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Intensity and direction of the geomagnetic field on 24 August 1179 measured at Vadum Iacob (Ateret) Crusader fortress, northern Israel

Yael Segal,[a] Shmuel Marco,[a,*] and Ronnie Ellenblum[b]
[a]Department of Geophysics and Planetary Sciences, Tel Aviv University, Tel Aviv 69978, Israel
[b]Department of Geography, The Hebrew University of Jerusalem, Jerusalem 91905, Israel

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ABSTRACT

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Paleomagnetic tests on two archaeological structures from the Crusader fortress Vadum Iacob (Ateret) reveal the use of these structures as an oven and a lime kiln. These fireplaces enable determination of the local direction and intensity of the geomagnetic field on 24 August 1179, when its construction was terminated by the Arab conquest. Stable field directions of the natural remanent magnetization were obtained in 31 specimens from a total of 16 building stones taken from the two archeological structures in the site. We consider the results as a negative stability test, indicating that a temperature above the Curie temperature erased the original in situ magnetization of each building stone when the stones were part of the fireplaces, and a new magnetization was acquired on the day the fire was extinguished. The mean magnetic directions of the two installations are statistically indistinguishable 013º/48º; α_{95} = 6.5° and 017º/58º ; α_{95} = 9.1º. The paleointensity of the Earth's magnetic field obtained by the original Thellier double-heating method from 8 basalt specimens from the lime oven is 72 ± 7 μT, about 1.8 times the current field. We demonstrate how the geophysical study of paleomagnetism helped resolve an archaeological question and how the archaeological and historical study helped resolve the dating of a geophysical feature.

INTRODUCTION

It is usually difficult to obtain precise records of the past behavior of geophysical properties that change over time. One major difficulty is the determination of their precise age. This study demonstrates the precision that is obtainable by combining a study in geophysics with archaeological and historical data. We show how both disciplines benefit from the cooperative study of the past behavior of the geomagnetic field and the history and archaeology of the Crusader fortress of Vadum Iacob: the geophysical study of paleomagnetism helped resolve an archaeological question and the archaeological and historical study helped resolve the precise date of the magnetization. The same site has already proven fruitful in another geological–archaeological–historical research, which documented

*Author to whom correspondence should be addressed.
E-mail: shmulik@terra.tau.ac.il

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two historical earthquake ruptures that offset the fortress by a total of 2.1 m (Ellenblum et al., 1998). The deformation associated with the fault is limited to less than a 10-m-wide zone. The studied structures are outside the fault zone and are only affected by a negligible lateral translation of 2.1 m.

THE BASIC PALEOMAGNETIC PRINCIPLE

Various rocks are magnetized while they are formed under the influence of the Earth's magnetic field. This magnetic vector, which is aligned with the Earth's field, can be measured using a magnetometer. If the magnetization is stable and the rocks remained in situ since their formation, it is possible to reconstruct direction and intensity of the paleofield. Clearly, when stably magnetized rocks are quarried, transported, and used as building stones they would show scattered directions of magnetization. However, when stone structures such as kilns, fireplaces, ovens, etc. are heated to above a certain temperature (the Curie temperature of the magnetic minerals), thermal agitation destroys the original magnetization. When the temperature goes down below the Curie temperature, all the stones will have acquired a new uniform magnetization, recording the Earth's magnetic field at the site at that time. By measuring the stable magnetization of several building stone specimens from different sides along the structure it is easy to reveal whether it was heated after its construction. Moreover, the newly acquired thermoremanent magnetization (TRM) can be used to calculate the intensity and direction of the field at the time of cooling.

STUDY SITE

The fortress of Vadum Iacob (now called Ateret) was built by the Crusader King Baldwin IV. It controlled the natural ford of the Jordan River between the swamps of the Hula Valley to the north and the Jordan Gorge to the south (Fig. 1). A crucial advantage to the study of Vadum Iacob fortress is the contemporary detailed and well-documented history of its construction and conquest. The construction of the fortress began on 1 October 1178 and was stopped less than a year later on 24 August 1179 by the Arab attack led by Saladin. The unique unfinished state of the fortress enables the detailed study of the construction techniques and timetable.

One important installation in any construction site of this period was a lime kiln, in which chalk was transformed into lime (for the production of cement) by intense heating. A circular, stone-lined structure that was discovered some 100 m north of the fortress was suspected to be a lime kiln. The structure is made of a 5-m-wide and 2-m-deep depression, with basalt stones forming a circumferential wall (Fig. 1).

The second structure of interest, at the SE corner of the fortress, is a unique dome-covered room built of limestone ashlars, very narrow at one end and circular at the other end. Its precise function is not clear, but a thick layer of ash on the floor, as well as a series of small (~10 cm) air conduits in the circumference, hint that it was some kind of a cooking oven. We therefore dub it "the kitchen".

The targets of our study—the lime kiln and the cooking oven at Ateret—were built from basalt and limestone blocks from nearby quarries.

DATE OF MAGNETIZATION

Baldwin IV, the King of the crusader Kingdom of Jerusalem, initiated the construction of the Vadum Iacob (Latin, meaning "Jacob's Ford") fortress on 1 October 1178. The fortress overlooks the strategic crossing on the Jordan River controlling the major road from Israel to Damascus. Historical records describe how the Crusader builders of the fortress were surprised by the Muslim attack (Barber, 1998). The attack on the castle began on Saturday, 19th Awal, 575 of the Muslim calendar, which is 24 August 1179 of the modern Gregorian calendar. Saladin and his best generals commanded the Muslim forces (Huygens, 1986). The suddenness of the attack is evident in the archaeological findings. We unearthed a complete inventory of medieval working tools: spades, hoes, picks, a wheelbarrow, plastering spoon, scissors, etc., altogether indicating a sudden end to the construction work on the day of the attack. One particularly dramatic find is a heap of lime with working tools imbedded in it. The heap and the tools were covered by Muslim arrow-heads, clearly demonstrating how the builders were interrupted by the sudden attack. Since the supply of lime required the operation of the lime kiln, we interpret the findings to show that the burning was shut down on Saturday, 24 August 1179.

SAMPLING AND MEASUREMENT METHODS

We drilled 31 standard core specimens. Nineteen were taken from 9 blocks of the lime kiln, located about 100 m north of the castle wall, and twelve specimens were

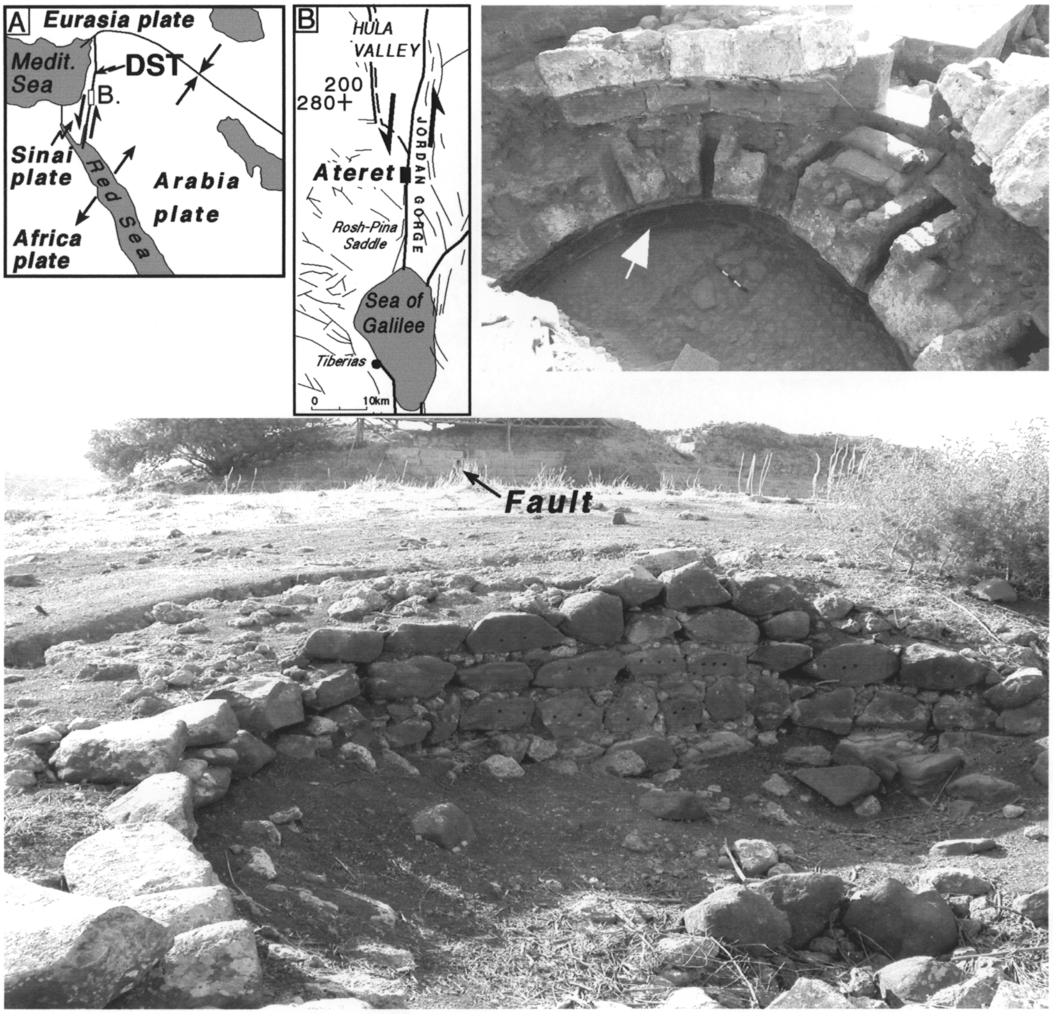

Fig. 1. A. Tectonic plates in the Middle East. B. Simplified map of the study area showing the location of Ateret on the Jordan Gorge Fault, between the Hula and the Sea of Galilee basins. Solid lines show major faults. Slim lines are secondary, mainly normal, faults (after Bartov, 1979). Upper photo shows the oven site; rule (on ground) is 0.5 m. Arrow points to the sampled row of ashlars. Lower photo shows the lime kiln. Drill holes of 2.5 cm diameter are seen in the basalt stones. The faulted wall of Ateret fortress is in the background about 100 m southward.

taken from 7 blocks of the oven, located within the fortified area. The samples were taken from all possible sides of the potentially baked parts of the objects.

Paleodirection measurements were performed in the paleomagnetic lab in the Geophysical Institute of Israel using a "2G" cryogenic magnetometer. The natural remanent magnetism (NRM) was measured first, and then the sample was subjected to stepwise demagnetization by alternating field (AF) with increasing intensities, starting at 5 mT and going up in 5- or 10-mT increments until the remaining intensity dropped to 10–5% of its initial NRM. In order to calculate the magnetic vector for each specimen we performed a principal component analysis (Kirschvink, 1980). We chose characteristic directions, which pass a 1-degree linearity test. Average directions for a few vectors were calculated using the Fisher method (Fisher, 1953). The precision of the average vector is indicated by three indexes: R, κ, and α_{95}. R is the length of the resultant vector normalized to the scalar sum of individual vectors. Its maximum size is 1 (when all the added vectors point to the same direction). κ is the precision parameter. It is best estimated as $\kappa = (N–1)/N(1–R)$, where N is the number of averaged individual specimens. α_{95} is the angular radius of the 95% circle of confidence, which is best estimated as $\alpha_{95} = 140/\sqrt{(\kappa N)}$.

Paleointensity measurements were performed in the laboratory of archaeomagnetism and geosciences in the University of Rennes 1, France using a spinner magnetometer and a thermal demagnetizer. We used the Thellier double-heating method (Thellier and Thellier, 1959), i.e., stepwise demagnetization by increasing temperature, starting at 100 ºC and going up in 20–100 ºC increments. Each temperature was maintained for at least 45 minutes to allow thermal equilibrium to be established (Levi, 1977) and was applied twice, until the remaining intensity dropped to 10–5% of its initial NRM. A field of 40 μT was applied along the Z-axis during both heating and cooling for each temperature. The specimens were reversed between heating at each temperature step. Measuring the remanence magnetization after cooling from temperature step *Ti* allowed us to determine the NRM that remains with blocking temperature *Tb* (>*Ti*) and the TRM acquired with a blocking temperature between *Ti* and the room temperature (Coe, 1978). The linear segment in the NRM–TRM diagram is used to estimate the paleointensity. During this process we obtained the direction of the specimens as well.

RESULTS

All the specimens show very stable single-component magnetization (Fig. 2). The magnetic field directions obtained from 19 specimens of the lime kiln and 12 specimens of the oven show a clear concentration of most of the specimens (Fig. 3), which rules out the preservation of preconstruction stable magnetization. The average of the field direction is improved when 3 outliers are omitted, yielding average directions of 013°/48°, R = 0.985, α_{95} = 6.5°, and κ = 57.9 for the lime kiln and 017º/58º, R = 0.979, α_{95} = 9.1°, and κ = 39.2 for the oven (Fig. 3). We argue that the small difference, which is statistically negligible, cannot be caused by deformation in the vicinity of the active fault, which ruptured in the earthquakes of 1202 and 1759 (Ellenblum et al., 1998). Such a deformation is not observed in the fortress, where the abundance of strain markers in the form of meticulously laid masonry makes the observation of deformation easy. The deformation is confined to a narrow fault zone, decaying rapidly to zero at less than 5 m from the shear plane. The

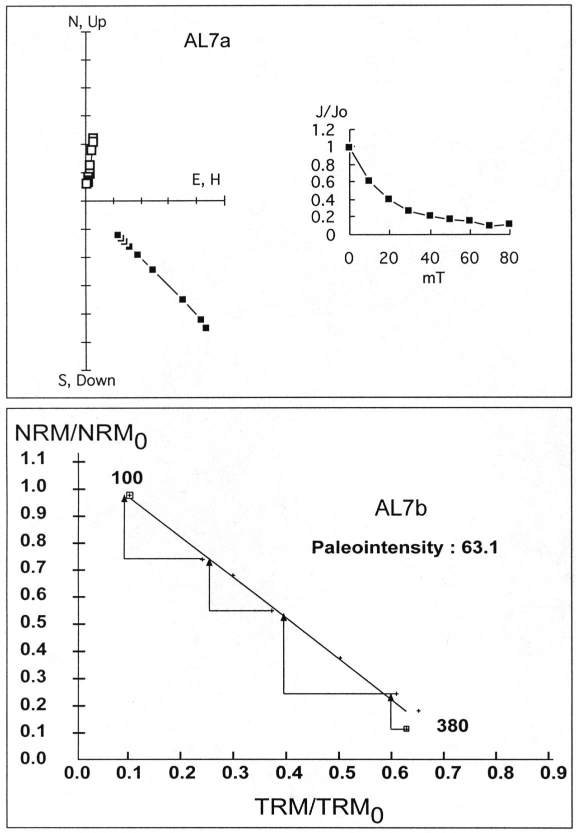

Fig. 2. Demagnetization curves and respective NRM/TRM diagram of a basalt specimen from a lime kiln at Ateret. In the demagnetization diagrams, the open (solid) symbols refer to the declinations (inclinations). In the NRM/TRM diagrams, the crosses along the diagonal line are the results of the Thellier double-heating experiment. The arrows represent the pTRM checks every one to three temperature steps. The arrow heads indicate the NRM obtained during the experiment along the Y-axis and the TRM measured in the check on the X-axis. In this example all the checks were good, enabling the use of all the data points for estimating the paleointensity.

Table 1
Paleointensity results from the lime kiln

Specimen	Intensity (μT)
1	82
2	75
3	78
4	65
5	70
6	67
7	63
8	73
Arithmetic average	72 ± 7

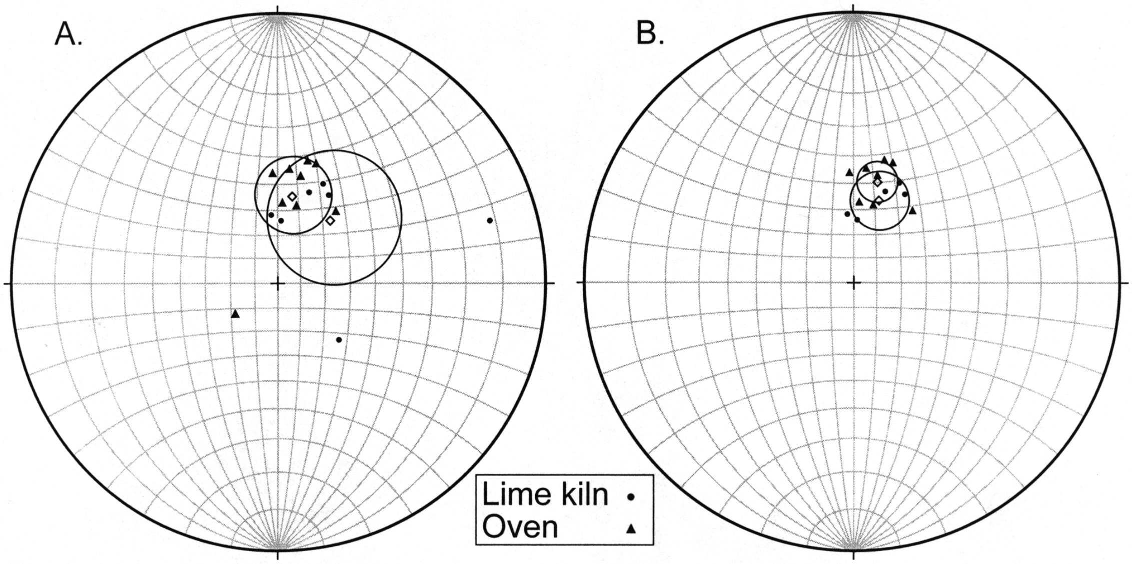

Fig. 3. A. Stereographic projection of nine mean directions of the kiln blocks (circles) and 19 mean directions of the oven blocks (triangles). The mean directions (open diamonds) are surrounded by α_{95} circles. B. The same data points excluding the outliers. The mean magnetic directions of the two installations, 013º/48º α_{95} = 6.5º and 017º/58º α_{95} = 9.1º, are statistically indistinguishable.

studied structures are outside the fault zone and are only affected by a negligible lateral translation of 2.1 m. We therefore consider the results to show the same direction.

Paleointensity was measured on 8 specimens from the lime kiln (Table 1). The average intensity is 72 ± 7 μT (Standard Deviation), about 80% higher than the present magnetic field in Israel. These results are in agreement with other measurements that document a decrease of the geomagnetic field intensity during the last eight centuries (Ali et al., 1999; Segal et al., 2003) but are somewhat higher than results from Syria and Egypt (Fig. 4).

CONCLUSIONS

The uniform paleomagnetic direction measured in different masonry blocks of the archaeological installations is interpreted as evidence of thermoremanent magnetization that was acquired due to their use as a lime kiln and an oven. The exact time of magnetiza-

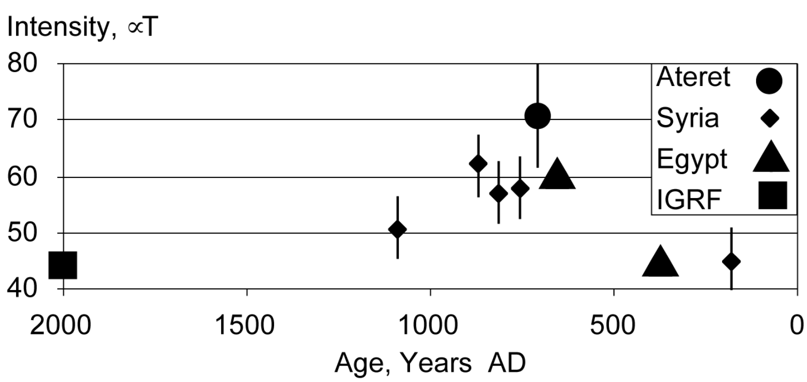

Fig. 4. Paleointensity results from Egypt (triangles, Hussain, 1987) and Syria (diamonds, Genevey et al., 2003) compared to Ateret (circle, this study) and the present field (square, IGRF2000).

tion is established by written contemporary accounts of the day of the Arab attack on the Crusader fortress, which was still under construction on 24 August 1179. The fires in the kiln and oven were extinguished on that day. The tightly clustered magnetic field directions of the specimens from the oven and from the lime kiln lead us to conclude that these two installations were heated to above the Curie temperature and subsequently cooled down at the same time. The magnetic field direction on 24 August 1179 was 015°/53° α_{95} = 9° (the average of both installations) and the intensity was 72 ± 7 mT, about 1.8 times the present intensity.

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