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Low paleosecular variation at the equator: a paleomagnetic pilgrimage from Galapagos to Esterel with Allan Cox and Hans Zijderveld

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Abstract

McFadden and Merrill (1995) suggested that the paleosecular variation (PSV) measured by the angular scatter of the virtual geomagnetic pole is minimal at the equator and should be smaller during a superchron than during the last 5 Myr. We revisited a key site of the 0–5 Ma database, the Galapagos archipelago, studied by Allan Cox in the early sixties. We obtained 79 sites with reliable mean directions on four islands (San Cristobal, Floreana, Santa Cruz and Pinzon), showing a larger proportion of transitional data than Cox (16 instead of 6%), because the sampling was concentrated on the Brunhes-Matuyama transition as delimited by Cox. This dataset allowed us to test the statistical method of Vandamme (1994) to separate PSV from transitional data. We obtained an angular scatter value of 11.2° (9.9–12.9°), instead of 16.8° for an a-priori rejection angle of 40°, compared with the 12.7° predicted from the global compilation (McFadden et al. 1991). Studies of sequences of lava flows are quite scarce in the Permian Kiaman Superchron, and the Esterel volcanics with their subequatorial paleolatitude are a good candidate to test the above prediction. We confirm the quality of the original data of Zijderveld (1975) and we improved the mean direction from one site. We also used new geological and geochronological data: Ar/Ar ages point to the period 264–278 Ma for a totally reversed volcanic sequence, in agreement with an ending of the Kiaman Superchron at 262–268 Ma. The extremely low angular scatter obtained (4 to 8°, depending on data selection) confirms the prediction, but an alternative interpretation invoking a post-volcanic Permian remagnetization is discussed.

Abbreviations: AF – alternating field, ARM – anhysteretic remanent magnetization, ASD – angular standard deviation, CRM – chemical remanent magnetization, GPS – global positioning system, MGF – main geomagnetic field, NRM – natural remanent magnetization, PSV – paleosecular variation, TRM – thermoremanent magnetization, VGP – virtual geomagnetic pole

Introduction

This paper is a tribute to two 'fathers' of modern paleomagnetism, Allan Cox who prematurely deceased ten years ago, and Hans Zijderveld. Although all we owe to these colleagues is by far sufficient to talk about their work as still living science, we may first explain the scientific argument connecting their respective studies on Galapagos (Ecuador) and Esterel (France), together with new data we obtained recently after revisiting their sites.

The definition of the spatial and temporal features of paleosecular angular variation (PSV) of the main geomagnetic field (MGF) has been a steady issue for the past 40 years (Merrill & McElhinny 1983; Courtillot & Valet 1995). This is needed to assess the reliability of paleomagnetic poles in tectonic studies, and in addition we hope that it will tell us something about the long-term behavior of the geodynamo. The present status of the subject is mainly illustrated by McFadden et al. (1991) and McElhinny et al. (1996a). These authors produced a global picture of PSV structure following the ideas of, for example, Cox (1970), Brock (1971), and Irving & Pullaiah (1976), but with a much improved database and theoretical background. They built a database of global paleomagnetic directions

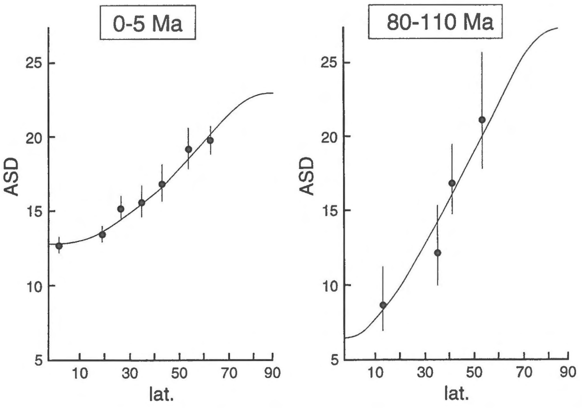

Figure 1. Angular standard deviation of VGP from latitudinal bands for the 0–5 and 80–110 Ma periods, after McFadden et al. (1991).

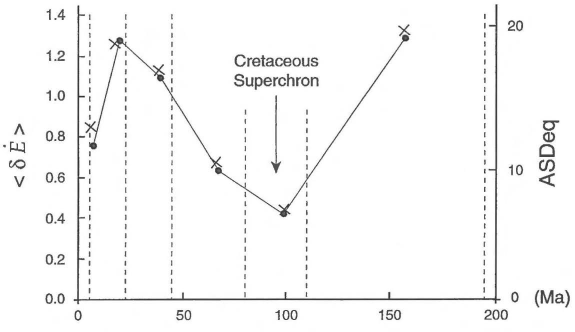

Figure 2. Global PSV estimates versus time: ASD surface integral < dE > (dots, after McFadden & Merrill 1995) and ASD at the equator (crosses derived from McFadden et al. 1991). Dashed lines indicate the time interval considered for each point.

from lava flows to deal with instantaneous and not-biased readings of the geomagnetic field. For a given period of time they grouped the dataset in latitudinal bands and calculated the angular standard deviation (ASD) of the virtual geomagnetic poles (VGP) set (two examples are shown in Figure 1). The structure of the results is interpreted as resulting from a combination of two families: the 'secondary' or symmetric (with respect to the equator) family with invariant ASD versus latitude, such as created by a wobbling dipole, and the 'primary' or antisymmetric family with zero ASD at the equator. For an updated discussion of these questions one may refer to Hulot & Gallet (1996) and Quidelleur & Courtillot (1996).

It appears that the PSV as measured either by a surface average of ASD (McFadden & Merrill 1995) or by the ASD at the equator, i.e. the ASD of the secondary family, is changing significantly over geological time (Figure 2) . This clearly supports the suggestion of Brock (1971) that long-term trends in PSV intensity and reversal rate are correlated. In particular, the PSV is minimal during the Cretaceous Superchron, about half of the PSV for the past 5 Myr, and about a third of the PSV for the period of maximum reversal rate (5–22.5 Ma). McFadden & Merrill (1995) derived from this evidence the hypothesis that two regimes of the geodynamo exist with different physics behind: a standard reversing one, and a non-reversing one acting during superchrons. The discussion of this hypothesis versus a simpler one invoking a single geodynamo regime but with more or less strong instabilities is beyond the scope of this paper and does not interfere with the following discussion.

On the other hand, the question of a similar PSV behavior during the Permian Kiaman Superchron immediately arises, as this superchron lasted approximately twice as long as the Cretaceous Superchron. McFadden & Merrill (1995) stopped back in time at 195 Ma because of the scarcity of data, the lower reliability of the results in terms of primary nature of the natural remanent magnetization, and because of poor control on paleolatitudinal drift and tectonic tilting. Irving & Pullaiah (1976) produced indeed PSV averages that were similar for both superchrons and lower than the values for the past 80 Myr, but with serious doubts on the reliability of the results.

This paper proposes a more modest but straightforward approach to answer this question by comparing the PSVs obtained for two equatorial volcanic regions, one active during the past 2 Myr and the other during the Permian, i.e. the Galapagos islands and the Esterel, respectively. A recapitulation of abbreviations used is given in the Appendix.

Methodology for paleosecular variation estimation

The basic requirement for a directional paleosecular database is to obtain paleomagnetic directions that are truly representative of the instantaneous field, i.e. with natural remanent magnetizations (NRM) acquired with a delay of the order of one year or less, no directional bias, a good control that secondary magnetizations are absent after adequate demagnetization, and a sufficient precision of the Fisher statistics on sites with several samples. Other main requirements are good age control and a reliable geographic position of the site at the time of NRM acquisition, as well as control on the paleohorizontal plane. Hence, data from lava flows carrying a thermoremanent magnetization (TRM) and treated with the standard paleomagnetic techniques are mandatory. A main problem is the tectonic correction in rocks old enough to have been tilted and eventually folded. The bedding plane is quite difficult to measure precisely on a lava flow; moreover, tilt correction usually leaves a larger error on declination than on inclination. Cretaceous and Permian rocks will surely have an increased part of measured ASD that results from tectonic instead of geomagnetic origin. We consider three other important points for the present study:

1. The TRM acquisition time span will increase with flow thickness. As a rule of thumb, one may consider that 1, 10 and 100-m-thick flows acquire their TRMs in the order of a few 10^{-2}, 1 and 10^2 years, respectively (Jaeger 1967). Therefore a suitable lava flow should be at most a few tens of meters thick, otherwise the ASD may be underestimated.
2. Anisotropy studies in lava flows usually reveal a very low anisotropy ratio excluding any directional bias (Tarling & Hrouda 1993). In acidic ignimbritic flows and tuffs, however, the anisotropy can be high, thus producing a significant inclination error.
3. After emplacement, a volcanic rock may have undergone alteration through hydrothermal circulation, and longer-term processes such as devritrification. Apart from alteration occurring above the Curie point, other effects will result in a chemical remanence (CRM) responsible for a longer acquisition time and thus again a bias in the estimation of the ASD.

These points raise the question of the exclusion of data from acidic rocks from the database as they are usually thicker, more anisotropic and more prone to alteration because of their richness in fluids and glass.

Choosing equatorial sites has the major advantage that around the equator the ASD is independent of latitude so that the control on the exact latitude is less important and one may safely compare data from the 0 to 15° bands, thus potentially offering more volcanic area in the analysis.

Now what is our reason to compare specific volcanic areas instead of latitudinal bands as was done by McFadden et al. (1991)? Strictly speaking, the assumption of these authors that a VGP set from the same latitudinal band truly represents temporal variation of the main geomagnetic field (MGF) is only valid if this field is a wobbling dipole. Otherwise, the ASD derived from this method will be a mixture of spatial and temporal variations. For example, the combination of two steady zonal harmonics, the axial dipole and quadrupole terms, leads to a consequent VGP scatter with zero temporal variation of the MGF. There is sufficient evidence for non-dipolar terms of the order of 10% of the dipolar terms, with a non-zero temporal average (e.g. far-sided effect; see Schneider & Kent 1990), to be seriously worried by this problem. Recent but controversial (see McElhinny et al. 1996b) suggestions of longitudinal dependence of the MGF characteristics may also plead against the latitudinal-band approach. The reason for that approach was to be able to compile data which were otherwise not numerous enough to constitute a good PSV estimate at the regional scale, and to overcome the bias introduced by the unknown temporal irregularities in local magmatic activity. However, it assumes that the paleolongitude and paleolatitude of the sites are precisely known. Clearly, this is not possible for Permian sites. Even the paleolatitude is available only if the regional dataset is large enough to obtain an average direction where the PSV has been cancelled out, assuming that the mean field is a geocentric axial dipole. Therefore, we believe that obtaining reliable ASD values on a regional basis before eventually trying to combine data on a latitudinal band, is a safer method to discuss the temporal structure of the MGF. Nevertheless, to be able to compare our data to those of McFadden et al. (1991), we will still use the same methodology by calculating the ASD of the VGP. This raw ASD will be corrected for the within-site ASD using an average within-site dispersion of 10° and a sample number of 8. Taking into account the actual dispersion in each site does not make significant changes.

Another difficulty in PSV studies is the way to separate the normal secular variation from excursional and transitional data. The standard approach is to choose an a-priori cutoff angle A below which the angle between the long-term averaged field and a given flow direction will point toward the normal PSV. The normal PSV is assumed to be a Fisher distribution (the ASD being derived from the Fisher statistics parameters), while excursional, transitional and spurious data may be considered as random noise (e.g. Prévot & Camps 1993). Assuming that real data is a mixture of a Fisher distribution and a small percentage of random noise leads to the conclusion that a fixed angle A (40° in McFadden et al. 1991) will produce an over- or underestimate of the ASD (Figure 3a), depending on the true ASD value. Therefore, Vandamme (1994) proposed a recursive method to adapt the angle A to the effective ASD value of the Fisher distribution, with the empir-

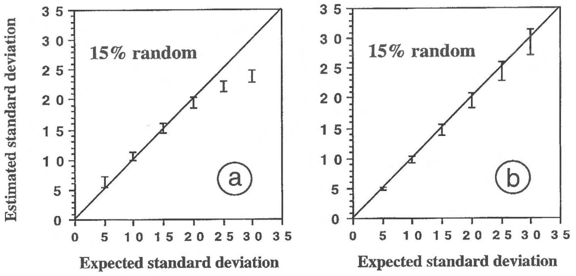

Figure 3. Estimated versus expected ASD of simulated datasets adding 15% of random noise to a Fisher distribution of the expected ASD; a) with an a-priori cutoff angle of 40°, b) using the recursive method of Vandamme (1994).

ical law $A = 1.8 \times \text{ASD} + 5°$ (1), derived from the analysis of simulated distributions. The method is simply to calculate an ASD of the whole dataset, then to calculate A from relation (1), discard the 'non-PSV' directions, recalculate the ASD, and redo the process until A is stabilized, which usually occurs after less than five steps. The effectiveness of this method has been demonstrated on simulated datasets (Figure 3b), and we will present here its ability to separate the PSV from transitional directions in the Galapagos dataset. Finally, we may note that at a regional scale, the cut-off angle refers to the mean VGP, while for a latitudinal band it refers to the geographic pole, thus assuming that the mean MGF is a geocentric axial dipole and that the plate movement reconstruction is sufficiently accurate. Again, this is an argument in favor of the present approach, provided that the regional dataset is robust enough to estimate the mean MGF correctly.

Geology, previous and present sampling

Galapagos

The Galapagos islands are situated within ± 1.5° of the equator on the Nazca plate, 2° south of the Galapagos spreading center. They have formed above an active hot spot in the past 3 Myr (White et al. 1993). As the 'stratotype' of Darwin's theory of evolution, this remote volcanic archipelago has received considerable interest from biologists. This pushed earth scientists to precisely date the formation of all islands, in an attempt to measure the rate of evolution. In the early sixties, the K/Ar method on young potassium-poor basalts was tedious and magnetostratigraphy appeared as a more productive way to give age maps of the islands. Therefore, Cox undertook a very comprehensive sampling of 15 major and minor islands, with a total of 185 evenly distributed sites. He produced polarity maps (based on 45 flows in Cox & Dalrymple 1966) from the raw NRM measurements, but actually published alternating-field (AF)-cleaned directions only on 24 flows from San Cristobal island (Cox 1971). Fortunately, this major sampling work is not lost for PSV studies as the samples still exist and are now on their way to be totally treated in Menlo Park. Thanks to E. Mankinen and M. Prévot we had access to the listing of latitude, longitude and paleomagnetic direction of Cox's sampling sites. Using this data and the updated radiochronological database of White et al. (1993) we selected four islands (Floreana, Pinzon, San Cristobal and Santa Cruz) as the best targets to do a regular sampling of the PSV for the past 2 Myr and to have a chance to encounter the Brunhes-Matuyama boundary.

Contrary to other hotspots such as Hawaii and Réunion, the Galapagos islands are characterized by hundreds of small volcanic centers, more or less randomly distributed in time and space. These volcanoes produce very smooth slopes, and there are no large calderas which could allow for tilted tabular structures, suitable for sampling time sequences. Due to the low-angle slopes and desert climate together with a lack of faults and anthropogenic outcrops, not a single outcrop is found outside the surf line along the seashore. Therefore, we had to sample at regularly spaced spots (each 0.1 to 1 km) along the coast. Structural control of the outcrops is difficult, so that it was not always possible, especially in the usual situation of subhorizontal flows, to tell which of two neighbouring outcrops was stratigraphically above the other. We used an accurate coastline map together with a GPS system to locate the outcrop and its position with respect to Cox's sites. In two instances we were able to find Cox's tracks (29 mm cylindrical holes) within 50 m of the latitude-longitude position of his table. This encounter, together with the perfect agreement we found between his and our paleomagnetic directions, deserves our admiration for the care he gave to his sampling, in a totally virgin environment devoid of any landmark apart from the monotonous coastline. We used Cox's polarities to focus our sampling in between his normal and reverse sites to increase our chances of finding transitional directions of the Brunhes-Matuyama reversal.

Only on Pinzon Island, surrounded by steep cliffs, a clear volcanic sequence was found. It is about 60 m high and we sampled six flows (51–56). Cox reported a transitional direction at this site but we did not find his holes. The surf erosion rate being very large at this

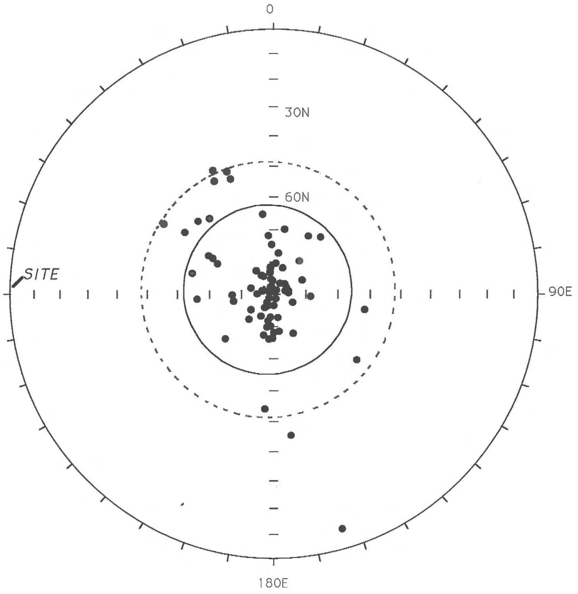

Figure 4. Stereoplot of the VGP from the 79 flows from Galapagos showing Fisher parameter k > 20 after AF demagnetization. The full and dotted circles (centered on the mean VGP) correspond to the limit between PSV and transitional directions according to Vandamme's (1994) recursive method and an a-priori 40° cutoff, respectively.

point, it may indicate that the 5 to 10-cm-long holes have been completely wiped out since Cox's sampling 30 years ago. We are quite certain that we landed at the very same place, since it is the only accessible place within ± 3 km of coastline. In the two other Cox sites we revisited, the holes had clearly rounded edges and depths of only 2 to 3 cm. Our paleomagnetic community may seriously consider the importance of this legacy of an erosion-rate database for the earth scientists of the next century. For the Galapagos rocky coastline, we obtain a rate of the order of a few mm/yr.

Esterel

The volcanic and sedimentary Permian formations of the Esterel are situated in a less remote but still picturesque area, the French Riviera. Paleomagnetic and rock-magnetic study of those volcanics was the subject of Zijderveld's (1975) thesis, as described by Vlag et al. (this issue). The geology of the area had been extensively described before Zijderveld presented his thesis, for example by Bordet (1951) and by the 1:50 000 geological survey map published in 1966 (Bordet et al.) which was already available to Zijderveld during his sampling in 1958. During our sampling, we noted that the map drawn by Zijderveld in his thesis was much more precise and practical than the survey one, thus unveiling a less well-known achievement of Zijderveld as a very efficient field geologist. Meanwhile, we have obtained a new version of the survey map (Toutin-Morin et al. 1994) that has identified quite important changes, particularly in the interpretation of the basaltic units. Zijderveld sampled 48 volcanic sites which he attributed to four rhyolitic and four basaltic flow units encountered in a large area, together with four other more limited basaltic flows. Therefore, each main unit (encountered as a single flow) was sampled several (2 to 5) times allowing for averaging the tectonic dispersion in paleomagnetic directions. The new geological observations, however, show that among the basalts only two units (D1 and D2) are actual flows, while the others are in fact sills that have been misidentified because of their consistent injection parallel to the bedding of the surrounding continental sedimentary rocks. The use of these sills in our paleomagnetic study is conditioned by the assumption that the sediments were still horizontal at the time of emplacement. Although all volcanic activity and sedimentation occurred quite continuously during approximately 10 Myr, one cannot exclude a synsedimentary tilt before injection, because tilted blocks are common features of active extensional basins, such as the Esterel, during volcanic activity. The most recent dating of the Esterel volcanics is between 264 (± 2) and 278 (± 2) Ma, using Ar/Ar plateau ages on feldspars (Zheng et al. 1992). This points to an emplacement right at the end of the Kiaman Superchron, estimated at 262 Ma by Opdyke (1995). More recently, Gialanella et al. (this issue; derived from Haag & Heller 1991 and Ross et al. 1994) suggested an age of 268 Ma for this limit.

In the framework of a limited study (8 sites) we tried to resample a few of Zijderveld's sites. As he used hand samples (with caps of plaster) we were not able to find his tracks, which would probably have been destroyed anyhow by the spread of residential areas. We added the sampling of a fifth rhyolitic flow (two sites; Vlag et al. this issue) and two conglomerate sites to perform a conglomerate test on rhyolitic boulders.

Paleomagnetic results

Galapagos

The detailed results of our study will be presented elsewhere and we will just comment here on the consequences of the new results in terms of PSV. Using

Table 1. Angular standard deviations (ASD) and their confidence limits calculated for the various VGP datasets corrected for within-site dispersion. N is the number of selected poles. ASD is around mean VGP except for a) and d) where geographic pole is used.

Locality	N	ASD	Conf. limits
Global 0–5 Ma, lat. $< 15°$			
a) McFadden	458	12.7	12.2–13.3
b) $A = 40$	348	12.8	12.2–13.6
c) $A = 25.6$	328	10.9	10.3–11.5
d) McElhinny	90	11.4	10.3–12.7
Galapagos			
$A = 40$	77	16.8	15.0–19.0
$A = 26.3$	66	11.2	9.9–12.9
Esterel options			
A, see text	6	4.0	1.7– 7.7
B, see text	8	6.2	4.2– 9.9
C, all units	12	9.7	7.3–13.7
D, all sites	35	7.6	6.3– 9.4
E, rhyolites	15	0.0	0.0– 2.3
F, basalts	20	10.2	8.2–13.3
G, flows only	8	8.2	5.7–12.7
Corsica-Sard.	22	8.7	7.0–11.3

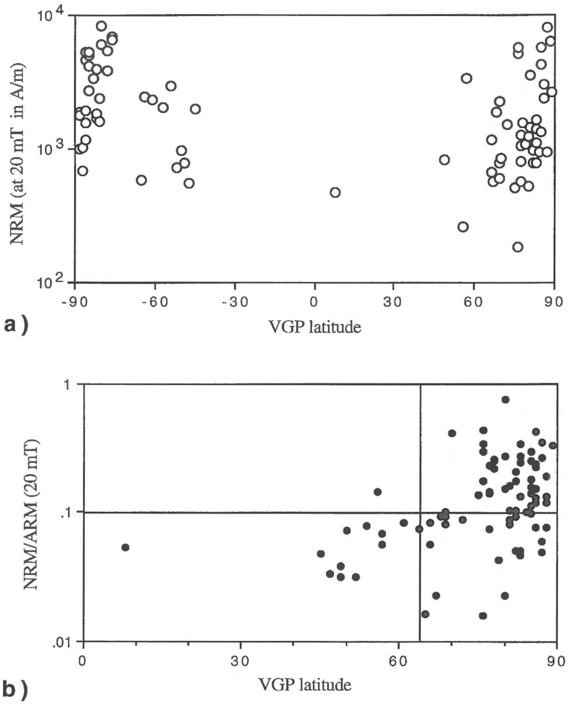

Figure 5. Relative paleointensity estimate (NRM/ARM at 20 mT on pilot samples) versus a) real and b) absolute VGP latitude for the 79 Galapagos flows with $k > 20$.

complete AF demagnetization of one sample per site we defined an optimal AF value for each site (usually 20 mT) and obtained the site's mean characteristic direction. We found acceptable grouping (Fisher parameters $k > 20$ and $\alpha_{95} < 14°$) on 79 sites, and good grouping ($k > 50$, $\alpha_{95} < 8°$) on 63 sites. Since both sets have a similar structure, with a few more intermediate sites in the first one, we decided to use the larger set in the PSV calculation. It contains approximatively equal numbers of normal (38) and reversed (28) sites, plus 13 intermediate sites (see below) .

Using the a-priori cutoff angle of 40° excludes only two transitional sites and leads to an unrealistically high ASD value of 16.8°. On the other hand, the recursive method of Vandamme (1994) excludes 11 more sites that are quite clearly outliers in the overall VGP distribution (Figure 4). The recursive method allows us to calculate an optimal cutoff angle of 26.2°. The resulting corrected ASD is 11.2° (confidence limits: 9.9–12.9°, Table 1), which compares much better to the value of 12.7° of McFadden et al. (1991) for the less-than-15° latitudinal band, thus clearly validating the recursive method for the first time in a real case study. The error made on the ASD estimate by incorporating transitional data through the overestimated a-priori cutoff angle is larger in this case than in the simulation produced in Figure 3 for the same percentage of transitional directions. This is because our transitional directions are not randomly distributed, showing only rarely VGP latitudes less than 30°. This situation has also been reported by Prévot & Camps (1993) in their global dataset. In an attempt to test the usual assertion that transitional directions are characterized by lower paleofield intensities (Camps & Prévot 1996), we used a relative paleointensity technique: the ratio of NRM to anhysteretic remanence (ARM) acquired in 100 mT AF and 1 mT bias field, for one sample per flow, both being demagnetized at 20 mT. Figure 5a shows the symmetry of our dataset in terms of normal and reverse data, confirming that secondary remanences have been properly eliminated. Otherwise, the intensity of the reverse directions would have been reduced. In Figure 5b we clearly reproduce the trend of increasing paleointensity versus VGP latitude, with a rather flat trend within the paleosecular variation domain. The transitional data defined by the angular cutoff of 26.2° are all but one characterized by low relative paleointensities (< 0.1) while two thirds of the non-transitional data show a relative paleointensity larger than 0.1. Therefore, both intensity and direction give a coherent separation of transitional data. This demonstration would have been less clear when presenting only NRM intensity as Camps & Prévot (1996) did, because the range of variation of NRM intensities for non-transitional directions is about ten times larger than the range for normalized intensities.

The fact that our corrected ASD value (11.2°) is lower than the value (12.7°) of McFadden et al. (1991) may have different explanations (bearing in mind that statistically the difference is marginal):

1. We have a value for an exactly equatorial site while the 0–15° bands include a slight increase of ASD with latitude. Figure 1a shows, however, that this effect is probably small.
2. Galapagos data is restricted to the past 2 Myr instead of the past 5 Myr. However, the age distribution in the global database is probably biased toward younger ages.
3. The McFadden et al. (1991) database relies partly upon data from the Cameroun line (Piper & Richardson 1972) of which the reliability may be questioned (usually 3 samples per site, limited AF demagnetization, large number of low k values) and which show a very large dispersion: ASD = 15.8° for the whole dataset of 107 flows, and 14.4° for the subset with $\alpha_{95} < 10°$ (69 flows).
4. The longitude band of Galapagos may be characterized by a lower PSV than the global one, in agreement with Hawaiian data (e.g. Doell & Cox 1965, but see McElhinny et al. 1996b).
5. The inherent disadvantages of the latitudinal-band approach and the a-priori cutoff angle described above account for an over-estimated ASD using the latitudinal-band approach.

To test the effect of changing the cutoff angle from 40° to the value of Vandamme's method on the global 0–5 Ma and lat. < 15° dataset, we computed the ASD on a database where only Cox's (1971) data were considered for Galapagos (348 instead of 458 data). Computing the optimal cutoff angle leads to a decrease of the ASD of 1.9° (Table 1: b, c). This demonstrates that the most likely explanation for the discrepancy discussed above is the problem of the cutoff angle. It is worth noting that we found for this independent dataset A = 25.6, i.e. the same value as found for our Galapagos data.

Interestingly, McElhinny et al. (1996b) computed an ASD of 11.4° (Table 1: d) for the Brunhes age data in the 0–5° latitudinal band, excluding the Galapagos data. This figure, undistinguishable from our Galapagos value, appears much lower than the value of McFadden et al. (1991) probably because of the use of Vandamme's (1994) method, restriction to the better defined Brunhes directions, and exclusion of sites with $\alpha_{95} > 10°$, leading to a site number of only 90. Therefore, we consider that our 11.2° Galapagos value is the most suitable one for comparison with the Permian data, at a regional scale. Its very good agreement with the global dataset treated using Vandamme's (1994) method also shows that the time span (Brunhes, 0–2 or 0–5 Ma) is not critical.

Esterel

The outcome of our study is detailed in Vlag et al. (this issue), where particular care has been taken of rock-magnetic characterization. To summarize the results we found that:

- all the Esterel volcanics are indeed representative of the Kiaman Superchron, thus making the Ar/Ar ages in agreement with the Opdyke (1995) estimate for the Kiaman ending at 262 Ma;
- in the four duplicate sites we found the same mean direction after thermal demagnetization as Zijderveld (1975) did, except in his Reyran rhyolitic site 17 that was departing from his other rhyolitic sites (Figure 6a), thus leading to a much better defined mean direction for the R2 Reyran rhyolite unit and a better grouping of data at the site or unit (Figure 6c) level;
- the fifth rhyolitic flow gave reversed Permian directions, but with such a bad precision caused by strong remagnetization and obvious alteration of the rock, that we did not integrate this new flow in the PSV estimate;
- rock magnetism indicates mixtures of magnetite, hematite and possibly maghemite that raise questions on the primary nature of the mineral assemblage;
- the two conglomerate tests on rhyolitic blocks yield ambiguous results: directions are neither random nor strongly grouped around the Permian direction, thus suggesting a partial remagnetization, which is not resolvable by stepwise thermal demagnetization, because Zijderveld's diagrams show unidirectional decay to the origin.

For the calculation of the ASD from the Esterel volcanics the choice is difficult. Seven possibilities of data selection can be tested (A to G). We could use only flow-unit mean directions (A: 6 poles including the D1 and D2 units), integrate the sills defined by

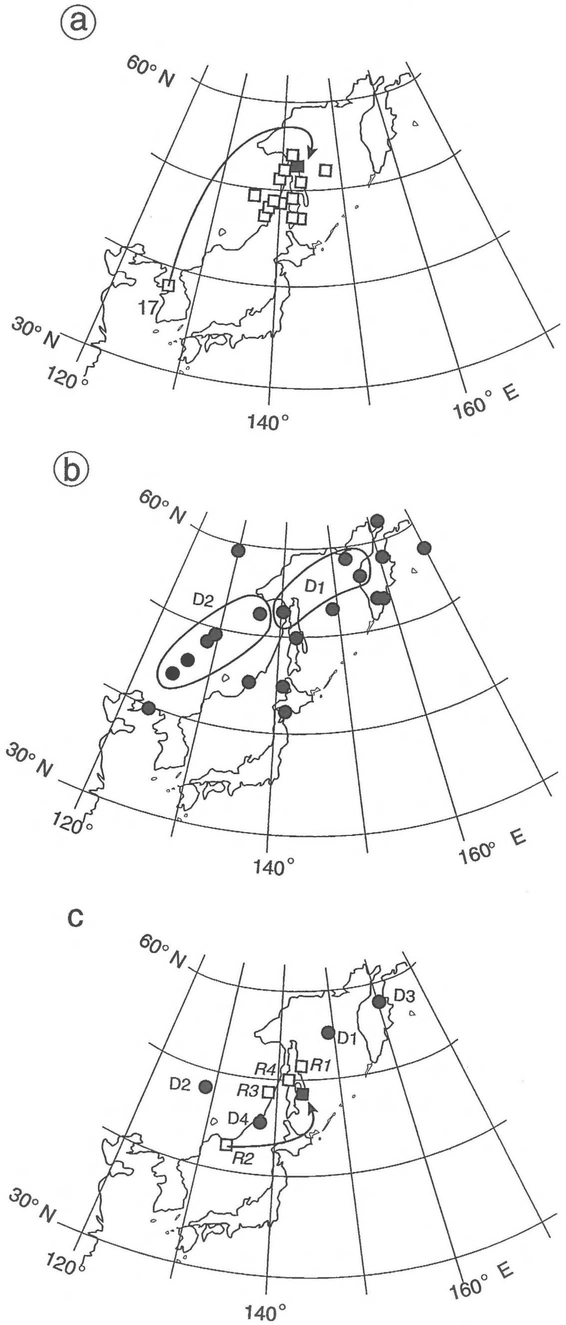

Figure 6. VGP directions from the Esterel volcanics (after Zijderveld 1975); a) rhyolites, showing the effect of remeasuring Zijderveld's Reyran rhyolite site 17; b) basalts, with the sites from the two real flow units D1 and D2 circled; c) formation mean values (R: rhyolites; D: basalts).

more than one site (B: 8 poles, Figure 6c), or use all separate 'flows' defined by Zijderveld in his table (C: 12 poles). Alternatively, we may compute the ASD at the site scale (D: 35 poles) or separate rhyolites (E: 15 poles, Figure 6a) and basalts (F: 20 poles, Figure 6b), among which a subset of 8 poles from real flows may be defined (G). The amount of scatter integrated in our ASD values due to local tectonic rotation depends on these different choices. These local rotations are clearly visible in the spread of poles from the same unit (Figure 6b) and may also be responsible for the spread in declination of the unit directions (Figure 6c). A balance between that problem and the need for a representative, i.e. large enough, dataset must be found.

After computing the ASD and Fisher parameters for the seven subsets A to G (Table 1), it appears that the ASD is significantly lower for the Esterel than for the Galapagos, except in cases C and F where the inclusion of sill sites may explain the larger dispersion. In fact, Zijderveld noticed the extremely low ASD of the rhyolites (corrected ASD zero for option E) compared to the one of the basaltic sites which he qualified as showing the expected scatter for the PSV. He used this fact to exclude the possibility for a global remagnetization that should have reduced the ASD for both rhyolitic and basaltic intercalated flows. The exclusion of the sill sites weakens this argument a lot, as it leads again to a very low dispersion (Figure 6b). His suggestions to explain the abnormally low scatter in the rhyolites was either chance, a probability that is not negligible for only four formations, or a cooling-rate effect. This latter explanation can be invoked for the two units R3 and R4 (with a thickness of the order of 100 m) but not for the other two rhyolitic units which, together with the basalt units, are less than 15 m thick.

It is worth mentioning that the averaged inclination is smaller by 3° in the rhyolitic than in the basaltic flows, thus marginally confirming the suspicion of an inclination error as raised above. This reminds us that Zijderveld's thesis identified a major example of an inclination error in sedimentary rocks, with his sedimentary rocks showing a 10° reduction in inclination compared to the volcanics. This clear example had been practically forgotten for a few decades, allowing some authors to invoke terranes transported thousands of kilometers northward, until a recent 'rediscovery' of the inclination error problem (see discussion in e.g. Collombat et al. 1993).

Discussion

The analysis of the Galapagos and Esterel datasets shows that the PSV was indeed lower during the end of Kiaman Superchron than during the past 2 Myr, as predicted by McFadden & Merrill (1995) . The alternative interpretation is that the Esterel rocks have undergone a pervasive late Kiaman remagnetization, the best candidate for that being a CRM acquired on a 10 to 1000-kyr time scale linked to hydrothermal activity after emplacement.

A reason for not including the Esterel data in a PSV database may be found in the magnetic mineralogy, petrography and geochemistry. Zijderveld (1975) and Vlag et al. (this issue) have shown that hematite and possibly maghemite, together with low-titanium magnetite, carry a large part of the NRM. This mineralogy questions the primary nature of the magnetic minerals, particularly for basalts. High oxygen fugacity can only be explained by hydrothermal processes, the problem being to discriminate between a rapid alteration above the Curie point or a slow alteration below this point. The two conglomerate tests are ambiguous but clearly raise the possibility for at least partial remagnetization of the rhyolitic boulders. Thin-section observations of the basalts show abundant secondary crystallization of chlorite and albite, indicative of greenschist-facies metamorphism (250–300 °C). Trace elements and isotopic investigations also point toward large hydrothermal transformation of the magmatic composition (Poitrasson et al. 1995).

On the other hand, we may look at other Permian volcanic studies to find some support for either a TRM or a CRM nature of the Esterel paleomagnetic results. Vigliotti et al. (1990) have obtained 22 good-quality site mean directions ($\alpha_{95} < 11°$) from Permian dikes in North Sardinia and South Corsica, using careful thermal demagnetization (Figure 7). The reverse polarity and sub-equatorial paleolatitude (3°N) make these sites interesting for our purpose, although the lack of tectonic correction will introduce an overestimate of true geomagnetic PSV. Nevertheless, we computed an ASD of 8.7° (confidence limits 7–11.3°), i.e. still significantly lower than the Galapagos value of 11.2°. Vandamme's (1994) method excluded only one datum, with the steepest inclination (Figure 7). We can only discard again this independent dataset (with no rhyolites and no hematite-bearing basalts) by invoking a ubiquitous long-term partial remagnetization of Permian volcanics, on a temporal range of the order of 1 Myr after emplacement. This is reminiscent of the long-term partial remagnetization invoked to explain the weakening of marine magnetic anomalies with the aging of the oceanic crust (Johnson & Pariso 1993; Johnson et al. 1996), or the saw-tooth intensity pattern in sediments (Kok & Tauxe 1996). If such an effect exists in lava flows, it may invalidate the conclusions of McFadden & Merrill (1995) concerning the PSV behavior back in time. Such a partial remagnetization may significantly decrease the ASD in superchrons or periods with much less than one reversal per million years, while for a high reversal frequency the effect should be a stable or even increased ASD. Remagnetization is not likely to be latitudinally dependent; therefore it should produce an ASD-versus-latitude pattern flatter than the actual one. The Cretaceous Superchron pattern, however, shows a steeper ASD-versus-latitude curve than the 0–5 Ma pattern (Figure 1).

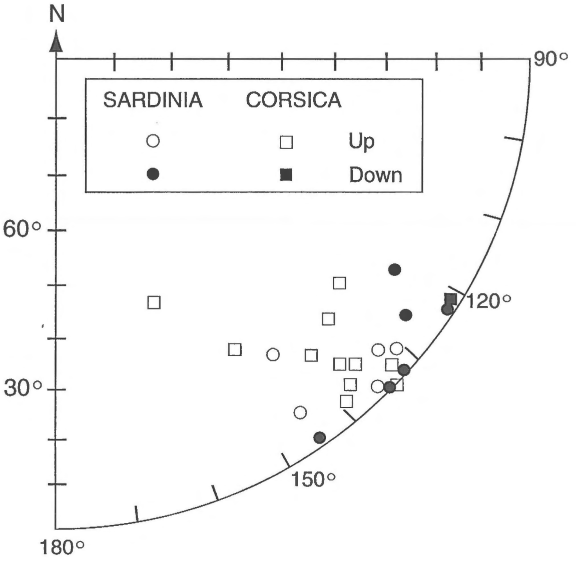

Figure 7. Paleomagnetic directions from Permian dikes of South Corsica and North Sardinia, after Vigliotti et al. (1990).

Conclusions

The first page of Zijderveld's (1975) thesis reads "When science ends, tradition begins". Publishing in the era of cryogenic magnetometers, his results obtained with an astatic magnetometer on samples collected 17 years before perhaps made Zijderveld feel that his data were already outdated. It is clear today that we can still confidently use his data to discuss key problems of paleomagnetism and geomagnetism.

This is mainly because what we are now considering as 'modern' paleomagnetic methodology was already well applied in Zijderveld's thesis. This remark also applies to Cox's sampling even though he dealt with simpler material in terms of secondary magnetization.

Returning to the definition of paleosecular variation and its angular standard deviation, we propose an alternative methodology by using a regional geographic scale and a variable cutoff angle following Vandamme's (1994) method, rather than the latitudinal-band approach and an a-priori cutoff angle of 40° (McFadden et al. 1991). The analysis of our new Galapagos dataset clearly demonstrates the need for a variable cutoff angle. The equatorial ASD value of 11.2° obtained may be regarded as a single-spot reference value, compared to the global average value of 12.7° for the past 5 Myr (McFadden et al. 1991).

The reappraised Esterel data from Zijderveld (1975), together with the Corsica-Sardinia data from Vigliotti et al. (1990), apparently demonstrate a significantly lower ASD (of the order of 8°) in the Kiaman Superchron than in the past 2 or 5 Myr. It is difficult, however, to discard the possibility of a long-term widespread remagnetization of these old volcanics. In particular, the zero ASD found for the Esterel rhyolites shows that these rocks have recorded an 'abnormally' stable direction. The significance of the above conclusion in terms of long-term geodynamo behavior remains therefore unsettled.

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