Geophys. J. Int. (1997) **128,** 73–83

New palaeomagnetic results from the Kerguelen Islands

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Accepted 1996 August 6. Received 1996 August 6; in original form 1996 March 28

SUMMARY

New palaeomagnetic analyses have been carried out in the Kerguelen Islands on 32 lava flows of well-established age (20–22 Ma). Combined with previous studies, they yield a reliable pole for the Lower Miocene for the Antarctic plate: $N=59$ flows, 349.9°E, 83.5°S, $A_{95}=6.1°$. A reversal sequence reversed–normal has been identified in the Port Jeanne d'Arc section.

Key words: Antarctica, geodynamics, Indian Ocean, Miocene, magnetic polarity, palaeomagnetism.

INTRODUCTION

The apparent polar wander path (APWP) for stable Antarctica is very poorly constrained, except for during the Jurassic. The Kerguelen Islands are part of the stable Antarctic plate, and the main part of the lava cropping out in these islands erupted in a relatively short period that has a well-established age (Lower Miocene). All these conditions are very favourable for obtaining a significant Cenozoic palaeomagnetic pole for this plate. Previous palaeomagnetic studies on these lavas were restricted to a few flows, and allowed only a poorly specified pole. Therefore, a new analysis of different lava sequences has been carried out in different parts of the archipelago. The main aim was to obtain an absolute reference for the reconstruction of the Indian Ocean during the Upper Cenozoic. Another aim of this study was to find reversals in these lava-flow sequences for future analyses of polarity transition periods.

THE KERGUELEN ISLANDS

Numerous arguments have been advanced to show that the Kerguelen archipelago (Fig. 1) is oceanic, rather than a continental fragment. No rocks older than 39 Ma have been found in these islands (Giret & Lameyre 1982). Granites, which crop out mainly in the southwestern part of the Kerguelen Islands, resulted from the differentiation of mantle magma (Bonin & Lameyre 1978; Dosso *et al.* 1976). The basement of the Kerguelen Plateau is basaltic (Leclaire *et al.* 1987). The crust under the Kerguelen Islands is 13–17 km thick (Recq, Charvis & Hirn 1983; Recq & Charvis 1986; Recq *et al.* 1990), with an underplating of magma of mantle origin (Grégoire *et al.* 1992). The southern part of the Kerguelen Plateau has a basaltic basement of Middle to Upper Cretaceous age, and a thicker crust.

The map of the oceanic magnetic anomalies of the western Indian Ocean (Schlich 1975, 1982) shows a drift from the Southeast Indian Ridge for the Kerguelen Plateau. Giret (1983, 1986, 1993) presented the following model of evolution of the Kerguelen Plateau: formation of a basaltic basement due to submarine volcanism on an aseismic ridge since the break up of Gondwana (about 120–110 Ma) and pelagic sedimentation since at least the Upper Cretaceous for the southern part of the Kerguelen Plateau (Munschy & Schlich 1987; Leclaire *et al.* 1987; Wicquart & Fröhlich 1986; Fröhlich *et al.* 1994), separation of a northeastern part (Broken Ridge) and a southwestern part (the Kerguelen Plateau) due to oceanic expansion along the Southeast Indian Ridge (45 Ma), and the drift of Kerguelen SW relative to the Southeast Indian Ridge, with slight geochemical and isotopic variations in the mantle sources of the magma, caused by the variation from ridge–mantle-plume interaction to mantle-plume interaction (Gautier *et al.* 1990; Weis *et al.* 1993; Saunders *et al.* 1994).

The oldest ages (39 Ma; K/Ar) in the Kerguelen Islands have been obtained from plutons (Giret, Cantagrel & Nougier 1981). Two main stages can be defined: from 40 to 26 Ma (ridge stage), with transitional-type magmatism; and from 26 Ma to Present (intraplate stage), with mildly to strongly alkaline magmatism (Giret 1983; Gautier *et al.* 1990; Leyrit 1992). The main volcanic activity (transitional alkali basalts to quartz trachytes) occurred during the Early Miocene (22–20 Ma in the southeastern Kerguelen; Nougier, Pawlowski & Cantagrel 1983). In this southeast province at least, a second important volcanic episode (basanites, tephrites, phonolites) occurred (Leyrit *et al.* 1990; Weis *et al.* 1993) during the Late Miocene (10–6 Ma). These ages have been confirmed by the marine Lower to Middle Miocene fauna observed in the sandstones interbedded between these two volcanic formations (Giret *et al.* 1994). Quaternary volcanoes (Mont Ross, Puy Saint Théodule, etc.) and present-day fumaroles (Nougier,

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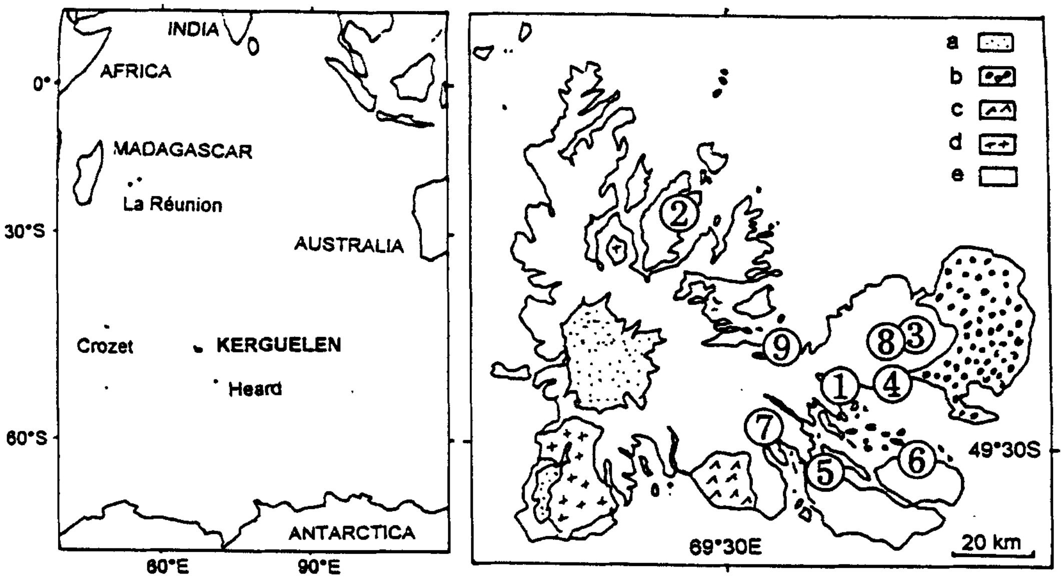

Figure 1. The Kerguelen Islands (after Giret 1986) showing the palaeomagnetic sites. 1: Ile Haute (Nougier & Plessard 1968; Derder *et al.* 1990); 2: Mont Bureau; 3: Grande Cascade (Watkins *et al.* 1974); 4: Molloy (Plessard, unpublished data; Henry & Plessard 1995); 5: Port Jeanne d'Arc; 6: Port Douzième; 7: Puy Saint Théodule; 8: Val Studer; 9: Port Couvreux (this study). a: glacier; b: Quaternary deposits; c: recent volcano; d: main plutonic complexes; e: basalts.

Ballestracci & Blavoux 1982; Delorme *et al.* 1994) show that the volcanic activity is still continuing.

Different zeolite parageneses (Nativel, Verdier & Giret 1994) are related to a hydrothermal period (the geothermal gradient reached 70–100 °C km^{-1}), giving a thermal evolution between 240 and 40 °C for the rocks of the Kerguelen Islands in the period 19–13 Ma (Verdier 1989).

GEOLOGICAL SETTING

Because of the lack of reference levels, it is usually not possible to distinguish the dip existing at the time of flow emplacement (called here the initial dip) from the dip acquired later from tilting (called here the tectonic dip). Tectonic activity is known to have occurred since at least the Upper Cretaceous in the Kerguelen Plateau (Munschy *et al.* 1994). Vertical movements are important in the whole archipelago, giving grabens such as the 'Passe Royale' in the Morbihan Gulf (Nougier 1970). The main tilting of the islands is mainly towards the SSE, but the tilting is for example mostly towards the N to NE in the Jeanne d'Arc (except the northwestern border) and Ronarc'h peninsulas (Leyrit *et al.* 1990). In practice, we cannot determine the tectonic dip. In order to limit the error in the mean palaeomagnetic direction for the whole archipelago due to the possible effect of such post-emplacement tilting, the sampling sites (Fig. 1) were chosen in areas with moderate to very low dips (dip lower than 5°) towards different directions. If all the measured dips are initial dips, this mean direction is exact. In the case of only tectonic dips, the different tilts are more or less compensating, and the error on the mean direction is negligible in comparison with the palaeomagnetic uncertainty. A worst-case scenario is where only dips towards one direction are tectonic, all the others being initial. The mean direction is then deflected (relative to the actual direction) in the direction opposite to the tectonic dip, but, because a majority of the directions have initial dips, the error should be very small.

At Port Jeanne d'Arc, the studied section (Fig. 2) is situated close to the Ravin du Charbon, except for the base of the section, which was chosen at the unloading area of Port Jeanne d'Arc in a subaphyric basalt containing plagioclase (Leyrit 1992). The cross-section of the Ravin du Charbon (Fig. 3) has been described by Nougier (1970) and Leyrit (1992). Samples were only collected from the aphyric basaltic flows of the 'western lower unit' of Leyrit (1992) and not from the conglomerates and volcanic breccia. Other samples were obtained from a section east of Port Douzième (Fig. 2) in the Ronarc'h peninsula (Leyrit *et al.* 1990). The studied flows are part of the unit called 'basalts of the centre of the archipelago' (Leyrit 1992). The top of the section is overlain by trachy-phonolitic bodies of Upper Miocene age (Leyrit 1992). At Puy Saint Théodule, one site (TA in Fig. 2) was selected in a dyke cutting the pyroclastics of the young volcano of Puy Saint Théodule in order to obtain the direction of the magnetic field during this volcanic event. Other sites (Fig. 2) are situated in the basaltic levels immediately adjacent to the volcano in order to detect the possible effect of this recent volcanism on the magnetization of these older flows. The section studied at Val Studer (Fig. 2) was chosen as it is far from the Montagnes Vertes pluton (Giret 1983), 500 m south of the Cascade Cachée area and it avoids the area where numerous dykes cross the basaltic flows. The basalts studied at Port Couvreux correspond to a section (Fig. 2) that includes a very thick lava flow in its middle part.

MAGNETIC MINERALOGY

Gautier (1987), analysing the submicroscopic crystals of titanomagnetite ($Fe_{3-x}Ti_xO_4$), found relatively high ulvöspinel contents ($x=0.44$ to 1) and weak oxidation. This composition indicates a late-magmatic counter-compounding of the titanomagnetites at a temperature below 600°C, and the age of the remanent magnetization carried by these titanomagnetites

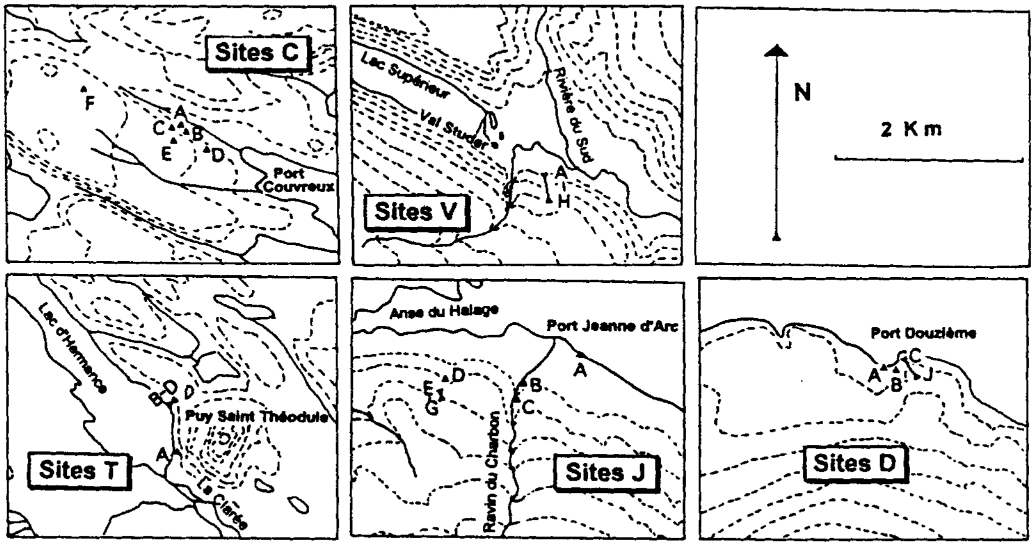

Figure 2. Sampling sites at Port Couvreux (sites C: 69.681°E, 49.252°S), Val Studer (sites V: 70.060°E, 49.291°S), Puy Saint Théodule (sites T: 69.618°E, 49.478°S), Port Jeanne d'Arc (sites J: 69.817°E, 49.557°S) and Port Douzième (sites D: 70.164°E, 49.516°S).

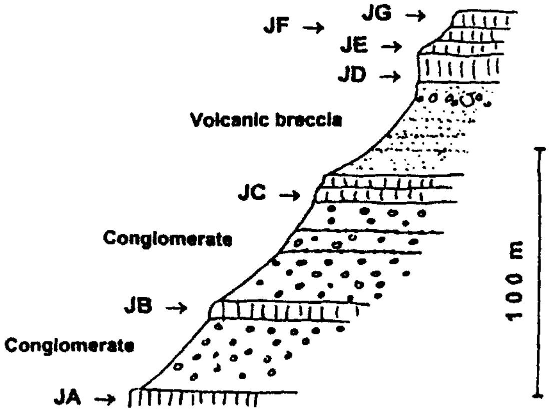

Figure 3. Port Jeanne d'Arc sampling sites JA to JG, referred to the cross-section of the 'Ravin du Charbon', modified after Nougier (1970) and Leyrit (1992).

could then be less than the age of emplacement. Such titanomagnetites are unsuitable for palaeomagnetism studies because of their low Curie temperatures (Readman & O'Reilly 1972): between 250 and 300°C for the minimum x value, and lower than 100 °C for the most frequently measured x values (Gautier 1987).

All nine Curie temperatures measured in flows at Ile Haute, however, are between 515 and 555° (Derder 1989; Derder, Plessard & Daly 1990). Similarly, a Curie curve determined using CS2 equipment (GEOFYZIKA-AGICO, Brno) in a sample from a flow of the Port Jeanne d'Arc section (Fig. 4) gives a Curie temperature of the order of 580°C. All these Curie temperatures indicate low ($x<0.12$) ulvöspinel contents (Readman & O'Reilly 1972). Clearly the ferrimagnetics determined using the magnetic approach differ from the visible grains and are thus very small. It is possible that these small grains have a higher degree of oxidation, and are therefore titanomaghemites with slightly higher x ($x<0.2$) values (Readman & O'Reilly 1972). On the other hand, no titanomagnetites with a Curie temperature between 300 and 20°C can be identified by analysing the curve in Fig. 4. This probably indicates that the visible grains of titanomagnetite (Gautier 1987; Leyrit 1992) have $x>0.8$ in the flow studied.

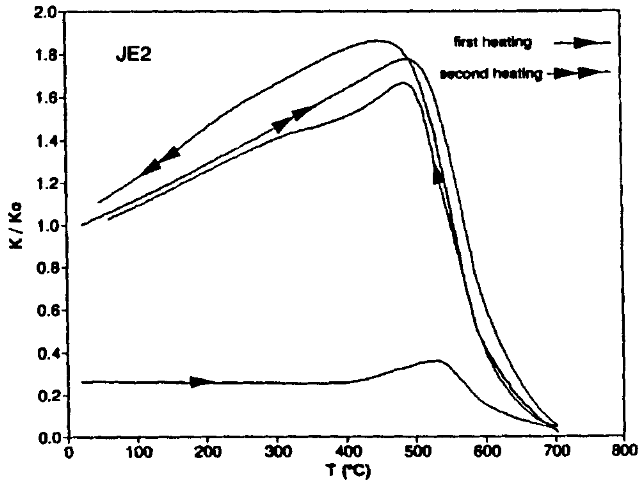

Figure 4. Variation of the susceptibility K/K_0 as a function of temperature T during two successive heating–cooling cycles (sample JE2 of the flow JE at Port Jeanne d'Arc; see Figs 2 and 3).

The small size of the grains with high Curie temperature has been confirmed by other rock magnetic analyses at Ile Haute (Derder 1989). The median destructive field (MDF) values are between 2.8 and 106 mT, but the MDF value for thermoremanent magnetization (TRM) is not a grain-size indicator (Heider, Dunlop & Soffel 1992a). The Day, Fuller & Schmidt (1977) diagram (Fig. 5) indicates pseudo-single-domain (PSD) grains of a few micrometres in diameter.

The MDF values have also been studied in our samples (Fig. 6). To take into account the frequent presence of two or more non-parallel components of the magnetization, the intensities of the magnetization during alternating-field treatment have been estimated by summing the difference vector intensities. The MDF values of natural remanent magnetization (NRM) of our samples, between 2.9 and 210 mT with a mean

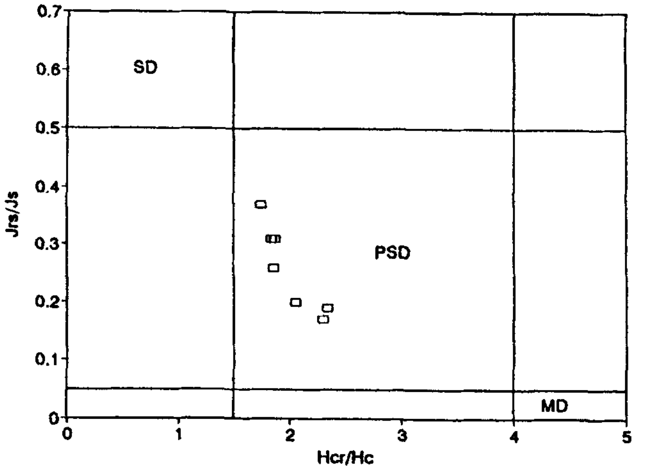

Figure 5. *J*rs/*J*s as a function of *H*cr/*H*c (Day *et al.* 1977) for samples from Ile Haute (Derder 1989).

value of 26 mT, are very similar to those of the Ile Haute samples.

Two 'generations' of ferro-titanium oxides are therefore present in the basaltic lavas of Kerguelen. Very small grains of Ti-poor titanomagnetites (or titanomaghemites) probably correspond to a relatively early phase, and larger grains of Ti-rich titanomagnetite to a late magmatic phase. These large grains might be the source of the large viscous magnetization observed in some flows.

On the other hand, the *K*(*T*) curve of Fig. 4 shows the presence of haematite. It is possible that the haematite formed during heating in the susceptibility bridge furnace. If not, the haematite could have been produced during zeolitization.

Lastly, we note that this thermomagnetic curve is irreversible. The Curie temperature does not change during heating and cooling, but the susceptibility strongly increases after the first heating. This could be the result of the conversion of some non-stoichiometric phase of titanomagnetite (Bina & Henry 1990) or of titanomaghemite. Because of this mineralogical change during the heating and the moderate values of the MDF, the analysis of the remanent magnetization has been carried out using alternating-field treatment. In addition, Derder (1989) showed that the results obtained at Ile Haute using thermal and alternating-field treatments are similar.

MAGNETIC PROPERTIES

The remanent magnetization was measured using a JR-4 magnetometer (GEOFYZIKA-AGICO, Brno) and analysed

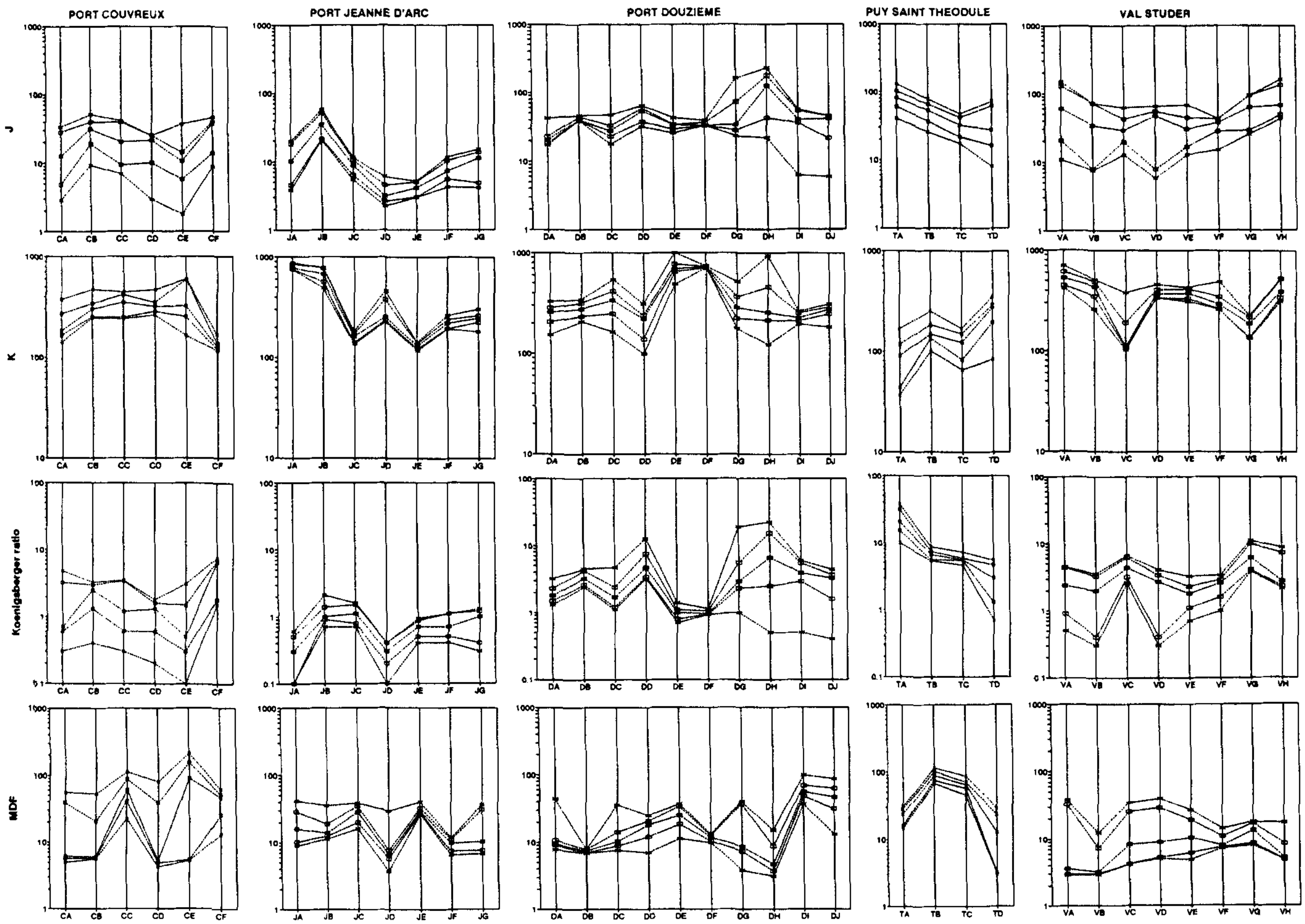

Figure 6. Values (presented using the minimum, 25th percentile, median, 75th percentile and maximum of their distribution) of NRM intensity *J* (in 10^{-5} A m^{-1}), susceptibility *K* (in 10^{-5} SI), Koenigsberger ratio and MDF (in mT) in the different volcanic bodies studied (see Table 1).

by alternating-field demagnetization (Le Goff 1985). The susceptibility was determined using a Kappabridge KLY-2. Fig. 6 shows the values of different magnetic parameters for the flows studied: NRM intensity, susceptibility, Koenigsberger ratio and MDF.

The values of the NRM intensity vary little within each flow at Port Jeanne d'Arc and Port Douzième (except for the two upper flows), whereas two clear groups of values within each flow are present at Port Couvreux and Val Studer. This is perhaps related to the presence of two components of the NRM in some of the samples at these sites. The NRM intensity has the lowest values in the flows JC to JF at Port Jeanne d'Arc.

The variation from one flow to another is mostly smaller for the susceptibility than for the NRM intensity. This gives a similarity in the variations of the NRM intensity and the Koenigsberger ratio from one flow to another. It is interesting to note that the lowest Koenigsberger ratios have been obtained in the Port Jeanne d'Arc section. This could indicate that the low NRM intensity measured in this section is not related to a smaller amount of ferrimagnetics, but rather to a low intensity of the magnetic field during the emplacement of these flows. The Koenigsberger ratios are also small in the Port Couvreux section. We will show later that a reversal has been precisely recorded in the Port Jeanne d'Arc section, and that the directions at Port Couvreux could be transitional. However, the variations of the Koenigsberger ratio can also be attributed to other causes, in particular to the existence of a large secondary component in the NRM in some flows. This is illustrated by the relatively high value of this ratio measured in the transitional flow VH at Val Studer (where the secondary component is of the same polarity as the primary one) compared with the low values obtained at Port Couvreux (where the two components have opposite polarities).

PALAEOMAGNETIC ANALYSIS

To limit the contribution of the viscous magnetization observed in several flows, the samples were kept in a zero field for at least six months. The Zijderveld diagrams show two different demagnetization behaviours depending on the site (Fig. 7). In the Port Douzième, Port Jeanne d'Arc and Puy Saint Théodule sections, a single component appears in the majority of the flows. In the Port Couvreux and Val Studer sites, two components are usually observed. The problem is to determine, for the samples with a single component, if this component corresponds to the low-coercivity or high-coercivity component of the samples with two components. Fortunately, some samples from Port Douzième, Port Jeanne d'Arc and Puy Saint Théodule sections have two components, and it is clear that the single component in these sites is equivalent to the high-coercivity one. Figs 8 and 9 show, respectively, the orientations of the low- and high-coercivity components.

The Zijderveld diagrams also show the existence of a very high-coercivity component by the fact that the regression lines associated with the high-blocking-field component do not cross the origin of the axes exactly for numerous samples (Fig. 7). Unfortunately, this weak component could not be isolated because of the occurrence of anhysteretic remanent magnetization (ARM) at the highest alternating fields and mineralogical alteration during heating. There is perhaps a connection between this very weak component of very high coercivity and the possible presence of haematite shown by the Curie curve.

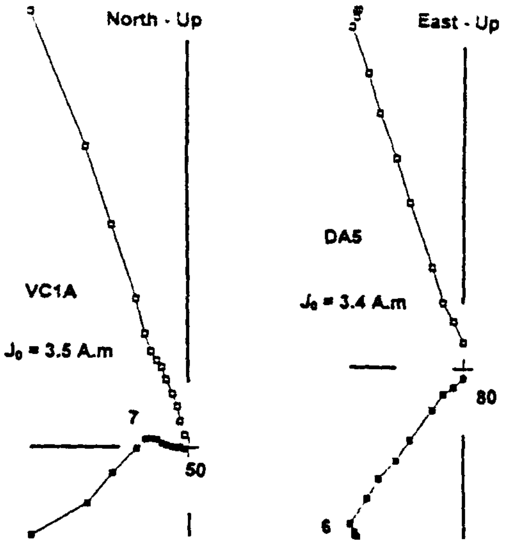

Figure 7. Orthogonal vector plot: projection on the horizontal (open squares) and vertical (full squares) planes; alternating-field intensity in mT.

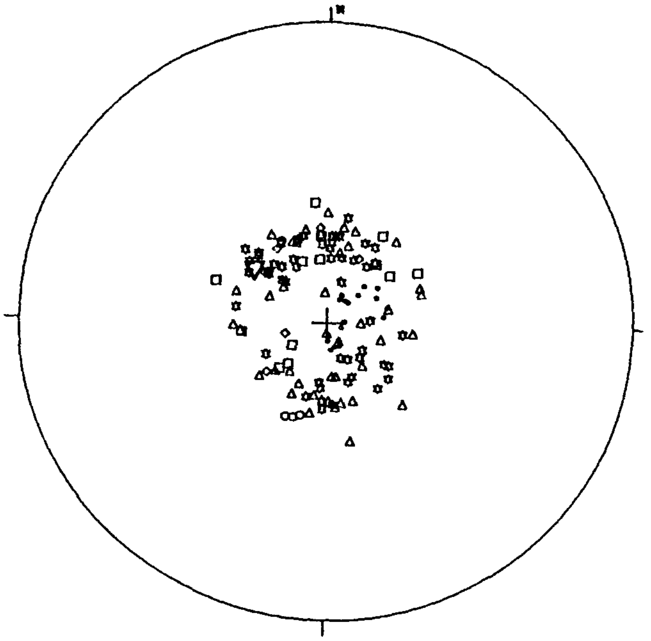

Figure 8. Characteristic remanent magnetization (high-coercivity component) of samples from a Quaternary dyke (site TA) at Puy Saint Théodule (small circles), and the low-coercivity components at Puy Saint Théodule (large circles), Port Couvreux (stars), Port Douzième (squares), Port Jeanne d'Arc (diamonds) and Val Studer (triangles). The larger downward-pointing triangle indicates the present-day field direction. Stereographic projection, open symbols upper hemisphere, closed symbols lower hemisphere.

DISCUSSION

Origin of the different components of the magnetization

The low-blocking-field component (Fig. 8) has normal polarity and high inclination only. It has a similar direction in the

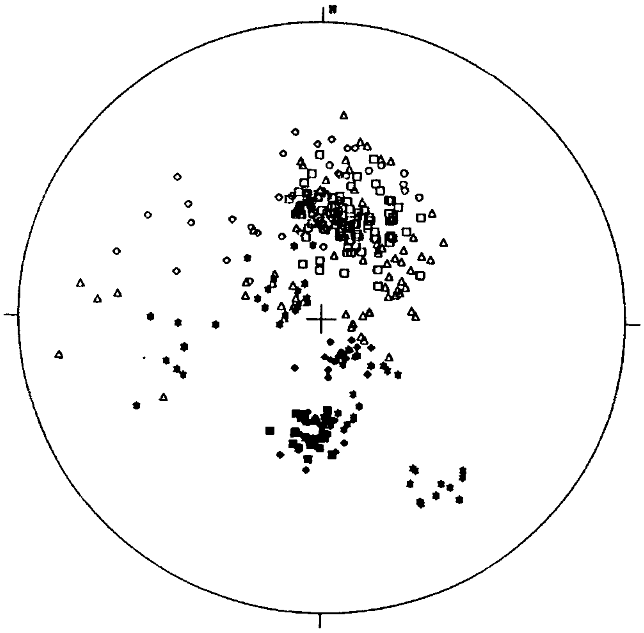

Figure 9. High-coercivity component (stereographic projection, open symbols upper hemisphere, closed symbols lower hemisphere) at different sites: Puy Saint Théodule (circles), Port Couvreux (stars), Port Douzième (squares), Port Jeanne d'Arc (diamonds) and Val Studer (triangles).

different flows and was therefore acquired after the emplacement of all the Lower Miocene lavas. The presence of only normal polarity may also indicate a relatively short period for the acquisition of this component, and seems thus to exclude thermal effects during zeolitization. Two main clusters of directions appear in all the sections. A cluster of WNW to NE directions includes the direction of the present magnetic field, and could correspond, at least partly (WNW directions), to a recent viscous remanent magnetization (VRM). The other cluster of directions has on average a southerly direction. The two clusters have a direction slightly different from the magnetization direction of the Quaternary dyke (site TA) at Puy Saint Théodule (Fig. 8). They are therefore evidently not related to the recent volcanic event of the Puy Saint Théodule. The origin of the low-coercivity component remains unknown, a possible cause being hydrothermal activity during various volcanic periods.

The direction and the polarity of the weak component of very high coercivity are unknown. The only indication about this component is the carrier, which appears to be haematite. In this case, the magnetization could have been acquired during zeolitization.

The high-blocking-field component has a coherent direction within each flow. It mostly has a different direction from one flow to another (and sometimes even a different polarity in two localities). It is therefore clear that the acquisition of this magnetization for each flow occurred during or very shortly after the flow emplacement.

Reversals

A change of the polarity of the high-coercivity magnetization has been observed in two sections. At Port Jeanne d'Arc, transitional directions have been found in the flows JB to JE. The Koenigsberger ratio is low (mean 0.8) compared with the others sections, suggesting that the magnetic field during the emplacement was weak. The central part of the studied section therefore clearly corresponds to a period of a reversal (Fig. 10), probably during chrons C6AA to C6 because of the age of the lavas (transition between polarity epochs 24–23 or 22–21 or 20–19).

In contrast to the other section with mixed polarity, at Port Douzième no transitional directions were obtained. The Koenigsberger ratio (mean value 4.2 for the whole section; mean values of 5.4 and 8.8, respectively, for the normal flows DG and DH, and of 3.9 and 2.8, respectively, for the reversed flows DI and DJ) is similar to that obtained in the sections with single polarity (mean value 3.1). Port Douzième therefore shows no evidence of a transitional period, and either a time gap in the volcanic activity exists between the emplacement of the flows DH and DI, or the flows DI and DJ have been remagnetized during the emplacement of the trachytic bodies just above them. Unfortunately, no samples have been taken in the Upper Miocene trachytic bodies, and we cannot choose at present between these hypotheses. Because of this ambiguity, the two upper flows of the Port Douzième section have been rejected for the determination of the average direction.

New results

Table 1 and Fig. 9 present the results obtained in the different flows for the high-blocking-field component. At Port Douzième, the directions are well defined and well grouped. The polarity is normal, except for the two upper flows (see above). At Puy Saint Théodule, the normal polarity has been found in the Quaternary dyke TA and in the flows TB to TD. The directions are well defined, with a moderate scattering about the mean direction. At Val Studer, the mean directions are a little more scattered, probably because the directions from the flow VH could be transitional. The polarity is normal

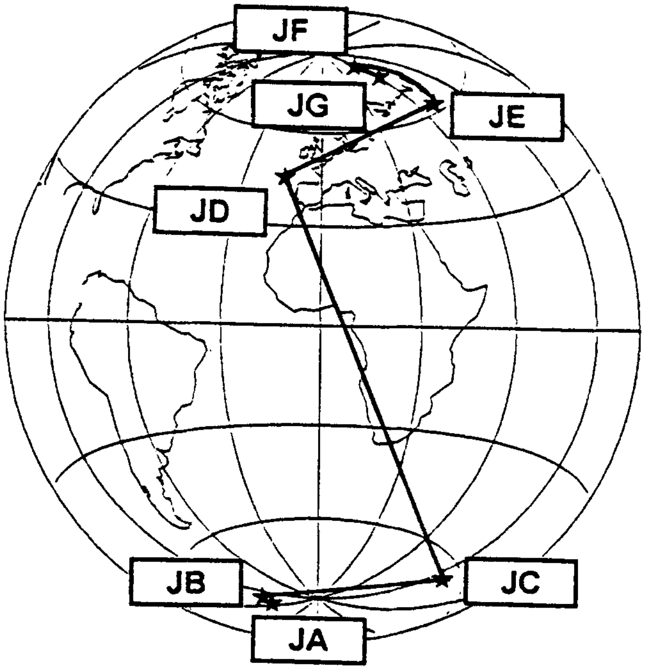

Figure 10. Reversal path at Port Jeanne d'Arc.

Table 1. New palaeomagnetic results from the Kerguelen Islands (asterisk indicates a direction retained for the calculation of the mean direction).

Site	Flow	$D^{(\circ)}$	$I^{(\circ)}$	N	k	$\alpha95^{(\circ)}$
Port Jeanne d'Arc	JA*	177.8	59.2	7	160	4.2
	JB*	185.8	56.0	10	228	2.9
	JC*	154.4	78.4	18	273	2.0
	JD*	306.3	−47.3	10	26	8.7
	JE*	0.1	−40.1	5	178	4.7
	JF*	353.8	−62.1	5	171	4.8
	JG*	352.2	−58.5	8	42	7.7
Port Douzième	DA*	15.1	−61.3	12	180	3.0
	DB*	10.2	−51.5	7	98	5.4
	DC*	355.4	−56.5	17	210	2.3
	DD*	7.6	−63.5	16	269	2.1
	DE*	19.9	−61.4	11	291	2.5
	DF*	28.5	−52.4	4	579	2.9
	DG*	28.9	−61.5	15	151	2.9
	DH*	23.3	−67.7	18	61	4.2
	DI	*190.2*	*56.9*	*11*	*261*	*2.6*
	DJ	*181.1*	*58.5*	*10*	*366*	*2.3*
Port Couvreux	CA*	145.9	*33.0*	11	117	3.9
	CB*	256.3	48.5	9	57	6.2
	CC*	147.5	70.4	12	97	4.1
	CD*	320.0	76.1	6	66	7.0
	CE*	304.0	78.6	10	150	3.6
	CF*	172.0	61.1	10	495	2.0
Puy Saint Théodule	(*TA*	*62.3*	*−81.8*	*14*	*151*	*3.0*)
	TB*	350.8	−57.6	10	1045	1.4
	TC*	355.8	−59.8	12	437	1.9
	TD*	20.7	−46.9	9	158	3.7
Val Studer	VA*	63.6	−66.8	12	227	2.7
	VB*	46.2	−61.7	11	53	5.8
	VC*	315.6	−77.9	12	71	4.8
	VD*	76.4	−75.8	11	92	4.4
	VE*	18.2	−40.5	10	82	4.9
	VF*	6.1	−57.4	12	112	3.8
	VG*	358.7	−48.2	12	145	3.4
	VH	*267.8*	*−35.1*	10	20	9.9

in all the Val Studer flows. At Port Couvreux, the polarity is reversed, and the directions well defined. However, the magnetization of the flows CB, CD and CE has a direction different from that of the other flows. Taking into account the low values of the Koenigsberger ratio in this section (Fig. 6), this could indicate a period of low intensity in the terrestrial magnetic field, such as an excursion or a reversal. At Port Jeanne d'Arc, there is a polarity change between reversed flows (JA–JC) and normal flows (JD–JG), and the values of the Koenigsberger ratio are low (Fig. 6). Three flows (JC–JE) have transitional directions (Fig. 10).

Previous results from the Kerguelen Plateau

The first palaeomagnetic result in the Kerguelen Islands (Nougier & Plessard 1968) was obtained at Ile Haute (Fig. 1). It involved 28 samples from five flows of reversed polarity and two overlying flows with transitional directions (Table 2). The magnetization analysis was made progressively by an alternating field up to 60 mT. The scatter of the directions is moderate, except within the two upper flows.

Watkins *et al.* (1974) mainly studied two sections (Fig. 1). At Foch Island (Mont Bureau), 19 samples showed both the normal (the four lower flows) and reversed (the three upper flows) polarities (Table 2). In the Courbet Peninsula (Grande Cascade), 61 samples from 11 flows had only normal polarity (Table 2), as did 12 samples from a trachytic intrusion; their paper also included results from 40 other samples showing a normal polarity, but without specifying their sampling area. The directions were mostly scattered, perhaps because of an inadequate analysis of the magnetization: only three steps of alternating field were used, and the mean direction was computed using the minimum dispersion criterion. In some of our sites we found a large secondary component with a moderate coercivity, which such an analysis may have mistakenly given as a primary component.

A more recent study at Ile Haute (Derder 1989; Derder *et al.* 1990) on five basaltic flows (89 samples) showed normal, transitional and reversed directions (Table 2). Thermal and alternating-field treatments yielded similar palaeomagnetic directions. For two of the flows, two different components of magnetization were isolated. One of these, with low coercivity and normal polarity, is likely to be a remagnetization, and the other a transitional direction. Normal polarity was obtained in one flow (Fig. 1) at Molloy (Table 2) (Plessard, unpublished data).

ODP Leg 119 (Barron *et al.* 1989) included drilling in the Kerguelen Plateau. Palaeomagnetic data (Sakai *et al.* 1990) were obtained in the sedimentary sequence and in basaltic bodies. Holes 745B, 737A and 746A involved a Pliocene magnetostratigraphy. At hole 738C, the limestone sequence from Turonian to Santonian age showed a palaeolatitude 10° less than the present latitude. The basalts under the Turonian limestones erupted subaerially and show two polarities.

ODP Leg 120 (Schlich *et al.* 1990) also studied a sequence of sediments and basalts from the Kerguelen Plateau. A magnetostratigraphy from Oligocene to Pliocene was established from holes 747, 749 and 751 (Heider, Leitner & Inokuchi 1992b). The titanomagnetites, slightly larger than single domain, in the volcanic ash particles (from the explosive volcanism of the Kerguelen Islands) carry the remanent magnetization in these deep-sea sediments (Heider, Körner & Bitschene 1993). Mid-Cretaceous basalts have been studied in holes 747–750. Shallower palaeomagnetic inclinations than the present inclination (the average difference of the palaeolatitude relative to the present is 17°) imply a southward movement of the Kerguelen Plateau with respect to the geographic pole (Inokuchi & Heider 1992). Low-temperature (titanomaghemites with Curie temperatures ranging from 340 to 395 °C in holes 748 and 750) as well as high-temperature (titanomagnetites with Curie temperatures higher than 500°C in holes 747 and 749) oxidation effects have been observed (Heider *et al.* 1992c).

Geodynamical implications

Fig. 11 shows the 59 remanence directions used for the determination of the mean palaeomagnetic direction. Only directions with a *k* precision parameter greater than 8 have been used, and some other directions (Table 2) have also been rejected

Table 2. Previous paleomagnetic results from the Kerguelen Islands (asterisk indicates a direction retained for the calculation of the mean direction).

Site	Flow	$D^{(\circ)}$	$I^{(\circ)}$	N	k	$\alpha 95^{(\circ)}$	Ref.
Ile Haute	H1A*	237	62	4	306	4	Nougier & Plessard (1968)
	H1B*	209	70	4	306	4	
	H1C*	159	69	4	100	7	
	H1D*	184	79	4	306	4	
	H1E*	185	75	4	196	5	
	H1F	*346*	*22*	4	60	9	
	H1G	*329*	7	4	5	31	
Foch Island	FA*	94.1	−61.8	2	13	–	Watkins *et al.* (1974)
	FB*	4.8	−75.1	3	15	32.6	
	FC*	25.8	−51.8	2	269	–	
	FD*	23.0	−64.2	3	8123	1.4	
	FE*	189.5	55.3	3	15	33.2	
	FF*	135.2	62.9	3	42	19.4	
	FG*	186.9	62.0	3	1167	3.6	
Grande Cascade	GA*	354.7	−74.4	4	254	5.8	Watkins *et al.* (1974)
	GB*	359.6	−78.0	4	366	4.8	
	GC*	329.8	−84.5	4	140	7.8	
	GD*	354.1	−78.4	4	157	7.4	
	GE*	23.5	−72.6	5	310	4.4	
	GF	50.7	−41.0	3	2	–	
	GG*	16.4	−30.4	5	597	3.1	
	GH*	9.7	−56.2	4	9	33.4	
	GI*	292.3	−54.7	7	645	2.4	
	GJ*	9.2	−50.0	6	170	5.2	
	GK*	352.8	−62.0	9	416	2.5	
	GL*	73.6	−55.9	6	117	6.2	
Ile Haute	H2A*	24.2	−27.2	6	1131	4.9	Derder *et al.* (1990)
	H2B*	349.1	−69.6	18	742	1.6	
	H2C*	342.4	−72.3	10	139	3.7	
	H2D*	199.0	72.6	18	282	2.0	
	H2E	*352.0*	*35*	15	75	4.2	
Molloy	M*	24.5	−64.7	11	132	3.7	Plessard, unpubl.

because they very probably correspond to transitional fields. The mean direction is then $N=59$ flows, $D=9.8°$, $I=-65.5°$, $k=17.4$, $\alpha_{95}=4.4°$ ($N=509$ samples, $D=9.7°$, $I=-65.5°$, $k=15.1$, $\alpha_{95}=1.6°$). The large number of flows studied reduces the effect on the mean direction of the geomagnetic-field secular variation recorded by the lava flows. The precision given by the parameter k does not reflect the actual precision of the results, because of the possible inclusion of some transitional directions.

The APWP for stable Antarctica is very poorly defined, except for the Jurassic. An APWP for Antarctica can be based on the neighbouring plates for which the absolute position is known, together with modelling of the geodynamical evolution from the spreading ridges (Watts, Watts & Bramall 1984; Idnurm 1986; Beck 1994; Beck, Schott & Westphal 1996). However, the uncertainty is mostly large because such reconstructions also have to take into account both the uncertainty in the neighbouring plate position and the uncertainty of the model used for the evolution of the ridges.

The recent compilation of Van der Voo (1993) for stable Antarctica contains only six poles for the Palaeozoic and 10 poles for the Jurassic. There are, however, some other poles for Cenozoic times, but these were not included in this compilation, mainly because of their insufficient precision or of their poorly defined age. For example, at Cape Hallet (Turnbull 1959; Delisle 1983) the age of the flows is not well determined (0–11 Ma?). The ChRMs of the samples have mainly reversed polarity (pole position 81.9°S, 256.8°E). More precise data have been obtained in the McMurdo Sound (Funaki 1979, 1984; Mankinen & Cox 1988) region (pole position 87.3°S, 137.3°E for 0–5 Ma) and at the Adare Peninsula (Delisle 1983) (pole position 83.6°S, 186.4°E for the Upper Miocene). Flows and intrusions have also been studied at Heard Island (Irving, Stephenson & Major 1965). Their age is recent (0–2 Ma, except perhaps for one of 10 sites with a poorly defined age of 0–40 Ma) and the palaeomagnetic pole is not precise (pole position 81°S, 221°E, $A_{95}=11°$). A poorly defined pole (83.2°S, 296.7°E for 40–25 Ma) has also been obtained in the Fildes Peninsula (Scharon *et al.* 1970). The palaeomagnetic pole from the Kerguelen Islands is therefore the first reliable Cenozoic pole for stable Antarctica. Determined using 59 different flows from 10 sections, it is of a well-specified age (20–22 Ma) and is located at 83.5°S, 349.9°E, $K=9.0$, $A_{95}=6.1°$.

The palaeolatitude deduced from the palaeomagnetic data is about 47.5°. The comparison of the latitudinal drift of Kerguelen since the Lower Miocene (about 2°) with the spreading rate for the Southeast Indian Ridge should indicate the stability of this ridge. Since the Middle Cretaceous, the

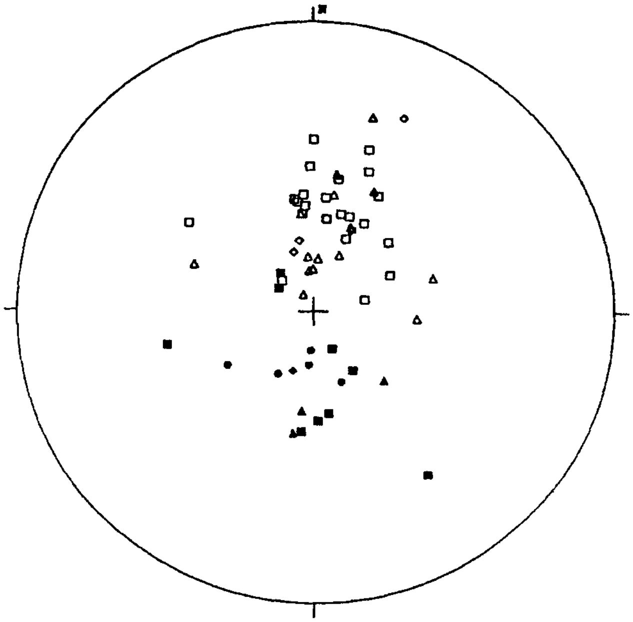

Figure 11. Retained mean directions for the different flows (stereographic projection, open symbols upper hemisphere, closed symbols lower hemisphere). Circles: Nougier & Plessard (1968); triangles: Watkins *et al.* (1974); diamonds: Derder *et al.* (1990); star: Plessard (unpublished data); squares: this study.

southward latitudinal drift of Kerguelen seems relatively regular (relative to the Present, the difference in palaeolatitude is 17° for the Middle Cretaceous, 10° for the Santonian–Turonian for the southern part of the Kerguelen ridge, and 2° for the Lower Miocene); however, only three data points, with large uncertainties, are obviously insufficient for reliable conclusions to be drawn. This change in palaeolatitude since the Middle Cretaceous has to be taken into account in the different models for the origins of the Kerguelen Plateau and of the Miocene to Present volcanism (see Giret & Lameyre 1987; Leyrit 1992; Weis *et al.* 1992; Giret 1993; Goslin & Maia 1993; Saunders *et al.* 1994). The flora found in the Val du Charbon section at Port Jeanne d'Arc indicate a temperate to warm climate (Mechkova 1968). The increase in latitude of about 2° since the Lower Miocene seems insufficient to explain the change to the present colder climate. The Early Miocene palaeomagnetic latitude for southern Australia is higher than the hot-spot estimate; Idnurm (1985, 1986) suggested that it might be due to a bias related to the approximate nature of the geocentric axial dipole model (Coupland & Van der Voo 1980) and proposed a bias-corrected synthetic Antarctic APWP. However, the palaeolatitudes of the Kerguelen Islands calculated using this APWP are a little higher than the measured one, and a palaeolatitude variation, even taking into account such a bias, does not explain the climatic variation. This variation could be caused by a change in the marine circulation around Antarctica since this period.

CONCLUSION

The palaeomagnetic analysis of the Kerguelen Islands has yielded the first reliable pole of stable Antarctica for the Cenozoic: 22–20 Ma, 169.9°E, 83.5°N, $K = 9.0$, $A_{95} = 6.1°$. A reversal sequence has been identified in the Val du Charbon section, close to Port Jeanne d'Arc.

ACKNOWLEDGMENTS

We are very grateful to the IFRTP and the TAAF for providing all transport and facilities and for support of this project. Special thanks to A. Lamalle, R. Pagny, all our field friends, M. Bina, M. Barbier and L. Boissin for their help. The comments of R. Schlich contributed significantly to the clarification and improvement in the interpretation of the results. The paper was substantially improved as a result of comments by M. Idnurm, F. Heider and an anonymous reviewer.

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