

Paleomagnetism of the Esterel rocks: a revisit 22 years after the thesis of Hans Zijdeveld

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Abstract

For his PhD. thesis, Zijdeveld (1975) studied the paleomagnetism of the Permian Esterel rocks (southern France). High-quality thermal and alternating-field demagnetization diagrams were interpreted to determine the direction of the characteristic natural magnetization. For the Esterel volcanics, a mean direction of $Dec = 206.5^\circ$, $Inc = -23^\circ$, $\alpha_{95} = 5.7^\circ$, $k = 112$ was found for this magnetization. The dispersion in this mean is remarkably low. Only the declination of the Reyran Rhyolite in the Reyran River quarry clearly deviated from this mean. This deviating direction is not found in our samples, taken at the same site. As many faults occur in this quarry, it is suggested that Zijdeveld sampled this rhyolite on a small rotated block.

To verify whether the small dispersion in the mean paleomagnetic direction of the Esterel rocks has a geomagnetic or a rock-magnetic origin, two conglomerate tests were carried out. One of these might be interpreted as positive. The results of the other conglomerate test (Agay Formation) are ambiguous: four of the six measured boulders show directions close to the mean paleomagnetic direction of the Esterel rocks. Rock-magnetic measurements show that the remanence is carried by a magnetite and a hematite fraction. The low dispersion in the paleomagnetic directions, the conglomerate tests, and hematite as remanence carrier suggest that the characteristic remanence in the Esterel volcanics was not instantaneously acquired during cooling, but might be affected by remagnetization due to weathering.

Introduction

The Esterel area ($43^\circ 28' N$, $6^\circ 49' E$) is situated along the Mediterranean coast between Fréjus and la Napoule (France; Figure 1). Its low mountains are made up by intensively faulted volcanics and sediments assumed to be of Late Permian age (Toutin-Morin et al. 1994). The Esterel rocks fill a wide east-west structural depression in the Hercynian metamorphic basement of Provence. The Permian Esterel rocks are entirely continental and determinable fossils are practically absent. A stratigraphic succession of four basaltic and four rhyolitic formations with interbedded sedimentary formations has been proposed by Bordet (1951) and Zijdeveld (1975) (Figure 2). An angular unconformity in the Permian Esterel succession leads to its division in an upper and a lower group. This unconformity is placed within the formation of tuffs and arkoses under the Amaran-

thine Rhyolitic Ignimbrite (Bordet 1951, Zijdeveld 1975). In the southeastern part of the Esterel an intrusive, the so-called Esterellite, is found. Based on the paleomagnetic results, Zijdeveld proposed a Tertiary age for this intrusive. Detailed maps of Esterel are presented by Bordet (1951), Zijdeveld (1975) and Toutin-Morin et al. (1994). Figure 2 shows the correlation between the stratigraphic column proposed by Zijdeveld and the updated one of Toutin-Morin et al. The basaltic flows of the Zijdeveld stratigraphy are differently interpreted by Toutin-Morin et al.: only the Auriasque and the Gondin Basalts are considered as flows, while all others are interpreted as sills (horizontal intrusions with concordant contacts). For further information about the geological history of Esterel, the reader is referred to Zijdeveld (1975) and Toutin-Morin et al. (1994).

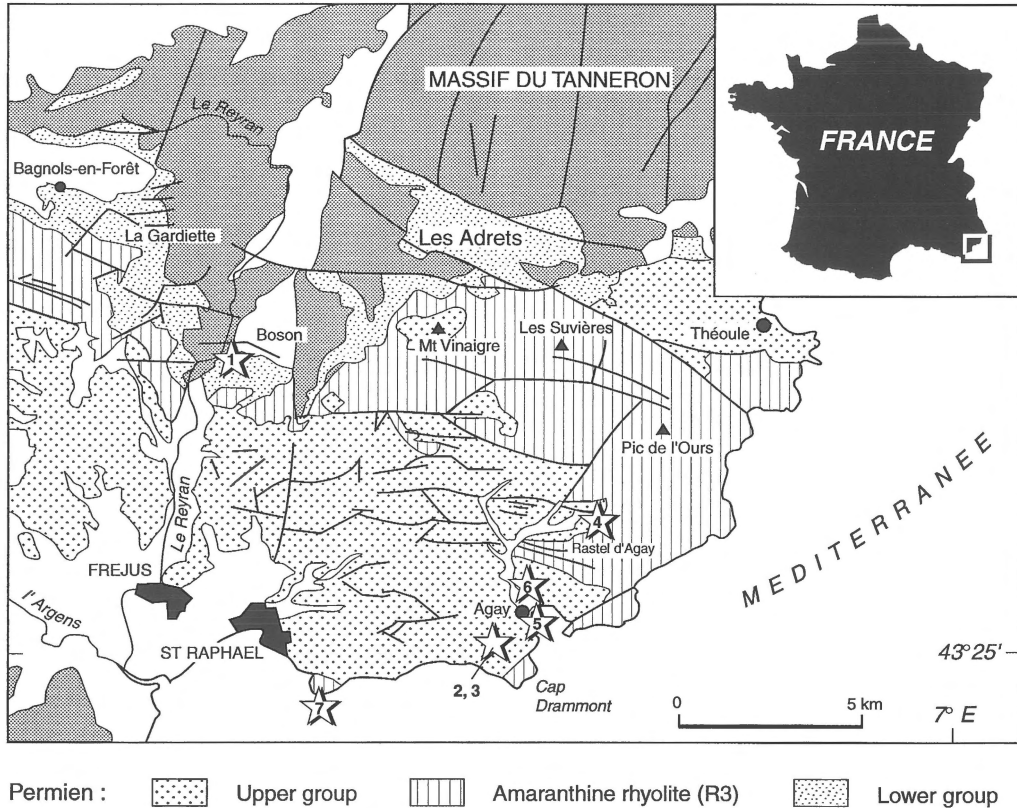


Figure 1. Geological setting of the central and eastern part of the Esterel (redrawn and modified after Zijdeveld 1975). Grey areas mark the metamorphic basement, lighter areas the Permian rocks. Numbers mark the resampled sites. 1: Reyran Rhyolite in the Reyran River quarry, 2 (3): Drammont Basalt (Esterellite) at the railway cutting near Agay, 4: Gondin Basalt in the Mourrefrey Valley, 5: conglomerate of the Agay Formation at a road cutting near Agay, 6: conglomerate in the Gargalon Formation north of Agay, 7: Lyons Rhyolite on two capes a few kilometers SE of St. Raphael.

Paleomagnetic results of Zijdeveld (1975)

Zijdeveld collected 780 oriented hand samples (volume: 100 to 200 cm³) in the central Esterel region. These samples were collected from all formations. Per formation two or more sites were sampled, and for each site four to twelve samples collected. Fifty samples of the Esterellite were collected in the area between St. Raphaël and Agay.

In the laboratory the natural remanent magnetization (NRM) of the hand samples was stepwise demagnetized with an alternating field (AF). A maximum peak AF of 300 mT was used. At a later stage, the NRM was also thermally demagnetized. For the latter experiments, standard paleomagnetic cores were drilled from the hand samples. The NRM directions were measured with an astatic magnetometer (As 1960). With this instrument the time needed per measurement is 20 minutes. Generally, between 12 and 17 demagnetization

steps were carried out. Zijdeveld already used orthogonal vector diagrams in his study (Zijdeveld 1967) to interpret the results of the stepwise demagnetization.

The study showed a large diversity in NRM properties. Demagnetization diagrams do not only differ between different formations and sites, but also within individual sites. Most demagnetization diagrams show, however, the presence of two magnetization components: a secondary, and a characteristic remanent magnetization (ChRM) component. The ChRM is reversed and has low inclinations. Generally this component was completely removed at 660–680°C and with a 300 mT AF. Usually, the secondary component was demagnetized with a peak AF lower than 30 mT and temperatures between 200 and 300°C. Its direction falls in the proximity of the present-day field for the Esterel, confirming its secondary origin. Inclinations of this secondary component, however, are steeper than the

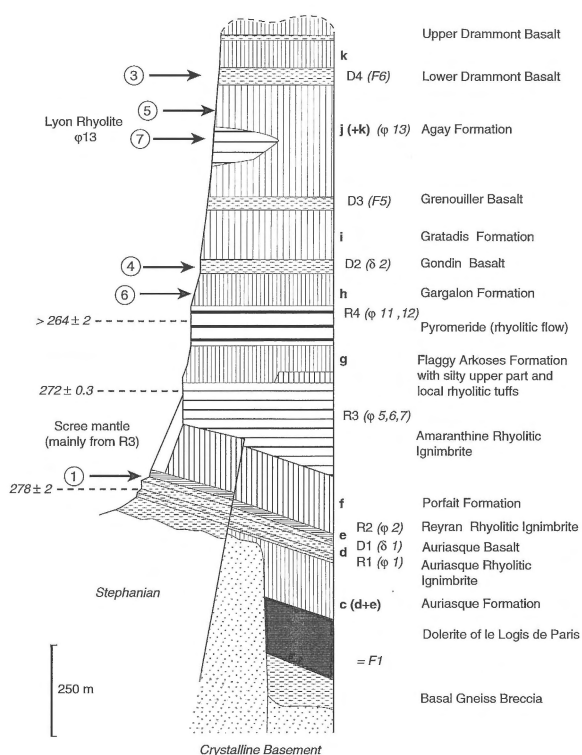


Figure 2. Stratigraphic column of the Permian succession in the central Esterel, according to Zijdeveld (1975). The resampled formations (numbers in circles) and well-defined $^{39}\text{Ar}/^{40}\text{Ar}$ ages (in Ma, Zheng et al. 1992) (*italics*) are shown on the left. The numbers and names of the stratigraphic formations labelled by Zijdeveld are shown on the right. The labels of the stratigraphy of Toutin-Morin et al. (1994) are shown between parentheses. (F1 etc., $\varphi 1$ etc., $\delta 1$ etc.)

present-day field. This might be due to the fact that at low AFs and temperatures not only the secondary but also a part of the ChRM component is demagnetized. In this case, the steeper inclinations may result from a vector addition of the positive inclinations of the axial dipole field and the low negative inclinations of the ChRM.

For each site the mean of the individual ChRM directions was calculated with respect to: 1) the present horizontal plane, and 2) the bedding plane. Then an average ChRM direction was calculated for each formation (for the basalts for each flow) and for each rock type. In a final stage a mean ChRM direction, including all basaltic flows and all rhyolitic formations was calculated. The dispersion in ChRM directions after bedding correction is smaller than for the in-situ directions. Hence, the bedding fold test is positive. In spite of the large differences in the demagnetization diagrams, the dispersion in ChRM directions is

low for each site ($5^\circ < \alpha_{95} < 8^\circ$) and for each formation ($4^\circ < \alpha_{95} < 8^\circ$). Taking into account the effect of secular variation, Zijdeveld (1975) already concluded that the dispersion in the mean ChRM directions of the basalts and especially the rhyolites is remarkably low (Table 1). The lower inclinations of the sediments were explained by a classical 'inclination' error due to compaction. Zijdeveld argued that the ChRM has a primary origin. His reasoning was based on: 1) the positive fold tests, and 2) the conviction that the major part of the structure of the Esterel rocks has been caused by syn-depositional volcanotectonics. Furthermore, the virtual geomagnetic poles (VGPs) derived from the ChRM directions are situated between the Permian VGPs of stable Europe and the Late Triassic VGPs of Eurasia, and correspond with the late Permian age of the rocks.

Dating of the Esterel formations

Since the Zijdeveld study, the Esterel rocks have been dated by Roubault et al. (1970), Baubron et al. (1985) and Zheng et al. (1992). The first authors reported K/Ar ages between 227 ± 10 and 273 ± 10 Ma. The K/Ar ages found by Baubron et al. (1985) are younger: 176 ± 5 up to 272 ± 2 Ma. Zheng et al. (1992) used the more accurate $^{39}\text{Ar}/^{40}\text{Ar}$ method to date the Esterel sequence. As no plateau was reached during stepwise degassing, only minimum ages could be given for the Agay Formation (> 228 Ma) and the Gondin Basalt (> 240 Ma). Well-defined $^{39}\text{Ar}/^{40}\text{Ar}$ ages range from 264 ± 2 Ma for a dike cutting the Pyromeride, up to 278 ± 2 Ma for the Auriasque Basalt (Figure 2).

The less accurate K/Ar ages of Baubron et al. (1985), which are younger than Permian, are likely to be too young. This is because: 1) Triassic and Jurassic sediments in the region do not show any trace of volcanic activity, and 2) the VGPs, derived from the Zijdeveld study, indicate a Late Permian age. Furthermore, all ChRM directions are reversed. This suggests that the ChRM was acquired during the reversed Permo-Carboniferous superchron, which ended about 262 Ma ago (Opdyke 1995). It seems to us unlikely that: 1) the huge Esterel sequence was deposited during exclusively (one of) the reversed periods of the Permo-Triassic mixed chron, or 2) that a widespread remagnetization took place during exclusively (one of ?) these relatively short reversed periods. Therefore, it is assumed that the ChRM acquisition took place

Table 1. Average directions for the basaltic, rhyolitic and sedimentary formations of the Esterel obtained by Zijderfeld (1975: Table 13).

Rock type	Average ChRM directions bedding coordinates				
	N	Dec	Inc	α_{95}	k
Basalts	8	205	-25	9.1	38
Idem, only several sites	4	206	-24	12.0	59
Rhyolites	4	210	-20.5	5.9	240
Idem, without Reyran Rhyolite	3	207.5	-22	3.2	1512
Basalts + Rhyolites	12	207	-23.5	6.1	52
Basalts, only several sites, + Rhyolites, without Reyran Rhyolite	7	206.5	-23	5.7	112
Sediments	3	203.5	-12	5.3	543

during the reversed Permo-Carboniferous superchron, implying a Permian age of the Esterel rocks.

Revisit of Esterel

The aim of this revisit is to check the actuality of the work of Zijderfeld (1975), 22 years after its publication. For this purpose, some sites were resampled and NRM properties were remeasured. In addition, rock-magnetic analyses were performed. A conglomerate test was carried out to verify whether the characteristic remanence was instantaneously acquired. In this paper, we use the same names for the stratigraphic formations as Zijderfeld did.

For each site, 6 to 12 standard cylindrical cores of 2.5 cm diameter and 4 to 10 cm length were collected, using a portable drilling machine. Sites close to faults were, of course, avoided. Four formations, already investigated by Zijderfeld, were resampled: the Reyran Rhyolitic Ignimbrite in the Reyran River quarry (site 1), the Esterelite (site 2) and the Dramont Basalt (site 3) in a railway cutting west of Agay, and the Gondin Basalt in the upper part of the Mourrefrey Valley (site 4). These four sites were selected because according to the data of Zijderfeld (1975) they reflect altogether the most frequently occurring characteristic NRM properties of the Permian Esterel volcanics. The Reyran Rhyolitic Ignimbrite in the Reyran River quarry was resampled because its ChRM direction clearly differs from all other ChRM directions of the Permian Esterel rocks, including the other sampling site of this rhyolite (Table 2). For this reason, Zijderfeld (1975) did not include the Reyran Rhyolite for the calculation of a mean ChRM direction for all

rhyolitic formations (Table 1). In order to obtain the best possible comparison with the reference work of Zijderfeld, our intention was to sample the same sites as Zijderfeld used. This turned out to be impossible, due to the construction of residential areas.

In addition to those of Zijderfeld, two new conglomerate tests were carried out and one new site was studied. For the conglomerate tests, boulders in the Agay Formation (site 5) and the Gargalon Formation (site 6) were cored south and north of the Agay village, respectively. The Lyons Rhyolite was sampled on two capes southeast of St. Raphaël (site 7). The distance between these capes is only a few hundred meters and these are the only sites at which this rhyolite is at the surface. The Lyons Rhyolite was not sampled by Zijderfeld (1975).

Demagnetization of the NRM

In the laboratory, the cores were cut to obtain 10.54 cm³ cylindrical samples. The cylindrical sample taken from the deepest part of the core was used for the progressive NRM demagnetization.

Per site three samples were thermally demagnetized. The heating was carried out with a MMTD1 furnace of Magnetic Measurements Inc.. After each heating step the remanence was measured with a 2G-Enterprises cryogenic magnetometer. The remaining samples were AF-demagnetized. This AF demagnetization was performed in three orthogonal axes with a Molspin demagnetizer. A maximum AF of 100 mT was applied. After each (AF) demagnetization step the remanent magnetization was measured on a Molspin spinner magnetometer. Measuring the NRM before any

Table 2. ChRM directions for the sampled formations. For comparison Zijdeveld's (1975) data are shown in *italics*.

Formation (sampling site)	ChRM directions								
	This study; <i>Zijdeveld, 1975</i>								
	N	Present horizontal plane				Bedding plane			
Dec		Inc	α_{95}	k	Dec	Inc	α_{95}	k	
Reyran Rhyolite (Reyran River quarry)									
	12	203.4	– 7.4	3.5	170	204.4	–14.9	3.5	170
	12	224.5	4.5	3.5	197	224.0	–16.0	3.5	197
Gondin Basalt (upper Mourrefrey valley)									
	4	213.6	–15.0	9.9	87	205.3	–19.7	6.5	198
	4	216.5	16.5	17.9	29	207.0	–21.5	17.9	29
Drammont Basalt (railway cutting near Agay)									
	5	201.1	– 0.8	8.7	114	202.8	–24.7	8.7	114
	3	209.5	8.5	4.3	823	210.5	–14.5	4.3	823
Lyons Rhyolite (cape SE St. Raphael)									
Site 1	4	206.1	–17.7	53.0	4	199.3	–31.0	53.0	4
Site 2	5	185.4	7.4	24.6	11	185.5	– 8.0	24.6	11
Esterellite (railway cutting near Agay)									
	5	0.1	45.0	16.6	23	–	–	–	–
	8	348.0	44.5	3.4	270	–	–	–	–

laboratory treatment on both the cryogenic and the spinner magnetometer yielded the same directions.

Demagnetization diagrams show similar trends as found by Zijdeveld, but those of Zijdeveld are usually of better quality (Figure 3). For the thermal demagnetization diagrams, this might be partially related to a non-zero field in the furnace. This effect can easily be shown for the Gondin Basalts, of which the remanence decays with a zigzag pattern, while the direction of the samples in the furnace was turned 180° at each demagnetization step (Figures 3 e, b).

The ChRM directions and characteristics of the Lyons Rhyolite are scattered. Furthermore, NRM intensities of these rhyolite samples vary from 70 to up to 10000 mA/m, while susceptibilities are fairly constant. As both sampling sites are situated on a cape rising above the sea, it might be that the remanence is acquired by lightning. The mean direction is consistent with the Permian reversed direction (Table 2). Therefore, it is concluded that this rhyolite is not suitable for paleomagnetic purposes.

ChRM directions of the Drammont Basalt, Gondin Basalt and the Esterellite do not significantly differ from Zijdeveld's study (Table 2). Hence, our data can be compared with this reference work. At some sites, Zijdeveld observed a secondary magnetization component in the Drammont Basalt, whose direction is 'reversed' compared to the present local geomagnetic

field. One of the aims of this study was to verify the origin of this reversed component. However, the Prola quarry, one of the sites showing a reversed secondary component, could not be resampled, because it is now situated in a residential area. The sampled Drammont Basalt in a nearby railway cutting does not show a reversed secondary component.

Zijdeveld (1975) measured a deviating ChRM direction for the Reyran Rhyolite of the Reyran River quarry (Tables 1, 2). The ChRM direction for the resampled Reyran Rhyolite in the same quarry agrees better with the other ChRM directions of the Esterel rocks (Table 2). For the thermal demagnetization diagrams, no ambiguity exists in the determination of the ChRM component (Figure 4b). Concerning the AF demagnetization, Zijdeveld as well as the present study consider the last demagnetization steps to be representative for the ChRM. Hence, the different ChRM directions found for the Reyran Rhyolite in this study and in that of Zijdeveld (1975) are not related to a different interpretation of the demagnetization diagrams. As the ChRM directions, both before and after bedding correction, differ between the two studies, this discrepancy is neither related to a wrong determination of the geological dip. As many faults were observed in the Reyran River quarry, it might be possible that Zijdeveld sampled this rhyolite on a small rotated lock. This would explain the deviating ChRM direction. Due

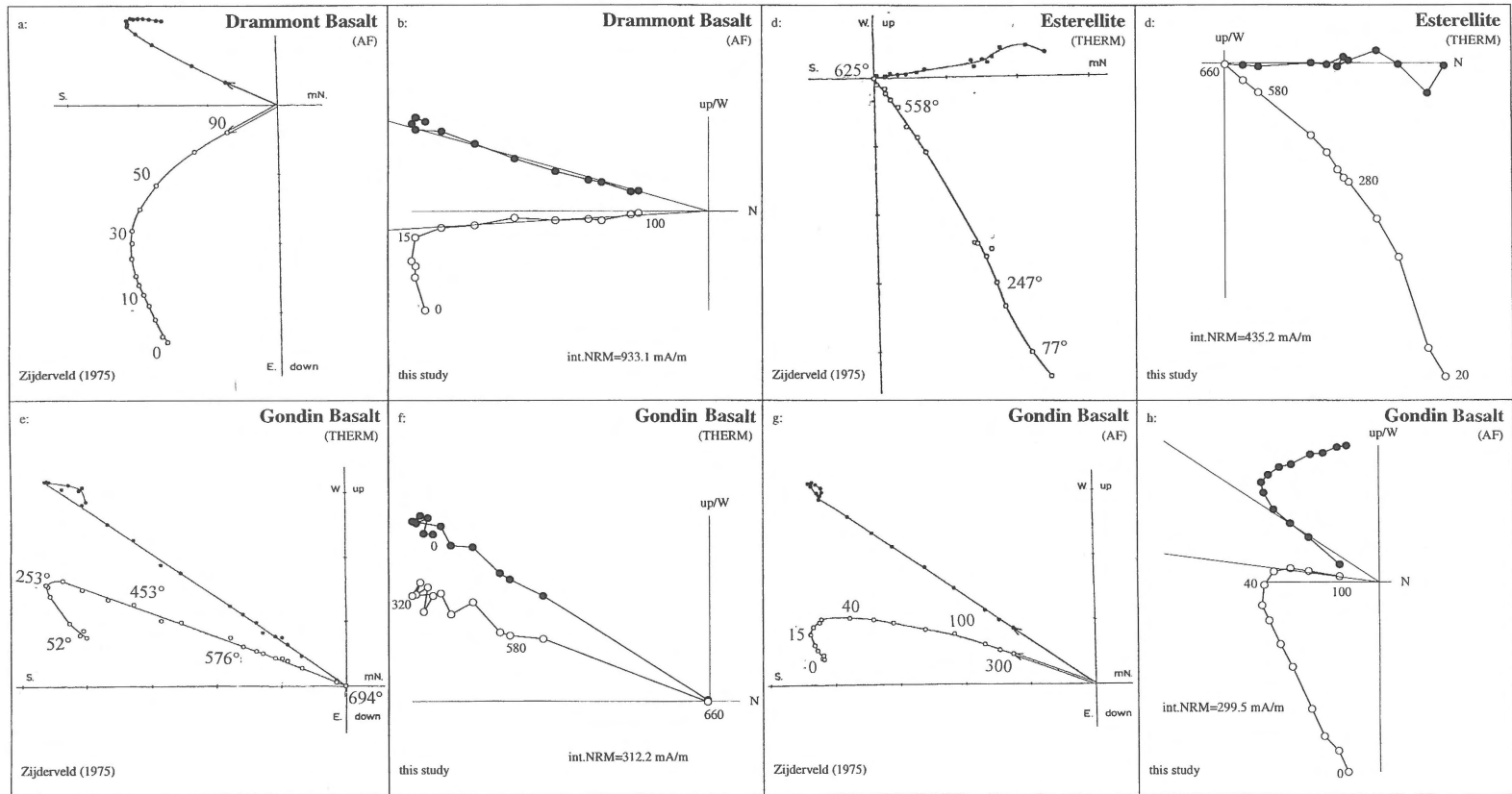


Figure 3. Typical demagnetization diagrams of Esterel rocks. Stepwise AF demagnetization of the Drammont Basalt by Zijdeveld (1975) (a) and this study (b). Stepwise thermal demagnetization of the Esterellite by Zijdeveld (1975) (c) and this study (d). Thermal and AF demagnetization diagrams of the Gondin Basalt by Zijdeveld (e, g) and this study (f, h). Note that in the AF demagnetization diagrams presented by Zijdeveld (this study), peak alternating fields are given in Oe (mT).

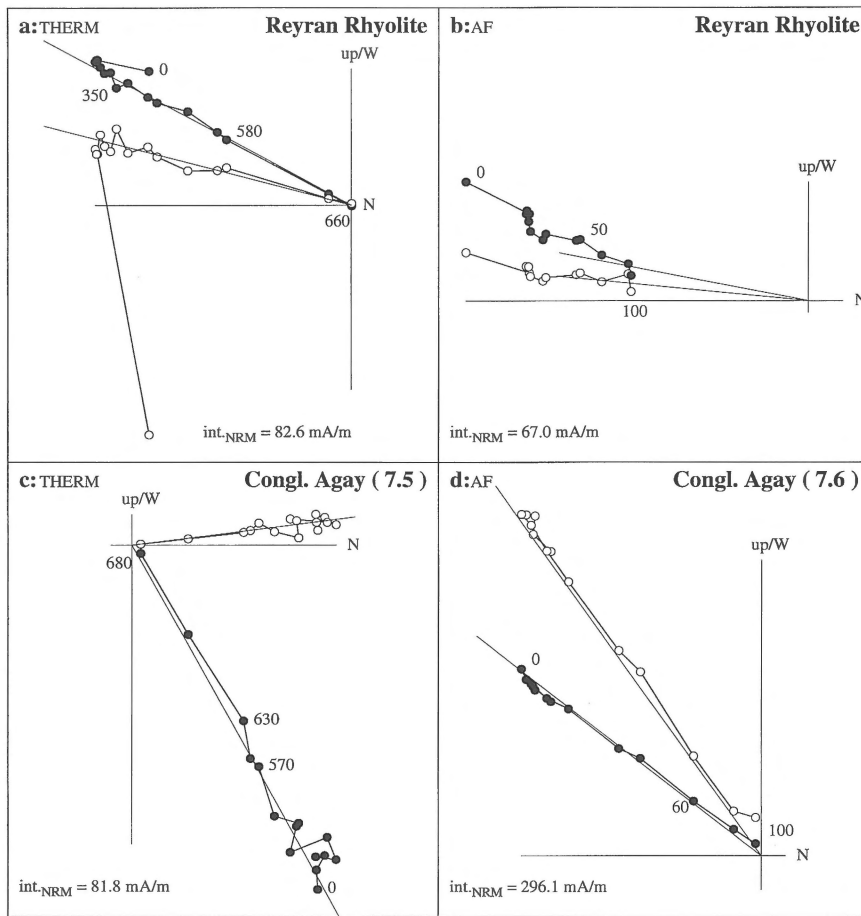


Figure 4. Typical AF and thermal demagnetization diagrams for the Reyran Rhyolite (a, b) and for samples 7.5 and 7.6 of rhyolite boulders in the Agay Formation (c, d).

to the almost complete exploitation of the Reyran River quarry, the exact site at which Zijdeveld (1975) sampled the Reyran Rhyolite has disappeared. Hence, this hypothesis cannot be verified. With the new data, average ChRM directions can be slightly modified. The modified mean ChRM direction for all rhyolitic formations is: Dec = 207.4° , Inc = -21.1° , N = 4, $\alpha_{95} = 3.2^\circ$, k = 835.

Rock magnetism

Based on his stepwise demagnetization diagrams, Zijdeveld (1975) described the magnetic properties of the Esterel rocks and concluded that the natural remanence in these rocks is carried by a magnetite and a hematite fraction. With nowadays commonly used techniques, like hysteresis, backfield measure-

ments and thermal demagnetizations of laboratory-implanted remanences, the validity of this argumentation can be easily tested. For this reason, we performed some rock-magnetic measurements. However, before discussing the rock-magnetic results, we present Zijdeveld's interpretation of the demagnetization diagrams in terms of magnetic properties of the Esterel rocks.

Zijdeveld (1975) showed that the ChRM component is removed by temperatures between 300 and 680°C and with alternating fields ranging from 30 to 300 mT. Unblocking temperatures between 660 and 680°C and peak alternating fields higher than 100 mT suggest that the ChRM is (partially) carried by (Ti-)hematite. However, the largest part of the ChRM unblocks at temperatures lower than 580°C (the Curie temperature of magnetite) and with lower AFs. Therefore, Zijdeveld (1975) concluded that the ChRM is

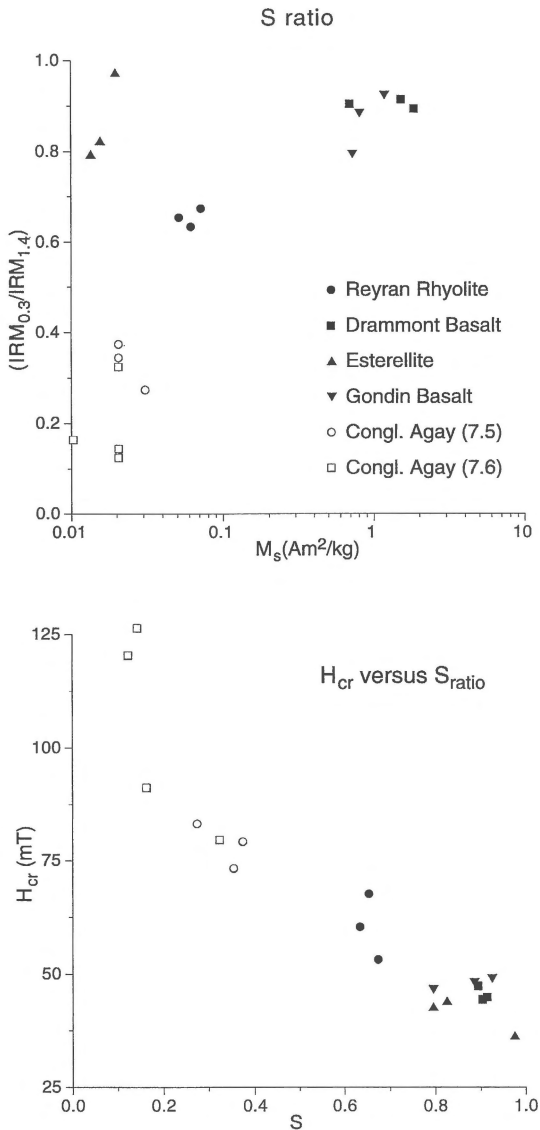


Figure 5. S-ratio versus M_s (above). H_{cr} versus S-ratio (below).

also carried by magnetite. He also pointed out that the percentage of NRM left at 580°C (a possible estimate for the relative contribution of magnetite and hematite as remanence carriers) varies considerably between the different formations, per formation, per site, and even within the site. Furthermore, no clear relation is observed between the remanences left at 580°C and 100 mT AF respectively.

For the resampled rocks, the percentage of NRM left at 580°C compared to the initial NRM intensity varies from 4% for some Esterellite samples (Figure 3b) to 65% for some (rhyolitic) conglomerate boulders

of the Agay Formation (Figure 4c). Generally, the Drammont and Gondin Basalts and the Esterellite show lower percentages NRM left at 580°C than the Reyran Rhyolite. Like in Zijdeveld's study, a relation between the remanence left at 580°C and at 100 mT AF is absent. This is, for example, shown in the demagnetization diagrams of the Gondin Basalt (Figures 3f, h). A considerable part of the remanence is left at 580°C, but the largest part of it is removed with a 100 mT peak AF. Hence, demagnetization diagrams apparently suggest the presence of a low coercivity and high temperature in this basalt.

For conglomerate boulder 7.5 of the Agay Formation, the NRM intensity starts decreasing at 540°C and unblocks at 680°C. These temperatures indicate the presence of hematite as remanence carrier. As boulder 7.6 has a similar lithology as boulder 7.5, a high-coercivity NRM was also expected for this boulder. Surprisingly, its NRM was removed with low AFs and its ChRM direction is close to the average paleomagnetic direction of the Permian of the Esterel (Figure 4d). This possibly indicates a remagnetization. To verify this possibility, rock-magnetic measurements were performed on these boulders to check whether: 1) the magnetic properties of boulders 7.5 and 7.6 differ, and 2) the high-coercivity remanence fraction in boulder 7.6 exists.

For the rock-magnetic study, we measured hysteresis loops, performed backfield demagnetizations, and thermally demagnetized the laboratory-induced remanences: ARM and IRM. Backfield and hysteresis-loop measurements were carried out with an Alternating Gradient Magnetometer (AGM, colloquially: MicroMag) of Princeton's Measurements Inc., using small rock chips of 20 to 30 mg. For each site, four to five chips were measured. A maximum field of 1.4 T was used for these measurements.

For the backfield measurements a remanent magnetization was implanted with a 1.4 T field ($M_{r(1.4)}$) and then demagnetized with an increasing opposite field. This $M_{r(1.4)}$ magnetization is compared with $M_{r(-0.3)}$, the remanent magnetization implanted with a backfield of 300 mT. The so-called S-ratio ($S = -M_{r(-0.3)}/M_{r(1.4)}$) varies from 0.15 for the boulders 7.5 and 7.6 of the Agay conglomerate to 0.95 for the Esterellite (Figure 5a). It is worth noticing that rhyolite boulder 7.6, having a low-coercivity NRM, contains a considerable amount of high-coercivity minerals (low S-ratios). Apart from the Esterellite, the saturation magnetization (M_s) decreases with decreasing S-ratio (Figure 5). The M_s of hematite is much lower than

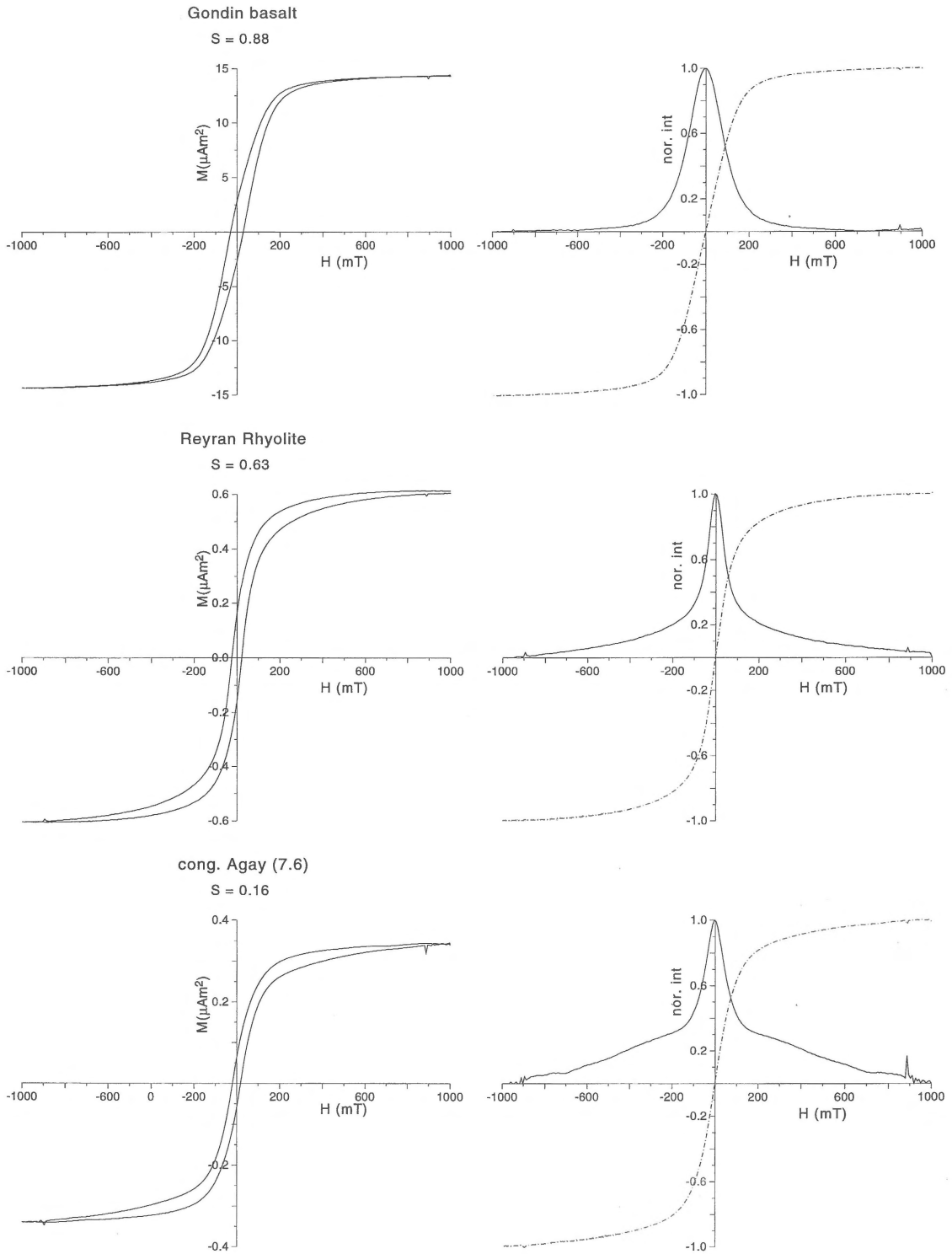


Figure 6. Hysteresis loops. Complete hysteresis loop for the Gondin Basalt (top-left,) and separation of this hysteresis loop in a 'sum' and 'difference' part (top-right). Idem for the Reyran Rhyolite (middle) and boulder 7.6 of the Agay Formation (bottom). Plots of the hysteresis loops are cut off at 1 T (maximum field 1.4 T).

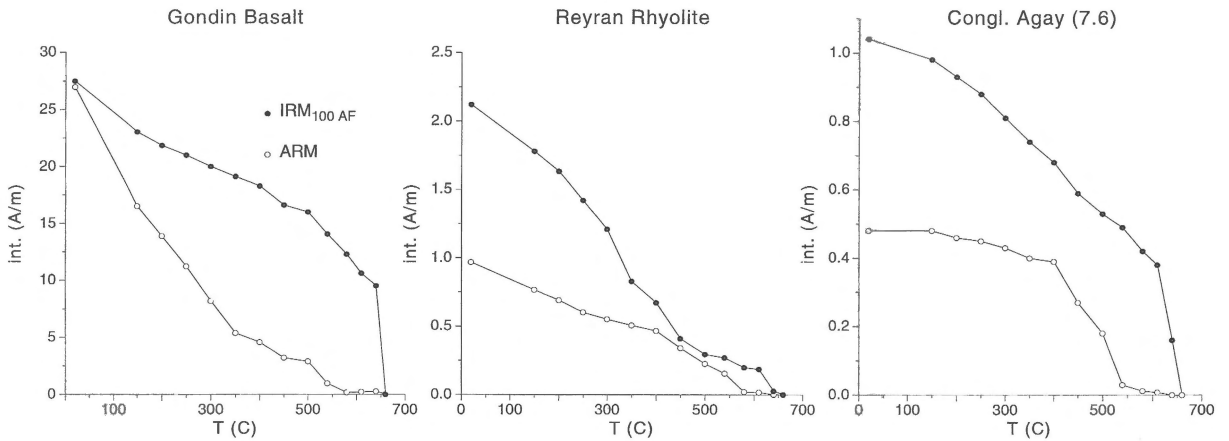


Figure 7. Thermal decay curves of simultaneous demagnetization of IRM_{100AF} and ARM for the Gondin Basalt (left), the Reyran Rhyolite (centre) and boulder 7.6 of the Agay Formation (right).

that of magnetite, and in the case of comparable grain sizes, coercivities are much higher for hematite than for magnetite. Hence, a decreasing S-ratio accompanied by a decreasing M_s , as observed for the Permian Esterel rocks, suggests the presence of a mixture of a magnetite and a hematite fraction. The remanent coercive force (H_{cr}) is defined by the backfield needed to demagnetize M_r . For the studied formations H_{cr} ranges from 45 to 125 mT and increases with a decreasing S-ratio (Figure 5b).

The ratio between the saturation remanence and the (total) saturation magnetization (M_r/M_s) ranges between 0.15 and 0.18 for the Gondin and Drammont Basalts to ~ 0.24 for the Reyran Rhyolite. The coercive force (H_c) ranges between ~ 15 mT for the same basalts to ~ 25 mT for the Reyran Rhyolite. No linear relationships between M_r/M_s , H_c and S-ratio exist, but H_{cr} and H_{cr}/H_c linearly increase with a decreasing S-ratio. As we probably deal with a mixture of magnetite and hematite grains in these rocks, absolute values of H_c , H_{cr} and the hysteresis ratios cannot be used to estimate the domain state of the magnetic grains.

After the determination of the classical hysteresis parameters, the hysteresis loops were separated into a 'sum' and a 'difference' part (Von Dobeneck 1996, Vlag et al. 1996). These parts were calculated by respectively adding and subtracting the upper and the lower part of the complete hysteresis loop. In this study, it was tested whether this further interpretation of hysteresis loops reinforces the idea that the magnetization in these rocks is carried by a low and by a high-coercivity fraction, probably corresponding with magnetite and hematite, respectively. For the Esterel-

lite, and the Gondin and Drammont Basalts, which have S-ratios higher than 0.85, saturation is reached at 500 to 600 mT (Figure 6). The 'difference' part of these hysteresis loops reaches 10% of its maximum value at 200 mT (Figure 6). Hysteresis loops of rocks (Reyran Rhyolite, some conglomerate boulders) with lower S-ratios are somewhat constricted in the middle sections (Figure 6). These loops are often referred to as 'wasp-waisted' (Roberts et al. 1995, Tauxe et al. 1996). Such wasp-waisted hysteresis loops result from a bimodal (or multi-modal) distribution of coercivities of the magnetic grains. For the samples of the Reyran Rhyolite ($0.60 < S < 0.65$), the 'difference' part of the hysteresis loops shows a strong decay between 0 and 150 mT and a slower decay in higher fields, suggesting the presence of a low and a high-coercivity mode. The 'difference' part of the hysteresis loops of the studied conglomerate boulders in the Agay Formation ($S < 0.3$) decreases strongly up to a 150 mT field and slowly decreases in higher fields (Figure 6). Its shape indicates that the hysteresis loop is constructed of two coercivity modes. It can, therefore, be concluded that for Esterel volcanic rocks having a low S-ratio, this further interpretation of hysteresis loops provides additional proof for the presence of a low and high-coercivity mode.

Thermal behaviour of the low and high-coercivity minerals was studied by the following method. In a first step an IRM (isothermal remanent magnetization) was implanted with a 1 T field. Then this IRM was demagnetized with a peak 100 mT AF in three orthogonal axes. The remaining intensity is called IRM_{100AF}. It is assumed that IRM_{100AF} is only carried by grains with a high coercivity. Secondly, an ARM (anhysteretic

remanent magnetization) was implanted perpendicular to the IRM component. This ARM was implanted with a 100 mT peak AF superimposed on a 0.1 mT continuous field and it is assumed that this ARM is carried by low-coercivity minerals. In a final step both magnetizations were thermally demagnetized by progressive heating. The described procedure is a modification of a method proposed by Lowrie (1990). This method consists of a thermal demagnetization of two or three different IRM coercivity fractions implanted along the orthogonal axes of one sample. Our modification has as advantage that: 1) it ensures a better independence of the two components than the multiple IRM method, and 2) in the (usual) case of a weak high-coercivity remanence the intensity of IRM_{100AF} is not negligible compared to the low-coercivity ARM component. Hence, in these cases the thermal decay of the high-coercivity fraction can still be determined. A disadvantage of this modification is that the contribution of the two coercivity fractions cannot be quantified.

Figure 7 shows typical decay curves for the simultaneous demagnetization of IRM_{100AF} and ARM. For all samples the ARM component is removed at 580°C. The IRM_{100AF} unblocks completely between 660 and 680°C. The 580°C maximum unblocking temperature for the low coercivities indicates that this fraction is carried by magnetite, while the unblocking temperatures for the higher coercivities confirm the presence of hematite. Replacing the 'soft' ARM component by an IRM implanted with a 100 mT field, provided similar results. Hence, together with the hysteresis measurements, simultaneous thermal demagnetization of two remanent magnetization components confirms the hypothesis of Zijdeveld (1975) that the remanence in the Esterel rocks is carried by a magnetite and a hematite fraction.

For the Gondin Basalt of the Mourrefrey Valley, the simultaneous thermal demagnetization of IRM_{100AF} and ARM shows that the high-coercivity hematite component is thermally stable and unblocks for the largest part above 660°C. The low-coercivity magnetite component is thermally less stable. The thermal stability of the high-coercivity minerals may explain the ChRM behaviour of the Gondin Basalt: a large part of the remanence is removed with a 100 mT peak AF in our samples, but a considerable amount of the NRM is not demagnetized at 580°C. Therefore, it may suggest the absence of a high-coercivity and low-temperature remanence.

For boulder 7.6, simultaneous thermal demagnetization experiments show that ARM unblocks between

400 and 540 to 580°C and IRM_{100AF} between 620 and 660°C, indicating the presence of thermally stable hematite. Hence, together with the hysteresis and backfield measurements, these results provide further suspicion for the low-coercivity NRM of this boulder.

Dispersion in the ChRM directions

Zijdeveld (1975) concluded that the ChRMs have a primary origin, because their associated VGPs are situated between the Permian VGPs of stable Europe and the Late Triassic VGPs of Eurasia. For all volcanics (basalts and rhyolites), the angular dispersion of the VGPs (S_{VGP}) (Cox, 1970) is 7.2. This limit is 3.0 for the rhyolitic formations and 10.4 for the basaltic flows. The corrected ChRM direction of the Reyran Rhyolite is included in these VGP scatters. The S_{VGP} for the basalts and the S_{VGP} for the rhyolites provide only a first-order estimate, because they are based on only four mean directions. Nevertheless, the extremely low VGP scatter of the rhyolites remains suspicious.

Zijdeveld (1975) explained this low dispersion by two mechanisms: 1) The deposition of most rhyolites happened accidentally at moments at which the local geomagnetic field had similar directions. 2) The paleosecular variation has been averaged out due to a slow cooling of some huge rhyolitic sheets in combination with a wide range of blocking temperatures. Two other explanations can be added: 3) The ChRM of the Esterel rocks was acquired during the Permo-Carboniferous reversed superchron and during this period secular variation was low. 4) The ChRM is not a thermoremanent magnetization, instantaneously acquired during the cooling, but might be acquired during weathering or hydrothermal alteration shortly after emplacement.

A comprehensive review of the problem of paleosecular variation during superchrons is given in McFadden & Merrill (1995) and Rochette et al. (this issue) and we refer to those papers for a more detailed discussion. According to McFadden & Merrill (1995) paleosecular variation is smaller at the equator, and also smaller during superchrons. Inclinations of the ChRM directions indicate that the paleolatitude of the Esterel was 10°N during the ChRM acquisition. According to the database of Lee (1983), S_{VGP} is 8.7 for the 0–25° latitude band during the long Cretaceous Superchron (85–119 Ma). This value is lower than the S_{VGP} of the Permian basalts in the Esterel. Compared to Lee's database the S_{VGP} is extremely low for the rhyolites.

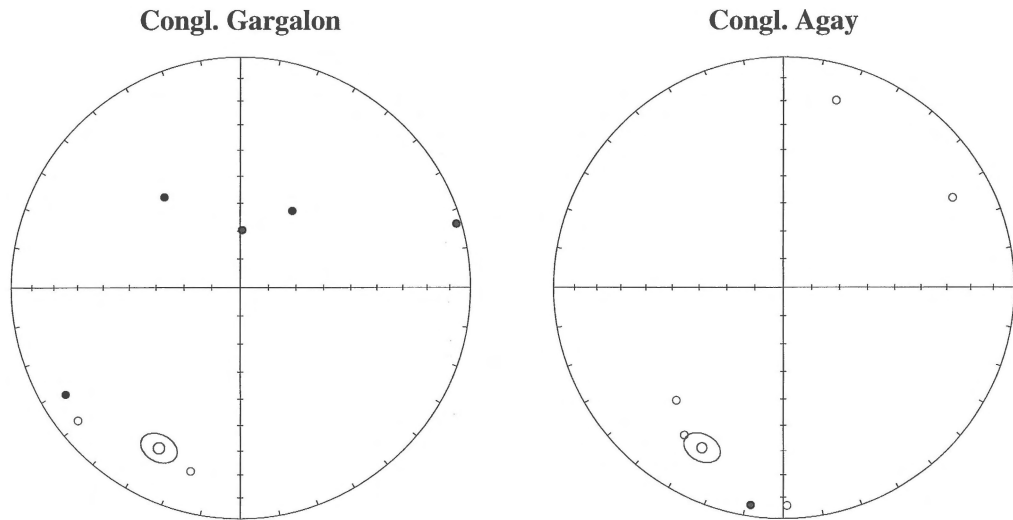


Figure 8. Stereographic plots of ChRM directions of the conglomerates of the Gargalon Formation (left) and of the Agay Formation (right). Closed (open) symbols denote positive (negative) inclinations. Large symbols with 95% confidence limit denote the mean ChRM direction for the Permian Esterel volcanics.

Furthermore paleosecular variation does not explain the lower VGP dispersion for the rhyolites compared to the basalts.

One conglomerate test, with rhyolitic boulders from the Amaranthine Rhyolite, was mentioned in Zijdeveld's thesis (1975). Inclinations of these boulders are low ($< 30^\circ$) and declinations are not homogeneously dispersed over the sphere. In view of the fact that the VGP dispersion for the rhyolites is remarkably low, two additional conglomerate tests were carried out in this study, to verify whether the remanence in the Esterel rocks was instantaneously acquired. If the ChRM of a rock is instantaneously acquired, conglomerate boulders of this rock should have scattered ChRM directions. In this case, the conglomerate test is interpreted as positive. A test was carried out on the Gargalon and the Agay Formations, which are positioned in the middle and in the upper part of the Esterel sequence, respectively. As the over- and underlying rocks of these conglomerates belong to the Esterel sequence, it is reasonable to assume that the conglomerates' boulders originated from the other Esterel formations. This was confirmed by field observations. Furthermore, demagnetization diagrams of conglomerate boulders do not systematically differ from the other Esterel rocks. Boulders large enough to drill cylindrical paleomagnetic cores were difficult to find. Therefore, only six to seven specimens per conglomerate could be analysed.

Although the conglomerate test of the Gargalon Formation might be interpreted as positive (Figure 8), it is suspicious that three of the seven measured boulders have remanence directions fairly close to the mean ChRM direction of the Permian rocks. For the conglomerate of the Agay Formation four ChRM directions are clustered nearby the average ChRM direction of the Permian Esterel rocks (Figure 8). The ChRM directions of the two other samples are in the proximity of the antiparallel direction of the average Permian ChRM. Five of the six samples have a low negative, and the sixth a low positive inclination. Furthermore, boulder 7.6 of this conglomerate showed a suspicious demagnetization diagram (Figure 4d): a low-coercivity ChRM close to the average paleomagnetic direction for all Permian Esterel rocks, and S-ratios (and also other rock-magnetic measurements) showing a considerable amount of high-coercivity minerals (Figure 5).

Especially for the Agay Formation the results of the conglomerate tests are ambiguous. Hence, the origin of the ChRM remains unclear. Neither an instantaneously acquired ChRM nor a widespread remagnetization can be proved. However, 1) one ambiguous conglomerate test, 2) an extremely low angular dispersion of the remanence in the rhyolites, and 3) the presence of a considerable amount of hematite in these volcanics suggest that assuming a priori an instantaneously acquired ChRM for the Esterel rocks might be an oversimplification. If a remagnetization took place, however, it should have taken place soon after the depo-

sition of the rocks. This is because the VGP positions suggest a Permian age of the remanence.

Conclusions

This revisit of Esterel shows the excellent quality of the paleomagnetic data obtained by Zijdeveld (1975). Zijdeveld measured deviating ChRM directions in the Reyran Rhyolite sampled in the Reyran River quarry, but such deviating directions are not found in this study. Hysteresis measurements and simultaneous thermal demagnetization of a high-coercivity IRM (IRM_{100AF}) component and an ARM component confirm Zijdeveld's idea that the characteristic remanence is carried by both a magnetite and a hematite fraction. The results of both conglomerate tests, especially that of the Agay Formation, are ambiguous. The unclear results of these conglomerate tests, together with the low dispersion of remanence for the rhyolites, and hematite as remanence carrier in these volcanics, create doubts whether the ChRM component in these volcanics was instantaneously acquired.

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