Magnetic Properties of Carbonate Rocks as a Tool for Estimating Strain near the Dead Sea Transform, Northern Israel

Ran Issachar
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Ran Issachar

Thesis submitted in partial fulfillment of the requirement for the degree of M.Sc Geophysical, Atmospheric and Planetary Sciences, Tel-Aviv University.

This work was carried out under the supervision of:
Dr. Tsafrir Levi, Geological Survey of Israel, Jerusalem
Prof. Ram Weinberger, Geological Survey of Israel, Jerusalem
Prof. Shmuel Marco, Department of Geophysical, Atmospheric and Planetary Sciences, Tel-Aviv University
Abstract

To improve the knowledge of the strain field along the Dead-Sea Transform (DST) system in northern Israel, I measured and analyzed the magnetic properties of ~400 samples of Eocene rocks from the Rosh-Pinna, Mt. Gilboa and the HaOnn-Cliffs areas. Analyses of XRD diffraction, thin-sections and scanning electron microscopy (SEM) images indicate that the Eocene Bar-Kokhba Formation consists of crystalline calcite and the amounts of Fe, Mn, Mg, Al and Si are very low. The Bar-Kokhba rocks are diamagnetic with low-field average bulk-susceptibility of $k_m = -10.95 \pm 1.01[\mu SI]$, indicating that the magnetic susceptibility is exclusively controlled by calcite crystals. The orientations of the anisotropy of magnetic susceptibility (AMS) $k_3$ axes are co-axial with preferred crystal orientation of the calcite $c$-axes and suggesting the maximum shortening axes. I show that the anisotropy parameters ($P'$ and $\Delta k$) are associated with the relative magnitudes of the finite strains accumulated in the rocks. The AMS of ~300 samples from the Eocene Bar-Kokhba Formation in the Rosh-Pinna region reveals ~N-S maximum horizontal shortening that is most likely associated with the DST activity. The strain magnitudes next to the DST are generally heterogeneous and in most cases not associated with distinct structures.

An isolation method of magnetic phases, developed in this study, reveals that the paramagnetic phase of Fe-bearing minerals above 500 ppm content mask the diamagnetic phase of calcite-bearing rocks, and dominate the AMS. The diamagnetic phase was successfully isolated from the AMS of multi-phases rock, in one study case, and reveals $P'$ values in the range between 1.01 to 1.04.

The Eocene chalks of the Adulam, Timrat and Maresha Formations have weak diamagnetic to weak paramagnetic low-field susceptibility. The AMS of the Timrat Formation consists of three magnetic phases: diamagnetic of calcite, paramagnetic of clay-rich minerals and ferrimagnetic of magnetite grains. Using integrative techniques in the isolation method the contribution of the sub-phases to the total AMS was evaluated. I infer that the principal axes of the total AMS in Timrat Formation are indicative of preferred crystal orientation of the calcite diamagnetic phase.
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Glossary of magnetic terminology

AMS - Anisotropy of Magnetic Susceptibility.
AARM - Anisotropy of Anhysteretic Remanent Magnetization.
IRM - Isothermal Remanent Magnetization.

\(k\) - Magnetic susceptibility.

\(H\) - Magnetic field.

\(M\) - Magnetization.

\(H_d\) - Demagnetization field.

\(k_1, k_2, k_3\) - Maximum, intermediate and minimum principal susceptibilities respectively.

\(k_m\) - Low-field Bulk susceptibility

\(P\) - Anisotropy degree.

\(P'\) - Corrected anisotropy degree.

\(\Delta k\) - Susceptibility difference.

\(T\) - Anisotropy shape factor.

\(L\) - Magnetic lineation.

\(F\) - Magnetic foliation.

\(k_t\) - The total susceptibility tensor of a specimen.

\(\hat{k}\) - Normalized susceptibility tensor \((k_m\) in the norming factor).

\(k_f, k_p, k_d\) - Ferromagnetic, paramagnetic, and diamagnetic susceptibilities tensors respectively.

\(c_f, c_p, c_d\) - Respective ferromagnetic, paramagnetic, and diamagnetic percentages respectively.

\(kT\) – Temperature dependence susceptibility.
1. Introduction

1.1. Background and significance

Elastic and inelastic strains that commonly accumulate close to plate boundaries are mainly released by seismic and aseismic movements along fault planes. The rocks in the surrounding areas are deformed in different styles of deformation structures. Knowledge of the strain field that developed during the geological time provides insight into the tectonic evolution of plate boundaries and helps in understanding the mechanisms and the nature of the processes associated with plate movements. The mutual dependence of the strain field, around continental plate-bounding transform faults on the regional stress field and mechanical properties of host rocks and the faults are only partially known. The importance of studying the strain fields and nature of deformation is growing due to the heavily dense population and human activities in close proximity to the continental transforms such as in California and the northern parts of Israel. Previous studies done in northern Israel are commonly based on the study of meso-scale kinematic indicators such as faults, joint sets, and folds (Eyal, 1996; Eyal and Reches, 1983; Hatzor and Reches, 1990; Reches, 1987; Reches and Hoexter, 1981; Ron and Eyal, 1985). These methods are commonly used by structural geologists and depend on finding meso-structures, which are sometimes hard to observe. In order to complement meso-structure methods, efforts are invested in finding microscopic deformation indicators. The texture of rocks in many cases can indicate the principal axes of the strain field (Rutter and Rusbridge, 1977). Neutron and X-ray diffraction are common methods used to determine the texture of deformed rocks (Wenk et al., 1984). Studies show that anisotropy of magnetic susceptibility (AMS) can also serve as a texture indicator of deformed rocks. The AMS is a rapid and more straight-forward method that sums up the magnetic contribution of all the components of the rock and presents an average magnetic fabric (Borradaile, 1988). The correlation between the magnetic fabric and the rock texture can be done when the magnetically-dominated minerals are known. Literature on the magnetic susceptibility of rocks is widely available (Borradaile, 1987; Borradaile, 1988; Borradaile, 1991; Borradaile and Henry, 1997; Borradaile and Jackson, 2004; Borradaile and Jackson, 2010; Hrouda, 1982; Hrouda, 1993; Hrouda et al., 2000; Hrouda and Jezek, 1999; Jackson and Tauxe, 1991; Tarling and Hrouda, 1993). The advance analytical tools and techniques enable accurate reproducible measurements of diamagnetic and weak paramagnetic rocks. Both AMS and strain are second-rank tensors, leading to
attempts of correlating AMS and strain (Borradaile, 1987; Borradaile, 1991; Hirt et al., 2000; Hrouda, 1993; Kligerfield et al., 1982; Tauxe, 1998). The AMS axes show, in many deformed environments, a fair to good correlation with the directions of the principal strain axes (Borradaile, 1987; Borradaile, 1988; Borradaile, 1991; Borradaile and Henry, 1997; Hrouda et al., 2009; Latta and Anastasio, 2007; Mamanti and Sengupta, 2009; Pares et al., 1999; Soto et al., 2007; Tarling and Hrouda, 1993). Plastic deformation can produce strong preferred crystal orientation and strong correlation of the AMS axial orientations (Borradaile and Jackson, 2010). For high symmetry crystals principal susceptibilities and crystal axes are parallel (Nye, 1957). The alignment of calcite crystallographic c-axes parallel to the shortening direction is directly inferred from the magnetic fabric (Owens and Rutter, 1978; Schmidt et al., 2006; Wenk et al., 1987). Previous works determined principal strain field directions from AMS measurements of carbonate rocks by correlating the AMS to the preferred crystal orientation of the calcite crystals in the rock (de Wall et al., 2000; Hamilton et al., 2004; Levi and Weinberger, 2011).

In this study I try to determine the strain field near the Dead-Sea-Transform (DST) in northern Israel. The DST extends along ~1000 km, from the northern ends of the Red-Searift to the Taurus convergence zone in Turkey, accommodating strike-slip motion along the plate boundary between the Arabian plate and the Sinai sub-plate (or African plate) (Figure 1) with ~105 km of left-lateral offset since the Early-Middle Miocene (Freund, 1970; Garfunkel, 1981; Joffe and Garfunkel, 1987; Quennell, 1956). The texture of calcite crystals in Eocene carbonate rocks is estimated, using the AMS method, and correlated to the principal directions of the regional strain field. Calcite has weak diamagnetic response that can be easily overprinted by paramagnetic and ferromagnetic minerals involved in the rock (Borradaile, 1988). Based on the above, I searched for rocks that contain negligible amounts of second-phase minerals and crystal impurities, lower than 400ppm. I focused on the magnetic fabrics of the Bar-Kokhba Formation, consisting of limestone that was identified from preliminary analysis as a pure calcite-bearing rock. In addition, I focused on the Eocene chalks of the Timrat, Adulam and Maresha formations that are widely spread along the DST. Based on preliminary results, the Adulam and Maresha formations are identified as weak diamagnetic or weak paramagnetic rocks. In this study I apply an isolation method of magnetic phases on the Bar-Kokhba and Timrat rocks in order to investigate the effect of paramagnetic/ferromagnetic minerals on the total AMS of carbonate rocks.
1.2. Objectives

Aiming to improve the understanding of the deformation and strain distribution on the one hand, and to broaden the knowledge on the magnetic properties of calcite-bearing rocks on the other, the objectives of this study were:

1) To improve the understanding of the spatial and temporal variations of the strain field associated with the deformation adjacent to the DST in northern Israel (Rosh-Pinna area). This objective is achieved by measuring the AMS of pure calcite-bearing rocks as proxies for the strain field next to the DST.

1) To develop a process method for isolating the effect of paramagnetic/ferromagnetic minerals on the magnetic properties of carbonate rocks. This would help to better understand the possibilities and limitations using the AMS of carbonate rocks as a strain proxy. By applying this method on Bar-Kokhba rocks which consist of multi magnetic phases associated with young chemical alteration processes, I could evaluate the effect of the second-phase minerals on the AMS.

2) To investigate the AMS of weak diamagnetic and weak paramagnetic chalks that crop out next to the DST. Correlating the AMS of these formations to the strain field could promote the understanding of the spatial and temporal variations of the strain field within the DST.
1.3. Geological setting

1.3.1 Strain fields around the Dead-Sea Transform

The DST extends along ~1000 km, from the northern ends of the Red Sea rift to the Taurus convergence zone in Turkey, passing through the Gulf of Elat-Aqaba, the Jordan valley, Lebanon and Syria. The DST accommodates strike-slip motion along the plate boundary between the Arabian plate and the Sinai sub-plate (or African plate) (Figure 1). A host of stratigraphic, structural and geochronological evidence suggests ~105 km of left-lateral offset across the southern parts of the DST since the Early-Middle Miocene (Bartov et al., 1980; Freund, 1970; Garfunkel, 1981; Joffe and Garfunkel, 1987; Quennell, 1956). The estimated slip rate, based on tectonic modeling and long-term geological considerations, range from 6 to 10 mm/yr (Joffe and Garfunkel, 1987), while current GPS-based models indicate a relative plate motion of 4-5 mm/yr (ArRajehi et al., 2010; Le Beon et al., 2008; Reilinger et al., 2006). Geological observations suggest that two distinct paleostrain regimes operated in the Sinai sub-plate (Eyal, 1996; Eyal and Reches, 1983): (1) WNW – ESE shortening and NNE – SSW extension, beginning in the Turonian, is associated with the development of the Syrian Arc fold belt (Krenkel, 1924); and (2) NNW – SSE shortening and ENE – WSW extension that was active from middle Miocene to recent, and is associated with the left-lateral motion along the DST. Garfunkel (1981) showed that the directions of the principal stresses adjacent to the DST are probably deflected toward the fault trace. He suggested that the deflection is greatest near rhomb-shape grabens, where the DST acts as a weak zone (e.g., "free boundary"). Ron and Eyal (1985) inferred, from combined analysis of mega- and meso-structures, a strain field characterized by NNW – SSE horizontal shortening in the Tiberias area. Studies within the Korazim block suggests that the striking geometry north to the Sea-of-Galilee has changed during the last million years (Heimann and Ron, 1993; Rotstein and Bartov, 1989). As a result the area absorbed deformation in the form of right-lateral slips and counterclockwise rotation within the Korazim block. Weinberger et al. (2009), who investigated the style of deformation between the Hula basin in northern Israel and the Lebanese restraining bend in southern Lebanon found evidence for the transition from an early (Miocene–lower Pliocene) phase of pure strike-slip motion, with NW – SE regional shortening, to a late (Pleistocene to Recent) phase of convergent strike slip with E – W shortening.
Figure 1. Geological map of the study area. Faults after Weinstein (2011). Red dots mark the sampling sites.
1.3.2 Structure and lithology of the Rosh-Pinna area

The ~75 km² Rosh-Pinna area consists of Eocene limestones and chalks (Figure 2). The Rosh-Pinna area is bounded on the east by the Korazim block (Sneh and Weinberger, 2006), which is mainly covered by Plio-Pleistocene basalts (Heimann, 1990). From the west, the Nahal-Amud creek serves as the western boundary of the Rosh-Pinna area; typically Galilee Cretaceous rocks are exposed west of it (Levitte, 2001). The Timrat Formation is exposed at the base of the Rosh-Pinna creek and in the western slopes of the Rosh-Pinna area. The layers dip slightly to the southeast; in the eastern parts the attitude of the layers is almost horizontal. No major fault structures or fold systems are found within the Rosh-Pinna area.

Figure 2. Geological map of the study area. Faults after Weinstein (2011). Red dots mark the sampling sites.
1.4. AMS and deformation of carbonate rocks

1.4.1. Magnetic anisotropy of carbonate rocks

The magnetic susceptibility ($k$) relates the applied magnetic field ($H$) to an induced magnetization ($M$) by

$$
\begin{bmatrix}
M_x \\
M_y \\
M_z
\end{bmatrix} =
\begin{bmatrix}
k_{xx} & k_{xy} & k_{xz} \\
k_{xy} & k_{yy} & k_{yz} \\
k_{xz} & k_{yz} & k_{zz}
\end{bmatrix}
\begin{bmatrix}
H_x \\
H_y \\
H_z
\end{bmatrix}
$$

(Borradaile and Jackson, 2004). In anisotropic materials the shape of the susceptibility is described by three principal values $k_{\text{max}} (k_1)$, $k_{\text{int}} (k_2)$, and $k_{\text{min}} (k_3)$, which correspond to the maximum, intermediate and minimum magnetic susceptibility magnitudes, respectively (Borradaile and Jackson, 2004). The orientations of the principal susceptibilities are usually presented on the lower hemisphere of an equal-area projection. There is a wide variety of parameters that have been used to describe the axial magnitude relationships of the susceptibility ellipsoid (Jelinek, 1981):

1) Mean susceptibility or bulk susceptibility, $k_m = \frac{k_1+k_2+k_3}{3}$.

2) Anisotropy degree, $P = \frac{k_1}{k_3}$ and corrected anisotropy degree,

$$
P^* = e^{\sqrt{2(n_1-n)^2+(n_2-n)^2+(n_3-n)^2}}
$$

where; $n_1$, $n_2$ and $n_3$ are the natural logarithms of the principal susceptibilities and $n = \frac{n_1+n_2+n_3}{3}$.

3) Shape of anisotropy, $U = \frac{2k_2-k_1-k_3}{k_1-k_3}$, and or shape factor, $T = \frac{2n-n_1-n_3}{n_1-n_3}$, where $U$ or $T = -1$ represents prolate ellipsoid, $U$ or $T = 0$ represents sphere and $U$ or $T = +1$ represents oblolute ellipsoid.

4) Susceptibility difference, $\Delta k = k_1 - k_3$.

5) Magnetic lineation, $L = \frac{k_1}{k_2}$.

6) Magnetic foliation, $F = \frac{k_2}{k_3}$.

Both AMS and strain are second-rank tensors, leading to attempts to correlate AMS and strain (Borradaile, 1987; Borradaile, 1991; Hirt et al., 2000; Hrouda, 1993; Kligfield et al., 1982; Tauxe, 1998). The AMS axes show a fair to good correlation with the directions of the principal strain axes in many deformed environments (Borradaile, 1987; Borradaile, 1988; Borradaile, 1991; Borradaile and Henry, 1997; Hrouda et al., 2009; Latta and Anastasio, 2007; Mamtani and Sengupta, 2009; Pares et al, 1999; Soto et al., 2007; Tarling and Hrouda, 1993). Studies show that new magnetic fabric develops in rocks during deformation.
(Almqvist et al., 2009; Borradaile and Jackson, 2004; Cogne and Perroud, 1988; Dietrich and Song, 1984; Hirt et al., 1988; Jayangondaperumal et al., 2010; Soto et al., 2009) but the correlation between the strain field and the magnetic fabric depends on the minerals that form the rock. Limited success and no reliable correlation has been established between the magnitudes of the AMS axes of diamagnetic and low-paramagnetic rocks and the strain magnitudes (Borradaile and Jackson, 2010; Latta and Anastasio, 2007; Parés and B.A., 2004). One major cause for the unsuccessful attempt to correlate magnitudes of the AMS axes with the magnitudes of strain axes is that the former are mainly governed by the amounts of strong magnetic minerals (ferromagnetic, ferrimagnetic and strong paramagnetic) in the rock (Borradaile and Henry, 1997). Nevertheless, Borradaile and Alfrod (1988) found a correlation between the change in the anisotropy degree $P$ and the bulk strain ratio. The AMS anisotropy degree of iron-free carbonate rocks is presumed to have a stronger dependency on the magnitude of strain than on the bulk susceptibility, $k_m$ (Almqvist et al., 2010).

In general, magnetic anisotropy is controlled by grain-shape anisotropy and by crystal anisotropy (Borradaile and Jackson, 2010). Grain-shape anisotropy is mostly effective in strong magnetic rocks, due to the nature of the demagnetizing field ($H_d$), when the AMS of low magnetic rocks, such as carbonate rocks, is controlled entirely by crystal anisotropy (see Appendix I). Crystal anisotropy is reflected by a preferred crystal orientation in the rock texture. Preferred crystal orientation in carbonate rocks may develop due to three different mechanisms: (1) crystallization under non-hydrostatic stress field (Kamb, 1959); (2) plastic deformation (Hobbs et al., 1976); and (3) crystal growth in veins and dikes. The third is not pertinent to this study. The theory of preferred crystal orientation due to crystallization under non-hydrostatic stress field was developed by Kamb (1959) and later by Patterson (1973) and McKenzie et al. (1996). Field-work and laboratory studies have confirmed and broadened these relationships (Hounslow, 2001; Neumann, 1969; Tullis and Yund, 1982). When crystallization takes place under stress, the weakest $c$-axis of calcite tends to align with the greatest principal pressure axis (Kamb, 1959), other carbonates belonging to the same crystal system show similar responses to stress (McKenzie et al., 1996; Patterson, 1973). Preferred crystal orientation as a result of plastic deformation by slip is directly related to the mechanics of dislocation glide (Hobbs et al., 1976). The theoretical basis for the development of preferred orientation by slip and consequent rotation is well established (Bishop, 1954; Bishopa, 1953; Bishopa and Hilla, 1951; Calnan and Clews, 1950; Calnan and...
Textural analyses show that calcite c-axis points to the shortening direction under pure shear and simple shear (Wenk et al., 1987). Laboratory experiments, performed on pure-calcite marbles and single calcite crystals, reveal a very good correlation between the preferred c-axis directions of calcite measured with neutron and X-ray diffraction and the easy-magnetizing directions as obtained from AMS measurements (Chadima et al., 2004; de Wall et al., 2000; Kligfield et al., 1982; Owens and Rutter, 1978; Siegesmund et al., 1995). Calcite was shown to be very sensitive to strain in compaction experiments, the AMS attains saturation (maximal P’ value) at about 40% shortening, and gets to its half value after deformation of 15-20% shortening (Owens and Rutter, 1978). Calcite twinning and other plastic deformation of crystals (Evans and Elmore, 2006; Rutter et al., 1994; Wenk et al., 1987) have long been used for petrofabric studies as sensitive indicators of incremental strain axes and are essentially parallel to the causative paleo-strain axes (Hamilton et al., 2004). It is well known that over a wide range of temperatures, calcite aggregates can be deformed experimentally by intercrystalline gliding. Commonly, samples that are subjected to axial compression result in coaxial finite strain and the alignment of the c-axis parallel to the shortening direction (Owens and Rutter, 1978). A series of compaction experiments of synthetic calcite-muscovite samples reveals that the strength of the diamagnetic anisotropy and the susceptibility difference generally increases with the shortening rate, and is not significantly influenced by the muscovite content (Schmidt et al., 2009). Pure calcite crystals are evidently magnetically anisotropic with susceptibility values of -13.8 [\mu SI] along the c-axis and -12.4 [\mu SI] along the a/b plane (Nye, 1957; Owens and Rutter, 1978). More recently Schmidt et al. (2006) found bulk-susceptibility of calcite at a room temperature of \( k_m = -12.09 \pm 0.5 \) [\mu SI], and susceptibility difference of \( \Delta k = 1.10 \pm 0.01 \) [\mu SI] (Schmidt et al., 2006). Calcite has a prolate AMS shape, using the absolute values of the principals susceptibilities for diamagnetic materials, (\( K_1 = |k_3| > K_2 = |k_2| > K_3 = |k_1| \)) (Borradaile and Jackson, 2010; Schmidt et al., 2006), with \( T = -1 \) and \( P' = 1.113 \) (Owens and Bamford, 1976). In this study the AMS axes of diamagnetic rocks are described by the assigned values of the principal susceptibilities, hence, the minimum susceptibility (\( k_3 \)) refers to the most negative susceptibility value. In addition, the AMS parameters (\( P, P', L, F, T, \Delta k \)) are calculated based on the absolute (unsigned) values of the principal susceptibilities. This convention is recommended for describing the orientations of the principal axes and their magnitudes (for more details see Hrouda, 2004).
1.4.2. Magnetic fabrics of geological environments

Generally, the corrected anisotropy degree ($P'$), and the susceptibility-difference ($\Delta k$) of deformed calcite-bearing diamagnetic rocks are expected to be lower than those of a single calcite crystal, because perfect alignments in sedimentary rocks are rare (Hrouda, 2004).

Under sedimentation and lithostatic pressure conditions, the orientation of some of the calcite c-axes are expected to align parallel to the maximum vertical shortening ($\varepsilon_1$) (Hrouda, 2004). In such cases, the AMS has well-grouped $k_3$ axes oriented vertical to bedding, and scattered $k_1$ and $k_2$ axes parallel to bedding. The magnitudes of the principal susceptibility reflect the strain field with $k_1 \approx k_2 > k_3$, and therefore L>F (using the absolute values of the principal susceptibilities for diamagnetic materials). This magnetic fabric is hereafter termed a sedimentary fabric (Figure 3a).

Under tectonic stress, the AMS axes are co-axial with the principal strain directions ($\varepsilon_1 \geq \varepsilon_2 \geq \varepsilon_3$), where $\varepsilon_1$, $\varepsilon_2$ and $\varepsilon_3$ are the maximum, intermediate and minimum shortening axis, respectively. Under these conditions, generally $k_1$, $k_2$ and $k_3$ are parallel to $\varepsilon_3$, $\varepsilon_2$ and $\varepsilon_1$, respectively, and the AMS fabric is 'normal' ($k_3$ parallel to c-axes) (Borradaile and Jackson, 2010).

Figure 3. Coaxial deformation path for diamagnetic carbonate rock, demonstrating the transition from sedimentary AMS fabric to different types of tectonic fabrics.
Under triaxial strain, when the vertical shortening is dominant the principal susceptibility axes are expected to be well-grouped with $k_3$ axes perpendicular to the bedding planes, $k_2$ axes parallel to the bedding planes in $\varepsilon_2$ direction, and $k_1$ axes parallel to the bedding planes and to minimum shortening ($\varepsilon_3$). This magnetic fabric is hereafter termed a tectonic vertical-shortening fabric (Figure 3b).

In dominant horizontal shortening with foliation plane, $k_3$ axes are perpendicular to the foliation planes and $k_1$ and $k_2$ axes are parallel to the foliation (Pares and van der Pluijm, 2003). The magnetic fabric shows well-grouped $k_3$ axes perpendicular to the foliation planes, and scattered $k_1$ and $k_2$ axes with overlapping of the 95% confidence ellipses. These magnetic fabrics are hereafter termed a tectonic horizontal-shortening with foliation fabric (Figure 3c).

Under triaxial strain where the horizontal shortening is dominant the principal susceptibility axes are expected to be well-grouped with $k_3$ axes parallel to the horizontal maximum shortening axis ($\varepsilon_1$), $k_2$ axes parallel $\varepsilon_2$ direction and $k_1$ parallel to the minimum shortening ($\varepsilon_3$). This magnetic fabric is hereafter termed a tectonic horizontal-shortening fabric (Figure 3d).

When a sample contains more than 400 ppm of Fe2+ or Mn2+ (iron-rich calcite) (Ihmle et al., 1989; Rochette, 1988; Schmidt et al., 2006), ions substitutions form within the crystal structure and inverse AMS fabric ($k_1$ parallel to c-axes) is produced (Rochette, 1988; Ihmle et al., 1989). Under these conditions, calcite becomes less diamagnetic, or more paramagnetic (Almqvist et al., 2009; Rochette, 1988; Schmidt et al., 2006; Schmidt et al., 2007) and the AMS is represented by an oblate AMS ellipsoid (Schmidt et al., 2006).
1.5. Isolation of magnetic phases in carbonate rocks

1.5.1. Background

The AMS is the sum of the magnetic contribution of all the components of the rock and presents an average magnetic fabric (Borradaile, 1988). These components can have different magnetic properties and quite often the AMS of a single mineral is of interest for isolating its susceptibility.

Various experimental techniques were developed using the difference in the physical properties of different magnetic phases in order to identify and characterize the sub-fabrics of the AMS (Martin-Hernandez and Ferre, 2007). There are methods that are based on measurements at different temperatures, using the temperature dependence of paramagnetics according to the Currie-Weiss law (Morrish, 1965). Other methods are based on measuring the magnetic remanence, using the ability of ferromagnetic and ferrimagnetic minerals to retain stable permanent magnetization (Jackson and Tauxe, 1991). Other methods are based on measurements in high fields, or using frequency dependency (Martin-Hernandez and Ferre, 2007). This study applies three experimental techniques (AARM, IRM and temperature-dependent susceptibility measurements; for more details see sections 1.6.3-5). Generally all the methods have serious limitations, in empirical as well as theoretical aspects, especially in identifying and isolating magnetic sub-phases from the AMS (Hrouda et al., 2000).

In this study I suggest an isolation method, based on a combination of analytical and experimental techniques, in order to isolate the calcite diamagnetic contribution to AMS of carbonate rocks.

The susceptibility tensor of a specimen ($k_t$) is described with sufficient accuracy as the sum of all the susceptibilities contributed by the minerals contained (Henry and Daly, 1983; Hrouda et al., 2000):

$$k_t = c_f k_f + c_p k_p + c_d k_d$$  \hspace{2cm} 1.1

when:

$$c_f + c_p + c_d = 1$$  \hspace{2cm} 1.2
where $k_f$, $k_p$ and $k_d$ are tensors of ferromagnetic, paramagnetic, and diamagnetic susceptibilities respectively, and $c_f$, $c_p$ and $c_d$ are the respective percentages (Hrouda et al., 2000).

Consider a rock consisting of two dominant magnetic phases: a diamagnetic phase marked with sub index $d$ and a paramagnetic (or ferromagnetic) phase marked with sub index $p$. In general, the susceptibility tensor ($k$) can be constructed from the product of normalized tensor ($\hat{k}$) and bulk susceptibility ($k_m$), which is also called a norming factor (Jelinek, 1977):

$$ k = k_m \cdot \hat{k} \quad 1.3 $$

Then rewriting Eq 1.1 for the two phases ($c_p$ and $c_d$) in that form:

$$ k_{m_t} \cdot \hat{k}_t = c_p \cdot k_{m_p} \cdot \hat{k}_p + c_d \cdot k_{m_d} \cdot \hat{k}_d \quad 1.4 $$

If the interest is in one magnetic phase, the diamagnetic phase in our case, it can be estimated using the following expression:

$$ k_{m_d} \cdot \hat{k}_d = \frac{1}{1-c_p} k_{m_t} \cdot \hat{k}_t - \frac{c_p}{1-c_p} k_{m_p} \cdot \hat{k}_p \quad 1.5 $$

Since the susceptibility tensors are normalized it can effectively be argued that the total bulk susceptibility is the sum of the bulk susceptibilities of the components:

$$ k_{m_t} \cong c_p \cdot k_{m_p} + c_d \cdot k_{m_d} \quad 1.6 $$

Using Eq. 1.2 (for $c_p$ and $c_d$) we can write:

$$ k_{m_t} \cong (k_{m_p} - k_{m_d})c_p + k_{m_d} \quad 1.7 $$

Generally, the values of the paramagnetic/ferromagnetic bulk susceptibilities are much greater than the value of the diamagnetic bulk susceptibility, $k_{m_p} \gg k_{m_d}$, therefore Eq. 1.7 will take the form:

$$ k_{m_t} \cong k_{m_p} \cdot c_p + k_{m_d} \quad 1.8 $$

Using Eq. 1.5 and 1.8 it is possible to isolate the AMS sub-fabric of the calcite diamagnetic phase of multi-phase carbonate rock.
Chemical composition and XRD analysis
Ensuring majority of calcite in the rock

1. $k_m > -9 \, [\mu SI]$  
   Indicative for multi-phase rock

2. Drawing a graph of $k_m$ vs $c_p$.  
   Finding the elements that show linear correlation

3. Linear fit intersect $k_m$ axis $\approx -12 \, [\mu SI]$  
4. Linear fit intersect $k_m$ axis above $-12 \, [\mu SI]$  

5. No more effective elements

Experimental methods in order to identify the properties of the effective mineral:  
- IRM  
- Temperature-dependent susceptibility  
- SEM  
- AF

AARM measurements

7. Ferro/Ferrimagnetic  
6. Paramagnetic

8. *SA1  
Choose the sub-fabrics, $\hat{k}_p$, from the AMS or from literature – if possible –  
Analytical isolation for calcite texture using Eq. 1.5

9. Analytical isolation for calcite texture using Eq. 1.5 when $\hat{k}_p$ is the AARM fabric

The AMS represents the calcite preferred orientation

**Figure 4.** Flow diagram, for the identification and isolation of the AMS sub-fabrics in carbonate rocks.

*SA1 and *NP2 relates to two study cases dealt with in this paper
1.5.2. Working hypothesis and testing procedures

The existence of magnetic phase in addition to a calcite diamagnetic phase, and a para/ferromagnetic sub-fabric in the AMS is suspected when the bulk-susceptibility of carbonate rock specimen \( k_{mt} \) is greater than \(-9 \, \mu SI\). According to Equation 1.5, in order to isolate the AMS sub-fabric of the calcite diamagnetic phase three independent quantities should be estimated; the respective percentages of the para/ferromagnetic phase \( c_p \), the bulk-susceptibility of the para/ferromagnetic phase \( k_{mp} \) and the normalized tensor of the para/ferromagnetic phase \( \hat{k}_p \). Chemical composition analysis can be used to estimate the respective percentages \( c_p \) of the elements involved in the rock (Schmidt et al., 2006). By preforming chemical composition analysis for group of specimens (of the sampling site) the relations between the specimens’ bulk-susceptibilities \( k_{mt} \) and the respective amounts of certain elements \( c_p \) can be estimated. Equation 1.8 predicts a linear correlation between \( k_m \) and \( c_p \) for the element carrying the para/ferromagnetic phase, where the slope represents \( k_m \) and the intersection with the \( k_m \) axis represents \( k_m \). If the linear fit intersects the \( k_m \) axis around -12 \( \mu SI \), namely \( k_m \approx -12 \, \mu SI \), then it is assumed that this particular element is carrying the para/ferromagnetic phase. If the linear fit intersects the \( k_m \) axis above -12 \( \mu SI \), namely \( k_m > -12 \, \mu SI \), then it is assumed that there is another element carrying another para/ferromagnetic phase. The difficulty rises in the estimation of the normalized tensor \( \hat{k}_p \) because of the unknown physical properties of the magnetic phase. Various experimental techniques are available to identify the physical properties of the magnetic phases involved (Martin-Hernandez and Ferre, 2007). If the magnetic phase \( c_p \) is ferromagnetic or ferrimagnetic, then the anisotropy of anhysteretic remanent magnetization (AARM) can be used to estimate the normalized tensor \( \hat{k}_p \) (for more details see section 1.6.3). However, If the magnetic phase \( c_p \) is paramagnetic, then no experimental method is available to estimate its magnetic principal axes (Martin-Hernandez and Ferre, 2007). Nevertheless, it may be possible to estimate \( \hat{k}_p \) from the AMS measurements (exemplified in section 2.5) or to estimate its contribution to the AMS theoretically from the literature.

Figure 4 presents a flow diagram of the testing procedure for the identification and isolation of the AMS sub-fabrics in carbonate rocks according to the working hypothesis presented above. In this study I use isothermal-remanent-magnetization acquisition curves (IRM),
temperature-dependent susceptibility measurements and scanning electron microscopy techniques (for more details see sections 1.6.3-5) to identify the physical properties of the magnetic phases involved in multi-phase carbonate rocks. I show two examples that use of this process, one for a Bar-Kokhba limestone (SA1 site) that contains second-phase minerals derived from chemical alteration (section 2.5), and the second for Timrat chalk (NP2 site) that contains magnetite grains and clay minerals within the rock texture (section 2.6).
1.6. Methods

1.6.1. Studied localities and sampling strategy

The majority of samples were taken from the Bar-Kokhba Formation in the Rosh-Pinna area (Figure 2). To compare different structural areas and different rock formations I took samples from two more different areas: three from Bar-Kokhba Formation in Mt. Gilboa area and five in the southern parts of the HaOnn-Cliffs area from different Eocene and Oligocene formations (Figure 1).

The sampling sites were distributed in different localities based on their distances from the main segments of the DST. I tried to avoid adjacency to local structures (subsidiary faults, folds) in order to examine the strain field that was influenced directly by the DST. I tried to collect 15-20 specimens from each site in order to have a statistically satisfactory sampling. The geology of the surrounding area, the nature of the rock, and the site coordinates were documented for every sampling site. The specimens were drilled with 2.5 cm core-drill. The drilling direction, the orientation and the name of the specimen were marked on every core (Figure 5). The cylindrical cores were cut to ~2 cm long samples (at the Geological Survey of Israel). Because of inaccuracies in the cutting process the volume of each sample was measured separately.

1.6.2. AMS measurements and analysis

Mathematically, the estimation of the susceptibility tensor of a sample is satisfied by six measurements however, a larger number of directions is preferred to achieve a better accuracy for estimating measurement errors (Hext, 1963). A common design for measuring direction is proposed by Jelinek (1977) for 15 measured directions. Practically, the use of that design is cumbersome and slow because each specimen needs to be flipped manually in each direction. Hence, the spinning specimen method was subsequently developed (Jelinek, 1995), whereby the specimen is measured while it spins about three perpendicular axes. The spinning specimen method is faster, and also more accurate than the manual method. In this study the AMS was measured by the spinning specimen method with KLY-4S Kappabridge, at the magnetic fabric laboratory of the Geological Survey of Israel (GSI). The
sensitivity of the Kappabridge is on the order of $1 \times 10^{-8}$ [SI], enabling the measurement of samples with mean susceptibility on the order of 1 [$\mu$SI]. The weak magnetic response of carbonate rocks requires rigorous consideration (Hamilton et al., 2004), the Kappabridge must be precisely calibrated and the susceptibility of the specimen-holder has to be measured several times (three times at least) before each measurement session. It was found that the Kappabridge is very sensitive to room temperature and to the magnetic environments. We therefore kept the room temperature stable and minimized the metallic objects in the laboratory. The measurements were repeated several times to ensure repetition. From each group of susceptibility tensors, of specimens belonging to same sampling site, the mean tensor and its 95% confidence intervals of the principal axes were calculated according to Jelinek's (1978). To verify whether the difference between the principal susceptibilities, determined by the measurements, compared to the measuring errors are great enough for the specimen to be considered as anisotropic, the F-test was performed (Jelinek, 1977). In this study, I considered only specimens that passed the F-test ($>3.9$) with 95% confidence (meaning that within the error distribution statistically 95 out of 100 specimens would be anisotropic) or its principal axes were within the total site mean-tensor 95% confidence intervals. The AMS magnitudes and principal axes and the anisotropy parameters were calculated using the software package Anisoft42, which relies on Jelinek's (1981) and Hrouda (2004). In this study the AMS axes of diamagnetic rocks are described by the assigned values of the principal susceptibilities, hence, the minimum susceptibility ($k_3$) refers to the most negative susceptibility value. In addition, the AMS parameters ($P, P', L, F, T, \Delta k$) are calculated based on the absolute (unsigned) values of the principal susceptibility, which means that the largest absolute magnitude is the maximum susceptibility. This convention is recommended for describing the orientations of the principal axes and their magnitudes (for more details see Hrouda, 2004).

1.6.3. AARM measurements

The Anisotropy of Anhysteretic Remanent Magnetization (AARM) is a method to estimate the magnetic fabric of minerals that obtain remanent magnetization (Borradaile and Stupavsky, 1995; Jackson, 1991; Jackson and Tauxe, 1991; McCabe et al., 1985). The sample is subjected to a direct magnetic field under the presence of a stronger alternating magnetic field. The alternating field is slowly reduced and the direct field is held constant. In that way
the sample is magnetized in the direction of the direct field. The magnetization vector, carried by the sample, is measured. By repeating this process six (or more) times, when each time the sample is magnetized by different polarity direction, the remanence susceptibility tensor \( k_r \) is constructed. In order to examine the anisotropy of ferromagnetic/ferrimagnetic minerals and its contribution to the magnetic properties of the rock, AARM measurements were performed on selected samples from the Bar-Kokhba limestones and Timrat chalks. The samples were magnetized using the AMU-1A magnetizer and then demagnetized with the LDA-3A demagnetizer and the magnetization vector was measured using the JR-6A spinner magnetometer. The AARM orientations and parameters were calculated using the software package Arem2W.

1.6.4. IRM

The IRM (Isothermal Remanent Magnetization) acquisition curves are constructed by exposing the sample to increasing values of high pulse fields and measuring its magnetization each time. By demagnetizing the rock sample and then exposing it to a high pulse field the sample is magnetized. The ratio between the high pulse field and the remanent magnetization obtained by the rock is dependent on the minerals involved in the rock. Since ferromagnetic and ferrimagnetic minerals have a unique IRM signature, IRM acquisition curves can be used to identify the ferromagnetic and ferrimagnetic minerals in the rock (Fuller et al., 1988; Stockhausen, 1998). For that purpose the IRM of a selected number of samples were measured. Natural Remanent Magnetization was measured using a shielded three axes 2G 750R SRM cryogenic magnetometer, with integrated Alternating Field (AF) coils, at the paleomagnetic laboratory of the Institute of Earth Science, the Hebrew University of Jerusalem. Each sample was subjected to stepwise demagnetization with increasing intensity starting at 5 [mT] and going up to 90 [mT]. Then the samples were exposed to a high pulse field using the ASC model IM10-30 Impulse Magnetizer, starting with a field of 25 [mT] up to 200 [mT] with increments of 25 [mT], then steps of 50 [mT] up to 400 [mT] and steps of 100 [mT] up to 1600 [mT]. After each step the IRM was measured using the Magnetometer in order to create an acquisition curve of Isothermal Remanence Magnetization (IRM)
1.6.5. Temperature-dependent susceptibility measurements

Diamagnetic substances exhibit no temperature dependence of the magnetic susceptibility. Other magnetic properties (such as paramagnetism, ferromagnetism, ferrimagnetism etc.) usually exhibit temperature dependence according to the Curie-Weiss law (Ballet et al., 1985; Beausoleil et al., 1983; Hirt et al., 1995; Hrouda and Jelinek, 1990). Since minerals have unique temperature dependence signatures, temperature dependence susceptibility measurements are useful to define and estimate the contribution of minerals (Cifelli et al., 2004; Hirt et al., 1995; Hirt and Gehring, 1991; Hrouda et al., 1997; Jover et al., 1989; Schultzkrutisch and Heller, 1985). To test the contribution and identify the dominant paramagnetic and ferromagnetic minerals in the rock, magnetic susceptibility measurements at variable temperatures were performed on selected samples. The measurements were performed at low temperatures, ranging from the temperature of liquid nitrogen (-192°) to 700°. For measuring susceptibility in high temperatures I use an agico CS3 furnace, and a CS-L cryostat for low temperatures.

1.6.6. Chemical composition

Chemical composition analyses were performed on selected number of samples to determine the relative content of trace elements. In order to estimate the relations between the magnetic properties and the respective amounts of certain elements in the rock for the isolation method, 8 to 11 samples were analyzed in each site. The chemical composition analysis was performed using ICP-OES optima 3300 at the Geological Survey of Israel. The content of Fe and Mn were measured using an ICP-MS Elan 6000 (at the Geological Survey of Israel) to achieve higher accuracy because of the special sensitivity of calcite magnetic properties to Fe²⁺ and Mn²⁺ ions (Schmidt et al., 2006).

1.6.7. XRD Measurements

To evaluate the proportion of calcite crystals, the mineralogical composition was determined by X-ray diffraction (Philips PW1730/1710, and PW1830/3710, CuKα1). Ground rock powders were side-packed into aluminum holders. Semi-quantitative composition was estimated by comparison with calibration curves and with the corresponding chemical data (IR and K concentrations).
1.6.8. *Thin-Sections*

In order to study the depositional environment and the petrology of the rocks, a number of representative thin-sections were analyzed using an optical microscope.

1.6.9. *Scanning Electron Microscope (SEM)*

To get a good understanding of the rocks micro-structure and to determine the chemical composition of specific points of interest within the rock, a limited number of selected samples were investigated using electron microscopy. This investigation was conducted using a Scanning Electron Microscope (SEM), model FEI Quanta 450, at the Geological Survey of Israel (GSI).

The following detectors were used:


The results are presented in three ways.

1. Secondary electron image (labeled LFD or ETD on image caption bottom) which displays surface texture, morphology, and surface roughness.
2. Backscatter electron image (labeled BSED on image caption bottom) which displays differences in atomic/molecular density and highlight chemical composition differences. In a backscatter image the shade of grey indicates molecular/atomic density. Heavier elements are whiter, and lighter elements are darker.
3. EDS Spectra of the number (intensity) and energy level of X-rays enables elemental composition to be determined.
2. Results

2.1. General
The AMS of 402 samples from 25 sites in the Rosh-Pinna, Mt. Gilboa and the HaOnn-Cliffs areas were measured and analyzed (Figure 1). Table 1 presents the AMS results and anisotropy parameters of all samples. Table 2 presents the selected samples for the regional study, samples that passed the anisotropy test (F-test) with over 95% confidence value (>3.9) (Jelinek, 1977) or presented principal axes within the total site mean-tensor 95% confidence intervals (meaning that their magnetic fabric is in agreement with the total site fabric). The susceptibilities of all samples indicate they all belong to the diamagnetic and weak-paramagnetic phases (Figure 6). The values of the bulk-susceptibilities are close to the values of pure calcite crystals, suggesting that the impurities and second-phase minerals concentrations are low. The susceptibilities of Eocene chalk rocks (Adulam, Timrat and Maresha formations) are close to zero, which means that the AMS comprises more than one magnetic phase (Borradaile and Henry, 1997).

![Figure 6. Percentage frequency diagram of the bulk-susceptibility (km) of all samples N=402. Note a high peak in the diamagnetic region of -10 to -11 [μSI] bulk-susceptibility values.](image)
Table 1. Magnetic properties of all specimens from low-field AMS measurements. The anisotropy parameters are the average parameters for the sites.

<table>
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<tr>
<th>Location</th>
<th>Site Name</th>
<th>Stratigraphic unit</th>
<th>No. of sample (N)</th>
<th>Mean susceptibility [μSI]</th>
<th>Corrected anisotropy Degree (P')</th>
<th>Susceptibility difference Δk [μSI]</th>
<th>Shape parameter (T)</th>
<th>Magnetic foliation (F)</th>
<th>Magnetic lineation (L)</th>
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<tr>
<td>Rosh-Pinna Area</td>
<td>EP1</td>
<td>Bar-Kokhba</td>
<td>10</td>
<td>-6.29</td>
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<td>0.049</td>
<td>1.022</td>
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Table 2. Magnetic properties of selected specimens from low-field AMS measurements of samples that either passed the anisotropy test "F-test" within 95% confidence (Jelinek, 1977) or presented principal directions oriented within the site confidence ellipses. The anisotropy parameters are the average parameters for the sites.

<table>
<thead>
<tr>
<th>Location</th>
<th>Site Name</th>
<th>Stratigraphic unit</th>
<th>No. of sample (N)</th>
<th>Mean susceptibility [μSI]</th>
<th>Corrected anisotropy Degree (P)</th>
<th>Susceptibility difference Δk [μSI]</th>
<th>Shape parameter (T)</th>
<th>Magnetic Foliation (F)</th>
<th>Magnetic Lineation (L)</th>
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<td>Bar-Kokhba</td>
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2.2. Rosh-Pinna area

The AMS of 272 samples from 16 sites from the Eocene Bar-Kokhba Formation, and 1 site from the Early Eocene Timrat Formation, from the Rosh-Pinna area (Fig. 2) were measured and analyzed. The rocks from four sites of the Bar-Kokhba Formation (EP2, AK1, SA2 and HC2) contain red veins related to young surface weathering processes and were excluded from the regional study. The influence of the veins on the magnetic properties are discussed in Section 2.5. Figure 7 shows optical microscopy images of thin-sections from sites NP1 and KN1. The rocks consist of marine shells fragments and foraminifera, interpreted as a result of transportation and sliding events during diagenesis. XRD analysis preformed on sample from the NP1 site a yields diffraction pattern indicative of more than 95% calcite (CaCO₃) crystals.
Figure 7. Optical microscopy images of thin-sections of Eocene Bar-Kokhba Formation limestone from the Rosh-Pinna area. (a) NP1 site and (b) KN1 site. Note uniform matrix, composed of fragments of marine shells, interpreted as a result of transportation and sliding events during diagenesis.

Figure 8. Scanning Electron Microscope (SEM) images of the Eocene Bar-Kokhba Formation limestone sample from the NP1 site. (a) 400 micro-meter view and (b) 100 micro-meter view. The images show calcite crystalline texture.
Table 3. Chemical content and bulk-susceptibility ($k_m$) of selected samples. The results are in ppm except Ca* which is in 10^4 ppm.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Location</th>
<th>Stratigraphic unit</th>
<th>$k_m$ [μSI]</th>
<th>Si</th>
<th>Al</th>
<th>Ca*</th>
<th>Mg</th>
<th>Fe</th>
<th>Mn</th>
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<td>55.0</td>
<td>2000</td>
<td>70</td>
<td>&lt;10</td>
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<td>55.9</td>
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<td>≤200</td>
<td>55.9</td>
<td>1200</td>
<td>≤50</td>
<td>≤10</td>
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<td>56.0</td>
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<td>55.9</td>
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<td>55.0</td>
<td>2000</td>
<td>110</td>
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</table>

Figure 8 presents SEM images of a sample from the NP1 site showing calcite crystalline texture. The grain size ranges between a few to a couple of dozen micrometers. This texture appears throughout the specimen while no irregularities or different texture spots are observed. Table 3 presents the results of the chemical composition analysis of selected samples from the Rosh-Pinna Bar-Kohba sites, which confirms the major calcium content and the minor content of other elements in the rock.

Table 2 presents results of AMS measurements preformed on 151 samples from Bar-Kohba limestones in the Rosh-Pinna area. The rocks are all diamagnetic with mean susceptibility of $k_m = -10.89 ± 1.16$ [μSI]. This value is sufficiently close to the measured value of pure calcite crystals, leading to the conclusion that the AMS is controlled by calcite. Figure 9 shows the corrected anisotropy degree ($P'$) and the shape parameter (T). The corrected anisotropy degree ($P'$) of 95% of the samples has $P'$ values lower than 1.02 whereas 60% has $P'$ values lower than 1.01 , indicating that the preferred crystal orientation in the rock is weak. The shape of the AMS (T) is getting closer to -1 with the growth of the corrected anisotropy degree ($P'$), reflects the development of preferred crystal orientation of calcite in the rock (Borradaile and Jackson, 2010).
Figure 10. AMS fabrics of the Rosh-Pinna area. Lower-hemisphere, equal-area projection of AMS principal axes and 95% confidence ellipses.
Figure 10 shows the projection of AMS principal axes and the 95% confidence interval of the mean tensor. All sites indicate tectonic fabrics with well-grouped $k_3$ axes. Magnetic fabrics of AK2, HA3 and SA2 sites are classified as Tectonic sub horizontal-shortening with foliation fabric, the principal directions of the mean tensors are similarly oriented. Magnetic fabrics of HC1, NP1 and TH1 sites are classified as tectonic horizontal-shortening with foliation fabric, as indicated by the 95% confidence interval of the mean tensor. Magnetic fabrics of KN1, NR1 and EP1 sites are classified as tectonic horizontal-shortening with sub foliation. Magnetic fabrics of EP3, HA1 and HA2 sites are classified as tectonic horizontal-shortening fabric. Figure 11 shows that the cumulative rose diagram of the AMS axis. $k_3$ has predominant horizontal orientation in $\sim$N-S, $k_1$ has predominant horizontal orientation in $\sim$W-E and $k_2$ shows no predominant horizontal orientation.

Figure 11. Cumulative rose diagrams of AMS principal directions in the Rosh-Pinna area, all samples statistics, N=151. (A.1), (A.2) and (A.3) represent declination distribution of $k_1$, $k_2$ and $k_3$ respectively. (B.1), (B.2) and (B.3) represent inclination distribution of $k_1$, $k_2$ and $k_3$ respectively.
2.3. Mt. Gilboa area

Samples from three sites at the top of Mt. Gilboa where measured and analyzed. The rocks defined as limestones, belong to the Eocene Bar-Kokhba Formation. Figure 12 shows optical microscopy images of thin-sections from the MG1 and MG3 sites. The image of the MG1 site (Figure 12a) shows that the rock is composed of unbroken Nummulite shells and foraminifera, suggesting that the rock did not undergo significant transportation and sliding during its diagenesis. The shell pores and contact spaces are filled with cement. On the other hand, the image of the MG3 site shows a relatively uniform matrix, composed of fragments of marine shells (Figure 12b), which are interpreted as a result of transportation and sliding events during diagenesis. XRD analysis performed on one of the samples from the MG1 site shows a diffraction pattern indicating that the rock is composed of more than 95% calcite ($CaCO_3$) crystals. Table 3 that shows the chemical composition of selected samples, confirms that calcium-carbonate is the main forming mineral (the large content of Ca), and the minor presence of other elements in the rocks.

![Figure 12. Optical microscopy images of thin-sections of Eocene Bar-Kokhba Formation limestone from the Mt. Gilboa area. (a) MG1 site, the rock is composed of whole Nummulite and foraminifera shells. The shell pores and contact spaces are filled with cement. (b) MG3 site, uniform matrix composed of fragments of marine shells, interpreted as a result of transportation and sliding events during diagenesis.](image-url)
Table 2 presents the results of AMS measurements of samples from the MG1, MG2 and MG3 sites. The rocks are characterized by diamagnetic response with bulk susceptibility ($k_m$) of $-11.18 \pm 1.09$ [$\mu$SI], very close to the value of calcite crystal (Schmidt et al., 2006). These results indicate that the magnetic properties are controlled by a diamagnetic phase of calcite. Figure 13 shows the corrected anisotropy degree ($P'$) and the shape parameter ($T$). The shape ($T$) of the AMS getting closer to -1 with the growth of the corrected anisotropy degree ($P'$), reflects the development of preferred crystal orientation of calcite in the rock (Borradaile and Jackson, 2010). The L parameter is greater than the F parameter in the MG1 and MG2 sites (Table 2) [Since the absolute values of the susceptibilities are used for the calculation of the anisotropy parameters, L > F reflects the fact that the difference in the magnitudes between $k_3$ and $k_2$ is greater than between $k_2$ and $k_1$]. The preferred crystal orientation is reflected by the magnetic fabric. Figure 14 shows the projection of AMS principal axes and the 95% confidence interval of the mean tensor, indicating tectonic fabrics with well-grouped $k_3$ axes. The magnetic fabrics of the MG1 and MG2 sites are classified tectonic vertical-shortening fabric, the principal directions of the mean tensors are identically oriented where the mean $k_3$ axis is oriented sub-vertically in 345°/02°. The magnetic fabric of the MG3 site is classified as tectonic sub horizontal-shortening fabric.

Figure 13. Corrected anisotropy degree ($P'$) and shape parameter ($T$). AMS data of Bar-Kokhba limestones from the Mt. Gilboa area, presented on a π/4 segment polar plot. $P'$ is represented by the radius and T by the arc length. Plot first introduced by Borradaile and Jackson (2004).
2.4. HaOnn-Cliffs area

Samples from five different sites in the southern parts of the HaOnn-Cliffs area (Figure 1) were measured and analyzed. The rocks were classified as sedimentary rocks from Early Eocene to Early Oligocene formations. Sites AD1 and MR1 are located on the southern slopes of the Golan-Heights north to the Yarmouk-Valley; the layers slightly dip in a SE direction. The AD1 site consists of soft chalks, of Early Eocene Adulam Formation, consist of micro-size marine shells and foraminifera. Table 4 presents the results of the chemical composition analysis of selected samples from the HaOnn-Cliffs area. The rock of the AD1 site has large amounts of Ca, indicative of calcite as major constituent of the rock. Relatively large amounts of Si, Al and Mg contained in the rock, indicate existent clay-minerals. Table 2 shows the magnetic properties and anisotropy parameters from AMS measurements. The bulk susceptibility values of the AD1 site indicate weak diamagnetic response with an average of $k_m = -3.04 \pm 0.46 \, [\mu S I]$. The AMS is anisotropic where the average anisotropy degree is $P^2 = 1.035$. 

![Figure 14. AMS fabrics of the Mt. Gilboa sites. Lower-hemisphere, equal-area projection of AMS principal axes and 95% confidence ellipses.](image)
<table>
<thead>
<tr>
<th>Site Name</th>
<th>Location</th>
<th>Formation</th>
<th>$k_m$ [μSI]</th>
<th>Si</th>
<th>Al</th>
<th>Mg</th>
<th>Fe</th>
<th>Mn</th>
<th>Ca*</th>
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</thead>
<tbody>
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<td>HaOnn-Cliffs</td>
<td>Fiq</td>
<td>17.62</td>
<td>17000</td>
<td>4000</td>
<td>7000</td>
<td>37.5</td>
<td>65</td>
<td>52.5</td>
</tr>
<tr>
<td>AD1</td>
<td>HaOnn-Cliffs</td>
<td>Adulam</td>
<td>-3.15</td>
<td>18000</td>
<td>3000</td>
<td>8000</td>
<td>860</td>
<td>&lt;10</td>
<td>52.0</td>
</tr>
<tr>
<td>MR 1</td>
<td>HaOnn-Cliffs</td>
<td>Maresha</td>
<td>3.51</td>
<td>51000</td>
<td>6300</td>
<td>10000</td>
<td>1500</td>
<td>20</td>
<td>50.9</td>
</tr>
<tr>
<td>MH 1</td>
<td>HaOnn-Cliffs</td>
<td>Maresha</td>
<td>9.61</td>
<td>35000</td>
<td>7200</td>
<td>19300</td>
<td>2270</td>
<td>42</td>
<td>30.7</td>
</tr>
<tr>
<td>MH 2</td>
<td>HaOnn-Cliffs</td>
<td>Susita</td>
<td>9.46</td>
<td>250000</td>
<td>2700</td>
<td>15500</td>
<td>1130</td>
<td>75</td>
<td>24.0</td>
</tr>
</tbody>
</table>

Table 4. Chemical content and bulk-susceptibility ($k_m$) of selected samples from the HaOnn-Cliffs area. The results are in ppm except Ca* which is in $10^4$ ppm.

Figure 15 shows the projection of AMS principal axes and the 95% confidence interval of the mean tensor. The magnetic fabric of the AD1 site indicates tectonic vertical-shortening fabric with well-grouped $k_3$ axes in a sub-vertical direction and loosely-grouped $k_1$ and $k_2$ axes on a sub-horizontal plane. The MR1 site rocks, from the late Eocene Maresha Formation, are soft chalk consisting of micro marine shells and foraminifera. It is located near the AD1 site, higher in the geological section. The chemical composition (Table 4) indicates calcite as major constituent of the rock. The large amounts of Si, Al and Mg content indicate clay-minerals. The AMS measurements indicate weak, positive magnetic response with average bulk susceptibility of $k_m = 3.60 \pm 2.41$ [μSI] (Table 2). The majority of the samples are anisotropic where the average anisotropy degree is $P' = 1.035$. The magnetic fabric (Figure 15) indicates tectonic vertical-shortening fabric with well-grouped $k_3$ axes in a sub-vertical direction and scatter of $k_1$ and $k_2$ axes on a sub-horizontal plane. The MH1 and MH2 sites are located on the lower slopes of the HaOnn-Cliffs, a few meters from each other. The soft, white color chalk of the MH1 site, of Early to Middle Eocene Maresha Formation consist of micro marine shells and foraminifer. The rock was difficult to sample because it disintegrated. Chemical composition (Table 4) shows relatively low amounts of Ca. AMS measurements indicate positive magnetic response with average bulk susceptibility of $k_m = 8.84 \pm 1.23$ [μSI] (Table 2). The majority of the samples are anisotropic where the average anisotropy degree is $P' = 1.010$. The magnetic fabric (Figure 15) indicates tectonic vertical shortening fabric with clustering of principal susceptibilities when $k_3$ is horizontal oriented in a 243°/04° direction, $k_2$ is oriented in a 343°/64° direction and $k_1$ is oriented in a 151°/25° direction. The rocks of MH2 site consists of a few millimeters grain size, sharp angular detritus of the Oligocene Susita Formation. Chemical composition (Table 4) shows relatively low amounts of Ca. AMS measurements indicate positive magnetic response with average bulk susceptibility of $k_m = 9.73 \pm 5.16$ [μSI] (Table 2). All samples are anisotropic.
with an average anisotropy degree of $P^* = 1.088$, and all measured samples pass the anisotropy F-test with high values (tens to hundreds). The magnetic fabric (Figure 15) indicates tectonic vertical shortening fabric with well-grouped $k_3$ principal axes in $015^\circ/19^\circ$ direction, and moderately-grouped $k_2$ and $k_1$ axes in $144^\circ/60^\circ$ and $278^\circ/21^\circ$ direction respectively. The PK1 site, located on the lower slopes of the HaOnn-Cliffs, 2 km north of the MH1/2 sites is from the Upper-Eocene Fiq Formation. The layers display a sharp inclination where the tendency is in a $260^\circ/62^\circ$ direction. Chemical composition (Table 4) is indicative of calcite rock. Large amounts of Si, Al and Mg suggest clay-minerals. AMS measurements indicate positive magnetic response with average bulk-susceptibility of $k_m = 22.30 \pm 10.40 \muSI$ (Table 2). The samples are anisotropic with an average anisotropy degree of $P^* = 1.006$. The magnetic fabric (Figure 15) indicates tectonic vertical shortening fabric with well-grouped $k_3$ axes oriented in a $051^\circ/05^\circ$ direction and moderately-grouped $k_2$ and $k_1$ axes oriented in $191^\circ/82^\circ$ and $321^\circ/05^\circ$ direction respectively.

![Figure 15. AMS fabrics of the HaOnn-Cliffs area. Lower-hemisphere, equal-area projection of AMS principal axis and 95% confidence ellipses.](image-url)
2.5. Isolation of diamagnetic phase in Bar-Kokhba rocks

Figure 17b shows a sample of Bar-Kokhba rock that contains reddish color material due to chemical alterations related to young geomorphological processes. Samples from four sites of the Rosh-Pinna area (EP2, AK1, SA1 and HC2) show this alteration, both as filling of small cracks (veins) and more-massively within the original rock. The susceptibility of these samples reaches positive values and their AMS indicate an isotropic fabric (Figure 16). Table 5 presents the results of AMS measurement for the SA1 site, indicating wide dispersion in the bulk susceptibility \( (k_m) \) values, ranging from -10 to +109 [\( \mu SI \)]. Figure 18 illustrates this dispersion by comparison between the altered samples from the SA1 and unaltered sample from SA2 site. The \( k_m \) values of the SA1 samples are widely dispersed between -10 and +25 [\( \mu SI \)] with one sample at +109 [\( \mu SI \)]. In contrast, the \( k_m \) values of the SA2 samples site are all grouped around the value of -11 [\( \mu SI \)]. The P’ values of the SA1 samples are generally higher than the P’ values of samples from site SA2. Table 6 shows the chemical composition of selected samples from site SA1. The rocks contain large amounts of Fe, Mg and Al. The distinct appearance of the alteration products implies that the elements associated with it were available as second-phase minerals and not as crystal impurities within the former rock. Sample SA1-10 shows a jump both in Fe content and in \( k_m \) (Table 6), suggesting that the Fe content is the most influential factor on magnetic properties.
Table 5. Magnetic properties and AMS parameters of all the samples of site SA1.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Mean susceptibility [μSI]</th>
<th>Corrected anisotropy Degree (P')</th>
<th>Susceptibility difference Δk [μSI]</th>
<th>Shape parameter (T)</th>
<th>Magnetic Foliation (F)</th>
<th>Magnetic Lineation (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA1-1</td>
<td>10.88</td>
<td>1.044</td>
<td>0.459</td>
<td>0.294</td>
<td>1.028</td>
<td>1.015</td>
</tr>
<tr>
<td>SA1-2</td>
<td>4.99</td>
<td>1.041</td>
<td>0.196</td>
<td>0.371</td>
<td>1.027</td>
<td>1.013</td>
</tr>
<tr>
<td>SA1-3</td>
<td>-1.53</td>
<td>1.150</td>
<td>0.213</td>
<td>-0.218</td>
<td>1.056</td>
<td>1.088</td>
</tr>
<tr>
<td>SA1-4</td>
<td>16.15</td>
<td>1.006</td>
<td>0.086</td>
<td>0.716</td>
<td>1.005</td>
<td>1.001</td>
</tr>
<tr>
<td>SA1-5</td>
<td>12.90</td>
<td>1.044</td>
<td>0.522</td>
<td>-0.702</td>
<td>1.006</td>
<td>1.035</td>
</tr>
<tr>
<td>SA1-6</td>
<td>-0.98</td>
<td>1.201</td>
<td>0.180</td>
<td>-0.090</td>
<td>1.087</td>
<td>1.105</td>
</tr>
<tr>
<td>SA1-7</td>
<td>-4.90</td>
<td>1.019</td>
<td>0.091</td>
<td>-0.525</td>
<td>1.004</td>
<td>1.014</td>
</tr>
<tr>
<td>SA1-8</td>
<td>22.50</td>
<td>1.017</td>
<td>0.334</td>
<td>0.948</td>
<td>1.001</td>
<td>1.000</td>
</tr>
<tr>
<td>SA1-9</td>
<td>-10.66</td>
<td>1.011</td>
<td>0.113</td>
<td>-0.381</td>
<td>1.003</td>
<td>1.007</td>
</tr>
<tr>
<td>SA1-10</td>
<td>109.70</td>
<td>1.018</td>
<td>1.739</td>
<td>0.805</td>
<td>1.014</td>
<td>1.002</td>
</tr>
<tr>
<td>SA1-11</td>
<td>-7.31</td>
<td>1.018</td>
<td>0.126</td>
<td>-0.320</td>
<td>1.006</td>
<td>1.012</td>
</tr>
<tr>
<td>SA1-12</td>
<td>-10.73</td>
<td>1.016</td>
<td>0.157</td>
<td>-0.811</td>
<td>1.001</td>
<td>1.013</td>
</tr>
<tr>
<td>SA1-13</td>
<td>-10.23</td>
<td>1.011</td>
<td>0.112</td>
<td>-0.246</td>
<td>1.004</td>
<td>1.007</td>
</tr>
<tr>
<td>SA1-14</td>
<td>-9.71</td>
<td>1.018</td>
<td>0.170</td>
<td>-0.270</td>
<td>1.006</td>
<td>1.011</td>
</tr>
<tr>
<td>SA1-15</td>
<td>-10.51</td>
<td>1.006</td>
<td>0.066</td>
<td>0.178</td>
<td>1.004</td>
<td>1.003</td>
</tr>
<tr>
<td>SA1-16</td>
<td>22.96</td>
<td>1.017</td>
<td>0.364</td>
<td>0.880</td>
<td>1.015</td>
<td>1.001</td>
</tr>
<tr>
<td>SA1-17</td>
<td>-10.17</td>
<td>1.009</td>
<td>0.091</td>
<td>0.310</td>
<td>1.006</td>
<td>1.003</td>
</tr>
<tr>
<td>SA1-18</td>
<td>-7.63</td>
<td>1.013</td>
<td>0.099</td>
<td>0.239</td>
<td>1.008</td>
<td>1.005</td>
</tr>
<tr>
<td>SA1-19</td>
<td>-7.21</td>
<td>1.024</td>
<td>0.164</td>
<td>-0.488</td>
<td>1.006</td>
<td>1.017</td>
</tr>
</tbody>
</table>

Figure 19 shows relation between $k_m$ and the Fe percentages ($c_p$), however the low linear fit, $R^2 = 0.57$, implies weak correlation. Figure 20 shows susceptibility-difference ($\Delta k$) versus the Fe content of samples from Bar-Kokhba limestones. Although no clear correlation is observed, there is an increase of the susceptibility-difference with Fe content. Figure 21 shows the projection of the principal axes of AMS and AARM measurements. The AARM measurements, performed on six samples containing relatively large amounts of Fe content, reveal no anisotropy of anhysteretic remanent magnetization (Figure 21b), the F-tests are low and the magnetic fabric shows no grouping of principal directions. Therefore, the ferromagnetic/ferrimagnetic minerals within the rock are magnetically isotropic. The AMS fabric (Figure 21a) shows scattered principal axes.

Figure 18. (a) Corrected anisotropy degree (P') versus bulk susceptibility (km) of the SA1 and SA2 sites. (b) Susceptibility difference ($\Delta k=k1-k3$) versus bulk susceptibility (km) of SA1 and SA2.
Figure 22 shows the AMS fabric of site AS1 separated to two groups: Group a; samples with bulk susceptibility lower than \(-4.90 \ (k_m < -4.90 [\mu SI])\) and Group b; samples with bulk susceptibility greater than \(-1.53 \ (k_m > -1.53[\mu SI])\). The fabric of Group a (Figure 22a) shows poorly-grouped \(k_3\) axes, with a mean oriented \(\sim\)NNE – SSW, and scattered \(k_1\) and \(k_2\) axes that form a magnetic foliation. The fabric of Group b (Figure 22b) shows well-grouped \(k_3\) axes oriented vertically, and scattered \(k_1\) and \(k_2\) axes on the horizontal plane; this fabric represents the more altered samples (containing more second-phase minerals).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stratigraphic unit</th>
<th>(k_m) [\mu SI]</th>
<th>Si</th>
<th>Fe</th>
<th>Mg</th>
<th>Al</th>
<th>Ca*</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA1-1</td>
<td>Bar-Kokhba</td>
<td>10.88</td>
<td>3000</td>
<td>1100</td>
<td>1200</td>
<td>2000</td>
<td>55.3</td>
</tr>
<tr>
<td>SA1-2</td>
<td>Bar-Kokhba</td>
<td>4.99</td>
<td>3000</td>
<td>1600</td>
<td>5000</td>
<td>1500</td>
<td>55.4</td>
</tr>
<tr>
<td>SA1-6</td>
<td>Bar-Kokhba</td>
<td>-0.98</td>
<td>(&lt; 1000)</td>
<td>400</td>
<td>1200</td>
<td>700</td>
<td>55.5</td>
</tr>
<tr>
<td>SA1-7</td>
<td>Bar-Kokhba</td>
<td>-4.90</td>
<td>(&lt; 1000)</td>
<td>320</td>
<td>1000</td>
<td>1000</td>
<td>55.4</td>
</tr>
<tr>
<td>SA1-8</td>
<td>Bar-Kokhba</td>
<td>22.49</td>
<td>5000</td>
<td>1300</td>
<td>1000</td>
<td>2500</td>
<td>55.3</td>
</tr>
<tr>
<td>SA1-10</td>
<td>Bar-Kokhba</td>
<td>109.70</td>
<td>8000</td>
<td>5800</td>
<td>1500</td>
<td>3800</td>
<td>55.1</td>
</tr>
<tr>
<td>SA1-11</td>
<td>Bar-Kokhba</td>
<td>-7.31</td>
<td>(&lt; 1000)</td>
<td>300</td>
<td>800</td>
<td>400</td>
<td>55.9</td>
</tr>
<tr>
<td>SA1-12</td>
<td>Bar-Kokhba</td>
<td>-10.73</td>
<td>(&lt; 1000)</td>
<td>800</td>
<td>800</td>
<td>1500</td>
<td>55.8</td>
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<tr>
<td>SA1-13</td>
<td>Bar-Kokhba</td>
<td>-10.22</td>
<td>(&lt; 1000)</td>
<td>500</td>
<td>800</td>
<td>200</td>
<td>56.0</td>
</tr>
<tr>
<td>SA1-14</td>
<td>Bar-Kokhba</td>
<td>-9.71</td>
<td>1000</td>
<td>175</td>
<td>2000</td>
<td>(&lt; 1000)</td>
<td>56.0</td>
</tr>
<tr>
<td>SA1-15</td>
<td>Bar-Kokhba</td>
<td>-10.50</td>
<td>(&lt; 1000)</td>
<td>200</td>
<td>600</td>
<td>300</td>
<td>56.0</td>
</tr>
</tbody>
</table>

**Figure 19.** Bulk susceptibility (\(k_m\)) versus Fe content in 0.01% (cp) of samples from the SA1 site. The linear fit marked with solid line includes only the filled diamonds.
The analytical isolation method (chapter 1.5) is used here in order to isolate the diamagnetic fabric of the samples of the SA1 site. From the linear fit of \( k_m \) versus \( Fe \) content (\( c_p \)) (Figure 19), the respective percentage of \( Fe \) content is estimated for the entire samples of SA1 site. According to Eq. 1.8 the slope of the graph represents the bulk susceptibility of the paramagnetic/ferromagnetic phase (\( k_m^p \)), and the intersect point with the \( k_m \) axis represents the bulk susceptibility of the diamagnetic phase (\( k_m^d \)). The graph yields \( k_m^p = 34858 \, [\mu SI] \) and \( k_m^d = -12.78 \, [\mu SI] \).

![Figure 20. Susceptibility difference (\( \Delta k \)) versus \( Fe \) content of samples from the Bar-Kokhba Formation. Empty squares refer to the values from Table 3, filled squares refer to values from Table 6.](image)

The value of \( k_m^d \) is very close to the value of a single calcite crystal (Schmidt et al., 2006), hence it is assumed that the \( Fe \) is the only effective element (beside \( Ca \)) controlling the AMS of SA1 site. The incompatibility of the AARM fabric with the AMS fabric of group b implies that the \( Fe \) mineral in the rock is paramagnetic. For the isolation method, the normalized AMS tensor of sample SA1-10 will be considered as representing the paramagnetic tensor \( \hat{k}_p \) (because it has the sufficiently higher susceptibility \( k_m = 109[\mu SI] \)). The bulk susceptibility \( k_m^p \) is estimated from the linear fit of \( k_m \) vs. \( c_p \) (Figure 19). Using Eq. 1.5 the diamagnetic phase \( (k_m^d \cdot \hat{k}_d) \) of the samples is isolated.
Figure 21. AMS and AARM fabrics of site SA1. Lower-hemisphere, equal-area projection of (a) AMS principal axis and 95% confidence ellipses and (b) AARM principal axis. The AARM fabric represents an isotropic fabric since the fabric shows scattering and all of the measurements failed the anisotropic F-tests.

Figure 22. AMS fabrics of site SA1 divided in two: (a) samples with bulk susceptibility lower than -4.90 $\mu$SI. (b) samples with bulk susceptibility larger than -1.53 $\mu$SI. Lower-hemisphere, equal-area projection of AMS principal axis and 95% confidence ellipses.
Table 7 and Figure 24 present the AMS parameters resulting from the isolation method. The bulk-susceptibilities of the samples are uniform and very close to the value of single a calcite crystal. However, it is important to emphasize that they are dependent on, and result from the linear fit of \( k_m \) vs. \( c_p \) (Figure 19). The P’ values are low, between 1.00 to 1.02 , and two samples have P’≈1.045. The anisotropy shape (T) does not grow with P’ (Figure 24) and generally ranges evenly between -0.7 and 0.8. Figure 23 shows the projection of AMS principal axes and the 95% confidence interval of the mean tensor as resulting from the isolation method. The magnetic fabric is classified as tectonic horizontal-shortening fabric. All three principal axes \( (k_1, k_2, k_3) \) are moderately-grouped, where mean \( k_1 \) is oriented in 149°/82° direction, mean \( k_2 \) in the 310°/08° direction and mean \( k_3 \) in the 040°/03° direction.

### Table 7. Magnetic properties and AMS parameters of sampling site SA1 as emerging from the isolation method.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Mean susceptibility [μSI]</th>
<th>Corrected anisotropy Degree (P')</th>
<th>Susceptibility difference ( \Delta k ) [μSI]</th>
<th>Shape parameter (T)</th>
<th>Magnetic Foliation (F)</th>
<th>Magnetic Lineation (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>-12.79</td>
<td>1.020</td>
<td>0.253</td>
<td>0.316</td>
<td>1.013</td>
<td>1.007</td>
</tr>
<tr>
<td>2.</td>
<td>-12.79</td>
<td>1.013</td>
<td>0.165</td>
<td>0.030</td>
<td>1.007</td>
<td>1.006</td>
</tr>
<tr>
<td>3.</td>
<td>-12.78</td>
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<td>0.115</td>
<td>-0.636</td>
<td>1.002</td>
<td>1.007</td>
</tr>
<tr>
<td>4.</td>
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<td>0.537</td>
<td>0.580</td>
<td>1.034</td>
<td>1.009</td>
</tr>
<tr>
<td>5.</td>
<td>-12.79</td>
<td>1.046</td>
<td>0.574</td>
<td>-0.295</td>
<td>1.016</td>
<td>1.029</td>
</tr>
<tr>
<td>6.</td>
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<td>1.010</td>
<td>0.127</td>
<td>0.417</td>
<td>1.007</td>
<td>1.003</td>
</tr>
<tr>
<td>7.</td>
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<td>1.020</td>
<td>0.253</td>
<td>0.421</td>
<td>1.014</td>
<td>1.006</td>
</tr>
<tr>
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<td>-12.82</td>
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<td>0.203</td>
<td>0.802</td>
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<td>1.002</td>
</tr>
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<td>9.</td>
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<td>0.241</td>
<td>0.364</td>
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</tr>
<tr>
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<td>0.195</td>
<td>0.253</td>
<td>1.010</td>
<td>1.006</td>
</tr>
<tr>
<td>11.</td>
<td>-12.78</td>
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<td>0.089</td>
<td>-0.442</td>
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</tr>
<tr>
<td>12.</td>
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<td>0.165</td>
<td>-0.150</td>
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<td>1.007</td>
</tr>
<tr>
<td>13.</td>
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<td>0.178</td>
<td>-0.618</td>
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<tr>
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<td>0.127</td>
<td>-0.334</td>
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</tr>
<tr>
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<td>0.178</td>
<td>-0.703</td>
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<td>1.012</td>
</tr>
<tr>
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<td>0.203</td>
<td>-0.512</td>
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<td>1.012</td>
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<td>Ave.</td>
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<td>0.205</td>
<td>-0.040</td>
<td>1.008</td>
<td>1.008</td>
</tr>
<tr>
<td>Mean</td>
<td>-12.78</td>
<td>1.012</td>
<td>0.153</td>
<td>0.144</td>
<td>1.007</td>
<td>1.005</td>
</tr>
</tbody>
</table>
2.6. Identification of magnetic phases in the Timrat Formation

The Early Eocene Timrat Formation is exposed at the base of the Rosh-Pinna Creek and in the eastern slopes of the study area (Figure 2). The rocks from the NP2 site, located at the bottom of Rosh-Pinna creek, are determined as soft chalk of the Timrat Formation. XRD analysis performed on two samples from the NP2 site yields a diffraction pattern indicating that the rock is composed of more than 95% calcite (CaCO₃) crystals. Figure 26 shows optical microscopy images of thin-section from one sample. The rock is porous and homogenous, composed of micro-size marine foraminifera, distinct golden dots are observed within the rock. Figure 26 shows SEM images, the rock matrix is composed of micro size crystals (less than one micron), and a large amount of foraminifera. Using the Scanning Electron Microscope EDS technology the composition of the distinct dots and the surrounding material were analyzed. The secondary electron image (Figure 27a) shows a large grain which is heavier than the rock matrix. EDS spectra of this grain (Figure 27b) show high peaks of Fe and O while the matrix spectra (Figure 27c) is characterized by high
peaks of $Ca$, $C$ and $O$), implying that the distinct dots are Fe-

oxide minerals. Table 8 shows the results of chemical composition analysis of selected samples, indicating large amounts of $Fe$, $Si$, $Mg$ and $Al$ in the rocks of the Timrat formation (compared to Bar-Kokhba limestones in Table 3). Table 9 and Figure 28 show the magnetic properties and anisotropy parameters from AMS measurements. The bulk susceptibility is between $-2$ to $+7$ $\mu$SI, where most of the samples are close zero ($-2 < k_m < 2$), suggesting that the magnetic properties are controlled by more than one magnetic phase (Hamilton et al., 2004; Hrouda, 2004). Figure 29 shows the projection of AMS and AARM principal axes and the 95% confidence interval of the AMS mean tensor. The AMS fabric (Figure 29a) is classified as tectonic vertical-shortening fabric. All principal directions are well-grouped, where mean $k_1$ is oriented in a $076^\circ/14^\circ$ direction, mean $k_2$ in a $166^\circ/02^\circ$ and mean $k_3$ in a $264^\circ/75^\circ$ direction. AARM measurement preformed on 9 samples (Figure 29b) reveal no anisotropy of anhysteretic remanent magnetization, the F-tests (of AARM measurements) are low and the magnetic fabric shows no gather of principal directions.
Figure 26. Scanning Electron Microscope (SEM) images of the Eocene Timrat Formation chalk of NP2 site from Rosh-Pinna Creek. (a) 400 micro-meter view and (b) 100 micro-meter view. The images reflect calcite crystalline texture built from micro size foraminifers.

Figure 27. (a) Secondary Electron Images of Eocene chalk, Timrat Formation, from NP2 site in the Rosh-Pinna creek. In this image heavier elements appear brighter. (b) Elemental composition EDS Spectra, (intensity and energy level of X-rays) of the bright grain, identified by peaks of Fe, O and C. (c) Elemental composition EDS Spectra, (intensity and energy level of X-rays) of random spot of surrounding matrix, identified by peaks of Ca, O and C.
Table 8. Chemical content and bulk-susceptibility ($k_m$) of selected samples from site NP2. The results are in ppm except Ca* which is in $10^4$ ppm.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stratigraphic unit</th>
<th>$k_m$ [μSI]</th>
<th>Si</th>
<th>Al</th>
<th>Mg</th>
<th>Fe</th>
<th>Mn</th>
<th>Ca*</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP2-1</td>
<td>Timrat</td>
<td>-1.05</td>
<td>25000</td>
<td>6300</td>
<td>5400</td>
<td>850</td>
<td>27</td>
<td>53.5</td>
</tr>
<tr>
<td>NP2-2</td>
<td>Timrat</td>
<td>-0.53</td>
<td>25000</td>
<td>5700</td>
<td>5500</td>
<td>950</td>
<td>28</td>
<td>53.5</td>
</tr>
<tr>
<td>NP2-5</td>
<td>Timrat</td>
<td>0.81</td>
<td>27000</td>
<td>6600</td>
<td>5700</td>
<td>1050</td>
<td>32</td>
<td>53.6</td>
</tr>
<tr>
<td>NP2-7</td>
<td>Timrat</td>
<td>-1.77</td>
<td>23000</td>
<td>5000</td>
<td>5000</td>
<td>600</td>
<td>20</td>
<td>52.3</td>
</tr>
<tr>
<td>NP2-9</td>
<td>Timrat</td>
<td>1.50</td>
<td>34000</td>
<td>8300</td>
<td>5900</td>
<td>1150</td>
<td>33</td>
<td>53.0</td>
</tr>
<tr>
<td>NP2-13</td>
<td>Timrat</td>
<td>-1.37</td>
<td>21000</td>
<td>5000</td>
<td>5300</td>
<td>2000</td>
<td>-</td>
<td>52.7</td>
</tr>
<tr>
<td>NP2-17</td>
<td>Timrat</td>
<td>2.27</td>
<td>26000</td>
<td>6400</td>
<td>5800</td>
<td>1900</td>
<td>20</td>
<td>53.4</td>
</tr>
<tr>
<td>NP2-23</td>
<td>Timrat</td>
<td>7.22</td>
<td>33000</td>
<td>7500</td>
<td>6000</td>
<td>4500</td>
<td>-</td>
<td>51.7</td>
</tr>
</tbody>
</table>

Table 9. Magnetic properties and AMS parameters of all samples from NP2 site.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Mean Susceptibility [μSI]</th>
<th>Anisotropy Degree (P')</th>
<th>Susceptibility difference $Δk$ [μSI]</th>
<th>Shape parameter (T)</th>
<th>Magnetic Foliation (F)</th>
<th>Magnetic Lineation (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP2-1</td>
<td>-1.05</td>
<td>1.149</td>
<td>0.143</td>
<td>-0.393</td>
<td>1.042</td>
<td>1.099</td>
</tr>
<tr>
<td>NP2-2</td>
<td>-0.53</td>
<td>1.25</td>
<td>0.117</td>
<td>-0.025</td>
<td>1.115</td>
<td>1.121</td>
</tr>
<tr>
<td>NP2-4</td>
<td>-1.48</td>
<td>1.06</td>
<td>0.086</td>
<td>-0.217</td>
<td>1.023</td>
<td>1.036</td>
</tr>
<tr>
<td>NP2-5</td>
<td>0.81</td>
<td>1.113</td>
<td>0.084</td>
<td>0.411</td>
<td>1.076</td>
<td>1.031</td>
</tr>
<tr>
<td>NP2-7</td>
<td>-1.77</td>
<td>1.054</td>
<td>0.091</td>
<td>-0.424</td>
<td>1.015</td>
<td>1.037</td>
</tr>
<tr>
<td>NP2-8</td>
<td>-1.39</td>
<td>1.092</td>
<td>0.117</td>
<td>-0.57</td>
<td>1.018</td>
<td>1.068</td>
</tr>
<tr>
<td>NP2-9</td>
<td>1.50</td>
<td>1.117</td>
<td>0.165</td>
<td>-0.167</td>
<td>1.047</td>
<td>1.066</td>
</tr>
<tr>
<td>NP2-10</td>
<td>-1.66</td>
<td>1.064</td>
<td>0.101</td>
<td>-0.215</td>
<td>1.024</td>
<td>1.038</td>
</tr>
<tr>
<td>NP2-11</td>
<td>-1.34</td>
<td>1.063</td>
<td>0.078</td>
<td>0.521</td>
<td>1.045</td>
<td>1.014</td>
</tr>
<tr>
<td>NP2-12</td>
<td>-1.61</td>
<td>1.048</td>
<td>0.074</td>
<td>-0.358</td>
<td>1.015</td>
<td>1.032</td>
</tr>
<tr>
<td>NP2-13</td>
<td>-1.37</td>
<td>1.074</td>
<td>0.096</td>
<td>0.138</td>
<td>1.041</td>
<td>1.031</td>
</tr>
<tr>
<td>NP2-14</td>
<td>1.03</td>
<td>1.104</td>
<td>0.097</td>
<td>0.528</td>
<td>1.075</td>
<td>1.023</td>
</tr>
<tr>
<td>NP2-16</td>
<td>1.66</td>
<td>1.067</td>
<td>0.102</td>
<td>0.477</td>
<td>1.047</td>
<td>1.016</td>
</tr>
<tr>
<td>NP2-17</td>
<td>2.27</td>
<td>1.069</td>
<td>0.151</td>
<td>-0.189</td>
<td>1.027</td>
<td>1.04</td>
</tr>
<tr>
<td>NP2-23</td>
<td>7.22</td>
<td>1.019</td>
<td>0.129</td>
<td>0.502</td>
<td>1.014</td>
<td>1.004</td>
</tr>
<tr>
<td>NP2-24</td>
<td>5.51</td>
<td>1.018</td>
<td>0.093</td>
<td>0.456</td>
<td>1.012</td>
<td>1.005</td>
</tr>
</tbody>
</table>

Figure 28. NP2 site (Timrat Formation) magnetic parameters from AMS measurements. (a) corrected anisotropy degree ($P'$) versus bulk susceptibility (km). (b) Susceptibility difference ($Δk=k_1-k_3$) versus bulk susceptibility (km).
Figure 30 shows thermomagnetic curves of high and low temperature susceptibility measurements performed on two samples from the NP2 site. No clear evidence of Fe-oxide minerals such as magnetite ($Fe_3O_4$) or hematite ($Fe_2O_3$) is observed. Figure 31 shows the IRM acquisition curves for sample NP2-24, revealing flat saturation just below 200 [mT], indicative of PSD (pseudo-single domain) or small MD (multidomain) magnetite grains (Borradaile et al., 2010; Lanci et al., 2001; Weinberger et al., 1997). Figure 32 presents good linear correlation between bulk-susceptibility ($k_m$) and the respective $Fe$ content (respective percentage, $c_f$), where $R^2 = 0.93$. The slope of the linear fit suggests that the Fe-oxide mineral has bulk-susceptibility of $km_f = 4865 \, [\mu SI]$ and the intersection with $k_m$ axis is at $-2.17 \, [\mu SI]$. From the IRM acquisition curves, the SEM results and the slope of the linear fit, I deduce that the distinct grains are magnetite grains. Magnetite is ferrimagnetic and its susceptibility greatly depends on the applied field, temperature and grain size (Borradaile and Jackson, 2004; Mullins, 1977). Magnetite presents anhysteretic remanent magnetization, therefore, the isotropic AARM fabric (Figure 29b) indicates that the magnetite grains in the rock have no preferred orientation, and hence no influence on the principal AMS axes. The intersection of the linear fit with $k_m$ axis at $-2.17 \, [\mu SI]$ (Figure 32) implies that the rock AMS is controlled by another magnetic phase, beside the calcite crystals diamagnetic phase and the magnetite grains ferrimagnetic phase (step 4 in Figure 4). The large amounts of $Si$ content in the rock, emerging from the chemical analysis (Table 8), suggest the presence of about 3% of clay-minerals. From Eq. 1.8 it appears that the clay-minerals are in the paramagnetic range with bulk susceptibility of $km_p = 367 \, [\mu SI]$, (where I take; $km_r = -2.17 \, [\mu SI]$), $km_d = -13.6 \, [\mu SI]$, $c_p = 0.03 \, [\mu SI]$ and $c_d = 0.97 \, [\mu SI]$. This result is in agreement with known susceptibility values of clay-minerals (Borradaile and Jackson, 2004).

![Figure 29](image_url) **Figure 29.** AMS and AARM fabrics of NP2 site. Lower-hemisphere, equal-area projection of (a) AMS principal axis and 95% confidence ellipses and (b) AARM principal axis. The AARM fabric represent an isotropic fabric since the fabric shows scattering and all of the measurements failed the anisotropic F-tests.
Figure 30. Thermomagnetic curves for selected samples from NP1 and NP2 sites. $k_T$ (temperature dependence susceptibility) versus temperature. A.1, A.2 and A.3 represent susceptibility measurements at low temperatures. B.1, B.2 and B.3 represent susceptibility measurements at high temperatures. Red color is for measurements in increasing temperatures whereas blue color is for measurements in decreasing temperatures.
Figure 31. IRM acquisition curve of a selected sample from NP2 site. Saturation obtained just below 200 [mT] indicates magnetite.

Figure 32. Bulk susceptibility (km) versus Fe content in 0.01% (respective percentages, cf) of selected samples from NP2 site.
3. Discussion

3.1. General

Results were obtained from repeated measurement, especially of the samples with negative susceptibility values. To estimate the measuring errors the specimen holder was measured several times before each measuring session. Samples with error greater than 100 \( \times 10^{-9} \) [SI], were not taken into account.

The Bar-Kokhba rocks from the Rosh-Pinna and Mt. Gilboa areas contain extremely low contents of Fe, Mn, Mg, Al and Si (Table 3), iron content is below 300 ppm. The XRD diffraction results indicate that the Bar-Kokhba rocks consist of more than 95% calcite crystals. This and the low-field magnetic bulk-susceptibility \( k_m = \sim -11[\mu SI] \) indicate that the AMS is exclusively controlled by pure calcite crystals. Therefore, the orientations of \( k_3 \) axes are co-axial with the shortening direction of the cumulative strain and are not controlled by second-phase minerals and crystal impurities.

3.2. Variations of anisotropy parameters in pure calcite-bearing rocks

The magnetic properties of the Bar-Kokhba rocks of the Rosh-Pinna and Mt. Gilboa area suggest that the AMS directly reflects calcite preferred crystal orientation. Magnetically, a single calcite crystal is anisotropic with a corrected anisotropy degree of \( P' = 1.113 \) (Nye, 1957; Owens and Rutter, 1978). Schmidt et al. (2006) found that the susceptibility difference of a single calcite crystal at room temperature is \( \Delta k = 1.10 \pm 0.01 \) [\( \mu SI \)]. Generally, the corrected anisotropy degree (\( P' \)) and the susceptibility-difference (\( \Delta k \)) of deformed diamagnetic calcite-bearing rocks are expected to be lower than those of a single calcite crystal, because perfect alignments in sedimentary rocks are rare (Hrouda, 2004). The AMS magnitude of diamagnetic rocks is highly affected by the amounts of strong paramagnetic, ferromagnetic and ferromagnetic minerals. In such a case the AMS magnitude cannot be correlated with the magnitudes of strain (Borradaile and Henry, 1997). There is no correlation between the \( P' \) and \( \Delta k \) and \( Fe \) content in Bar-Kokhba rocks from the Rosh-Pinna and Mt. Gilboa area (Figure 33) and the anisotropy degree is not controlled by Fe-bearing minerals. Likewise, in the isolated diamagnetic phase of calcite (site SA1, after isolation method) the \( P' \) values also vary in a range of 1.00 to 1.45 (Table 7). Recently, several studies suggested that the anisotropy degree parameters are associated with strain magnitudes
rather than impurities. In carbonate mylonites from the Morcles napp in Switzerland Almqvist et al. (2009) found that the increase in the anisotropy degree is associated with an increase in strain levels. Schmidt et al. (2009) experimentally showed in pure-calcite rocks that $\Delta k$ generally increases with uniaxial stress under 100 [MPa] and reaches $\sim 0.2$ [$\mu$SI]. Levi and Weinberger (2011) found that the differences in $P'$ (2%) and in $\Delta k$ (0.2) in Bar-Kokhba rocks are related to strain magnitudes. Figure 34 shows $P'$ and $\Delta k$ versus $k_m$ of Bar-Kokhba rocks from the Rosh-Pinna and Mt. Gilboa areas. There is no correlation between $P'$ and $\Delta k$ parameters and $k_m$ as is likely to be in the case of impurities. In the majority of the samples (Figure 34) $P'$ are between 1.00 and 1.02, and $\Delta k$ between 0 and 0.2 [$\mu$SI] in agreement with the anisotropy values measured in the Bar-Kokhba rocks in the Metulla area (Levi and Weinberger, 2011). Based on the present results and the aforementioned studies, it is suggested that the variations of $P'$ and $\Delta k$ in the Bar-Kokhba rocks are related to the strain magnitudes that accumulated in the rocks during the geological history.

Figure 33. (Left) Corrected anisotropy degree ($P'$) and (Right) $\Delta k$ versus Fe content of Bar-Kokhba rocks from the Rosh-Pinna and Mt. Gilboa areas.
3.3. Sedimentary fabric in carbonate rocks

In the early geological history of sedimentary rocks, during diagenesis, the rocks underwent vertical-shortening due to the weight of the sediments above. The AMS is expected to reflect the strain field with well-grouped $k_3$ axes oriented vertical to the bedding, and scattered $k_1 \sim k_2$ axes parallel to bedding. This fabric is termed as sedimentary fabric (Fuller, 1963; Jackson and Borradaile, 1991). The sedimentary fabric reflects preferred crystal orientation that can develop by different mechanisms: (1) crystallization under non-hydrostatic stress field (Kamb, 1959); (2) plastic deformation (Hobbs et al., 1976); and (3) crystal growth in veins and dikes (for more details see section 1.4.1).

Thin-sections images of the Bar-Kokhba rocks from the Rosh-Pinna and Mt. Gilboa areas (Figure 12 and Figure 7) reveal calcite fossils and calcite cement. In MG1 the calcite cement fill of voids between the shells and the inside cavities. It is also recognized by its bright appearance (indicative of large crystals). The calcite cement formed after the arrangement of the shells, and, hence, it is reasonable to assume, that the crystals grew under the pressure of the sediments above (a few centimeters at least of sediments above). As a result, a preferred crystal orientation may have been developed by the mechanism of crystallization under non-hydrostatic stress field. Hence, it is suggested that a sedimentary fabric can be acquired by crystallization of calcite cement in the early stages of diagenesis. If the lithostatic pressure is high enough, then a continued process of plastic deformation might also develop and the mechanism of crystal growth in veins is not appropriate to the present sedimentary fabrics.
3.4. Tectonic fabrics of carbonate rocks

After diagenesis, preferred crystal orientation and a new magnetic fabric in carbonate rocks can develop due to deformation events. Under tectonic conditions with dominant horizontal shortening the calcite crystal c-axes are expected to be coaxial with the shortening axis (Figure 3d). If the horizontal strain component is lower than the vertical component then a tectonic vertical-shortening fabric is developed (Figure 3b).

The AMS of the Bar-Kokhba rocks from the Rosh-Pinna and Mt. Gilboa areas are characterized by tectonic fabrics with different magnetic patterns (Figure 10, Figure 14). The P’ and Δk values are lower by at least one order of magnitude than the parameters of single calcite crystal (P’=1.113 and Δk = 1.10 [μSI] for single crystal (Owens and Rutter, 1978; Schmidt et al., 2006)).

3.5. Isolation of magnetic sub-phases

3.5.1. Sub-phases in the Bar-Kokhba Formation

The diamagnetic phase was isolated from the total AMS of site SA1 (section 1.5, Figure 4). The diamagnetic sub-fabric (Figure 23) is defined as having a tectonic origin with horizontal-shortening fabric. The paramagnetic phase (Figure 22b), formed by second-phase minerals (mainly Fe bearing minerals), is probably related to chemical alteration that evolved during the young surface weathering processes. The paramagnetic sub-fabric is classified as sedimentary fabric, suggesting that sedimentary fabric of chemical alteration origin can develop without the loading of lithostatic pressure. The linear correlation between the Fe content in the rock (cp) and bulk susceptibility (km) has a low R² value (Figure 19). According to Eq. 1.6, it suggests that Fe bearing minerals content is not the only factor influencing km, but also the presence of other minerals (such Mn bearing minerals). For instance, sample SA1-8 has a lower Fe content than sample SA1-2 but a much higher km value (Table 6). In this case, the linear fit gives an index for estimating the amount of paramagnetic minerals that influence the magnetic properties and masks the AMS of the diamagnetic calcite minerals.
The inclinations of the $k_3$ axes in the paramagnetic sub fabric are sub-vertical, whereas the $k_3$ axes in the diamagnetic sub-fabric are sub-horizontal. Figure 35 shows the relations between the $k_3$ inclinations of samples from the SA1 site versus the Fe content in ppm, estimated from the linear fit. The results suggest that above Fe content of 500 ppm the diamagnetic sub-fabric is masked and the paramagnetic-sub fabric controls the total AMS.

Figure 35. $k_3$ inclination versus Fe content in ppm, of samples from SA1 site. The Fe contents are estimated from the linear fit (Figure 19). Two samples were not taken into account due to incompatibility.
3.5.2. Sub-phases in the Timrat Formation

The AMS of samples from the Timrat Formation consists of three magnetic phases: 1) diamagnetic phase of calcite crystals; 2) paramagnetic phase of clay-minerals; and 3) ferrimagnetic phase of PSD to small MD magnetite grains. The identification of the three sub-phases was carried out by the isolation method, applying integrative experimental technics. AARM measurements indicate anisotropic fabric of the magnetite ferrimagnetic phase, and therefore have no influence on the principal axes of the AMS. AMS studies in clay-rich sediments and mud rocks found a correlation between principal magnetic axes and maximum shortening axis (Cifelli et al., 2004; Mattei et al., 1997; Pares et al., 1999). Therefore, the similar respond of diamagnetic calcite crystals and paramagnetic clay-minerals to strain results in a contribution of the clay-minerals to the AMS fabric of calcite-bearing rocks. In conclusion, although the AMS of the Timrat Formation consists of three magnetic phases it is suggested that the AMS principal axes are mainly controlled by the orientation of the calcite axes. This conclusion shows that the AMS of calcite-bearing rocks is a good strain indicator, even in carbonate rocks with weak diamagnetic to weak paramagnetic susceptibility.

The total bulk susceptibility becomes zero in cases where the magnetic susceptibilities cancel each other. Previous studies (Hamilton et al., 2004; Hrouda, 2004) suggest that, when the bulk-susceptibility is close to zero, the anisotropy parameters are unreliable and should be omitted from further analysis, in particular the high values of P’ close to zero susceptibility (see Appendix II). Nevertheless, the present study shows that samples with low bulk susceptibility values have tectonic vertical-shortening fabric e.g. well grouped principal axes of the NP2 site (Figure 29a). The majority of \( k_3 \) axes of the Bar-Kokhba limestones in the Rosh-Pinna area is oriented in the horizontal direction (Figure 10 and Figure 11). The layers of the Timrat Formation are located below the layers of the Bar-Kokhba Formation, which means that the rocks of the NP2 site were subjected to equally, or more, influence of tectonic stress fields. It is well known (Hobbs et al., 1976) that in carbonate rocks preferred crystal orientation is associated with plastic deformation like development of glide systems and dislocations in the crystal structure and calcite twines. Therefore, I suggest that the Timrat and the Bar-Kokhba formations response differently to same stress regime and produce different AMS fabrics. It could be that the Bar-Kokhba and Timrat formations respond differently, because they have different mechanical properties.
3.6. Strain field in the Rosh-Pinna area

Figure 36 shows $P'$ and $\Delta k$ values of the Bar-Kokhba rocks in the Rosh-Pinna area. The EP3 site, in the east parts of the Rosh-Pinna area and which is located close to a suspected segment of the DST, (Figure 2) indicates the strongest anisotropy and also shows the most grouped principal susceptibility axes (Figure 10). This means that the strain magnitude in the EP3 site is higher than that of the other sites in the Rosh-Pinna area. Because $P'$ and $\Delta k$ values vary from one place to another and in most cases they are not associated with a distinct structure, it is suggested that the strains in the Rosh-Pinna area are heterogeneous.

![Figure 36.](image)

Figure 36. (Left) Corrected anisotropy degree ($P'$) of sampling sites in the Rosh-Pinna area. (Right) Susceptibility difference ($\Delta k$) of sampling sites in the Rosh-Pinna area.

The mean vector of the $k_3$ axes of the Rosh-Pinna sites shows the post-Eocene finite shortening directions (Figure 37). Based on statistical analyses of the $k_3$ axes in the Rosh-Pinna area the mean horizontal shortening is $007^\circ$ (Figure 11). This direction is sub-parallel to the strikes of the main segments of the DST system in the study area (Figure 1). The $\sim N$-$S$ horizontal shortening is also in agreement with a local horizontal shortening direction of $013^\circ$-$193^\circ$ that was suggested by Eyal (1996), who measured stylolites in one site of the Eocene rocks in the Rosh Pinna area.

Based on analysis of mega and meso-structures in the Tiberias province, Ron and Eyal (1985) suggested a stress field with maximum compression ($\sigma_1$) in the NNW – SSE direction. They suggested that this stress field is compatible with the lateral shear along the DST. According to the stress trajectory of their map (Figure 38), the stress directions vary locally between NNW and NNE directions next to segments of the DST. For example, in the Rosh-Pinna area the stress direction is rotated clockwise relative to that in Tiberias.
Assuming that stress and strain axes are coaxial, the stress direction to ~N-S is in agreement with the AMS of the Eocene rocks.

The sub-parallelism of the ~N-S trending horizontal shortening to the DST strike may be explained by the deflection process. Garfunkel (1981) showed that the directions of the principal stresses adjacent to the DST are probably deflected toward the fault trace. He suggested that this process along the DST system is dominant mainly close to “free boundaries” that form in rhomb-shape grabens. In the Rosh-Pinna area I recognize this deflection by the orientation of the horizontal shortening direction.

Recently, Levi and Weinberger (2011) measured the magnetic properties of the Bar-Kokhba and Kefar-Giladi formations in the Metulla area. They found three distinct horizontal shortening directions: 1) NW – SE shortening axis related to the pure left-lateral motion along the DST during the Neogene; 2) W – E shortening axis related to strain partitioning along the strike-slip motion during the Pleistocene to Recent; and 3) NNE shortening axis related to the early stage of the DST branching in the area. In contrast to the Metulla area, no evidence for E-W shortening was found in the Rosh-Pina area. In only one site, TH1 which is located on the structural border between Hula-Valley and Rosh-Pinna area, the k3 axes suggest E-W shortening similar to that of Levi and Weinberger (2011). Therefore it is suggested, that the strain field that probably form pre and during the Pleistocene-to-recent in the Metulla area was different in the Rosh-Pinna area.
Figure 37. Map of the main fault segment of the Dead-Sea Transform (DST) and stereograms of AMS principal axes. Arrows mark the inferred horizontal shortening directions at the sites.
Figure 38. A stress trajectory map along the DST after Ron and Eyal (1985).
4. Conclusions

The main conclusions of this study are:

1. The Bar-Kokhba rocks in the Rosh-Pinna and in Mt. Gilboa areas are controlled by calcite diamagnetic phase and therefore can be considered as almost pure calcite-bearing rocks. The average low-field bulk-susceptibility of the rocks is \( k_m = -10.95 \pm 1.01 [\mu S/\text{m}] \).
2. The orientations of \( k_3 \) axes in the Bar-Kokhba rocks are co-axial with the maximum shortening axes.
3. Variations of \( P' \) and \( \Delta k \) parameters of the Bar-Kokhba rocks indicate the relative magnitudes of the finite strains that have accumulated in the rocks over the geologic time.
4. The isolation method shows that the AMS of the Bar-Kokhba rocks is mostly controlled by the diamagnetic phase when the paramagnetic Fe minerals content is below 500 ppm.
5. The magnetic properties of the Timrat Formation are controlled by three different magnetic phases; diamagnetic, paramagnetic and ferrimagnetic. The results of the isolation method suggest that the principal axes of the total AMS are related to the diamagnetic sub-fabric of calcite.
6. The Timrat and the Bar-Kokhba formations response differently to same stress regime and produce different AMS fabrics.
7. The strain in the Rosh-Pinna area is heterogeneous, as rises from the AMS anisotropy parameters \( P' \) and \( \Delta k \) of the Bar-Kokhba rocks.
8. Based on the orientation of \( k_3 \) axes of the Bar-Kokhba rocks, the maximum horizontal shortening direction in the Rosh-Pinna area is \(~N-S\).
5. Appendix

5.1. Appendix I: Shape anisotropy of diamagnetic rocks

In general, magnetic anisotropy is controlled by grain shape anisotropy and crystal anisotropy (Borradaile and Jackson, 2010). In order to evaluate the source of magnetic anisotropy in diamagnetic rocks I will consider the effect of grain shape anisotropy.

Shape anisotropy occurs due to the demagnetization field \( \mathbf{H}_d \), which forms inside the magnetized material and tends to demagnetize it (Cullity, 1972). Suppose a bar is magnetized by a magnetic field applied from left to right and subsequently removed. Then a north pole is formed at the right end and a south pole at the left, as shown in Figure 39(a). H lines radiating from the N pole and ending at the S pole, constitute a field inside the bar, which acts from N to S and therefore tends to demagnetize the bar; this field is called the “demagnetization field”, \( \mathbf{H}_d \). The total field \( \mathbf{B} \) inside the substance will be \( \mathbf{B} = -\mathbf{H}_d + 4\pi \mathbf{M} \), (where \( \mathbf{M} \) is the magnetization) because \( \mathbf{H}_d \) is the only field acting. The field inside the bar therefore is less than \( 4\pi \mathbf{M} \) but is in the same direction, because \( \mathbf{H}_d \) can never exceed \( 4\pi \mathbf{M} \) in magnitude. These vectors are indicated in Figure 39(b), in which the B field of the bar is sketched. The demagnetizing field along a short axis is stronger than along a long axis or in other words, the applied field along a short axis has to be stronger to produce the same true field inside the specimen. Thus shape alone can be a source of magnetic anisotropy. From magnetostatic energy considerations it follows that the demagnetizing field of a body is proportional to the magnetization which creates it:

\[
\mathbf{H}_d = N \mathbf{M}
\]

where \( N \) is called the “demagnetizing factor” that mainly depends on the shape of the body. Demagnetizing factors for ellipsoids have been given by Stoner (1945) and Osborn (1945) defining general ellipsoid with three unequal axes \( a, b \) and \( c \) the results are as follow:

![Figure 39](Image)

**Figure 39.** Fields of a bar magnet in zero applied field: (a) \( H \) field, and (b) \( B \) field. The vectors in the center indicate the values of these quantities at the center of the magnet (Cullity 1972).
i. Prolate spheroid with axes length, \(a = b \neq c, \ \frac{c}{a} \equiv r\) then,

\[
N_c = \frac{4\pi}{r^2-1} \left[ \frac{r}{\sqrt{r^2-1}} \ln \left( r + \sqrt{r^2-1} \right) - 1 \right]
\]

\[
N_a = N_b = \frac{4\pi-N_c}{2}
\]

where \(N_a, N_b\) and \(N_c\) are the demagnetizing factors along axes a, b and c respectively.

ii. Prolate spheroid with axes length, \(a \neq b = c, \ \frac{c}{a} \equiv r\) then,

\[
N_a = \frac{4\pi r^2}{r^2-1} \left[ 1 - \frac{1}{\sqrt{r^2-1}} \sin^{-1} \left( \frac{\sqrt{r^2-1}}{r} \right) \right]
\]

\[
N_b = N_c = \frac{4\pi-N_a}{2}
\]

where \(N_a, N_b\) and \(N_c\) are the demagnetizing factors along axes a, b and c respectively.

The magnetic susceptibility \(\kappa\) of a material is given by the ratio of the magnetization \(M\) and the field \(H\) which creates it:

\[
\kappa = \frac{M}{H}
\]

Supposing an applied field \(H_0\) then considering the demagnetization field as well, we get the total field acting on the specimen:

\[
H = H_0 + H_d
\]

Rearranging:

\[
\kappa = \frac{M}{H_0 - NH}
\]

Using the above equations we can estimate the shape anisotropy degree \(P, (\kappa_{\text{max}}/\kappa_{\text{min}})\) for specific prolate and oblate substances in a known magnetic field. In Figure 40 the estimation for diamagnetic substance with bulk susceptibility of \(-12 [\mu\text{SI}]\) measured in a magnetic field of \(300 [\text{A/m}]\) is presented where the horizontal axis of the graph represents the ratio between the long and short axes of the ellipsoid \((r)\). One can see that even for a very eccentric ellipsoid the magnetic shape-anisotropy degree is very low, on the order of \(10^{-4}\).

The crystal anisotropy degree of calcite is on the order of \(10^{-1}\) \((P = 1.113)\) (Nye, 1957). It follows that the AMS of a low magnetic rock is controlled almost entirely by crystal anisotropy and not by grain shape anisotropy.
5.2. Appendix II: Limitations of $P'$ parameter

From Figure 18 and Figure 28 one can see that the corrected anisotropy degree, $P'$ parameter, is increasing intensively inverse to $k_m$ in the region of $km \to 0$. For natural anisotropy ellipsoid $P' = P$, where for rotational anisotropy ellipsoid $P' = P^{1.155}$ (Jelinek, 1981). The anisotropy degree is defined as the ratio between maximum susceptibility and minimum susceptibility, $P = k_1/k_3$ when principal susceptibilities referred in the absolute (unsigned) values. We can present the anisotropy degree $P$ parameter as a function of maximum susceptibility $k_1$ and the strength of the anisotropy $\Delta k = k_1 - k_3$.

$$P = \frac{k_1}{k_3} = \frac{1}{1 - \frac{\Delta k}{k_1}}$$

4.8

It is clear that always $k_1 > \Delta k$, but when $k_1$ becomes zero then $\Delta k$ becomes zero as well, therefore:

$$\lim_{k_1 \to \Delta k} P = \infty$$

4.9

This theoretical discussion explains the inverse increase of $P'$ with $k_m$, shown in Figure 18. One can see where $k_m < 5$, then $P'$ starts to grow intensively. The $\Delta k$ parameter, on the other hand, is steady in the zero susceptibility vicinity. Therefore I suggest the $\Delta k$ parameter be used to describe the scatter of principal susceptibilities for low magnetic response rocks such as the Eocene chalk formations in northern Israel.
5.3. Appendix III: Computer program for analytical isolation method

Matlab script. Program for isolating diamagnetic sub-fabric from AMS measurements.

clc
clearall

% Program for estimating a diamagnetic tensor from group of samples
% Using: readdata
% parasub
% decincarray
% decinctxt
% parameters

% kp - Para/ferromagnetic normed tensor in Geo coordinates system
% km - bulk susceptibility of Para/ferromagnetic tensor (norming factor)
kp=[1.0043 1.00551 0.99019 0.00057 0.00036 0.00183]; %SA1-10 normed row tensor
kmp=34858; % estimated bulk susceptibility
ktfile='SA1_combine.txt'; % text file of AMS data of the sample Anisoft42 format
data=importdata(ktfile); % importing text file of AMS data
[kt,kmt]=readdata(data.data); % [kt,kmt]-array of row normed tensors and bulks

cpfile='cp_SA1.txt'; % text file of respective weights of Para/ferromagnetic
cp=load(cpfile); % importing text file of respective weights
[kd,kmd]=parasub(kt,kmt,kp,kmp,cp); % estimating diamagnetic sub-fabric
% [kd,kmd] - diamagnetic normed row tensors and bulks
kddecinc=decincarray(kd); % Declination and Inclination in Geo system of kd principal axis
decinctxt(kddeinc); % Printing Declination and Inclination on text file
parameters(kd,kmd); % Calculating anisotropy parameters and mean vector.
% Printing on text file

% readdata - Program for reading AMS data from anisoft 42 text file
function [k,km]= readdata(data)
% data - imported text file of AMS measurement using anisoft 42
% k - normed susceptibility tensors
% km - bulk susceptibilities
N=size(data,1);
for i=1:N
  for j=14:19
    k(i,j-13)=data(i,j);
  end
end
for i=1:N
  km{i,1}=data(i,1);
end
return

% parasub - a program that subtract a tensor from tensors array
function [kd,kmd]=parasub(kt,kmt,kp,kmp,cp)
% input:
% kt - array of row normed tensors
% kmt - array of bulk susceptibilities
% kp - row normed tensor
% kmp - bulk susceptibility
% cp - array, respective weights of Para/ferromagnetic
% output:
% kd 6xN every line contain a row normed tensor
% kmp 1xN every line contain bulk susceptibility
% use subtraction1_l

61
m=size(kmt,1);
if (m~=size(cp))
    disp 'wrong cf size'
    return
end

count=0;
for j=1:m
    count=count+1;
    [kd(count,:),kmd(count,1)]=subtraction1_2(kt(j,:),kmt(j),kp,kmp,cp(j));
end
return

function [kd,kmd] = subtraction1_2(kt,kmt,kp,kmp,cp)

% input:
% kt 1x6   Normed tensor from total site
% kmt      Bulk susceptibility, norming factor of kt
% kmp      Bulk susceptibility of Para/ferromagnetic
% cp respective weights of Para/ferromagnetic

% output:
% kd 1x6   Normed tensor from diamagnetic site
% kmd      Bulk susceptibility, norming factor of kd

Kt=abs(kmt)*kt;
Kp=abs(kmp)*kp;
Kd=  (  (1/(1-cp)) * Kt ) - ( (cp/(1-cp)) * Kp ) ;

% converting row tensor to 3x3 matrix form
K(1,1)=Kd(1);        K(1,2)=Kd(4);        K(1,3)=Kd(6);
K(2,1)=K(1,2);     K(2,2)=Kd(2);        K(2,3)=Kd(5);
K(3,1)=K(1,3);     K(3,2)=K(2,3);     K(3,3)=Kd(3);

[V,D]=eig(K) ;

if D(1,1) > D(3,3),
    [dec,inc]=decincvector(V(1,1),V(2,1),V(3,1)); % declination and inclination of max eigenvector
    out(i,1)=dec; out(i,2)=inc; % writing the values to the output matrix
end
if D(1,1) < D(3,3),
    [dec,inc]=decincvector(V(1,2),V(2,2),V(3,2)); % declination and inclination of int eigenvector
    out(i,3)=dec; out(i,4)=inc; % writing the values to the output matrix
end
if D(1,1) == D(3,3),
    [dec,inc]=decincvector(V(1,3),V(2,3),V(3,3)); % declination and inclination of min eigenvector
    out(i,5)=dec; out(i,6)=inc; % writing the values to the output matrix
end

-----------------------------------------------------------------------------------------------------------------------------

decincarray a program that gives the Declination and Inclination of tensors array

function[out]= decincarray(k)

% input:
% k - tensors array, every row must contains a susceptibility tensor (k11 k22 k33 k12 k23 k13)

% output:
% the output is a matrix, every line is the declination and inclination of the eigenvectors of the susceptibility tensor in the Geo system
% every line in out matrix (k1dec k1inc k2dec k2inc k3dec k3inc)
% use the function decintvector

n=size(k,1);
for i=1:n
    tensor=k(i,:); % vector form
    matrix=[tensor(1) tensor(4) tensor(6) ;
            tensor(4) tensor(2) tensor(5) ;
            tensor(6) tensor(5) tensor(3)];

    [V,D]=eig(matrix); % eigenvectors and eignvalues of the matrix

    if D(1,1) > D(3,3),
        [dec,inc]=decincvector(V(1,1),V(2,1),V(3,1)); % declination and inclination of max eigenvector
        out(i,1)=dec; out(i,2)=inc; % writing the values to the output matrix
    end
    if D(1,1) < D(3,3),
        [dec,inc]=decincvector(V(1,2),V(2,2),V(3,2)); % declination and inclination of int eigenvector
        out(i,3)=dec; out(i,4)=inc; % writing the values to the output matrix
    end
    if D(1,1) == D(3,3),
        [dec,inc]=decincvector(V(1,3),V(2,3),V(3,3)); % declination and inclination of min eigenvector
        out(i,5)=dec; out(i,6)=inc; % writing the values to the output matrix
    end
end
if D(1,1) < D(3,3)
[dec,inc]=decincvector(V(1,3),V(2,3),V(3,3));  % declination and inclination of max eigenvector
out(i,1)=dec; out(i,2)=inc;  % writing the values to the output matrix

[dec,inc]=decincvector(V(1,2),V(2,2),V(3,2));  % declination and inclination of int eigenvector
out(i,3)=dec; out(i,4)=inc;  % writing the values to the output matrix

[dec,inc]=decincvector(V(1,1),V(2,1),V(3,1));  % declination and inclination of min eigenvector
out(i,5)=dec; out(i,6)=inc;  % writing the values to the output matrix
end
end
return

% decincvector - calculating Declination and Inclination of a vector

function [D,I]=decincvector(x,y,z)

% x point to the North
% y point to the East
% z point vertical

if x>0 && y>=0
    D=atan(y/x);
    if z<0
        D=D-pi;
    end
end
if x>0 && y<0
    D=atan(y/x)+2*pi;
    if z<0
        D=D-pi;
    end
end
if x<0
    D=atan(y/x)+pi;
    if z<0
        D=D-pi;
    end
end
D=(180/pi)*D;
if D<0
    D=360+D;
end
arg=z/(((x^2)+(y^2)+(z^2))^0.5);
I=(pi/2)-acos(arg);
if z<0
    I=-I;
end
I=(180/pi)*I;
return

% decinctxt - exporting text file with declinations and inclinations designed for stereonet program

function []= decinctxt(decinc3)

% input:
% decinc3 - an array of declination and inclination
% decinc3  (k1dec k1inc k2dec k2inc k3dec k3inc)

N=size(decinc3,1);
fid=fopen('kmax.txt','wt');
fprintf(fid,'%c%c
','TP');
for i=1:N
    fprintf(fid,'%f  ',decinc3(i,1));
    fprintf(fid,'%f   ',decinc3(i,2));
end
fclose(fid);

fid=fopen('kint.txt', 'wt');
fprintf(fid, '%c%c
', 'TP', n', decinc3(i, 3));
end
fclose(fid);

fid=fopen('kmin.txt', 'wt');
fprintf(fid, '%c%c
', 'TP', n', decinc3(i, 5));
for i=1:N
fprintf(fid, '%f  %f
', decinc3(i, 3), decinc3(i, 4));
end
fclose(fid);

return

% parameters - calculating anisotropy parameters of susceptibility tensors estimating mean tensor printing anisotropy parameters and mean tensor on text file

function []= parameters(kq, kmq)

% input:
% kq - tensors array, every row must contains a susceptibility tensor (k11 k22 k33 k12 k23 k13)
% Using:   eigrow
%          meantensor2
%          decinctensor

n=size(kq,1);
fid=fopen('parameters.txt', 'wt');
fprintf(fid,'   Sample             km             L           F          P         U 

kkm=0;LL=0;FF=0;PP=0;UU=0;
for i=1:n
tensor=kq(i,:); % vector form
[V,D]=eigrow(tensor); % eignvectors and eignvalues of the tensor
D=abs(D);
if D(1,1) > D(3,3) , max=D(1,1);int=D(2,2); min=D(3,3); , end
if D(1,1) < D(3,3) , max=D(3,3);int=D(2,2); min=D(1,1); , end
L=max/int;F=int/min;P=max/min;U=(2*int-max-min)/(max-min);
fprintf(fid, '\%3.0f.\%3.2fE-06\%1.3f\%1.3f\%1.3f\%1.3f\n', i, kmq(i), L, F, P, U);
end
fclose(fid);
fprintf(fid,' Ave.\%3.2fE-06\%1.3f\%1.3f\%1.3f\%1.3f\n', kkm/n, LL/n, FF/n, PP/n, UU/n);

[k, km]=meantensor2(kq, kmq);
dcm=decinctensor(k);
[V,D]=eigrow(k); % eignvectors and eignvalues of the tensor
D=abs(D);
if D(1,1) > D(3,3) , max=D(1,1);int=D(2,2); min=D(3,3); , end
if D(1,1) < D(3,3) , max=D(3,3);int=D(2,2); min=D(1,1); , end
L=max/int;F=int/min;P=max/min;U=(2*int-max-min)/(max-min);
fprintf(fid, 'Mean\%3.2fE-06\%1.3f\%1.3f\%1.3f\%1.3f\n', km, L, F, P, U);

fclose(fid);
fprintf(fid, '\n\n\nMean Tensor \nDec/Inc:\nk1 %3.1f / %2.1f \nk2 %3.1f / %2.1f \nk3 %3.1f / %2.1f
\n', dcm);
return

% eign values and vectors 0f row tensor

function [V,D]=eigrow(k)
% 3x3 matrix form
K(1,1)=k(1);        K(1,2)=k(4);        K(1,3)=k(6);
K(2,1)=k(1,2);     K(2,2)=k(2);        K(2,3)=k(5);
K(3,1)=k(1,3);     K(3,2)=k(2,3);     K(3,3)=k(3);

[V,D]=eig(K);  % eigenvectors and eigenvalues of the matrix
Return

% meantsensor2 - Estimating a mean tensor from group of specimens
function [k, km] = meantsensor2(kq, kmq)
% kq - array of tensors every specimen is a row
% kmq - bulk susceptibilities
N=size(kq,1);
% mean tensor 1x6
k(6)=0;
for j=1:6
    for i=1:N
        k(j)=k(j)+kq(i,j);
    end
    k(j)=k(j)/N;
end
k;
km=mean(kmq);
return

% decintensor - a program that gives the Declination and Inclination of tensor
function [out] = decintensor (k)
% k - a row tensor (k11 k22 k33 k12 k23 k13)
% out file is a row contain the declination and inclination of
% the eigenvectors of the susceptibility tensor in the geograph system
% out - (k1dec k1inc k2dec k2inc k3dec k3inc)
% use the function decintvector

% 3x3 matrix form
K(1,1)=k(1);        K(1,2)=k(4);        K(1,3)=k(6);
K(2,1)=k(1,2);     K(2,2)=k(2);        K(2,3)=k(5);
K(3,1)=k(1,3);     K(3,2)=k(2,3);     K(3,3)=k(3);

[V,D]=eig(K);  % eigenvectors and eigenvalues of the matrix
if D(1,1) > D(3,3)
    [dec,inc]=decintvector(V(1,1),V(2,1),V(3,1));  % declination and inclination of max eigenvector
    out(1)=dec; out(2)=inc;  % writing the values to the output matrix
else
    [dec,inc]=decintvector(V(1,3),V(2,3),V(3,3));  % declination and inclination of min eigenvector
    out(5)=dec; out(6)=inc;  % writing the values to the output matrix
end

if D(1,1) < D(3,3)
    [dec,inc]=decintvector(V(1,3),V(2,3),V(3,3));  % declination and inclination of min eigenvector
    out(5)=dec; out(6)=inc;  % writing the values to the output matrix
else
    [dec,inc]=decintvector(V(1,1),V(2,1),V(3,1));  % declination and inclination of max eigenvector
    out(1)=dec; out(2)=inc;  % writing the values to the output matrix
end

return

------------------------------------------------------------------------
6. References


Cullity, B.D., 1972. Introduction to magnetic materials. ADDISON-WESLEY, University of Notre Dame.


לקציר

לשם שיפור הבנת שדה-המעוטים לאלור בקע-מהלה בצפון ישראל, נמדדו נווקרים ההנקודות המגנטיות של 40~80 מטרות ממולעות מאקופים מאזורים רаш-פניה, הר הגלבוע ומוצק האון. דיפרקציה קריקטר-י, נקימה שקופים ומגנטונים מייקרוסקופים אלקטרונים ממולדים כ-100 ובכמה

מרוכבים במרווחים סלעיים שונים בתוהות שונים, יבש ואפסים. למסעותים, במדשימים וא倴ים ניתן בנימוח.

וןמציא כ-120 נקודות ממד.annotate בר-כוכב ו-3000 נקודות סוספטיות ממולעות של $k_m = 1.01 \pm 0.05 [\mu\text{S/I}]$-9.95, המעדיך כי התוכנות המגנטיות של הנקודות, גביש קלייזת גרז. אחרים של $k_3$ הארגונורוורית של הסוספטיים המגנטים (אי.אס.א. אמצעי מלהוגון המעודפס על צירי-$c$ בגביש הקלייזת ומצביעים ליוון התחזקתם המפורטית. בעבודה זו כר מhamster, האימפרוריה ( çekוטט סכום סוספטיות המגנטים (אי.אס.א) של המבוקש על הח nokייזים.) ובמהלך (finite strain) של 300-300 נקודות מתזורר בר-כוכב. מזרחיอาหาร ראשו פנינו במובשות על הרxeeת ממד. משניות בוערונות ובארכיוןinizות למעטינון ממומינים. 

ובנוסף, לנקודות הנקודות המגנטיות של תורמות הקירוק_legacy לאוקיאנוס אדולוס, תימרת ומורשה ומ İz.א.א. מ bande את דיאימגנטнтיצות不属于 דיאימגנטнтיצות של קלייזת, פאתורה מתצורה בר-כוכב, והאימגנטнтיצות של בוגרי

משלים פאונים מנדטים: דיאימגנטнтיצות של קלייזת, פאתורה מתצורה בר-כוכב, והאימגנטнтיצות של בוגרי

מנגננים. סכום ש筲ון משלולים בכתף קלייזת, מנהוגים שנועת ביהלקן אל-adiens הסושʬואין הרמזים

הказалו השונות-כ-10.آ.א.ס. בעבודה זו, עם כ-500 כנימייר. אי.אס.א. עם ציון ערי-ה-adiens.-סושʬואין הרמזים

משlesai את כ-500 המגנטונים של גביש הקלייזת ב槛.
תכונות מגנטיות של סלעים קרבוניים ככלי להערכת מעוות ליד בקעת-ים-המלח בצפון ישראל

רות יששכר

העבודה הוכנה בהדרכתם של:
דר' צפריר לוי, המכון הגיאולוגי, ירושלים
פרופ' רם ויינברגר, המכון הגיאולוגי, ירושלים
פרופ' שמואל מרקו, החוג לגיאופיסיקה ומדעי אטמוספירי ואטמוספירי פלנטריים, אוניברסיטת תל אביב

דו"ח מס' GSI/25/2013, ירושלים, יולי 2013