J.K.A.U.: Earth Sci., vol. 3, Special Issue: 1st Saudi Symp. on Earth Sci., Jeddah, 1989, pp. 341-347 (1410 A.H. / 1990 A.D.)

Paleointensity by the Thelliers' Technique: A New Reliability Criterion

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ABSTRACT. One of the weaknesses of the Thelliers' technique for paleointensity determination is the lack of definitive criteria by which the reliability of the results can be assessed. Linearity of the NRM-TRM curves, though a necessary condition of ideal behavior, has been experimentally shown to be insufficient. We propose an approach in which the entire paleofield vector (intensity and direction) is determined by the Thelliers' method. The reliability of the intensity estimate is then judged on the basis of internal consistency within and between specimens from the same sample, and on concordence between experimentally determined directions and the directions of stable NRM. Testing of the method on real and synthetic data indicate its viability.

Introduction

The standard method adopted by most laboratories for the determination of paleointensity from igneous rocks is the Thelliers' technique (Thellier and Thellier 1959). This method exploits the linearity and additivity properties of TRM (thermo remanent magnetization) and makes comparisons with NRM (natural remanent magnetization) and an artificial TRM in a series of temperature intervals between room temperature and the Curie point. The results are conventionally presented in the form of an x-y plot (Arai diagram) and the paleofield intensity is obtained from the slope of its linear segment if any.

This technique has frequently been criticised for its time consuming nature and low rate of successful determinations. However, attempts to replace it by more efficient methods have been unsuccessful and the techniques still remains as the best approach to obtaining internally consistent paleointensity data (Van Zijl *et al.* 1962, Benetjee and Mellema 1974 and Shaw 1974). Recently, however, the method was sharply criticised by Walton (1984, 1985, and 1988) on a more serious ground; namely lack of reproducibility. Specifically, Walton sited results obtained by Aitken *et al.* (1984 and 1985) from Egypt and Mesopotamia and pointed out the discrepancies between paleointensity values of the same points in time. He argued that the large scatter shown by these and other results can not be attributed to simple random errors inherent in the experimental procedures used. He claimed that he has "obtained compelling evidence that mineral alteration is responsible for the scatter. Indeed, there is no other candidate."

Walton previously (1983) raised the question of mineralogical alterations and their probable effect on paleointensity estimates obtained by different methods. He considered a thermally activated process and showed that if such change occurs in the course of the Thelliers' experiment it will severely bias the slope of the NRM-TRM curve with the menace of keeping its linearity characteristic intact. Thus, Walton's results indicate that linearity, which is the main criterion used in judging the reliability of paleointensity values obtained by the Thelliers' method, can be deceptive. In fact, his results seem to support a long suspected conclusion that linearity is a necessary but not a sufficient condition for the validity of paleointensity estimates obtained by the Thelliers' method. Walton (1984 and 1988) proposes an elaborate method to detect such alterations and to correct the systematic bias they introduce in the slope of Arai plot.

In this paper, we suggest a new approach for the determination of paleointensity by the Thelliers' technique which we believe could provide a more direct means to detect the effect of alterations and judge the reliability of paleointensity results. Our approach is based on using the total information content of the NRM signal to retrieve the paleofield vector, *i.e.*, its intensity as well as its direction. Thus, in this method we use the Thelliers' technique to obtain estimates not only of the scaler magnitude of the paleofield vector, but also of its components relative to the sample-fixed coordinate system. A paleointensity result is judged as reliable if it is derived from internally consistent field intensity values and it reproduces the stable NRM direction within experimental errors.

Experimental Procedure

Background

Several modifications of the Thelliers' method have been suggested but the one in common use is that described by Coe (1967). In this version, the specimen is subjected to a series of paired heatings with field-on and field-off steps. After the field-off heating step to temperature T_i ($\geq T_r$) the remanence measured is :

$$D_n(T_i, T_c) = J_N - J_n(T_r, T_i) \qquad (1)$$

where T_r and T_c are room temperature and the Curie point, respectively. J_N is the total NRM, D_n and J_n are the NRM remaining between T_i and T_c and that (PNRM) lost between T_r and T_i. After the field-on heating step to the same temperature T_i, the remanence measured is :

$$R(T_r, T_i) = D_n(T_i, T_c) + J_a(T_r, T_i) \qquad (2)$$

where $J_a(T_r, T_i)$ is the artificial TRM acquired between T_r and T_i in a known laboratory field F_a. Assuming that D_n and J_n are parallel, and also assuming that linearity and additivity hold for both the original NRM and laboratory TRM, Coe (1967) showed that :

$$D_n(T_i, T_c) = J_N - (F_e / F_a)\, J_a(T_r, T_i) \qquad (3)$$

where F_e is the paleofield intensity. If we relax the assumption of parallelism of D_n and J_n and write the equations above in terms of vector quantities, then the vector equivalent of equation (3) written in terms of scaler components is :

$$D_{nj}(T_i, T_c) = J_{Nj} - (F_{ej} / F_{aj})\, J_{aj}(T_r, T_i),\ (j = x, y, z) \qquad (4)$$

Our experimental procedure consists of using three specimens from the same core which we arrange in the furnace in such a way that the applied field F_e is parallel to one of the coordinate axes of each specimen. Thus, by applying equations (3) and (4), we obtain from each specimen estimates of F_e and F_{ej}(j = x, y, z); the latter is used to determine the direction of F_e(*i.e.* inclination I, and declination D). A paleointensity value in this procedure is, therefore, derived from three independent estimates of F_e and its reliability is judged on the basis of internal consistency between these estimates and on concordance between the direction of F_e and that of stable NRM.

Mathematical Basis

The gist of our approach is the fact that the direction of stable NRM and, hence, of F_e is known prior to any destructive treatment of NRM. Therefore, if in the course of the Thelliers' experiments mineralogical alterations occur and bias the slopes of the linear segments of the NRM-TRM curves, then the values of the scaler components of F_e obtained from these slopes will not reproduce the direction of stable NRM except in a few predictable cases. This is illustrated in the vector diagram of Fig. 1, where F is the true paleofield vector, F' is the experimentally determined estimate of F by the Thelliers' method, and E is the error vector. It is clear from the diagram that :

$$F' = F + E.$$

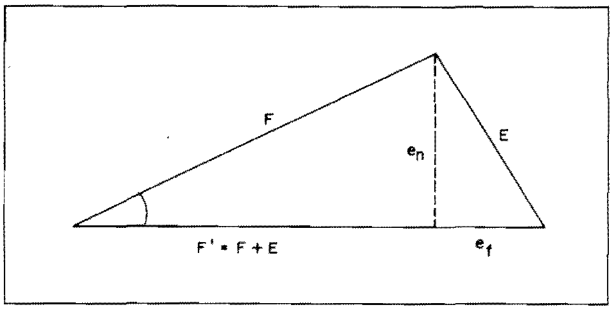

FIG. 1. Vector representation of the true paleofield (F), the experimentally determined paleofield (F'), and the error (E) vectors. E is partitioned normal to $F'(e_n)$ and parallel to $F'(e_f)$; only (e_n) contributes to φ.

The error vector E can be written as :

$$E = \varepsilon_x \hat{i} + \varepsilon_y \hat{j} + \varepsilon_z \hat{k} = e_f \hat{F} + e_i \hat{I} + e_d(\cos I)\, \hat{D} \qquad (5)$$

where : ε_x, ε_y, ε_z are the relative (to F) errors in F_x, F_y, and F_z respectively; e_f, e_i, e_d are the relative errors in intensity, inclination, and declination of the paleofield. Throughout this discussion, we assume equal relative errors in the paleofield components (i.e. $\varepsilon_x = \varepsilon_y = \varepsilon_z = \varepsilon$). This is a reasonable assumption, since these components are determined from adjacent specimens from the same core (implying similar magnetic mineralogies) and are thermally treated under similar conditions. Under this assumption one may write :

$$e_f = \varepsilon(G \cos I + \sin I) \qquad (6)$$

$$e_i = \varepsilon(\cos I - G \sin I) \qquad (7)$$

$$e_d = \varepsilon\, G' / (\cos I) \qquad (8)$$

where (I, D) is the direction of stable NRM and :

$$G = \cos D + \sin D \qquad G' = \cos D - \sin D \tag{9}$$

Thus, for $e_f \neq 0$, and $e_i = e_d = 0$, we have from equations (7), (8), and (9), $D_o = 545°$, and 225°, and $I_o = \pm 35.26°$, respectively.

These are the only two ambiguous cases for which the test fails; where $\varphi = 0$ (the angle between F and F'), and e_f has an extermum value ($\pm 1.732\varepsilon$). For all other values of I and D, the error vector E has a component normal to F and thus the direction of F(*i.e.* direction of stable NRM and that of F') will diverge resulting in a measurable φ.

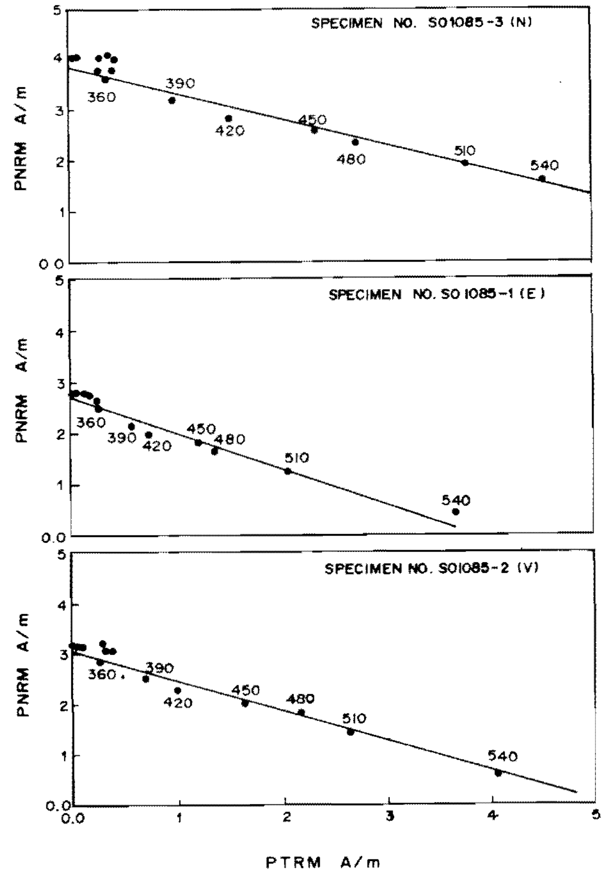

FIG. 2. Variation of e_f(a), e_i(b), e_d(c) with declination of stable NRM for I = 5° (solid), 350° (dashed), 55 (dotted) and 75° (dash-dot) variation of φ with e_f is shown in (d).

Figure 2 illustrates the behaviour of e_f, e_i, and e_d as functions of D at several values of I. Figure 2a and equation (6) show that for all values of $-54.73° \leq I \leq 54.73°$ e_f has at most two zeros at either side of D = 225°. This indicates that the possibility exist for $\varphi \neq 0$, while $e_f = 0$, which occurs when E is entirely perpendicular to F. In this case equation (6) yields :

$$\sin (2D) = \tan^2 I - 1 \tag{10}$$

Therefore, before assessing the reliability of F', it may be necessary to check if relation (10) is satisfied by stable NRM direction; if it is, then $\varphi \neq 0$ is merely a false alarm. Referring back to Fig. 1, it is easy to show that :

$$\cos \varphi = (1 + e_f) / \sqrt{(1 + 2e_f + E^2)} \tag{11}$$

This relation is sketched in Fig. 2c for $\varepsilon = 0.15$. Note that for a fixed E, φ increases as e_f decreases.

Experimental Test

We tested this approach on synthetic and real data. In the first case, we selected three specimens of standard size and heated them to 700°C, then cooled back to room-temperature in the ambient geomagnetic field of our laboratory. Direct measurements using a portable fluxgate magnetometer yield values of 36.0 ± 2.0 μT and 35.0 ± 5° for the intensity and inclination, respectively, of the field in the laboratory. The specimens were then subjected to the conventional routine of the Thelliers' experiments, but with the specimens arranged such that the applied field in the furnace is parallel to one of their coordinate axes.

The Arai diagrams for this sample are shown in Fig. 3. We note that the three specimens behave almost identically; in the temperature range 25-500°C they exhibit no mineralogical instabilities, but above 500°C, they undergo large increases in their TRM acquisition capacity probably due to further high temperature oxidation. For paleofield determination, we used the NRM-TRM points in the stable range (25-500°C). The results are summarized in Table 1a. The sample reproduces the paleofield vector almost exactly. This and other similar results (not included here) indeed attest to the reliability of the Thelliers' technique in the absence of mineralogical alterations. The fact that $\varphi = 0$, and (I, D) are not near the critical values, assures that F' does not contain significant error. In the present case, this conclusion is easily verified by comparing the experimentally determined parameters (F', I', and D') of the paleofield vector with those known from direct measurements given above.

In the second test, we used a sample from Harrat Rahat near the town of Rabigh. The age of the lava flows in this area is estimated at 25 My (Coleman 1987). Analysis of the NRM direction of this sample clearly indicates that the primary remanence is overprinted by a large secondary component. The direction of this secondary component is nearly 180° away from that of the primary remanence, and has a blocking temperature spectrum between 25 and 300°C. The

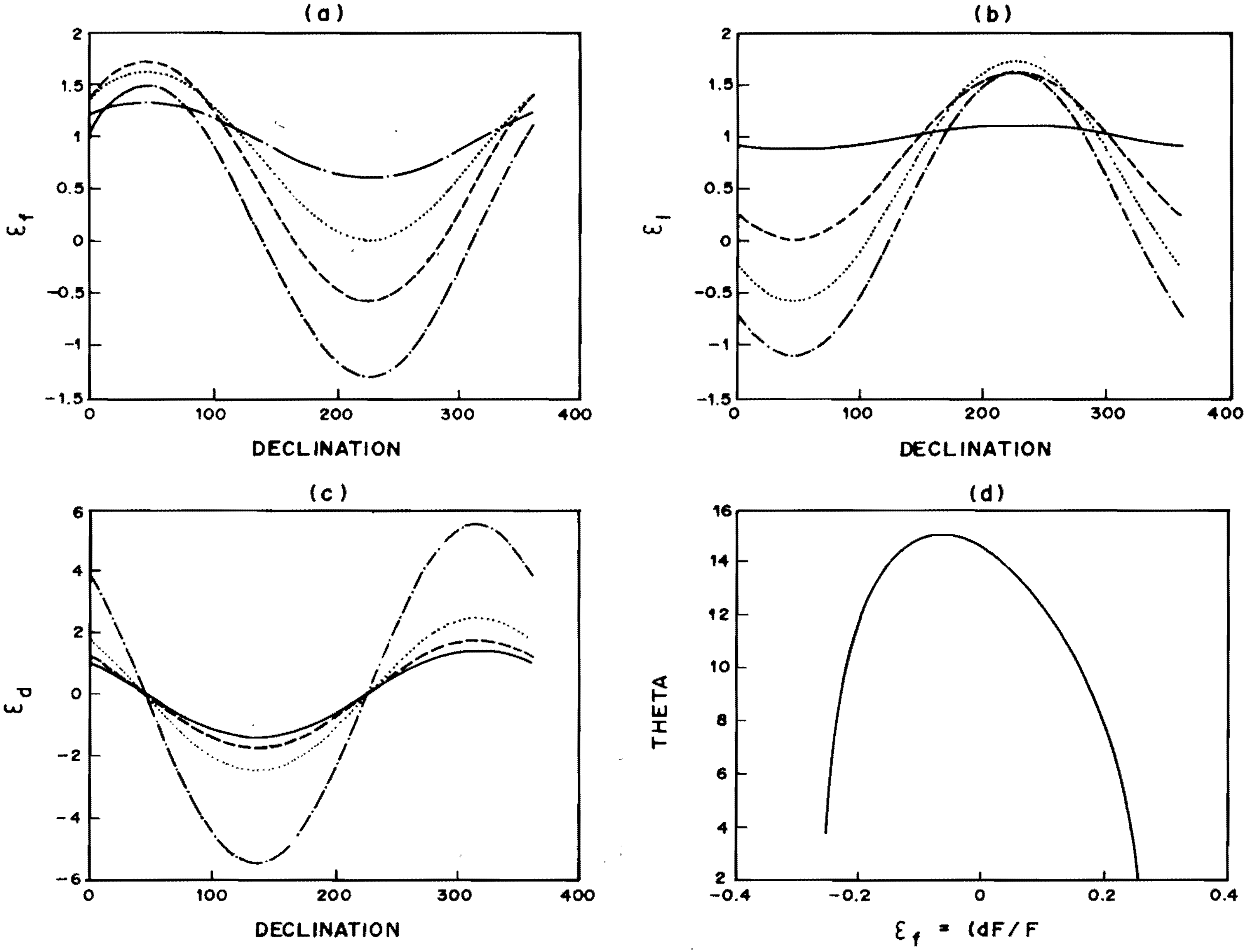

FIG. 3. Arai diagrams of sample VCTR-03 for the synthetic data. The sample behave ideally up to about 500°C above which it undergoes in TRM capacity.

TABLE 1. Summary of results for the synthetic (a) and real (b) data. Fc and Ft are component and total intensities. Mean values of the various estimates are given in the lower tables.

(a) Sample No: VCTR-03

Specimen	Fc	Ft	Stable Direction I	Stable Direction D
N	-22.25	39.23	55.50	182.51
E	- 1.56	33.68	54.01	184.51
V	31.05	38.40	53.94	187.10

Mean Val.	Intens.	I	D	Theta
Ft	37.10	54.49	184.74	0.46
Fc	38.23	54.31	184.01	

(b) Sample No: S01085

Specimen	Fc	Ft	Stable Direction I	Stable Direction D
N	9.33	24.84	-37.69	61.84
E	30.00	36.06	-37.72	66.24
V	-18.36	28.29	-40.39	65.39

Mean Val.	Intens.	I	D	Theta
Ft	29.73	-38.62	64.48	10.73
Fc	36.39	-30.30	72.72	

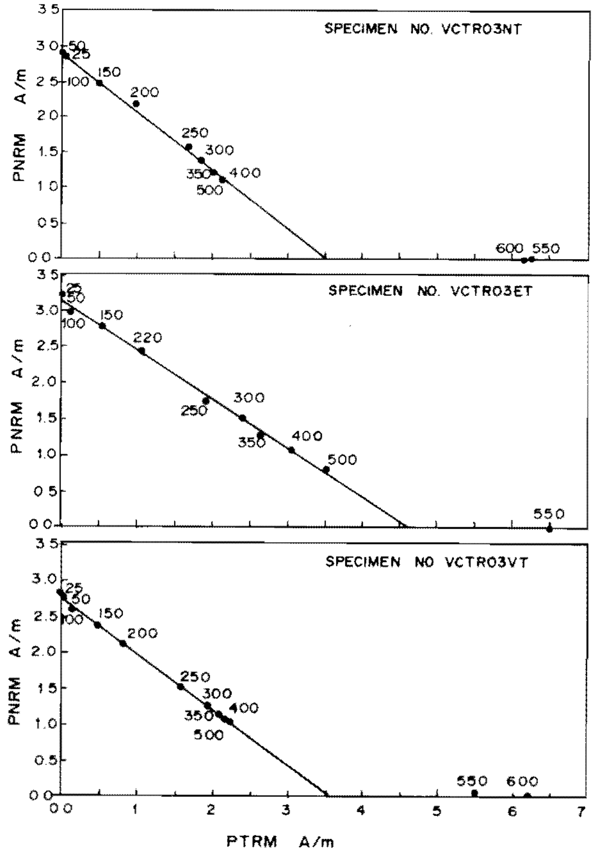

FIG. 4. Arai diagrams for sample S01085 from Harrat Rahat. The sample from lava flow dated at 25 My BP. Note that the effect of soft secondary magnetization at lower temperature range 25-300°C.

Arai diagrams for this sample are shown in Fig. 4. We observe in these figures that above 300°C, the NRM-TRM points define a linear segment up to about 510°C above this temperature the points appear to deviate toward increasing TRM capacity. We therefore, used the points in these interval 300-510°C to determine the paleofield vector and obtained the results in Table 1b. It is clear from the figures that the paleofield vector (F_c) diverges from the direction of stable NRM with $\varphi > 10°$. That is to say, the experimentally determined components of F' do not reproduce the true paleofield direction. Moreover, the NRM direction for this sample does not satisfy equation 10, implying that F' is in error.

Conclusion

As we pointed out in the introduction, the Thelliers' technique suffers from lack of a definitive criterion for assessing its results. The method as conventionally applied offers no more than the linearity of a segment of the NRM-TRM curve which is routinely interpreted as indicative of ideal behaviour and is, thus, used for paleointensity determination. Moreover, the NRM-TRM curve frequently may contain more than one linear segments and the decision on which one to be used for intensity estimation is often based on subjective criteria. The approach we described in this paper uses all the information in NRM signal to provide an additional constraint on the validity of a paleointensity estimate obtained by this technique.

References

Aitken, M.J., Allsop, A.L., Bussel, G.D. and **Winter, M.B.** (1984) Geomagnetic intensity in Egypt and western Asia during the second millennium BC. *Nature* **310:** 305-306.

————. (1985) Matters arising: Re-evaluation of Greek archaeomagnetiudes, *Nature* **314:** 753.

Banetjee, S.K. and **Mellema, J.P.** (1974) A new method for the determination of paleointensity form the ARM properties of rocks, *Earth Planet. Sci. Lett.* **23:** 177-184.

Coe, R.S. (1967) Paleointensities of the Earth magnetic field determined from Tertiary and Quaternary rocks. *J. Geophys. Res.* **72:** 3247-3262.

Shaw, J. (1974) A new method for determining ancient geomagnetic field strengths: Application to five historic lavas, *Geophys. J. R. Ast. Soc.* **39:** 133-141.

Thellier, E. and **Thellier, O.** (1959) Sur l'intensite' du champ magnetique terrestre dans le passe' historique et geologique, *Ann. Geophys.* **15:** 285-367.

Van Zijl, J.S., Graham, K.W. and **Hales, A.L.** (1962) The paleomagnetism of the stormberge lavas of South Africa, Parts I & II, *Geophys. J.R. Ast. Soc.* **7:** 23-29.

Walton, D. (1983) The reliability of ancient intensities obtained by thermal demagnetization *in:* **Creer, K.M., Tucholka, P.** and **Barton, C.E. (ed.),** *Geomagnetism of Backed Clays and Recent Sediments,* Elsevier, New York, 78-87.

————. (1984) Re-evaluation of Greek Archaeomagnitudes, *Nature* **310:** 740-743.

————. (1985) Reply to comment by Aitken *et al.*, *Nature* **314:** 753-754.

————. (1988) The lack of reproducibility in experimentally determined intensities of the Earth's magnetic field, *Reviews Geophys.* **26:** 15-22.

قيـــاس الشـــدة القـــديمة بطريقـــة ثاليـــيه
معيار جديـــد لـمُعَوَّليـــة نتـــائج القيـــاس

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المملكة العربية السعودية

المستخلص . من صور القصور في طريقة ثالييه لتحديد الشدة القديمة ، افتقارها إلى شواهد محددة يمكن بها تقويم دقة النتائج المتوصل إليها . فاستقامة منحنيات المغنطيسية المتبقية الطبيعية ، والمغنطيسية المتبقية الحرارية والتي هي من ضروريات السلوك المثالي ، قد ثبت بالتجربة أنها غير كافية لذلك . وعليه ، فإننا نقترح متجها يمكن تحديد حقله القديم بأكمله فيه (الشدة والاتجاه) باستخدام طريقة ثالييه . وفي هذه الطريقة ، يمكن تحديد دقة تقدير الشدة بالتجانس الداخلي لكل عينة على حدة ، ولكل العينات المدروسة من صخرة واحدة ، وعلى أساس من التوافق بين الاتجاهات المحددة بالتجربة ، وتلك الثابتة للمغنطيسية الطبيعية المتبقية . وقد أوضحت نتائج اختبار هذه الطريقة صلاحيتها لكلٍّ من البيانات الحقيقية والمجمعة .