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Paleointensity of the earth's magnetic field during the Laschamp excursion and its geomagnetic implications

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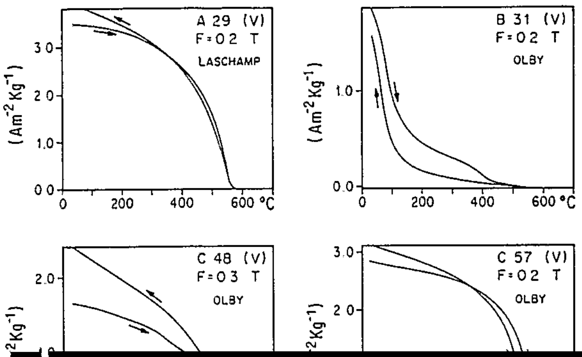
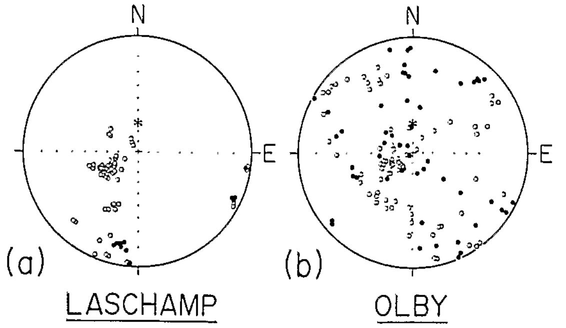
The reversed paleomagnetic direction of the Laschamp and Olby flows represents a specific feature of the geomagnetic field. This is supported by paleomagnetic evidence, showing that the same anomalous direction was recorded at several distinct sites, including scoria of the Laschamp volcano. To examine this anomalous geomagnetic fluctuation; we studied the paleointensity of the Laschamp and Olby flows, using the Thellier method. Twenty-five samples were selected for the paleointensity experiments, and from seven we obtained reliable results. Because the paleointensity results of the Olby and Laschamp flows as well as Laschamp scoria are very similar, they can be represented by a single mean paleointensity, $F = 7.7$ μT. Considering that this low paleointensity is less than 1/6 of the present geomagnetic field and is more characteristic of transitional behavior, our results suggest that the paleomagnetic directions of the Laschamp and Olby flows were not acquired during a stable reversed polarity interval. A more likely explanation is that the Laschamp excursion represents an unsuccessful or aborted reversal.

1. Introduction

When the Laschamp excursion was originally reported in 1967 by Bonhommet and Babkine [1] in two volcanic flows of Laschamp and Olby, it provided the first evidence for a possible short geomagnetic reversal in the Brunhes epoch. Since

Due to the rapid cooling and acquisition of thermal remanent magnetization (TRM) in extrusive igneous rocks, lavas often represent essentially an instantaneous recording of the geomagnetic field. Moreover, rocks with TRM can, in principle, be used for a complete description of the paleofield including both the intensity and the


A 29 (V)
F=0.2 T
LASCHAMP
B 31 (V)
F=0.2 T
OLBY
C 48 (V)
F=0.3 T
OLBY
C 57 (V)
F=0.2 T
OLBY
(Am^{-2}Kg^{-1})
600 °C


N
E
(a)
(b)
LASCHAMP
OLBY

[redacted]

TABLE 1

Summary of paleomagnetic directions of the reversed units

Extrusive unit	N	n	I (°)	D (°)	k	α_{95} (°)	Lat.	Long.
Laschamp	1	23 (28)	−66	241	120	3	−49	246
Olby	3	43 (53)	−68	231	162	2	−56	245
Laschamp Volcano (Scoria) [a]	1	6 (7)	−65	239	110	5	−46	245

N = number of sites; n = number of samples used in the mean calculation; the total number of samples studied is indicated in brackets; I, D = the mean inclination and declination; k = Fisher precision parameter; α_{95} = angular radius of the 95% cone of confidence of the mean direction; Lat., Long. = the VGP latitude and longitude.

[a] Data from Bonhommet [7].

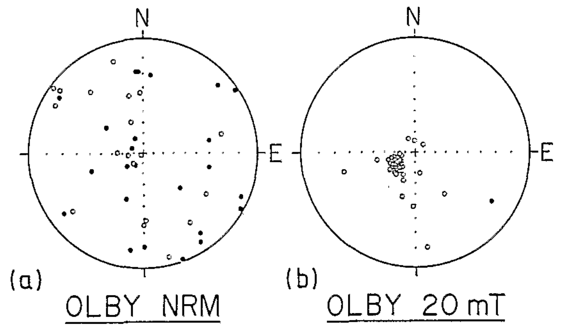


Fig. 6. Stereographic projections of paleomagnetic directions of Olby specimens. (a) NRM; (b) after AF demagnetization to 20

(2) For samples having more than one magnetic phase, the laboratory experiments show that the magnetic species with the lowest Curie point exhibits partial self-reversal by magnetostatic interaction. The reversed remanence has higher blocking temperature. Obviously, these observations do not imply the further proposition that the high-temperature reversed remanence was acquired by self-reversal. This interpretation is strongly supported by similar behavior observed in recent Colombian volcanic pumices which have very strong self-reversed components with very low un-

scoria samples whose oxidation state is higher than for the flows and where there is no evidence for significant contributions to the remanence by low T_C/high T_I phases. Moreover, a significant fraction of the remanence of these specimens resides in hematite. Fig. 7 shows that the reversed remanence in the scoria persists over the entire blocking temperature range from room temperature to above 650 ° C.

5.2. A contact test

The identification of similar reversed remanence in an igneous unit and the seiment it baked serves as key evidence supporting geomagnetic polarity reversals, because it is difficult to argue a self-reversal origin for the reversed polarity of both the igneous unit and the baked sediment. The presence of small fragments of baked clay under the Olby flow has been known for some time, because of the search for such material for thermoluminescence dating, but it was not possible to find enough material for a reliable paleomagnetic work. Only two oriented samples of baked sediment underlying the Olby flow were obtained. The intensity of magnetization of one sample was 0.06 A m^{-1}, and the NRM direction ($D = 240°$, $I = -40°$) was upwards. Upon stepwise thermal demagnetization there was a sharp drop in intensity (Fig. 8) at 250 ° C. However, the orthogonal projection diagram (Fig. 8) shows that the remanence direction remained upwards and southwest up to 550 ° C. The second sample had an NRM direction close to the first one, but

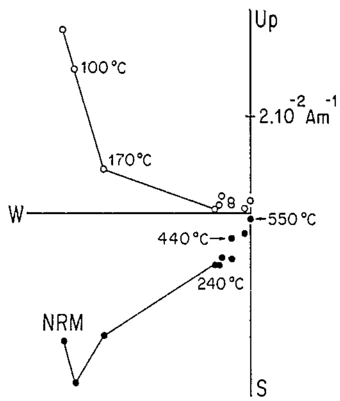


Fig. 8. Stepwise thermal demagnetization of sediment baked by the Olby flow. A southwest and upwards (reversed) direction is clearly observed. Symbols as in Fig. 5.

attempts to demagnetize it did not yield reliable results. Although, of course, these results are not sufficiently reliable to stand alone, they strengthen the case for a geomagnetic origin of the Laschamp excursion.

6. Paleointensity results

Before performing paleointensity experiments, we tried to select the most suitable samples. Generally, the criteria used in selecting samples for paleointensity studies were based on a low viscosity index, single high Curie temperatures and high degree of reversibility during strong field thermomagnetic analyses. In addition, NRM with minimum secondary overprinting is a very important selection parameter [17]. For example most of the Laschamp samples are not severely affected by secondary remanences, whereas for the Olby flow, only 1 core from site B, 3 from site D and 6 from site C satisfied this criterion. We note that 4 of the last 6 cores correspond to the top of the flow, which might have experienced more intense high-temperature oxidation during the initial cooling of the flow. In all, twenty-five samples were selected; all had a viscosity index less than 5% and a good reversibility in the strong field thermomagnetic measurements. During the Thellier experiments, the samples were treated with different procedures and various applied fields (10, 15, 20 and 40 μT). Two-thirds of the samples were rejected, because of concave-up NRM-TRM diagrams resulting from three causes:

(1) Progressive increase in the TRM capacity due to chemical changes during the heatings. This cause can usually be detected by the PTRM checks [6], which consist of measuring the PTRM acquired at a lower temperature after the sample was heated at a higher-temperature step. An increase or a decrease in the TRM capacity reflects a magnetic mineralogical change. This test appears necessary but still is not sufficient to assert a suitability of the sample.

(2) Paleointensity experiments on prepared samples composed of magnetite particles with different grain sizes have shown that multidomain grains can give rise to non-ideal behavior during Thellier experiments [18]. Even if the properties of the samples indicate that they contain mostly single- or pseudo-single-domain grains, the contri-

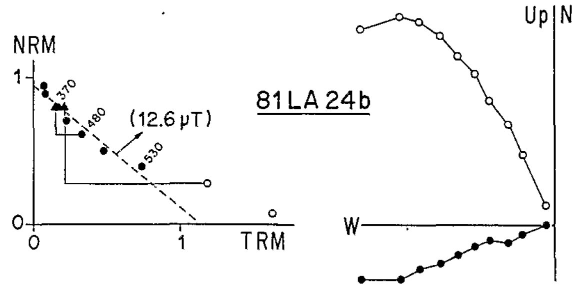


Fig. 9. Example of a NRM-TRM diagram of a Thellier paleointensity experiment with typical concave-up behavior but no large variations in the PTRM capacity at lower temperatures. The remanence direction rotates slightly towards a more upward characteristic inclination, showing that the NRM might not be a pure TRM at the lower temperatures. This is the reason we rejected samples with this type of behavior. (All the NRM-TRM diagrams are normalized by the total NRM.)

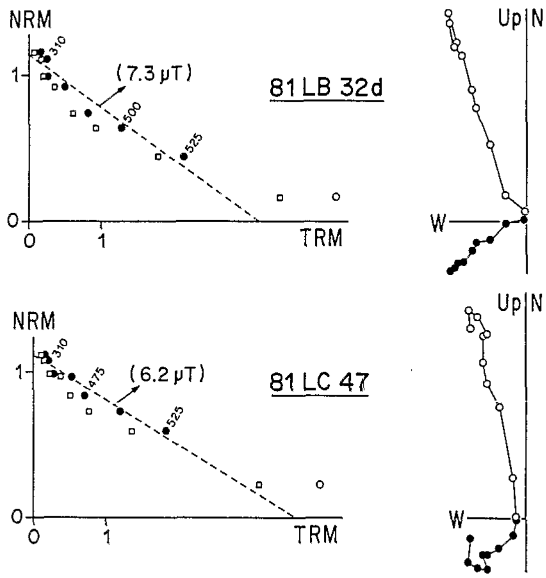


Fig. 10. NRM-TRM diagram of Thellier paleointensity experiments with the addition of 10 mT AF cleaning of the NRM (solid circles: no AF cleaning of the PTRM at each step; squares: 10 mT AF cleaning of the PTRM at each temperature step). Evolution of the NRM during thermal demagnetization is shown at right on a vector projection plot.

bution of some fraction of multidomain grains to the remanence might produce concave up behavior. Such behavior was observed for samples from Olby site D, for which no significant result was obtained.

(3) Even though samples with large secondary magnetizations were avoided, samples selected for paleointensity studies were not usually absolutely free from small secondary components, and they probably exhibited varying but minor amounts of VRM or IRM which alter the lower part of the temperature spectrum. An example is given by the sample LA24b (Fig. 9) where the progressive destruction of the secondary component induces a systematic shift of the remanence through the characteristic direction. In order to minimize this problem, an AF cleaning at 10 mT was introduced for the NRM and after each PTRM acquisition;

TABLE 2

Paleointensity results

Sample	J_{NRM} (A m^{-1})	D (°)	I (°)	N	T_{min} (°C)	T_{max} (°C)	f	g	q	F_{lab} (μT)	F (μT)
81LA27a	1.70	237	−60	6	230	525	0.593	0.605	4.3	40	7.7
81LA28b	2.03	251	−69	6	300	530	0.545	0.697	6.0	15	8.5
81LC46	1.85	221	−75	11	240	530	0.355	0.889	12.6	10	7.5
81LC48b	1.04	188	−76	8	230	550	0.698	0.818	12.6	15	5.7
81LC57c	1.15	258	−61	15	150	540	0.341	0.891	6.1	10	10.6
SC303a	1.52	226	−65	7	270	590	0.920	0.629	16.8	20	7.3
SC303b	0.98	217	−63	7	270	590	0.860	0.717	11.0	20	6.4

Mean: 7.7 ± 1.6 μT

J_{NRM} = intensity of the magnetization; D, I = declination and inclination of the NRM in the $T_{min}-T_{max}$ interval. T_{min}, T_{max} = minimum, maximum temperature; N = number of points in the $T_{min}-T_{max}$ interval used to determined the paleointensity; f, g, q = NRM fraction, gap factor and quality factor respectively [39]; F_{lab} = laboratory field (μT) applied during the experiment; F = the paleointensity.

Samples 81LA27a and 81LA28b from Laschamp site A; 81LC46, 81LC48b, 81LC57c: Olby site C; SC303a and SC303b are two specimens from a block of scoria of the Laschamp volcano.

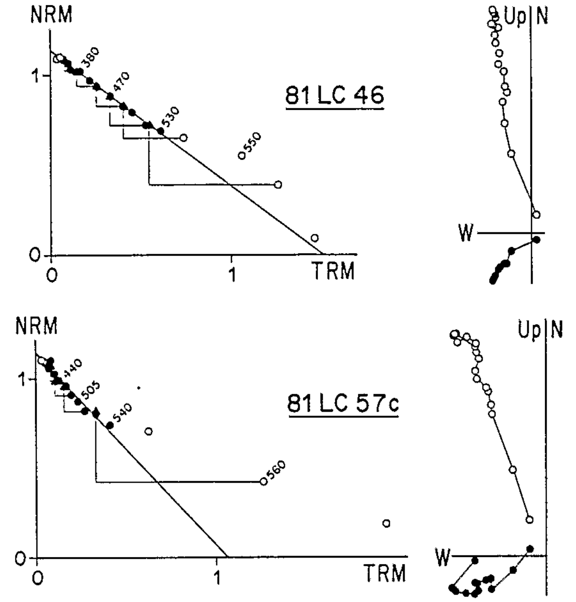


Fig. 11. Paleointensity results by the original Thellier method for two samples from Olby site C. Black dots correspond to points used to calculate the slope. Triangles represent PTRM checks. Thermal demagnetizations of the NRM are shown as the orthogonal plots.

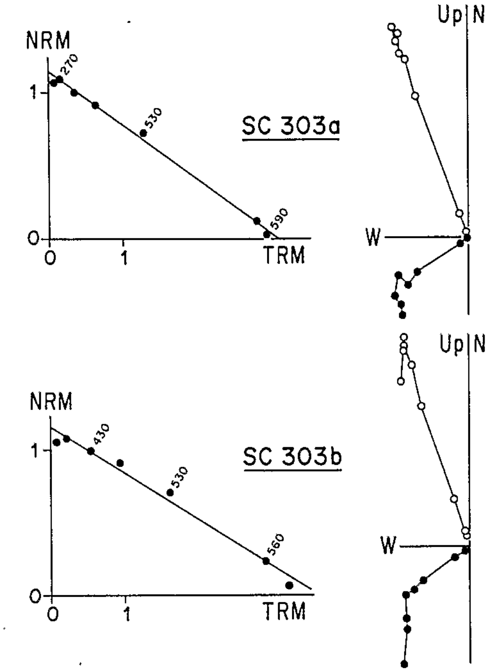


Fig. 12. Paleointensity results, using the Coe version of the Thellier method, for two specimens of a scoria block from the Laschamp volcano. Symbols and conventions as in Fig. 11.

this procedure was tried on 6 specimens. Fig. 10 shows two examples for which an AF cleaning was performed. The circles correspond to the PTRMs before cleaning and the squares correspond to the cleaned PTRMs. This procedure, even though it allows a better determination of the primary natural remanence, does not improve the linearity of the NRM-TRM curve, as previously noted by Coe and Grommé [19]. Although we decided not to consider these results, it is interesting to notice that these samples provide a paleointensity (i.e. the slope of the dashed line, Fig. 10) close to the mean determined for the 7 chosen samples.

Table 2 and Figs. 11, 12, 13 summarize the paleointensities of the best seven specimens. In order to show that these samples possess remanence, the evolution of the NRM during the demagnetization is shown on the right of each NRM-TRM diagram either as orthogonal vector projections or equal area stereoplots. Samples LC46 and LC57c (Fig. 11) were treated by the original Thellier method using numerous steps. Sample LC46 provides a very good determination of the paleointensity. Two specimens from a block of scoria from the Laschamp volcano also provide

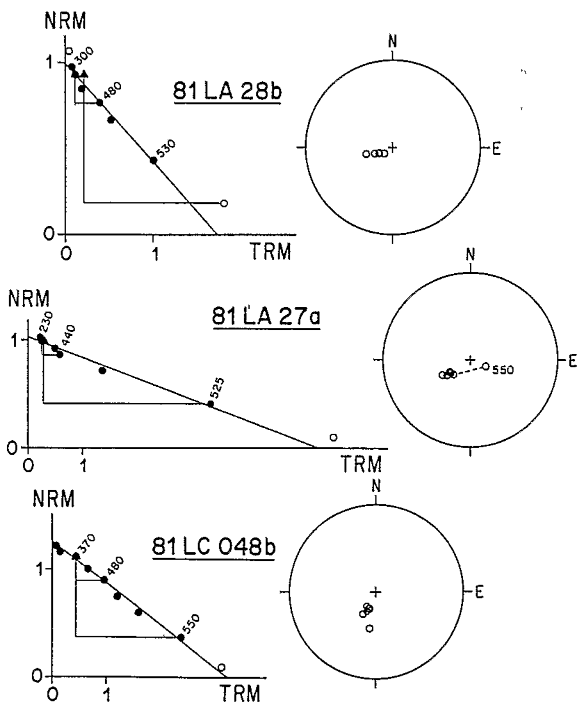


Fig. 13. Paleointensity results by the Coe version of the Thellier method; the evolution of the NRM thermal demagnetizations is shown on an equal area projection.

was not thermally reactivated at the time when the second direction was recorded. Barbetti and McEhlinny [26] dismissed the lightning hypothesis, but they recognized that the shape of the AF demagnetization curve of the natural remanent magnetization was not incompatible with an isothermal origin for the remanence associated with the Lake Mungo intermediate directions. Moreover, the two main directions have a spatial distribution at the site with a maximum paleointensity which occurs at the center of the site for both directions. In the end, perhaps an external magnetic origin such as lightning might explain the Lake Mungo excursion. This interpretation would remove the difficulty of explaining such intense intermediate fields, which are generally not found during polarity transitions.

Excursions recorded in sediments. Critical reviews by Verosub [5] and Merrill and McEhlinny [3] suggest that most of the excursions inferred in late Pleistocene are inconclusively supported and probably not of geomagnetic origin. Recent secular variation studies on lake sediments up to 30,000 years show no evidence for geomagnetic excursions in this period [27,28]. The best supported excursion seems to be the Mono Lake excursion [29,30], with an age estimate of 25,000 years, more

8. Discussion

The low paleofield recorded at Laschamp is consistent with those obtained during polarity transitions [17], excursions and aborted reversals [35–37]. Moreover, the very low paleointensity values of the Laschamp and Olby flows suggest that during the Laschamp excursion the reversed polarity state was not fully established. The first phase of a polarity transition is usually characterized by a large decrease in the intensity of the main dipole field [17]. During this first step, interferences with the non-dipole field might produce regional transitional directions while the main field was still dipolar, with normal polarity but lower strength. If the attempted reversal failed before the destruction of the main field was completed, the excursion might not be observed everywhere. Paleointensity determinations on dated lavas from the Chaîne des Puys, in the period following the Laschamp excursion, indicate an intensity of paleofield which was two-thirds of the mean archeomagnetic field [38]. This fact supports an anomalous behavior of the geomagnetic field at that time. The major importance of the Laschamp excursion is the observation of recent unstable geomagnetic behavior. Its local, regional or global extent as well as its time span might aid in con-

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