6 Palaeomagnetic Geochronology of Quaternary Sequences in the Levant[1]

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6.1 INTRODUCTION

Palaeomagnetic dating methods are based on comparing magnetic information from materials or sequences, whose ages are at least partly unknown, with the geomagnetic chronology. The global Quaternary geomagnetic chronology is continuously updated, and currently includes 10 polarity reversals and at least 18 validated geomagnetic excursions that serve as chronological markers for sedimentary and volcanic sequences. In addition, short-term secular variations of the past several millennia can be used for the Holocene. Here, we review the principles underlying palaeomagnetic chronology with emphasis on Quaternary rocks, sediments, and archeological substances. We summarize a number of successful applications of palaeomagnetic dating in the Levant, and provide insight into future possibilities for Quaternary palaeomagnetism.

6.1.1 GENERAL PALAEOMAGNETISM

The Earth's magnetic field is constantly changing on time scales of decades to millions of years. The effort to reconstruct past geomagnetic variations has been motivated mainly by a geophysical interest in understanding the behaviour of the Earth's magnetic field, its origin, and its impact on the Earth's atmosphere and biosphere. The outcome of this research is a fairly robust geomagnetic record that can be used as an independent chronological reference framework.

To apply palaeomagnetism for dating, a robust geomagnetic chronology needs to be established first, by compiling the global palaeomagnetic database into three independent variation records: (1) reversals, (2) excursions, and (3) short-term (secular) changes in direction and intensity. Then, on the basis of comparison with the appropriate reference chronology, the magnetic polarity, direction, and intensity of materials or sequences are used to obtain age estimates.

Palaeomagnetism is a powerful chronological tool that has been used for decades (Sternberg 1997; Singer 2014). Yet it is important to emphasize that it involves a series of experimental procedures that require several stages of interpretation. Also, it is based on the reference geomagnetic chronology to date. Hence, when adopting palaeomagnetism, an understanding of how it works is required. Here we review the principles underlying palaeomagnetic methods, so that readers may adopt a realistic and critical view, and can adequately design palaeomagnetic dating applications in their research. In Section 6.2 we briefly explain how different materials record magnetic information. In Section 6.3 we outline the basic palaeomagnetic laboratory procedures. In Section 6.4 we review the up to date geomagnetic chronologies. Finally, in Section 6.5 we review the application of palaeomagnetic dating in selected geological and archeological studies of the Levant.

6.2 PRINCIPLES OF NATURAL MAGNETIC RECORDING

Ferromagnetic minerals (for simplicity, we group different types of magnetic minerals – with ferro-, ferri-, anti-ferro, canted-, and defect-magnetism – under the one term ferromagnetic) are the fundamental building blocks of magnetic recording. Ferromagnetic minerals have an intrinsic spontaneous magnetization, which makes them act as small-scale 'compass needles'. The ferromagnetic minerals that are relevant to palaeomagnetism are those whose magnetization is locked in space at room temperature. The most abundant groups of ferromagnetic minerals are iron oxides: magnetite (Fe_3O_4), hematite (Fe_2O_3), and maghemite (γ-Fe_2O_3); iron sulfides: greigite (Fe_3S_4), pyrrhotite ($Fe_{1-x}S_x$), and iron oxyhydroxides (e.g. goethite, α-FeOOH). These groups can appear in their pure form or with substitutes. They are so abundant that they can be found virtually everywhere: in rocks, sediments, soils, dust, and various archeological materials.

The mechanisms by which ferromagnetic minerals record and retain magnetic information (called hereafter remanent
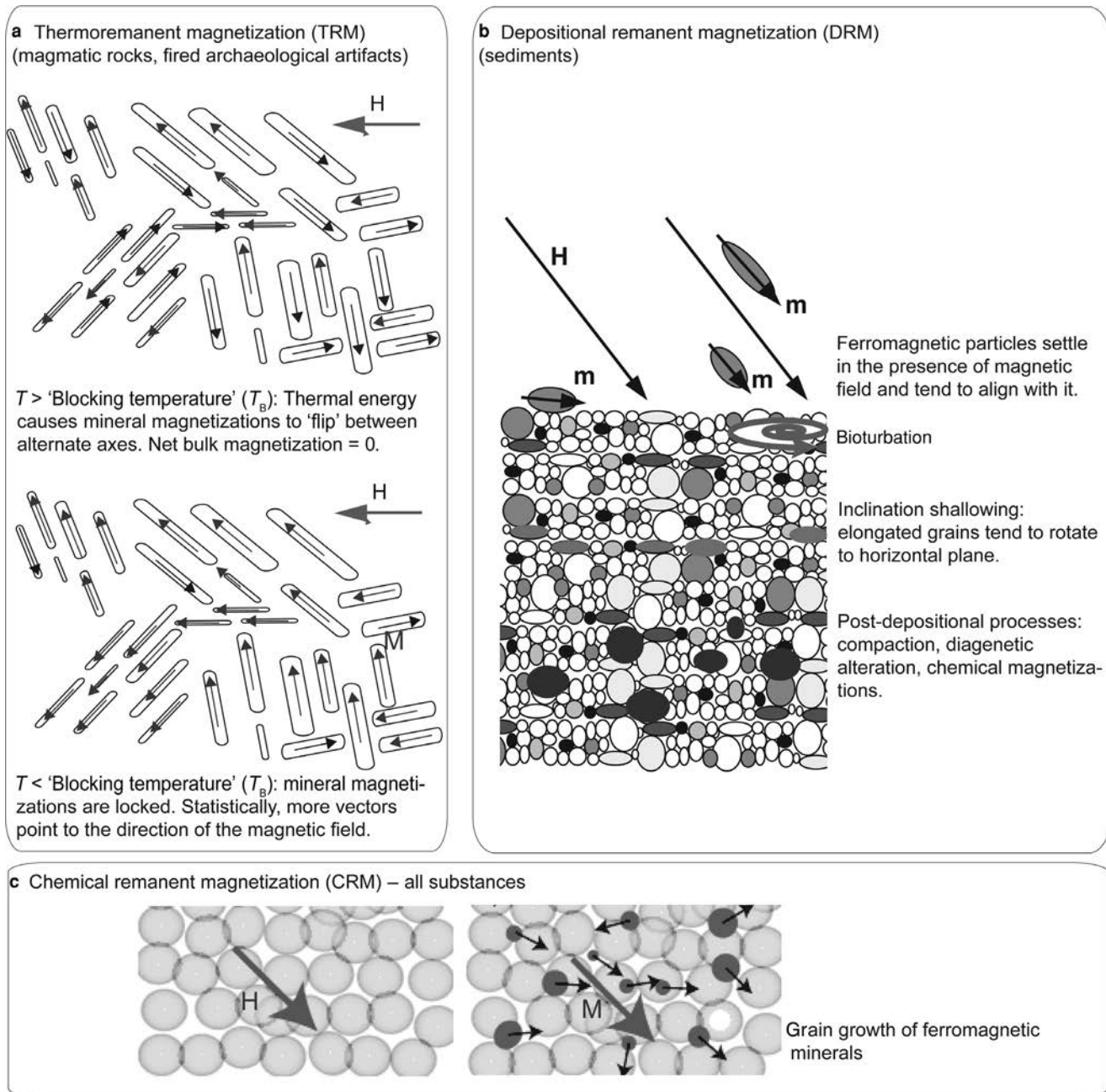
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[1] This chapter is dedicated to the memory of our late mentor and dear friend Professor Hagai Ron, who pioneered paleomagnetic research in the region.

https://doi.org/10.1017/9781316106754.006 Published online by Cambridge University Press

Figure 6.1 Schematic illustration of the three main mechanisms of magnetic remanence acquisition. Redrawn after Butler (1992) and Tauxe (2010).

magnetization) can be classified into: thermomagnetic (TRM – magnetization acquired by cooling), depositional (DRM – physical settling of magnetic particles in sedimentary environments), and chemical (CRM – chemical growth of magnetic minerals). Figure 6.1 illustrates these mechanisms graphically. For further reading, see Dunlop and Özdemir (2001), and Tauxe (2010). TRM (Fig. 6.1a) is acquired in igneous rocks and fired archeological materials when ferromagnetic minerals are cooled through a critical temperature called the blocking temperature (T_B). In T_B, the spontaneous magnetization becomes locked in space, and a magnetization is gained in a direction parallel to the ambient field. DRM (Fig. 6.1b)

can be acquired in marine, lake, and aeolian environments. DRM occurs when ferromagnetic particles align in the direction of the ambient field before settling. CRM (Fig. 6.1c) is acquired when new ferromagnetic grains grow and possess magnetization. In addition to the mechanisms shown in Fig. 6.1, other processes contribute to the net magnetization of a material. The stability (or the 'decay' time) of the magnetization, which depends on the age, mineralogy, and size of the particles, may lead to an acquisition of a 'viscous' magnetization (VRM). Various physical and chemical alterations may also distort, erase, and even re-magnetize an existing magnetic signal through time.

To exemplify the concept and complexity of palaeomagnetic recording, we consider as case studies three lithologies relevant to Quaternary sequences: a lava flow, a lake varve, and a buried soil. Ideally, the lava flow would have a TRM recorded on the day the basalt cooled, the lake varve would have a pure DRM that became locked in over a season, and the buried soil would have a CRM acquired over a specific polarity chron (see below for definitions of chrons). In these examples, the original primary magnetization is tied directly to the age of the material, and is referred to hereafter as the characteristic remanent magnetization (ChRM). In practice, the ChRM is often overprinted by many magnetic signals postdating the age of the ChRM. For example, the basalt can acquire 'viscous' magnetization (VRM), can be demagnetized by chemical and physical weathering (CRM), and might even be struck by lightning (totally erasing the original TRM); the lake varve can lose its DRM by bioturbation, oxidation, dissolution, and alteration (Fig. 6.1b), and can be masked by new ferromagnetic minerals growing in the sedimentary column (i.e. CRM); the buried soil can have a 'soft' and unstable magnetization that decays with time or becomes masked by new CRM that continues to form as the soil ages.

6.3 BASIC PALAEOMAGNETIC PROCEDURES

Given the complexity of the natural magnetic acquisition (Section 6.2), there are some questions that should be properly addressed before one uses palaeomagnetism: (1) '*Which* minerals carry the magnetic signal?', (2) '*What* are the processes by which the magnetic signal was acquired?', and (3) '*When* was the magnetic signal acquired?' Also, obviously, we need a methodology for measuring the ChRM and isolating it from all possible overprints. Assessing these questions is the art of palaeomagnetic lab work.

There are different parameters and levels of palaeomagnetic information that can be retrieved by palaeomagnetic analyses. In some cases, the desired information might simply be the polarity of the ancient field ('Normal' or 'Reverse'; Section 6.4). In other cases, the aim might be to recover the precise direction and/or intensity of the ancient field.

Almost all types of palaeomagnetic investigations require isolation of the ChRM. This is done by progressively demagnetizing the net magnetization (natural remanent magnetization, NRM) of the sample. Demagnetization can be done thermally, by heating
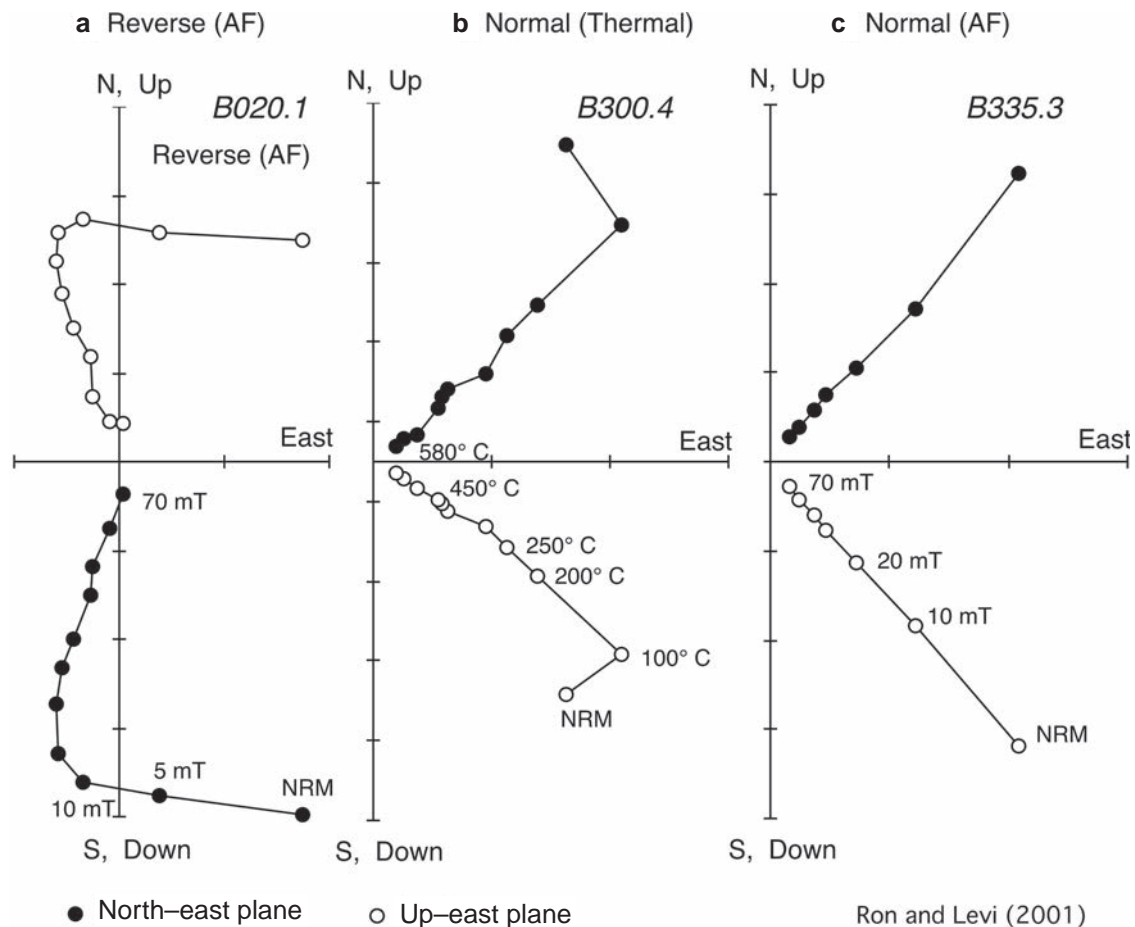

Figure 6.2 Examples of demagnetization experiments displayed on orthogonal plots, modified from a study of Erq el Ahmar Formation by Ron and Levi (2001). a: AF demagnetization revealing stable Reverse polarity (up and south; see Fig. 6.3); b and c: thermal and AF experiments on sister specimens showing similar Normal polarity (down and northeast).

the sample in zero-field conditions, or magnetically, by exposing the sample to a strong alternating magnetic field (AF). After each demagnetization step, a portion of the NRM vector is lost, and the x, y, z components of the remaining vector are measured with a high-sensitivity magnetometer. Consecutive measurements of the remaining NRMs are plotted on an orthogonal plot where the length of the magnetization vector is normalized to the length of the initial NRM. An orthogonal plot that appears as a straight line converging toward the origin (Fig. 6.2) means that the direction of the vector remained the same after all the demagnetization steps. In this case the ChRM is calculated through principal component analysis (Kirschvink 1980). A more complicated orthogonal plot should be interpreted with care. A robust demagnetization procedure would include both AF and thermal techniques. An example is shown in Fig. 6.2.

The palaeomagnetic vector is described by the declination (deviation from the geographic north), and inclination (the angle between the vector and the horizontal plane). The palaeomagnetic direction is usually calculated as a mean of several samples collected from the same 'site', where a 'site' is a unit representing the same point in time, e.g. a lava flow or a particular horizon in a sedimentary sequence. The site palaeomagnetic mean is calculated via Fisher statistics (Fisher 1953). Similarly, one can calculate the palaeomagnetic mean of a locality by a Fisher mean of several sites.

Estimating the intensity of the ancient field (palaeointensity) is by far more complicated than estimating the palaeomagnetic direction. The experimental principles of palaeointensity are beyond the scope of this chapter (see Valet 2003; Tauxe & Yamazaki 2007; Shaar *et al.* 2010; Shaar & Tauxe 2013), but it is the basis of a relatively new archeomagnetic chronological tool for the Holocene (Section 6.4.2).

As mentioned above, a robust palaeomagnetic analysis would not be complete without assessment of the 'which', 'what', and 'when' questions on the ancient magnetization. Yet this is far from being a trivial task. Above all, the fundamental data to consider are the geological setting, the detailed lithology, and the history of the system (formation and post-depositional). Then, there is a wide range of magnetic experimental procedures and microscopic observations that can assist in characterizing the magnetic mineralogy, grain size distributions, magnetization stability, and the origin of the magnetization (Dunlop & Özdemir 2001; Tauxe 2010; Liu *et al.* 2012).

There is no simple recipe for this so-called 'rock-magnetic analysis', and its scope depends on the specific requirements of the study. Also, interpreting rock-magnetic data is not always simple. It is likely that some uncertainties about the rock-magnetic properties of the material will still remain open after rigorous analysis. However, we stress that palaeomagnetic interpretations based on inadequate assessment of the source, the age, and the stability of the magnetization should always be regarded with extreme caution.

6.4 GEOMAGNETIC CHRONOLOGY

6.4.1 GEOMAGNETIC POLARITY/INSTABILITY TIME SCALES

Geomagnetic reversals are one of the most prominent chronological markers in the Quaternary. During a reversal, the polarity of the field rapidly switches between N/R states, where N (Normal) stands for northerly oriented field and R (Reverse) stands for southerly oriented field. The duration of a reversal is less than 10^4 years, perhaps even less than 10^3 years (Valet & Fournier 2016). The reversal chronology, known as the 'Geomagnetic Polarity Time Scale' (GPTS), started to be developed in the early 1960s (e.g. Cox *et al.* 1964), when Quaternary GPTS included only two polarity 'chrons' and one short-term event. The chrons were initially named after pioneers in geomagnetism (Brunhes, Matuyama, and Gauss; Cox *et al.* 1964; Fig. 6.3). With time, more reversals were discovered, and the nomenclature of GPTS became too complicated to maintain. The currently accepted terminology divides the Quaternary into chrons and subchrons (Cande & Kent 1995; Gee & Kent 2007). Some of the subchrons are still known by their initial names (Jaramillo, Cobb Mountain, Olduvai, Reunion/Feni), and this nomenclature remains in widespread use. We note that GPTS terminology in the published literature, especially for short-term events in the Matuyama, such as Cobb Mountain, Gilsa, and Reunion, is not always consistent (for further reading see Gee & Kent 2007; Tauxe 2010; Singer 2014). As the age accuracy of the GPTS is of great importance in Quaternary research, it is continuously updated using new high-quality data from sedimentary, oceanic, and volcanic sources (Gee & Kent 2007; Gradstein *et al.* 2012; Singer 2014). Recently published Quaternary GPTSs differ
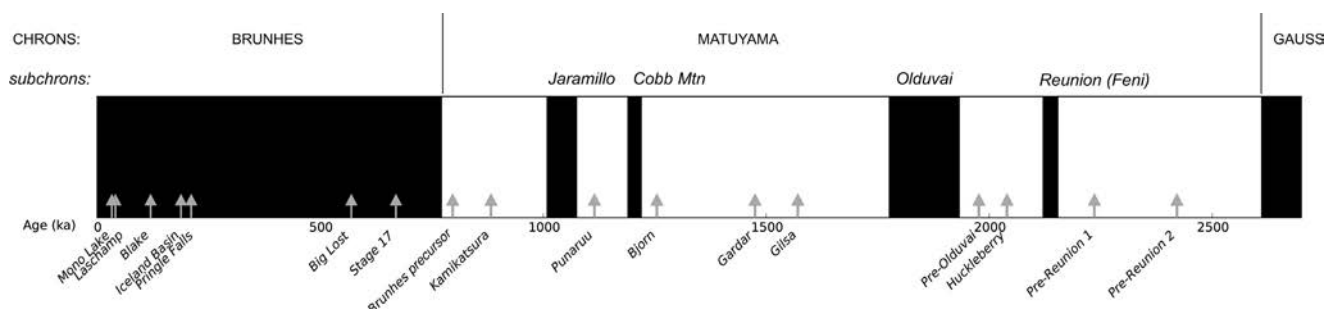

Figure 6.3 The Quaternary Geomagnetic Polarity Time Scale. The chrons and subchrons shown follow Singer (2014). Excursions validated by Laj and Channell (2007) and Roberts (2008) are shown as arrows.
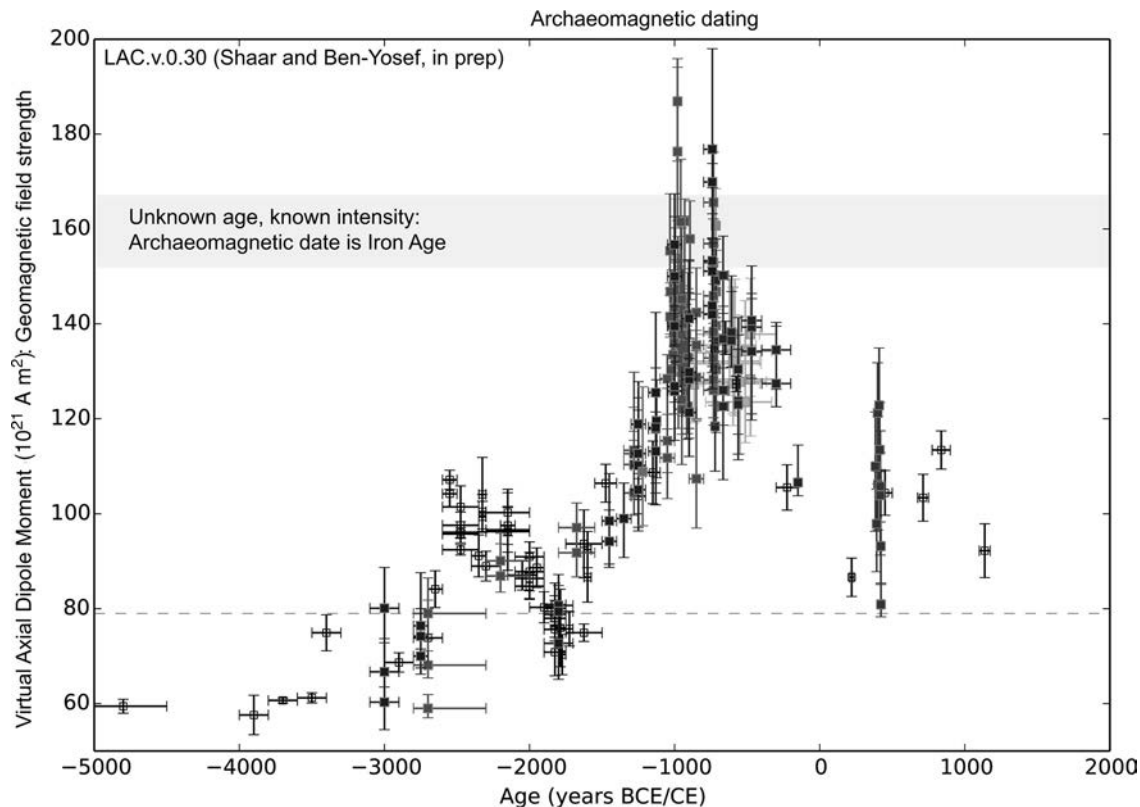
Figure 6.4 Archeomagnetic ages of young materials using palaeointensity. The Levantine Archaeomagnetic Compilation (LAC) is an in-progress effort to construct a new archeo- and geochronology for young fired archeological objects (R. Shaar & E. Ben-Yosef, unpublished). The grey stripe is palaeointensity results from a sample whose age is unknown. A comparison with LAC suggests an Iron-Age date. Similar declination/inclination curves for the Holocene may provide geochronology for young sediments.

slightly from each other and display some minor discrepancies, reflecting that the precise chronology is a work in progress.

Geomagnetic excursions are additional important detectable chronological markers. Excursions are brief ($<10^4$ years) and substantial deviations of field direction from northerly/southerly oriented geomagnetic field ($>45°$ declinational change; Laj & Channell 2007), accompanied by a significantly low field intensity (Roberts 2008). As excursions are short events, they are hard to detect, and therefore there is controversy in the literature regarding some of the published Quaternary excursions. We show in Fig. 6.3 excursions validated by Laj and Channell (2007), and by Roberts (2008).

6.4.2 HOLOCENE GEOMAGNETIC SECULAR VARIATIONS

A relatively new addition to the palaeomagnetic geochronology toolbox is regional curves of geomagnetic secular variations. Secular variations are short-term ($<10^5$ years) changes in the direction and intensity of the field. If a regional secular variation curve is established for a given time interval, then palaeomagnetic dating can be applied by comparing direction and/or intensity of material/sequences whose age is unknown with the reference secul-

ar variation curve. While this concept is not new, its application requires robust and accurate reference curves for secular variations. We have compiled such a curve for the Levantine intensity using a range of well-dated archeological materials. This is a work in progress, and its initial version is illustrated in Fig. 6.4.

6.5 APPLICATIONS OF PALAEOMAGNETIC GEOCHRONOLOGY IN THE LEVANT

Palaeomagnetic chronology has been applied in a number of Levantine sequences for which direct absolute age dating could not be accomplished, or as a complementary method. Here, we briefly review some successful applications of palaeomagnetic chronology in geological and archaeological contexts. Notably, the most densely sampled area is within Israel where the late Professor Hagai Ron established a laboratory in 1980 (Fig. 6.5).

6.5.1 PALAEOMAGNETIC DATING OF GEOLOGICAL UNITS

VOLCANIC SECTIONS

In a pioneering piece of research, Freund *et al*. (1965) conducted one of the first worldwide palaeomagnetic chronostratigraphic
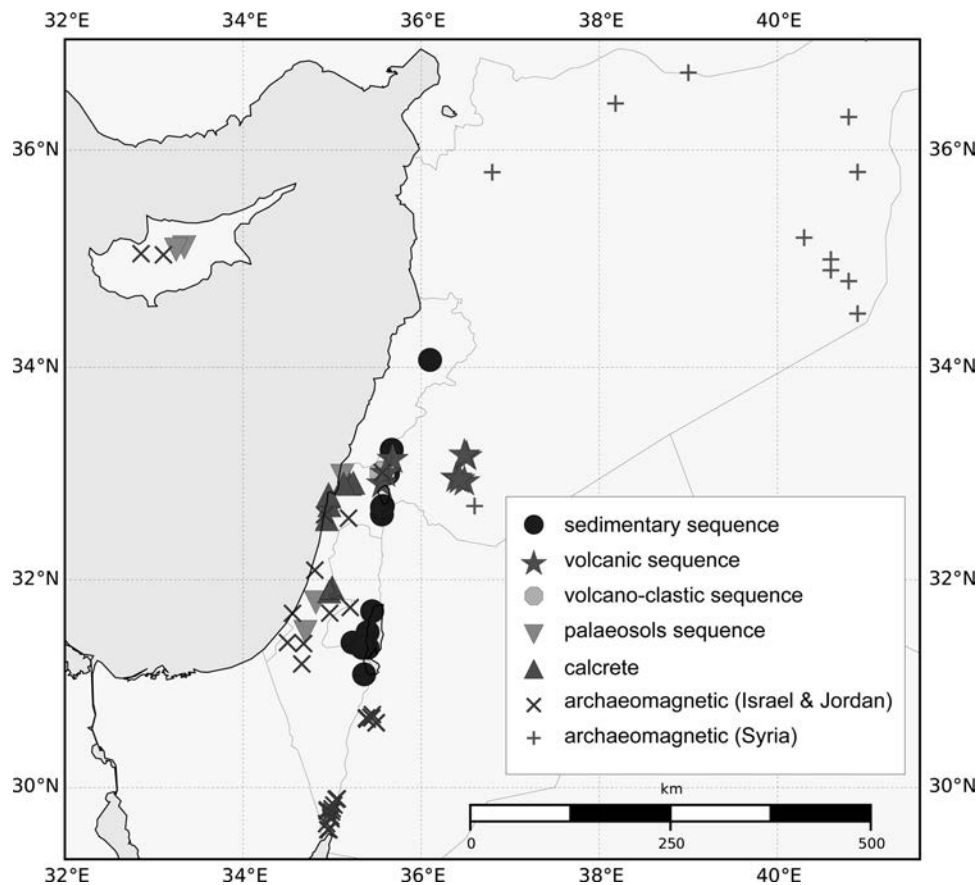
Figure 6.5 Location map of the studies listed in Section 6.5.

applications, studying the Plio-Pleistocene volcanic field in Northern Israel. This volcanic field was later densely sampled for both palaeomagnetic and radiometric analyses (Ron *et al*. 1984, 1992; Heimann & Ron 1993; Heimann *et al*. 1996; Hurwitz *et al*. 1999). Magnetostratigraphy was used by these authors to refine K–Ar ages of successive lava flows (e.g. Nahal Orvim, Nahal Ashaf), infer ages of fluvial units (e.g. Nahal Hazor), and correlate different sections in the Golan Heights and Korazim block (Heimann & Ron 1993). These two methods were combined by dating a few of the flows in each sequence, including the uppermost and the lowermost ones, and then using them as anchors for GPTS correlation of all flows. The volcanic field outside the Golan Heights was less studied. Vandonge *et al*. (1967) and Gregor *et al*. (1974) investigated volcanic units in Syria and Lebanon. Abou-Deeb *et al*. (1999) used palaeomagnetic directions and polarities to obtain a chronological differentiation between independent volcanic units in Syria.

LOESS AND ANCIENT SOILS

Aeolian deposits and buried soils carry excellent magnetic signal. Yet their net magnetization is a complex combination of different DRM, post-depositional DRM (pDRM), and CRM mechanisms acting over a relatively long period (Evans & Heller 2001; Liu *et al*. 2007). Thus, magnetostratigraphy analysis of loess and buried soils should take into account possible palaeomagnetic delay (lock-in depth) of the order of 10^5 years. Despite this complexity, magnetostratigraphy was successfully applied on different types of buried soils, loess, and Hamra soil in Israel: Evron Quarry (Ron *et al*. 2003), Revadim Quarry (Gvirtzman *et al*. 1999; Marder *et al*. 1999), and the Ruhama badlands (Laukhin *et al*. 2001; Ron & Gvirtzman 2001).

CALCRETES

Mashiah *et al*. (2009) recognized that calcretes (consolidated carbonate soil horizons) carry stable CRM. They used this phenomenon to date successive sections of calcretes in the base of Mt Carmel via magnetostratigraphy as a means to put temporal constraints on the development of the Western Carmel escarpment. Zilberman *et al*. (2011) and Zilberman (2013) used a similar approach to investigate calcretes overlying faults in Western Galilee and Modiin to constrain termination of the tectonic activity. Greenbaum and Zilberman (Chapter 47 of this volume), using similar approaches, were able for the first time to decipher a Plio-Pleistocene chronology of alluvial and coastal units in the north-western Negev. Matmon *et al*. (2010) applied palaeomagnetic methods to investigate the temporal evolution of successive colluvial units in the Zurim escarpment, Bet-Kerem Valley.

LACUSTRINE DEPOSITS

Palaeomagnetism of the thick lacustrine sequence of the Dead Sea Group has been extensively studied, including the Sedom, Erq el Ahmar, 'Ubeidiya, Lisan, and Zeelim Formations (e.g. Matmon & Zilberman, Chapter 3; Bar-Yosef & Belmaker, Chapter 20; Stein *et al.*, Chapter 8 of this volume). Key palaeomagnetic studies are reviewed here as examples.

Weinberger *et al.* (1997) employed palaeomagetism for reconstructing the tectonic evolution of the Sedom diapir. In their analysis, they isolated a secondary normal-polarity magnetization associated with Brunhes polarity. This CRM postdates the main tilt and constrains the termination of diapir emplacement.

The magnetostratigraphy of the Erq el Ahmar (EEA) Formation was investigated in three different works (Braun *et al.* 1991; Ron & Levi 2001; Davis *et al.* 2011). There are only minor differences between the palaeomagnetic profiles, and they all agree well with the initial profile of Braun *et al.* (1991). Yet the palaeomagnetic age interpretations given in the above publications are different. This exemplifies the dependency of magnetostratigraphy on absolute dates at tie points. Using an estimated biostratigraphic age of 1.5–2 Ma, Braun *et al.* (1991) correlated the EEA Normal polarity to either Olduvai or Reunion subchrons. Later, Ron and Levi (2001) obtained a more detailed inclination profile, concluding that the subchron is more likely Olduvai. Recently, Davis *et al.* (2011) obtained 11 cosmogenic burial ages of 3.5–5.3 Ma, pushing the magnetostratigraphy sequence to the Gauss or Gilbert chrons. Magnetostratigraphy analysis of the younger 'Ubeidiya Formation, located a few kilometres north of Erq el Ahmar, yielded four reversal events. Given faunal constraints of about 1.4 Ma, Sagi (2005) provided several possible age interpretations, all within the Matuyama chron.

Sections of the late Pleistocene Lisan Formation near Nahal Prazim, Masada, and southern Sea of Galilee (Lake Kinneret) (Ohalo; Nadel, Chapter 33 of this volume) were studied for palaeomagnetism for recovering short-term secular variations of the geomagnetic field (Marco *et al.* 1998, 1999; Marco 2002). Using AF and thermal demagnetization procedures, they isolated the palaeomagnetic direction, and obtained detailed secular variation profiles revealing two excursions in the Peratzim section (Marco *et al.* 1998) and one excursion in Ohalo (Marco 2002). Similar investigations targeted the Holocene in Lake Kinneret (Thompson *et al.* 1985) and in the Dead Sea exposure and core data (Segal 2003; Frank *et al.* 2007a, 2007b).

Despite the success of the studies above, questions regarding the stability and origin of the magnetization in the Dead Sea sediments were not raised until recently (Ron *et al.* 2006, 2007; Frank *et al.* 2007a, 2007b; Nowaczyk 2011). Using thorough rock-magnetic and microscopic investigation of the Lisan and Zeelim Formations, they deciphered complex histories of magnetic acquisition. Ron *et al.* (2006) suggested a three-stage model for the complicated magnetization: (1) DRM acquisition of fine magnetite particles, (2) CRM acquisition of greigite accompanying the dissolution of the primary magnetite, and (3) oxidation of the greigite following outcrop exposure. This model suggests that palaeomagnetic data from Dead Sea rift lacustrine deposits should be cautiously examined.

Only few sedimentary Quaternary sequences outside the Dead Sea basin were studied using palaeomagnetic methods. Frank *et al.* (2002) investigated Holocene palaeomagnetic secular variations in Birkat Ram, the Golan Heights. Develle *et al.* (2011) used inclination anomalies derived from the Yammouneh basin core, Lebanon, to establish a palaeomagnetic chronology based on excursion markers.

6.5.2 ARCHAEOMAGNETISM

Over the past several decades, Levantine archeological research has involved palaeomagnetic research, predominantly for constraining ages of archeological finds. The GPTS records obtained from sedimentary and volcanic sequences associated with archeological material have been used to estimate ages of several important prehistoric sites, some of which are key for understanding early human evolution and migration routes. The age of 'Ubeidiya (Bar-Yosef & Belmaker, Chapter 20 of this volume), the earliest site in the Levant and one of the earliest outside Africa, was further constrained by palaeomagnetic study of the 'Ubeidiya sequence to specific time intervals (1.55–1.2 Ma or 1.2–1 Ma; Sagi 2005). It has been suggested that a nearby site, Erq el Ahmar, is even earlier (>2 Ma; see above and Davis *et al.* 2011; Matmon & Zilberman, this volume). However, the magnetostratigraphy has no palaeoanthropological material and the association of the Erq el Ahmar Formation with such material is debated. Another key prehistoric site is Gesher Benot Ya'aqov (GBY) (Goren-Inbar, Chapter 21 of this volume). The site, an accumulation of artefacts and ecofacts along a thick sedimentary sequence, was deposited through the Brunhes/Matuyama transition (~780 ka; Goren-Inbar *et al.* 1992, 2000). Similar to 'Ubeidiya, GBY is also in the Rift Valley of northern Israel, along which hominin expansion northward probably took place. The palaeomagnetic stratigraphy contributes to our understanding of this process, and possibly also to the question of the timing of the first deliberate use of fire (see Goren-Inbar *et al.* 2004). Other Lower Palaeolithic excavations at which magnetostratigraphy has successfully been applied are Evron Quarry (Middle Acheulian, Ron *et al.* 2003), Bizat Ruhama (Laukhin *et al.* 2001; Ron & Gvirtzman 2001), Late Acheulian Revadim Quarry (Gvirtzman *et al.* 1999; Marder *et al.* 1999) and Kefar Menachem (lower Palaeolithic, Malinsky-Buller *et al.* 2016). However, considering the importance of the Levant in early prehistory and the substantial number of key sites subjected to systematic excavations, the number of reported sites applying palaeomagnetism is surprisingly low.

While the GPTS is the basis for constraining the age of prehistoric sites, secular variations records are used for dating younger sites (usually not earlier than the Pottery Neolithic, the time when ceramic technology was introduced). However, the application of the latter is still limited as the resolution of the published records is currently low (Fig. 6.4). Improvement of resolution and accuracy of the reference curves for the Holocene is an ongoing effort (Figs. 6.4, 6.5). Such efforts are taking advantage of the rich archeological landscape of the Levant, based on well-dated heat-impacted

archeological materials, e.g. Ben-Yosef *et al*. (2008b), Gallet *et al*. (2006), Shaar *et al*. (2011). Recently, the availability of the Levantine Archaeomagnetic Compilation (LAC) data consisting primarily of intensity values was instrumental in constraining the age of important archeometallurgical sites, some of which are considered the earliest in the Levant if not anywhere. While some of these results corroborate the early age of smelting in the southern Levant (Ben-Yosef *et al*. 2008a), others (Ben-Yosef *et al*. 2010) contradict proposals of Neolithic copper smelting in the region. As the resolution of the LAC improves, its application in young archaeological contexts will become more effective, with potential to become a potent dating tool in the research of this archaeologically rich region.

ACKNOWLEDGEMENTS

REFERENCES

Abou-Deeb, J.M., Otaki, M.M., Tarling, D.H. & Abdeldayem, A.L. 1999. A palaeomagnetic study of Syrian volcanic rocks of Miocene to Holocene age. *Geofisica Internacional-Mexico* 38: 17–26.

Ben-Yosef, E., Ron, H., Tauxe, L. *et al*. 2008a. Application of copper slag in geomagnetic archaeointensity research. *Journal of Geophysical Research – Solid Earth* 113. doi:10.1029/2007JB005235.

Ben-Yosef, E., Tauxe, L., Ron, H. *et al*. 2008b. A new approach for geomagnetic archaeointensity research: Insights on ancient metallurgy in the Southern Levant. *Journal of Archaeological Science* 35: 2863–79.

Ben-Yosef, E., Tauxe, L. & Levy, T.E. 2010. Archaeomagnetic dating of copper smelting site F2 in the Timna valley (Israel) and its implications for the modelling of ancient technological developments. *Archaeometry* 52: 1110–21.

Braun, D., Ron, H. & Marco, S. 1991. Magnetostratigraphy of the hominid tool-bearing Erk el Ahmar Formation in the northern Dead Sea Rift. *Israel Journal of Earth Sciences* 40: 191–7.

Butler, R.F. 1992. *Paleomagnetism: Magnetic Domains to Geologic Terranes*. Boston: Blackwell Scientific Publications.

Cande, S.C. & Kent, D.V. 1995. Revised calibration of the geomagnetic polarity timescale for the late Cretaceous and Cenozoic. *Journal of Geophysical Research – Solid Earth* 100: 6093–5.

Cox, A., Doell, R.R. & Dalrymple, G.B. 1964. Geomagnetic polarity epochs. *Science* 143: 351–2.

Davis, M., Matmon, A., Fink, D., Ron, H. & Niederniann, S. 2011. Dating Pliocene lacustrine sediments in the central Jordan Valley, Israel – implications for cosmogenic burial dating. *Earth and Planetary Science Letters* 305: 317–27.

Develle, A.L., Gasse, F., Vidal, L. *et al*. 2011. A 250 ka sedimentary record from a small karstic lake in the northern Levant (Yammouneh, Lebanon) Paleoclimatic implications. *Palaeogeography Palaeoclimatology Palaeoecology* 305: 10–27.

Dunlop, D.J. & Özdemir, Ö. 2001. *Rock Magnetism: Fundamentals and Frontiers*. New York: Cambridge University Press.

Evans, M.E. & Heller, F. 2001. Magnetism of loess/palaeosol sequences: Recent developments. *Earth-Science Reviews* 54: 129–44.

Fisher, R.A. 1953. Dispersion on a sphere. *Proceedings of the Royal Society of London Series A* 217: 295–305.

Frank, U., Schwab, M.J. & Negendank, J.F.W. 2002. A lacustrine record of paleomagnetic secular variations from Birkat Ram, Golan Heights (Israel) for the last 4400 years. *Physics of the Earth and Planetary Interiors* 133: 21–34.

Frank, U., Nowaczyk, N.R. & Negendank, J.F.W. 2007a. Palaeomagnetism of greigite bearing sediments from the Dead Sea, Israel. *Geophysical Journal International* 168: 904–20.

Frank, U., Nowaczyk, N.R. & Negendank, J.F.W. 2007b. Rock magnetism of greigite bearing sediments from the Dead Sea, Israel. *Geophysical Journal International* 168: 921–34.

Freund, R., Oppenheim, M.J. & Schulman, N. 1965. Direction of magnetization of some basalts in Jordan Valley and Lower Galilee (Israel). *Israel Journal of Earth Sciences* 14: 37–44.

Gallet, Y., Genevey, A., Le Goff, M., Fluteau, F. & Ali Eshraghi, S. 2006. Possible impact of the Earth's magnetic field on the history of ancient civilizations. *Earth and Planetary Science Letters* 246: 17–26.

Gee, J.S. & Kent, D.V. 2007. Source of oceanic magnetic anomalies and the geomagnetic polarity timescale. In *Treatise on Geophysics.* Vol. 5. *Geomagnetism*, ed. M. Kono. Amsterdam: Elsevier.

Goren-Inbar, N., Belitzky, S., Verosub, K. *et al*. 1992. New discoveries at the middle Pleistocene Acheulean site of Gesher Benot Yaaqov, Israel. *Quaternary Research* 38: 117–28.

Goren-Inbar, N., Feibel, C.S., Verosub, K.L. *et al*. 2000. Pleistocene milestones on the out-of-Africa corridor at Gesher Benot Ya'aqov, Israel. *Science* 289: 944–7.

Goren-Inbar, N., Alperson, N., Kislev, M.E. *et al*. 2004. Evidence of hominin control of fire at Gesher Benot Ya'aqov, Israel. *Science* 304: 725–7.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg, G.M. (ed.) 2012. *The Geological Time Scale*. Amsterdam: Elsevier.

Gregor, C.B., Mertzman, S., Nairn, A.E.M. & Negendan. J. 1974. Paleomagnetism and alpine tectonics of Eurasia. V. Paleomagnetism of some mesozoic and cenozoic volcanic-rocks from Lebanon. *Tectonophysics* 21: 375–95.

Gvirtzman, G., Wieder, M., Marder, O. *et al*. 1999. Geological and pedological aspects of an Early Paleolithic site: Revadim, Central Coastal Plain, Israel. *Geoarchaeology* 14: 101–26.

Heimann, A. & Ron, H. 1993. Geometric changes of plate boundaries along part of the northern Dead-Sea Transform – geochronological and paleomagnetic evidence. *Tectonics* 12: 477–91.

Heimann, A., Steinitz, G., Mor, D. & Shaliv, G. 1996. The Cover Basalt, its age and its regional and tectonic setting: Implications from K–Ar and ^{40}Ar/^{39}Ar geochronology. *Israel Journal of Earth Sciences* 45: 55–71.

Hurwitz, S., Matmon, A., Ron, H. & Heiman, A. 1999. Deformation along the margins of the Dead Sea Transform: The Yehudiyya Block, Golan Heights. *Israel Journal of Earth Sciences* 48: 257–64.

Kirschvink, J. 1980. The least-squares line and plane and the analysis of paleomagnetic data. *Geophysical Journal of the Royal Astronomical Society* 62: 699–718.

Laj, C. & Channell, J.E.T. 2007. Geomagnetic excursions. In *Treatise on Geophysics.* Vol. 5. *Geomagnetism*, ed. M. Kono. Amsterdam: Elsevier, pp. 347–416.

Laukhin, S.A., Ronen, A., Pospelova, G.A. *et al*. 2001. New data on the geology and geochronology of the Lower Palaeolithic site Bizat Ruhama in the southern Levant. *Paléorient* 27: 69–80.

Liu, Q., Deng, C., Torrent, J. & Zhu, R. 2007. Review of recent developments in mineral magnetism of the Chinese loess. *Quaternary Science Reviews* 26: 368–85.

Liu, Q., Roberts, A.P., Larrasoana, J.C. *et al*. 2012. Environmental magnetism: Principles and applications. *Reviews of Geophysics* 50: RG4002. doi:10.1029/2012RG000393.

Malinsky-Buller, A., Barzilai, O., Ayalon, A. *et al*. 2016. The age of the lower Palaeolithic site of Kefar Menachem West, Israel – Another facet of Acheulian variability. *Journal of Archaeological Science: Reports* 10: 350–62.

Marco, S. 2002. Late Pleistocene paleomagnetic secular variation from the Sea of Galilee, Israel. *Geophysical Research Letters* 29. doi:10.1029/2001GL014038.

Marco, S., Ron, H., McWilliams, M.O. & Stein, M. 1998. High-resolution record of geomagnetic secular variation from Late Pleistocene Lake Lisan sediments (paleo Dead Sea). *Earth and Planetary Science Letters* 161: 145–60.

Marco, S., Ron, H., McWilliams, M.O. & Stein, M. 1999. The locking in of remanence in Late Pleistocene sediments of Lake Lisan (palaeo Dead Sea). In *Palaeomagnetism and Diagenesis in Sediments*, ed. D.H. Tarling & P. Turner. London.

Marder, O., Gvirtzman, G., Ron, H. *et al*. 1999. The Lower Paleolithic site of Revadim Quarry, preliminary finds. *Journal of the Israel Prehistoric Society – Mitekufat Haeven* 28: 21–53.

Mashiah, M., Greenbaum, N., Zilberman, E., Ron, H. & Ronen, A. 2009. Pleistocene tectonic stability of the western Carmel escarpment – evidence from magnetostratigraphy of calcretes. *Geological Survey of Israel, Report GSI/19/2009*.

Matmon, A., Katz, O., Shaar, R. *et al*. 2010. Timing of relay ramp growth and normal fault linkage, Upper Galilee, northern Israel. *Tectonics* 29.

Nowaczyk, N.R. 2011. Dissolution of titanomagnetite and sulphidization in sediments from Lake Kinneret, Israel. *Geophysical Journal International* 187: 34–U624.

Roberts, A.P. 2008. Geomagnetic excursions: knowns and unknowns. *Geophysical Research Letters* 35: L17307. doi:10.1029/2008GL034719.

Ron, H. & Gvirtzman, G. 2001. Magnetostratigraphy of Ruhama badland Quaternary deposits: A new age of the Lower Paleolithic site. *Abstracts of the Annual Meeting – Israel Geological Society*.

Ron, H. & Levi, S. 2001. When did hominids first leave Africa? New high-resolution magnetostratigraphy from the Erk-el-Ahmar Formation, Israel. *Geology* 29: 887–90.

Ron, H., Freund, R., Garfunkel, Z. & Nur, A. 1984. Block rotation by strike-slip faulting – structural and paleomagnetic evidence. *Journal of Geophysical Research* 89: 6256–70.

Ron, H., Heimann, A. & Garfunkel, Z. 1992. Pliocene paleomagnetic pole of the Arabian Plate: Implication for the Levant plate kinematics. *Institute for Petroleum Research and Geophysics Report, 889/33/90*.

Ron, H., Porat, N., Ronen, A., Tchernov, E. & Horwitz, L.K. 2003. Magnetostratigraphy of the Evron Member – implications for the age of the Middle Acheulian site of Evron Quarry. *Journal of Human Evolution* 44: 633–9.

Ron, H., Nowaczyk, N.R., Frank, U., Marco, S. & Mcwilliams, M.O. 2006. Magnetic properties of Lake Lisan and Holocene Dead Sea sediments and the fidelity of chemical and detrital remanent magnetization. *Geological Society of America Special Papers* 401: 171–82.

Ron, H., Nowaczyk, N.R., Frank, U. *et al*. 2007. Greigite detected as dominating remanence carrier in Late Pleistocene sediments, Lisan Formation, from Lake Kinneret (Sea of Galilee), Israel. *Geophysical Journal International* 170: 117–31.

Sagi, A. 2005. *Magnetostratigraphy of 'Ubeidiya' Formation, Northern Dead Sea Transform*. Unpublished M.Sc. thesis, Hebrew University of Jerusalem.

Segal, Y. 2003. *Paleomagnetic Secular Variation of the Last 4 Millennia Recorded in Dead Sea Sediments and Archaeological Sites in Israel*. Unpublished M.Sc. thesis, Tel-Aviv University.

Shaar, R., Ron, H., Tauxe, L. *et al*. 2010. Testing the accuracy of absolute intensity estimates of the ancient geomagnetic field using copper slag material. *Earth and Planetary Science Letters* 290: 201–13.

Shaar, R., Ben-Yosef, E., Ron, H. *et al*. 2011. Geomagnetic field intensity: How high can it get? How fast can it change? Constraints from Iron-Age copper-slag. *Earth and Planetary Science Letters* 301: 297–306.

Shaar, R. & Tauxe, L. 2013. Thellier GUI: An integrated tool for analyzing paleointensity data from Thellier-type experiments. *Geochemistry Geophysics Geosystems* 14: 677–92.

Singer, B.S. 2014. A Quaternary geomagnetic instability time scale. *Quaternary Geochronology* 21: 29–52.

Sternberg, R.S. 1997. Archaeomagnetic dating. In *Chronometric and Allied Dating in Archaeology*, ed. R.E. Taylor & M. Aitken. New York: Plenum Press.

Tauxe, L. 2010. *Essentials of Paleomagnetism*. Berkeley: University of California Press.

Tauxe, L. & Yamazaki, T. 2007. Paleointensities. In *Treatise on Geophysics*. Vol. 5. *Geomagnetism*, ed. M. Kono. Amsterdam: Elsevier, pp. 509–63.

Thompson, R., Turner, G.M., Stiller, M. & Kaufman, A. 1985. Near-East paleomagnetic secular variation recorded in sediments from the Sea of Galilee (Lake Kinneret). *Quaternary Research* 23: 175–88.

Valet, J.P. & Fournier, A. 2016. Deciphering records of geomagnetic reversals. *Reviews of Geophysics* 54: 410–46.

Vandonge, P.G., Vandervo, R. & Raven, T. 1967. Paleomagnetic research in Central Lebanon Mountains and in Tartous area (Syria). *Tectonophysics* 4: 35–53.

Weinberger, R., Agnon, A. & Ron, H. 1997. Paleomagnetic reconstruction of a diapir emplacement: a case study from Sedom diapir, the Dead Sea Rift. *Journal of Geophysical Research – Solid Earth* 102: 5173–92.

Zilberman, E. 2013. The Plio-Pleistocene tectonic history of the Modi'in fault and its implications on the seismic hazard assessment for the Modi'in area. *Geological Survey of Israel Report GSI/06/2013*.

Zilberman, E., Ron, H. & Shaar, R. 2011. Evaluating the potential seismic hazards of the Ahihud Ridge fault system by paleomagnetic and morphological analyses of calcretes. *Geological Survey of Israel Report GSI/15/11*.