Paleomagnetic Secular Variation of the Last 4 Millennia recorded in Dead Sea Sediments and Archeological Sites in Israel

Thesis submitted for the degree “Master of Science” In Geophysics
Tel – Aviv University
Department of Geophysics and Planetary Science

By
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This work was carried out at the Tel – Aviv University
Under the supervision of Dr. Shmuel Marco

June 2003
Acknowledgements

I would like to thank Shmulik Marco for given me the chance to do this interesting study. For finding time and helping me whenever I needed. And for always being there - thank.

I would like to thank Haim Barbe for making the archeomagnetism study possible and for his enthusiasm and interest in this study.

I am grateful to Hagai Ron and Annick Chauvine for constructive and fruitful discussions and help in the lab work.

Thanks to Ayal Rozenberg, Kineret Shapira, Philip Dufresne and Bruno for assistance in fieldwork and in lab work.

Thank to Revital Ken Tor, Gruny, Ellenblum, Holzer, Finkelshtein, Igal Israe, Vitto and Aviam, for the very useful information about the sampling sites and to Uta Frank and M. Ali for the data of their study.

Thanks to Philip Lanos who mad my stay in Renne possible and to Jean Raynald and Noelle who mad this stay more than just work.

I would like to thank the Israel Science foundation, the ministry of infrastructure and France-Israel Arc en Ciel program for financial support of this study.

And last but not least Ayal Rozenberg, Segal family and grandma Shulman for being there.
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## Abbreviations

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<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AD</td>
<td>L. Anno Domini - the count of the Christian (years)</td>
</tr>
<tr>
<td>AF</td>
<td>Alternating Field</td>
</tr>
<tr>
<td>ave</td>
<td>Average</td>
</tr>
<tr>
<td>BC</td>
<td>Before Christ</td>
</tr>
<tr>
<td>BP</td>
<td>Before Present</td>
</tr>
<tr>
<td>CRM</td>
<td>Chemical Remnant Magnetism</td>
</tr>
<tr>
<td>Dec</td>
<td>Declination</td>
</tr>
<tr>
<td>DRM</td>
<td>Detrital Remnant Magnetism</td>
</tr>
<tr>
<td>Fig</td>
<td>Figure</td>
</tr>
<tr>
<td>GRM</td>
<td>Gyro Remanent Magnetization</td>
</tr>
<tr>
<td>H</td>
<td>Relative paleointensity – in ZT</td>
</tr>
<tr>
<td>IGRF</td>
<td>International geomagnetic reference field</td>
</tr>
<tr>
<td>Inc</td>
<td>Inclination</td>
</tr>
<tr>
<td>J</td>
<td>Magnetization</td>
</tr>
<tr>
<td>MDF</td>
<td>Median Distractive Field</td>
</tr>
<tr>
<td>NRM</td>
<td>Natural Remnant Magnetization</td>
</tr>
<tr>
<td>PRM</td>
<td>Partial Remanent Magnetization</td>
</tr>
<tr>
<td>PSV</td>
<td>Paleomagnetic Secular Variation</td>
</tr>
<tr>
<td>pTRM</td>
<td>Partial Thermal Remanent Magnetization</td>
</tr>
<tr>
<td>SV</td>
<td>Secular Variation</td>
</tr>
<tr>
<td>Tb</td>
<td>Blocking temperature</td>
</tr>
<tr>
<td>Ti</td>
<td>Experiment temperature</td>
</tr>
<tr>
<td>TRM</td>
<td>Thermal Remanent Magnetization</td>
</tr>
<tr>
<td>VDM</td>
<td>Virtual Dipole Moment</td>
</tr>
<tr>
<td>VGP</td>
<td>Virtual Geographic Pole</td>
</tr>
<tr>
<td>VRM</td>
<td>Viscous Remnant Magnetization</td>
</tr>
<tr>
<td>ZT</td>
<td>Ze'elim Terrace</td>
</tr>
</tbody>
</table>
1 Abstract

This study aims at recording the paleo-geomagnetic field intensity and direction (inclination and declination) during the last four millennia in Israel. The data for the paleo field directions were collected from the Ze’elim Formation in the alluvial terrace of the Zeelim Creek (hereafter - ZT) at the Dead Sea shore and several archeological sites in Israel. Successive sedimentation of fine laminas in most of the sediments at the ZT site can provide continuous paleomagnetic record. They show a high accumulation rate, ranging from 3 to 13 mm/yr, which enables high-resolution sample collection. Dense $^{14}$C dating, and earthquakes chronology were investigated in a previous study at the site. I obtained 310 oriented samples from about 6.5m of the 9m of exposed sections. The sediment ages are estimated to the 17th century BC till the 13th century AD. Stability tests were performed on the samples to explore the properties of the measured NRM, estimate the accuracy of the results, and define the relationships between the magnetization and the post depositional deformation in ZT section. Alternative field demagnetization reveals stable, single-component vectors in most of the samples. The Fisher mean direction of 176 horizons is 355°/43° (Dec./Inc.), R= 0.97, $\alpha$95=1.88° and $\kappa$=31. I observe four types of direction variations with time in the ZT record. The first is rapid directional fluctuation, with a shift of up to several tens of degrees from one horizon to the other, interpreted as noise. The second is gradual directional change of a few tens of degrees within several centuries interpreted as a non-dipole field effect. The third type is slow westerly shifting of about 0.01 °/yr between 17th century BC and 4th century AD, which is interpreted as a change in the dipole field. The fourth is an antiphase variation of the Inc to the Dec.

The record from ZT is compared to data collected from eighteen archeological objects originating from ten archeological sites. The objects were heat sources such as ceramics production, lime production, fireplaces and thermal baths. These installations were heated to above the Curie temperature and acquired the magnetic field while cooling. I sampled sites from the 8th century BC till the 19th century AD. The mean direction sampled is 001°/50° (Dec./Inc.), R= 0.979, $\alpha$95= 5.2°, $\kappa$= 45.6, which is identical to the present direction (003°/48°). There is a good agreement between the paleomagnetic secular variations (PSV) obtained in ZT and the results from the archeological sites. There is also correlation between the PSV results from ZT and paleomagnetic results from other regions in most of the section. The results
of this study suggest that the paleomagnetic direction curves (inclination and declination) obtained in Ze’elim sediments can be used as a paleomagnetic field reference to estimate ages of archeological sites and geological units.

For the measurements of geomagnetic absolute paleointensity I sampled nine archeological objects from five archeological sites. Their ages range from the 1st to the 19th century AD. The paleointensity measurements were performed using the original double-heating Thellier method. Testing of partial thermal remanent magnetization (pTRM) and corrections for the anisotropy of thermo remanent magnetization were performed. The behavior was ideal in most samples during the Thellier experiment. The results show a trend of intensity decrease during the last 13 centuries. The paleointensity results show good correlation with measurements from other regions and with the global dipole moment curves. At the ZT site I obtained relative paleointensity of the field, which correlates well with the intensity measured from Syria and with the record obtained from the archeological sites in Israel.
2 Introduction

2.1 Background

2.1.1 The magnetic field of earth

About 90% of the magnetic field of the earth at its surface can be modeled as an inclined geocentric axial dipole at the core (Butler 1998), currently at 10.5° from the rotation axis of earth (McElhinny and McFadden 2000). Oscillations of the dipole field typically have a time constant of the order of $2 \times 10^4$ years. Higher order non-dipole fields can explain a field that does not fit a dipole. The non-dipole components are not symmetrical around the center of the earth.

2.1.2 Secular variation

Changes in the geomagnetic field over time, which occur randomly, may be divided into three types: reversals, excursions, and secular variation (SV). The main distinction between the three is in the quantity change of deviation in the vectors. Reversal is the most significant change of the three. During reversals the magnetic field changes its polarity. The duration of the transition is in a scale of $10^4$ years, during this time the intensity of the magnetic field decreases to almost zero (Glatzmaier and Roberts 1995; Jacobs 1994; Opdyke et al. 1973). Reversals are global phenomena, which may be explained by changes in the main geocentric axial dipole. The reversals have been used as a stratigraphic and dating tool.

Magnetic field excursions are defined as deviations of the Virtual Geographic Pole (VGP) in more then 40° from the geographic north, accompanied by an intensity decrease of the field. These deviations occur over a shorter period of time than the reversals ($10^2$-$10^3$ yrs), after which the field returns roughly to its previous polarity (Jacobs 1994; McElhinny and McFadden 2000). The excursions occur globally and might be explained by changes in the direction of the inclined geocentric axial dipole (true polar wandering). Due to their short duration, excursions provide valuable accurate regional, or even global, chronological datum.

SV show the smallest amplitude changes of the three types of geomagnetic field variations. SV is a deviation of the geomagnetic field direction by up to 40° from the geographic north, and is occasionally accompanied by a change in the intensity of the field. Several theories attempt to explain the sources of SV. SV may display a local
phenomena with a non-dipole source (Butler 1998; Courtillot et al. 1992; Games 1980; Hagstum and Champion 2002; Thompson et al. 1985), a combined effect of variations in the axial dipole field (on the global scale) and variations in the strength and location of the non-dipole field (smaller geographical distances) (Constable et al. 2000; DuBois 1989; Kovacheva 1982; Marco et al. 1998) or changes in the core source (Courtillot and Mouel 1988; Kawai et al. 1967). A study of the Lisan Formation in the Dead Sea basin also shows four types of variations in the measurement of SV: 1. High frequency (shifts of up to several tens of degrees from one horizon to the other), 2. Swings, 3. low frequency (shifts of 30°-50° within 100 to1000 years), and 4. A decrease in the inclination as the age of the rock increases (Marco et al. 1998). Similar SV occurs over distances of the order of $10^3$ km (Jacobs 1994; Kovacheva 1982; Tauxe 1993; Thompson et al.1985) and may serve as chronostratigraphic markers for periods between reversals in this distance.
2.1.3 Natural Remanent magnetization (NRM)

Sample measurement yields two magnetic components (Equation 2.1.1): the induced magnetization ($J_i$) and the natural remnant magnetization ($J_r$). $J_i$ is a product of the local geomagnetic field.

\[
J = J_i + J_r
\]  
(2.1.1)

Minimum potential energy requires that the induced magnetization is parallel or anti-parallel to the local geomagnetic field. $J_i$ is affected by rock properties, which defined by bulk susceptibility, which is the combined susceptibility of all minerals in the rock. $J_r$ present by ferromagnetic grains in the rock sample prior to the laboratory treatment. It depends on the geomagnetic field, the geological processes which occurred during rock formation, and the rock history- from deformation till sampling. The NRM can be acquired in one or more of several ways: 1. Cooling of the rock from high temperatures (TRM- thermal remanent magnetization), 2. Growth or transport, precipitation, and accumulation of ferromagnetic grains in sediments (DRM - detrital remnant magnetism) and 3. Chemical crystallization in the water column, or chemical changes of minerals in the rock that create ferromagnetic minerals (CRM- chemical remanent magnetism). The TRM direction and intensity are proportional to the ambient magnetic field during cooling down to below the Curie temperature (Thellier 1938). The DRM is affected by post-depositional physical processes, compaction, and chemical processes. Post-depositional magnetization occurs after deposition but before consolidation in the upper 10-20 cm of the accumulation sediment, where the water content is high (Butler 1998; Verosub 1977). The NRM may acquire a secondary field in a number of ways. It may acquire a low temperature partial TRM by accidental fire, partial reheating or regional heating. It may acquire a high intensity magnetization isothermal remanent magnetization by a strike of lightning or a viscous remanent magnetization (VRM) carried by less stable ferromagnetic grains, which remagnetized at ambient temperatures during extended exposure to a low magnetic field (Bucur 1994; Sternberg et al. 1999; Thompson et al. 1985). The CRM may be regarded as a secondary component if acquired long after deposition. The NRM may also acquire a gyro remanent magnetization (GRM) during the cleaning process by AF, which appears in the high field (Frank et al. 2002a). The GRM may be observed by NRM rotation and an increase of the NRM intensity in the high intensities of the applied field. The new direction obtained is correlated to the direction of the applied...
field (Hu et al. 2002). In the current study I investigated the NRM carried by sediments at the ZT section and by heated materials in archeological sites. At ZT section the magnetization might be acquired by DRM and CRM and GRM may be observed in some of the samples. The NRM, carried by heated materials in the archeological sites, is generally TRM acquired during the last cooling of the sample. Folgheraiter (1899) suggested obtaining paleointensity by comparing NRM of baked clays with their TRM, achieved by heating and cooling the sample in a known field.

\[
\frac{|J_n|}{|J_t|} = \frac{|H|}{|H_l|}
\]

The paleointensity estimation can be obtained from equation 2.1.2 where \(J_t\) is the measured TRM produced in the laboratory by \(H_l\) field, \(J_n\) is the measured NRM, and \(H\) is the unknown field intensity (Levi 1977). This suggestion was used in order to calculate the absolute paleointensity of nine archeological objects.
2.2 Objectives

The main objective of this work is to record and analyze the magnetic field behavior in Israel in the last 4 kyrs in high resolution in sediments, and compare it with independent records from other regions. A secondary objective is initiating systematic archaeomagnetic studies in Israel, which will benefit both disciplines.

2.3 Significance

SV records will help us to identify local and regional characteristics of the earth's magnetic field. By combining worldwide results we can also improve the global perspective of the magnetic field. This work provides a better understanding of the magnetization differences of different samples, which include sediments, archeological sites, and cores samples. The SV record presented in this study may supply important chronological markers and holds implications for the improvement of dating of archeological sites and geological layers.
3 Sample collections

In order to obtain a record of the changes of the magnetic field during the last 4 kyrs in Israel I acquired two types of samples: sediments from a stratigraphic sequence at ZT by the Dead Sea shore (Table 3, square in Fig 3) and discreet data from archeological sites around Israel (Table 3, ellipses 1-10 in Fig 3). The samples from ZT section were collected from 6.5 m out of the 9 m exposed section. They are dated as 17\textsuperscript{th} century BC to 13\textsuperscript{th} century AD. The archaeomagnetic samples are from eighteen separate archeological units from ten archeological sites: Ahihud, Ateret, Bet Shean, Habonim, Harat Hadid, Kastr, Kfar Menahem, Nahef, Yodfat and Zefat. They are dated as 8\textsuperscript{th} century BC to 19\textsuperscript{th} century AD.

Before sampling the ZT sediments I scraped about 10 cm off of the rock surface in order to avoid collecting the oxidized face. The oxidation is apparent as gold-brown spots in the rock and a lighter than usual hue. I carved the edges of an 8cc cube from the rock with a sharp penknife, pressed the cube into a standard plastic box, and measured its orientation with a Brunton compass. I measured the height of the sample with a meter relative to a reference layer, chosen along the section. Normally I collected one to three samples every 1 to 3 cm along the section, with the exception of several very friable sand layers, of which I could not collect any samples. From several horizons, distributed throughout the section, I collected six samples, in order to estimate the uncertainty.

At the archeological sites I shaped 8 cc cubes from the archeological artifacts with a penknife, put the plastic boxes on the cube, and measured the sample orientation and inclination by Brunton. When the material was stiff (Ateret, Ahihud, Harat Hadid, Nahef, Bet-Shean, Zefat and Yodfat) I performed core drilling to extract the sample. Most of the archeological objects used in this study have cylindrical shapes and I sampled all accessible parts of the objects in order to ensure measurement of the magnetic field of the last cooling, to exclude mechanically distortion in the object by the site formation processes such as earthquakes, subsidence or slumping (Sternberg et al.1999; Tarling et al. 1986) and in order to learn about the heat distribution in the object. The preferred sites for sampling are those with good age constraints, such as Ateret, which was active for one year only (1178-1179). Preferred sample types are objects that did not suffer deformation such as breaks or dislocated bricks.
Table 3: samples collection sites- location and ages.

<table>
<thead>
<tr>
<th>Site</th>
<th>Number in Fig 3</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Age in Calendar year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ahihud</td>
<td>4</td>
<td>35.07</td>
<td>32.8</td>
<td>200-300AD</td>
</tr>
<tr>
<td>Ateret</td>
<td>1</td>
<td>35.4</td>
<td>32.9</td>
<td>A1-2: 1178-1179 AD</td>
</tr>
<tr>
<td>Bet She’an</td>
<td>7</td>
<td>35.25</td>
<td>32.4</td>
<td>BS1-3: 650-750 AD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BS4: 500-600 AD</td>
</tr>
<tr>
<td>Habonim</td>
<td>8</td>
<td>34.85</td>
<td>32.3</td>
<td>1400-1500 AD</td>
</tr>
<tr>
<td>Harat Hadid</td>
<td>10</td>
<td>34.95</td>
<td>29.8</td>
<td>600-800AD</td>
</tr>
<tr>
<td>Kastra</td>
<td>6</td>
<td>34.95</td>
<td>32.6</td>
<td>K1: 500-700AD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>K2: 150-50 BC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>K3: 400-700 AD</td>
</tr>
<tr>
<td>Kfar Menahem</td>
<td>9</td>
<td>34.8</td>
<td>31.75</td>
<td>750-650 BC</td>
</tr>
<tr>
<td>Nahef</td>
<td>3</td>
<td>35.2</td>
<td>32.82</td>
<td>N1-2: 150-350 AD</td>
</tr>
<tr>
<td>Yodfat</td>
<td>5</td>
<td>35.15</td>
<td>32.72</td>
<td>50-70 AD</td>
</tr>
<tr>
<td>Zefat</td>
<td>2</td>
<td>35.3</td>
<td>32.85</td>
<td>ZE1-2: 1800-1900 AD</td>
</tr>
<tr>
<td>E’elim Terrace</td>
<td></td>
<td>35.25</td>
<td>31.4</td>
<td>1686 BC – 1293 AD</td>
</tr>
</tbody>
</table>
Fig 3 Map of sample sites in Israel. Square indicates the Ze’elim Terrace. Ellipses indicate the archaeological sites.
3.1 Ze’elim Terrace section

The fieldwork was conducted in a gully in ZT, where the gully enters the Dead Sea, and approximately 9 m of ZT formation is exposed (Fig 3.1.1). The deposits consist of alternating aragonite and detrital laminae (1-2 mm thick) and thicker clastic layers (>10 cm) (Ken-Tor et al. 2001a). The aragonite precipitated chemically from the water column, as was described for the Lisan Formation (Begin et al. 1974; Stein et al. 1997). The detrital layers consist of clay and silt size grains derived from Cretaceous and younger rocks exposed in the catchments area and therefore represent flood input to the lake during rainy seasons.

Massive beds of well-sorted carbonate salty sand that were deposited in the near shore environment, often exhibit ripple marks. This site was chosen due to successive sedimentation of fine laminas along most of the section, which can provide a continuous paleomagnetic record in most of the section. A high accumulation rate, ranging from 3 to 13 mm/yr, enables high-resolution sample collection. In addition, dense $^{14}$C dating and earthquakes chronology was investigated in a previous study in the gully (Ken-Tor et al. 2001a; Ken-Tor et al. 2001b).

No data was acquired between 500 and 1000 AD due to an unconformity (Ken-Tor et al. 2001a; Ken-Tor et al. 2001b) and prior to the year 0 due to very friable sand layers, of which I could not collect any samples.

3.2 Archeological sites

Archeological sites, in contrast with the continuous sediment record, contain discrete and sparse data of the magnetic field. Fortunately, archeological sites of the last 4 kyrs are abundant in Israel. I collected samples, which were heated above the Curie temperature from heat sources such as ceramics and lime production installations, fireplaces, cooking ovens, and thermal baths.
3.2.1 Ahihud (#4 in Fig 3): This site is located northwest of the modern Ahihud Village. Three stages of settlement have been defined. The first was during the middle Roman period, during which period the site was subsequently deserted. During the second settlement stage a ceramics factory with two ceramics ovens were built in the southern part of the site. During the last settlement stage, the ovens were no longer used for their original purpose and rubbish ceramics from the area were discarded in them. When ceramics production ceased, the site was deserted permanently. The age of the site, estimated by the ceramics found at it, is the 3rd century AD. I drilled samples from a single oven at this site. The samples were taken from the oven wall and from the center stand of the oven used to hold the oven floor (Fig 3.2.1). (גרוני 2002)

Fig 3.2.1 The oven, which was sampled at the Ahihud archaeological site
3.2.2 Ateret- Vadum Iacob (#1 in Fig 3): The Ateret- Vadum Iacob site dominated the only natural crossing of the Jordan River between Baniyas and the Sea of Galilee. The Templars began building the castle walls at the beginning of October 1178. The construction of the walls was completed 6 months later. Salah al Din, the Muslim leader, attempted to purchase the castle from the Templar knights but the price was too high and the Muslims attacked the castle in May of 1179. In August of 1179 the Muslims succeeded in breaking the walls, conquering the castle and destroying it (Ellenblum). At the Ateret site I sampled two archeological objects, both of them dated to 1178-1179AD. The first is a lime furnace installation located outside of the castle walls, and the second, probably the kitchen oven, is located within the castle walls.
3.2.3 Bet She'an (#7 in Fig 3): The settlement of Bet She'an first began in the 5th millennium BC on a Tel in the heart of a fertile area, enjoying an abundance of water and located on a major crossroads. In the Byzantine period, Bet She'an became largely Christian. The bathhouse, excavated at the eastern side of the site, was built during the Roman period and was renovated during the Byzantine period. In the aftermath of the Arab conquest, the city steadily declined in prominence and the number of its inhabitants dwindled. A severe earthquake in 749 AD devastated the city (Graicer 1999). In Bet She'an I sampled three ceramics ovens of the Arabic period, their ages estimated as the end of the 7th century AD, until the year 749 AD (A, B and C in Fig 3.2.3). The earthquake created some breaks in the western and eastern blocks of the walls of the oven. I also took samples from the heat source area in the Byzantine bathhouses (D in Fig 3.2.3). The age of this object is estimated to the 6th century AD.
3.2.4 Habonim (#8 in Fig 3): The Habonim castle has a roughly trapezoidal shape. Human activity in the castle area is evident during the Chalcolithic, Persian, Hellenistic, Roman, and Byzantine periods. The castle, with its towers, occupies an area of 3 dunams (Barbe et al. 2002). I collected samples from a single adobe oven (Fig 3.2.4) located outside the castle walls, next to the entrance gate. The samples were collected in plastic boxes. The age of the oven is estimated as the 15th century AD.

Fig 3.2.4 The adobe oven sampled at the Habonim site (length of penknife is about 9 cm).
3.2.5 Harat Hadid (#10 in Fig 3): The Harat Hadid site contains a large pile of slag and poor remnants of copper production ovens. The site age is estimated as the early Arabic period (the end of the 7th until the beginning of the 8th century AD). This site was not excavated and the age estimation is based on the archaeological survey and artifacts on the surface (Holzer 2002, personal communication). I took five pieces of not in-situ slag (Fig 3.2.5), and drilled unoriented core samples from them.

Fig 3.2.5 Five slag pieces taken from the Harat Hadid site with drill holes of core samples.
3.2.6 Kastra: (#6 in Fig 3) Several sources indicate that the Kastra site is a village of the Samaritans. During excavation of the site cross and other Christian objects were found, which insinuate that the site is the Porferion, which is known to be a Christian settlement in the area (Finkelstein 2001, personal communication). Archeologists found four ovens at the site. I sampled and measured three of them, estimated to ages of 400-700 AD, 500-700 AD, and 150-50 BC (A, B, and C in Fig. 3.2.6, respectively).

Fig. 3.2.6. Three ovens sampled at Kastra (length of penknife is about 9cm)
3.2.7 Kfar-Menahem: (#9 in Fig 3) The Kfar Menahem site is a potter’s house. All the ceramics in the site were hand made by potter's wheel. All the ovens in the site are either square or rectangular. The cells of the ovens are very small. The ceramics and the kindling were placed into the oven together and the openings were filled with stones (Israel 2001, personal communication). At this site I measured a single oven (Fig. 3.2.7) with an estimated age of 650-750 BC.

Fig. 3.2.7. The oven sampled at the Kfar Menahem site.
3.2.8 Nahef (#3 in Fig 3): The Nahef site is potter's workshop. It consists of two large and well-preserved circular kilns and the remains of a few rooms. In the center of the fireplace of each of the kilns is a massive round column (Vitto 1980). The pottery fragments collected at the site date from the end of the Roman period or beginning of the Byzantine period 150-350 AD. I sampled the walls and the center columns of the two kilns.
3.2.9 Yodfat (#5 in Fig 3): The old city of Yodfat is located on a low hill next to the present village of Yodfat. Excavation of the site revealed remains of a Jewish rural town from the Second Temple period, which is the only preserved site from this period in the Galil. Along with many other artifacts, various types of houses, water holes, an oil press, and ceramics ovens were found at the site. The city was surrounded by a wall, which was built in a number of stages. At the eastern end of the site the wall was built on a ceramic oven from the early Roman period. This type of construction demonstrates the urgency of the wall construction. This wall was probably built on the last night of the Jewish revolution against the Romans in Israel. The city was attacked, occupied, and evacuated by the Romans in one day, before the middle of the first century AD (אמירת חשמל). At this site I sampled the oven wall and its column (Fig 3.2.9). The oven was last used prior to 67AD, when the wall was built on top of the oven to protect the site from the Roman attack.

Fig. 3.2.9. The oven wall (right), the oven column (center), and the wall built to protect the city from the Romans (top), sampled at Yodfat site.
3.2.10 Zefat (#2 in Fig 3): Sources indicate that the Crusaders built the castle at the Zefat site in the 12th century. In the same century Selah al Din conquered the castle and his Moslems army destroyed it. The Mamlukim conquered the castle in the 13th century. They rebuilt it and added to it. In the 16th century the Ottomans conquered the castle and the site remained a military castle until it was destroyed in an earthquakes in 1837 (Berbe 2002, personal communication). I sampled two limes hole (Fig 3.2.10) that estimated as the 19th century, after the earthquake took place. I drilled samples along the walls of the holes.

Fig 3.2.10 Two lime installations sampled at Zefat site.
4 Measurements and statistical calculations

I measured the paleodirection (inclination and declination) for 310 samples collected from 6.5m of sediment section from the ZT formation, and 106 samples from 10 archeological objects in six archeological sites (Ahihud, Ateret, Habonim, Kastra, Kfar Menahem and Nahef). The measurements were performed in the paleomagnetic lab in the Geophysical Institute of Israel using a “2G” cryogenic magnetometer. The NRM was measured first, and then the sample was subjected to "magnetic cleaning", i.e., stepwise demagnetization by alternating field (AF) with increasing intensities, starting at 5 milliTesla (mT) and going up in 5 or 10 mT increments until the remaining intensity drops to 10%-5% of its initial NRM. In order to calculate the magnetic vector for each sample I performed a principal component analysis (Kirschvink 1980). I chose characteristic directions, which pass a 1° linearity test. The average direction for a number of vectors was calculated using the Fisher method (Fisher 1953), which calculates the scatter of vectors on a sphere. The precision of the obtained average vector is indicated by three indexes: \( R, \kappa \) and \( \alpha_{95} \). \( R \) is the length of the resultant vector normalized to the absolute sum of individual vectors. Its maximum value is 1 (when all the combined vectors point to the same direction). \( \kappa \) is the precision parameter, best estimated as \( \kappa = (n-1)/n(1-R) \), where \( n \) is the number of sampled vectors. \( \alpha_{95} \) is the angular radius of the 95% circle of confidence, which is best estimated as \( \alpha_{95} = 140/\sqrt{(\kappa n)} \).

I also measured paleointensity on 74 samples from nine archeological objects, collected at five archeological sites (Yodfat, Bet Shean, Harat Hadid, Ateret and Zafat). The measurements were performed in the laboratory of archeomagnetism and geosciences in the University of Rennes 1, France using a spinner magnetometer, an RS3 cryogenic magnetometer, and a thermal demagnetizer. I employed the Thellier double-heating method (Thellier and Thellier 1959), i.e. stepwise demagnetization by increasing temperature, starting at 100°C and going up in 20°C to 100°C increments until the remaining intensity dropped to 10%-5% of its initial NRM. Each temperature was maintained for at least 45 minutes to allow thermal equilibrium to be established (Levi 1977) and was applied twice. A laboratory field of 40\( \mu \)T was applied along the Z-axis both during heating and cooling for each temperature. The samples were reversed between the two heating to the same temperature. Measuring the remnant magnetization after cooling from temperature step \( Ti \) allowed us to determine the
remaining NRM with blocking temperature \( T_b > T_i \) and the TRM acquired with a blocking temperature between \( T_i \) and the room temperature (Coe 1978). The slope of the linear segment in the NRM-TRM diagram allows us to estimate the paleointensity of the magnetic field. When choosing the point from the linear segment I take into account secondary magnetization, which may have been superimposed on the initial TRM during the working life of the baked materials, viscosity, edge point, and the shape of the sample that may affect the anisotropy test. Nonlinearity in the NRM-TRM curve may be due to chemical or physical changes in the magnetic minerals during Thellier experiment (a fact that was tested in the pTRM test – chapter 5.5), due to multi-domains magnetic grains or due to temperature differences between opening and closing temperature of the minerals (Kosterov and Prevot 1998; Levi 1977). During the paleointensity analysis processes I obtained the paleomagnetic directions of the samples as well.
5 Stability Tests

The initial hypotheses of my study are:
1. The magnetic field in the ZT section represents the ambient geomagnetic field some time after deposition of the sediments (Frank et al. 2002a; Hagstum and Champion 2002; Marco 1996; Thompson et al. 1985).
2. The magnetic field at the archeological sites represents the ambient geomagnetic field when the heat source objects at the sites cooled.
3. The NRM record (from ZT and from the archeological sites) is original and has not been affected by later processes.

These hypotheses are examined by the following tests, which explore the properties of the measured NRM, estimate the accuracy of the results, and define the relationships between the magnetization and the post depositional deformation in ZT.
5.1 Partial magnetization test

This test examines whether the magnetic vectors obtained in ZT section are stable and were affected by a single magnetic field. This test is performed by vector analysis of the step-demagnetization direction of ZT vectors. Approximately 60% of the vectors contained a secondary component, which was either removed by AF demagnetization of 5 mT (Fig 5.1.1A) or appeared at 60-70 mT (Fig 5.1.1B). The secondary field, which appears in the beginning of the AF demagnetization process may be caused by VRM and secondary field, which appears in the end of the AF demagnetization process may be caused by VRM or GRM (Frank et al. 2002a). This components are negligible compared to the stable vector appearing throughout the demagnetization process. Moreover, the resolved characteristic vectors for each sample do not include the high-coercivity component and therefore the secondary overprint does not affect the ZT PSV record.

Fig 5.1.1: Demagnetization vectors of two samples containing a secondary field. Solid squares are the true inclination and empty squares are the declination. A reflects a secondary field, which was removed after 5mT. B reflects a secondary field, which appeared at 60-70mT.

In order to examine the fields, which appears during the demagnetization process I analyzed the first three and the last three steps of the AF demagnetization process. The vectors directions of the first three steps (0-30 mT) of 64 horizons appear to be
similar to each other along the demagnetization process (Fig 5.1.2). The directions of the last three steps (50-70 mT) of 161 horizons reveal a different last step (70 mT) (Fig 5.1.3). The inclination of the last step appears to decrease and increase along the section without an obvious trend, compare to the previous steps (Fig 5.1.3A). The declination of the last step reveals a shift to the west up to about 4m, which is more significant in the upper part and then a shift to the east in most of the vectors up to 6.5m (Fig 5.1.3 B). The westerly shift along the first 4m of the section may insinuate a GRM along this part of ZT section. This magnetization should be followed by intensity increase, which does not appear in the intensity analysis of the last three steps (Fig 5.1.4). Yet demagnetization by higher AF intensities might have revealed an increase in the NRM intensity along this part of the section. In the northern part of the Dead Sea the mineral greigite, which is likely to acquire strong GRM (Hu et. al. 2002), was found along the lower part of the section, i.e., older than 2000 BP (Frank et. al. 2002a). This observation might strengthen the option for greigite presence in ZT section too.

**Conclusion**: most of the vectors along ZT section appear to contain a single stable magnetic field direction along most of the AF demagnetization process. The westerly shift at 70mT step of the demagnetization, which appears along the first 4m of ZT section, may reflect a presence of greigite along this part. This test requires further demagnetization process of higher AF intensities in order to prove the presence of greigite along the section.
Fig 5.1.2: Magnetic components of the first three demagnetization steps (0-30 mT) of 64 horizons along ZT formation. All three steps appear to be similar to each other.
Fig 5.1.3: Magnetic components of the last three demagnetization steps (50-70 mT) of 161 horizons along ZT formation. A is the Inc demagnetization steps and B is the Dec demagnetization steps. The last step of demagnetization (70mT) reveals a significant shift along all the section compared to the other two steps.
Fig 5.1.4. NRM intensity of the last three demagnetization steps (50-70 mT) of 161 horizons along ZT formation. The intensity decreases, as the applied field is higher.
5.2 Horizon test

This test defines the precision ($\kappa$) and the angular radius confidence ($\alpha_{95}$) of the PSV record from ZT section. This record is affected by magnetic mineral scatter, measurement and sample collection accuracy, post-depositional processes, unknown magnetization model, dating uncertainty, random noise, local disturbances, and tectonic disturbances (Aiken et al. 1989; Ali et al. 1999; Daly and Goff 1996; DuBois 1989; Hongre et al. 1998). In this test I compared the scatter in several horizons with the scatter along vertical segments of the section using Fisher statistics (Fisher 1953).

Fig 5.2.1 Three groups of samples (rectangles A, B and C) were collected for the first part of the horizon test along a single horizon.

In the first part of this test I sampled three groups of samples, from a single horizon, along about 15m of Ze'elim gully (Fig 5.2.1). The average scatter obtained in this part (table 5.2.1) reveals a scatter of: $\alpha_{95} = 7^\circ$, $\kappa = 20$ along this horizon.

Table 5.2.1: Results from three groups of measurements taken from a single horizon (first part of the horizon test - Fig 5.2.1). $\alpha_{95}$, $\kappa$ and $R$ are precision of the obtained average vector using Fisher method (Fisher 1953) and $n$ is the number of samples.

<table>
<thead>
<tr>
<th>Group</th>
<th>$\alpha_{95}$ ($^\circ$)</th>
<th>$\kappa$</th>
<th>R</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.9</td>
<td>41</td>
<td>0.98</td>
<td>6</td>
</tr>
<tr>
<td>B</td>
<td>14.1</td>
<td>16</td>
<td>0.9483</td>
<td>6</td>
</tr>
<tr>
<td>C</td>
<td>11.8</td>
<td>20</td>
<td>0.95714</td>
<td>7</td>
</tr>
<tr>
<td>A, B and C</td>
<td>7</td>
<td>20</td>
<td>0.96</td>
<td>19</td>
</tr>
</tbody>
</table>

In the second part of this test I compared the scatter of nine horizontally-sampled groups (Table 5.2.2) with nine vertically sampled groups (Table 5.2.3). The results reveal higher horizon angular radius confidence ($\alpha_{95}$ is more than 60% smaller) along with much higher horizon precision ($\kappa$ is about twice).
Table 5.2.2 Scatter nine of nine horizontally-sampled groups taken along ZT section (second part of the horizon test). \( \alpha_{95} \), k and R are precision of the obtained average vector using Fisher method (Fisher 1953). n is the number of samples.

<table>
<thead>
<tr>
<th>Height (cm from bottom)</th>
<th>( \alpha_{95} ) (°)</th>
<th>k</th>
<th>R</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>252</td>
<td>3.1</td>
<td>345</td>
<td>0.998</td>
<td>6</td>
</tr>
<tr>
<td>263</td>
<td>12.7</td>
<td>20</td>
<td>0.958</td>
<td>6</td>
</tr>
<tr>
<td>282</td>
<td>9.3</td>
<td>38</td>
<td>0.978</td>
<td>6</td>
</tr>
<tr>
<td>285</td>
<td>5.3</td>
<td>114.3</td>
<td>0.993</td>
<td>6</td>
</tr>
<tr>
<td>332</td>
<td>4.9</td>
<td>137</td>
<td>0.993</td>
<td>6</td>
</tr>
<tr>
<td>366</td>
<td>3.2</td>
<td>281</td>
<td>0.997</td>
<td>7</td>
</tr>
<tr>
<td>402</td>
<td>3.3</td>
<td>366.1</td>
<td>0.998</td>
<td>5</td>
</tr>
<tr>
<td><strong>Arithmetic average</strong></td>
<td><strong>5.97</strong></td>
<td><strong>185.91</strong></td>
<td><strong>0.988</strong></td>
<td><strong>6</strong></td>
</tr>
</tbody>
</table>

**Discussion and conclusions:** Both parts of the horizon test show higher horizon angular radius confidence (\( \alpha_{95} \) is 6° - 7°) than vertical one (\( \alpha_{95} \) ~ 10°) and horizon precision (in the second part) much higher than vertical precision (k is about double). The conclusion is that the horizon scatter may represent single horizon scatter (\( \alpha_{95} \) is 6° and k is 180), while the dispersion in the vertical samples may represent the PSV along ZT.

There is an important difference between the horizons scatter results obtained in the first part and the second part of the horizon test. The horizon scatter of the first part (along a single horizon) is much higher: k is about tenth and \( \alpha_{95} \) is about 12% higher. This difference requires a further check of the magnetic field direction behavior along the gully.
Table 5.2.3 Scatter of nine vertically sampled groups along the ZT section (second part of the horizon test). $\alpha_{95}$, k and R are precision of the obtained average vector using Fisher method (Fisher 1953). n is the number of samples.

<table>
<thead>
<tr>
<th>Height (cm from bottom)</th>
<th>$\alpha_{95}$ (°)</th>
<th>k</th>
<th>R</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>48-67</td>
<td>2.8</td>
<td>406.7</td>
<td>0.998</td>
<td>6</td>
</tr>
<tr>
<td>208-236</td>
<td>16.9</td>
<td>11.4</td>
<td>0.927</td>
<td>6</td>
</tr>
<tr>
<td>413-428</td>
<td>6.6</td>
<td>63.4</td>
<td>0.986</td>
<td>7</td>
</tr>
<tr>
<td>509-524</td>
<td>5.8</td>
<td>98</td>
<td>0.991</td>
<td>6</td>
</tr>
<tr>
<td>536-550</td>
<td>8.1</td>
<td>49.2</td>
<td>0.983</td>
<td>6</td>
</tr>
<tr>
<td>556-576</td>
<td>14.5</td>
<td>15.6</td>
<td>0.947</td>
<td>6</td>
</tr>
<tr>
<td>630-640</td>
<td>13.4</td>
<td>21.8</td>
<td>0.963</td>
<td>5</td>
</tr>
<tr>
<td>Arithmetic average</td>
<td>9.73</td>
<td>95.157</td>
<td>0.971</td>
<td>6</td>
</tr>
</tbody>
</table>
5.3 Mixed layer test

In the ZT section there are eight mixed layers. These units are mixtures of dark clay and silt with tabular fragments of aragonite lamina (Fig 5.3.1), which were interpreted as representing seismic events (Ken-Tor et. al. 2001a). The thickness of the mixed layers in the sampled area is up to 20cm, with undisturbed horizontal layers above and below them. The motivation of this test is to verify by which mechanism the samples obtained their magnetization along the section. There are three possible mechanisms for recording the magnetic field: 1. during sedimentation of the layers (pre-disturbance), 2. immediately after the earthquake that disturbed the layers, or 3. when the mixed layers were buried and consolidated. This test examined my assumption that the magnetization in ZT was acquired after the water was extracted from the layers (after the earthquake) and not during consolidation of the original layers.

![Fig 5.3.1 Mixed layer from ZT section.](image)

I first compared the vertical scatter with the horizontal scatter along a single mixed layer, dated as the earthquakes of 31 BC (Ken-Tor et. al. 2001a). Secondly, I compared this scatter with the vertical and horizontal scatter obtained throughout the section.

The arithmetic average of the vertical scatter along two sets of samples from the mixed layer is $\alpha = 13.1^\circ$ and $k = 33.6$, and the horizon scatter along one horizon is $\alpha = 9.3^\circ$ and $k = 38$. The vertical scatter along the mixed layer is higher than the horizontal one, but not significantly. The fact that the horizon scatter is low and the horizontal and vertical scatter are not the same may insinuate that the magnetization was acquired after the earthquake, which means that the earthquake predates the magnetization. The age difference between the sedimentation and the magnetic acquisition can be up to hundreds of years (Lund 1996; Marco 1996). Considering a
maximum of 20 cm thickness of the mixed layers in the sampling area and the minimum sedimentation rate of 2mm/yr, throughout the section, I obtain a maximum difference of 100 years between the time of sedimentation and the age of the earthquake.

Comparison of the scatter of the magnetization of the mixed layer with Ze’elim Formation scatter (chapter 5.2) indicates that the scatter is higher in the mixed layer. This difference may be caused by difference between the magnetization acquisition along the section and in the mixed layer. The difference in magnetization may be caused by diverse acquisition rates, while the higher scatter in the mixed layer may insinuate that the age difference between the sedimentation and the magnetization is smaller along the section. The difference between the mixed layer scatter and ZT section scatter may be also an effect of fragments arrangement along the layer. In the mixed layers there are “pieces” of aragonite in the clay layer, which might affect the magnetization acquisition.

**Conclusions:** The test results on the 31 B.C. mixed layer lead to the conclusion that the layer recorded the magnetic field after the earthquake. The difference between the sedimentation age and the magnetization age may be more than 100 yr. Stability tests, done in the Lisan, show the same results (Marco 1996). The difference in magnetization scatter between the section and the mixed layer may be caused by different acquisition rates, which indicates that this time difference is smaller in the section or by fragments arrangement of the magnetic particles along the layer.
5.4 Magnetic anomaly test

The spatial changes in the magnetic field vectors (intensity and direction) in Israel are presented in the international geomagnetic reference field (IGRF) and in the local anomalies maps of Israel (Rybakov et al. 1997; Shirman 1999). Here I examine whether these magnetic anomalies and variations in the area should be taken into account when calculating the PSV and when comparing the PSV record from ZT with results from archeological sites spread around the country.

The difference between the magnetic field direction in ZT and the rest of the country, according to the declination map by Shirman (1999), is up to 30' (1/2°). This difference is less than 10% of our sample angular radius confidence. The IGRF inclination changes from 43.1° in Elat (southern tip of Israel) up to 44.75° at the northern border of Israel. The maximum difference in the inclination between ZT and the rest of the country, according to Shirman’s map, is 1°, which is less than 18% of our sample angular radius confidence angular radius confidence angular radius confidence angular radius confidence angular radius confidence.

Conclusions: The magnitudes of the anomalies are not sufficient to distort the orientation measurements or the resulting data. The differences between the magnetic field in ZT and the rest of the country are minor and need not be considered when comparing the PSV records. Moreover samples from archeological sites elsewhere, which were subject to volcanic activity or lava flows do not show disturbed magnetization (DuBois 1989).
5.5 Partial Thermal Remanent (pTRM) check
The purpose of the pTRM check is to test the stability of the TRM during demagnetization by heating and to detect the presence and development of unwanted chemical or physical changes in the magnetic carrier minerals during the Thellier experiment. This check was performed every one to three temperature steps throughout the entire experiment. I demagnetized the sample at a lower temperature (T-test) than the previous temperature used in the experiment, calculated the TRM of the sample and compared it to the TRM obtained during demagnetizing to T-test during the experiment. A good pTRM check is when the TRM in the check is similar to the TRM measured during the experiment. For example, in Fig 5.5.1 the pTRM checks are good along all the experiment. The plus signs along the diagonal line are the NRM-TRM curve results obtained in the Thellier experiment. The arrows are the pTRM checks. The location of the arrows heads along the y axis is the NRM obtained for the T-test during the experiment. The location of the arrows head along the X-axis is the TRM obtained in the pTRM check. In Fig 5.5.1 the TRM measured in the pTRM checks is similar to the TRM measured during the experiment (head of the arrows and pluses along the diagonal line meet).
Fig 5.5.1 Schematic diagram of the NRM-TRM curve and the pTRM checks. The plus signs along the diagonal line is the result of Thellier double-heating experiment. The arrows represent the pTRM check every one to three temperature steps. Location of the arrows heads along the y-axis is the NRM obtained during the experiment. Location of the arrows heads along the X-axis is the TRM measured in the check. In this diagram all the checks were good, enabling the use of all the data points for estimating the paleointensity.

In most of the samples the pTRM checks were successful. I rejected the last one to three temperature points of the experiment when the pTRM check was poor. For example, in the last pTRM check in Fig 5.5.2 the original TRM (plus symbol) and the TRM obtained in the pTRM check (arrow head) are not the same, meaning that unwanted chemical or physical changes in the magnetic carrier minerals took place between the T-test and the last temperature of the experiment. Therefore I did not use the last two points of the TRM-NRM curve for calculating the paleointensity. The pTRM test was also used to reject samples with bad checks along all the experiment.
Fig 5.5.2 NRM-TRM curve and the pTRM checks. The plus symbols along the diagonal line is the result of Thellier double-heating experiment. The arrows represent the pTRM check every one to three temperature steps. Location of the arrows head along the y-axis is the NRM obtained during the experiment. Location of the arrows head along the X-axis is the TRM measured in the check. In this diagram the last check was not good and the two last points of the NRM-TRM diagram cannot be used for paleointensity estimation.

Paleointensity : 69.11 μT
5.6 Anisotropy test

The parallelism between the lab magnetic field and the acquired TRM in the Thellier experiment (Thellier and Thellier 1959) is the basis for defining the paleointensity of the samples. Some samples display “easy” and “hard” magnetization plane, which affects the magnetic acquisition direction. If the sample displays a hard magnetization plane along the acquired field or easy magnetization plane in another direction then this sample has a magnetic anisotropy (Lanos et al. 1999), which must be defined in order to correct the TRM-NRM curves.

The purpose of the anisotropy test is to find the tensor of anisotropy ($A$ in equation 5.6.1—which is the three dimensional susceptibility tensor), which defines the relationship between the applied lab magnetic field ($H_{lab}$ in equation 5.6.1) and the acquired magnetization (TRM in equation 5.6.1).

\[
\begin{pmatrix}
TRM (x) \\
TRM (y) \\
TRM (z)
\end{pmatrix}
= (A) \ *
\begin{pmatrix}
H_{lab} (x) \\
H_{lab} (y) \\
H_{lab} (z)
\end{pmatrix}
\]

(5.6.1)

The test was performed by demagnetizing the samples six times (once at each axis direction). The samples were demagnetized at the temperature at which 70% to 80% of the initial NRM was removed. A field of 40\(\mu\)T was applied during heating and cooling of the samples. After all six measurements the anisotropy tensor are determined (Chauvin et al. 2000) and then the TRM and the NRM are corrected accordingly, for every temperature step along the Thellier experiment.

The most significant correction performed as the result of the anisotropy tests, which demonstrates the importance of the anisotropy correction for obtaining correct paleointensity and paleodirections, was performed on a sample from Zefat. This sample contains two magnetic field components (Fig 5.6.1 A), but calculation of the intensity from the NRM-TRM curve without the anisotropy correction (Fig 5.6.1 B) yields a single magnetic field intensity (a single linear component throughout all the temperature steps). After correction of the anisotropy the two magnetic field intensity components of this sample are evident (Fig 5.6.1 C). I choose the second magnetic field intensity, which was obtained in the higher temperature of the experiment and reflects the intensity of the stable vector, which reaches the axis’ intersection.
Fig 5.6.1 Plot presenting the Thelier experiment for sample taken from Zefat. A is the vector analysis of the sample. White points are inclination and black points are declination. Two components of the vector direction can be observed. B is the NRM-TRM curve without anisotropy correction. Single magnetic field intensity may be calculated. C is the NRM-TRM curve with anisotropy correction. Two components of magnetic field intensity can be observed.

In most of the sites the magnetic field paleointensity after anisotropy correction was different in less than 7% from the original intensity (table 5.6.1). In almost all the sites the intensity after anisotropy correction is higher. The average anisotropy correction is about 2% increase in the magnetic field intensity.
Table 5.6.1 Anisotropy correction for the archeological objects. Fourth column is the intensity after anisotropy correction divided by the intensity without correction. Fifth column is the addition in the intensity in % after anisotropy correction. Sixth column is the number of samples per object. The last row is the arithmetic average of all the sites.

<table>
<thead>
<tr>
<th>Archeological Site</th>
<th>Intensity (μT)</th>
<th>Intensity with Anisotropy correction (μT)</th>
<th>int(An)/int</th>
<th>% Addition</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ateret lime installation</td>
<td>95.91</td>
<td>71.4</td>
<td>0.74</td>
<td>-26</td>
<td>8</td>
</tr>
<tr>
<td>Yodfat</td>
<td>52.01</td>
<td>53.77</td>
<td>1.03</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Bet Shean 1</td>
<td>83.26</td>
<td>85.13</td>
<td>1.02</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Bet Shean 2</td>
<td>59.92</td>
<td>66.21</td>
<td>1.10</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Bet Shean 3</td>
<td>75.53</td>
<td>89.22</td>
<td>1.18</td>
<td>18</td>
<td>8</td>
</tr>
<tr>
<td>Bet Shean 4</td>
<td>61.63</td>
<td>62.81</td>
<td>1.02</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Zefat 1</td>
<td>48.61</td>
<td>50.22</td>
<td>1.03</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Zefat 2</td>
<td>46.42</td>
<td>45.11</td>
<td>0.97</td>
<td>-3</td>
<td>8</td>
</tr>
<tr>
<td>Harat Hadid</td>
<td>62.48</td>
<td>66.41</td>
<td>1.06</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td><strong>Arithmetic ave.</strong></td>
<td><strong>65.08</strong></td>
<td><strong>65.59</strong></td>
<td><strong>1.02</strong></td>
<td><strong>2</strong></td>
<td><strong>7.11</strong></td>
</tr>
</tbody>
</table>

6 Results

6.1 Age estimation

At the ZT site I collected and measured 310 samples along 176 horizons, taken from 6.5m of an outcrop of more than 9m high. The ages of the samples range from 17th century BC to 13th century AD. The ages of the lower part of the mixed layers that I sampled have been constrained by the accurate dating of the earthquakes that created them (Ken-Tor et. al. 2001a; Ken-Tor et. al. 2001b). I used six earthquakes to determine the ages of the lower part of the mixed layers: 64 BC, 31 BC, 33 AD, 363 AD, 1212 AD, and 1293 AD. A harmonic average (equations 6.1.1 and 6.1.2) (Bowman 1990) of the calibrated radiocarbon ages (Ken-Tor et. al. 2001a; Ken-Tor et. al. 2001b; Ken-Tor 2003, personal communication) was used, when possible.

\[
\begin{align*}
(6.1.1) & \quad y_{\text{ave}} = \Sigma(y_i/\sigma_i^2) / \Sigma(1/\sigma_i^2) \\
(6.1.2) & \quad \sigma_n^2 = s_n^2 / n = 1 / \Sigma(1/\sigma_i^2)
\end{align*}
\]

The variables \(y_{\text{ave}}\) and \(\sigma_n\) are the average age and age error correspondingly, and \(y_i\) and \(\sigma_i\) are the age and age error from a single data point respectively. I used radiocarbon ages to estimate ages of six horizons (Table 6.1.1). The earthquake error is estimated at one year and the radiocarbon age error is estimated using equation 6.1.2. In the interpolated parts, between every two errors, I used the arithmetic average of the two.
Table 6.1.1 Calibrated radiocarbon ages of the ZT section

<table>
<thead>
<tr>
<th>Section height (cm)</th>
<th>Reference</th>
<th>Calibrated radiocarbon ages (calendar yr)</th>
<th>Average ages (calendar yr)</th>
<th>Error (σ) (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>[Ken-Tor, 2003, personal communication]</td>
<td>970-950BC, 930-800BC</td>
<td>-960</td>
<td>10</td>
</tr>
<tr>
<td>81</td>
<td>[Ken-Tor, 2003, personal communication]</td>
<td>770-610BC, 600-400BC</td>
<td>-616</td>
<td>62</td>
</tr>
<tr>
<td>106</td>
<td>[Ken-Tor, 2003, personal communication]</td>
<td>800-510BC</td>
<td>-655</td>
<td>145</td>
</tr>
<tr>
<td>166</td>
<td>14.5 cm (Ken-Tor et. al. 2001a)</td>
<td>390-200BC, 380-160BC</td>
<td>-284</td>
<td>72</td>
</tr>
<tr>
<td>421</td>
<td>282.5 cm (Ken-Tor et. al. 2001a)</td>
<td>130-390AD, 80-390AD</td>
<td>250</td>
<td>100</td>
</tr>
</tbody>
</table>

Assuming local stratigraphic succession, I used linear interpolation to link the ages acquired from the historical earthquake and ages determined by radiocarbon dating in ZT. The sedimentation rate model in the ZT section, according to the age estimation processes mentioned above (Fig 6.1.1), is not constant. Two sedimentation rates existed. A rapid sedimentation rate, which occurred from 1293 to 1212 AD and from 363 AD to 64 BC, is 5.6 and 7.5 mm/yr, respectively, which correlate to the rates obtained in a previous study in ZT (Ken-Tor et. al. 2001a) and a low sedimentation rate, which occurred from 950 BC to 64 BC is 1.66 mm/yr, slightly lower than the rate until about 500 BC. On the other hand this low rate of sedimentation is found in the section and interpreted as erosion area (Ken-Tor et. al. 2001b).
In the archeological sites I sampled 18 archeological objects from 10 archeological sites. Their ages are estimated as the 8th century BC to the 19th century AD. The ages and their errors were defined by the archeological context in which the samples occur or by historical records as interpreted by the archeologists (see details in chapter 3.2).
6.2 Geomagnetic paleodirections measured at the ZT section

In the ZT I collected and measured 310 samples along 176 horizons. The Fisher mean direction of all the samples is $354/45$, $R=0.967$, $\kappa=31$, $\alpha_{95}=1.44^\circ$. This average is $7^\circ$ to the west from the present magnetic field in Israel and almost similar to the present magnetic field inclination (003/48) (www.ngdc.noaa.gov/cgibin/seg/gmag/fldsnth2.pl). The scatter of these samples (Fig 6.2.1) may reflect sampling and measuring error, magnetic minerals anisotropy between the layers and along the creek, and paleomagnetic field variations.

I estimated the inclination and the declination for the 176 horizons sampled (Fig 6.2.2) using the Fisher method (Fisher 1953). The mean direction of these horizons is $355.5/43$, $R=0.968$, $\kappa=31$ and $\alpha_{95}=1.88^\circ$. This average is similar to the average direction obtained for all the 310 samples taken from ZT. Meaning that the precision of all the samples ($\kappa=31$) arose from the scatter across the section and not from horizontal scatter. The horizon inclination and declination (Fig 6.2.2) appear to contain four kinds of direction variations. The first is rapid directional fluctuation, shifting up to several tens of degrees from one horizon to the other. The second variation is a more gradual directional change of a few tens of degrees over several centuries (about $0.1^\circ$/yr). This variation of the surface geomagnetic field results primarily from changes in the core-produced field coupled with local contribution of magnetic, conductance, or thermal anomalies in the crust, mantle or core (DuBois 1989). The third type of variation is a very slow shift, which appears both in the declination and in the inclination curves. In the declination there is a westerly shifting of about $20^\circ$ between the 17th century BC and 4th century AD (gray line over the declination curve in Fig 6.2.2), which is about $0.01^\circ$/yr. In the inclination there is a decrease of about $20^\circ$ between the 10th century BC and the 4th century AD (gray line over the inclination curve in Fig 6.2.2), which is about $0.02^\circ$/yr. This inclination variation is in an opposite trend than compaction. Another phenomenon that may be observed in Fig 6.2.2 is a mirror image of the inclination and the declination. This tendency was observed in the last 4kyrs in other researches as well (DuBois 1989; Kovacheva and Toshkov 1994).
Fig 6.2.1 Magnetic components measured in all 310 samples from ZT section. The height is measured from the bottom of the sampling section in cm. Note the scatter of the vectors directions.
Fig 6.2.2 Magnetic components of ZT horizons. The magnetic components and their error were calculated using Fisher average. The directions vary in four different frequencies: rapid fluctuation, a more gradual change, a very slow shift- the Gray line and a mirror image of the inclination and the declination.
6.3 Paleodirection obtained in archeological sites

I sampled 18 archeological objects from 10 archeological sites. Their ages are estimated as 8th century BC to 19th century AD. The ages of the objects and their errors are determined by archaeological factors discovered in the excavations or by historical (or other data) known about the site (see chapter 3.2 for more details).

The samples, which were subjected to AF demagnetization cleaning in Israel (taken from five archaeological sites: Ahihud, Ateret, Kastra, Kfar Menahem and Nahef appear to contain a single stable magnetic vector direction (Fig 6.3.1). A secondary component, which appears in some of the samples, was removed after 5mT. Most of the samples were cleaned to less than 20% of their initial NRM by 60mT. In Ateret 18% of the samples taken from the kitchen and 67% of the samples taken from the lime installation were cleaned to more than half of the initial NRM by 70mT. Yet the vectors obtained in the demagnetization process appear to be very stable and tends to the axis transaction (Fig 6.3.2). Due to these reasons the samples from Ateret were not cleaned by a higher subjected field. Their direction was defined by the vectors direction obtained in the demagnetization process till 70mT.
Fig 6.3.2 Demagnetization of a sample from Ateret. A is the vector components at each demagnetization step. The inclination is the solid squares and the declination is the open squares. B is the measured NRM intensity normalized by the initial NRM at each demagnetization step. A stable single magnetic vector, which is not cleaned to half of its initial intensity by 70mT is observed.

The median destructive field (MDF), which is the field required to remove half of the initial intensity of the samples, were calculated from the cleaning curves (graph B in figures 6.3.1 and 6.3.2). Ateret lime installation appears to contain two groups of samples: one with low MDF (31mT) and the other with a MDF higher than 70mT. Ateret kitchen and Ahihud contain high variation of MDF values. The other archaeological objects have similar low MDF of all the samples, with a standard deviation of up to 6mT (Table 6.3.1).

I display stereographic projections of all the samples taken in the archeological object to determine the magnetic component per object (Fig 6.3.3). At Ateret and Harat Hadid sites, in order to avoid noise from a single stone, which may have moved from its original place in the oven, I used an average direction per stone, for multiple samples from a single stone of the archeological object.
Table 6.3.1: MDF values of archaeological sites cleaned by AF demagnetization in Israel. Second column is the MDF range for each object. Third and fourth columns are the objects average MDF and its error respectively (using standard statistic method). n is the number of samples.

<table>
<thead>
<tr>
<th>Archaeological object</th>
<th>MDF values (mT)</th>
<th>Average MDF (mT)</th>
<th>Stdev (mT)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ateret Kitchen</td>
<td>27 – 67</td>
<td>50</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>&gt;&gt;70</td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Ateret lime installation</td>
<td>25 – 40</td>
<td>31</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>&gt;&gt;70</td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Ahihud</td>
<td>10 - 60</td>
<td>30</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Kastra 1-3</td>
<td>14 - 27</td>
<td>18</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>Kfar Menahem</td>
<td>13 - 15</td>
<td>14</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Nahef 1-2</td>
<td>13 - 35</td>
<td>19</td>
<td>6</td>
<td>16</td>
</tr>
</tbody>
</table>

For each archeological object I rejected extreme outliers, as is required. The outliers can be rejected since there are more than six samples per site and that the average angular radius confidence, obtained in this way, is <7° for most of the sites. The exceptional objects are Kastra 3 and Nahef 2 where there were not enough stable samples originally. The scatter of the samples per site, which may be observed in many sites (Fig 6.3.3), may be caused by: (1) orientation error when sampling, (2) instability of the sample, (3) a secondary field effect, (4) inhomogeneity of heat distribution in the oven, or (5) due to movements or breakage of parts of the ovens by geological processes such as earthquakes and subsidence or during the excavation (Sternberg et. al. 1999; Yassi 1987).

The vectors directions obtained for each archaeological object (Fig 6.3.4) correlate between two or more objects from the same period. The objects from the same period are not always from the same site (see table 3 for more details). The directions appear to contain two kinds of variations: a rapid directional fluctuation, shifting up to several tens of degrees from one unit to the other and a gradual directional change of few tens of degrees within several centuries. The Fisher mean magnetic field direction of 17 archeological units (without Harat Hadid, which has only inclination) is 001/49, R= 0.97, κ= 34.5 and α₉₅= 5.8°.
Fig 6.3.3 Equal angle stereographic projections of the 18 archeological objects sampled at various sites in Israel. The points are the stereographic projection of the samples taken along the archeological object. Triangles and Circles are the average direction and error of the object respectively, obtained using the Fisher method.
Table 6.3.2 The magnetic component (Inc and Dec) of each archeological object and their scatter parameters (R, k and $\alpha_{95}$) using Fisher method without the scatter samples. n is the number of samples.

<table>
<thead>
<tr>
<th>Archeological Site</th>
<th>DEC (°)</th>
<th>INC (°)</th>
<th>R</th>
<th>k</th>
<th>$\alpha_{95}$ (°)</th>
<th>n</th>
<th>Calendar year</th>
<th>Age error (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ateret kitchen</td>
<td>13.2</td>
<td>48.3</td>
<td>0.985</td>
<td>57.9</td>
<td>6.5</td>
<td>8</td>
<td>1179</td>
<td>0.5</td>
</tr>
<tr>
<td>Ateret lime hole</td>
<td>31.0</td>
<td>50.7</td>
<td>0.909</td>
<td>9.2</td>
<td>18.9</td>
<td>6</td>
<td>1179</td>
<td>0.5</td>
</tr>
<tr>
<td>Ahihud</td>
<td>10.3</td>
<td>37.7</td>
<td>0.987</td>
<td>67.7</td>
<td>5.4</td>
<td>10</td>
<td>250</td>
<td>50</td>
</tr>
<tr>
<td>Bet Shean 1</td>
<td>-8.2</td>
<td>56.9</td>
<td>0.982</td>
<td>47.7</td>
<td>7.2</td>
<td>8</td>
<td>700</td>
<td>50</td>
</tr>
<tr>
<td>Bet Shean 2</td>
<td>-4.4</td>
<td>55.3</td>
<td>0.990</td>
<td>84.9</td>
<td>5.4</td>
<td>8</td>
<td>700</td>
<td>50</td>
</tr>
<tr>
<td>Bet Shean 3</td>
<td>0.7</td>
<td>56.6</td>
<td>0.980</td>
<td>41.9</td>
<td>8.2</td>
<td>7</td>
<td>700</td>
<td>50</td>
</tr>
<tr>
<td>Bet Shean 4</td>
<td>1.7</td>
<td>43.5</td>
<td>0.997</td>
<td>333.1</td>
<td>2.6</td>
<td>9</td>
<td>550</td>
<td>50</td>
</tr>
<tr>
<td>Habonim</td>
<td>2.7</td>
<td>54.0</td>
<td>0.993</td>
<td>133.9</td>
<td>2.8</td>
<td>19</td>
<td>1450</td>
<td>50</td>
</tr>
<tr>
<td>Harat Hadid</td>
<td>???</td>
<td>43.0</td>
<td>0.991</td>
<td>80.1</td>
<td>7.8</td>
<td>4</td>
<td>700</td>
<td>100</td>
</tr>
<tr>
<td>Kastra 1</td>
<td>8.6</td>
<td>50.9</td>
<td>0.988</td>
<td>77.7</td>
<td>4.6</td>
<td>12</td>
<td>600</td>
<td>100</td>
</tr>
<tr>
<td>Kastra 2</td>
<td>5.4</td>
<td>40.6</td>
<td>0.993</td>
<td>108.1</td>
<td>6.0</td>
<td>5</td>
<td>-100</td>
<td>50</td>
</tr>
<tr>
<td>Kastra 3</td>
<td>4.4</td>
<td>50.0</td>
<td>0.999</td>
<td>465.3</td>
<td>3.7</td>
<td>3</td>
<td>550</td>
<td>150</td>
</tr>
<tr>
<td>Kfar Menahem</td>
<td>-5.9</td>
<td>80.9</td>
<td>0.987</td>
<td>69.5</td>
<td>5.6</td>
<td>9</td>
<td>-700</td>
<td>50</td>
</tr>
<tr>
<td>Nahef 1</td>
<td>-2.9</td>
<td>27.8</td>
<td>0.986</td>
<td>59.8</td>
<td>6.8</td>
<td>7</td>
<td>250</td>
<td>100</td>
</tr>
<tr>
<td>Nahef 2</td>
<td>-0.3</td>
<td>34.4</td>
<td>0.999</td>
<td>490.1</td>
<td>3.7</td>
<td>3</td>
<td>250</td>
<td>100</td>
</tr>
<tr>
<td>Yodfat</td>
<td>-15.5</td>
<td>56.1</td>
<td>0.994</td>
<td>143.9</td>
<td>4.4</td>
<td>7</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>Zefat 1</td>
<td>-13.2</td>
<td>42.8</td>
<td>0.988</td>
<td>72.1</td>
<td>6.2</td>
<td>7</td>
<td>1850</td>
<td>50</td>
</tr>
<tr>
<td>Zefat 2</td>
<td>-14.7</td>
<td>45.5</td>
<td>0.989</td>
<td>82.5</td>
<td>5.4</td>
<td>8</td>
<td>1850</td>
<td>50</td>
</tr>
</tbody>
</table>
Fig 6.3.4 magnetic components of the 18 archeological objects, excluding the outlier’s vectors of each object. There is a correlation between two or more objects.
6.4 Relative paleointensity data obtained in ZT section

I measured the magnetic moment of 151 horizons from the ZT section in cgs units, using the NRM results before magnetic cleaning. The resulting magnetic moment is normalized by the sample volume (8 cc) to obtain the magnetization intensity (J) of the samples. The arithmetic average of all the horizons of J is 2e-4 G, which is 2e-8 mT. J is then normalized by the susceptibility of the samples (χ) (measured at the paleomagnetic lab at the Hebrew University in Jerusalem) to obtain a relative paleointensity (H=J/χ) (Butler 1998). The arithmetic average of H is 3 G, which is 3e-4 mT. The comparison of the J and H, normalized by their average values, shows general similarity in the trend of the two data sets along most of the section (Fig 6.4.1). The results appear to contain three frequencies of variations: 1. a rapid fluctuation from one horizon to the other, 2. a more gradual change of a few tens of percentages over several tens of cm and 3. a very slow decrease of J and H between 50 and 640 cm from the bottom of the sampled ZT section, which reflects sediments from the 10th century BC till the 13th century AD. In this part of the section the values of J and H decreases in about 30%. The MDF of the samples (Fig 6.4.2) appears to contain three frequencies of variations as well: 1. a rapid fluctuation from one horizon to the other, 2. a more gradual change of a few tens of mT over several tens of cm and 3. a decrease of more than 50% along all the section. In this part of the section the values of the MDF decrease from more than 40mT to less than 20mT. This decrease means that the coercivity is higher in the upper part of the section (Marco 1998) meaning that the magnetic minerals are different or that there is different amount of minerals along the section. Both the MDF and H decreasing along the section. Yet the amount of decreasing is different between the two. This fact may insinuate that the relative intensity curve (H) does not reflect only changes in the magnetic minerals along the section but also changes in the magnetic field.
Fig 6.4.1 The magnetization (J) and the relative magnetic field (H), normalized by their averages. The data appear to contain three variations: rapid fluctuation from one horizon to the other, a more gradual change of a few tens of percentages over several tens of cm and a very slow decrease of J and H between 50 and 640 cm from the bottom of the sampled ZT section (10th century BC till 13th century AD).
Fig 6.4.2 The MDF obtained in the ZT section. The results appear to contain three types of variation: rapid fluctuation from one horizon to the other, a more gradual change of a few tens of mT over several tens of cm and a decrease in more than 50% (from more than 40mT to less than 20mT) along all the section.
6.5 Absolute paleointensity obtained at archeological sites

For absolute paleointensity measurements I sampled 9 archeological objects taken from 5 archeological sites (out of the 10 sampled sites). Their ages are estimated as the 1st to the 19\textsuperscript{th} century AD. The intensity of the objects and their intensity error (\(\sigma\)) are measured in SI units (\(\mu\)T) and are calculated using a simple statistic method to provide an average of a number of samples per object. The paleointensity curve obtained from these objects (Fig 6.5.1) shows a maximum intensity at about 700AD. The intensity increased from about the year 0 until 700AD and then decreased till today. The intensity of the samples from about 700AD correlate, if I take into accounts their error. Cooling effect correction, which may change the intensity by up to 13\% (Aitken et al. 1984; Aitken et. al. 1989; Genevey et al. 2003) may lower the difference between the two groups and should be performed. Age estimation problem may be another cause for the difference between the two groups intensity at 700AD.

Fig 6.5.1 The absolut paleointensity obtained from nine archeological objects. The intensity increased from about the year 0 until 700AD and then decreased till today. The intensities of the samples from about 700AD correlate, if I take into accounts their error.
7 Discussion

7.1 Paleomagnetic secular variations

The magnetic field PSV, obtained in ZT, might represent a magnetic field variation, rock magnetic effect, or noise. In this chapter I examine the nature of the magnetic PSV obtained in ZT section and the magnetic field results obtained from the archeological sites in Israel, in order to examine the nature of the PSV results. In the archeological sites samples from the same archaeological object show the same direction (chapter 6.3). I conclude that these samples acquired the magnetization after the archaeological object was constructed, during the last cooling. The fact that there is an agreement in the directions of two or more archeological objects from the same age, which were sampled in different archaeological sites, suggests that the magnetic field measured represents the paleodirection at the time of the objects last cooling rather than a later field effect (Sternberg et. al. 1999). Changes in the declination and the inclination in time (Fig 6.3.4), in combination with the above mentioned conclusions indicate that these changes represent changes of the past magnetic field. Greigite presence along the ZT section (chapter 5.1) might result in rock magnetic processes in ZT, such as strengthen CRM (Frank et. al. 2002a). This CRM could have been acquired either immediately after deposition, simultaneously along a major part of the section or long after deposition. If the CRM was acquired immediately after deposition the PSV curves should reflect the magnetic field variation close to deposition. If the chemical change were epigenetic and took place simultaneously along a major part of the section than a constant magnetic signal should be found along this part, representing the magnetic field direction when the chemical changes took place.
Fig 7.1.1 ZT PSV curves smoothed by running average of six consecutive points. Gray vertical lines indicate the present magnetic field, with the angular radius confidence used in this study ($\alpha_{95} = 6^\circ$, chapter 5.2). The data characterize successive direction changes in time, rather than discrete changes or constant directions.
If the PSV record of this study were only noise, it is expected that the smoothing process would result in a Dec/Inc that are approximately single value. These values may resemble the present magnetic field. The smoothed magnetic components obtained in ZT section (a running averages of 6 horizons) characterize successive changes in time, rather than discrete changes or single value (Fig 7.1.1). These properties suggest that the PSV curves are neither noise nor chemical change, which took place simultaneously along a major part of the section. Moreover if the magnetic components fluctuations were only noise, then the present magnetic field including the angular radius confidence of this study (gray lines in Fig 7.1.1) obtained in the horizon test ($\alpha_{95}=6^\circ$, section 5.2), should contain all of our data. Clearly this is not the case and almost half of the results are not within the study angular radius confidence. If the chemical change of the magnetic mineral in ZT section took place long after deposition but not simultaneously along a major part of the section than it will appear as SV, which represents the field long after the time of deposition. One way to examine this option is to compare the curves obtained in ZT section with other well dated records, such as the results obtained from archeological sites in Israel in this study, the results from Birkat Ram (BR) in the Golan Heights, northern Israel (Frank et al. 2002b) and the results from Japan (Ali et. al. 1999).
Fig 7.1.2 Inclination (A) and declination (B) obtained from ZT (solid curve) and from archeological sites (circles) during the last 4kys. The data sets from the same periods show very good agreement excluding the youngest objects (1179AD-Ateret).
I obtained magnetic field directions from both ZT and the archaeological objects (Fig 7.1.2) in limited periods: 1179AD, 250AD, 63BC, 100BC and 700BC. Taking into account the α95 angles and the age's uncertainty, of both data sets, there is a very good agreement between the two, excluding the youngest objects (1179AD-Ateret), which might be affected by site formation processes. The comparison with BR was performed using a 25 yr average of the ZT record where more than 4 samples per 25 yrs were measured (Fig 7.1.3). The cores in BR were not oriented and so I should expect a similarity in the declination trend and not in the declination values between BR and ZT. In most of the cases, there is agreement in both inclination and declination trend between the two data sets. From 1000 BP to 500 yrs BP there is very poor agreement between ZT and BR. I did not obtain data from archeological sites for this period. This discrepancy requires additional study of the ZT record for this period. Between 2000 and 3000 yrs BP ZT record shows a westerly shift in the virtual geomagnetic pole (VGP) longitude, which is seen in Japan (Ali et. al. 1999) as well (Fig 7.1.4). This shift also correlative to the westerly shift observed in BR for the same period (Fig 7.1.3) suggesting a global event. The similarity of ZT PSV record and the results from other studies suggest that the chemical change in ZT minerals did not take place long after deposition in most of the section. Moreover the fact that the magnetic vectors contains a single component along most of the cleaning process may insinuate that the time in which the chemical change took place is less than the lock in time for the particles or that the chemical magnetized particles contribution to the NRM is negligible (Frank et. al. 2002a).

In the ZT record three direction variations are evident (chapter 6.2). According to the discussion above I conclude that the slow shift of about 0.03 °/yr in declination, which was seen in BR and Japan and which is about ten times lower than rates of changes in the geomagnetic nondipole field (Bullard et al. 1950; Butler 1998; DuBois 1989; Kovacheva 1982) might reflect a dipole field effect. The gradual directional change of a few tens of degrees within several centuries, which corresponds to the geomagnetic nondipole field rates, may reflect changes in the nondipole field in the study area and the rapid directional fluctuation in the curves, shifting up to several tens of degrees from one horizon to the other may reflect noise.
Fig 7.1.3 Inclination (A) and Declination (B) of ZT and Birkat Ram (BR) (Frank et. al. 2002b). Solid diamonds are BR data and empty circles with vertical lines are ZT data with its αs. In the Declinations data only trend may be compared (see text). There is agreement in both inclination and declination between the two data sets in most of the section.
Fig 7.1.4 VGP of ZT and Japan (Ali et al. 1999). Between 2000 and 3000 yrs BP the results show a westerly shift in the VGP longitude both in ZT and in Japanese records.
7.2 Paleointensity results

If the quantity and type of magnetic minerals vary within the sedimentary sequence the NRM intensity alone does not provide a reliable measure of relative paleointensity (Tauxe 1993). Moreover, if there are significant chemical effect throughout the section or if there is mixing of the sediment, an accurate relative intensity cannot be obtained, even from the normalized curve (Johnson et al. 1975). The changes in the MDF along the ZT section (Fig 6.4.2) may reflect changes in the magnetic minerals. These changes were also observed in a study in the northern part of the Dead Sea (Frank et al. 2002a). The magnetic minerals found by Frank et al. (2002) are a mix of titanomagnetite and Fe-sulphides, which point toward DRM and CRM, respectively. Moreover in the ZT section a few mixed layers, representing earthquakes, are evident. The facts mentioned above may indicate that neither the NRM intensity nor the normalized H (Fig 6.4.1) can be used as a relative paleointensity record. On the other hand, the mixed layer test (chapter 5.3) shows that the magnetization of the samples was acquired after the earthquakes. The discussion regarding ZT PSV (chapter 7.1) reveals that chemical changes of the magnetic minerals did not obliterate the primary record and that the PSV obtained in most of the ZT section reflect real changes in the magnetic field in the area close to the deposition time. A comparison of the relative paleointensity from ZT normalized by its average (diamond symbols in Fig 7.2.1) and the absolute intensity normalized by its average obtained in archeological sites from Syria (Genevey et. al. 2003) and Israel (circles and Xs in Fig 7.2.1, respectively) show very good agreement. These results lead to the conclusion that the relative paleointensity record obtained from ZT reflects changes in the magnetic field intensity in the study area.

A comparison of the absolute intensity curve obtained from the archeological sites in Israel with the results from Syria (Fig 7.2.2) (Genevey et. al. 2003) reveals a possible agreement in the intensity prior to 700 AD and a higher intensity in Israel from this period onward, although the data are sparse. There is a maximum at about 700AD, seen in the results from Israel, which also present in the results from Egypt (Hussain 1987) and in the South West US (DuBois 1989). The decreasing in the field intensity is also seen in Bulgaria (Kovacheva 1982) and in the global dipole moment (Hongre et. al. 1998; McElhinny and Senanayake 1982). These results suggest that the absolute
intensity from the archaeological sites in Israel reflects changes in the intensity of the dipole field.

Fig 7.2.1 Relative paleointensity from ZT normalized by its average and absolute intensity obtained in Syria (Genevey et. al. 2003) and in archaeological sites in Israel normalized by their average. The three data sets show very good agreement.

Fig 7.2.2 Absolute paleomagnetic intensity obtained from archaeological sites in this study and in Syria (Genevey et. al. 2003). The data show a possible agreement in the intensity prior to 700 AD and a higher intensity in Israel from this period onward, although there is not sufficient data.
8 Conclusions

The paleomagnetic directions recorded in ZT and in the archeological sites represent variation in the paleomagnetic field. The magnetization in ZT is approximately synchronous with deposition in most of the studied section. Three types of direction variations are observed in ZT PSV curves: slow westerly shift at about 0.03 °/yr in declination, gradual directional change of few tens of degrees within several centuries, and rapid directional fluctuation, shifting up to several tens of degrees in few years. I conclude that these variations reflect a global dipole field effect, changes in the nondipole field in our area, and superposed random noise respectively. The relative paleointensity from ZT reflect changes in the magnetic field in our area. The absolute intensity obtained from the archeological sites reflects changes in the global magnetic field intensity, in particular a decrease during the last few centuries by a factor of about 30%.
9 Reference


תיעוד שעונים סקולריים بشדה המגנטי באורבת
אלפי השנים האחרונות במישקע市の המחלול והתריס
איריצי-אוליבייבי בישראלי

M.Sc. הlevance וו ה הנוכ בחלק מדחישות למקבי התזונה "מסמר למדעי".ับ
באניברפסטים של – אוב
הוזג ליגتفكוק מדעי פלורידים

על די
על סכל

העבורה והונח בהונבייסטים של – אוב
בהדרקט dobr שמוולמרוק

2003
фессיר

משתת המחבר ויא.NotFound של השנות הקורות בפאת השדה המשנה בישראלי בברכה אלפי
השנים החבעות. הנControlEvents הגובעולים בעילוי השדהנאסף בחקר משקיעים בנכיפה השקה של
נחל אפרים לחך ים המלח. ורצף המשקיעים ראש קבוע תחנת ריפוי לשנתה השדה
המענים. קצב השעתה מחודש. חנה בני 3 כולל 13 חלק מבית, מאספר את הסיפורliable על
רולינגרי שהבישה. החות מ './../../הemale ברק הקדום huston C14 repaired על ריפוי
א�名 הסטריאווף שוחלט הפערת בשיכוך. באספור 310 למאת זלאר 6.5 מעורר מחוון
משעון המפיקה שפייה השופים בחזק למירה (2002-2002). גלי המשקיעים המדינה
והמעון 18 לח"ם" על המאה 13 לسمي". מבטיא יציבות בין ברזים kristalית עד להב חן את
המעון שCanceled, ליתריכי את מידי ידיד ההצאות והיהים להלך על הקשר בין המגנונים
ולחלציאים שהתרחשו באחר בחר עב 176 יאפורים
. 355°/43° (אינקประสงית/דקילציזיו), \(R=0.97, a_{95}=1.88^\circ\)
שנדברם לאורח התוך והאתר 176°
שליש תריזית של השנתון הזכוכית בוכן הובלה לאורח התוך. התריזית

האשוננה לא שוניות מורה של שערית מולה בין אוטק ואתו למשקז, המשופרת.
קריש. התריזית ה.fastjsonיה לשוניות ייחוסי ייחור של שערית מולה רמה שינמ.
המיצג השנתון בריכב השדה שלא ריפולי של השדה המגנונים. התריזית ושלישית היא
ונחנת משכבה בקצוב של 0.01 מעלת בשעה בין המאה 17 לח"ם" לעומד הפרישית
ולسمي". המיצג השנתון בריכב הדיפל של השדה המגנונים. התצרות השוחקה
בצלאים והווה להנימים שבאמפי 18 אספוריט פארקואליגנים שואפים ובשריה אוטיר
ארקואליגנים: האואפקטים ומי מקורות זה קונוגר קרמייק. בורו צידי, מרצואות
ארואור שיפות אוריר. האואפקטים והם מעיל טופוסטרטרוד קרוי בודקר ההנגולים

בוחנה לאושדו המגנונים ששרור סיפרג. התארים הארקואליגונים שואפים מתאריכים
מודמיה השמנים לופנה"ס ועד המאה ה 19 לسمي". כוית הממוצע של כל הדגמאות הזה
מمواנת הזה לושרה המגנונים מבווכי ביראלאי
\(=45.6, R=0.98, a_{95}=5.2^\circ \), 001°/50°
. ישנש הנחתהطبق בין השנות השדה המגנונים שבאגים לצלים

שהוחקה באיתרים הארקואליגנים. ישנה גם הנחתה בין התצרות השוחקה לאורח רב
החות מצלאים להנימים שוחקה באוריר אחריהם. התצרות המתקפלות סממנים מרסות

כי بوית להשתמש בהשנתון השדה המגנני של הקבולה בצלאים לזרוע אירור אתרום
ארכאולוגים רוזית גאולוגית.

עצמת השדה המגנני שיל Doctrine בערב מדד דבר למפוזה שנוספה נתנסות אובייקט ב
ארכאולוגים שגילם bin המשנה הראשה למפוזה ה 19 לפנה"ג המדריך במצהות תחכ.

שימור בשיטת טליין (Thellier). במצה מבิน מנגנים חלקי חום הנקות ונייצים פלוריים.

ההצאות מרואת רוזית מגצם השדה בעי 1300 השנה הזרית. המנצחות המ '}ף
להצאות החכמה בצלאיםnormally והمضي על השדות עצמה השדה המגנני.

במעקיע ימי מחקה בצלאים מגцентр עצמה יסוד בלולב. צור השוכמנה על השתייה
התריס בצעמה השדה מתאימה להצאות המדריד אתרגמים ארכאולוגים ישראלי

ובשראל.