

## Interpretation of Ramon Basalt magnetic anomalies: Magnetic modeling and a paleomagnetic study

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### ABSTRACT

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We present an interpretation of the two strongest magnetic anomalies produced by Ramon Basalt (Early Cretaceous volcanics within the Hatira Formation) located in the west Ramon area (central Negev, southern Israel). The shape of the anomalies, particularly the WNW location of the low in relation to the high, suggests a WNW magnetization caused by a strong remanent magnetization. This hypothesis was confirmed by a paleomagnetic study that revealed this magnetization in the exposed edge of the southern body. All three basalt flows comprising this body have remarkably strong natural remanent magnetization (NRM) ranging from 8 to 23 A/m, with Königsberger ratios ranging from 6 to 15. The upper flow has the strongest NRM of the three, with a WNW declination ( $288^\circ$ ), as expected from the shape of the aeromagnetic anomaly. The unusual intensity and direction of the NRM are uncommon in outcrops of Ramon Basalt and are related to a late overprint.

In our model, the effective magnetization of the southern body is a vector sum of the induced magnetization and the NRM. According to the model, the upper flow alone produces almost the entire aeromagnetic anomaly. Its calculated effective susceptibility, i.e., susceptibility that incorporates the NRM, is  $711 \cdot 10^{-3}$  (SI) and its effective declination is  $291^\circ$ . These results emphasize the importance of a direct NRM measurement in each flow for better modeling and interpretation of aeromagnetic data. However, it was found technically complicated to implement this method for the northern body which is composed of 6 exposed flows. For a first approximation we modeled it as a homogeneous body. Its declination was chosen to be  $305^\circ$  according to the high–low trend; an inclination of  $20^\circ$  and susceptibility of  $314 \cdot 10^{-3}$  (SI) were assigned to give the best fit with the observed anomaly. This approximated effective susceptibility is about 10 times stronger than the average susceptibility of Ramon Basalt and indicates a strong component of remanent magnetization, as expected from analyzing the aeromagnetic map.

### INTRODUCTION

Basaltic flows, intercalated within the Hatira Formation, are exposed in the Makhtesh Ramon erosion cirque (Fig. 1; Bentor, 1952; Mazor (Posner), 1955; Bonen, 1980). These flows are known by the stratigraphic name "Ramon Basalt", and were dated as Early Cretaceous (Lang et al., 1988). Several outcrops of Ramon Basalt

are associated with aeromagnetic anomalies (Domzalski, 1967). Two anomalies in western Makhtesh Ramon have exceptionally high amplitudes of 400–450 nT (section AA' in Fig. 1). Their shapes, namely, the WNW location of the low in relation to the high, differ from the south–north trend which is expected from the magnetization induced by the present geomagnetic field. In our study we intend to interpret these anomalies and show

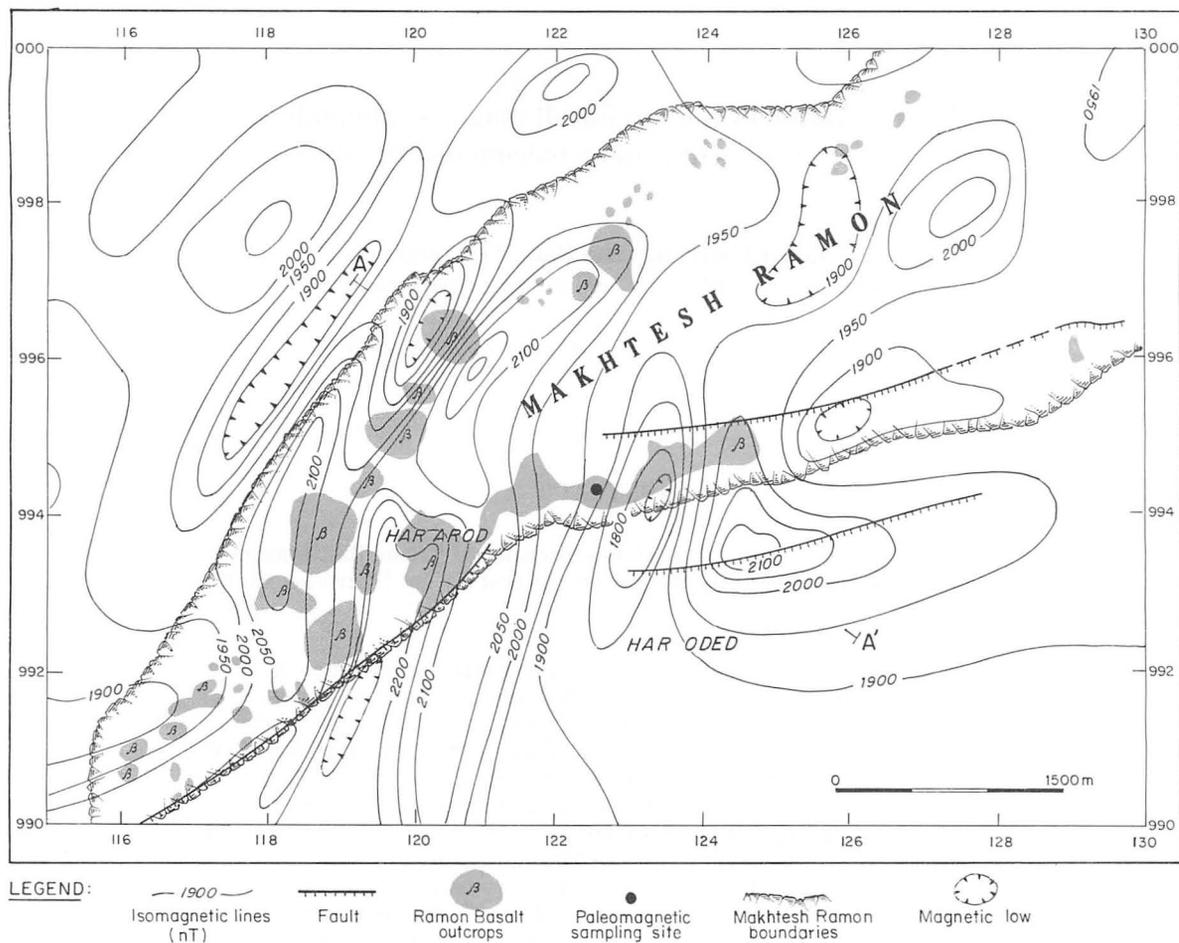


Fig. 1. Aeromagnetic map of western Makhtesh Ramon (from Domzalski, 1967). Flight altitude: approximately 1000 masl; Flight lines spacing: 2000 m; Base value: 40,000 nT, regional magnetic gradient has been removed. Interpretation of the magnetic cross section AA' is presented in Fig. 3. The geology after Segev (1982).

that the WNW trend is caused by a strong component of remanent magnetization.

The contribution of remanent magnetization to aeromagnetic interpretation has been demonstrated in several studies (e.g., Green, 1960; Books, 1962; Grant and West, 1965; Alva-Valdivia et al., 1991). Quantitative interpretation of aeromagnetic anomalies requires measurements of induced as well as remanent magnetization components. This becomes obvious when the remanent component has a direction significantly different from that of the present field, as will be shown in our case.

In the Mount Govai aeromagnetic anomaly (5 km south of Makhtesh Ramon), the low is NW of the high. Gvirtzman (1992) showed that an effective magnetiza-

tion with a declination of  $330^\circ$  and an inclination of  $30^\circ$  is consistent with the observed anomaly. This direction differs from the direction of the induced magnetization, which has a declination of  $0^\circ$  and an inclination of  $45^\circ$  (Domzalski, 1967), and was interpreted by Gvirtzman (1992) as a result of a significant component of remanent magnetization. The interpretation is supported by the high inferred susceptibility, but could not be confirmed by paleomagnetic measurements because the Mount Govai anomaly is caused by a subsurface body. In contrast, in the west Ramon area, the aeromagnetic anomalies are associated with exposed flows and their remanent magnetization can be directly measured. The present case enables us to calculate the magnetization as a vector sum of the induced and the remanent compo-

nents, and to use the results for modeling. To the best of our knowledge, this method of using paleomagnetic data for magnetic modeling was never used in Israel before.

### INDUCED AND REMANENT MAGNETIZATION

The magnetization  $\mathbf{J}$  of a rock is a vector sum of the induced  $\mathbf{J}_i$  and the remanent  $\mathbf{J}_r$  vectors (Hood, 1964):

$$\mathbf{J} = \mathbf{J}_i + \mathbf{J}_r = k\mathbf{F} + \mathbf{J}_r$$

where  $k$  is the magnetic susceptibility and  $\mathbf{F}$  is the geomagnetic field. The ratio between the intensities of the remanent and induced vectors is defined as the Königsberger ratio  $Q$ :

$$Q = \frac{J_r}{J_i}$$

In aeromagnetic interpretation, the remanent magnetization is frequently neglected, usually because the remanent magnetization is unknown. In most rocks  $Q \ll 1$ , so neglecting  $\mathbf{J}_r$  is justified, but in some rocks the remanent magnetization is strong and well preserved. Young basalts usually have  $Q$  smaller than 1, but in some extreme cases  $Q$  can even reach 100 (Hood, 1964). In these cases, neglecting  $\mathbf{J}_r$  is a serious error.

When the direction of  $\mathbf{J}_r$  is similar to that of the present geomagnetic field, the intensity of the effective vector is obtained by a scalar addition of their intensities:

$$J = kF + J_r \approx kF(1 + Q) \approx k_e F$$

where  $k_e = k(1 + Q)$  is the effective susceptibility (Hood, 1964), representing enhancement of the actual susceptibility by a factor of  $1 + Q$  ( $1 - Q$  for reversed magnetization with antiparallel induced and remanent components). Thus, a  $Q$  of 1 will increase the magnetization by 100%, and therefore can cause a similar increase in the amplitude of the magnetic anomaly.

When the direction of remanent magnetization differs from the present geomagnetic field, the magnetization vector  $\mathbf{J}$  does not point to the magnetic north, and this can influence not only the amplitude, but also the shape of the magnetic anomaly. Therefore, a body's direction of magnetization can be estimated by the shape of the anomaly it produces. In the northern hemisphere, induced magnetization produces an aeromagnetic anomaly in which the low is north of its high. Therefore, a high-low trend which is not S-N may

indicate a significant remanent magnetization. Strictly speaking, this is true for a simple dipole, as in most geological bodies. Other misalignments might be related to the body's shape and orientation (see discussion in Gvirtzman, 1992).

### THE AEROMAGNETIC ANOMALIES OF RAMON BASALT AND ITS MAGNETIZATION

In the aeromagnetic map of the Ramon area (Domzalski, 1967), the amplitude of most Ramon Basalt anomalies are less than 100 nT. In contrast, two anomalies in western Makhtesh Ramon are conspicuous with magnitudes of 400–450 nT. One is located exactly above a basaltic hill (1205/9963 Israel grid); the other is probably related to a subsurface body centered 500–1000 m south of Makhtesh Ramon (1240/9935 Israel grid), with its northern edge exposed (Fig. 1).

It should be noticed that these two strong anomalies are not associated with the thickest outcrops of Ramon Basalt. Indeed, the subsurface parts of the bodies are not known, but it seems that there is no direct correlation between the volume of the bodies and the aeromagnetic anomalies they produce. Givat Metzah, for example (central Makhtesh Ramon), is one of the two thickest outcrops of Ramon Basalt, yet it is not associated with any aeromagnetic anomaly. Therefore, it seems that the magnetization of the causative bodies, and not their volume, is the reason for the strong aeromagnetic anomalies in western Makhtesh Ramon. This approach is supported by the exceptional shape of these anomalies: the high-low trend is  $305^\circ$  in the northern anomaly and  $290^\circ$  in the southern one. Deviation of  $55^\circ$ – $70^\circ$  from the expected magnetic north is another evidence for the strong remanent magnetization of the causative bodies.

A previous paleomagnetic study of Ramon Basalt by Ron and Baer (1988) revealed that the Cretaceous declination in the Ramon area is  $320^\circ$ – $350^\circ$ . These data were obtained after removal of post-Cretaceous overprint, and show the direction acquired when the lava cooled (thermal remanent magnetization — TRM). The original Cretaceous TRM is not applicable to magnetic interpretation because aeromagnetic anomalies are influenced by the present magnetization, i.e., the natural remanent magnetization (NRM). Ron and Baer (1988) indicated that 80% of the samples showed an overprint, probably induced by the present geomagnetic field, which caused the NRM to point almost to the north. In the present study, the high-low trend of the investigated anomalies ( $290^\circ$ – $305^\circ$ ) cannot be explained by the NRM directions, nor by the primary Cretaceous

directions.

In addition, the intensity of the NRM, which was previously measured in Ramon Basalt, is also insufficient to explain the magnetization expected in our case; in 35 out of 41 samples which were measured by Gvirtzman (1992) in four Ramon Basalt outcrops (1173/9915; 1190/9925; 1187/9937; 1202/9938; Fig. 1), the intensity was of the order of  $10^{-1}$ – $10^{-2}$  A/m with  $Q$  less than 1. This  $Q$  value indicates a weak remanent magnetization, which is insufficient to explain the deviation of  $55^{\circ}$ – $70^{\circ}$  from the north. The purpose of our paleomagnetic study was to find evidence for NRM which explains the shape and magnitude of the two exceptional aeromagnetic anomalies at western Makhtesh Ramon.

### PALEOMAGNETIC MEASUREMENTS

The sampling sites were located at the southern wall of

Makhtesh Ramon, in the exposed edge of the southern body (1223/9942; elevation point 793 m), and were very close to the magnetic profile we interpreted (AA', Fig. 1). Twenty-three oriented samples were collected from three basaltic flows, using a sun compass for orientation. Remanent magnetization was measured using a cryogenic magnetometer of the paleomagnetic laboratory at the Institute for Petroleum Research and Geophysics. The NRM of all 23 samples were measured, and a few samples were stepwise demagnetized in an alternating field (AF) of up to 100 mT. Figure 2 shows vector demagnetization, and normalized intensity ( $J/J_0$ ) plots (Zijderveld, 1967).

The stepwise demagnetization shows that the NRM is the sum of a secondary component (overprint), which was removed by AF demagnetization of maximal 20 mT, and a stable component (Fig. 2). The intensity of the NRM in all the samples (Table 1) is about two orders of magnitude larger than what was previously measured

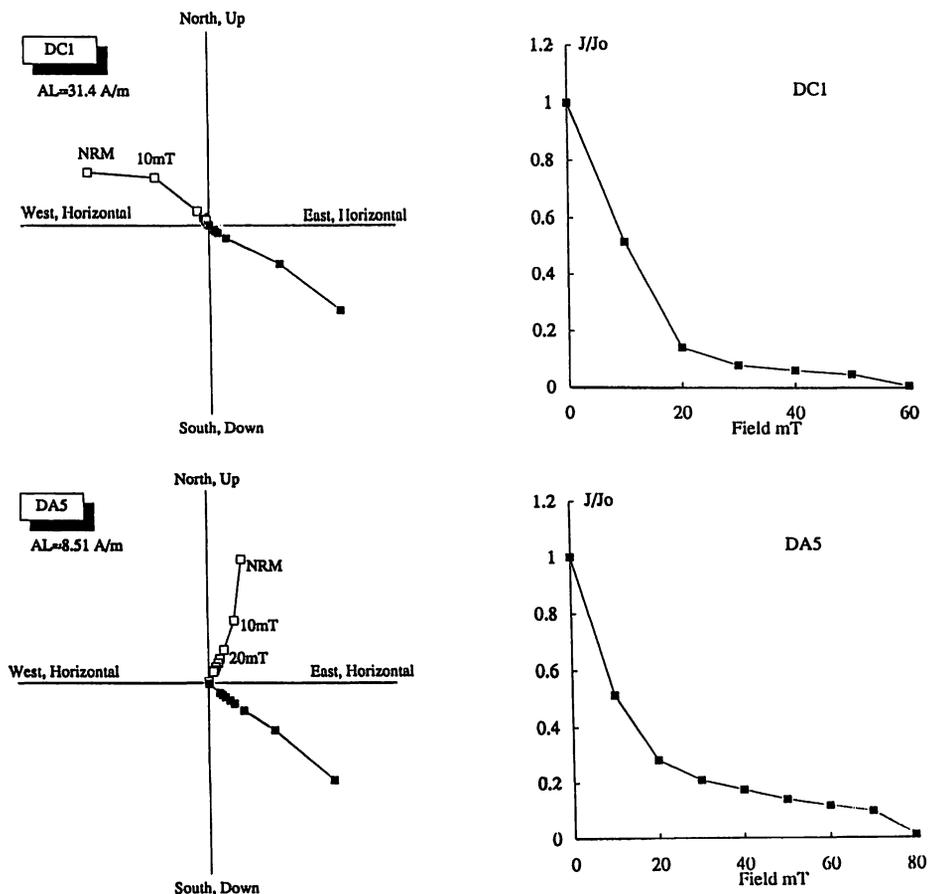


Fig. 2. Orthogonal vector plots and normalized intensity ( $J/J_0$ ) of 2 samples during stepwise demagnetization in an alternating field (AF). Open squares represent the declination component. Solid squares represent the inclination component. DC1: upper flow, DA5: lower flow. Note the westerly overprint of DC1.

Table 1. NRM, effective magnetization, susceptibility, and Königsberger ratio

Flow	NRM			Effective vector			$k(10^5)$ SI	$k_e(10^5)$ SI	$Q$	# of samples
	int.(A/m)	dec.(°)	inc.(°)	int.(A/m)	dec.(°)	inc.(°)				
Upper	23.40	288	31	24.40	291	33	4675	71,126	14.60	10
Middle	8.11	27	12	9.09	24	17	3770	26,515	6.10	4
Lower	8.66	17	25	9.75	16	28	4122	28,526	6.30	9

Note that  $k_e/k$  is smaller than  $1 + Q$  because the induced and remanent components are not in the same direction.

by Gvirtzman (1992) in nearby outcrops. The most interesting results were obtained from the upper flow, which has the strongest NRM intensity and a WNW declination, as expected from the shape of the aeromagnetic anomaly.

### CALCULATING THE MAGNETIZATION FOR MODELING

For interpretation of the aeromagnetic anomalies, the effective vector was obtained by a vector sum of the induced magnetization and the NRM. The results are presented in Table 1.

Most computerized interpretation programs assume that the magnetization of a body is parallel to the present geomagnetic field. Therefore, the intensity of  $J$  is calculated as the product  $kF$ , and its direction is calculated according to the present local inclination and declination. The interpreter is asked to enter the values:  $F$ ,  $k$ , inclination and declination. In our interpretation  $J$  is different from the present geomagnetic field. Therefore, we used  $F = 43,000$  nT (the intensity in southern Israel; Domzalski, 1967);  $k_e = J/F$ ; declination and inclination of the calculated  $J$ .

These parameters were calculated for each flow:

Upper flow: inc. =  $33^\circ$ ; dec. =  $291^\circ$ ;  $k_e = 711 \cdot 10^{-3}$  (SI)

Middle flow: inc. =  $17^\circ$ ; dec. =  $024^\circ$ ;  $k_e = 265 \cdot 10^{-3}$  (SI)

Lower flow: inc. =  $28^\circ$ ; dec. =  $016^\circ$ ;  $k_e = 285 \cdot 10^{-3}$  (SI)

### A GEOLOGICAL-GEOPHYSICAL MODEL

The oval shape of the two interpreted anomalies (Fig. 1) justifies the use of a 2.5-D modeling procedure (two dimensional with end corrections). The continuous exposure of some basaltic bodies along the strike line of the northern anomaly reinforces the basis for a two-dimensional calculation.

The geological cross section along the interpreted magnetic profile (Fig. 3; section AA' in Fig. 1) is

perpendicular to the eroded Makhtesh Ramon anticline. The northern body is well exposed in the northern flank of the anticline. The southern body is mostly below the surface in the southern flank of the anticline, but its edge is exposed. This edge is composed of three flows which were sampled at 1223/9942 (Israel grid), as described above. The subsurface continuation of the body and the relative contribution of each flow to the total aeromagnetic anomaly is not known. Nevertheless, it seems that the contribution of the upper flow is dominant because the high-low trend of the anomaly ( $290^\circ$ ) is controlled by its declination. We modeled the body by fitting the calculated anomaly to the observed one. According to the model we obtained (Fig. 3a), the dominance of the upper flow is explained (a) by its strong magnetization (which is more than 2.5 times stronger than that of the lower and middle flows), (b) by the fact that the upper flow was the closest to the measuring equipment (airborne magnetometer, 200 m above surface; Domzalski, 1967), and (c) by the thickening of the upper flow toward the main part of the body. For comparison we also calculated the anomaly which is produced by the upper flow alone (Fig. 3b), and the anomaly which would have been produced by all three flows if there was no remanent magnetization (Fig. 3c). The results emphasize the critical importance of the remanent magnetization for correct interpretation, and show that the upper flow controls the amplitude of the anomaly as well as its shape.

The northern body is composed of six exposed flows and is therefore technically complicated for modeling. In this stage of the study, we chose to demonstrate the integrated method of magnetic modeling and paleomagnetic study on the southern body alone, as described in detail above. Nevertheless, for getting a first approximation for the shape and magnetization of the northern body, we modeled it as a homogeneous body. Its declination was chosen to be  $305^\circ$  according to the high-low trend; an inclination of  $20^\circ$  and susceptibility of  $314 \cdot 10^{-3}$  (SI) were assigned to give the best fit with the observed anomaly. We assume, for

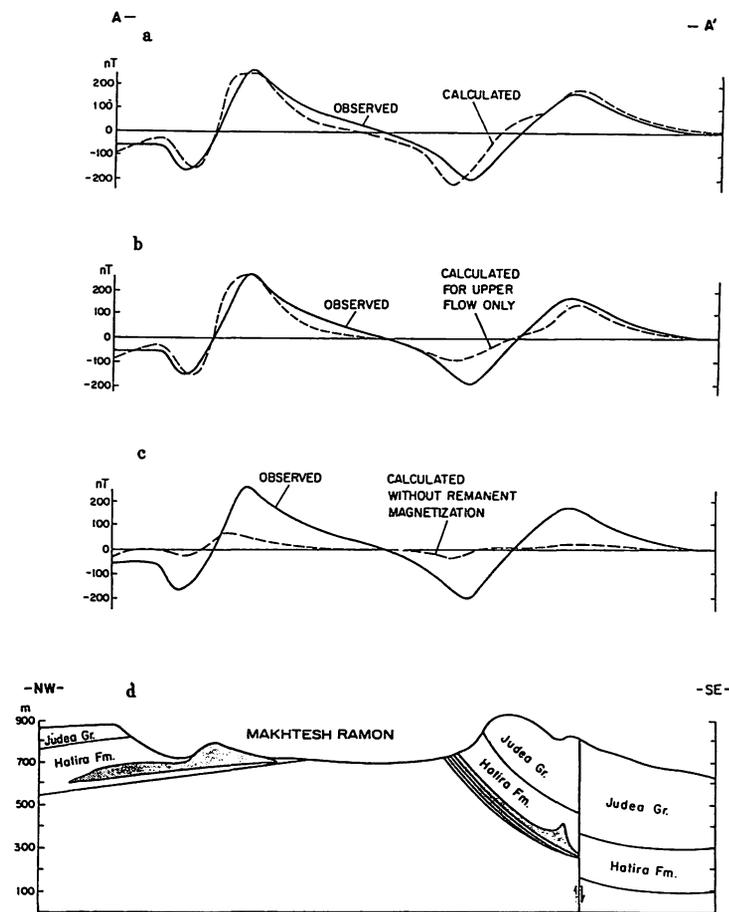


Fig. 3. Interpretation of cross section AA' (see Fig. 1).

(a) The complete model:

Southern body:

upper flow: inc. =  $33^\circ$ , dec. =  $291^\circ$ ,  $k_e = 711 \cdot 10^{-3}$  (SI)

middle flow: inc. =  $17^\circ$ , dec. =  $024^\circ$ ,  $k_e = 265 \cdot 10^{-3}$  (SI)

lower flow: inc. =  $28^\circ$ , dec. =  $016^\circ$ ,  $k_e = 285 \cdot 10^{-3}$  (SI)

Northern body: inc. =  $20^\circ$ , dec. =  $305^\circ$ ,  $k_e = 314 \cdot 10^{-3}$  (SI)

(b) The anomaly calculated for upper flow only.

(c) The anomaly calculated without the remanent magnetization.

(d) Geological cross section, prepared from the geological map of Makhtesh Ramon (Segev, 1982). Units thickness from Garfunkel (1964) and Avni (1991). Causative basaltic bodies are shaded.

The interpretation shows that the NRM of the upper flow is the main cause for the aeromagnetic anomaly.

simplicity, that this magnetization gives the total effect of all the flows together. The effective susceptibility obtained by this approximation is about 10 times stronger than the average susceptibility of Ramon Basalt and therefore indicates a strong component of remanent magnetization, as expected from analyzing the aeromagnetic map.

## SUMMARY AND CONCLUSIONS

Analysis of the Makhtesh Ramon aeromagnetic map leads to the suggestion that the declination component of the magnetization in two bodies of Ramon Basalt is WNW. This hypothesis was confirmed by a paleomagnetic study of the southern body which included suscep-

tibility measurements, NRM measurements, and calculation of the total magnetization vector.

The magnetization of all three flows is significantly stronger than the magnetization of other outcrops of Ramon Basalt:  $Q$  ranged from 6 to 15, while in other outcrops sampled in a previous work (Gvirtzman, 1992),  $Q$  was usually less than 1. The upper flow is quite different; its NRM intensity is more than 2.5 times stronger than that measured in the lower and middle flows, and its NRM is directed almost to the west. The unusual direction of magnetization is related to a strong overprint. The explanation for the direction and intensity of this late overprint, and for the fact that the west overprint affected only the upper flow, is still unknown.

Our interpretation shows that the remanent magnetization of the upper flow is the main cause for the southern anomaly. This clearly illustrates that remanent magnetization is critically important to aeromagnetic interpretation. It also demonstrates that homogeneous magnetization cannot always be assumed, particularly for a geologically layered body.

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