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Further details on the applicability of Thellier paleointensity method: The effect of magnitude of laboratory field

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Abstract

Twenty years after Tanaka and Kono's pioneering contribution (Tanaka and Kono, 1984), we give some new details on the effect of applied field strength during Thellier paleointensity experiments. Special attention is paid to the relation of magnitude of laboratory field and Coe's quality factors (Coe et al., 1978). Full thermoremanent magnetizations were imparted on natural samples containing low-Ti titanomagnetites of pseudo-single domain structure in a 40-μT magnetic field from 600 °C to room temperature. The samples were subjected to the routine Thellier procedure using a wide range of applied laboratory fields. Results indicate that values of laboratory fields may be accurately reproduced within 2% of standard error. The quality factors, however, decrease when the magnitude of 'ancient' field does not match to applied laboratory fields. ***To cite this article: J. Morales et al., C. R. Geoscience 338 (2006).***

Résumé

Nouveaux détails sur l'applicabilité de la méthode de paléointensité de Thellier : l'effet de l'intensité du champ en laboratoire. Vingt ans après la contribution pionnière de Tanaka et Kono (Tanaka et Kono, 1984), nous donnons de nouveaux détails sur l'effet de l'intensité du champ appliqué au cours d'expériences de paléointensité de Thellier. Une attention particulière est apportée à la relation de l'intensité de champ en laboratoire et des facteurs de qualité de Coe et al. (Coe et al., 1978). L'ensemble des l'aimantation thermorémanentes ont été imparties aux échantillons naturels contenant des titanomagnétite pauvres en titane et de structure en pseudo-mono-domaine, dans un champ magnétique de 40 μT, depuis 600 °C jusqu'à la température ambiante. Les échantillons ont été soumis à la procédure de routine de Thellier, utilisant une vaste gamme de champs appliqués en laboratoire. Les résultats indiquent que les valeurs de champ en laboratoire peuvent être reproduites avec précision, avec une marge d'erreur de 2%. Cependant, les facteurs de qualité diminuent lorsque la magnitude de champ « ancien » n'est pas similaire aux champs appliqués en laboratoire. ***Pour citer cet article : J. Morales et al., C. R. Geoscience 338 (2006).***

Keywords: Paleointensity; Thellier method; Rock magnetism

Mots-clés : Paléo-intensité ; Méthode de Thellier ; Magnétisme des roches

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1. Introduction

Absolute paleointensity data provide an important source of information on the physics of the Earth's deep interior. Despite more than forty years of research, paleointensity data are scarce [9,17,19,22] and they cannot be yet used to document a long-term variation in the intensity of the Earth's magnetic field through geological time. The major reason for this small number of determinations is that paleointensity is the most difficult component of the magnetic field to determine and that the failure rate is often large, in general of the order of 80% [2,12].

The Thellier method [23] is currently considered as the most reliable technique to retrieve the absolute intensity of geomagnetic field [8,15] from volcanic rocks and archaeological material. Although numerous methodological studies (e.g., [2,4,5,10–13,20,21]) were devoted to investigate the causes of failure and its prevention, the problem is still not fully understood.

Recent critical analyses of paleointensity variation trough time [1,9] indicate that all reported data might differ by a factor of 2 or 3 from present-day strength. During geomagnetic reversals or excursions, however, the paleointensity may decrease by a factor of 5 to 8 [3,8,18]. The laboratory field used during Thellier experiments may frequently differ from true geomagnetic paleointensity. In this note, we report new high-quality experimental data to evaluate the effect of applied field on the quality of paleointensity determination.

2. Samples and laboratory procedures

Samples used in this study belong to three independent, Late Quaternary lava flows from Chichinautzin volcanic field in Central Mexico [14]. The main magnetic carriers are low-Ti titanomagnetites as evidenced by reasonably reversible susceptibility versus temperature curves. On the other hand, the ratios of hysteresis parameters point out that all samples fall in the pseudo-single domain grain size region, probably indicating a mixture of multidomain and a significant amount of single-domain grains (more detailed description of samples are reported in Morales et al. [14,15]). The natural remanence of these samples is characterized by stable univectorial magnetization, observed upon both alternating field and thermal treatments. The median destructive fields (MDF) range mostly from 50 to 70 mT, suggesting 'small' pseudo-single domain grains as remanent magnetization carriers [7].

The full TRM's (thermoremanent magnetizations) were imparted to previously AF (alternating field)-treated samples from 600 °C to room temperature in a 40-μT magnetic field. Thellier experiments in their modified form [6] were carried out on each set of samples using 10-, 20-, 40-, 60- and 80-μT laboratory fields, respectively. Finally, the extreme case was also investigated: a full TRM was imparted on 16 samples in a 10-μT magnetic field while the laboratory field was set to 80 μT. Ten to 16 double-heating steps were distributed between room temperature and 600 °C, according to the sample's blocking temperature spectra [14]. Several control heating steps (commonly referred as partial TRM checks (pTRM checks)) were performed throughout the experiment. Remanence measurements were made using both AGICO Ltd. JR5 and JR6 spinner magnetometers.

3. Results

Paleointensity data are reported on Arai-Nagata [16] plots in Fig. 1 and in Tables 1 and 2. The accepted determinations fulfill the following conditions: (1) at least 8 NRM–TRM points, corresponding to a NRM fraction larger than 0.4 (Tables 1 and 2); (2) a quality factor q [6] of about 8 (a minimum value obtained in this study, excepting two cases) or more. The q factor is related to f (remanence fraction used to determine paleointensity) and g (the gap factor) by following expression: $q = fgm/\delta m$, where m is slope of the best fit line adjusted to the 'NRM'–TRM points and δm is the standard deviation of the slope; and (3) positive 'pTRM' checks (i.e. pTRM checks must agree with the original pTRM data within 15%).

The magnetic field of 40 μT used to impart most of TRM's was very accurately reproduced by paleointensity determination in each case. Standard error of the mean (S.E.) does not exceed 2% of the expected value in any of the cases. For these samples, the 'NRM' fraction $\boldsymbol{f}$ used for determination ranges between 0.774 to ~ 1.0, except for two cases; and the quality factor $\boldsymbol{q}$ varies from 8.4 to 84.6, except for two cases (Table 1). It should be noted that when the strength of applied laboratory field matches to 'ancient' field intensity, the mean q value is at least 30% higher. The same is true for f and g factors, respectively. Moreover, the combination of these latter factors yields the same pattern as the q factor alone (Fig. 2).

In the specific case in which TRM's were imparted in 10 μT and the laboratory field was set to 80 μT, the intensity was also precisely reproduced (S.E. $< 0.2\%$, Table 2, Fig. 3). It is quite evident that the intensity of the magnetic field may be reproduced even if the magnitudes of 'ancient' and laboratory fields differ too much.

Table 1
Experimental results. n, Number of 'NRM'–TRM points used for determination; m, slope of the best fit line adjusted to the 'NRM'–TRM points; δm, standard deviation of the slope; $H_{\text{lab est}}$, estimated strength of the laboratory field intensity used to create the full TRM; $\delta H_{\text{lab est}}$, associated error of $H_{\text{lab est}}$; f, g and q fraction of extrapolated NRM used for intensity determination, gap and quality factor [6], respectively; and H_{lab}, laboratory field intensity employed in each experiment (10, 20, 40, 60, and 80 μT)

Tableau 1
Résultats expérimentaux. n, Nombre de points « NRM »–TRM utilisés pour la détermination ; m, pente de la droite la mieux ajustée aux points « NRM »–TRM ; δm, déviation standard de la pente ; $H_{\text{lab est}}$, intensité au champ estimée, utilisée pour créer TRM total ; $\delta H_{\text{lab est}}$, erreur associée à $H_{\text{lab est}}$; f, g et q ; fraction de NRM extrapolé utilisée pour la détermination de l'intensité, de groupement et de qualité facteurs [6], respectivement et H_{lab}, intensité de champ en laboratoire, utilisée dans chaque expérience (10, 20, 40, 60 et 80 μT)

TRM (600 °C, 40 μT, T0)								
Sample	n	m	δm	$H_{\text{lab est}}$ [μT]	$\delta H_{\text{lab est}}$ [μT]	f	g	q
$H_{\text{lab}} = 10$ μT								
JJ2Y	10	−3.8130	0.2220	38.130	2.220	0.8550	0.8200	12.030
JJ8	*10*	*−3.8944*	*0.7475*	*38.944*	*7.475*	*0.9307*	*0.4916*	*2.384*
JJ10	*10*	*−4.1000*	*0.9020*	*41.000*	*9.020*	*0.9320*	*0.5990*	*2.537*
JJ11V	11	−4.1325	0.4000	41.325	4.000	1.0052	0.8049	8.360
JJ11X	11	−4.1295	0.0630	41.295	0.630	0.9841	0.8544	55.105
JJ11Y	11	−4.1648	0.1586	41.648	1.586	0.9779	0.8519	21.873
JJ11Z	11	−4.1669	0.1367	41.669	1.367	1.0010	0.8515	25.976
JJ12	12	−4.4834	0.1495	44.834	1.495	1.0013	0.8702	26.446
Mean		−4.111	0.347	41.11		0.961	0.768	19.34
S.E. =				0.71		0.018	0.050	6.16
$H_{\text{lab}} = 20$ μT								
JH10Y	8	−1.8400	0.1000	36.800	2.000	0.8084	0.7890	11.736
JH10Z	9	−1.9500	0.1000	39.000	2.000	0.9487	0.8014	14.825
JH11U	8	−2.1400	0.0840	42.800	1.680	0.8822	0.7218	16.223
JH11Y	9	−1.9200	0.0700	38.400	1.400	0.9140	0.8477	21.252
JH12Y	9	−1.9100	0.1400	38.200	2.800	0.9095	0.8657	10.742
JH14Y	9	−1.9900	0.0980	39.800	1.960	0.9010	0.8434	15.431
JH15	9	−2.1500	0.1500	43.000	3.000	0.5972	0.8451	7.233
JH17Z	8	−2.0300	0.1200	40.600	2.400	0.8738	0.8424	12.452
Mean		−1.991	0.108	39.83		0.854	0.820	13.74
S.E. =				0.78		0.039	0.017	1.49
$H_{\text{lab}} = 40$ μT								
JJ2Y	11	−1.0169	0.0188	40.676	0.752	1.0010	0.8770	47.500
JJ8	11	−1.0229	0.0271	40.916	1.082	0.9970	0.8250	31.000
JJ10	10	−1.0600	0.0120	42.408	0.480	0.7210	0.8700	54.040
JJ11V	11	−0.9689	0.0097	38.756	0.388	0.9690	0.8750	84.590
JJ11X	11	−1.0850	0.0126	43.400	0.502	0.9710	0.8520	71.500
JJ11Y	11	−1.0121	0.0143	40.486	0.573	0.9900	0.8760	61.250
JJ11Z	11	−1.0204	0.0109	40.814	0.436	0.9910	0.8680	80.580
JJ12	11	−1.0386	0.0115	41.543	0.460	0.9990	0.8640	78.040
Mean		−1.028	0.015	41.12		0.955	0.863	63.56
S.E. =				0.49		0.034	0.006	6.57
$H_{\text{lab}} = 60$ μT								
JM5A	9	−0.6606	0.0216	39.636	1.296	0.9244	0.7909	22.401
JM6A	9	−0.6779	0.0250	40.674	1.500	0.7742	0.7843	16.453
JM7A	9	−0.7043	0.0196	42.258	1.176	0.7653	0.7826	21.533
JM9A	10	−0.6889	0.0136	41.334	0.816	0.9764	0.7537	37.197
JM10A	9	−0.7073	0.0165	42.438	0.990	0.8383	0.7858	28.174
JM11A	9	−0.6957	0.0168	41.742	1.008	0.8629	0.7720	27.634
JM12A	9	−0.6571	0.0251	39.426	1.506	0.9198	0.7657	18.454
JM12B	9	−0.6434	0.0197	38.604	1.182	0.9750	0.7095	22.549
Mean		−0.679	0.020	40.76		0.880	0.768	24.30
S.E. =				0.50		0.029	0.009	2.32

(*continued on next page*)

Table 1 (*continued*)

TRM (600 °C, 40 μT, T0)								
Sample	n	m	δm	$H_{\text{lab est}}$ [μT]	$\delta H_{\text{lab est}}$ [μT]	f	g	q
$H_{\text{lab}} = 80$ μT								
JH10Y	8	−0.5043	0.0106	40.344	0.848	0.5554	0.7995	21.130
JH10Z	8	−0.4856	0.0170	38.852	1.359	0.4179	0.7332	8.760
JH11U	11	−0.4826	0.0045	38.608	0.363	0.9843	0.7264	76.010
JH11Y	9	−0.4930	0.0072	39.441	0.576	0.9897	0.8113	55.120
JH12Y	11	−0.4966	0.0096	39.732	0.764	0.9938	0.8551	44.200
JH14Y	11	−0.5070	0.0066	40.558	0.532	0.9979	0.8253	62.810
JH15	11	−0.5364	0.0040	42.912	0.319	0.6893	0.8426	78.030
JH17Z	11	−0.4965	0.0106	39.722	0.845	1.0015	0.8312	39.290
Mean		−0.500	0.009	40.02		0.829	0.803	48.17
S.E. =				0.47		0.084	0.017	8.77

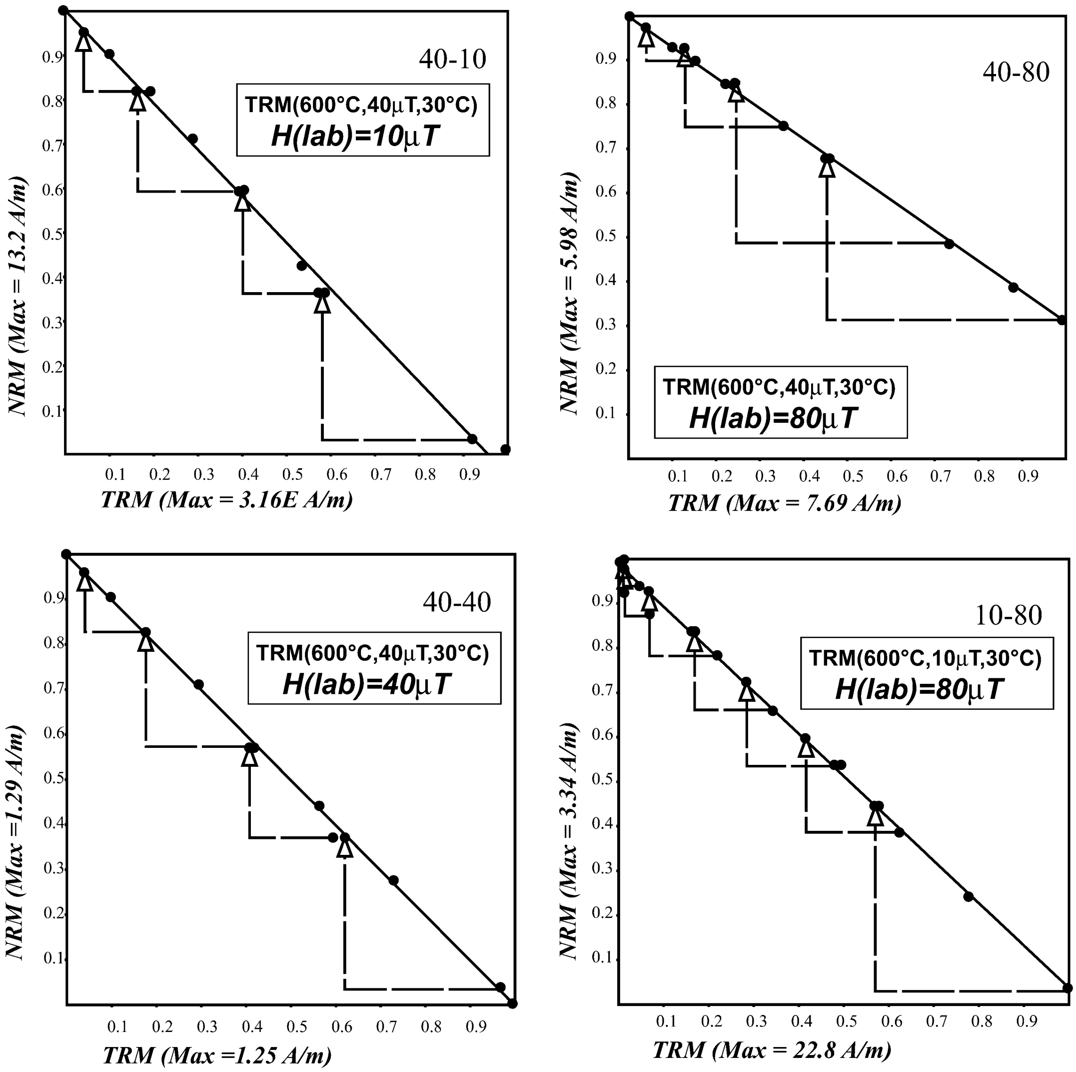

Fig. 1. Representative NRM–TRM plots for different set of samples (see also text).

Fig. 1. Diagrammes représentatifs NRM–TRM pour les différentes séries d'échantillons (voir aussi le texte).

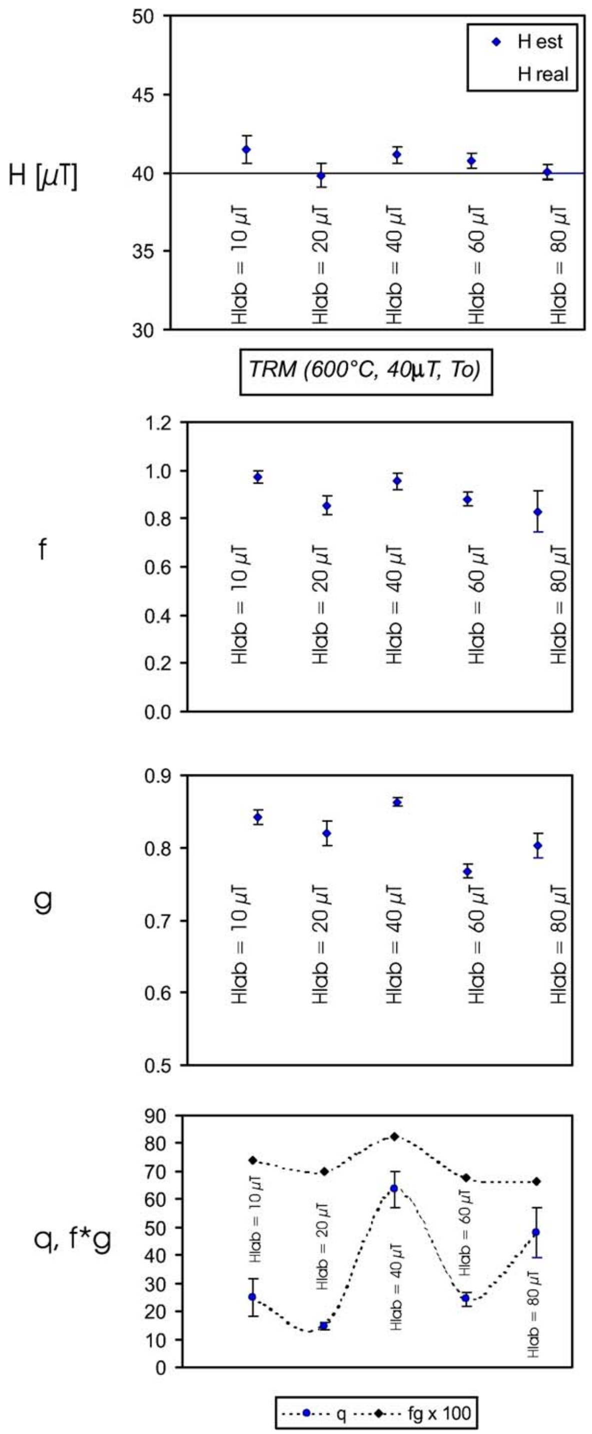

Fig. 2. Paleointensity and Coe's [6] quality factors versus applied laboratory field. The full TRM is produced under a 40-μT magnetic field from 600 °C to room temperature (see text for details).

Fig. 2. Paléointensité et facteurs de qualité de Coe et al. [6] en fonction du champ appliqué en laboratoire. TRM total est produit sous un champ magnétique de 40 μT, depuis 600 °C jusqu'à la température ambiante (voir le texte pour les détails).

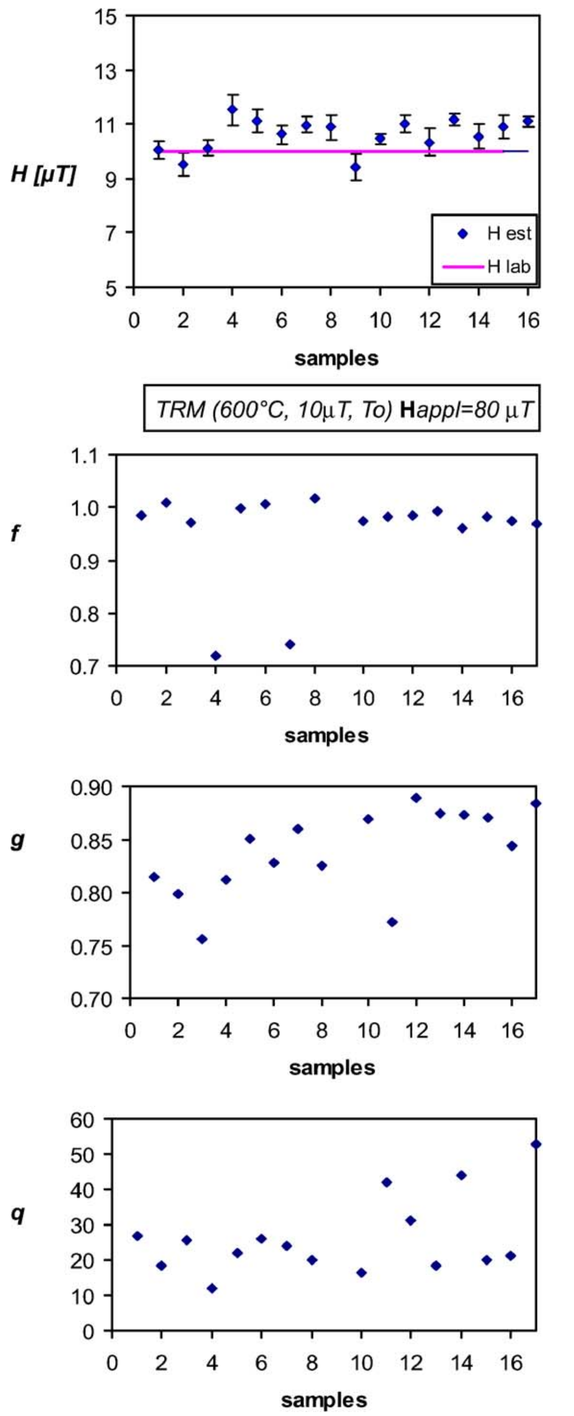

Fig. 3. Paleointensity and Coe's [6] quality factors for each one of the 16 samples. The full TRM is produced under a 10-μT magnetic field from 600 °C to room temperature and the laboratory field is set to 80 μT (see text for details).

Fig. 3. Paléointensité et facteurs de qualité de Coe et al. [6] pour chacun des 16 échantillons. TRM total est produit sous un champ magnétique de 10 μT, depuis 600 °C jusqu'à la température ambiante (voir le texte pour les détails).

Table 2
Same notations as in Table 1. The full TRM is produced under a 10-μT magnetic field from 600 °C to room temperature and the laboratory field is set to 80 μT

Tableau 2
Mêmes notations que dans le Tableau 1. TRM total est produit sous un champ magnétique de 10 μT depuis 600 °C jusqu'à la température ambiante, et le champ imposé en laboratoire est de 80 μT

Sample	n	m	δm	$H_{\text{lab est}}$ [μT]	$\delta H_{\text{lab est}}$ [μT]	f	g	q
$\text{TRM}_{\text{tot}} = 10$ μT	$H_{\text{lab}} = 80$ μT							
92H010A	15	−0.1257	0.0038	10.058	0.300	0.9844	0.8153	26.886
92H010B	15	−0.1189	0.0052	9.509	0.418	1.0090	0.7990	18.324
92H011A	15	−0.1264	0.0036	10.109	0.292	0.9714	0.7562	25.451
92H011B	13	−0.1440	0.0070	11.519	0.560	0.7185	0.8116	12.002
92H012A	15	−0.1391	0.0054	11.128	0.433	0.9993	0.8511	21.874
92H014A	15	−0.1328	0.0043	10.626	0.342	1.0015	0.8286	25.905
92H015A	15	−0.1373	0.0036	10.982	0.292	0.7399	0.8596	23.960
92H017A	15	−0.1360	0.0057	10.880	0.453	1.0017	0.8251	20.172
92J02A	16	−0.1177	0.0060	9.418	0.480	0.9729	0.8693	16.590
92J08A	16	−0.1309	0.0024	10.474	0.189	0.9815	0.7716	41.921
92J10A	16	−0.1377	0.0039	11.018	0.310	0.9858	0.8897	31.140
92J11A	16	−0.1293	0.0062	10.343	0.493	0.9933	0.8746	18.224
92J11B	16	−0.1393	0.0027	11.148	0.213	0.9613	0.8738	44.007
92J11C	16	−0.1320	0.0057	10.558	0.453	0.9816	0.8702	19.907
92J11D	16	−0.1362	0.0052	10.894	0.420	0.9735	0.8443	21.298
92J12A	16	−0.1389	0.0022	11.110	0.180	0.9690	0.8835	52.750
Mean ($H_{\text{lab est}}$) = 10.61								
S.E. = 0.15								

4. Conclusion

Results obtained in this study reinforce the general conclusion reached by Tanaka and Kono [21]. On the other hand, the quality of determination, expressed here as Coe's quality factors (Figs. 2 and 3), are significantly higher when the strength of the applied laboratory field matches the 'ancient' field intensity.

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