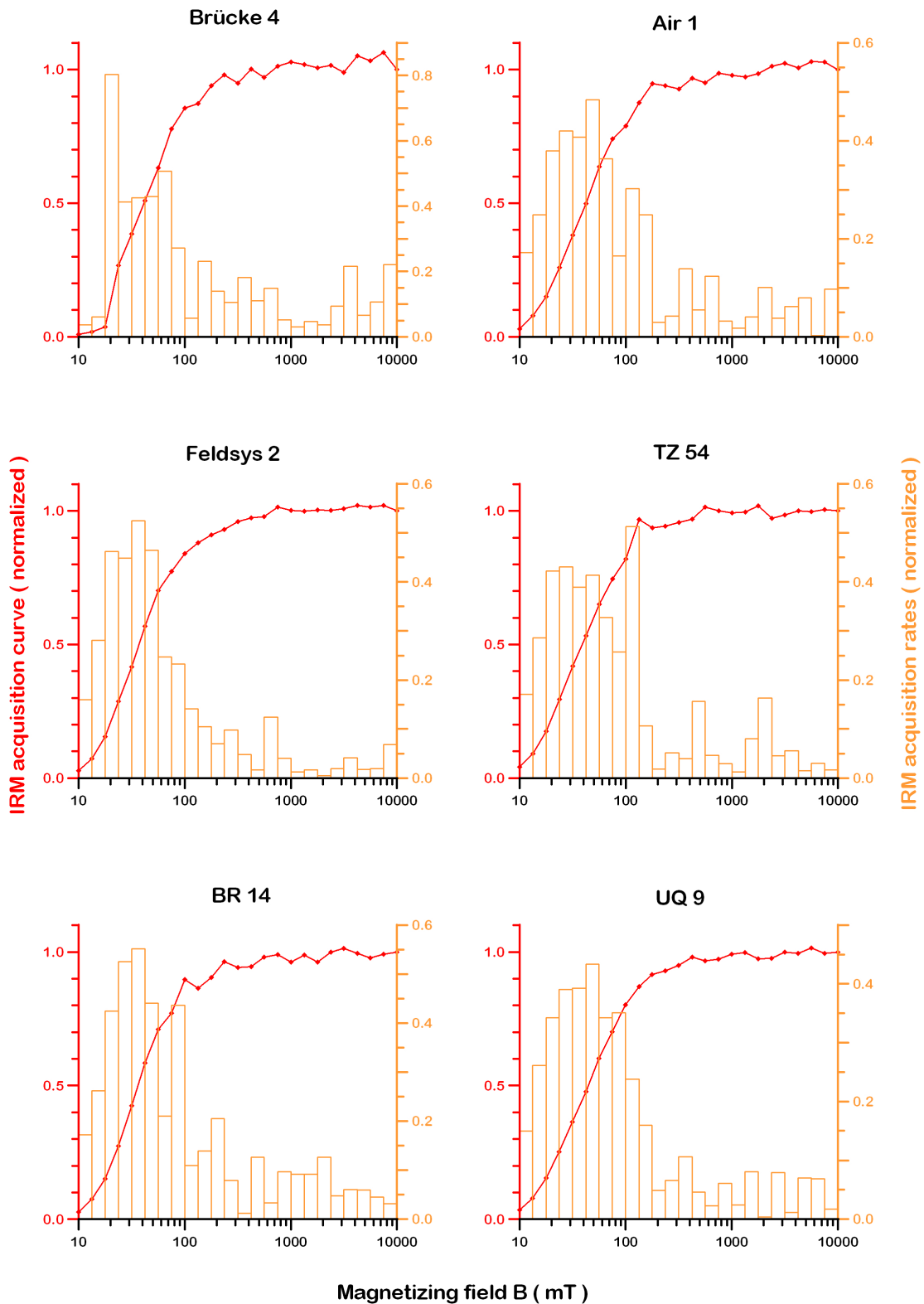


Figure 44: Remanence acquisition.

In summary, magnetic analyses seem to be an excellent tool for soil studies in Jordan. If connected with the field evidence, susceptibility well reflects pedogenesis and ash deposition such as sample Jer 1a. The magnetic studies confirm the earlier conclusion that pedogenesis was stronger in the past, and reduced by increasing aridity and chalk additions. In soils where soil development was never interrupted by quick deposition, such as Feldsys 2, slightly lower susceptibilities than in the paleosols are observed which might be related to some incorporation of foreign material as suggested by Gvirtzman and Wieder (2001), but which is not reflected by other parameters. Finally, there is a potential to utilise susceptibility for paleoclimate reconstructions, as demonstrated by Heller et al. (1993) and Maher et al. (1994) for the case of the Chinese loess plateau. The methodology should work with sedimentary soils like in the Jordan valley or in the coastal plain of Israel, where the pedogenic susceptibility can be separated from approximate basic detritus susceptibilities. In the case of the Terrae Rossae and paleosols however, this will not be feasible as the soils are polygenetic and the studied periods too long. But considering larger areas, it might be possible to draw gradients of moisture and vegetation distribution with regard to the relief and paleoprecipitation. Since magnetic measurements are comparatively easy and fast, they should be applied more widely.

4.6 Thin sections and element mapping

Thin sections were prepared from a selection of samples in order to evaluate whether there are textural differences between the paleosols and present soils, to check whether clay cutans could be observed, and to further check the reliability of the untypical rock fragments found under the binocular, using a scanning electron microscope (SEM) combined with energy dispersive analytics (EDS). The latter was examined in a soil covering the ruins of the Umm el-Amad basilica in Abila.



Figure 45: Soil/debris cover on fallen basilica stones.

Here, about 20 cm of loose, grey debris covers fallen stones of the basilica wall. It has a bulk density of 0.9 g/cm^3 , which is significantly lower than that of Terra Rossa (1.6 g/cm^3 according to Purschke, 1990), and is easily blown away when disturbed e.g. by excavations. As well, the pattern of well-hewn stones seems to indicate that the basilica fell before the surrounding debris was deposited (fig. 45). It

however consists not only of fine grey soil, but is mixed with numerous small broken stones, pottery, glass and bones. The rather random distribution of debris led Lucke (2002) and Schmidt et al. (2006) to the conclusion that it represents remains of mortar and other materials used for construction of the city. If however the majority of the soil covering the ruins came from Saharan dust deposition, it would have been very considerable during historic times. 20 cm dust, even if not significant for agricultural productivity, would be more than average deposition on the Chinese loess plateau, one of the most active loess regions in the world (Heller and Liu, 1982).

Microscopic as well as SEM investigation of the thin sections however clearly showed that the debris covering Abila's ruins is not related to long-range aeolian deposition (fig. 46). It consists mostly of microfossils from chalk, bone and pottery fragments, and sharp angular calcite pieces. A small garnet fragment was discovered and interpreted as remains of gems from the basilica decoration. One well-rounded quartz grain may represent some aeolian activity, but may also have been released from the chalk.

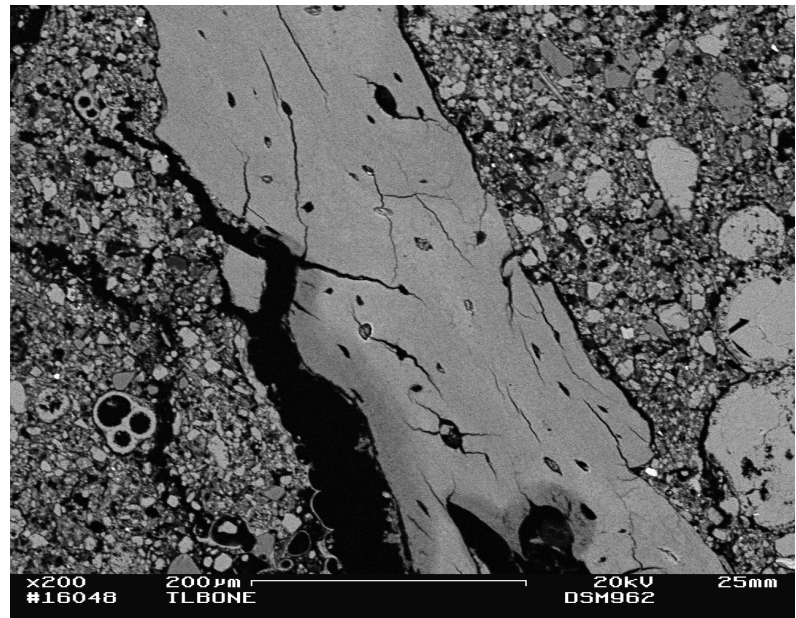


Figure 46: *Micromorphology of the debris covering the Abila basilica. A piece of bone is in the centre, surrounded by microfossils and calcite fragments.*

Titanomagnetite was not noticed. In summary, the debris comes from mortar and broken stones, and was washed between the fallen stones which created the present smooth surface of the tell.

As shown under binocular, the basalt soil on the Ard el-Ala contains quartz-grains of fine and medium sand size. Since quartz is not part of the mineralogical composition of basalts, this might indicate aeolian deposition. Apart from that, this soil sample was characterised mainly by calcium-rich feldspars (plagioclases of andesine to labradorite composition), and by some Fe- and Ca-rich aluminosilicates. The clay mineral composition can be derived from the weathered basalt: Mg and Fe come from olivine and pyroxene, and Al mostly from feldspars. All three form the main components of the basaltic source rock as was confirmed in a thin section of the basalt. This also showed some calcite-filled fissures. Allochthonous clay minerals with K or Na could not be observed. Clay cutans were missing, too, although some initial skins had formed at some calcite pieces. The soil contained organic

4. The soil evidence

remains that looked like worm excreta, and many small charcoal pieces. Si and Ca were mostly finely dispersed and seemingly bound in clay minerals. Some fine and medium sand-size titanomagnetite was well visible in the back-scatter mode (BSE) of the SEM, where minerals consisting of elements with a high atomic weight appear brighter than others. A surprising discovery was however K-feldspar of fine and medium sand size, which is interpreted to belong to an unknown granitoid source rock confirming the observations under binocular, and which is not present in the investigation area (fig. 47). The nearest possible source is 400 km south in the Wadi Araba and at the Red Sea. Like the quartz grains, these feldspars seemed weakly rounded, which may indicate fluvial

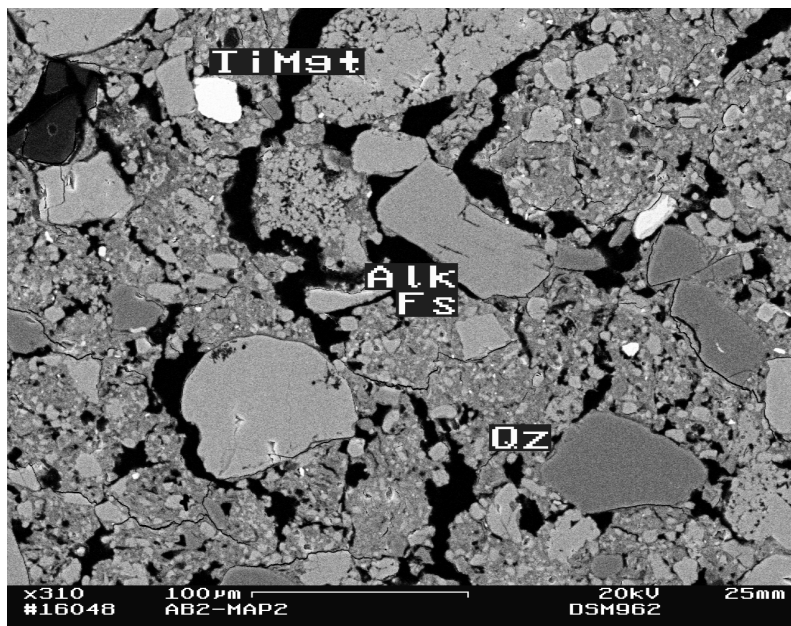


Figure 47: Sample AB 2 viewed under the SEM in the BSE-mode, showing fragments of quartz, K-feldspar and titanomagnetite.

transport. To further investigate this, a quartz grain surface analysis was performed. Sand-sized grains were separated from sample UQ 9 (ca. 100 g) by washing and sieving the fractions < 250 and > 63 μm . The remaining fraction > 250 μm was then boiled in 18% hydrochloric acid for 20 min and dried in an oven overnight (50°C). Further dry-sieving was not necessary as the remaining sand-sized fraction was of < 5 g, so that it could easily be viewed under a binocular. The selected grains were mounted on aluminium stubs and gold-palladium coated for examination in the SEM. The quartz grain samples as well as the polished and carbon-coated thin section were examined and analyzed with a Zeiss SEM (DSM 962), equipped with an energy-dispersive system and a NORVAR Si-Li detector (Thermo Fisher Scientific).

It turned out that as well the degree of roundness (angular to subangular) and grain size (medium-sand to fine-gravel size) of the K-feldspars and fragments of granitoidic rocks cannot be explained by a long-distance aeolian transport within dust clouds. In contrast, as a preliminary result, the surface analysis of quartz grain (fine to medium sand-sized) reveals the effect of aeolian abrasion of different intensity. The rounded to well-rounded ones seemed to come from sand dunes. The next modern dunes, however, are located at the Mediterranean coast, some 150 km away. Interestingly, the aeolian features cover older microtextures that indicate high-energetic collisions between angular

particles of different sizes (figs. 48). The paleosol AB 7 in the Yarmouk-profile yielded no K-feldspars and titanomagnetite, but few strongly weathered quartz grains. Well-rounded quartz was however observed in limestone fragments in the soil and might well come from the sedimentary source rock. Element mapping showed that K was nearly absent. Clay minerals in the matrix are characterised by Si, Al, Mg, Fe and Ca. There were many limestone fragments which showed microfossils, but calcite fragments like in the basalt soil were not so ubiquitous. While in the thin section some layering of the soil seemed to be imaged, closer examination with the SEM could not confirm any orientation or incipient cutans. AB 7 may be taken as indication that deposition of K-feldspars, quartz and titanomagnetite occurred only after the deepest paleosol in the Yarmouk-profile had been covered by some of the upper horizons. In this context, OSL (which is based on quartz or feldspar) may not work with the oldest paleosols as well as it did with the upper layers, which produced very strong signals.

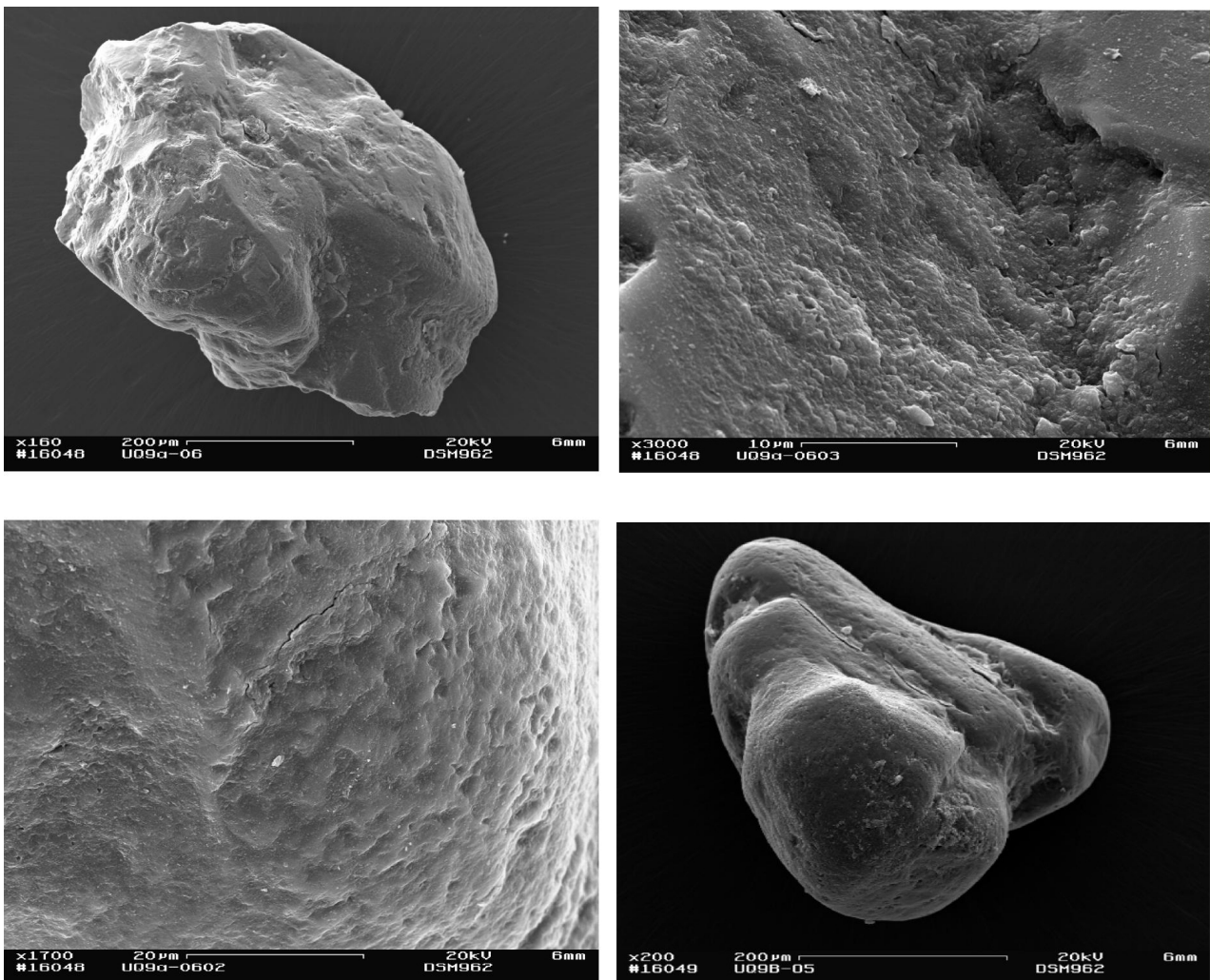


Figure 48: Features of quartz grains under the SEM. Older large fracture planes and impact features indicating collision with particles of different size were partly deleted by aeolian surface abrasion. Typical aeolian small V-pits (upper left), and a so-called orange peel developed (lower left). Partly, the surface shows small uplifted silica plates, also caused by constant percussion (upper right). To the lower right, aeolian well-rounded grain with bulbous edges.

In AB 2, 250 cm above in the same profile, the pattern has changed. Now quartz is abundant, as well as alkali-feldspar and titanomagnetite. Also, many calcite fragments are present, but limestone remains with microfossils are rare. The matrix again consists of clay minerals with Si, Al, Ca, K, Mg and Fe. Charcoal and bones point to land use activities.

The Abila fields looked very similar to AB 2. In field 1 (AB 1-2 2), quartz, K-feldspar and magnetite are abundant, as well as snail shells (fossils?) and fragments of caliche and limestone. Many small pieces of bone and charcoal indicate intensive land use, possibly connected with deposition of garbage and manure. A lot of organic remains (mainly roots) were also visible. There was no difference between field 1 and 2 in the thin sections – the colour variations cannot be explained by micromorphology.

4.7 Summary of soil evidence

It can be summarised that soil laboratory analyses confirm and refine the interpretation from the field. As it seems, *Terrae Rossae* in the Decapolis region are very old soils, and formed out of three parent materials:

- the underlying source rock
- local chalk dust additions
- long-range aeolian deposition of clay minerals

It is not yet possible to quantify the contribution of each component. Chalk additions seem to vary locally and to depend on the soil's position in the relief. Since the end of the Ice Age, these additions have either grown, or were less well incorporated into the soils due to increasing aridity.

The contribution of the bedrock would be minor if only consisting of the non-calcareous residue, since most of the limestones are very pure. But isovolumetric growth of clay minerals out of a supersaturated solution in the bedrock would lead to a 1:1 replacement of rock with soil, and produce acids which could explain the karst features of the limestone. If isovolumetric replacement is connected with setting free of the non-calcareous minerals of the bedrock, it would well explain the pattern of soil distribution in the Decapolis region.

The mineral replacement requires the presence of aeolian dust. Saharan dust in the area has been confirmed by numerous studies, and its deposition seemingly was most intense during the last Glacial and the Younger Dryas. Issar et al. (1987) suggested that heavy sand storms occurred during this time, too, which is possibly indicated by abundant quartz, K-feldspars and titanomagnetite in soils

of the Decapolis region. In contrast, aeolian deposition during historical periods seems very limited.

There is no indication that Terra Rossa was eroded during history. Younger colluvia consist of weakly developed chalk from the wadi slopes. In this context, manganese oxides and magnetic susceptibility are best suited for assessing soil age and maturity, since pre-weathered iron in dust and the calcareous rocks skews results from iron oxides. The presence of manganese oxides and the strongly elevated magnetic susceptibilities in depressions point to much moister conditions in the past, possibly connected with periodic waterlogging.

While man may locally have altered soils, and probably contributed to local additions of calcareous dust, climate and the geological pre-disposition are decisive for landscape development. If confronted with climatic change like during the Younger Dryas, it is likely that none of the present land use systems will survive.

5. Air photo evaluation

*Throughout Egypt hail struck everything in the fields — both men and animals;
it beat down everything growing in the fields and stripped every tree.*

Exodus 9:25

*The locusts covered all the ground until it was black.
They devoured all that was left after the hail —
everything growing in the fields and the fruit on the trees.
Nothing green remained on tree or plant in all the land of Egypt.*

Exodus 10:15

The earliest air photos of the region date from 1918 and were taken by Australian and German pilots during World War I. Starting in the 1950s, the coverage became more regular when the Jordanian air force conducted several aerial mapping missions. As well, historic CIA spy images from the CORONA satellite were recently declassified⁶. Today, the region can freely be observed using Google Earth⁷ with an already good resolution, and expensive state-of-the-art satellite systems offer images of excellent quality for purchase. Yet, already the old air and satellite images are of good quality – and provide a historical context.

Since this thesis is not focused on remote sensing, the technology shall not be discussed in detail. It should only be mentioned that most of the WW I air photos are oblique, which means they are not focused in 90° to the ground. Therefore they show the landscape in three dimensions, which is a disadvantage for drawing maps, but very helpful for optical identification of features like field systems. Unfortunately, the WW I air photos are scattered over the world, and an unknown amount was lost. Recently, so far unknown collections appeared in the Packard Institute of the Humanities in Los Altos (PHI), California, and in the German Archaeological Institute in Berlin (DAI). I had the chance to study these as well as the known archives in Munich (Bavarian War Archive⁸), Greifswald (Gustav-Dalman Institute) and the pictures of the Australian War Memorial⁹. As it seems, the coverage during WW I was much better than expected, and it can be hoped that more pictures will be rediscovered in the future. For example, a photo map of the Jordan valley appeared in the PHI, and pictures of Umm Queis in the DAI (which was thought to have never been photographed). Although unfortunately only few photos are available for the area examined in this thesis, they allow for many conclusions regarding old land use systems, and evaluation of early travellers' reports. For the younger past, the support of the Royal Geographic Center of Jordan made it possible to collect frequent images of some areas (Umm Queis, Abila, Beit Ras, Irbid, Jerash, Madaba and Ajloun), which allow in combination with CORONA satellite images to document landscape development in steps covering basically every 8 years since 1954. Kedar (1999) followed such an approach on a much larger scale and published a fascinating review of landscape change in Israel since 1918.

Combined with soil and vegetation studies, air photos allow to select sites according to the greater landscape context which cannot be grasped on the ground. As well, the historic dimension makes it possible to focus e.g. on sites which were not affected by modern machinery and building

⁶ Available at: <http://edcsns17.cr.usgs.gov/EarthExplorer>.

⁷ <http://earth.google.com>.

⁸ Dalman (1925) provides a complete index and reference map of the images available in Munich.

⁹ Available online at: <http://www.awm.gov.au>.

activities. But only a selection of the above mentioned pictures could be evaluated for this thesis. The 1918 air photos play a key role since they show the land when it was still widely depopulated, and modern machinery had not yet been used. This can be illustrated with a set of three photos showing British troops movement on Madaba plains close to an unknown, ruined site that can very clearly be seen (fig. 49). What is remarkable with these photos is the total absence on any visible field system around to the ruined town. A well and rests of streets can be seen, as well as remains of buildings outside the town and trails crossing the plain, but no fields or signs of cultivation.

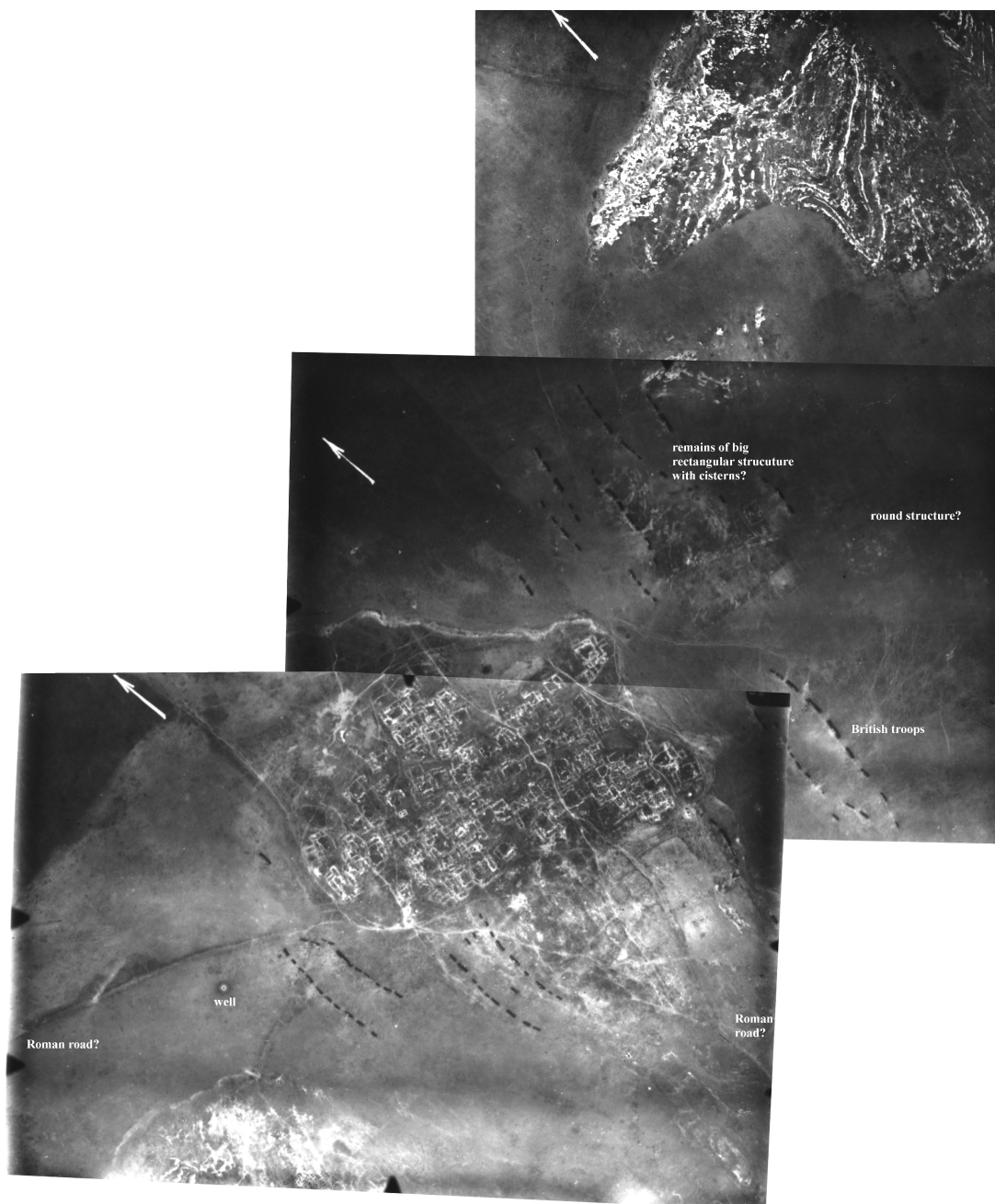


Figure 49: Unknown site on the Madaba plains. Collage of photos no. 1160, 1160a and 1161, Kefr el-Wasta/Kefr Abu Chinan, 3 km north of Madaba, May 1st 1918. Courtesy of Bavarian War Archive.

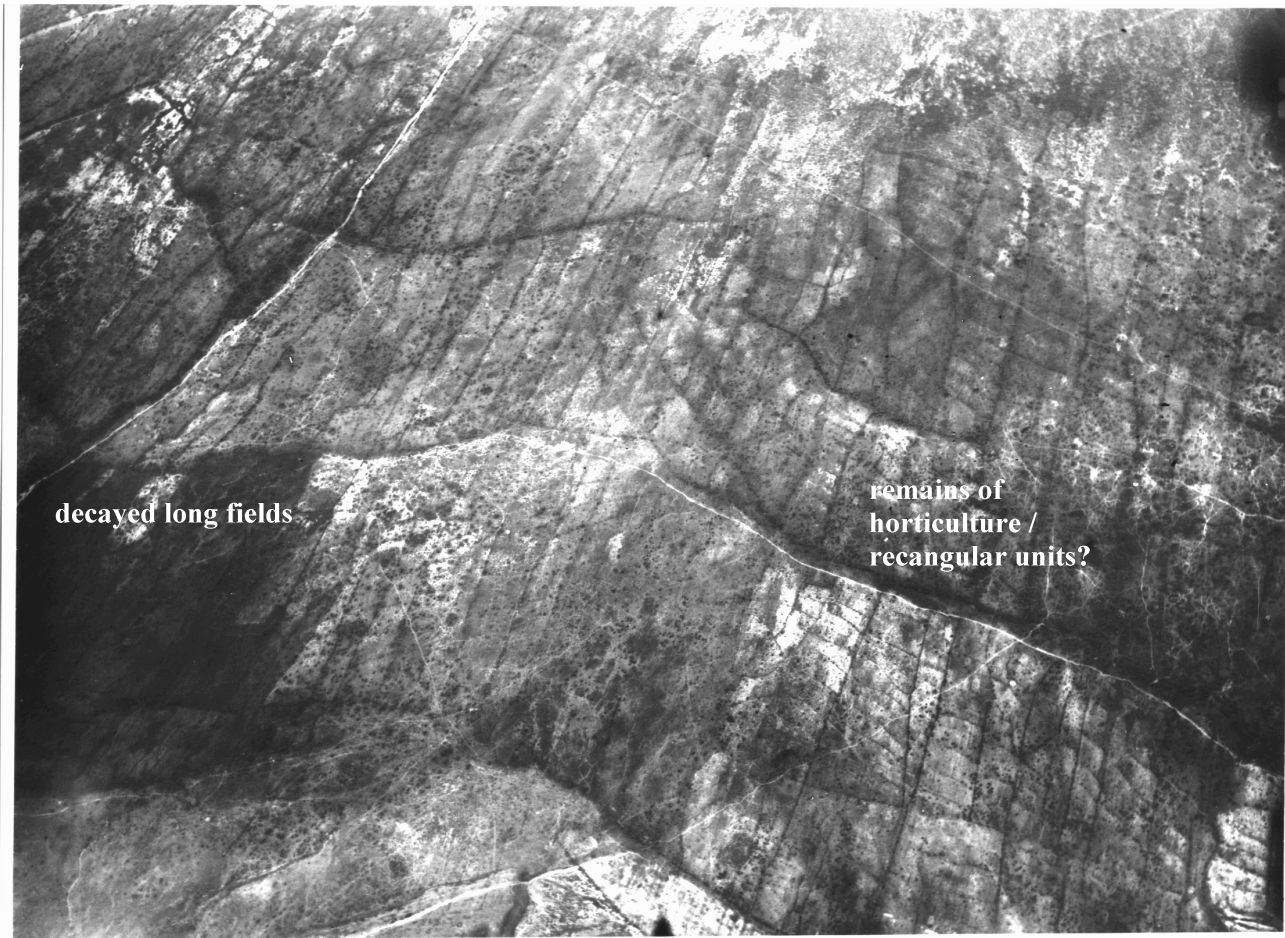


Figure 50: Abandoned fields south of Madaba. Their patterns are still well visible. Photo no. 1191, April 19th 1918. Courtesy of Bavarian War Archive.

This looks completely different on a photo taken not far away to the south of this site (fig. 50). Here remains of long strip fields are visible. Shrubs and bushes show that these are abandoned, however it is not possible to say since when the fields were laid idle. Unfortunately the nature of the field borders cannot be determined, whether they consist of small ditches, stone walls, different vegetation, small hedgerows or just shadowing due to small ridges. Air photos of Madaba (fig. 51) and Jerash (fig. 52) show similar field patterns. At Jerash, Circassians had been given land by the Ottomans in the late 19th century, and started to cultivate the ruins of the town and its vicinity. In the old town, horticulture is visible. The area is divided into rectangular field units that are separated into many small plots using field stones. This pattern seems to be present on the picture showing the abandoned field systems south of the unknown site, too, although the field borders are strongly decayed. In contrast, outside the towns of Jerash and Madaba only narrow long fields are visible.

In comparison, another 1918 air photo shows different field systems close to Ramallah in Palestine (fig. 53). Here the terrain is characterised by a network of field stone walls. Reflecting areas on top of the hills are threshing floors: the thin soil cover was turned into an advantage, since the cleaned

areas allow easier threshing and collection of the grain. The network of field stone walls looks similar to the remains of structures which can today be seen in el-Wustije, where the terrain also consists of hills although they are more gently sloping. These patterns were in fact already mentioned by early travel reports. This seems to apply even to the very details: for example, a photo taken of Salt in 1918

shows that some slopes close to the river are covered with many well-built terraces, while others on the other side are decayed. This looks exactly like reported by Seetzen (1854) from his visit to the Zarqua river in 1806.

And how is the situation today? Basically unchanged. Even though the terraces at Salt are now covered by the quickly spreading town, the same basic patterns as visible on the 1918 air photos can be observed on CORONA images and pictures taken by the Jordanian air force. For example, most fields are still strip fields. On the ground level, they are

separated by unploughed ridges, e.g. close to Abila. They are not very durable, and if the fields were abandoned, the landscape would soon look like the open plain visible around the unknown site south of Madaba. The absence of more durable field border remains indicates that they may never have been there. In contrast, the hilly areas like in el-Wustije show remains of at least two phases of land use (see fig.16, chapter 3). The long shadows of the evening sun show a pattern of narrow slope-parallel fields,



Figure 51: Aerial view of Madaba, September 11th, 1918. Photo no. 1182, courtesy of Bavarian War Archive.

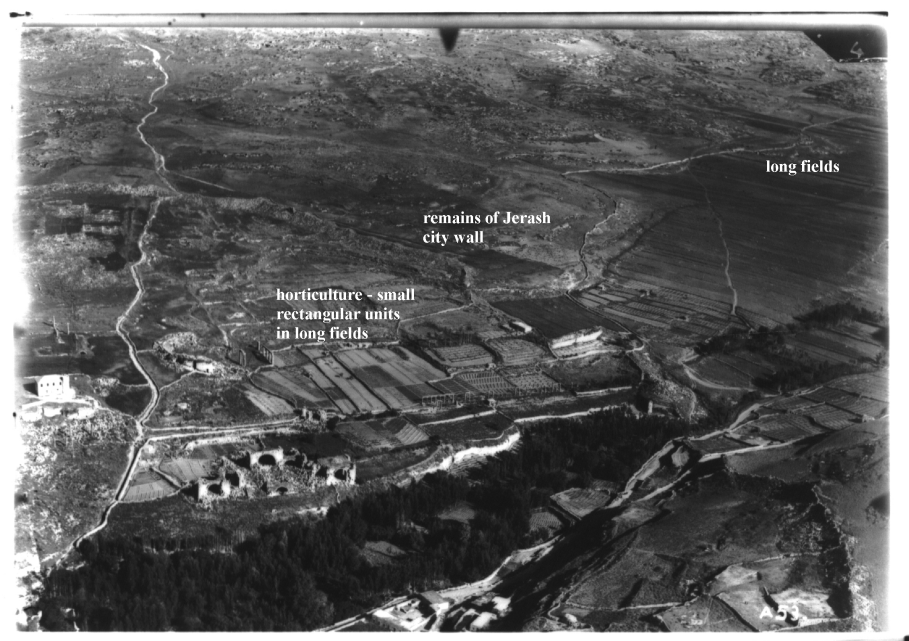


Figure 52: Aerial view of Jerash, April 9th, 1918. Photo no. 1129, courtesy of Bavarian War Archive.

5. Air photo evaluation

which is seemingly older than broader long fields crossing the slope and the slope-parallel fields. Interestingly, modern fields seem to re-use this pattern instead of constructing new fields which would



Figure 53: Well-maintained field stone walls close to Ramallah, January 3rd 1918. Photo no. 596, courtesy of Bavarian War Archive.

require more work and investment.

Land use systems seem to be strongly related to the terrain – while hilly areas are covered with a network of field stone walls, the level plains are ploughed with long narrow fields. In 19th-century Jerash, well-built field borders can be found close to the creek, seemingly connected

with irrigated gardens. Such walls were not only built to delineate property, but served a very practical purpose: they kept sheep and goats out (Schumacher, 1897). This is also why ancient roads like reported by Dar (1986) in Samaria, or like today still visible in Syria, were walled (fig. 54). So it was easy to drive herds through the countryside without damaging anyone's crops.

Ancient streets are an interesting feature since they are frequently mentioned by early travellers (Seetzen, 1854, Schumacher, 1890, 1897), but not visible in the countryside today. Close to Abila, Fuller (1987) observed a street with still intact pavement and field stone lines in some areas¹⁰. Yet, all that was left during my visit to the area in 2005 were varying concentrations of stones on the fields. Farmers reported their grandparents had seen the pavement still intact, but which was destroyed when tractors were introduced. One should however not expect a "pavement" of well-hewn stones like in the ancient cities. The roads reported by Dar (1986) from Samaria, or like still visible at the Dead Cities in Syria, rarely had a "real" pavement. They mostly took advantage of shallow soils or rocky areas, but were walled with field stone walls. So it is not surprising that the old roads at Abila can still be observed on air photos, where they are shown as a diffuse bright band (fig. 55) – and although only nothing more

¹⁰ A picture can be downloaded at: <http://users.stlcc.edu/mfuller/abila/AbilaSurveys.html>.

than stone concentrations can be seen on the ground, these still make sense when seen in the broader perspective of an air photo.



Figure 54: Ancient road close to the Dead Cities running parallel to modern street. Note the walls bordering the old road.

Unfortunately, the old field structures were not yet dated in the Decapolis, or investigated in relation to the material culture and soil properties. But we can refer to Dar's (1986) study of Samaria. There, no field divisions could be traced to the Early Bronze Age, but rectangular and irregular field systems were dated to the Early Iron Age (1000 – 586 BC) and the Hellenistic period. Long strip fields were introduced after the 2nd Jewish revolt and mostly belong to the Roman and Byzantine period¹¹. An interesting feature from a soils point of view is that small plots similar to the ones in Jerash had carefully been cleaned of stones, a situation still preserved in 1986. There was no re-use of some areas since the Byzantine period, which means this is another indication of how limited historic erosion and soil movement was. As well, most small plots were irrigated by cisterns, which confirms the impression from Jerash and lets me expect that cisterns can be found close to the small rectangular plots on the Madaba plains. After reviewing historic sources, Dar (1986) concluded that these areas must have been

¹¹ In contrast, Dalman (1932) argues that strip fields were already mentioned in the old testament.

allocated for vegetable cultivation, and provided an important part of the farmer's income.

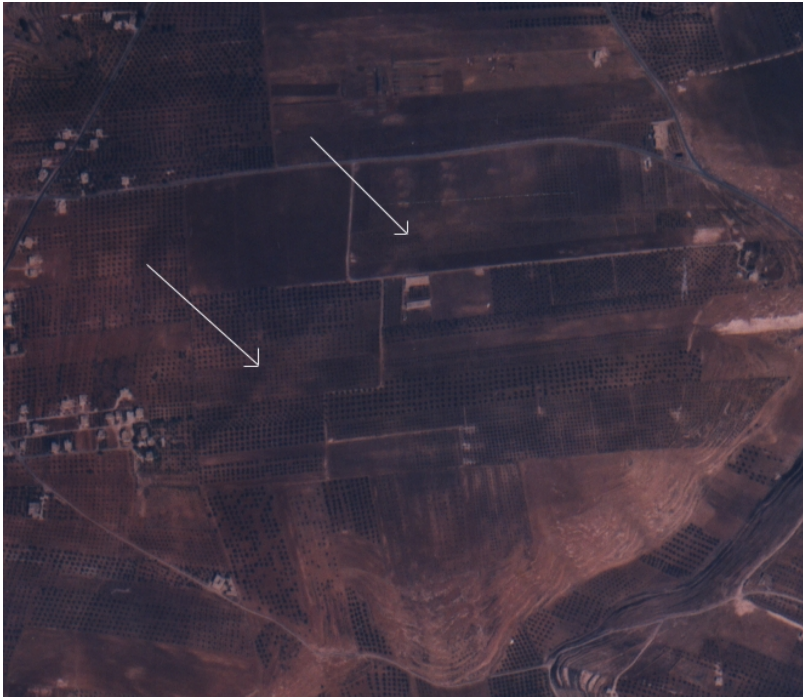


Figure 55: Remains of ancient road close to Abila. Photo no. 1456, taken in summer 2000. Courtesy of Royal Geographic Centre of Jordan.

Wine was grown in rock-cut boxes and trenches amidst rock areas, a pattern that I could observe in the area of the Dead Cities in Syria, too, and which might be related to numerous rock-cutting activities in the Decapolis region. So the rocks could on the one hand be utilised to channel water to the vines, while the grapes could on the other hand easily be harvested and stayed clean. Vine cultivation was also connected with the construction of field towers (Dar, 1986). These

towers posed an enigma to researchers for a long time, but their relation to vine cultivation is indicated by a number of reasons. They provided a stable temperature which is necessary for the fermentation process, sometimes with thicker southern walls to better block radiation. Chinks in the walls allowed evaporation of CO₂ from the fermentation, but made the towers unsuited for military purposes. As well, they operated like freezers and kept moisture which prevented quick dehydration of freshly harvested grapes. According to Dar (1986), small vineyards were of decisive economic importance during the Byzantine period. Agricultural towers had been constructed in the Decapolis region, too, for example on the Ard el-Ala (Riedl, 1998). They are however not as well preserved as in Samaria or the region of the Dead cities, because population growth and introduction of modern machinery in Jordan was much faster and intense.

It can be concluded that traditional Arab agriculture did not strongly alter landscape in the Decapolis region. This applies to forest as well: the suggested "deforestation" due to overgrazing and incursions of bedouins probably never took place. Historic travel reports show that a great part of the investigation area experienced a vast natural reforestation prior to 1806 (Burckhardt, 1823, Seetzen, 1854). While forest was quickly reduced during re-settlement in the late 19th century (Schumacher, 1890), air photos show that coverage improved again since at least 1963. This can be illustrated with a

series of air and satellite views of Umm Queis and vicinity, showing that the oak forest north of the town increased until the year 2000. This is especially true in the valleys where the water supply should be best (figs. 56 and 57). Forest seems to be well-able to regenerate naturally close to old stands. As there are strict laws protecting the trees since 1920 (Dalman, 1935), and as there is no need for firewood any more, the pressure on the trees has again decreased. This is in agreement with results from other parts of the Mediterranean: according to Hill et al. (2004), deforestation in Crete was postulated due to construction of

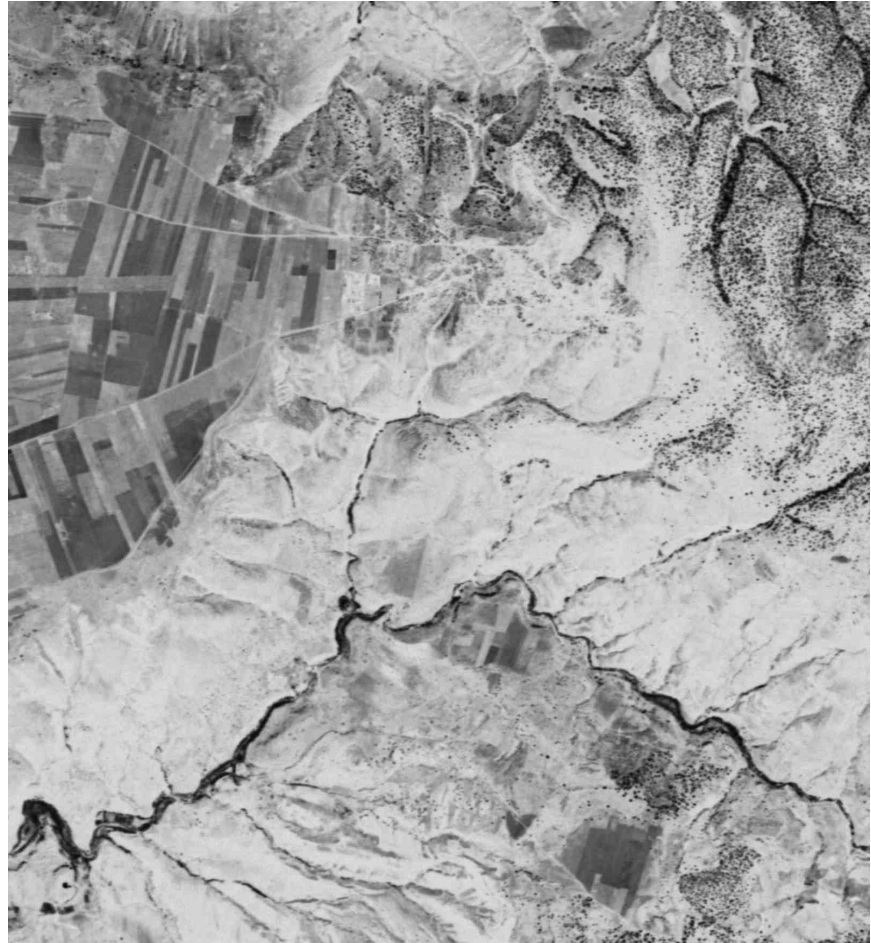


Figure 56: Forest coverage at Umm Queis (in the centre) in 1970. CORONA satellite image, courtesy of USGS.

streets into remote areas, and an increase of the sheep and goat numbers by 150%. But in fact, Landsat-pictures showed that forest coverage was stable during the last 20 years, especially in rugged areas which consequently suffer from a higher fire risk (Hill et al., 2004). In Jordan, one can observe the growth of the town Umm Queis and the beginning of excavations, but the photos also demonstrate that the basic field systems did not change. It can be concluded that deforestation, often mentioned as a growing threat and leading to desertification, cannot be confirmed for the Decapolis region. The opposite seems true.

Let us have a final look from the air on the varying field colours at Abila: the respective areas showed a colour difference only on one air photo. As it seems, differing soil moisture and vegetation mostly overrule the slight colour differences of the soil. Therefore structures as observed by Wilkinson et al. (2006) are most likely connected with soil skeleton and moisture. For the case of the Decapolis region, the example of the Roman road illustrates that it may be possible to use air photos for drawing

5. Air photo evaluation

virtual maps of past land use. This would have to be connected with detailed mapping of archaeological material on the ground. It can also be expected that the remote-sensing technology will provide additional tools in the future, especially if the non-visible wavelengths can be analysed. Hyperspectral scans from aircrafts allow already now to get a basic impression of soil properties (Ben-Dor et al., 2002), while different wavelengths of SPOT satellite images are useful for assessing vegetation cover¹²

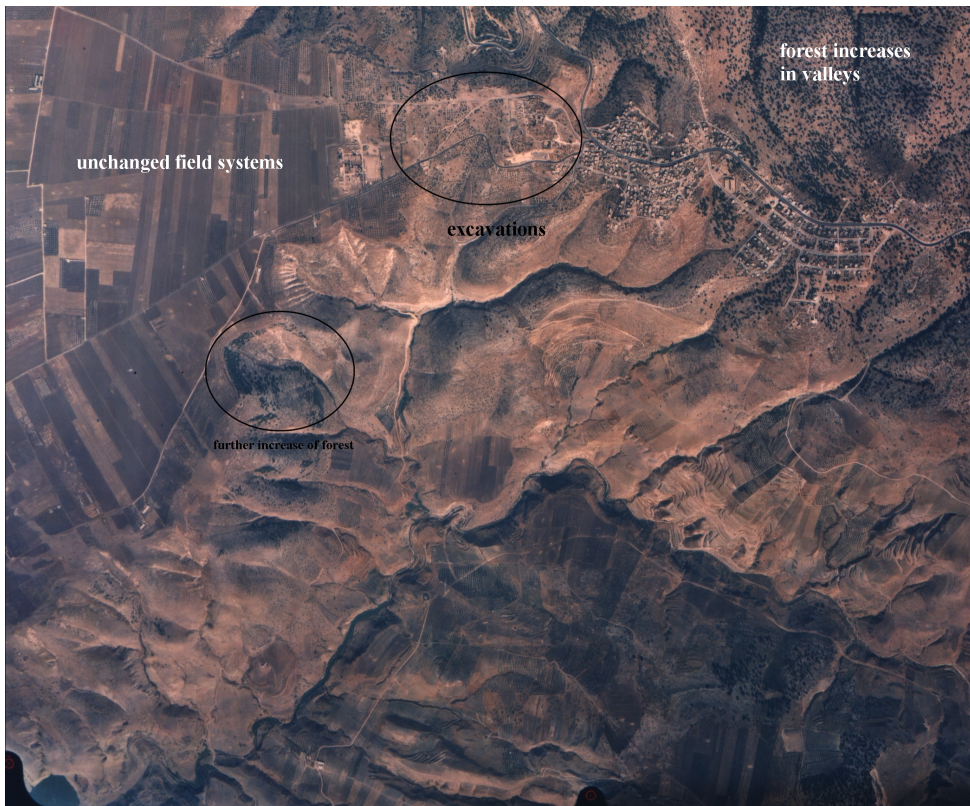


Figure 57: Forest cover at Umm Queis (in centre) in 2000. Photo no. 1517, courtesy of Royal Geographic Centre of Jordan.

It can be summarised that land use patterns in Jordan experienced pronounced changes since the introduction of modern machinery, but still refer to a basic pattern that might be very old. This contrasts sharply with the development in Israel (excluding the territories occupied after 1967, as Samaria). There a

modern, industrialised state-of-the-art agriculture introduced a completely new land use pattern without relation to the earlier structures (Richter, 1979). The old field systems were largely covered and removed, as well as many ruins of Arab settlements whose inhabitants had been displaced during the 1948 war (Kedar, 1999).

Agriculture in the Decapolis region is characterised by stability and diversity. Not traditional land use, but introduction of modern machinery led to landscape change. In this context, desertification is a matter of industrial agriculture, but not traditional grazing.

¹² See Stephen Savage's website for very useful information on GIS systems in Jordan, and freely available maps and satellite images: <http://archaeology.asu.edu/jordan/index.html>.

6. Forest, tree rings, and land use history

Vae victis!

The Gaul king Brennus, after the siege of Rome 390 BC

Forest in the Decapolis region today consists either of reforested pine, or oak associated with carob, whitethorn and some other Mediterranean trees. Fig. 58 shows the distribution of the natural climax vegetation in Jordan, and its relation to soils, average annual precipitation and altitude. Travellers reported that natural oak forest was widespread in the highland during the 19th century (Burckhardt, 1823, Robinson, 1837, Seetzen, 1854, Schumacher, 1890). It can still be found in rocky areas. There, it covers remains of small water channels, cisterns, wine presses and potholes, making clear that part of these areas had been cleared in antiquity. The forest observed during the 19th century is the result of natural reforestation, and the reports indicate that it was mixed with the remains of abandoned plantations (e.g. almond at the Zarqa river, "Mandeln groß wie Taubeneier", Seetzen 1854, p. 393). In some areas, giant old trees can still be found: e.g. oak in Wadi Ziqlab, ca. 600 years old, pistachio near Amman, approximately 880-1130 years old (Nueimat and Alkilani, 2002), or hollow olives in Wadi Kufranji near Ajloun, estimated to be older than 1000 years (pers. comm. with Kamal Nueimat, July 2005). These huge old trees were regarded sacred and served as burial places for local saints. People believed that spirits protect the trees, so touching them would bring misfortune and havoc. They also served as the first "banks", since material deposited in their shadow would not be stolen (Schumacher, 1890).

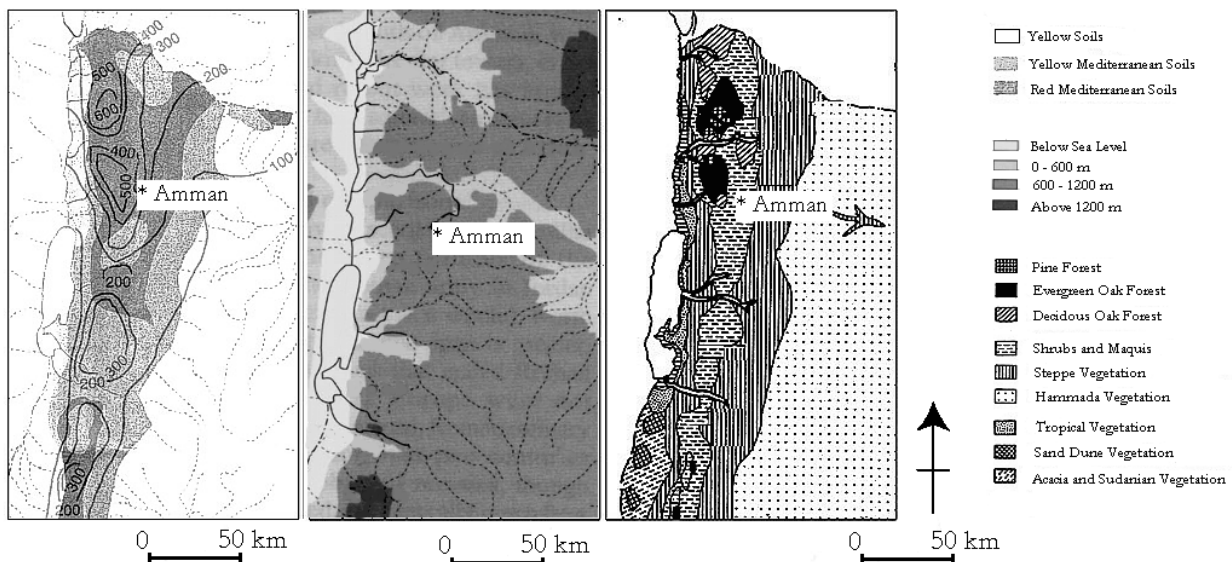


Figure 58: Map showing the soil distribution and average annual rainfall, altitude, and natural vegetation (after National Atlas of Jordan, 1984 and al-Eisawi, 1985).

It would be interesting to learn when the natural reforestation took place, and whether the trees can serve as climate archive. Local people regard the oaks as dating back to the "Romans": in the communities' memory, the trees were always there. With support of the Forestry Department of the Ministry of Agriculture of Jordan, an orientating study of trees in the investigation area was conducted

in 2004. The available driller was short, so it was not possible to reach the trees' centre, but the samples showed clear rings which allowed for some valuable initial interpretations (Lucke et al., 2007). Therefore additional trees were sampled in 2005 using longer drills whenever surveys and attempts to collect soil samples brought me close to remains of forest. 13 deciduous oaks (*Quercus ithaburensis* – "Ballût" in Arabic, while the subspecies *Quercus aegilops L. var. ithaburensis (Decne.) Boiss.* is called "Mallûl"), one evergreen oak (*Quercus calliprinus* – "Sindiân"), one carob tree (*Ceratonia siliqua*) and one chestnut (*Kastanea sativa*) were studied. The deciduous oak, carob, pistachia and whitethorn represent the natural climax vegetation of the area (al-Eisawi, 1985) and form a symbiotic alliance (Zohary, 1982). As well, two olives (*Olea europea*) and one mulberry (*Morus spec.*) were sampled as typical trees for plantations. Finally, one tall pine (*Pinus spec.*) from a reforestation was cored. Pine is probably a non-native tree, introduced only during the Roman period or later (Liphschitz and Biger, 2001).

The evergreen oak, carob and olive may produce false rings since their period of rest is not as pronounced as that of deciduous trees (Liphschitz, 1986). They showed however rings that were clear, sometimes clearer than those of the summer-green oaks. All evergreen shrubs and trees in the area replace their larger winter leaves with smaller summer leaves at the onset of the drier season and thus show wood differentiation (Zohary, 1982). I think with some caution they can be used for climate reconstructions, especially as the deciduous oak is not easy to analyse, too. Its earlywood pores in the small rings are sometimes hard to distinguish from latewood when the next earlywood follows immediately. Oak wood is very hard and most old trees are hollow. Hollows are a special problem, since if hit, they will make it impossible to pull a driller out of the tree. Due to the wood's hardness, the core may start turning inside the driller which makes it difficult to get a clear cut. As well, it was sometimes very hard to get the core out of the driller – it may come out in pieces and the bark can be lost, making it difficult to determine which is the last ring. Therefore the available drillers allowed only for chronologies of up to 100 years – special hollow-resistant equipment is needed for longer cores. In summary, tree ring studies in the area are possible and produce consistent results, but probably belong to the hardest type of this scientific exercise (pers. comm. with Uwe Heusser, DAI Berlin, February 2006).

After losing one driller in a hollow trunk, I focused on coring thick branches. Therefore the age of most trees can only be estimated. But the branches can be very thick, and are close to the ground since most of the trees show signs of past coppicing. Coring the branches can thus be turned into an advantage since it delivers an impression when the tree was last harvested. All trees were sampled twice.

6. Forest, tree rings, and land use history

Six areas were sampled: a summary is presented in table 22. Ages were estimated on the basis of the mean ring width and the trunks' girth – the age of the branches, which could mostly be determined exactly, is not given in the table. The tree-ring curves and growth rates can be found in the appendix. Here only the longest core shall be compared with the available rainfall measurements in northern Jordan.

Table 22: Summary of sampled trees.

Tree	Species	Coordinates	Area	Girth [cm]	Age [years]
Baum 1	<i>Quercus ithaburensis</i>	N 32° 31' 24.7", EO 35° 42' 40.8", 412 m asl	Wadi Ziqlab	374	~240
Baum 2	<i>Quercus ithaburensis</i>	N 32° 31' 45.0", EO 35° 42' 18.9", 331 m asl	Wadi Ziqlab	440	~100?
Seidur 1	<i>Quercus ithaburensis</i>	N 23° 37' 00.4", EO 35° 40', 53.2", 270 m asl	Wadi el-Arab	220	~208
Seidur 2	<i>Quercus ithaburensis</i>	N 32° 36' 58.6", EO 35° 40' 56.5", 295 m asl	Wadi el-Arab	210	~215
Seidur 3	<i>Quercus ithaburensis</i>	N 32° 36' 37.3", EO 35° 41' 59.3", 291 m asl	Wadi el-Arab	337	~345
Seidur 4	<i>Quercus ithaburensis</i>	N 32° 36' 45.9", EO 35° 42' 04.5", 311 m asl	Wadi el-Arab	110	~115
Seidur 5	<i>Quercus ithaburensis</i>	N 32° 36' 37.5", EO 35° 42' 04.1", 317 m asl	Wadi el-Arab	>177	>167
Tree no. 4	<i>Quercus ithaburensis</i>	N 32° 36' 53.6", EO 35° 41' 08.0", 321 m asl	Wadi el-Arab	342	~242
Tree no. 5	<i>Quercus ithaburensis</i>	N 32° 37' 00.1", EO 35° 40' 53.2", 288 m asl	Wadi el-Arab	220	~150
Tree no. 6	<i>Ceratonia siliqua</i>	N 32° 36' 55.9", EO 35° 40' 56.1", 304 m asl	Wadi el-Arab	123	~233
Tree no. 7	<i>Quercus calliprinus</i>	N 32° 37' 10.5", EO 35° 41' 00.5", 287 m asl	Wadi el-Arab	147	~304
Umm Queis 1	<i>Quercus ithaburensis</i>	N 32° 39' 03.3", EO 35° 42' 51.2", 405 m asl	Umm Queis	160	~106
Umm Queis 2	<i>Quercus ithaburensis</i>	N 32° 39' 03.8", EO 35° 42' 51.2", 403 m asl	Umm Queis	340	~225
Olive WQ	<i>Olea europea</i>	N 32° 41' 18.6", EO 35° 52' 10.4", 372 m asl	Abila	125	27
Pine WQ	<i>Pinus spec.</i>	N 32° 39' 40.7", EO 35° 52' 11.4", 434 m asl	Abila	200	37
Tree no. 1	<i>Quercus ithaburensis</i>	N 32° 32' 16.5", EO 35° 46' 34.8", 440 m asl	el-Wustije	196	~125
Tree no. 2	<i>Quercus ithaburensis</i>	N 32° 36' 19.8", EO 35° 41' 49.8", 325 m asl	el-Wustije	242	~171
Olive WS	<i>Olea europea</i>	N 32° 90' 52.8", EO 35° 54' 13.1", 157 m asl	Wadi Shellalah	150	~100
Tree no. 8	<i>Morus spec.</i>	N 32° 41' 02.2", EO 35° 54' 07.8", 127 m asl	Wadi Shellalah	170	~108
Tree no. 10	<i>Kastanea sativa</i>	N 32° 40' 51.5", EO 35° 54' 19.1", 176 m asl	Wadi Shellalah	100	~95

6.1 Natural reforestation: when and why?

Some caution regarding the tree age has to be voiced first: the branches usually show stronger growth than the trunks, since the trees will invest into those parts which are most essential for their survival (pers. comm with Achim Bräuning, Erlangen, May 2006). Trees that could be cored to their centre, such as Seidur 4 and the pine at Abila, showed their strongest growth when they were young. Nevertheless, a comparison counting rings of freshly cut trees in the area leads me to assume that the ages as given in table 22 are a good estimate.

It can be seen that the trees are not as old as local people's memory would suggest. Like already indicated by their description in travel reports, many trees must have been young when Seetzen visited the area in 1806. The reforestation is thus a phenomenon of the late 18th and early 19th century, with another phase of regeneration in the early 20th century. However the air photo analysis (chapter 5) indicates that the presence of a core of old trees is a prerequisite for forest regeneration, and the growth of oaks is not very fast. Therefore forest was probably never completely absent in the area, and the spreading of trees might have started in the 17th century. This fits a decline of settlements which commenced some time after the last Ottoman tax register was completed in

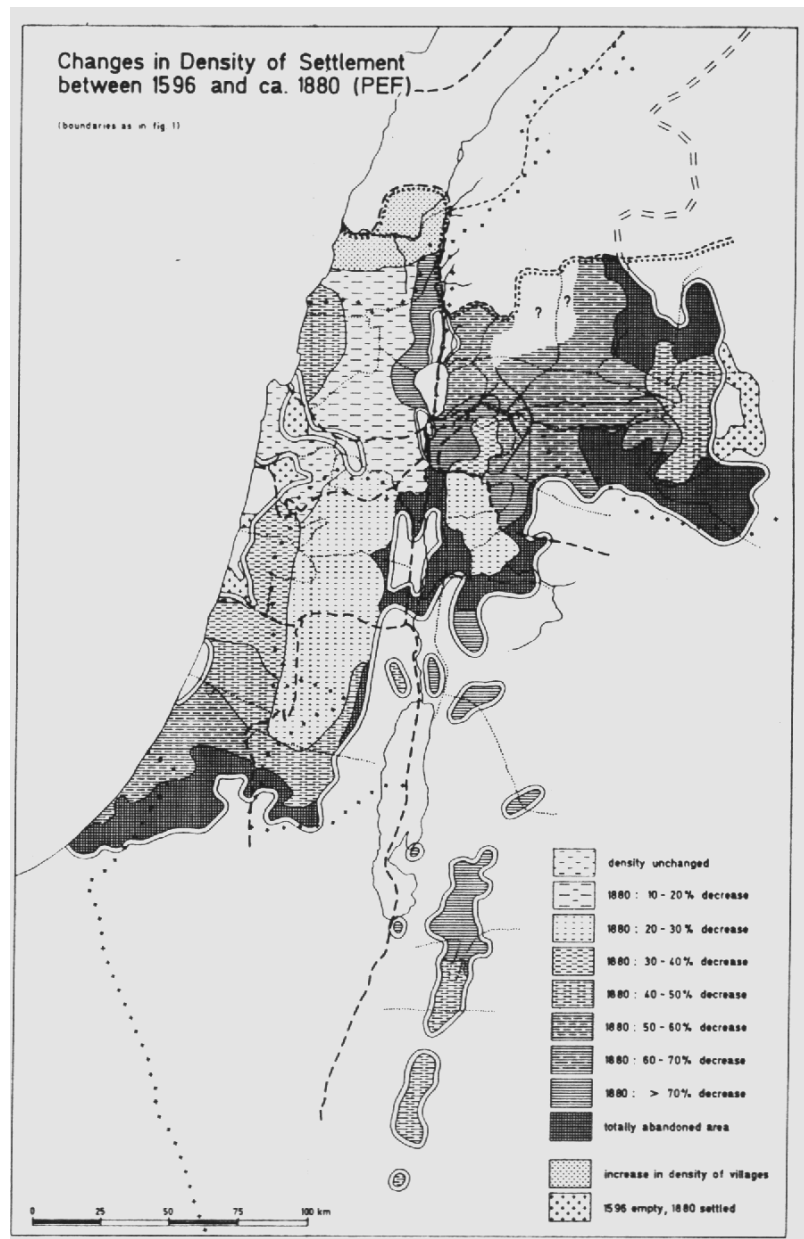


Figure 59: Changes of settlement density between 1596 and 1880. From: Hütteroth and Abdulfattah, 1977, p. 57, with permission.

1595 – the next not to come before the end of the 19th century (Hütteroth and Abdulfattah, 1977). From the 17th to the 19th century, most of the region was characterised by nomadic life, and in fact a great part of the tribes today living in Jordan migrated there from the Arabian peninsula during the 19th century (Abujaber, 1989). Hütteroth and Abdulfattah (1977) found that significant settlement persistence was restricted to the well-watered and well-defensible mountainous areas (fig. 59).

The oaks are not only younger than it seems, but also well-able to regenerate if cut. Only few trunks did not show bulges from past coppicing, and these were either very young or very old. As well, I observed how even trees that had completely been cut at the ground regenerated. It is possible that trees are older than suggested by the wood which can be seen today. To judge from the age of the branches, coppicing stopped around 90 – 60 years BP. It seems to coincide with another phase of reforestation, since numerous young oaks sprouted around 90 – 60 years BP. This seems related to the laws protecting the forest since 1920 (Dalman, 1935): most of the thick branches of the oldest trees started regeneration during World War I and were not harvested again.

The trees show different mean ring widths. These are however not related to soil properties: the ring pattern of trees growing close to each other is similar. Tree Seidur 3 grows on a deep Vertisol, while the other Seidur-trees are situated on rocky ledges, but which seems no disadvantage. It seems merely a matter of moisture availability, indicated for example by the evergreen oak (tree no. 7) in the Wadi el-Arab. Despite its small size, it seems old, but grows at a steep slope where most of the rainwater is lost as runoff. In fact, the deep soils are reported as harmful for trees and should be avoided by plantations, because their shrink-swell behaviour might damage the roots while the better moisture storage makes grasses more competitive (Purschke, 1990). But tree roots are able to penetrate fissures in the rock and can frequently be met if one climbs into moist caves and water tunnels. According to Grove and Rackham (2003), it is again the geology which has decisive influence on forest growth in the Mediterranean. Oaks will not appear on chalk marl which has no fissures, but flourish on limestone regardless whether it carries soil or not – a pattern that can be confirmed for the Decapolis region. In this context, the shrink-swell behaviour of Vertisols, or a missing core of old trees, may be the reason why reforestation never reached the Irbid plain, but which was one of the most completely deserted areas (Hütteroth and Abdulfattah, 1977). When Burckhardt (1823) rode over that plain in May, the grass was so high that it reached his saddle, and his horse had difficulties to get through. A clear indication of the widespread abandonment, but which involved little chances for trees to dominate the vegetation, and underlines why the Irbid plain is considered one of the best areas for wheat production (Purschke, 1990). Burckhardt's (1823) report suggests in this context that the persistent nomadic grazing had no strong impact on the vegetation, which is further discussed below.

At the crossing point of Wadi Shellalah and Wadi Charja, a perennial spring creates a lush area in the otherwise bare wadi. Interestingly, forest covers the slopes of Wadi Shellalah only at this point and only up to a certain height (fig. 60). The forest does not fade out, but is cut in a straight horizontal line. As the character of the slopes does not change at the line of forestation, and as there are no obstacles that would prevent shepherds or loggers to enter the forested area, it seems that the limit of trees has to do with changing moisture due to water-bearing strata in the rock or closeness to the spring. However, as a single small chestnut (tree no. 10) on the upper slopes indicates, trees can survive also in other parts of the Wadi Shelallah. It has to be left open whether the wadi was once forested, but the observed similarity of the trees' mean annual growth rates in the wadi strongly suggests that their presence is related to moisture and not the terrain.



Figure 60: Forest cover in Wadi Charja, July 2005.

6.2 Past and present forest and its environmental relevance

In order to check how strongly forest was reduced since the 19th century, I walked part of the historic travel routes and compared their landscape descriptions with the present situation. As well, historic sources and evidence from pollen cores in Lake Birkat Ram, Lake Huleh, Lake of Galilee (Neumann, 2005) and the Dead Sea (Litt, 2005) were consulted to assess how forest coverage was connected with the environmental history.

Ancient Egyptian letters and execration texts indicated that the Decapolis region was once densely forested (Wineland, 2001). Pella had to pay tribute to Egypt in form of timber and when Thutmoses III. led a campaign to Palestine, he was especially interested in wood of carob trees (Wilson, 1958). According to Zohary (1962), the natural climax vegetation of the region is oak forest, while olives, other fruit trees and cereals grow wild in the transition zone to the steppe. Bones of deer and wild pig in the archaeological record support that the area was covered by huge forests in the Bronze and Iron Age (Geraty and Herr, 1989). This is also reflected in the pollen cores: According to Neumann (2005), the deciduous oak *Quercus ithaburensis* clearly dominated during the Early Bronze Age. While it was gradually reduced in the Lake Huleh and Lake of Galilee cores during the Iron Age, it

dominates at Lake Birkat Ram until dramatically reduced with the beginning of the Hellenistic period. This is attributed to the first industrial land use: charcoal from *Quercus*-wood is best suited for iron smelting which was conducted in close-by mines after the Greek conquest of the area (Neumann, 2005). Archaeological evidence from the Decapolis region indicates that the Mediterranean highland was cleared and cultivated during the Roman and Byzantine period (Geraty and Herr, 1989). There was a strong ceramic industry which required much wood, intensive olive and wine cultivation, and construction of many cisterns on the fields (Fuller and Fuller, 1992). Geraty and Herr (1989) concluded that agriculture reached its physical limits during this time, and could only be extended so far because the whole rainwater was made available by cisterns. The forest was partially replaced by fruit trees, which is reflected by a strong olive peak in the pollen cores from the Hellenistic to Byzantine period (Neumann, 2005). In the 2nd century AD, wood became so scarce that the Roman administration decreed the first forest protection law in order to retain the few remaining reserves on Mount Lebanon (Mirkesell, 1969). The intensive agricultural system of the Late Antiquity required much labour input, e.g. for maintenance of the water collection systems, which was seemingly not fully possible any more in the late Byzantine period (Geraty and Herr, 1989). Historic sources speak about plagues, earthquakes, droughts and diseases as most important factors for depopulation and agricultural decay (Wineland, 2001). Geraty and Herr (1989) concluded from an increase of the goat to sheep ratio that the grazing areas had deteriorated.

Kuhnen (1990) investigated settlement patterns of the Karmel mountains and compared them i.a. with the Decapolis region. He found that land was increasingly concentrated in big agricultural holdings (*Latifundia*) during the late Roman period, which employed slaves and day labourers, eventually forcing small farmers to migrate to the cities. These experienced a fast growth. According to Kuhnen, abandonment of settlements in the Karmel mountains probably started with the emergence of the *Latifundia*, and was contemporaneous with an intensification of agriculture on the plains below the mountains. Long narrow fields were ploughed over rectangular ones, which might be related to a new land ownership, and were characterised by high productivity. A slight decline of olive in the Lake Huleh and Lake of Galilee cores seems to coincide with this development, since olive plantations are thought to have prevailed in the Mediterranean highland and sloping areas (Geraty and Herr, 1989).

After the Muslim conquest, new farming techniques and crops were introduced which the Arabs had brought from India. These included sugar cane, rice, colocasia, coconut palm, sour orange, lemon, lime, bananas, plantains, mangoes, sorghum, cotton, hard wheat, eggplant and watermelons (Watson, 1981). However while agriculture boomed in Mesopotamia, farming in Jordan was gradually replaced with transhumance while the Decapolis cities declined and were finally abandoned. Villages

and small farmsteads, mixed with nomadic and half-nomadic production and lifestyle, characterised the region till the Ayyubid-Mamluk period (Johns, 1994, Walmsley 1992, 2001). In the pollen cores, olive was sharply reduced while the evergreen oak expanded – interestingly, now *Quercus calliprinus* dominated at the lakes, while there deciduous *Quercus ithaburensis* recovered only very slightly.

During the 13th and 14th century AD, the Mamluks invested heavily in Jordan (Walker, 2003). Especially important were huge sugar cane plantations in the Jordan valley. These brought a high revenue but quickly exhausted the soil, needed much water and required a high work input. Also the cereal and olive-producing agriculture was extended during this time, and the infrastructure improved. In this context, old land use installations dating to the earlier periods were partially repaired and reused (Walker, 2007). This overall activity seems connected with a slight drop of *Quercus calliprinus* in the pollen cores. But Mamluk agriculture faced decay already in the 15th century during the general decline of the empire. However, this was initially a regional phenomenon – while the southern regions like the Kerak plateau and the Madaba plains around Tell Hisban faced depopulation, the greater part of the former Decapolis region in the northern countryside continued to flourish (Walker, 2007). Historic sources again speak about plagues, earthquakes, droughts and diseases as important factors for depopulation and agricultural decay (Walker 2004, 2007). The decline of Mamluk economy is usually understood to be related to corruption, confiscation of private property, extremely high taxes and lack of reinvestment and maintenance for the agricultural systems (Udovitch, 1981, Ashtor 1977). Changing trade routes and trouble with unruly Bedouin are seen to be consequences of this development (Walker, 2004). Sato (1997) even understands the general decline of the Mamluk state to be caused by the unfavourable development in the Jordanian countryside. European competition in sugar production and the spice trade are also seen as important reasons for the decline of Mamluk economy, however this has recently been questioned (Luttrell, 1995, Walker, 2003).

The 16th century saw a brief recovery of the region and high Ottoman investments. Two preserved tax registers were evaluated by Hütteroth and Abdulfattah (1977). The last was established in 1596, but a long documentation gap followed. New systematic information was only collected in 1880. In the meantime, strong depopulation had taken place in the east, the south and the Jordan valley, while settlement density in the Ajloun mountains remained nearly unchanged. It seems that the mountainous region was continuously occupied since the Middle Islamic period, while the eastern plains suffered from a dramatic drop of population .

When the first European scholar arrived in 1806, Seetzen (1854) observed many abandoned villages and a wealth of ruins of once splendid cities. While the vicinity of still inhabited places was cleared, he encountered spreading forest in the Mediterranean highland. As well, he discovered remains

of olive, pomegranate and wine groves, mulberries, fig trees, and olive presses in the abandoned areas. The deserted villages and groves were in utter decay, and most of the fruit trees dead. There were only two houses in Irbid: it was one of the biggest settlements, and its 50 families lived in vaults of ruined ancient buildings. The closer vicinity of Irbid was an open plain haunted by robbers and dangerous Bedouin. Walking through el-Wustije, Seetzen's path led through a hilly area dotted with single trees and cereal fields. To the southwest, again oak forest appeared, becoming denser and denser as Seetzen approached Ajloun castle. When Burckhardt (1823) visited the castle a decade later, he reported that there was the thickest forest he ever observed, which was too dense to let him pass.

Today, the forest in Ajloun still looks very much like described by Seetzen and Burckhardt. On top of the ridges, evergreen oaks dominates, while pistachio, deciduous oak and pine are found on the lower slopes. Walking Burckhardt's route, there suddenly appears a very thick forest which is indeed too dense to get through. This is a typical coppice (mainly *Quercus calliprinus*), is still harvested by locals, although the forestry department tries to slowly change its character into a timber forest (pers. comm. with Kamal Nueimat, forestry department, Ministry of Agriculture of Jordan, May 2004). Walking north towards el-Wustije, the character of the landscape becomes very much what Seetzen (1854) described as 'hills dotted with single trees and fields'. However the number of trees seems reduced, and introduction of bulldozers also led to the vanishing of thousands of Dolmens which once crowned the hills (Schumacher, 1890). But there still is the oak forest reported from the southern slopes of the Wadi el-Arab, and north of Umm Queis towards the Yarmouk valley (Schumacher, 1890), all dominated by the deciduous oak *Quercus ithaburensis*.

In contrast to the quickly growing urban centres of Jordan, it seems the countryside changed little since the 19th century. Probably there never was a full annihilation of forest, but very low coverage was present in the Roman-Byzantine period. Forest seems not negatively affected by nomadic grazing: during the periods of Bedouin rule, it spread. This is not a surprising result if one considers how temporary nomadic land use is, and how few people can be supported by this way of life. Nomads do not cut many trees and have little demand for wood, since they do not build anything. And grazing may in fact positive as it reduces the underbrush. This is supported by recent results from Ethiopia, where immigration of nomads led to reduced pressure on forests and local regeneration (Darbyshire et al., 2003).

When modern "forest protection" prevented grazing, it led to high and well-developed underwood which sometimes had a catastrophic impact on subtropical forests in the Mediterranean, the U.S. and Australia. The frequent forest fires suddenly developed temperatures high enough to ignite the crowns of big trees, causing the fires to extinguish complete forests (Fairhead and Leach, 1996, Vale,

2002, Grove and Rackham, 2003). Otherwise, fires would burn some grasses and shrubs, but leave the big trees intact, which may grow even better (Zohary, 1982, Inbar et al., 1998). In the case of the U.S., the fire threat led to the "Healthy Forest Restoration Act" of 2003, which should facilitate the cutting of underwood but was widely criticised to follow an inadequate strategy (Wilderness Society, 2004). In the Mediterranean, van der Leeuw (2004) found in a case study of Epirus that population movements led to an abandonment of rural areas in the Ioannina prefecture. The resulting quick and massive spread of maquis and forest made large parts of the uplands inaccessible even for goats, aggravated the fire problem, and led to a drop of the groundwater table. Local inhabitants understand "degradation" as synonymous with "reforestation" (van der Leeuw, 2004, p. 123).

According to Grove and Rackham (2003), the extent of maquis is independent of browsing, and the "climax theory" (suggesting a degradation order forest -> maquis -> phrygana -> steppe) unsuited for Mediterranean vegetation. The Mediterranean vegetation is very resilient: maquis may quickly revert to forest if browsing stops, but then turns from a browsing-dominated to a fire-dominated landscape. According to Naveh and Carmel (2004), this resilience developed due to adaptation during millennia of land use, while the similar Californian vegetation is not so resistant. In this context, Grove and Rackham (2003) found that vegetation dynamics in the Mediterranean are fully governed by water. For example, new woodland is not always continuous, which depends on root competition for water. The forest will become thinner and the maquis will die if big trees prevail, however it may also be the maquis who is more competitive and prevents the growth of big trees. According to Grove and Rackham's (2003) research in the framework of the MEDALUS project, the pattern of forest distribution in the Decapolis seems applicable to the Mediterranean in general: rocky areas are covered by trees, while grasses dominate on deep soils, especially vertisols. Grove and Rackham (2003) further evaluated how the carrying capacity of the Mediterranean landscape can be determined. They found that it is problematic to calculate, since factors like the productivity of vegetation, annual consumption per head of livestock etc. are hard to estimate in light of the highly variable environment. However they estimated that due to the resilience of Mediterranean vegetation, the ecological carrying capacity is typically 50% larger than the optimal economic density of herd animals (determined according to the health and milk production of the animals). Whether the degree of browsing is excessive depends mainly on how long it continues. In this context, it frequently happens that areas with watering places are overgrazed, while more remote regions are under-grazed which involves a high fire risk (Grove and Rackham, 2003). Again it seems modern land use which is most detrimental: the construction of watering places led to a concentration of herds, while reforestation and the subsequent fencing out of animals concentrated grazing in other areas, sometimes moving the pressure to more sensitive regions

like the desert fringes (Purschke, 1990).

Well-managed herding is not negative for the vegetation. In contrast, areas that are not browsed are soon building up wood, which reduces their nutritive value but increases the fire risk (Dalman, 1928b). The current rise of sheep and goat in Jordan, connected with high meat prices, cannot be taken as indicator for growing pressure on the environment. In fact there is a lack of shepherds due to the compulsory schooling of children, and more and more herds are raised on fodder (Purschke, 1990). This development had very negative impacts in Epirus: grazing, especially by goats, is essential to keep infrequently visited areas free of maquis (van der Leeuw, 2004).

In this context, it seems questionable whether Mediterranean forest has high significance for erosion control. It would play a soil-conserving role if the crowns were closed, so they would disperse heavy rains as the main agents of erosion. But this is unlikely because of the frequent fires and limited moisture supply, which do not allow trees to stand as close as in northern Europe (Grove and Rackham, 2003). As well, pine as the most frequent reforestation tree produces a layer of needles which leads to quick runoff and may aggravate gully formation. One may argue that limited forest cover is better than no forest, and that such a limited cover would reduce the impact of less heavy rains, even if it cannot stop deluges. Yet according to Pursche (1990), maquis and grasses perform as well as forest roots in retaining soil. Since trees compete with grasses and perennials, they may in fact lead to areas which are less protected than fallow land. Leopold (1994) also suggested that forest has little relevance for soil conservation, and cannot stop a flood – climate variations, not human activities, lead to erosion. Grove and Rackham (2003) devoted a full chapter to the discussion of tree evidence from the MEDALUS project, discussing that even closed forests do not stop erosion if the soil is water-saturated and excess water cannot be swallowed by karst. They too arrived at the conclusion that forest has no special relevance for Mediterranean erosion, and that the natural climax vegetation is not a "forest" in the northern European sense of the word, but a savannah. The positive impact of forest might be more indirect, for example connected with the reduction of wind speed, more dew due to stronger temperature gradients between day and night, and changing local atmospheric circulation patterns (see chapter 8.3). This might be countered by dropping water tables, but which depend on the tree species (Müller, 2005). A final assessment of the benefits of forest cannot be given on the basis of the available data, but it seems that its positive impact is overestimated, and that massive reforestation with pine has created more problems than benefits.

It is interesting to note that pine spread quickly after depopulation during the Umayyad period as reported from Dead Sea cores (Litt, 2005). This fits well to the picture of an abandoned cultural landscape, since pine is pioneer tree but which does not persist if slower growing oaks are not

suppressed by agriculture, fire or grazing (Zohary, 1982). At the Dead Sea, these cannot have been intense since pine was soon replaced by evergreen oak. However in the case of the Argolis discussed in chapter 2, the persistent invasion of pine in the 10th century AD (Jahns, 1995) may be connected with the immigration of Albanian pastoralists. Without grazing, pines in the Mediterranean are dependent on frequent fires for their survival: they are thus easily flammable, attract lightnings, and their seeds are fire-resistant (Grove and Rackham, 2003). *Pinus radiata* and *Pinus serotina* do not even germinate until a sufficiently hot fire opens the seed cones. Yet as long as the brushwood is not very high, forest fires do not reach temperatures that would damage older oaks. In this context, it is interesting to note that the dense man-made oak coppice close to Ajloun castle survived for at least 200 years. Although there are severe problems with forest fires in Jordan, these are seemingly concentrated in the areas reforested with pine (pers. comm. with Kamal Nueimat, Forestry Department, May 2004). In the light of sustainability, it would be worth to further examine how pine vs. oak perform in Jordanian forests, but reforestation with pine seems generally questionable. For now it can be concluded that limited grazing in the Decapolis region may have favoured the reforestation by oak.

It is settled life that exercises the greatest pressure on wood resources. This is confirmed for the case of the Decapolis region: during his numerous travels to the region, Schumacher (1890, 1897, see also Steuernagel, 1924) noted how forest was gradually cut close to emerging villages. But again, the picture of reckless villagers destroying the woods and leaving the soils prone to erosion is a wrong one. Not only that the soils are not prone to erosion, and that forest likely plays a subordinate role for soil conservation: the cutting marks of the trees point to conscious harvesting of trees. As well, forest was not so strongly cut as suggested by some writers (Lowdermilk, 1944). The need for wood was probably overestimated: for example, lime in the 19th century was burnt with brushwood and thistles, and some chalks are so bituminous that they are self-burning (Dalman, 1942). Hearths were usually fired with dung and old olive wood. Forest was only harvested for making tools and roofs (Dalman, 1942). For the Mediterranean, Grove and Rackham (2003) calculated how much wood and charcoal would have been needed for the famous Attic silver mines of Láurion, or shipbuilding, which are thought to be prime examples of unsustainable land use (Scarre, 2003). But if Athens had only reserved 15% of Attica's land for wood harvesting (which not necessarily requires trees, since shrubs provide firewood as well), "Láurion could have gone on forever" (Grove and Rackham, 2003, p. 172). Regarding shipbuilding, one vast fire on the Bozburun peninsula (Turkey) in 1996 killed as many trees in a few days as would the nearby shipyard in a decade. As well, shipbuilding does not necessarily lead to cutting whole forests since only the tallest trees are suited. Grove and Rackham (2003, p. 169) conclude that the "scholars' obsession" with shipbuilding and other wood-harvesting activities as reason for

environmental degradation cannot be supported with field evidence. Similarly, there was no dramatic loss of woodland in Jordan. In this context, it is the most continuously populated area which has the densest forest cover (Ajloun). This is probably due to the high precipitation, which makes the area best suited for tree growth, and to the regular harvesting of trees which likely was economically important.

In this context, there is widespread agreement that the Ottoman rule was environmentally very detrimental, inhibited development and led to decay (Carmel, 1985). For example, it is argued that the construction of the Hedjaz railway led to a widespread destruction of Palestinian forest. But in fact this railway (which I used, since it is still running from Amman to Damascus) was constructed with iron bars, and the trains were fired with coal. Using iron bars was more expensive than importing wood, but necessary, because local tribesmen found the wooden bars well-suited for building their houses' roofs (Frantzke, 2003). Iron bars were too heavy to pull out of the tracks - nevertheless one can observe early 20th-century houses in villages close to the rail line which (probably illegally) used rail tracks for construction of the roofs. Timber was evidently in need, but the forests mentioned in the early travellers' reports did not vanish. Although coal shortage during World War I led to a cutting of forest close to the railway, the Ottoman period seems better than its reputation. Reviewing the supposed anthropogenic degradation of the landscape, it is remarkable how the timing suggested by different authors varies: while Israeli writers see it connected with Roman oppression of the rural population (Dar, 1986), western authors relate it to the Muslim conquest (Lowdermilk, 1944). Many Arabs think that the degradation mainly took place during Ottoman rule (numerous pers. comms., Amman and Irbid, 2001-2006). But from an environmental point of view, the Ottoman period seems neither worse nor better than the other periods – the reports from the early 19th century point in contrast to a growing environmental awareness. This is indicated by e.g. a military order to photograph archaeological sites when possible during the operations of World War I (published by Djemal Pasha, 1918), which included the re-discovered archive of air photos in Berlin showing archaeological sites throughout the Ottoman empire (Wiegand, 1970). The bad environmental reputation of the Ottomans might merely be connected with their defeat in World War I – nobody wanted to be responsible for the erosion, but which took place during the Pleistocene.

It is worth to review the two main oak species in Jordan, the deciduous *Quercus ithaburensis* and the evergreen *Quercus calliprinus*. In the pollen cores, the deciduous oak dominates until the Hellenistic period, but after the Byzantine period it is *Quercus calliprinus* which prevails. This was attributed to greater tolerance of the evergreen oak to grazing, and thus as evidence for greater pastoral pressure since Muslim conquest (Neumann, 2005). As well, it was suggested that *Quercus ithaburensis* needs deeper soils than *Q. calliprinus*, and thus was in disadvantage after the supposed widespread

erosion after the Muslim conquest (pers. comm. with Frank Neumann, March 2006). This is however not in agreement with the vegetation found in the Decapolis region: here *Q. ithaburensis* clearly dominates in the lower altitudes (0-700 m), while *Q. calliprinus* covers the higher mountain ridges (700-1000 m, al-Eisawi, 1985). That distribution is attributed to a temperature gradient, since the evergreen oak copes better with low winter temperatures – which is also the reason why the *Q. ithaburensis*-communities are not found close to the deserts, even if enough water is available (Zohary, 1982). There is no indication that the distribution of the oak species in Jordan has to do with anything else than altitude, moisture and temperature. I observed both species frequently cut and regenerate, and it does not seem that either is better able to withstand browsing than the other. An extensive literature search and inquiries did not yield any studies which systematically investigated the matter; and therefore it seems to me that *Q. calliprinus*' "better tolerance" of grazing is the personal estimate of some forester which was cited and cited again, and some day taken as established fact.

One has to mention that there are two forms of *Q. calliprinus*, a shrub- and tree-form, which might be genetically fixed (Zohary, 1982). If this proves true, evergreen *Quercus*-maquis might pretend a suppressed forest, while it consists in fact of shrubs that will never become trees. Regarding the supposed dependence of *Q. ithaburensis* on deep soils, the evidence from Decapolis region makes clear that these trees grow perfectly well on rocky spots, and not only the roots of *Q. calliprinus* can be found in limestone fissures 10 m below the trees. In fact, although the deep soils store more moisture, they might be detrimental for the trees if characterised by vertic behaviour (Purschke, 1990).

The different deciduous oak species (*Q. ithaburensis*, *Q. libani*, *Q. boissieri*) cannot be distinguished by their pollen (pers. comm. with Frank Neumann, March 2006). *Quercus libani* and *Q. boissieri* are much less frequent and need more moisture and cooler temperatures than *Q. ithaburensis*, and rarely occur in pure stands (Zohary, 1982). At the high altitudes of Lake Birkat Ram, these species might have been more important than *Q. ithaburensis*, but which should have dominated at Lake Huleh, the Lake of Galilee and the Dead Sea. In this context, the increase of evergreen oak seems not related to temperature change (pers. comm. with Frank Neumann, March 2006), although it seems possible that the end of the Byzantine epoch was characterised by decreasing temperatures (Bar-Yosef and Kra, 1994). The rise of *Q. calliprinus* is unprecedented: other temperature variations during the Holocene did not lead to a change of the dominating oak species (see Litt, 2005). Horowitz (1979) suggested the rise of *Q. calliprinus* might be related to reduced summer precipitation and a more seasonal rainfall. According to Zohary (1982), only 50% of the trees in Israel are evergreen which is surprising in the light of the current seasonal climate. Zohary (1982) assumes that a dry and hot climate

during the Late Pleistocene forced the retreat of many mesic elements northwards and westwards from their Neogene positions, leaving a large number of relics along their withdrawal path. Therefore the complex architecture of the present vegetation was established between 28,000 – 12,000 BC, and no further climate change drastic enough to change the general vegetation took place. Horowitz (1979) interpreted the strong presence of deciduous trees as inherited from a long period with summer rains, and assumed that the vegetation would over time change towards evergreen species and *Acacia*-communities, which are best adapted to the present climate. But if this process gained momentum 1400 years ago, it contradicts the widespread presence of *Q. ithaburensis* in Jordan. The pollen at Birkat Ram might represent the shrub-form of *Q. calliprinus* due to continuous rural settlement and cutting of trees, but other anthropogenic pollen are not elevated, suggesting that land use was merely pastoral (Neumann, 2005). The evidence from Jordan makes clear that pastoralism did not prevent reforestation, and might in fact be beneficial for the establishment of a *Q. ithaburensis*-dominated park forests. One may speculate that Birkat Ram was an important watering place for the Bedouin herds returning from the winter pasture in the deserts, like the Lake Baddsche near el-Muzerib in the Syrian part of the Decapolis region (Schumacher, 1897), which prevented the re-establishment of deciduous oak. But it is unlikely that similar grazing pressure existed at Lake Huleh, the Lake of Galilee and the Dead Sea.

I think the most likely explanation for the dominance of *Q. calliprinus* vs. *Q. ithaburensis* can be found in the geology, and the nearly complete cutting of forest during the Roman-Byzantine period. A different distribution of forest regeneration was already observed in the early 19th century: according to Seetzen (1854) the trees north of the river Yarmouk were restricted to small groups and steep slopes, but a thick forest of oak, whitethorn and almond could be observed in the south. The Yarmouk valley is also the border of the basalt flow (with the exception of the Ard al-Ala). Therefore one finds continuous (basalt) soil cover in the north, but many rocky (limestone) spots in the south. Since the trees grow well on limestone, and as there is little suitability of rocky areas for cultivation (except water collection), it is likely that more oaks survived in the south, and were perhaps harvested. So there was a core of *Quercus ithaburensis* trees in Jordan, while the other areas were possibly completely cleared. Only the shrub-form of *Q. calliprinus* was left and dominated forest regeneration. Again, this seems comparable with Ethiopia where the original *Podocarpus-Juniperus* forest did not regenerate, but only *Juniperus*, which was attributed to a virtual elimination of *Podocarpus*, the wood of which is well-suited for tools and construction (Darbyshire et al., 2003).

The concentration of pollen in the sediments of Birkat Ram was reduced when the deciduous

oaks were cut, which does not say much about the general pollen flux and production, but indicates that sedimentation increased, although it cannot be said how it took place (by earth slumps, aeolian deposition, increased sheet erosion etc. - Neumann, 2005 and pers. comm., March 2006). This is in agreement with sharply rising susceptibility values of the sediments after the cutting of the deciduous trees, which remain elevated during the periods of intensive land use in the vicinity. As well, the total sedimentation rose during that time. It seems clear that deforestation at Lake Birkat Ram led to increased erosion. Neumann (2005) found that intense olive cultivation in the vicinity during the Roman and Byzantine period did not conserve the soil, but which is not surprising since olive plantations have no closed crowns, and are usually ploughed up to six times a year to suppress grasses and increase infiltration (Purschke, 1990). In humid Mediterranean climates like at Birkat Ram (1042 mm average annual precipitation), water erosion is seemingly much more important than in the Decapolis region. This is also indicated by the soil distribution, which follows a climatic gradient: according to Urman (1985), little infiltration in the clay-rich basalt soils in humid areas leads to high runoff, and therefore overall thinner soils in the humid north than in the semi-arid south of the Golan. At Birkat Ram (as possibly in Ajloun) a continuous forest cover with closed crowns seems therefore well possible and connected with very low erosion rates. Unfortunately, the Birkat Ram-sediments are mixed and show no clear structure – it is thus impossible to say anything about the frequency and impact of heavy rainstorms, which might be connected with some sandy layers (pers. comm. with Markus Schwab, GFZ Potsdam, November 2006).

6.3 Precipitation reconstruction

Touchan and Hughes (1999) established a 400-years dendrochronology of *Juniper* in the Dana reserve in southern Jordan, but in northern Jordan around Kufr Wasta and Dibbin only younger trees were detected which allowed for a 100-years record. Their results suggest that tree growth in Jordan is climate sensitive with a 69% correlation, but extreme precipitation events are not reflected because most of the water is immediately lost as runoff. While there was a good correlation of sites in the north, and between different species in the same area, stands in southern and northern Jordan show very different annual growth patterns (Touchan and Hughes, 1999). This was attributed to different regional and local climatic patterns, making clear that climatic forcing throughout the country cannot be deduced from local proxies.

For this thesis, rainfall data in northern Jordan was available from two measuring stations: Irbid

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and, to the west, Baqura (fig. 61). The pattern of both stations is very similar, with a correlation of $R^2=0.7504$. But the annual precipitation variations are very severe, and reach more than 100% of the mean values. Since the tree rings (see appendix) show some variations between different areas, but are very similar between trees growing close-by, probably not only precipitation but also varying local moisture availability are connected with different growth patterns.

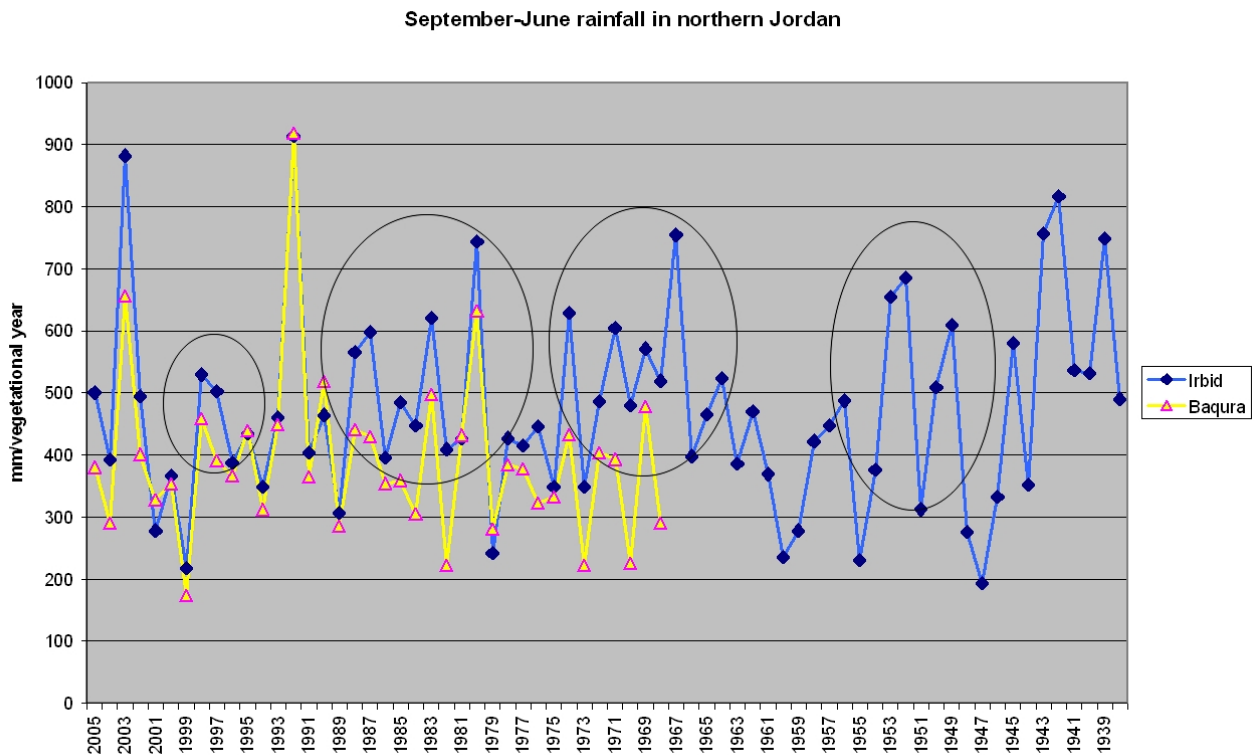


Figure 61: The available rainfall data from northern Jordan. Periods of good tree growth are marked with circles.

Despite the slight local differences of tree growth, four phases of elevated precipitation can be identified in agreement with Touchan and Hughes' (1999) northern study. These coincide with enhanced growth of all species in all examined areas (fig. 62). However, the highest peak rainfalls 1992 and 2003 are not reflected. Obviously the trees could not profit from the enhanced rainfall, since a great part fell in heavy rainstorms (Field and Banning, 1998). There seems however a good growth documented for one or two years after these events: as it seems part of the elevated water supply was still available. The Abila team reported in this context that much snow fell at Abila during 1991/92. Thus the otherwise dry creek was flowing all the year 1992, thistles on the site were head high, several tombs collapsed, and the steep slopes were so slippery in summer that one could "ski" down (pers. comm. with Bob Smith, January 2007). The tree-rings reflect droughts, but not extreme events. In this context, Touchan and Hughes (1999) found no periods of drought lasting longer than 5 years during

the past 400 years, but suggested that some of the data might point to times of increased climate variability that was hard to evaluate. These variabilities might however be most relevant for agriculture, which will be discussed in chapter 7.

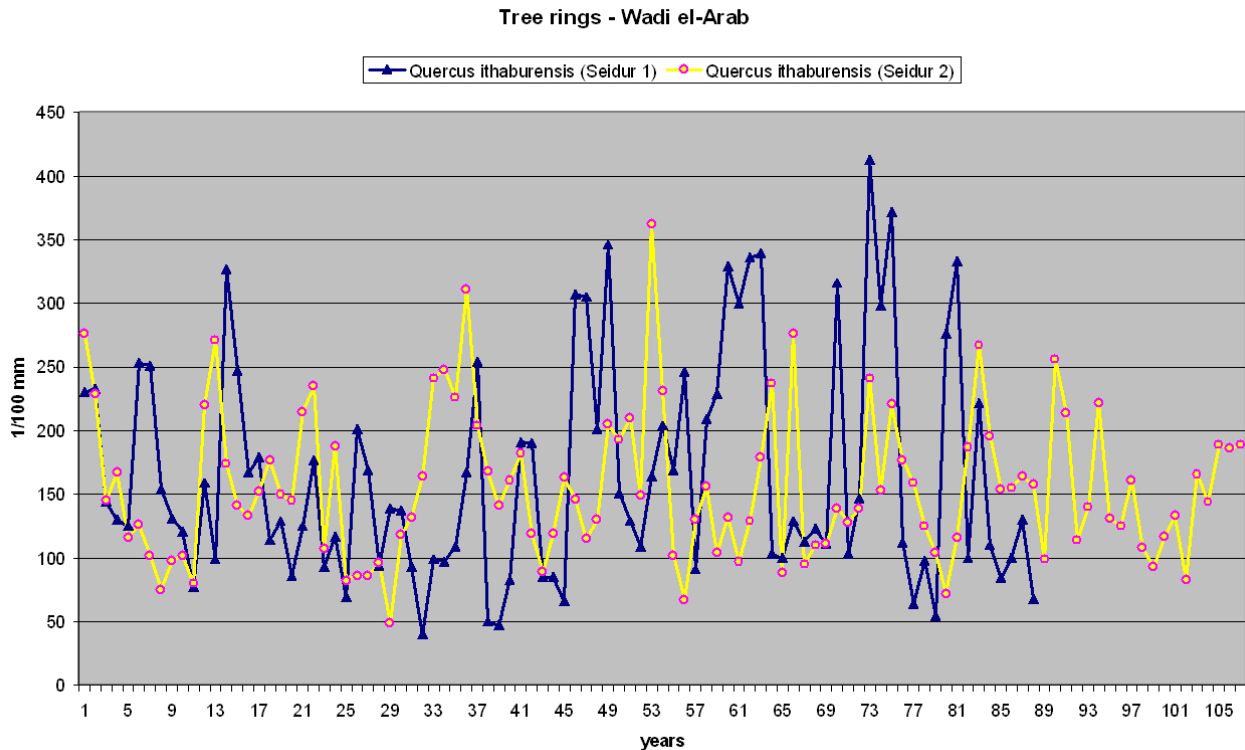


Figure 62: The longest available tree-ring curves.

In order to grasp climate variabilities with tree-rings, Touchan et al. (2005) conducted a larger study of the eastern Mediterranean with advanced methods. They found that tree-ring indices are related to the (usually scarce) May-August precipitation, which is driven by pressure and convection anomalies. These can be translated into a surface air temperature distribution, and resulting dry and wet years. Using this technique, Touchan et al. (2005) could relate several historic events to extreme dry and wet periods. For example, the longest reconstructed period of drought 1590 – 1595 AD is coincident with widespread famine in Turkey and Syria. As well, a 2-years event in 1570 – 1571 AD was recorded when wheat exports in the Ottoman empire were forbidden. Local extremely dry events could be identified, too, such as a 1579 famine in the Aegean and Syria, and 1585 in west Anatolia and Eastern Asia. As well, the great drought of Ankara in 1874 was recorded, which led to 30% of the population starving to death and an unknown loss of herd animals.

In summary, the available tree ring data from the Decapolis region did not yield new insights for precipitation reconstruction, but matched earlier studies. Tree rings have their limits as they do not record extreme events, but which might be most relevant for crop failures and destruction of

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agricultural systems. As well, the rings might change locally. However, they can be very useful in combination with other methods as demonstrated by Touchan et al. (2005). For the case of the Decapolis, they provide a baseline for the discussion of climate-agriculture interactions which is presented in the next chapter.

7. Agriculture and food supply

*Amateurs talk about tactics.
Experts discuss logistics.*

German military saying

7.1 Agriculture and climate

Agricultural crops in Jordan strongly depend on rainfall. The National Atlas of Jordan (1984) collected information about wheat harvests in relation to precipitation. The data for the period 1966 – 1975 and the areas of Irbid, Madaba, Mafraq and Balqa is shown in fig. 63, and reflects how the impact of precipitation varies regionally. The pattern from Madaba, Mafraq and Balqa is very similar to the pattern from Irbid and Baqura which was discussed in chapter 6.3, and matches a period of good water supply and according growth of trees. In the mountains at Balqa, the mean annual precipitation fluctuated between 400 and 700 mm and had a limited impact on production. In contrast, the Irbid and Madaba plains show a stronger dependence of production on rainfall – but here precipitation varied between 300 and 500 mm. This dependence is even more pronounced in the Mafraq area further east, where precipitation varied between 200 and 300 mm: a year with less than 200 mm led to a complete failure of wheat.

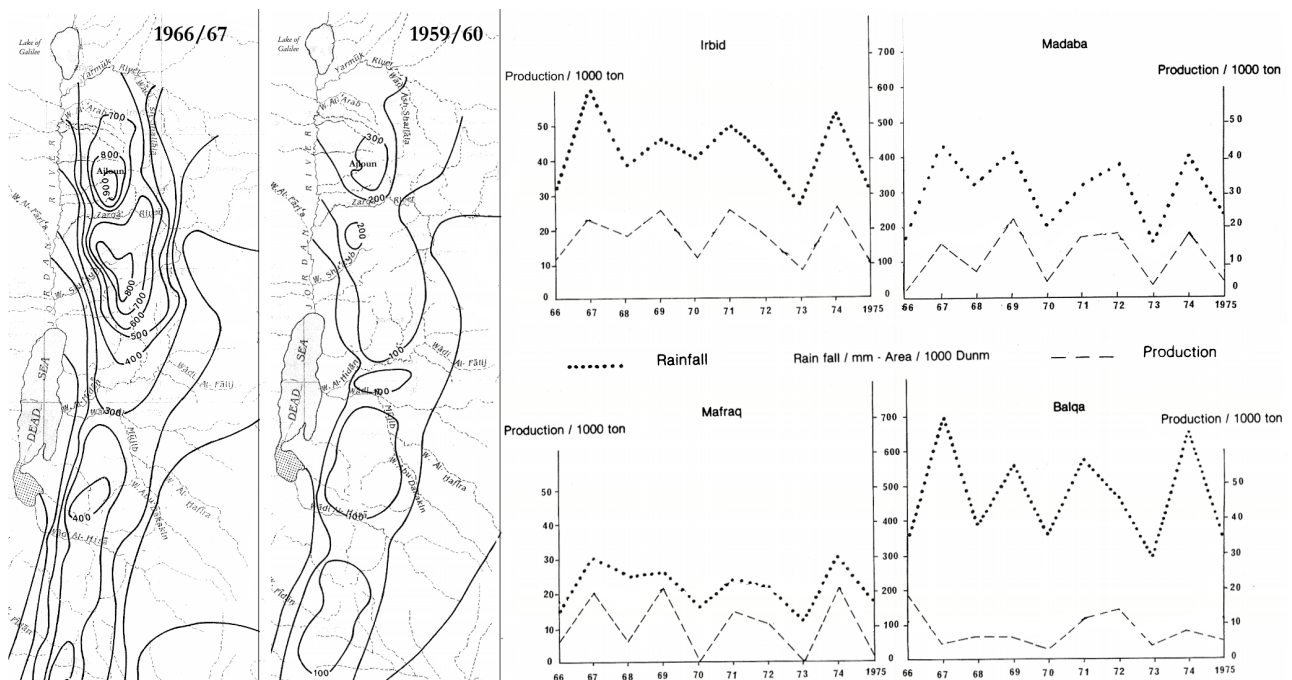


Figure 63: Map showing the precipitation distribution during a wet (1966/67) and dry (1959/60) year, and agricultural production in relation to rainfall from 1966-1975 for different areas. After National Atlas of Jordan, 1984.

According to Lanzendörfer (1985), farmers in Jordan try to adapt to climate fluctuations by not deciding which crops to sow before the first rainfalls, assessing from the timing and character of the earliest precipitation whether a dry or moist year has to be expected. According to al-Karablieh et al. (2002), this approach can be supported with scientific data, since it is indeed the amount of early rain in

October and November which is decisive for the expected harvest. It allows an estimation of necessary food imports (only 10% of Jordan's present wheat consumption is produced in the country). Some farmers in the well-watered areas, for example in the Ajloun mountain, sow nevertheless before the first rains appear. Early seeding (*Afir*) allows optimal use of the year's rainfall and brings better revenues due to higher prices at early harvest, but involves a high risk. Late seeding as described above (*Schatwi*) provides more security and makes cultivation easier, since the first rains soften the hard crust that forms on most soils during the summer drought, and because later ploughing destroys weeds which usually germinate after the first rains (Barham, 1979). Should the first rains come as late as December, sowing often does not make sense any more, since the vegetation period will be too short for satisfying yields (Barham, 1979). In such cases, fields are ploughed and laid fallow (*Witterungsbrache*), which keeps evaporation at a minimum and allows storing the year's rain, which is available during the next year (Andreae, 1983).

One can see that traditional farming in Jordan is well-adapted to the highly variable environment, and probably much better than its reputation (Barham, 1979). In this context, risk agriculture is practised in the Mafraq area, which can be very successful if precipitation is sufficient, but includes frequent crop failures. The National Atlas of Jordan (1984) shows a probability map for successful growing of wheat in the total planted area of Jordan. It indicates that more than 50% of the total wheat production is risk farming with an average success probability of less than 66%. The comparison of the moist year 1966/1967 with the dry year 1959/1960 demonstrates that rainfall variations can be very significant. Keeping in mind that the 200 mm mean annual precipitation line is usually the threshold for successful rain-fed wheat production, the eastern and southern areas would suffer crop failures during a dry year like 1959/60. Only the central Ajloun mountains between the Wadi el-Arab and Zarqua river would receive enough water. The precipitation pattern during the dry year 1959/1960 shows a remarkable correlation with the settlement patterns as reconstructed by Hütteroth and Abdulfattah (1977): the only area in Jordan that showed a stable settlement pattern are the well-watered Ajloun mountains, while the greatest decline took part in areas that would have suffered most from a dry period. But it has to be added that the plains would also be the first target for attacks of hungry Bedouin. For the case of Israel, Richter (1979) found that depopulation took place mainly in the fringes of the settled areas. Israel's coastal plain had not been settled since the Mamluks ordered the destruction of coastal towns in order to prevent a return of the crusaders, and as it seems open plains were generally avoided during the times of Bedouin rule due to missing hiding places. Also, settlements were moved some km away from main traffic routes to avoid plundering by troops on the march (Richter, 1979).

Annuals like wheat and barley occur naturally in the transition zone to the desert (Zohary, 1962), and are well adapted to the highly variable precipitation. Due to their short vegetation period, they are less dependent on continuous good water supply. And although risk agriculture in the eastern plains often not even returns the invested seeds, wheat and barley can still be grazed (Barham, 1979). Fruit tree plantations like olives are in contrast much more dependent on precipitation, even if woody plants are better able to survive a dry year. They will yield no or only minimal fruits if the water supply is not secured, which is why they are often irrigated (Barham, 1979). According to the National Atlas of Jordan (1984), olive production shows a slightly different relation to precipitation than annuals: as long as annuals rains are higher than 300 mm, the production curve will follow rainfall as did wheat. But if rains are diminished, olive production will fall not only in the dry year, but remain low during the following 1-2 years. Since all springs and rivers are fed by rainwater, a dry year also leads to a quickly dropping water table (al-Farajat, 1997) and empty cisterns, with negative consequences for all irrigated plants. Despite modern irrigation technologies, agriculture in Jordan is still strongly dependent on rainfall. This dependence will only grow: Jordan's water balance is negative, and fossil water reserves steadily depleted, which is why future irrigation will be restricted to the Jordan valley and use sewage water to a major degree (KfW, 2005).

Good rains lead to high water storage in deep soils, e.g. in the Irbid basin, and allow cultivation of a summer crop (Purschke 1990). But since the summer seed would have to be sowed while the winter crops are not yet ripe, a regular changing cropping pattern is necessary (Dalman, 1932). The order usually is: summer crop + winter crop, one year fallow with ploughing (Witterungsbrache), and again summer crop + winter crop. The winter crop is mostly cereals, and the summer crop vegetables, peas or beans (Dalman, 1932). After the harvest, stubbles are grazed or ploughed under to retain soil water. During years with summer seeds, the fields are ploughed in spring and summer to remove weeds and prevent the loss of soil moisture (Barham, 1979).

Discussing the dependence of agriculture on climate, one should consider not only rainfall. *Climate variations* are in fact difficult to measure: proxies usually only record *rainfall variations*, but not their character, or radiation, temperature and wind which are important for cultivation as well. In contrast, the effect on the natural vegetation is normally only dramatic if climate change is dramatic, as discussed with the tree rings in chapter 6.3.

Not only the total amount, but also the distribution of rainfall is of prime relevance for yields: for example, 1920/21 was a slightly above-average year, but produced bad harvests due to missing late rains (Dalman, 1928a). If no sufficient late rains appear in April, it is usually decided not to harvest the grain, but to graze it (Barham, 1979). But the early rains are even more important: the year 1924/25

brought good late rains, but very poor early rains. This had the following consequences (Dalman, 1928a):

- harvests were minimal (the grain was even too low to be cut by sickles)
- natural vegetation grew sparsely, and thus there was no pasture
- many springs dried up
- cisterns were soon empty

Additional results:

- whole villages migrated with their herds to the Jordan valley, in search for water
- Jerusalem's water supply could only be secured by water transports on the railway

Water is the limiting factor for agriculture. In this context, already variations of the wind direction have a great impact on harvests due to different air humidity: all winds except west wind are detrimental (Dalman, 1928a), especially the dry eastern wind from the desert (*Khamsin*). If western winds prevail, they bring a lot of dew and even thunderstorms in summer – and might make it possible to cut wheat and barley already in March before the seed production starts. This allows hay collection while the cereals will still provide a normal harvest in May or June (Dalman, 1928a). Dalman estimates that dew is of utmost importance: summer crops would not grow without it, and the region might look like a desert during summer if dew was missing (Dalman, 1928a). According to Purschke (1990), a *Khamsin* may last up to one week and has a catastrophic impact on harvests. One can summarise that even the best annual proxies like tree rings and warves provide only estimates how the harvests looked like. It is very likely that a part of the bad or below-average years locally led to complete crop failures. In this context, the impact of climate variations changes regionally. For example, a 50 mm reduction of average annual rainfall as calculated from the Soreq cave speleothem record for the early Arab period (Bar-Matthews et al., 1998) could mean 100-150 mm for the eastern plains (Nützel, 1976, Lucke, 2002). In percent, a precipitation reduction by 8% in the well-watered highland like at Soreq cave could mean 20-75% less rain in the eastern plains, which are the main production areas for staple crops.

7.2 Soil fertility, terraces, field patterns, and runoff farming

7.2.1 Soil fertility

According to Jordanian farmers (pers. comms., Wadi el Arab, 2003), and Dalman (1932), Rendzinas and are not as fertile as Terrae Rossae. Basalt Soils are the best, while caliche crusts store moisture and

are good for forest, but not suited for agriculture. Purschke (1990) found that there is no major difference of nutrient levels between Rendzinas and Terrae Rossae: the cation exchange capacity numbers 55 mval/100 g in Rendzinas, and 50-75 mval/100 g in Terrae Rossae. Yet, the high contents of calcium carbonate in Rendzinas may lead to a fixation of phosphorus.

According to the National Soil Map and Land Use Project (NSM&LUP, 1993), soils in Jordan show a general N-deficiency. Manure with artificial fertiliser is however not recommended. On the one hand because it is expensive and may not be compensated by the additional return if there is not enough rain. On the other had, sufficient rain is necessary to dissolve the fertiliser which otherwise will poison plants. In the light of the highly variable rainfall, only manure with organic material is recommended, which does not only improve the nutrient level, but also the water-holding capacity.

Since water supply is decisive for harvests in the Decapolis region, plant-available moisture is a very important factor of soil fertility. But as discussed in chapter 4.2.4, the texture of the calcareous soils is difficult to determine as calcium carbonate has to be removed, and it is not possible to distinguish between primary and secondary carbonates. A solution might be the year-round weighting of soil blocks in the field as conducted by Singer et al. (1998). As discussed in chapter 4.2.1, their results indicate that secondary carbonate in Mediterranean Red Soils has little impact on the moisture holding capacity. Things are different with primary carbonates: according to Purschke (1990), the density of Terrae Rossae is 1.6 g/cm³, and their plant-available moisture capacity ~23%, which is low and due to the high clay content. But the plant-available moisture capacity of Rendzinas numbers only ~13%, and their density 1.2 g/cm³, which is marginal for permanent crops.

We can also utilise plants as indicators for water and fertility. As discussed by Ackermann et al. (2004), *Sarcopoterium spinosum* is very resistant to heat and drought. It spread rapidly at the end of the Byzantine period, a typical indicator for abandoned fields (Baruch, 1990). As well, it continuously occupied a berm representing the spoil of an ancient siege ditch close to the site of Tell es-Safi (Ackermann et al., 2004). As it seems, primary carbonates have a bad water-holding capacity since the berm is nearly exclusively occupied by *Sarcopoterium spinosum*. In the light of the thin section discussed in chapter 4.6, this pattern is not surprising since the ruin soils consist mainly of microfossils and small rock fragments. According to Ackermann et al. (2004), *Sarcopoterium spinosum* prefers rock-free areas. Rocky areas at Tell es-Safi had woody vegetation, but which on the berm only occurred at rock boulders, indicating how rocks and their fissures are connected with plant-available water.

The nutrient level seems generally overruled by soil moisture and rainfall, which may also directly be connected with nutrients supply: according to Singer et al. (1992), dustfall on Mount Carmel provides 100% of the nutrients requirement of pine forest. However there are regional differences,

again indicated by plants: according to Danin (2006), *Laurus nobilis* dominates Terrae Rossae of Galilee because of low magnesium levels, which again speaks against Saharan dust as main soil parent material (see chapter 4.4).

In conclusion, the Jordanian farmers' opinion that Terrae Rossae are better than Rendzinas is correct, because the red soils store more water. Also, P-fixation may take place in Rendzinas. These two prevailing soils represent the pattern described in Jesus' parable of the sower (Matthew 13:3-23). Seeds will sprout quickly on Rendzinas as they warm up faster, but are more endangered by the summer drought than on the deep and clay-rich Terrae Rossae. The biblical narrative suggests that the present soil pattern was well-known in antiquity, and although cation exchange capacities were not studied in this thesis, there is no indication that nutrient losses led to an overall reduction of productivity.

The main process reducing fertility seems not erosion of topsoil, but calcareous additions. Accumulation of calcareous material seems closely connected with reduced leaching. In this context, long-term climate change may alter soil properties, and may not only be related to CaCO₃-levels: for example, Imeson and Lavee (1998) found that higher temperatures may lead to reduced aggregate stability. According to Bens et al. (2006), increasing dryness may lead to hydrophobic behaviour, reducing infiltration and increasing runoff. As well, the soil's resistance to root growth may increase, leading to reduced biomass. However, the comparison of present soils in the Decapolis region with the available paleosols indicates that these processes were not relevant for historical time frames, or were quickly reversed under improved conditions. But a more thorough investigation is needed to examine whether, when and how global warming may trigger soil transformation.

7.2.2 Terraces

The narratives postulating degradation after the Muslim conquest of the Decapolis region attributed environmental decay among other reasons to a lack of terrace maintenance. However the area investigated in this thesis is devoid of terraces. Remains of field stone walls could only be found on the slightly sloping hills of el-Wustije, but seemed not connected with retaining soil (see fig. 16). It is interesting to note that there are no ancient written sources referring to terraces – either they did not exist, or were not considered important (Grove and Rackham, 2003). In the context of the disappointing results from the Zarqa-river basin (GTZ, 1991), it appears questionable whether terraces are an efficient way of soil conservation. As already discussed in the introduction, the Zarqa-river basin project found that it is modern machinery and not traditional land use which aggravates the impact of heavy rainfall (GTZ, 1991). Especially the bulldozing of "false terraces" into the soft chalk of

the slopes has negative impact, although it is feasible since most crops grow well on the soft rock (Grove and Rackham, 2003). In this context, it should be noted that 95% of the sediments arriving at dams is not "soil", or even "topsoil", but soft rock (Grove and Rackham, 2003, p. 246).

According to Dalman (1928a), terrace construction in Palestine depended on the yields made possible by them, and on whether the farmers had the time and energy for their maintenance. Dalman observed how the winter floods very frequently destroyed terraces, even if they were well-maintained – and these floods did not only damage terraces, but washed out houses, streets and bridges. For example, strong rain on January 4th, 1917 destroyed all bridges from Salt to the Jordan valley (Dalman, 1928a, p. 209). That such events were not less frequent in the past is indicated by a regulation in the Jewish law regarding responsibilities in the case of house collapses due to heavy rain (Dalman, 1928a). As well, Dalman points out that foreigners often took natural banks of harder limestone for the remains of ancient terraces (see also Koepfel, 1930). In the framework of the MEDALUS project, Grove and Rackham (2003, p. 110) found that terraces in the Mediterranean are far more prevalent in erosion-resistant areas than in unstable ones, and are constructed according to the following reasons (ordered after importance):

- collection of sediments at the slopes
- increasing root penetration
- making a slope less steep
- making a wall with field-stones that might otherwise damage the plough
- increasing water absorption
- creating a foothold for fruit trees
- erosion control

The last point is a double-edged sword: terraces control sheet erosion, and may control gully erosion if well designed, but will worsen it if badly made. There is no effect on wind erosion. Terraces may however aggravate slumping since they bring extra weight on the karstic rock, and their moisture holding capacity may lubricate slip planes within the rock (Grove and Rackham, 2003). Since the greatest part of colluvia in Jordan was eroded in form of earth slumps, terraces might contribute to the problem. In the general context of the Mediterranean, there is no evidence that terraces ever protected deep and well-developed soils. For example, 50 cm thick brown terrace soils overly red, clayey and sherd-free remnants of Early Holocene or Pleistocene soils near Methana (close to Athens). The slope soils were long eroded before the terraces were made (James et al., 1994). More examples can be found in Grove and Rackham, 2003, p. 112 – according to these authors, the best measure against erosion is (any) vegetation cover, but which depends on moisture. In summary, terrace construction makes sense

if the population density is so high that the slopes have to be cultivated, but has little relevance for the overall agricultural productivity.

7.2.3 Field systems

Land fragmentation in Jordan is a greater obstacle for productivity than soil properties (Barham, 1979). When the Ottomans introduced land registration in the 19th century, many peasants did initially not register their land as it required them to pay taxes and serve in the army. In this context, part of the empty villages observed by the early travellers may not have been deserted, but temporarily left due to the semi-nomadic lifestyle of their inhabitants (Shami, 1987). But even after the Ottomans had enforced registration, a great part of the cultivated land remained in communal but non-egalitarian use (*Musha'a*). It was re-distributed every 2-3 years (Barham, 1979). As this involved a lot of disputes, the Jordanian government conducted a re-registration and surveying of the land during 1928 – 1933 ("mother landmark").

In contrast to other Arab countries, there never was an agrarian reform in Jordan (Barham, 1979). Therefore property rights remained unchanged and holdings were more and more split due to the Islamic inheritance law. This led to a lack of capital for investments, and was an obstacle for agricultural mechanisation (Lanzendörfer, 1985). For example, highly mechanised wheat cultivation is only possible on the Irbid and Madaba plains (Barham, 1979). The inheritance law did however not necessarily lead to a splitting of fields: land might have several owners who share the revenues in varying agreements with those who cultivate the fields – and tribes are cautious that their lands remain connected (Wählin, 1993). Even though this pattern does not allow to maximise yields and use heavy machinery, it seems environmentally advantageous from a traditional point of view as it leads to diversification. In the light of the strongly varying landscape and precipitation, diversity is an advantage as it provides more security against bad years. As well, mass-production for export and a strong dependence of agriculture lead to dependency on world market prices. In the case of some African countries, the collapse of banana prices caused a breakdown of the economy, leaving a deserted countryside since subsistence economy had been abandoned in favour of plantations. The consequences were a dramatic disintegration of the society and quick growth of slums (Lachmann, 1999a). In this context, the very traditional structure preserved in Jordan may not only have favoured soil scientists looking for historic field patterns. Village subsistence economies are still basically intact, and careful investment led to a slow introduction of machinery although most people work in the cities to secure an additional income (Lanzendörfer, 1985, Purschke, 1990).

While the traditional field systems are not suited for heavy machinery, they can still be very productive if labour is invested. According to Barham (1979) and Wählin (1993), there is a hierarchical order of fields. The best soils close to the villages are planted with vegetables, wine and olives, and irrigated if possible. These areas are very carefully weeded and manured with organic garbage. Secondary areas a little more distant from the villages are usually planted with olives, sometimes in undercropping with cereals and leguminosae. Stones are only partially removed from the fields to retain moisture. Tertiary areas host wheat fields (Barham, 1979). Interestingly, this pattern is very similar to the one Dar (1986) described for Iron Age agriculture in Israel. In this context, olives, grapes and vegetables are "cash crops", while wheat provides the basic staple food. Again, the traditional pattern seems better than its reputation: for example, the German colonists at Haifa took the missing removal of stones as another sign of Arab laziness (Schumacher, 1890). However Dalman (1932) points out that removing them does not make much sense since the plough brings always new stones to the surface, and actual research indicates that the stones indeed retain moisture (Whiting et al., 2006).

Missing dung from cattle is however a difference to antiquity, and many Arab villages collected their garbage at a central location instead of making it fully available for manure (Dalman, 1932). Here, agricultural knowledge was lost – but the Muslim conquest is probably the wrong timing for this development. Watson (1981) found that the Umayyad and Abbasid periods did not see an invasion of shepherds, but land use systems being repaired and high agricultural investments made. According to Watson (1981), the early Muslim period saw in fact a green revolution and intensive agriculture: irrigated and rain-fed crops were grown in rotations and under sophisticated manure system, making fallow periods unnecessary. The early Arab agriculture was based on experience, and their writers knew and to some degree refuted the recommendations by ancient authors, if they could not be proven by experiments. So the early Muslim agriculture was the first scientific agriculture, but required a lot of investment in form of capital and labour (Watson, 1981). During the 8th and 9th century, a great agricultural surplus was produced in Mesopotamia, and many new cities founded (Watson, 1981). Increasing production led also to a strong industry, high wealth and rapid expansion of trade, yet the Decapolis region was spared of this boom. We can conclude that a lack of agricultural skills may to some degree be relevant for the state of 19th-century Palestine, but is not suited to explain the decline of the Decapolis region. The traditional field pattern makes optimal use of the environment, but is too labour intensive to compete with world market prices. That the land is still highly productive is also shown by the example of Israel (Richter, 1979).

7.2.4 Runoff farming

Agriculture in marginal areas close to deserts is often connected with runoff farming. This pattern is not present in the investigation area, but shall shortly be outlined since it has relevance for the abandonment of ancient cities in today's steppe, and is similar to risk agriculture like in Mafraq. It has been claimed that runoff farming never made the supply of ancient cities possible, but that e.g. the famous Byzantine sites in the Negev depended on trade (Karmon, 1994). However, papyri from the 6th and 7th century AD found in the ruins of Nitzana mention the growing importance of locally produced wheat and barley for the economy and supply of the cities (Bruins et al., 1987). They imply an amount of rainfall and runoff, and a seasonal distribution of rain, that was sufficient for the production of food crops in the Negev. In this context, it is remarkable that wheat is the dominant crop mentioned in the papyri although it is more sensible to drought than barley. Bruins et al. (1987) suggest that stockpiles had to be gathered for bad years – and here the frequent "unplastered cisterns" could play a key role. These structures seemed enigmatic, but could be connected with the storage of wheat which would desinfect itself due to degassing of CO₂ if closed hermetically (Dar, 1986).

How productive flood farming can be is discussed by Shaw (1982), who reviewed historical sources. Simple earth and stone dams are the best way to collect winter floods, which are damaged every year, but quickly rebuilt. The relation of the catchment area to the fields is about 20:1, enabling an increase of water supply from ~100 mm rain to 300-500 mm. The returns of flood farming number usually 1:8, but in good years 1:100 and more, which is extraordinary for ancient agriculture (Shaw, 1982). There should be at least one good year in ten. In comparison, ancient yields in rain-fed areas reached normally a relation of 3:1 to 4:1, and in good years up to 12:1 or 18:1 (Shaw, 1982). But there should be one good year in five in the rain-fed areas. The exceptional high returns possible from flood farming seem to be connected with the high nutrient levels of the virgin desert soils and sediments, and might explain why North Africa was Rome's grain basket. In this context, it is interesting to note that strong floods washed out check dams and runoff-fields in Cyrenaica at the end of the Byzantine period (Vita-Finzi, 1969). It can be concluded that the steppe and desert could be successfully farmed using runoff plots, but only as long as rains were sufficient and floods not too strong.

7.3 Ancient trade, economy and food transport

In this chapter, ancient trade and economy shall shortly be outlined in order to evaluate the relevance of local changes for regional developments. According to Rathborne (1983), ancient farmers followed a

mixed cereal economy: wheat was preferred because of its better taste, but barley was always produced simultaneously for emergency and fodder. This subsistence economy had normally 40% overproduction to keep a 1-2 years reserve in case of bad harvests (Garnsey, 1988). Reserves were especially important in rural areas without access to ports: the limited and expensive land transport facilities did not allow to supply inland areas in case of food shortages. This is also the reason why *Metropoleis* were always situated at the sea (Garnsey, 1983).

The importance of water lines for supply was discussed by Whittaker (1983) for the case of the Roman borders. Many were located close to rivers although this was not always the optimal defensible line, especially since the areas on the other side of the rivers were often under Roman control or allied. But it was necessary to secure the supply of troops – for example, it is estimated that the provinces of Germania inferior and Germania superior were not able to support the troops stationed there, but depended on imports from England (Whittaker, 1983). In this context, cities like in the Decapolis and the Negev could only survive if the necessary agricultural goods were produced in the vicinity. Things were different with less quickly perishing products like wine and olive oil, which could be exported. That agricultural products were behind the wealth of the Decapolis cities is clearly indicated by the depictions of grapes, olives and other agricultural products in the art (Fuller, 1987).

Regarding the efficiency of Roman-Byzantine agriculture, as well as early Muslim farming, we probably have to envisage systems that were far more specialised than the Palestinian agriculture of the 19th century. Even though the basic field patterns remained the same, Kuhnen (1990) found indicators for increasing concentration of land and rising productivity during the late Roman period. Kron (2004) concluded from ancient texts and bones found in excavations that the Romans could breed larger cattle than possible during the earlier antiquity or medieval period, which is of great importance for assessing their economy. Advances in cattle breeding were decisive for agricultural revolution in Europe during the 19th century as well (Müller, 1986). Breeding tall cattle variants is only possible if they receive nutritious fodder and are not only grazing. It also seems that fields in the highlands were laid idle for some years and seeded with especially nutritious pasture during the Roman period, where the livestock was grazed in summer to avoid the heat (Kron, 2004). In combination with Roman aquaculture, which seemingly exceed even the production rate of present systems (Kron, 2006), agricultural intensification made high yields and a very nutritious diet possible, which is indicated by taller skeletons from the Roman imperial period (Kron, 2004). However, breeding large cattle variants only makes sense if a certain level of urbanisation and demand for meat is given (Kron, 2006).

In this context, it seems likely that the Roman-Byzantine period witnessed agricultural intensification due to population growth as outlined by Boserup (1965). She suggested that population

growth does not lead to over-exploitation of the land, but to intensification of agriculture. Migration to the cities and unemployment take place and enforce advances in agricultural production. Intensification however requires more labour input, and the economy is endangered if the required labour force is missing. This pattern seems to fit well to the situation in the late Byzantine period, when land use installations in the Decapolis region seemingly suffered from a lack of available labour (Geraty and Herr, 1989). According to Boserup (1965), Malthus' theory of collapse due to overpopulation and following regeneration is wrong: regeneration of a complex society is only possible if population growth takes place. She assumes that the Neo-Malthusian theory is also wrong: overpopulation does not lead to the destruction of the land, indicated by examples like Japan and Java where growing populations did in fact improve the fertility of the land.

According to Whittaker (1983), cereal production in the northern border areas of the Roman empire was reduced during the Late Roman period, probably because imports from the Roman core territory, the Black Sea and Egypt were cheaper. This context might represent a market economy made possible by population growth and a very sophisticated, intensive agriculture. However, the dependence on a market economy might also have contributed to the collapse of the empire. The food demands of the late Empire grew dramatically, i.a. due to the doubling of the army and increase of cavalry, which requires four times as much food than foot soldiers (Whittaker, 1983). As well, many romanised Germanic tribes had become dependent on Roman food imports, which might explain why Alaric offered to spare Rome from plunder if offered an annual ratio of grain (Whittaker, 1983). But perhaps this offer had to be rejected since the vast wheat fields around the Black Sea been turned into pasture for Hunnish horses. According to Whittaker (1983), famine was doubtless behind the great migration.

7.4 Summary of agriculture and food supply

The limiting factor for agriculture in the Decapolis region, as well as the Mediterranean and steppe areas in general, is moisture. If the water supply is secured, manure can elevate yields. Flood farming on virgin desert soils could in this context be extraordinarily successful for the standards of antiquity. Ancient agriculture seemingly developed systems optimal adapted to the environment, which were still present in the Palestine of the 19th century. The main difference to antiquity was however the level of intensification. Population growth during the Roman-Byzantine period, and the early Arab period in Mesopotamia, made the construction and maintenance of sophisticated water systems possible which led to a market economy. The sea trade was most relevant for the supply of bigger cities and armies,

7. Agriculture and food supply

and led to a decline of agriculture in less productive areas. Inland cities like the Decapolis depended on locally produced staple foods like cereals, which could not be transported in great amounts over land. However this looked different with "cash crops" like olive oil and wine, which were easier to transport since they do not perish quickly, and were a main source for the cities' wealth. The intensity and efficiency of agricultural production during late antiquity made the economy however vulnerable to crop failures.

8. Climate, desertification and historical developments

*And I saw when the Lamb opened one of the seals,
and I heard, as it were the noise of thunder, one of the four beasts saying, Come and see.
And I saw, and behold a white horse: and he that sat on him had a bow;
and a crown was given unto him:
and he went forth conquering, and to conquer.
And when he had opened the second seal, I heard the second beast say, Come and see.
And there went out another horse that was red:
and power was given to him that sat thereon to take peace from the earth,
and that they should kill one another: and there was given unto him a great sword.
And when he had opened the third seal, I heard the third beast say, Come and see.
And I beheld, and saw a black horse;
and he that sat on him had a pair of scales in his hand.
And I heard a voice in the midst of the four beasts say,
A measure of wheat for a penny, and three measures of barley for a penny;
and see thou hurt not the oil and the wine.
And when he had opened the fourth seal, I heard the voice of the fourth beast say, Come and see.
And I looked, and behold a pale horse: and his name that sat on him was Death,
and Hell followed with him.
And power was given unto them over the fourth part of the earth,
to kill with sword, and with hunger, and with death, and with the beasts of the earth.*

Revelation 6:1-8

8.1 Historical developments in the context of climate

Climate reconstructions of the Near East became increasingly precise in the recent past. As well, the resolution and correlation of proxies was improved. Three of the most prominent climate reconstructions are summarised in fig. 64, each based on different proxies. Gvirtzman and Wieder (2001) based their climate reconstruction on soil development in the coastal plain of Israel. They could establish the longest possible record, but only draw relative estimates of moisture levels. In comparison, Bar-Matthews et al. (1998) based their research on δO^{18} - and δC^{13} -values from the Soreq cave speleothem, and were able to calculate average annual rainfalls at the cave. Their reconstruction shows a high degree of similarity to the curve from Gvirtzman and Wieder (2001), but differs in some details. For example, the cold and dry spell during the Last Glacial Maximum was recorded by the speleothem, but not the paleosols. In contrast, the cold and dry conditions during the Younger Dryas are strongly shown by the paleosols, but not the speleothems. Gvirtzman and Wieder (2001), explained this apparent contradiction with the character of pedogenesis: as long as sedimentation stays below a certain threshold, pedogenesis continues and no change is visible. However, when sedimentation is very fast and abrupt, as during the Younger Dryas, soil development is interrupted. This also gives an indication that dust deposition during the Younger Dryas must have been more severe than during the Last Glacial Maximum. In comparison, the absence of the Younger Dryas in the speleothem record is explained by the obscuring impact of irregular thin laminae and much detritus (see Bar-Matthews et al., 1998) which formed in the speleothem during this period. Migowski et al. (2006) reconstructed levels of the Dead Sea according to cores drilled in the lake, and sediments exposed at the shores. Again there is a high similarity between the paleosols and lake record, but it seems that the Dead Sea recorded also events too short to be reflected by the other proxies. As concluded by Gvirtzman and Wieder (2001), the different proxy records seem not to contradict, but to complement each other since each proxy has a different sensitivity.

A detailed discussion of the climate reconstructions is out of the scope of this thesis. However some conclusions can be drawn, which fit the results of soil analysis discussed in the previous chapters:

1. The Decapolis region was significantly moister during the Pleistocene. Apart from many fluctuations, there seems to be a general trend towards increasing dryness.
2. Short and dry periods were connected with incision, dust deposition and massive erosion.
3. Periods of elevated settlement activity coincide with moist periods. The last which was significant enough to leave a trace in soil development ended with the Byzantine period. In this

context, "desertification" seems a natural process related to moisture fluctuations and a subsequent move of the desert fringes.

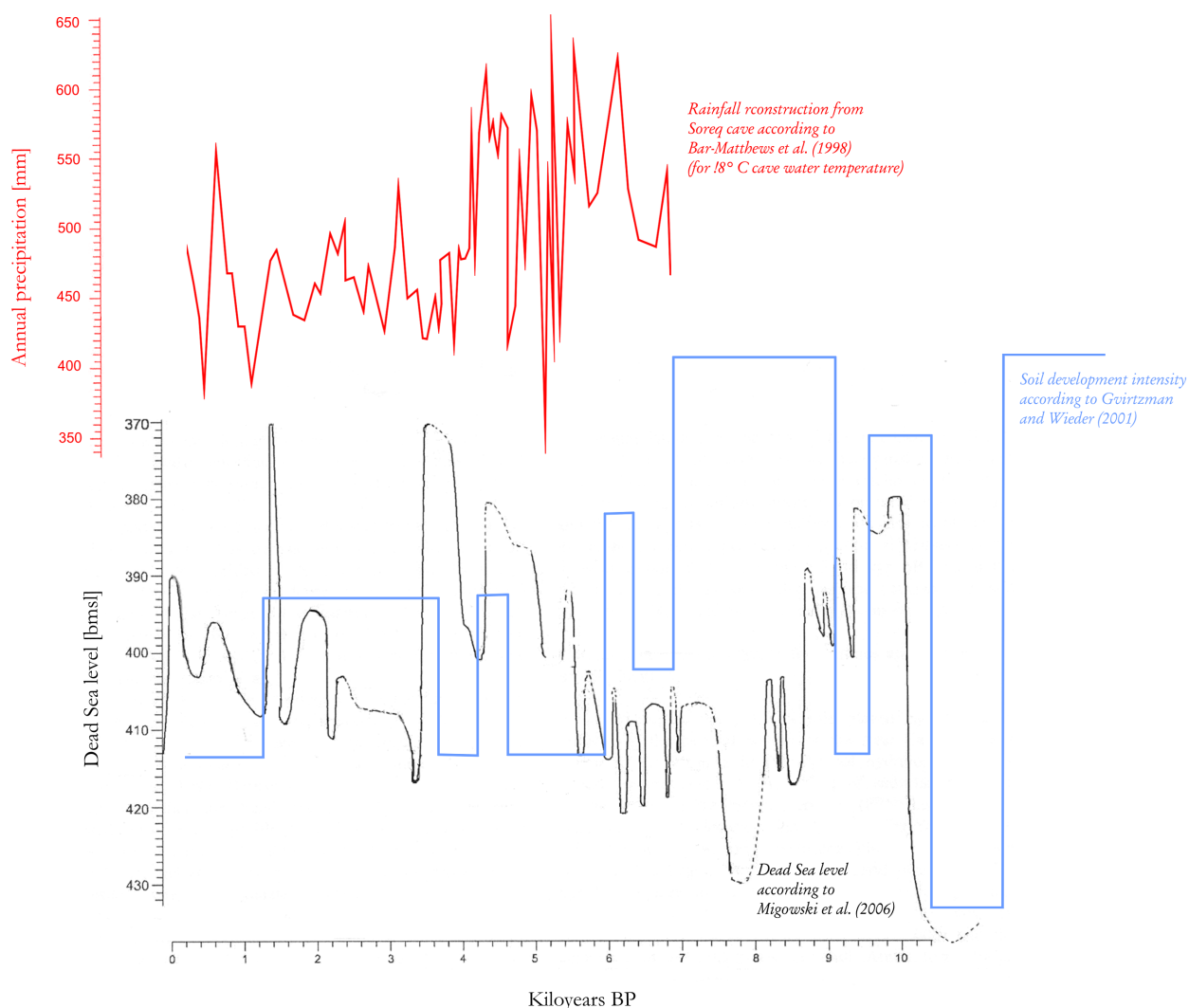


Figure 64: Diagram showing climate reconstructions from different proxies: Dead Sea levels (black; re-drawn according to Migowski et al., 2006), rainfall reconstruction from Soreq cave (red; re-drawn according to Bar-Matthews et al, 1998), and relative soil development intensity (blue; re-drawn from Gvirtzman and Wieder, 2001). Note that the soil development intensity is only relative and has no scale. The different time-resolutions of the reconstructions also imply a scale-error.

The simplicity of the above described relationship could lead one to connect the ups and downs of historic societies with climatic fluctuations. This is the approach suggested by Issar and Zohar (2004), related to the Neo-Deterministic school of thought. According to Issar and Zohar (2004), Occam's razor should be applied to history, and not the search for a complex solution continued if a simple explanation can be given. However many colleagues consider the Neo-Deterministic approach as simplistic and unable to take human technology into account. Migowski et al. (2006) concluded in this context that settlement fluctuations until the Early Bronze Age were related to climate variations, but

not thereafter. What might have contributed to their assessment is a very high lake stand at the end of the Byzantine period, which was only recently documented.

But let us closer examine this Dead Sea level. It is a very short, very pronounced high in a period of otherwise low lake levels. The key for understanding this shoreline is given by the sediments in the theatre of Beit Ras, and by Roman piers in the Lake of Galilee. According to Hazan et al. (2005), the Lake of Galilee levels follow the pattern of the Dead Sea, and indicate a rapid rise in the early Arab period – but with high-energy transport of sediments, represented by boulder-bearing strata burying Roman docks and piers. Massive floods must have swept through the region during this time, also burying the theatre of Beit Ras. It does not seem that this period was characterised by particularly elevated precipitation, since there is no such indication in the speleothem record or the paleosols. In fact, these lake level variations seem to describe a sudden dramatic increase of extreme events, possibly connected with otherwise dry conditions. They might have taken place during a very short period of perhaps less than a century, which is indicated by the very short rise of the Dead Sea curve. In this context, it is interesting to note that there are historical indicators for severe regional floods during this time: The famous dam of Marib in Yemen broke 575 AD, and the great Nimrud-dam at the Tigris 627 AD, creating a big swamp that is still present today (Watson, 1981). Were these events related to insufficient maintenance due economic decline, or simply unprecedented amounts of water? It is very likely that economic decline was connected with *climatic anomalies* as represented by such floods.

8.2 The four horsemen of apocalypse

When the impact of climate change on ancient societies was discussed, the argumentation usually assumed a linear relationship: less water meant less crops, and thus famine. This follows the idea outlined by Bryson and Murray (1977), who showed that certain climatological conditions may cause severe droughts over the Peloponnese and other areas in the Mediterranean. The concept is in the tradition of desertification research as outlined in the introduction, assuming that e.g. the cutting of forest might lead to a lack of rain, soil erosion and famine. This pattern has been widely transferred to other examples, attempting to explain the ups and downs of societies with rainfall variations, and was subsequently criticised for being mono-causal. Critics argued that plagues, earthquakes, wars, politics, technology and economic developments can have a much greater impact than bad harvests due to drought, and that some societies managed to cope with dry conditions while others did not. But are these events always independent from each other? The biblical narrative suggests that the four

horsemen of apocalypse belong together. To illustrate this point, let us review a first-hand report of famine in Edessa (Syria) from 499 – 501 AD.

The chronicle of Joshua the Stylite (Wright, 1882), from Garnsey, 1998, pp. 3-6:

"The year 499 AD. [...] In the month of Adar [March] of this year the locusts came upon us out of the ground, so that, because of their number, we imagined that not only had the eggs that were in the ground been hatched to our harm, but that the very air was vomiting them against us, and that they were descending from the sky upon us. [...] And because the locusts had devoured all the crop, and left neither pasture nor food for man or beast, many forsook their native places and removed to other districts of the north and west. And the sick who were in the villages, as well as the old men and boys and women and infants, and those who were tortured by hunger, being unable to walk far and go to distant places, entered into the cities to get a livelihood by begging; and thus many villages and hamlets were left destitute of inhabitants. They did not however escape punishment; for the pestilence came upon them in the places to which they went, and even overtook those who entered into Edessa; about which I shall tell presently to the best of my ability, though no one, I think, could describe it as it really was. [...] Hunger affected the people more and more. Everything that was not edible was cheap, such as clothes and household utensils and furniture, for these things were sold for a half or a third of their value, and did not suffice for the maintenance of their owners, because of the great dearth of bread. At this time our father Mar Peter set out to visit the emperor in order to request him to remit the tax. The governor, however, laid hold of the landed proprietors, and used great violence on them and extorted it from them. [...] The poor were in straits, because they had not money wherewith to buy bread; [...] so that the people actually dared to enter the holy places and for sheer hunger to eat the consecrated bread as if it had been common bread. Others cut pieces off corpses, that ought not to be eaten, and cooked and ate them. [...]

The year 500 AD. In this year, after the vintage, wine was sold at the rate of six measures for a dinar, and a kab of raisins for three hundred numia. The famine was sore in the villages and in the city; for those who were left in the villages were eating bitter-vetches; and others were frying the withered fallen grapes and eating them, though even of them there was not enough to satisfy them. And those who were in the city were wandering about the streets, picking up the stalks and leaves of vegetables, all filthy with mud, and eating them. [...] The whole city was full of them, and they began to die in the porticoes and in the streets. After the governor Demosthenes had gone up to the emperor, he informed him of this calamity; and the emperor gave him no small sum of money to distribute among the poor. And when he came back from

his presence to Edessa, he sealed many of them on their necks with leaden seals, and gave each of them a pound of bread a day. Still, however, they were not able to live, because they were tormented by the pangs of hunger, which wasted them away. [...] Children and babes were crying in every street. Of some the mothers were dead; others their mothers had left, and had run away from them when they asked for something to eat, because they had nothing to give them. [...] The pestilence became worse about this time, namely the month of the latter Teshri [November]; [...] For a report had gone forth throughout the province of Edessa, that the Edessenes took good care of those who were in want; and for this reason a countless multitude of people entered the city. [...] Dead bodies were lying exposed in every street, and the citizens were not able to bury them, because, while they were carrying out the first that had died, the moment they returned they found others. [...] In short there was a dearth of everything edible. In the month of Nisan [April] the pestilence began among the people of the city and many biers were carried out in one day, but no one could tell their number. And not only in Edessa was this sword of the pestilence, but also from Antioch as far as Nisibis the people were destroyed and tortured in the same way by famine and pestilence. Many of the rich died, but not of hunger; and many of the grandees too died in this year. [...]

The year 501 AD. In the months of Khaziran [June] and Tammuz [July], after the harvest, we thought that we might now be relieved from dearth. However our expectations were not fulfilled as we thought, but the wheat of the new harvest was sold as dear as five modii for a dinar [...]."

As can be seen, the events at Edessa follow a certain order:

- first there is a plague of locusts
- bad harvests follow
- food supply in the countryside becomes critical, and people migrate to the cities
- emergency food and things that are not edible are consumed
- finally pestilence breaks out amongst the densely concentrated, weakened people.

The final remark is very revealing: "many rich died, but not of hunger". Famine, in itself bad enough, triggered a plague which caused the greatest casualties. But all the events show some relation to climatic *anomalies*.

Let us first consider the plague of locusts: this is an indicator of unusual weather in the desert. During the first joint meeting of ICSU and IGCP 490, January 2004 in Mauritania, the participants enjoyed unusual cool and rainy conditions in the Sahara, and could observe many groups of solitary locust that were changing to the gregarious form. These soon became the largest infestation of Desert

Locusts in West and North Africa since more than 15 years and affected a number of countries in the fertile northern regions of Africa (FAO, 2004). A first increase of Desert Locust (*Schistocerca gregaria*) breeding activity was noted in autumn 2003 when four unrelated outbreaks occurred simultaneously in Mauritania, Mali, Niger and Sudan¹³. Shortly thereafter, *unusually heavy rain fell for two days* over a large area that extended from Dakar, Senegal to the Atlas Mountains in Morocco. Some areas in Western Sahara received more than 100 mm of rain where about 1 mm per year is normal. Consequently, ecologically conditions remained favourable for at least six months and allowed several successive generations of Desert Locust breeding. By early 2004 swarms of locusts started to move north into important agricultural areas in Morocco and Algeria. During the summer of 2004, large swarms invaded the Sahel in West Africa. As the year progressed, the swarms migrated over the continent, and in November 2004 appeared in northern Egypt, Jordan and Israel for the first time in 50 years. One swarm in Morocco between Tarfaya and Tan-Tan was 230 km long, at least 150 m wide, and contained an estimated 69 billion locusts (Ullman 2006). Lack of rain and cold temperatures in the winter breeding area of Northwest Africa slowed the development of locusts down and allowed control agencies to stop the cycle in early 2005. We can conclude that none of the available proxies will record plagues of locusts or other pests, but their impact can be very severe, and is connected with climate fluctuations.

Let us now turn to the bad harvests at Edessa. Droughts might lead to food shortage, but not necessarily to famine (Garnsey, 1988). The occurrence of famine required several consecutive bad years, and its frequency varied regionally. Garnsey (1988) points out that food crises in antiquity were common, appearing from time to time, but were not always serious. Food shortage has to be distinguished from famine, which was a catastrophe, but rare. In this context, it is important to note that not only droughts led to bad harvests. For example, the island of Samos was well known to be susceptible for food crises, but most of which were not due to insufficient precipitation, but excess rainfall (Garnsey, 1988). Not only droughts, but climatic irregularities are behind famines, especially if occurring suddenly, severely and unexpectedly. They are not only connected with rainfall, but with frosts, pests, deluges, hail and storms. Such events never ceased, but probably were much more frequent during the time represented by the quickly rising levels of the Dead Sea and the Lake of Galilee in the early Arab period. To illustrate how they could have looked like, let us listen to Schumacher (1913) who observed a "weather catastrophe" in the Decapolis region:

"Am 18. Mai dieses Jahres fielen außerordentlich heftige Regenmengen in der Gegend des

¹³ See FAO locust watch, <http://www.fao.org/ag/locusts/en/info/info/index.html>.

mittleren *hamad*, südlich vom *hauran* sowie östlich der Hedschasbahn zwischen *ed-dschize* und *el-katrani*. Nach übereinstimmenden Berichten der Beamten dieser Bahn füllten sich die bereits leeren, großen, alten Wasserbehälter bei den Stationen von *ed-dschize* (eigentlich *kal'at ziza*) in zwei bis drei Stunden. Diese Wasserbasins fassen je 70 bis 75000 cbm! Die Regen fielen am Nachmittage des 18. Mai so plötzlich und wolkenbruchartig, daß Menschen aus den Bedouinenlagern, Kamele, Schafe und auch wilde Tiere durch die ungeheuer rasch anschwellenden Fluten hinweggeschwemmt und getötet wurden. Begleitet von einem orkanartigen Sturm, endete der Regen mit einem Hagelwetter. Die Hagelkörner lagen noch stundenlang bis 0,80 m hoch um die Bahnstationen herum. [...]

Die abfließenden Regenmengen verteilten sich namentlich in die Wasserläufe des *wadi ez-zerka* (Jabbok) und des *wadi esch-schellaleh*. [...] Der Fluß [Yarmouk] war sonach in 20 Minuten bei einer Breite von rund 60 m um 3,20 m bis 3,30 m gestiegen. [...] Als ich am 20. Mai 1913 nach *el-makarin* kam, fand ich längs der Felswände des Flußrandes die Spuren der vorangegangenen Flut. [...] Die Regenmengen hatten auch die Bahnlinie an gewissen Orten überschwemmt und Schaden angerichtet.

Ähnliche Regengüsse sollen zwar in Abständen von zehn bis zwölf Jahren in der arabischen Wüste sich ereignen, jedoch nicht mit solcher Vehemenz wie in diesem Vorsommer."

From: Schumacher 1913, pp. 314-315.

A greater frequency of such events would not only be very damaging for crops, but also have a devastating impact on any kind of land use installations. Cisterns would silt up, water collection dams be swept away, and streets and bridges be damaged. There are differences between the negative impacts of climate variations, as discussed in chapter 7.1: a bad distribution of rain may lead to bad harvests, but very extreme weather might cause the complete loss of crops.

In the case of Edessa, famine broke out due to two subsequent bad harvests combined with a plague of locusts. It is very likely that drought alone might have produced only a minor food shortage, and given rural communities enough time to prepare themselves, or move to other regions with better supply. Gallant (1991) suggested that droughts do not generate disequilibrium, but reveal a pre-existing one. In this context, land fragmentation and diversification are strong means against crop failures, but late Roman intensification of land use may have led to a greater vulnerability. As well, it is worth to consider the response of the Edessan authorities. According to the report of Joshua the Stylite, the famine could have been mitigated earlier had the rich not profited so much from rising grain prices. According to Garnsey (1988), it would have been possible to transport grain over long distances on

land during famine, even if it was slow and expensive – but as it seems the authorities showed mostly no interest. In the case of Edessa, it took a year until the emperor and the church intervened, persuading landowners to share grain with the poor and distributing bread. Yet it was already too late to stop the pestilence, and the generosity of Edessa's governor attracted more of the hungry to the city, aggravating the plague. It is interesting to note that basically all of the few preserved written reports of famine mention an epidemic (Garnsey, 1988). This pattern repeats later, and is also true for the most famous historical disease: before the outbreak of the Black Death, the Great Famine ravages.

Let us shortly review this event, since it is much better documented than the Byzantine period. In the spring of 1315, unusual heavy rain fell in much of Europe with the onset of the little Ice Age (Jordan, 1996). Throughout spring and summer, it continued to rain and the temperatures remained cool. Under these conditions grain could not ripen, the straw and hay for the animals could not be harvested and there was no fodder for the livestock (Aberth, 2000). The price of food began to rise, growing by as much as 320% in Lorraine (Aberth, 2000). People began to harvest wild edible roots, plants, grasses, nuts, and bark in the forests. In the spring of 1316, it continued to rain, but the population was already deprived of energy and reserve to sustain itself. The height of the famine was reached in 1317 as the wet weather continued. Finally in summer the weather returned to its normal pattern. But by now, people were weakened by diseases such as dysentery, pneumonia, bronchitis, tuberculosis, and other sicknesses, and much of the seed stock had been eaten, that it was not until 1325 that the food supply returned to relatively normal conditions (Jordan, 1996). It is estimated that 10-25% of the population of many cities and towns died during the Great Famine, and although the Black Death killed more people in 1338-1375, many experienced the Great Famine as worse. This is because the Black Death swept through in a matter of months, but the Great Famine lingered for years, drawing out the suffering of those who would slowly starve to death, commit cannibalism, child-murder and rampant crime (Jordan, 1996). According to Jordan (1996), life in Europe became tougher and more violent, which could be seen across all segments of society and seems best expressed in the bloody 100 Years War.

The result also was a mounting human vulnerability to disease due to weakened immune systems. The European economy entered a vicious circle in which hunger and chronic, low-level debilitating disease reduced the productivity of labourers. So the grain output suffered and grain prices stayed high (Barry and Gualde, 2006). The famine was self-perpetuating, affecting life in places like Flanders and Burgundy as much as the Black Death was later to affect all of Europe.

A critical part of the Great Famine was the consumption of non-edible things, and typhoid epidemics were predictors of the Black Death (Barry and Gualde, 2006). In 1318 a pestilence of

unknown origin, perhaps anthrax, hit the livestock. The disease targeted sheep and cattle, further reducing the food supply and income of the peasantry (Vasold, 2003). As well, it put another strain on the economy since the failure of England's wool exports led to the destruction of the Flemish weaving industry, breeding unemployment and poverty. These uprooted people without perspective were a factor of instability in themselves (see Heinsohn, 2003), and probably provided the bulk of the armies fighting in the 100 Years War. The Black Death also made his way into Syria and Palestine, where it coincides with the beginning decline of the Mamluk empire. There and in Europe the plague persisted with local, less virulent outbreaks until it disappeared in the 1700s (Barry and Gualde, 2006).

Although reports from the late Byzantine period are more sparse, the "Justinianic plague" is well attested. According to Little (2007), bubonic plague was endemic in the ancient Near East and theoretically known to Roman medics. It was however only in 541 AD when the plague broke out on a large scale. It first appeared in Egypt, coinciding with the closing of the temple of Isis, a goddess known to teach the cure of diseases (Sarris, 2002). The plague then spread rapidly over the empire, depopulating both cities and rural areas, and eventually contributing to the failure of the *Renovatio Imperii* (Little, 2007). According to Sarris (2002), the depopulation had far-reaching and long-term consequences for the Byzantine empire. For example, it caused inflation and led to a chronic shortage of state finances: the bureaucracy and army became too huge for the population that supported it. But plague was not the only catastrophe: according to Ostrogorsky (1984), the 6th and 7th centuries in Byzantium were characterised by a remarkable accumulation of plagues of locusts, floods, diseases, storms and bad harvests. In the light of the finance crisis, Justinian's successor Justin II. refused to pay further tribute to the Sassanian empire, which resulted in nearly 100 years of war between these two superpowers of antiquity, paving the way for the Muslim conquest. Bubonic plague persisted, breaking out locally and less virulent in rhythms of approximately 12 years, until mysteriously disappearing around 770 AD (Little, 2007).

The Black Death was seen as punishment from heaven by those who suffered from it, and pharisees usually see it as result of god's anger about sinful life. The modern public perception is that an unknown virus or bacterium appeared and caused sickness. That new germs can lead to dramatic death rates is not in question - the destructive power of unknown epidemics is clearly illustrated by the widespread extinction of the Great Plains Indians by smallpox in the 16th century (Snipp, 1991). It was also found that bacteria and viruses can be transported by meteorites (Widauer, 2005). But did the medieval pandemics really "fall from the sky"?

As clearly seen by the description of the Edessan famine, pestilence could only spread so strongly because people were concentrated in the city, and their immune systems weakened. The

Edessan pestilence was probably different from Bubonic plague, which was supposedly the disease of the pandemic in 541/542 AD (Sarris, 2002). However we cannot be sure since a detailed description is missing in Joshua the Stylite's report, and bubonic plague was endemic in the ancient Near East, breaking out locally from time to time before becoming a pandemic (Little, 2007). In this context, the last major occurrence of Bubonic plague took place during the Third Pandemic, starting 1855 AD in China, and lasting until approximately 1900, though it was by far not as virulent as the Black Death. During this time, it was possible to isolate the infectious agent *Yersinia pestis*, the occurrence of which is thought to have caused the pandemic (Bockemühl, 1994). DNA of *Yersinia pestis* was also found in the teeth and corpses of victims buried in mass graves of the Black Death, while absent in others who supposedly died from other epidemics (Drancourt and Raoult, 2002). However, the infectious agent never became extinct, and it is in fact unknown why the pandemics suddenly ceased. The non-plague variants *Yersinia pseudotuberculosis* and *Yersinia enterocolitica* are widespread in fruits and vegetables, and rodent populations in North America, Africa and Asia are still infected with the plague variant (Hoffmann, 1980). Occasional and recent human infections with *Yersinia pestis* are reported as well¹⁴. It has been argued that the plague vanished due to better hygiene, which reduced chances of transmission by rat fleas, and that the black rat (*Rattus rattus*) was displaced by the bigger brown rat (*Rattus norvegicus*), which is not as prone to transmit the germ-bearing fleas to humans during mass die-offs of rats¹⁵. This is due to a different rat ecology, and the brown rat more carefully avoids contact with humans (Appleby, 1980). There is however no clarity and agreement. As well, Scott and Duncan (2004) recently challenged the idea that the Black Death was caused by *Yersinia pestis*. They claim that neither the rapid spread nor the infectious symptoms reported from the Black Death match the Third Pandemic. The incubation period of bubonic plague (4-5 days) is vastly different from the incubation period of the Black Death (37 days), and the fatality rate is highly dissimilar: below 10% for bubonic plague, but over 40% for the Black Death (Scott and Duncan, 2004). They suggest that the Black Death was an Ebola-like virus infection (hemorrhagic fever), which left its trace in about 10% of the European population in form of a mutation of the gene CCR5, providing immunity against some virus infections.

That modern societies are not safe against new plagues was demonstrated by the Spanish Flu 1918 – 1920, a virus infection which killed approximately 50-100 million people, dwarfing the bloodshed of World War I, and then mysteriously disappearing (Tumpey et al., 2005). It is assumed that

¹⁴ See <http://www.health.state.nm.us/plague.html>.

¹⁵ The mass dying of rats preceding plague was hauntingly described by Camus (1947) – although there were no rats in Island when the Black Death broke out there (Karlsson, 2001).

dense troop quarters and mass movements during the war supported its spread, as well as the overall weakened health of people. However, an odd characteristic of this disease was that its victims were mainly healthy young adults, possibly more susceptible to succumb due to the occurrence of a cytokine storm upon infection (Tumpey et al., 2005). In contrast, alternative medical sciences such as homoeopathy see viruses and bacteria not as reasons, but symptoms of infection. According to Vithoulkas (2005), it is the general state of a society which makes pandemics possible or not.

It has to be left open why pandemics occurred at certain moments of history, and why they later suddenly disappeared. In any case, climatic variations likely contributed to the spread of diseases, leading to food shortages and famines, and changing the environments of germs. In this context, climate change might directly impact the occurrence of new germs: for example, three alien cyanobacteria are currently spreading in German lakes, possibly connected with global warming (Stüken et al., 2006). As consequence of pandemics, social networks were destroyed, criminality rose and a general lack of resources may also have triggered wars. So we have the four horsemen of apocalypse together: pests (locusts), famine, war and plague. Not the consideration of climate fluctuations as important driving agents of history means mono-causality, but the assumption that climate change means drought, and that there is a linear relationship between economy, society and climate.

8.3 Feedbacks and thresholds

It would be interesting to learn whether the climate variations recorded by the above mentioned proxies were governed by external forces, or whether internal factors, especially land use changes, played a role too. As well, it is unclear how temperature is related to precipitation fluctuations. While it is clear that the Ice Age was moister, likely connected with a southward move of the westerlies (Issar and Bruins, 1983), the climate-temperature relationship during the Holocene is disputed. According to Issar and Zohar (2004), cool periods were moister. However, cool periods also seem connected with drought as during the Younger Dryas. Treydte et al. (2006) found in this context that the 20th century was the warmest and wettest in Pakistan since 1000 years. Does global warming lead to more precipitation? In any case, it seems likely that cooling periods were connected with the above mentioned anomalies, which might be much more relevant for the environment than drought. The timing seems to fit: while the Mamluk decline coincided with the beginning of the little Ice Age, the Byzantine historian Procopius noted that the sun 'gave light without brightness' and had 'unclear beams' in 536 AD (Arjava, 2005). This phenomenon could be connected with a volcanic eruption at sea

level, eventually carrying huge amounts of aerosol-laden water vapour to the stratosphere and forming ice-clouds with hyperfine volcanic ash. This possibly destabilised climate for some decades (Stothers, 1984, Wohletz, 2000).

Such events would point to an external forcing of climate in the Decapolis region, seemingly connected with fluctuations of world-wide circulation patterns. However, landscape change might play a role, too. According to Otterman et al. (1990), an increase in early rains followed land use change in the Negev since 1948. Early precipitation in arid regions is characterised by daytime dominance, indicating that surface-to-atmosphere heat fluxes are a strong control factor. In contrast, later rains are large-scale, low-intensity phenomena occurring predominantly at night (Otterman et al., 1990). For daytime rainfall, differentiate boundary-layer development leads to mesoscale circulations which provide the organisation often required for the development of precipitating clouds. Plant cover can play an important role in this process due to reducing the albedo and the sensible heat flux to the atmosphere, and due to shadowing of the ground, leading to a reduced day-to-night heat storage in the soil. This might cause a very significant increase of the daytime sensible heat flux. A first study in 1975, comparing a 20 years-period of rain in the Negev before and after 1948, found no changes (Otterman et al., 1990). But this changed when the study was repeated in 1990. Otterman et al. (1990) concluded that the greening of the Negev since the Israeli conquest as visible on satellite images might be the reason for an increase of early rains, and that a lack of dynamic processes capable of producing ascending motions is the principal cause of drought.

Bolle (2003) confirmed that large scale changes of land cover might contribute to climate change. A coupled land-atmosphere model was re-run with present vegetation exchanged against the suggested land cover of the Roman classical period. As result, North Africa was significantly wetter in the simulation (Bolle, 2003). This fits historical reports: Grotzfeld (1991) evaluated Arabic sources for meteorological observations, and found that there was a moist phase in Mesopotamia from the 9th – 13th century, and in Syria and Palestine from 1270 – 1530 AD. The total number of rainy days did not exceed today's, but they brought more water so that today's maxima fell in average (Grotzfeld, 1991).

Otterman et al. (1995) assumed in this context that there are different stable-state situations of regional climate, which may change from one pattern to another, but not take a "transitional" state. Alternative regimes of surface air circulation and rainfall are especially valid in sandy arid regions. Weiss et al. (1993) found that a rapid and dramatic change of climate contributed to the fall of the Akkadian empire 2200 BC, possibly connected with a volcanic eruption or the impact of a meteorite. According to Otterman et al. (1995), the climatic forcing of this event might not have been short-lived, but triggered a switch into a more arid equilibrium. An important factor of this switch were saltating sand

grains in the desert which kept moving under drier conditions, eventually preventing the establishment of vegetation. This continued until an prolonged wet phase occurred which finally enabled vegetation to fix the moving sand, and allowed climate to return to the initial equilibrium (Otterman et al., 1995).

In this context, it seems possible that land use intensification and the strong reduction of natural vegetation during the Byzantine period contributed to climate variations. However, it may not have been land cover change in the Decapolis region, but in a remote area that impacted circulation patterns ultimately affecting Transjordan. As well, the increasing precipitation measured by Otterman et al. (1990) may simply be connected with a general trend towards higher moisture levels as found by Treydte et al. (2006). In this context, the relationship between temperature and precipitation is not necessarily linear: according to Nützel (1976), precipitation variations in Mesopotamia were not simultaneous with temperature changes, but retarded. It has to be left open what will happen under global warming. In any case, it is possible that large-scale land cover changes contribute to climate anomalies. Such anomalies may precede the switch to a new equilibrium, perhaps expressed by the increasing amplitude of extreme events and their variability-frequency which is actually observed (Bolle, 2003). The switch to a new equilibrium can be dramatic and take place in only 5 years as during the Yarmoukian landslides 6200 BC (Prasad et al., 2006), and might lead to large-scale landscape change, which, in turn, likely had a feedback on climate.

Up to now, simply not enough is known about possible feedback relationships and the general functioning of world climate. It would be interesting to learn whether there are thresholds of land cover change regarding its significance for climate, or whether already slight changes impact the system. It seems generally problematic to think in linear relations: the environment is a complex system of non-linear functions, which are connected in feedback relationships (Vester, 1999). Land cover change may sometimes be irrelevant, and at other times have severe impact on the atmospheric circulation. As well, the role of temperature is unclear and may follow a non-linear function dominated by thresholds, and environmental change may enter a self-supporting feedback circle until a new equilibrium is reached. The impact of change may vary as well. For example, Stine (1994) found that severe wetland desiccations occurred in California and Patagonia during the medieval warm period while the weather was rather optimal for Europe. He therefore suggested not to use the term 'medieval warm period' but 'medieval climatic anomaly'.

It remains speculation whether land use change in the Decapolis region had relevance for climate variations. In any case, it seems safe to assume that the intensive land use during the Byzantine period was more susceptible to climate anomalies than earlier and later subsistence economies.

8.4 Responses of the society

It is a challenging question whether ancient societies exposed to climate variations had a choice to mitigate their impact. This is a very complex field requiring much more in-depth historical research. However, on the basis of the data discussed in this thesis, I would argue: they had no chance, not least because they did not know what happened.

Let us shortly review this point, using the Byzantine and Mamluk periods as examples. In this context, the first question that should be addressed is not the decline, but the tremendous population growth during the Byzantine time. Johns (1994) points out that the Byzantine and modern periods are peaks – from their point of view, all other periods look like decline, but it is in fact the Byzantine era which is exceptional. Hirschfeld (2004) found archaeological evidence for increasing humidity during the Roman and Byzantine period, indicated by e.g. a Roman bathhouse at the Dead Sea submerged after 300 AD, and springs in the Judean desert which are today dry, but were flowing in the Byzantine period and irrigated terraces. Amongst numerous other installations, a dam system close to Caesarea points to excess runoff water in winter, which was blocked, creating an artificial lake and channelling the water in a huge aqueduct to the town. Last but not least, remote and previously unsettled areas in the desert fringes were cultivated. These indicators support the picture from the aforementioned proxy data and clearly point to climate as one of the main reasons which made population growth possible. Hirschfeld (2004) points out that the climatic improvements led only to profits because a high technological ability and level of organisation was secured by a strong state.

However according to Johns (1994) the Byzantine boom in the area reached its peak when Constantinople withdrew its forces and entrusted its Ghassanid confederates to protect the border. Although the positive role of a strong state is out of question, it does not seem to be a prerequisite for economic development. It merely seems that the role of Bedouin is overestimated and seen to negatively. Banning (1986) assumed accordingly that peasants and nomads are no enemies, but connected in a symbiotic relationship. Both exploit different niches of the environment, and Bedouin settle down in good times, while peasants turn to nomadism during bad times.

In this context, the high development of the Decapolis region and the surrounding areas took place long before the Roman-Byzantine forces arrived. All technologies as well as a well-organised (Nabatean) state were already there (Taylor, 2001). It merely seems that the region's wealth and development attracted Rome's interest, and not that Roman control led to development. For example, it has been argued that only the construction of aqueducts made the vast expansion of cities possible. However, not only the Romans, but also the Nabateans were masters of water systems. Shaw (1984)

suggested that the massive aqueducts constructed by the Romans were consequences of, but not reasons for rural and urban development. It enabled additional population growth in the cities, but the main supply was always cisterns and collected rainwater, and huge cities in North Africa existed without aqueducts. In another study, Shaw (1991) concluded that aqueducts were pure prestige objects.

Now let us turn to the Byzantine decline. As already discussed with the plagues, governments lose authority and stability during bad times. One may argue that if the Byzantines had emphasised the construction of granaries, negotiated peace with their neighbours, and reduced social disparities, they might have mitigated the impact of climate variations. However they did not know what was going to happen, and their best explanation for the catastrophes of their time must have been the divine will testing their faith. As well, the empire was under constant attack of migrating tribes, which made defence the utmost priority and left little resources for investment in rural development. As it seems, the late Byzantine period faced the decline of a complex system: a market-oriented, highly specialised economy was struck by shortages of food and labour, the two prime resources necessary to keep things running. As Johns (1994) points out, subsistence does not make big cities, but less sophisticated systems are also less affected if a resource is missing. Therefore to some degree specialisation, the same reason which led to strong economic growth under more positive circumstances, may have contributed to the Byzantine decay. It reduced the society's flexibility and enlarged the number of people not contributing to primary production. The case of the Decapolis seems one of a marginal area that was never as important as the core regions of the empire, and very sensitive to environmental fluctuations. Population decline in the context of greater migrations and catastrophes in the Mediterranean, and triggered by climatic anomalies, seems the most reasonable explanation for its demise, and the state could only adapt to the new situation.

The Mamluk period saw heavy investments by the state, and especially sugar cane was cultivated in large irrigated plantations (Walker, 2004). One wonders whether earlier investments on the Mamluk scale could have returned prosperity to the region, too, and whether population levels rose only during that period. More likely, the medieval had already seen a slight but steady recovery, so that a sufficient settlement density justified the Mamluk expenditures with corresponding tax returns. It is worth to note that also during the medieval period, development could take place when a strong state was absent, and vice versa. For example, when Kerak was a Mamluk outpost, it declined from market economy to subsistence. The later absence of Ottoman authority did in contrast not lead to Bedouin raids, but permitted the formation of tribal elites and agricultural investment (Johns, 1994).

If we now turn to the Mamluk decline, the events of the late Byzantine period seem to repeat. The well-populated village of Hebras, close to Abila, was buried by rubble and boulders, seemingly

deposited by heavy rain and similar to the debris covering the theatre of Beit Ras. According to Arab writers, drought and climatic anomalies led to inflated prices, forced purchases, bribery, high taxes and inflated currency (Walker, 2007). The state could perhaps have countered this development, but the crisis led to a fight between the feudal lords (*Amirs*) which made everything worse. The Ottoman conquest seems the direct consequence of the mounting weakness of the Mamluk state. The conquerors invested in rural development, which is best expressed by the tax registers (Hütteroth and Abdulfattah, 1977), but these activities ceased in the early 17th century. Is the reason the state's occupation with other problems, was investment simply not justified any more by the possible returns? By then, Bedouin leaders were in charge of the tax collection which indicates that the taxed population in Transjordan was not too huge and wealthy any more. Entrusting the Bedouin may have been maximising benefits for the Ottomans, as it required only minimal investments by Constantinople while the corruption of tribal leaders secured their loyalty – controlling them with force would have been more costly and probably not worth the efforts.

Hirschfeld (2004) argued that the Ottoman empire was not able to exploit the situation when conditions in the Decapolis region turned more favourable again during the 19th century. In the light of the travel reports, I would however not agree. There can be no question that the Ottomans seriously invested in the region, which saw quick growth in the late 19th century, especially if one considers how depopulated it was. This development however does not appear great, since the tremendous technological advances in the last century dwarf any improvements of traditional societies. In this context, the Ottoman problem might not have been a lack of will to develop the empire. It seems more likely that the socio-cultural framework of the Muslim societies made quick progress like in Europe impossible. For example, Carmel (1985) argued that it was mainly the activities of the European powers that led to a quick development of Palestine, and that the Muslims had merely blocked advances to their own disadvantage. This might however be a colonial European perspective: in fact Muslims as well as other developing countries did not reject technology, but the social and cultural implications. Memmi (1965) showed how the relationship of colonizers and colonized is on the one hand centred on resource control, but on the other hand cannot be sustained if one side does not change its cultural identity. In this context, there seems to be a contradiction in the narratives about Ottoman rule. They are criticised for not investing enough in their provinces, but if they did so and enforced the basic requirements for civilisation – which are land registration, taxation, and military service – the local population resisted. The true problem seems related to identities: the Muslim sultanate had long lost its moral and ideal power, but nationalism was a strange concept for Islam. People's loyalty belonged to the tribes, not the central authority, and as long as the tribal pattern prevails, competition with

8. Climate, desertification and historical developments

European powers will not be possible. It is nevertheless not only Europeans who benefit from stable environments, and who invest if returns are good. The comparison with the western world might put the advances of the late Ottoman empire into a bad light.

To summarise, the state and the environmental framework both played important roles for development in the Decapolis region, but were not the key variables. Economic development was possible with and without strong states, and the basic environmental framework did not change. The key, as it seems, is population growth. The role of climate was that stable conditions made long-term growth possible, while instabilities likely led to quick population decline. Once population density was diminished, the society had to revert to a less complex organisation, and the state's room for manoeuvres was severely limited.

9. Conclusions

*As the man went eastward with a measuring line in his hand,
he measured off a thousand cubits and then led me through water that was ankle-deep.
He measured off another thousand cubits and led me through water that was knee-deep.
He measured off another thousand and led me through water that was up to the waist.
He measured off another thousand, but now it was a river that I could not cross,
because the water had risen and was deep enough to swim in-a river that no one could cross.
He asked me, "Son of man, do you see this?"
Then he led me back to the bank of the river.
When I arrived there, I saw a great number of trees on each side of the river.
He said to me, "This water flows toward the eastern region and goes down into the Arabah,
where it enters the Sea. When it empties into the Sea, the water there becomes fresh.
Swarms of living creatures will live wherever the river flows.
There will be large numbers of fish, because this water flows there and makes the salt water fresh;
so where the river flows everything will live. Fishermen will stand along the shore;
from En Gedi to En Eglaim there will be places for spreading nets.
The fish will be of many kinds-like the fish of the Great Sea.
But the swamps and marshes will not become fresh; they will be left for salt.
Fruit trees of all kinds will grow on both banks of the river.
Their leaves will not wither, nor will their fruit fail
Every month they will bear, because the water from the sanctuary flows to them.
Their fruit will serve for food and their leaves for healing.*

Ezekiel 47:3-12

Desertification indicators are dependent on time and space, making it difficult to identify anthropic influence against the natural background variation. However, the look into the past allows to see environmental change in a greater context, and suggests that the role of humans is marginal. Desertification seems not an issue of land use: movements of the desert belt are likely governed by climate variations. Mazzonleni et al. (2004) argued in this context that desertification due to global warming does not happen, which is shown by the recent vegetation aggradation in the Mediterranean.

The impact of climate change is however not predictable on the basis of the current data. Change will in any case be problematic: the rainy year 1991/92 was mild compared with the possible impact of extreme events as reported from the 19th century, but already caused considerable trouble in Jordan. Too much water might cripple the economy as much as too few water, because the present land use systems are rather inflexible (Dracup, 1987). A general research and management problem seems the thinking in linear dimensions, and missing knowledge about possible thresholds and feedback processes. Changing climatic patterns might be much more relevant than linear rises or decreases of temperature or rainfall. Since natural systems usually operate in non-linear functions, it would be important to learn more about the relevant factors and possible feedbacks. The impact of global warming may not only depend on temperature, but many simultaneously changing parameters which all play a role for the general atmospheric circulation.

Yet considering the physical landscape in the Decapolis region, little has changed since the end of the Early Bronze Age. There is no indication that Terra Rossa was eroded during history, and younger colluvia consist of weakly developed chalk from the wadi slopes. Man may locally have altered soils, and probably contributed to additions of calcareous dust. Nevertheless climate and the geological pre-disposition are decisive for landscape development. Butzer (2005) argued that the impact of climate variations would not be so severe if man did not clear the vegetation, and that the "political economy" was important for landscape development. However the evidence from Jordan suggests that climate variations caused dramatic erosion during the Late Pleistocene and the Younger Dryas without any human assistance. As well, the suggested positive role of forest, and the supposed negative role of grazing and agriculture, seem far overestimated. I concur with Grove and Rackham (2003) that the overall impact of traditional land use is negligible. The course of landscape development in the Decapolis region is determined by the geology, and governed by climate.

Manganese oxides and the strongly elevated magnetic susceptibilities in depressions point to much moister conditions in the past, and the decreasing maturity of soils may have reduced the overall productivity. The available paleosols suggest however that this process had no relevance for historic

time frames. It seems possible that a less pronounced change of soil structure took place under drier and warmer conditions, but was reversed when moisture levels increased again. Land use did not reduce fertility, but application of organic manure may have improved yields. Nevertheless water is the limiting factor of agricultural productivity. Very good yields are possible as long as moisture supply is good, but already slight changes in the distribution of rain, or the main wind direction, will ruin farmers.

Traditional agriculture seems optimally adapted to the environment, but dependent on high labour input. Population growth during the Roman-Byzantine period made the construction and maintenance of sophisticated water systems possible, which led to a market economy. Specialisation may have been both the strength and weakness of this economy, as diversification was reduced and many non-producing people had to be supported. The repeated decay and abandonment of the region seems in this context related to climatic anomalies which triggered pests, famines, plagues, and wars. The general environment in the Decapolis region did not change: as long as the weather was stable, it needed only a sufficient population to exploit the riches of the land.

Optimal climatic conditions in the past could have made the Decapolis region very productive and superior to e.g. northern Europe. Its disadvantage was however a great sensitivity to irregularities, and the location close to the arid zone determined the more or less frequent occurrence of extreme events. This could explain why societies in the desert belts and the Mediterranean experienced periods of quick growth and collapse, while northern societies developed more slowly, but steadily. In this context, "Neo-Determinism" as proposed by Issar and Zohar (2004) seems the best abstract for the reasons of cultural developments in the Near East. Neo-Determinism does not mean that humans are forced to suffer a fate dictated by some fluctuations of the environment, but that the environmental and technological limits determine the possible choices of a society. A lack of understanding of what happened may have contributed to making the wrong choice. The true motives of politics and societal decisions might be rather trivial: people want to survive, to secure a sufficient resource basis for a good survival, and to invest as little as possible. The last point could be the key for the failure of ancient societies: a missing ability or willingness of adaptation. During periods of unfavourable conditions, they may simply have continued with business as usual, hoping that things might improve soon again. This does however not apply to the Arab peasants: they reverted to nomadism and thus preserved their culture – in contrast to many Indian societies of the American Southwest, who were not so flexible and became extinct (Diamond, 2005).

There is no reason to assume that our culture will perform better. According to Lamb (1982), our modern society is the one which is most vulnerable to climate change. One may argue that modern

technology will save us: but modern technology may in fact turn out to be a disadvantage. Reliance on technology may reduce our willingness to adapt, since it is more comfortable to wait for a new machine than to change one's way of living. As well, technology depends on resources, and we have become dependent on technology. For example, drought in Greece this year did not only cripple the water supply, but also electricity generation¹⁶. As well, modern agriculture can only produce its high yields as long as a lot of energy is invested. Semi-arid areas still depend on annual rainfall variations for their water supply, even if it is now pumped. Wasteful use of resources, wars for resource control, and the negative water balance of many countries do not look like promises for a good future.

To some degree, the Janus-face of technology seems represented by development aid. It may on the one hand provide most important resources for the development of emerging societies. But it may on the other hand lead to stabilisation of inefficient systems and power structures, on the long run working to the society's disadvantage (Lachmann, 1999b). It seems that there is no alternative to development aid: Heinsohn (2003) argued convincingly that the most violent conflicts of the world are connected with population growth, lack of development and diminishing resources in the respective areas. Reviewing that about 10% of the world's population use approximately 90% of its resources, it seems likely that the future will see growing conflicts if participation and cooperation cannot be achieved. The impact of climate change will depend to a large degree on our willingness to work together. In this context, the examples from history are not encouraging: the Byzantine nobility was unwilling to sacrifice its fortunes for the survival of the peasants, and I am afraid that present leaders may also opt for conflicts if resources become scarcer, although we should know better.

The best strategy to deal with global warming seems designing more flexible land use systems, and fostering international cooperation. The environmental challenges could in this context even lead to positive developments. For example, in the case of the Decapolis region and the Near East, the actual drying of the Dead Sea can only be stopped if all neighbouring countries work together. It has been proposed to build a channel from the Mediterranean or the Red sea, which could deliver water and energy, and become an important asset for the future development of the region. If realised, it was again foretold by biblical narratives¹⁷.

¹⁶ See http://ta-nea.dolnet.gr/print_article.php?e=A&f=18758&m=N15&aa=1, and <http://www.ekathimerini.com/4dcgi/news/content.asp?aid=80249>.

¹⁷ See <http://ezekielproject.org>.

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11.3 Total element contents

Table 23: Total element contents from X-ray fluorescence. Rocks are marked with (R).

%	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	(SO ₃)	(Cl)	(F)	LOI*	SUM
Jordan valley															
Jor 10	35	0.81	7.74	4.27	0.051	1.85	23.27	0.2	1.01	0.951	0.05	0.04	<0.01	24.42	99.7
Wadi Ziqlab															
Ziq 1	58.9	1.38	15.8	8.78	0.184	2.99	11.22	0.35	1.94	0.35	0.01	<0.01	<0.01	35.15	137.0
Ziq 4	25.7	0.53	7.84	4.06	0.047	0.91	29.53	0.17	0.8	2.62	0.18	0.05	<0.01	27.23	99.7
Wadi el-Arab															
TZ 50	15.9	0.33	4.06	2.13	0.04	1.57	38.51	0.09	0.53	0.949	0.09	0.06	<0.01	32.65	96.9
TZ 54 (chalk)	8.5	0.15	3.2	1.5	0.016	0.61	44.54	0.21	0.43	3.09	0.23	0.11	0.03	36.13	98.7
TZ 65	23.9	0.33	3.28	2.41	0.047	1.48	31.33	0.04	0.37	0.628	<0.01	0.05	<0.01	18.81	82.6
TZ 66 (R)	2.7	0.08	1.04	0.56	0.009	0.59	51.94	0.01	0.14	0.14	0.03	0.09	<0.01	42.86	100.2
TZ 106	40	1	12.24	6.33	0.098	1.63	12.04	0.18	0.89	0.573	<0.01	0.02	<0.01	24.84	99.8
Ard al-Ala															
UQ 9	43.2	1.23	13.03	7.37	0.122	2.6	10.02	0.22	0.82	0.277	<0.01	0.01	<0.01	20.56	99.4
UQ 21	44.3	1.23	13.31	7.58	0.121	2.73	9.6	0.25	0.89	0.247	<0.01	0.01	<0.01	18.87	99.1
UQ 23 (caliche)	1.1	0.03	0.38	0.3	0.006	0.48	53.91	0.01	0.04	0.901	0.02	0.09	<0.01	42.4	99.7
Basalt UQ (R)	44.6	2.02	15.48	11.93	0.162	5	12.33	2.92	0.73	0.405	<0.01	0.02	<0.01	3.78	99.3
Med. highland															
AB 1	28.7	0.74	8.26	4.62	0.073	1.62	26	0.13	0.58	0.35	<0.01	0.04	<0.01	29.13	100.3
AB 4	35.8	0.95	10.47	5.84	0.089	1.79	19.14	0.16	0.83	0.315	<0.01	0.03	<0.01	24.56	99.9
AB 7	25.1	0.55	6.45	2.95	0.048	1.39	31.65	0.14	1.03	0.282	0.06	0.05	<0.01	18.4	88.1
AB 8 (R)	5	0.06	1.46	0.91	0.005	0.56	50.23	0.01	0.12	0.838	0.02	0.09	<0.01	40.51	99.8
Yar 5 (R)	1.8	0.04	0.72	0.44	0.006	0.38	53.45	0.01	0.07	0.235	0.01	0.09	<0.01	42.75	99.9

* LOI = Loss Of Ignition

	%	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	(SO ₃)	(Cl)	(F)	LOI*	SUM
AB 9		51.5	1.38	13.67	7.55	0.161	1.47	5.69	0.15	0.79	0.195	<0.01	<0.01	<0.01	17.22	99.8
AB 10 (R)		4.3	0.08	0.86	0.63	0.018	0.6	51.48	0.01	0.07	0.378	0.01	0.09	<0.01	41.32	99.8
AB 1-2 2		32.4	0.85	9.54	5.21	0.09	1.11	22.65	0.12	0.69	0.309	0.03	0.03	<0.01	26.91	99.9
AB 1-2 5 (R)		1.2	0.04	0.65	0.4	0.007	0.41	53.76	0.01	0.06	0.175	0.04	0.09	<0.01	43.22	100.0
AB 2-2 2		26.4	0.68	7.38	3.99	0.076	1.04	28.59	0.12	0.57	0.345	<0.01	0.04	<0.01	30.6	99.9
AB 2-2 6 (R)		2.3	0.06	0.83	0.49	0.009	0.5	52.81	0.01	0.08	0.317	0.02	0.09	<0.01	42.6	100.1
Q 2		27.1	0.65	7.13	3.94	0.076	1.04	28.52	0.1	0.52	0.592	<0.01	0.05	<0.01	29.97	99.6
Q 12		34.1	0.84	9.47	5.3	0.089	1.12	21.9	0.12	0.71	0.474	0.04	0.03	<0.01	25.62	99.8
Q 18		35.9	0.92	10.09	5.65	0.098	1.1	20.56	0.11	0.66	0.44	0.03	0.03	<0.01	24.2	99.7
Q 19 (R)		1.2	0.04	0.49	0.3	0.007	0.45	53.75	0.01	0.05	0.133	<0.01	0.09	<0.01	43.37	99.9
BR 2		32.8	0.83	9.56	5.28	0.091	1.2	22.23	0.15	0.73	0.501	<0.01	0.03	<0.01	26.52	99.9
BR 14		43.8	1.15	13.23	7.18	0.119	1.35	10.73	0.2	1.14	0.36	0.03	0.01	<0.01	19.34	98.6
BR 21		48.4	1.29	14.59	7.96	0.134	1.41	7.38	0.23	1.25	0.327	0.02	<0.01	<0.01	16.7	99.6
Irbid basin																
I 14a		57.9	1.55	13.09	7.27	0.218	1.13	2.77	0.22	0.56	0.131	<0.01	<0.01	<0.01	14.14	98.9
I 04		14.7	0.37	6.51	3.54	0.029	0.94	37.6	0.03	0.29	0.258	<0.01	0.06	<0.01	35.5	99.8
I 00 (R)		93.2	0.03	0.65	0.45	0.005	0.1	2.55	0.01	0.04	0.059	0.01	<0.01	<0.01	3.19	100.3
Amrawah																
AmFw 1		42.9	1.08	11.88	6.56	0.1	2.2	13.28	0.28	1.44	0.305	0.01	0.02	<0.01	19.41	99.5
AmFw 3		37	0.94	9.45	5.35	0.085	1.82	20.32	0.28	1.24	0.397	0.03	0.03	<0.01	22.95	99.9
Am 1		13.2	0.25	4.9	2.49	0.015	0.54	40.06	0.09	0.37	2.47	0.15	0.07	0.01	18.09	82.7
Basalt Amrawah (R)		42.7	2.22	14.33	14.03	0.181	9.74	8.13	2.24	0.88	0.43	<0.01	0.01	<0.01	3.89	98.8
AmO 7		32.4	0.77	8.41	4.79	0.066	1.52	24.67	0.15	1.08	0.349	<0.01	0.03	<0.01	25.52	99.8
AmO 12		43.7	1.04	11.2	6.17	0.057	2.03	13.95	0.23	1.23	0.229	<0.01	0.02	<0.01	20.16	99.9
AmO 20 (R)		3.8	0.09	1.16	0.75	0.016	0.71	51.2	0.02	0.11	0.253	0.03	0.09	<0.01	41.8	100.0

* LOI = Loss Of Ignition

	%	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	(SO ₃)	(Cl)	(F)	LOI*	SUM
Ruins soils																
TZ 14		32	0.73	8.41	4.64	0.077	1.84	23.87	0.21	1.86	0.871	0.92	0.04	<0.01	24.63	100.1
TZ 15		32.2	0.75	8.62	4.75	0.075	1.86	23.25	0.16	1.55	0.687	0.04	0.03	<0.01	24.25	98.2
TZ 16		32.7	0.75	8.59	4.76	0.073	1.89	23.53	0.21	1.7	0.842	0.06	0.04	<0.01	27.61	102.7
TZ 16 (II)		33.4	0.76	8.71	4.84	0.074	1.87	23.23	0.25	1.97	0.69	0.26	0.04	<0.01	25.23	101.3
TZ 17		20.9	0.45	4.65	3.15	0.027	1.08	35.83	0.1	0.83	1.41	0.1	0.06	<0.01	31.11	99.7
Abila relik		24.9	0.47	5.93	2.37	0.04	1.44	32.98	0.06	1.08	0.462	0.05	0.06	<0.01	17.03	86.9
AB 4-2b		10.7	0.24	2.72	1.56	0.027	0.76	43.94	0.05	0.32	0.712	0.02	0.08	<0.01	38.29	99.4
AB 4-4		30.9	0.7	7.19	4.31	0.076	3.54	24.24	0.25	0.9	0.342	0.05	0.04	<0.01	40.8	113.3
Jer 3a		46.2	1.22	13.54	7.54	0.122	2.29	9.5	0.32	1.24	0.448	0.02	0.01	<0.01	31.02	113.4
Jer 2a		47.3	1.2	13	7.15	0.131	1.7	9.03	0.27	2.04	0.347	0.04	0.01	<0.01	30.46	112.7
	<i>[ppm]</i>	(As)	Ba	Bi	Ce	Co	Cr	Cu	Ga	Hf	La	Mo	Nb	Ni	(Pb)	Rb
Jordan valley																
Jor 10		6	249	<1	104	13	104	23	14	2	25	<1	15	68	9	43
Wadi Ziqlab																
Ziq 1		5	402	<1	100	34	133	70	22	<1	27	<1	27	96	21	69
Ziq 4		9	228	<1	85	13	276	42	14	<1	48	<1	11	112	9	27
Wadi el-Arab																
TZ 50		1	223	<1	67	11	49	9	8	<1	18	<1	8	50	7	26
TZ 54 (chalk)		2	364	<1	47	5	328	15	8	<1	54	<1	7	68	8	8
TZ 65		<1	185	2	41	11	30	5	6	<1	6	<1	6	15	<1	16
TZ 66 (R)		2	84	3	21	5	10	2	2	<1	6	10	3	3	<1	3
TZ 106		5	645	<1	100	21	138	23	18	5	49	<1	22	62	16	55

* LOI = Loss Of Ignition

	[ppm]	(As)	Ba	Bi	Ce	Co	Cr	Cu	Ga	Hf	La	Mo	Nb	Ni	(Pb)	Rb
Ard al-Ala																
UQ 9	5	522	1	96	28	112	19	18	6	31	<1	25	60	26	50	
UQ 21	6	546	<1	110	30	111	35	18	5	39	<1	24	66	28	51	
UQ 23 (caliche)	<1	56	2	26	3	32	2	3	<1	14	20	2	<1	<1	<1	
Basalt UQ (R)	1	450	<1	45	46	182	60	22	7	18	2	21	74	3	5	
Med. highland																
AB 1	2	394	<1	75	19	73	15	14	2	25	<1	17	41	12	36	
AB 4	2	433	1	83	21	96	18	16	4	39	<1	19	52	13	42	
AB 7	<1	117	2	64	14	31	6	12	1	12	<1	13	11	28	34	
AB 8 (R)	5	27	2	11	6	58	9	3	<1	20	9	2	67	<1	3	
Yar 5 (R)	3	52	2	6	3	18	4	2	<1	3	10	3	9	<1	<1	
AB 9	8	484	2	131	28	124	33	19	9	38	3	26	72	19	56	
AB 10 (R)	2	91	2	31	3	26	2	5	<1	12	10	3	5	<1	1	
AB 1-2 2	1	254	<1	91	22	92	15	17	4	31	<1	19	49	17	46	
AB 1-2 5 (R)	<1	64	2	16	4	16	<1	3	<1	14	16	2	4	<1	<1	
AB 2-2 2	<1	198	1	62	19	74	9	12	2	19	<1	15	34	16	37	
AB 2-2 6 (R)	2	86	1	<1	3	28	4	1	<1	<1	7	2	8	<1	1	
Q 2	<1	265	1	63	16	98	5	11	1	20	<1	14	41	8	33	
Q 12	3	341	<1	88	24	111	24	15	3	34	<1	18	62	14	41	
Q 18	6	337	2	115	21	114	27	17	3	38	<1	20	68	10	39	
Q 19 (R)	4	81	2	11	<1	11	2	1	<1	3	11	3	<1	<1	<1	
BR 2	4	295	1	84	19	111	28	15	3	25	<1	18	64	13	47	
BR 14	7	377	<1	108	26	139	26	19	6	56	<1	25	75	16	59	
BR 21	9	416	<1	111	25	151	35	20	6	46	<1	29	91	15	63	

<i>[ppm]</i>	(As)	Ba	Bi	Ce	Co	Cr	Cu	Ga	Hf	La	Mo	Nb	Ni	(Pb)	Rb
Irbid basin															
I 14a	4	414	2	171	38	123	52	18	10	35	2	30	69	22	46
I 04	3	86	1	44	10	31	5	12	1	13	<1	10	16	4	23
I 00 (R)	<1	494	10	7	1	12	<1	4	<1	<1	5	3	8	7	<1
Amrawah															
AmFw 1	5	291	<1	86	23	98	23	16	6	39	<1	22	54	16	56
AmFw 3	4	207	1	64	21	75	28	14	3	34	<1	18	42	9	45
Am 1	9	184	1	62	7	271	30	9	<1	59	<1	7	102	5	12
Basalt Amrawah (R)	4	628	1	54	69	423	73	18	6	22	3	27	308	2	9
AmO 7	3	184	1	67	15	67	17	13	2	23	<1	15	36	7	44
AmO12	6	228	<1	89	20	99	15	15	4	32	<1	20	50	11	53
AmO20 (R)	3	129	1	33	6	16	4	4	<1	5	8	3	6	<1	2
Ruin soils															
TZ 14	5	330	<1	75	22	87	12	13	2	45	<1	15	56	7	50
TZ 15	5	274	<1	88	18	83	17	15	3	25	<1	15	61	13	52
TZ 16	6	314	1	100	17	89	13	13	2	14	<1	15	65	10	52
TZ 16 (II)	6	327	<1	75	15	87	16	13	2	39	<1	16	58	9	53
TZ 17	6	542	1	58	9	71	12	9	<1	27	<1	8	51	7	27
Abila relik	<1	102	<1	58	11	26	5	11	<1	25	<1	10	8	56	29
AB 4-2b	<1	269	2	45	8	43	8	4	<1	7	<1	7	20	24	15
AB 4-4 (R)	4	1029	2	67	21	81	24	12	2	23	<1	13	66	6	31
Jer 3a	7	423	<1	101	28	131	39	19	5	37	<1	24	88	16	61
Jer 2a	10	351	<1	115	28	120	24	18	6	38	<1	22	68	15	71

<i>[ppm]</i>	Sr	Ta	Th	U	V	W	Y	Zn	Zr	Ti%	Ti/Zr
Jordan valley											
Jor 10	371	<1	7	8	140	<1	37	198	241	0.486	20
Wadi Ziqlab											
Ziq 1	188	<1	5	3	170	3	47	147	335	0.828	25
Ziq 4	568	2	<1	17	134	<1	57	365	78	0.318	41
Wadi el-Arab											
TZ 50	460	<1	4	4	55	<1	22	207	73	0.198	27
TZ 54 (chalk)	1168	5	2	23	126	<1	59	391	40	0.090	23
TZ 65	294	1	5	<1	46	<1	16	66	79	0.198	25
TZ 66 (R)	249	<1	5	5	24	<1	7	157	27	0.048	18
TZ 106	176	<1	9	4	139	1	43	146	209	0.600	29
Ard al-Ala											
UQ 9	174	1	16	5	141	<1	35	102	222	0.738	33
UQ 21	187	<1	12	4	144	1	35	96	232	0.738	32
UQ 23 (caliche)	385	<1	4	9	5	<1	17	28	24	0.018	8
Basalt UQ (R)	521	<1	7	<1	230	6	25	105	151	1.212	80
Med. highland											
AB 1	239	<1	8	5	104	<1	28	101	149	0.444	30
AB 4	209	<1	16	2	124	<1	34	116	191	0.570	30
AB 7	256	2	8	4	65	<1	19	53	137	0.330	24
AB 8 (R)	484	2	3	12	50	<1	28	199	34	0.036	11
Yar 5 (R)	344	<1	4	<1	23	<1	12	66	28	0.024	9
AB 9	115	2	20	5	147	4	44	108	320	0.828	26
AB 10 (R)	408	<1	4	8	14	<1	22	51	35	0.048	14

<i>[ppm]</i>	Sr	Ta	Th	U	V	W	Y	Zn	Zr	Ti%	Ti/Zr
AB 1-2 2	202	<1	10	2	103	<1	31	111	186	0.510	27
AB 1-2 5 (R)	273	7	4	7	16	<1	11	39	23	0.024	10
AB 2-2 2	226	1	8	4	89	<1	26	104	151	0.408	27
AB 2-2 6 (R)	330	<1	5	8	20	<1	13	61	29	0.036	12
Q 2	351	<1	7	2	94	<1	33	135	146	0.390	27
Q 12	261	<1	10	4	113	<1	35	143	181	0.504	28
Q 18	252	<1	12	<1	119	<1	37	141	204	0.552	27
Q 19 (R)	306	<1	4	4	4	<1	7	32	27	0.024	9
BR 2	211	<1	9	5	123	<1	37	155	177	0.498	28
BR 14	143	<1	14	2	152	3	43	151	250	0.690	28
BR 21	135	3	20	1	167	3	47	156	289	0.774	27
Irbid basin											
I 14a	120	<1	22	3	161	5	43	105	404	0.930	23
I 04	116	<1	6	5	81	<1	14	76	56	0.222	40
I 00 (R)	39	<1	5	2	12	<1	7	14	11	0.018	16
Amrawah											
AmFw 1	183	<1	15	5	137	<1	35	111	248	0.648	26
AmFw 3	187	<1	11	4	119	<1	32	101	219	0.564	26
Am 1	1004	<1	<1	17	126	<1	51	411	55	0.150	27
Basalt Amrawah (R)	471	2	8	4	235	6	32	125	197	1.332	68
AmO 7	130	<1	9	2	97	<1	26	91	169	0.462	27
AmO 12	153	<1	10	5	130	1	34	104	242	0.624	26
AmO 20 (R)	482	<1	4	8	32	<1	15	41	44	0.054	12

	[ppm]	Sr	Ta	Th	U	V	W	Y	Zn	Zr	Ti%	Ti/Zr
Ruin soils												
TZ 14		296	1	5	2	120	<1	35	154	147	0.438	30
TZ 15		281	<1	6	4	151	<1	33	139	153	0.450	29
TZ 16		304	1	6	4	135	<1	34	171	155	0.450	29
TZ 16 (II)		285	<1	6	2	132	<1	34	147	159	0.456	29
TZ 17		438	<1	3	13	169	<1	29	199	95	0.270	28
Abila relikt		299	1	7	<1	58	<1	18	53	125	0.282	23
AB 4-2b		383	<1	5	4	51	<1	19	105	57	0.144	25
AB 4-4 (R)		731	<1	6	<1	126	<1	27	130	157	0.420	27
Jer 3a		193	<1	9	4	149	2	43	143	233	0.732	31
Jer 2a		132	2	17	3	167	2	41	123	271	0.720	27

11.4 Tree ring curves

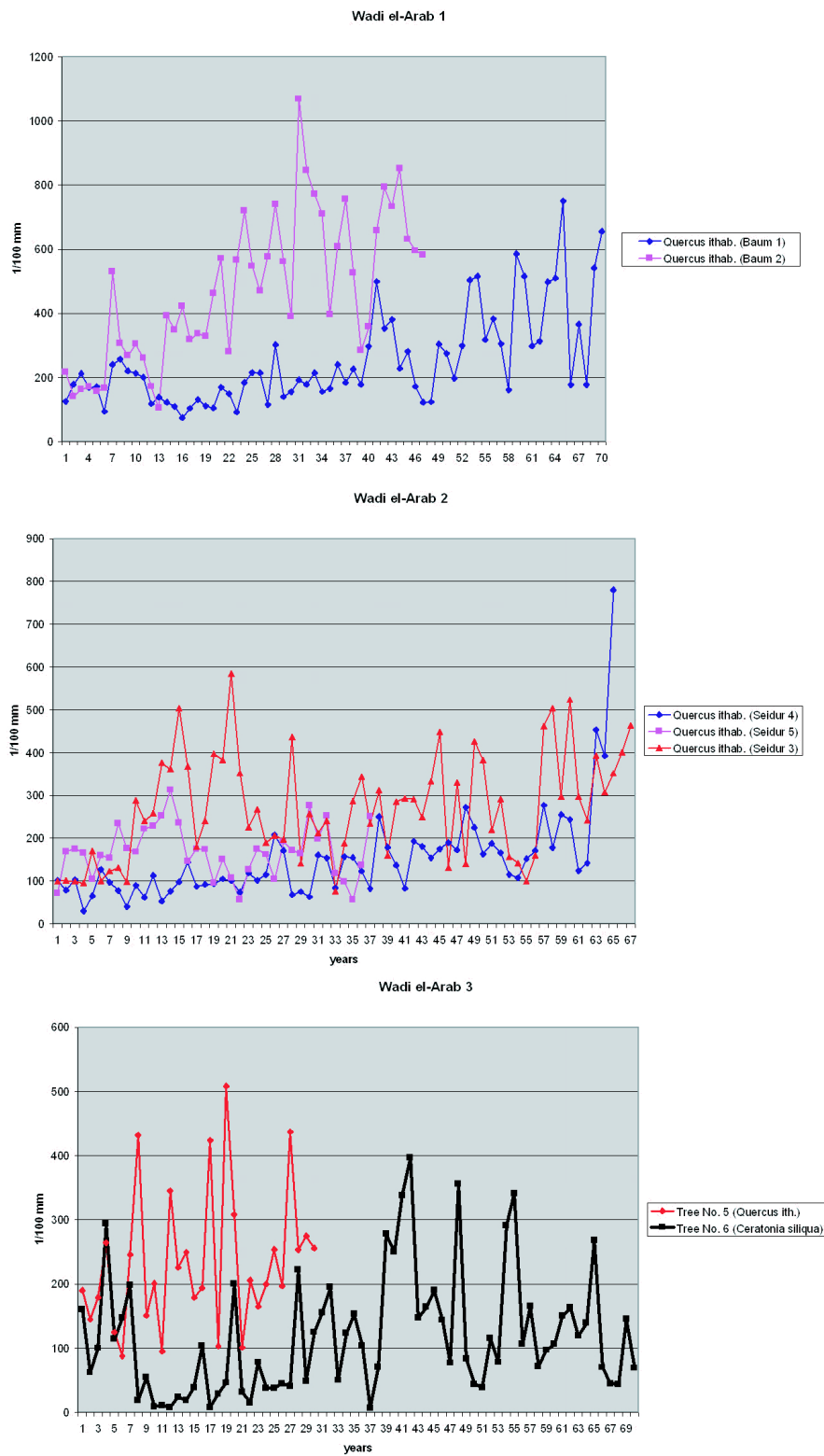


Figure 65: Tree ring curves from the Wadi el-Arab.

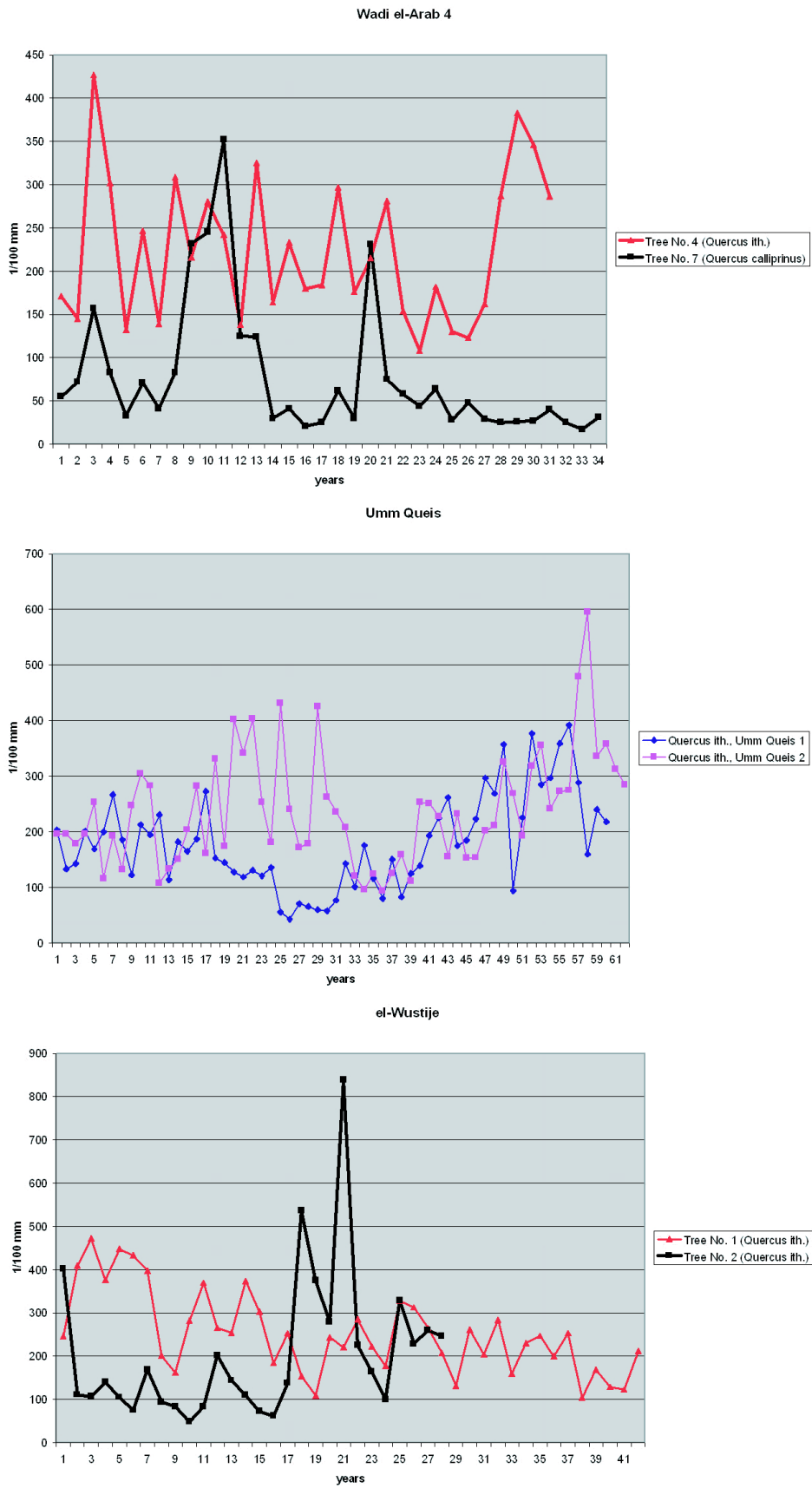


Figure 66: Tree ring curves from the Wadi el-Arab, Umm Queis and el-Wustije.

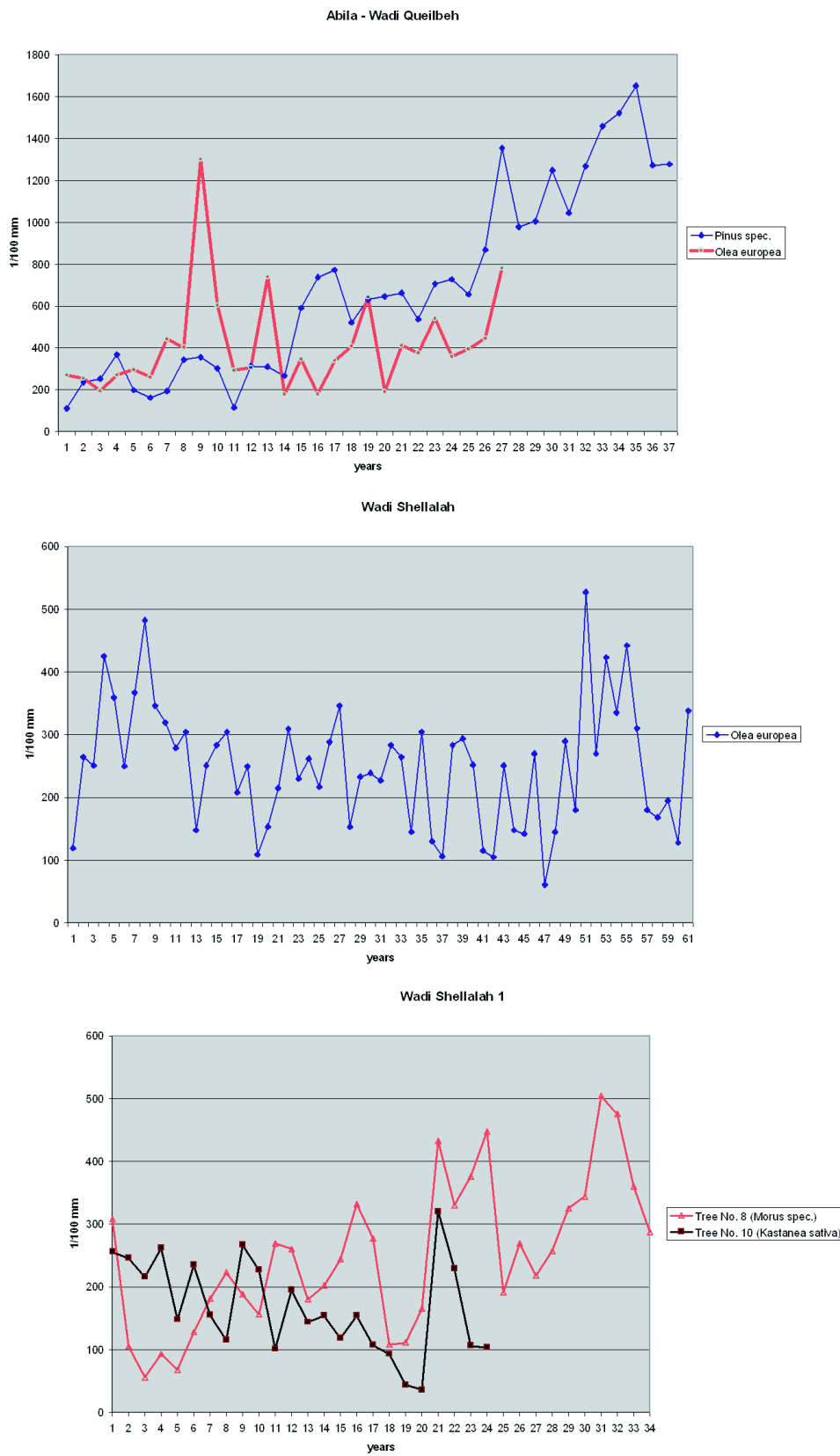


Figure 67: Tree ring curves from Abila and Wadi Shellalah.