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New K-Ar ages from La Montagne massif, Réunion Island (Indian Ocean), supporting two geomagnetic events in the time period 2.2–2.0 Ma

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SUMMARY

We present new radiometric ages obtained at the type locality in La Réunion Island where palaeomagnetic records of the Réunion events have first been identified. Seven dated lava flows from the Rivière Saint Denis section, which recorded a reverse-to-normal transition, display ages from 2.12 ± 0.03 to 2.17 ± 0.03 Ma, with a mean age of 2.15 ± 0.02 Ma. Two significantly younger flows from this section, interpreted here as valley fill flows from trace elements compositions and Pb isotopic data, have been dated at 2.06 ± 0.03 and 2.08 ± 0.03 Ma. Within the Grande Chaloupe section, where a normal-to-reverse transition is recorded, two coherent ages of 2.05 ± 0.03 and 2.03 ± 0.03 Ma have been obtained. When a direct comparison was possible, our new K-Ar ages performed on separated groundmass show a rather good coherence with previous ages from La Réunion Island. When considered with continuous palaeomagnetic sedimentary records in the 2.2–2.0 Ma interval, these new results suggest that two distinct events are recorded in La Montagne lava flows at La Réunion Island, with ages of 2.15 ± 0.02 and 2.04 ± 0.02 Ma. Following recent nomenclature, the former is the Réunion event *s.s.*, while the latter can be related to the Huckleberry Ridge event. Globally distributed volcanic and sedimentary records show that the first (Réunion *s.s.*; RU-1) is associated with a large dipole intensity decrease at 2.15 ± 0.02 Ma, and hence is recorded in many sequences. On the other hand, the dipole intensity decrease was not as pronounced at 2.04 ± 0.02 Ma, when the Huckleberry Ridge (RU-2) palaeomagnetic event occurred. Consequently, it is not present as a full directional change in many sections worldwide, but rather appears as a geomagnetic excursion during an episode of increased secular variation. Finally, the use of the Réunion event for magnetostratigraphic studies is recommended, while the clear identification of the Huckleberry Ridge excursion might often be difficult, preventing its use as a reliable time marker.

Key words: Geomagnetic excursions; Reversals: process, timescale, magnetostratigraphy; Oceanic hotspots and intraplate volcanism; Indian Ocean.

1 INTRODUCTION

Magnetostratigraphy is a powerful tool to constrain the timing of sedimentary sequences. It is widely used in continental sections or in deep-sea sediment cores where volcanic layers, which can allow radiometric dating, are infrequent or missing. Magnetostratigraphy relies on the assumption that geomagnetic field reversals are globally recordable at the Earth's surface without significant time gap between different sites. However, when a resolution better than about 1 Myr is needed, it is tempting to rely on geomagnetic excursions, which are much more frequent than reversals, with at least six

of them occurring in the past 0.78 Myr, within the Brunhes chron (Langereis *et al.* 1997; Lund *et al.* 2006). Excursions are often described as aborted reversals (Valet *et al.* 2008) and are characterized by palaeomagnetic directions significantly different than those due to the normal (N) secular variation, that is, associated with a virtual geomagnetic pole (VGP) more than 45° away from the geographic north or south direction. Excursions are less straightforward to use for magnetostratigraphy than reversals as they can display different characteristics at different locations, mainly related to the intensity of the dominant dipolar field. Recent numerical modelling demonstrated that they may not even be globally synchronous (Brown

et al. 2007), reinforcing the difficulty of correlating their different records. When the dipolar intensity decrease is pronounced, it is likely that the non-dipolar field would be dominant at most places on the globe (Valet & Plenier 2008), and, hence, that excursions palaeomagnetic directions that are not consistent with a dipole field could be recorded in sediments or lava flows emplaced at that time (Guyodo & Valet 1999). Alternatively, a model suggesting the dominance of the equatorial dipole during the Laschamp excursion has been advocated (Laj *et al.* 2006). Such opposing hypotheses proposed to describe the behaviour of the geomagnetic field during excursions illustrates that the ability of most sediments to accurately record palaeomagnetic changes when the field intensity is low remains the primary limitation in obtaining nearly continuous records of excursions (Quidelleur & Valet 1994; Quidelleur *et al.* 1995).

In addition to excursions, palaeomagnetic events, also called sub-chrons, have been reported and are of great importance for magnetostratigraphy since they are globally recordable, full polarity episodes lasting from about 10 to 100 kyr.

Within the relatively long Matuyama chron (from 2.54 to 0.78 Ma; Cande & Kent 1995), several excursions have been recorded in deep-sea sediments (e.g. Channell *et al.* 2002) between the Olduvai and Jaramillo subchrons (from 1.78 to 1.07 Ma; Cande & Kent 1995), but between the Gauss Matuyama transition and the base of the Olduvai, only the Réunion event is observed at about 2.15 Ma, which makes its precise dating very important for magnetostratigraphy in this time frame. However, dating of this magnetic event in deep-sea sediments largely depends on poorly controlled parameters such as the accumulation rate and the magnetization lock-in depth, and on an accurate counting of Milankovich cycles during astronomical tuning. It appears therefore fundamental to also rely on radiometric ages to better constrain the age of this geomagnetic feature. Furthermore, the Réunion event appears as a single subchron with a few 10 kyr duration in some studies, while others display evidence for an additional excursion preceding or following it by about 100 kyr. Following the initial work from Réunion Island sites (McDougall & Watkins 1973), several recent studies have focused on the dating of the Réunion event (Baksi *et al.* 1993; Kidane *et al.* 1999; Baksi & Hoffman, 2000; Lanphere *et al.* 2002; Roger *et al.* 2000), but no consensus arisen regarding the number of events, nor regarding their precise age.

The aim of this study is to provide new K-Ar age determinations on the type locality in the Réunion Island (Indian ocean) where this geomagnetic event was first identified in lava flows of the La Montagne massif, and to decipher between one or two N polarity events occurring around 2.1 Ma within the Matuyama chrons by comparison with deep-sea and continental sedimentary records.

2 GEOLOGICAL SETTING AND SAMPLING

The volcanic island of La Réunion lies within the Indian Ocean and has been linked to the present day superficial activity of hot-spot magmatism initiated with the Deccan traps emplacement about 65 Ma (Duncan & Richards 1991). La Réunion Island is composed of two main volcanoes, the now extinct, Piton des Neiges (PN) and the presently active Piton de la Fournaise (PF; Fig. 1), with basaltic eruptive centres migrating towards the southeast from about 2 Ma to present (McDougall 1971). PN volcano terminated its activity with the emplacement of differentiated products, which probably evolved in an isolated shallow reservoir, between 330 and 30 ka (Gillot &

Nativel 1982), while the main deep magma feeding system was already displaced below the younger massif of PF volcano since 500 ka (Gillot & Nativel 1989).

The oldest products found on the island are approximately 2 Ma old lavas and constitute the Oceanite series of La Montagne (McDougall 1971), which are located to the north–northwest of the PN volcano. They have been associated with the initial building stage of PN volcano and they were emplaced at a high extrusion rate in less than 100 kyr, (McDougall 1971), during the construction of the primitive shield volcano of La Réunion (Gillot *et al.* 1994).

The Oceanite Series are made of olivine-bearing basalts and olivine-rich oceanites that are gently dipping ($< 5^\circ$) towards the northwest. Based on palaeomagnetic investigations of this massif (Chamalaun & McDougall 1966; McDougall 1971), a N polarity event was identified within the Matuyama chron, at two distinct locations, in the Rivière St Denis (RSD) and Grande Chaloupe (GC) sections (McDougall & Watkins 1973). The former consists of several tens of 0.5–2-m thick lava flows, while the latter, stratigraphically above (Fig. 1), is much smaller and consists of about 10 superimposed 2–5-m thick lava flows. A reverse-to-normal (R-to-N) polarity transition was recorded between lava flows 13 and 14 at the RSD section, while a N-to-R transition was recorded at the GC section, between flows 9 and 7 (McDougall & Watkins, 1973). Because all these flows yielded undistinguishable whole-rock K-Ar ages at about 2.02 ± 0.02 Ma (recalculated at 2.07 ± 0.02 Ma using the conventional decay constants; Steiger & Jäger 1977), the existence of a new single geomagnetic event called the Réunion event was proposed (McDougall & Watkins 1973). However, because these previous individual lava flow ages are scattered between 2.00 and 2.11 Ma, and because there is a large elevation gap between these sections (Fig. 1), the existence of multiple distinct geomagnetic events recorded in La Montagne lavas cannot be ruled out.

This study focuses on the same two reference sections. Three flows have been sampled for K-Ar dating from the GC section (labelled 00RUxG; which are identical to GCxx of McDougall & Watkins 1973) and nine flows from the RSD section (labelled 00RUxx or 99x). A correlation in the field with the previous sampling in this section (McDougall & Watkins 1973) was less straightforward. In addition, several oriented blocks were taken for palaeomagnetic polarity determinations. Site locations are shown in Fig. 1.

3 TECHNIQUES

3.1 Geochemistry

Whole-rock major and trace element analyses were performed at the Service d'Analyse des Roches et des Minéraux (SARM)—Centre de Recherches Pétrographiques et Géochimiques (CRPG; CNRS, Nancy, France). Samples were fused with LiBO_2 then dissolved with HNO_3 . Major element contents were determined by ICP-AES (Jobin – Yvon JY 70) and trace element concentrations by ICP-MS (Perkin Elmer 5000). Uncertainties for each element can be found at <http://www.crpq.cnrs-nancy.fr/SARM/index.html>.

3.2 Palaeomagnetism

Two cores were drilled in the laboratory from one block of each sampled flow. The blocks were oriented in the field using a magnetic compass, which, given the relatively high magnetization of basaltic lava flows, yields a relatively large declination uncertainty.

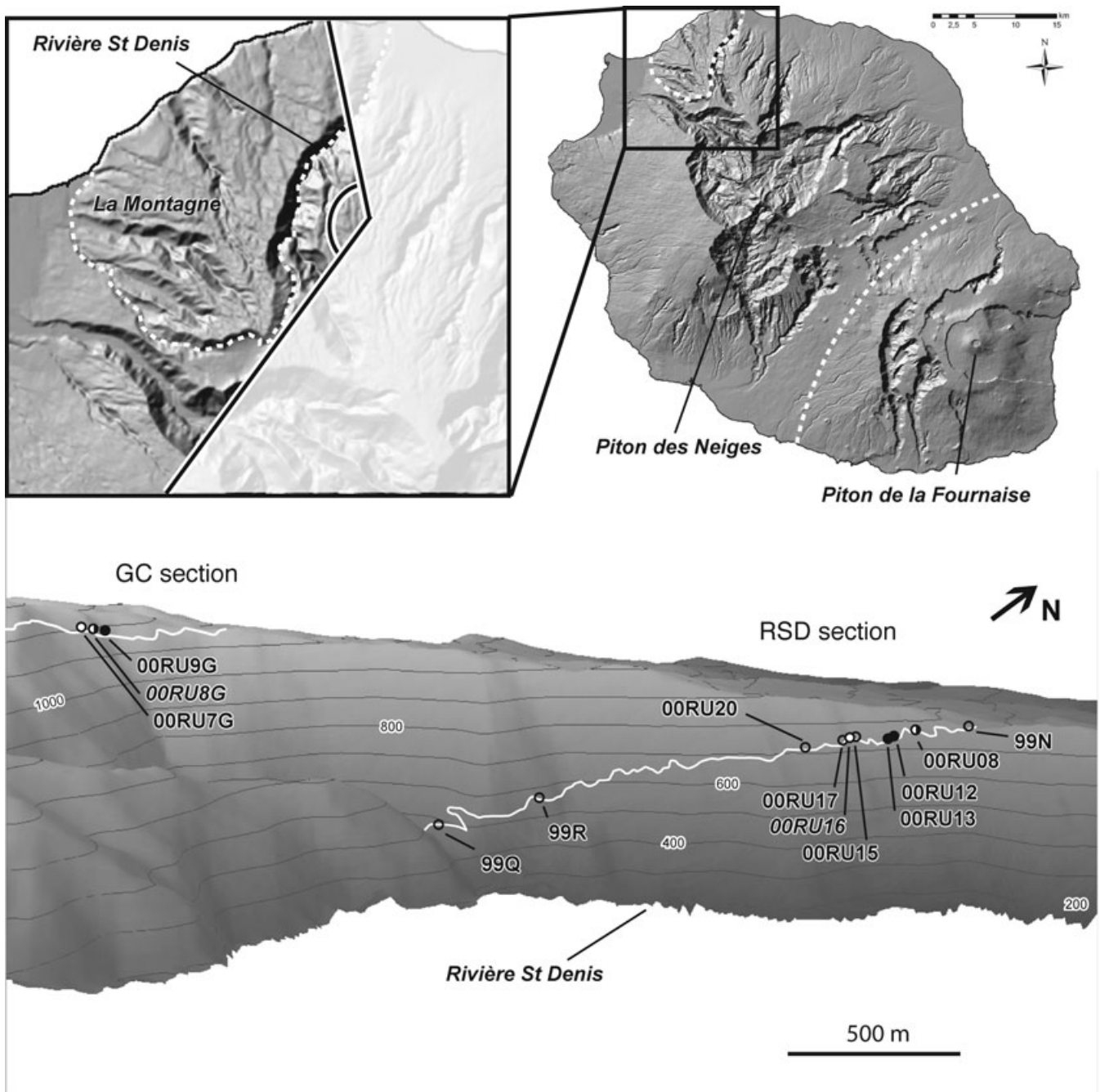


Figure 1. Location of sampled sections. (a) Shaded digital elevation model (Institut Géographique National) of the Réunion Island with Rivière St Denis (RSD) section close-up. (b) Perspective view of the western wall of the RSD canyon. Elevation is given in metres above sea level. White (black) symbols show lava flows with a measured reverse (normal) magnetic polarity, while black and white symbols are for transitional direction lava flows. No palaeomagnetic measurements were made in this study for dated lava flows with open symbols. Names in *italic* indicate lava flows not selected for K-Ar dating.

The measurements were made on two specimens per core in the magnetically shielded room of the Institut de Physique du Globe de Paris (IPGP) using a JR5 spinner magnetometer. Alternating field (AF) demagnetization was preferred to remove possible isothermal magnetization due to lightning strikes, and was performed with 10 incremental steps, from 2 to 40 mT. The characteristic directions of magnetization (ChRM) were determined with the Paleomag software (Cogné 2003), using Zijdeveld projections (Zijdeveld 1967) and principal component analysis (Kirschvink 1980).

3.3 K-Ar dating

The petrographic examination of all sampled flows revealed that the groundmass of 00RU8G and 00RU16 display a slight evidence of weathering and thus were discarded for K-Ar analyses. Hand-size samples (1–2 kg) from all other flows were crushed to a 125–250 μm size fraction and were ultrasonically cleaned for 15 min in a 5 per cent nitric acid solution to remove possible trace of weathered material such as secondary minerals. To make the contribution of

magmatic argon and weathered phases negligible, we have removed mafic phenocrysts from the groundmass using heavy liquids. The remaining groundmass obtained within a narrow density range, typically between 2.95 and 3.00 g cm⁻³, was kept for analysis of K and Ar. K was measured by flame emission spectroscopy and was compared with reference values of MDO-G and ISH-G standards (Gillot *et al.* 1992). Between 1 and 2 g of sample were wrapped in Cu foil and fused for 15 min above 1500 °C using a high-frequency furnace, which is sufficient for complete extraction of argon from basaltic groundmass. Before analysis, multiple-step gas cleaning was performed using Ti foam at 700 °C and SAES MP-10 getters at 400 °C. Argon was measured following the K-Ar Cassinot-Gillot technique (Cassinot & Gillot 1982), which is based on a direct comparison between the unknown (sample) and an air pipette aliquot measured with the same ⁴⁰Ar signal conditions, with a mass spectrometer identical to the one described by Gillot & Cornette (1986). The interlaboratory standard GL-O, with the recommended value of 6.679 × 10¹⁴ atom g⁻¹ of ⁴⁰Ar* (Odin *et al.* 1982), was used for ⁴⁰Ar signal calibration. Typical uncertainties of 1 per cent are achieved for the ⁴⁰Ar signal calibration (including GL-O standard uncertainty) and for the K determination. The uncertainty on the ⁴⁰Ar* determination is a function of the radiogenic content of the sample. The detection limit of the system is 0.1 per cent of ⁴⁰Ar (Quidelleur *et al.* 2001). The total age uncertainty for each analysis is then given by the square root of the quadratic sum of the three sources of uncertainty mentioned earlier (e.g. Quidelleur *et al.* 1999). To take into account the systematic errors, the age uncertainty for each flow is conservatively calculated by simply weighing each duplicate uncertainty using the proportion of radiogenic argon, similarly to the mean flow age calculation. All uncertainties herein are quoted at the 1-sigma (σ) level. The decay constants and isotopic ratios of Steiger & Jäger (1977) have been used.

This technique is especially suitable for dating low K and/or Quaternary lavas. It has been used to calibrate the geomagnetic polarity timescale (GPTS) (Quidelleur *et al.* 1999, 2003). Direct comparison with the ⁴⁰Ar/³⁹Ar technique has shown identical ages (Coulié *et al.* 2003), while dating of MMhb-1 standard, for instance, provided ages of 525 ± 2 Ma using the GL-O standard (Fiet *et al.* 2006), in perfect agreement with the values of 523 ± 2 Ma obtained by ⁴⁰Ar/³⁹Ar (Renne *et al.* 1998).

4 RESULTS

4.1 Geochemistry

Whole-rock major and trace elements for all flows investigated here are given in Table 1. Analysed samples from the GC and RSD sections show a narrow range of composition within the basaltic field of the total alkali versus silica content (TAS) diagram (Le Bas *et al.* 1986), with SiO₂ values between 46.0 and 48.5 wt. per cent (Fig. 2). The rocks define a linear array, which suggests an evolution by a fractional crystallization, except sample 00RU9G, which is characterized by slightly lower alkali concentration. Spider diagrams of trace elements (normalized to primitive-mantle concentrations; McDonough & Sun 1995) show similar patterns for all samples with an overall enrichment of incompatible elements typical of oceanic island basalts, and relative depletions in Rb, U, Pb and Zr (Fig. 2b). Note that 00RU15 and 00RU8G, the less evolved samples from this data set, show a slight depletion in all elements.

In addition, Pb, Hf, Nd and Sr isotopes were measured on seven out of 12 samples from this study (Bosch *et al.* 2008). These re-

sults, together with those from all stages of the PN and PF volcanoes, support an origin from a very homogeneous mantle-plume source composition, mixed with a small amount of depleted mantle component similar to the source of central Indian Ocean ridge basalts. The small isotopic variations observed between the two volcanoes have been interpreted as the presence of two distinct blobs sampling different parts of a single large plume (Bosch *et al.* 2008). The La Montagne lavas, which are the oldest subaerial lavas of the island and display slightly distinct isotopic compositions, have been related to the impingement of the first upwelling mantle blob and disruption of the lithosphere (Bosch *et al.* 2008). Interestingly, these lavas show the same range of Pb isotopic compositions than the whole PN lavas, although the time interval covered is one order of magnitude shorter (McDougall 1971).

4.2 Palaeomagnetism

Examples of typical demagnetization diagrams are shown in Fig. 3 and ChRM direction are given in Table 2. Most samples were demagnetized at about 80 per cent following a 40 mT AF treatment, suggesting that magnetite or low Ti titanomagnetite is the main carrier of the natural remanent magnetization (NRM). The ChRM is easily identified for all specimens, but with a N polarity overprint, removed at about 15 mT, observed in the three flows of the GC section. In the RSD section, the lowermost flow measured here (00RU16) display a R direction, while, as noted earlier, flows 00RU123 and 00RU12 recorded a N polarity, and 00RU08 appears transitional. In the GC section, a N-to-R transition is recorded (Figs 3 and 4 and Table 2).

As expected, these directions confirm that a R-to-N transition is recorded in the RSD section, while GC section recorded a N-to-R transition, as previously observed (Chamalaun & McDougall 1966; McDougall & Watkins 1973), and moreover, confirm that the lava flows dated here recorded one or two palaeomagnetic events within the Matuyama chron.

4.3 K-Ar dating

New K-Ar Cassinot-Gillot ages obtained for 11 flows are given in Table 3. All analyses have been duplicated and yield reproducible ages within the 1-σ uncertainty.

In the RSD section, the lowermost (99Q) and uppermost (99N) flows give undistinguishable ages of 2.16 ± 0.03 and 2.14 ± 0.03 Ma, respectively. However, two out of the seven ages obtained for lava flows located between them are significantly younger, with ages of 2.06 ± 0.03 and 2.08 ± 0.03 Ma, for 00RU20 and 00RU08, respectively. When the latter two are not considered further (see later for discussion), the seven remaining ages of the RSD section are undistinguishable between 2.17 ± 0.03 and 2.12 ± 0.03 Ma, and yield a weighted mean (Taylor 1982) age of 2.15 ± 0.01 Ma. To take into account the 1 per cent uncertainty on the GL-O standard used for the absolute calibration of our argon measurements, this weighted mean age becomes 2.15 ± 0.02 Ma, our best estimate for the R-to-N transition recorded in the RSD section (Fig. 5).

In the GC section only two ages were obtained. 00RU9G and 00RU7G yield undistinguishable ages of 2.05 ± 0.03 and 2.03 ± 0.03 Ma, respectively, with a weighted mean (Taylor 1982) of 2.04 ± 0.02 Ma. The latter is therefore our best age for the N-to-R transition recorded in the GC section (Fig. 5). Note that despite a radiogenic argon content varying by a factor of three (Table 3), these two flows yielded undistinguishable ages, which support the evidence that the

Table 1. Major and trace elements concentrations.

Element	00 RU7G	00 RU8G	00 RU9G	99N	00 RU08	00 RU12	00 RU13	00 RU15	00 RU17	00 RU20	99R	99Q
SiO ₂ (wt per cent)	47.17	45.83	48.4	47.49	47.76	46.73	47.28	46.03	47.23	48.46	47.51	47.47
Al ₂ O ₃	12.68	11.65	13.71	13.29	13.93	12.85	12.89	10.37	13.15	14.13	14.28	13.8
Fe ₂ O ₃	12.67	12.78	12.57	12.63	12.55	12.7	12.42	12.39	12.61	12.53	12.65	12.5
MnO	0.17	0.18	0.18	0.18	0.17	0.18	0.18	0.17	0.18	0.18	0.18	0.17
MgO	10.46	13.68	7.72	8.09	6.97	10.21	9.94	16.64	9.79	6.23	7.19	7.86
CaO	10.54	9.55	11.22	10.76	11.38	10.35	11.02	9.40	10.76	11.21	12.00	11.30
Na ₂ O	2.27	1.96	2.44	2.49	2.57	2.31	2.37	1.87	2.54	2.74	2.56	2.49
K ₂ O	0.68	0.56	0.66	0.79	0.82	0.50	0.71	0.47	0.78	0.89	0.67	0.67
TiO ₂	2.72	2.35	2.67	2.77	2.9	2.62	2.57	2.02	2.74	2.95	2.71	2.69
P ₂ O ₅	0.35	0.29	0.34	0.36	0.38	0.34	0.33	0.26	0.36	0.38	0.33	0.35
LOI	0.13	0.94	-0.17	1.01	0.51	0.48	-0.26	-0.08	0.06	0.26	0.04	0.43
TOTAL	99.84	99.76	99.73	99.85	99.94	99.25	99.44	99.54	100.2	99.95	100.1	99.75
Ba (ppm)	139	124.4	144.6	170.9	174.8	145	141.1	116.8	161.7	166.2	157.4	150
Ce	45.77	38.01	44.8	50.72	54.17	46.9	46.56	35.56	51.47	51.93	46.39	48.04
Co	52.79	67.13	47.02	50.91	46.01	52.04	54.67	72.74	54.29	42.07	48.37	48.6
Cr	525	830	293	398	233	495	522	1268	509	105	166	315
Cu	81.82	87.35	93.98	94.41	109.5	89.86	99.92	80.86	109.9	121.9	64.7	115.1
Dy	5.02	4.28	5.29	5.50	5.67	5.30	5.01	4.09	5.39	5.59	5.20	5.25
Er	2.39	2.04	2.54	2.55	2.73	2.51	2.35	1.92	2.48	2.68	2.46	2.51
Eu	2.07	1.77	2.09	2.25	2.35	2.11	2.03	1.61	2.20	2.30	2.08	2.12
Gd	6.129	5.168	6.288	6.688	6.976	6.321	6.032	4.848	6.472	6.849	6.229	6.288
Hf	4.774	3.868	4.685	5.012	5.19	4.751	4.608	3.665	5.058	5.256	4.642	4.876
Ho	0.91	0.768	0.963	0.982	1.045	0.961	0.908	0.729	0.953	1.021	0.939	0.95
La	19.75	16.72	19.57	23.53	24.88	20.75	20.26	15.47	22.6	23.59	20.49	21.4
Lu	0.293	0.25	0.304	0.321	0.335	0.317	0.299	0.239	0.311	0.331	0.306	0.302
Nb	20.45	17.84	20.12	23.67	26.07	20.83	20.32	15.82	23.58	23.48	21.82	22.85
Nd	26.17	21.78	25.54	28.77	30.35	26.52	25.93	20.06	28.82	29.58	26.42	27.52
Ni	288.4	482.3	118.4	177.8	116.1	294.7	250.9	654.4	262.6	75.97	93.87	149.5
Pb	1.731	1.572	1.821	1.925	2.517	1.812	1.747	1.354	1.977	2.03	1.736	1.879
Pr	6.011	5.001	5.846	6.673	7.114	6.142	6.028	4.639	6.657	6.765	6.073	6.35
Rb	8.936	8.056	13	14.02	16.78	8.217	12.85	7.665	13.01	19.85	8.422	8.498
Sm	6.236	5.233	6.228	6.741	7.044	6.25	6.079	4.82	6.709	6.895	6.279	6.397
Sr	339	303	365	359	404	334	350	273	379	376	382	363
Ta	1.61	1.41	1.58	1.86	2.02	1.68	1.66	1.27	1.87	1.95	1.72	1.77
Tb	0.90	0.77	0.93	0.97	1.03	0.94	0.89	0.72	0.94	1.00	0.93	0.94
Th	2.287	1.905	2.306	2.74	2.871	2.525	2.419	1.895	2.686	2.746	2.428	2.51
U	0.324	0.27	0.335	0.346	0.359	0.345	0.326	0.265	0.343	0.37	0.342	0.345
V	0.486	0.4	0.487	0.629	0.633	0.433	0.543	0.383	0.599	0.71	0.461	0.482
Y	318.7	295.6	314.2	325.6	349.9	286.5	301.9	246.5	325.7	334.8	352.3	328.7
Yb	24.94	21.37	26.5	27.83	29.81	25.93	24.82	20	26.29	28.39	25.84	26.72
Zn	2.017	1.729	2.12	2.17	2.298	2.113	2.002	1.617	2.095	2.253	2.136	2.157
Zr	118.3	116.1	121.4	128.7	125.6	122.1	120	111.3	126.4	124.3	126.9	128.2

atmospheric contamination of a given lava flow cannot be used as a criteria of age validity.

5 DISCUSSION

5.1 Volcanic series of La Montagne massif and K-Ar ages

Within the RSD section, lava flows 00RU20 and 00RU08 display ages significantly younger than all others (Table 3) and two hypotheses can be proposed. First, that they have experienced weathering with fluids circulations, which have affected their ages. Second, that they might be valley fill flows emplaced significantly later in this section.

Because 00RU08 is the least contaminated sample analysed, with about 50 per cent of radiogenic ⁴⁰Ar (Table 3), and since 00RU20 is also relatively poor in atmospheric argon, the first hypothe-

sis appears unsupported. In addition, their loss on ignition (LOI; Table 1) is only of 0.51 and 0.26 wt. per cent, and the relatively good correlation between K and Rb elements (Fig. 6a) for all studied samples also suggests that 00RU08 and 00RU20 (the most evolved lavas) did not experience significant secondary K enrichment. Similar conclusions arise when Rb/Nb or K/Nb ratios (not shown) are scrutinized.

The second hypothesis can be tested using the isotopic signatures to identify slight source changes. Pb isotopes of PN and La Montagne lavas display two distinct trends as previously identified (Bosch *et al.* 2008). Fig. 6(b) shows that ²⁰⁶Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb isotopic ratios of La Montagne lavas vary between 18.92 and 19.08, and between 38.75 and 38.96, respectively. Although the isotopic data set is relatively limited, two slightly overlapping domains can be identified. More radiogenic Pb isotopes are observed for RSD lavas, except 00RU08, which displays the lowest ratios, below the lower end of the GC lavas domain (Fig. 6b). The lower Pb isotopic

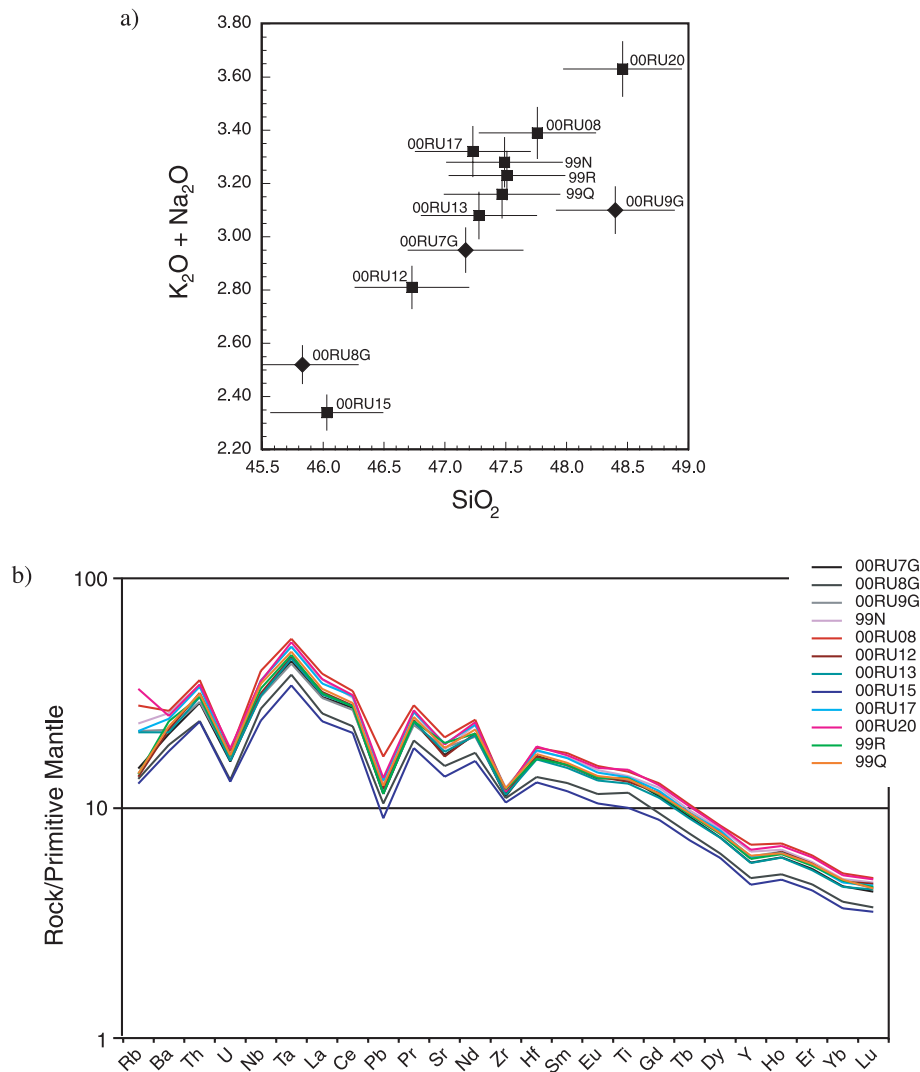


Figure 2. (a) Total alkali versus silica (TAS) diagram, with diamonds and circles for the Grande Chaloupe (GC) and Rivière St Denis (RSD) samples, respectively. (b) Spider diagrams of incompatible trace elements normalized to primitive-mantle concentrations (McDonough & Sun 1995).

ratios can be interpreted as a shallow contamination of upwelling plume material at the base of the lithosphere by upper-mantle and oceanic-crust material, suggesting a certain time lag between lavas from La Montagne (Bosch *et al.* 2008). This suggests that 00RU08 flows comes from a source with geochemical characteristics of the second series of La Montagne lavas emplaced between 2.08 and 2.03 Ma, while the first series emplaced earlier, around 2.15 Ma.

5.2 Comparison with previous radiometric ages from Réunion Island

Within the earlier effort of calibrating the GPTS, a detailed investigation of the oldest massif from the Réunion Island was performed (McDougall & Watkins 1973). Ages recalculated using the decay constants of Steiger & Jäger (1977), display values ranging from 2.13 ± 0.02 Ma for a R polarity flow within the bottom of the section, to 2.00 ± 0.02 Ma for two reverse polarity flows sampled above the N polarity interval. Within the latter polarity interval, ages range from 2.10 ± 0.02 to 2.00 ± 0.02 Ma. Because of the discontinuity of the records and overlapping ages from the two sections, it

has been challenging to give an age for the Réunion event from this data set, but also to decipher between one or two events. However, within the GC section, the ages of 2.05 ± 0.02 Ma obtained for both GC7 and GC8 (McDougall & Watkins 1973) are fully compatible with lava flows 00RU7G (same as GC7) and 00RU9G (lava flow below GC8) dated here at 2.03 ± 0.03 and 2.05 ± 0.03 Ma, respectively. Within the RSD section previous K-Ar ages are more scattered with values of 2.03 ± 0.02 (RN14) and 2.00 ± 0.08 Ma (RN13) for flows located just below and above the transition (McDougall & Watkins 1973), while we obtained ages of 2.13 ± 0.03 for 00RU17 and of 2.14 ± 0.03 for 00RU15, the last R and first N polarity flow dated in this section, respectively (Table 3).

Baksi *et al.* (1993) have reinvestigated one of the previous section (RSD) using whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$. The direct comparison with our results is not straightforward, since about 40 N polarity flows have been identified by these authors, while we (this study) and McDougall & Watkins (1973) only found 15 and 13 individual lava flows, respectively, for the same stratigraphic interval. However, from their stratigraphic position and chemical analyses, we can suppose that our flow 00RU15 corresponds to flow 44, and 99N to flow 52 or 53. An age of 2.14 ± 0.03 Ma has been obtained here for

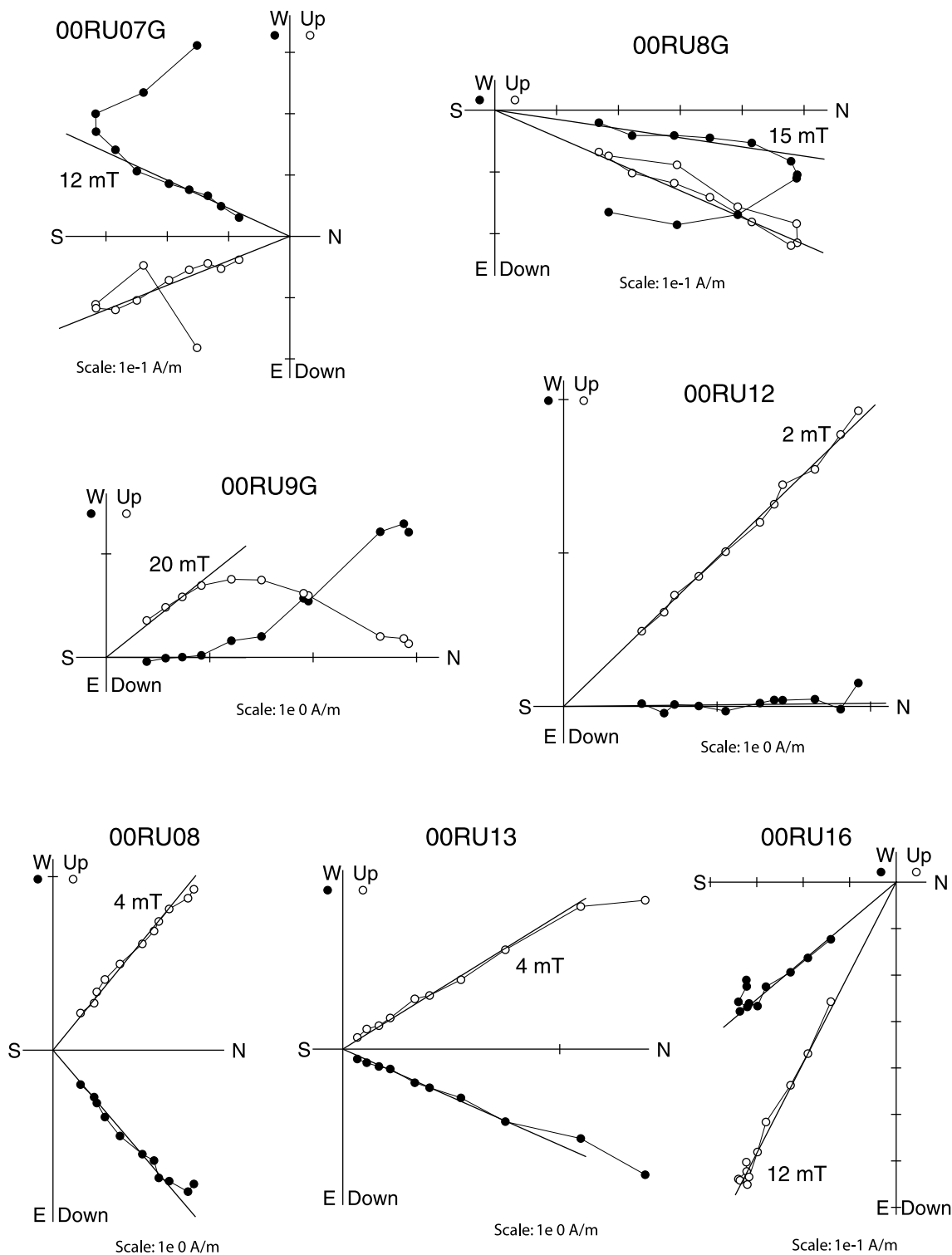


Figure 3. Typical Zijderveld (1967) projection diagrams obtained during alternating field (AF) demagnetization. Straight lines show the ChRM calculated between a given step (value indicated in mT) and the origin. Solid symbols correspond to projections onto the horizontal plane, while open symbols are projections onto the vertical plane.

both 00RU15 and 99N (Table 3), in perfect agreement with the age of 2.15 ± 0.03 Ma reported for both flows 44 and 53 (Baksi *et al.* 1993).

Baksi & Hoffman (2000) presented two new whole-rock $^{40}\text{Ar}/^{39}\text{Ar}$ ages, one (GC42) obtained on the previously studied GC section, and one (LM41) from La Montagne section, which is lo-

cated farther north from the GC and RSD sections. The plateau age obtained from LM41 is 2.137 ± 0.034 Ma (isochron age: 2.18 ± 0.10 Ma), in agreement with our mean age of 2.15 ± 0.02 Ma calculated for the nearby RSD section (Fig. 5). Only the VGPs, showing the N-to-R polarity change are reported in that study, but it shows that no less than 46 flows were reported for the GC section while

Table 2. Palaeomagnetic directions. Column headings indicate Site #; n: number of samples measured; Dec: declination, in degrees; Inc: inclination, in degrees; α_{95} : radius of the 95 confidence cone from Fisher's statistics (Fisher 1953). Polarity: N = normal, R = reverse and T = transitional. Note that declination is only indicative relative since only a magnetic compass was used for orientation and the local declination of about 25°W was not taken into account.

Site	n	Dec (°)	Inc (°)	K	α_{95}	Polarity
00RU7G	4	205	21	904	3	R
00RU8G	4	15	24	76	11	N
00RU9G	4	355	-38	825	3	N
00RU08	4	57	-38	421	4	T
00RU12	4	10	-46	97	9	N
00RU13	2	19	-28	165	19	N
00RU16	4	135	56	468	4	R

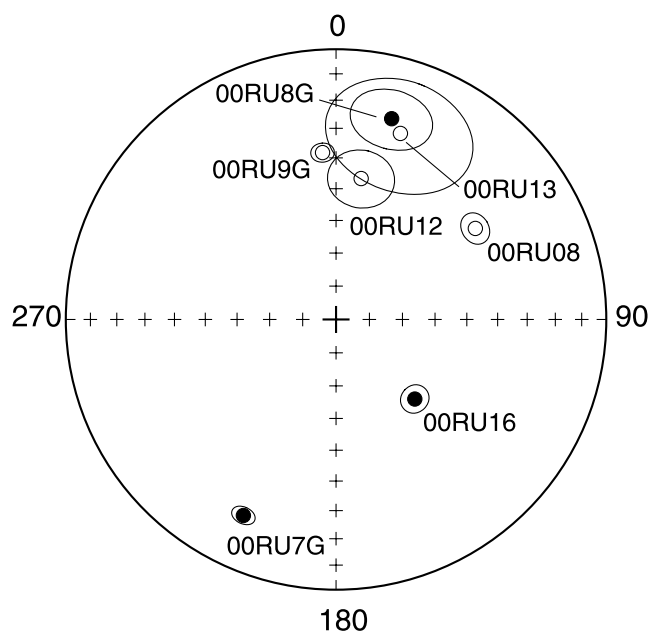


Figure 4. Stereographic projection of individual flow directions. Solid and open symbols indicate directions in the upper and lower hemisphere, respectively.

we found only 10 flows there, as previously described (McDougall & Watkins 1973). We have identified only 00RU8G lava flows as transitional (Table 1), while Baksi & Hoffman (2000) reported five distinct transitional flows. One of which, GC42, yielded plateau and isochron ages of 2.125 ± 0.03 and 2.10 ± 0.06 Ma, respectively (Baksi & Hoffman 2000). Because 00RU8G was slightly weathered it was not dated here, but we obtained a mean age of 2.04 ± 0.02 Ma for the GC section (Fig. 5). Although the step heating analysis of GC 42 display an age decrease pattern (Baksi & Hoffman 2000), typical of ^{39}Ar recoil having biased the age towards too old values, the rather large uncertainty associated with the inverse isochron, makes this age compatible with both our RSD and GC mean ages, precluding any further speculation about its validity or its sampling location.

5.3 Other radiometric ages proposed for the Réunion event(s)

At the Gamarri section in Afar (Ethiopia), 33 lava flows emitted during the Matuyama chron display a full N polarity interval towards the top of the section (Kidane *et al.* 1999), and a high palaeosecular

interval, associated with a low absolute palaeointensity interval (Carlut *et al.* 1999), towards its base. K-Ar ages obtained on five flows distributed within the section yield a mean value of 2.07 ± 0.05 Ma (Kidane *et al.* 1999), with ages of 2.14 ± 0.06 and 2.02 ± 0.04 Ma, for the bottom and top flow, respectively. When only ages associated with the two low palaeofield intervals are considered, the last flow of the first interval is dated at 2.09 ± 0.06 Ma, while the second flow of the second interval at 2.03 ± 0.08 Ma. Although, the relatively high uncertainties of these ages prevent unique solutions for GPTS calibration, it appears clearly that the Réunion events occurred as two distinguished palaeomagnetic events in the Gamarri section. Note that this relatively high age uncertainty is due to the high atmospheric contamination of these lavas, which is a constant phenomenon observed for all Ethiopian Afar dated flows (Lahitte *et al.* 2001, 2003), and cannot be directly related to weathering effects as claimed by some authors (Baksi & Hoffman 2000).

The Huckleberry Ridge Tuff (HRT), which was erupted during the major explosive stage of the Yellowstone caldera, has recorded a transitional polarity direction (Reynolds 1977; Anders *et al.* 1989; Byrd *et al.* 1994). Recent $^{40}\text{Ar}/^{39}\text{Ar}$ ages constrained its age to 2.059 ± 0.008 Ma (Lanphere *et al.* 2002), a significantly younger value than those obtained for ages associated with the Réunion *s.s.* N polarity interval. This led Lanphere *et al.* (2002) to propose a new event designation associated with the HRT.

A combination of step heating $^{40}\text{Ar}/^{39}\text{Ar}$ performed on multi-grains and total fusion approach applies to single grains from a N polarity tephra horizon sampled within the Senèze maar (France) yielded an age of 2.10 ± 0.01 Ma (Roger *et al.* 2000). This result has been challenged by Baksi (2001) who pointed out that possible weathering processes have affected the sanidine feldspars, which led Singer *et al.* (2004) to propose a revised age of 2.135 ± 0.050 Ma for this tephra.

In southern Argentina, a well-defined age of 2.136 ± 0.019 Ma, therefore associated with the Réunion event *s.s.*, has been obtained from transitional and N polarity lavas from Cerro del Fraile dated by step heating $^{40}\text{Ar}/^{39}\text{Ar}$ performed on groundmass separates (Singer *et al.* 2004). Finally, note that the ages of standards used as flux monitors have been significantly revised in the last decades, inducing systematic age changes significantly larger than the age uncertainty reported for most $^{40}\text{Ar}/^{39}\text{Ar}$ ages, which highlights the fact that uncertainties reported above are often largely underestimated (i.e. reflecting analytical precision rather than absolute accuracy). Effectively, it is now admitted that total (analytical plus systematic) uncertainties for previous $^{40}\text{Ar}/^{39}\text{Ar}$ ages is on the order of 1–2 per cent (Kuiper *et al.* 2008), that is, 0.02–0.04 Ma for the Réunion event.

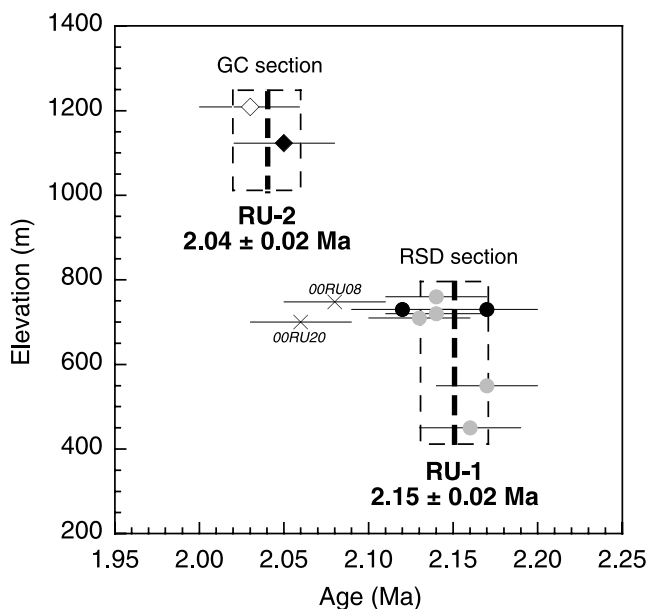
5.4 Records of the Réunion events and/or associated features within sedimentary sections

Sedimentary sequences offer the advantage of providing a more or less continuous record of the Earth's geomagnetic changes and hence are required to identify if one or two events occurred between 2.20 and 2.00 Ma.

Below the Olduvai subchron in lacustrine sediments of the Confidence Hills in Death Valley, California, USA (Holt & Kirschvink 1995) the sequence displays a N polarity event. About 10 m above this event (but well below the Olduvai subchron) the HRT, unambiguously recognized in this section from tephrostratigraphy (Sarna-Wojcicki *et al.* 1991), serves as a tiepoint for this section (Holt & Kirschvink 1997) and allows the correlation of this N polarity event with the Réunion event *s.s.* As discussed, since the HRT captured

Table 3. New Cassinot-Gillot K-Ar ages $^{40}\text{Ar}^*$ (per cent): radiogenic argon in percentage; $^{40}\text{Ar}^*$ ($\times 10^{12}$ at g^{-1}): radiogenic argon in number of atoms per gram of sample. Pol.: magnetic polarity.

Flow	N coord. (UTM)	E coord. (UTM)	K (per cent)	$^{40}\text{Ar}^*$ (per cent)	$^{40}\text{Ar}^*$ ($\times 10^{12}$ at g^{-1})	Age $\pm 1\sigma$ (Ma)	Mean (Ma)	H (m)	Pol.
00RU7G	334209	7682158	0.739	45.4	1.5658	2.028 \pm 0.029			
				41.0	1.5919	2.031 \pm 0.029	2.03 \pm 0.03	1209	R
00RU9G	334282	7682112	0.636	15.2	1.3929	2.065 \pm 0.032			
				15.8	1.3771	2.041 \pm 0.032	2.05 \pm 0.03	1123	N
99N	334924	7685470	0.815	32.9	1.8205	2.137 \pm 0.031			
				31.9	1.8231	2.140 \pm 0.031	2.14 \pm 0.03	760	
00RU08	334878	7685264	0.816	50.3	1.7948	2.074 \pm 0.030			
				48.6	1.8046	2.085 \pm 0.030	2.08 \pm 0.03	748	T
00RU12	334867	7685165	0.691	18.9	1.6037	2.188 \pm 0.033			
				19.5	1.5774	2.152 \pm 0.032	2.17 \pm 0.03	730	N
00RU13	334870	7685141	0.678	25.3	1.5082	2.129 \pm 0.031			
				26.9	1.5022	2.120 \pm 0.031	2.12 \pm 0.03	730	N
00RU15	334831	7684984	0.582	25.5	1.3037	2.143 \pm 0.031			
				24.8	1.3010	2.139 \pm 0.031	2.14 \pm 0.03	720	
00RU17	334872	7684935	0.745	27.0	1.6905	2.139 \pm 0.031			
				35.0	1.6469	2.115 \pm 0.031	2.13 \pm 0.03	710	
00RU20	334850	7684787	0.785	31.7	1.7018	2.074 \pm 0.030			
				31.7	1.6702	2.036 \pm 0.029	2.06 \pm 0.03	700	
99R	334778	7683727	0.636	29.9	1.4391	2.165 \pm 0.031			
				26.7	1.4523	2.185 \pm 0.032	2.17 \pm 0.03	550	
99Q	334783	7683332	0.669	27.8	1.5068	2.155 \pm 0.031			
				37.0	1.5110	2.161 \pm 0.031	2.16 \pm 0.03	450	

**Figure 5.** K-Ar ages from this study (Table 3) shown as a function of elevation (in metres above sea level). Diamonds are for Grande Chaloupe (GC) and circles are for Rivière St Denis (RSD) samples. Open and closed symbols are for reverse and normal polarity, respectively, and no polarity was measured for grey symbols. Crosses indicate rejected samples (see text). Dashed lines show the mean age and the associated 1 sigma uncertainty for each section.

some part of a polarity excursion dated at about 2.06 (Lanphere *et al.* 2002) or 2.09 Ma (Singer *et al.* 2004), this Death Valley record clearly demonstrates that two distinct deviations from reversed polarity exist in the GPTS within the 2.0–2.2 Ma interval. Assuming a constant sedimentation rate calculated between the lower Olduvai

transition and the HRT, led Holt & Kirschvink (1997) to propose an age of 2.15 Ma for the Réunion event *s.s.* Note that there, the sediments stratigraphically near the HRT do not display a full N polarity episode, but only an episode of increased secular variation around 2.04 Ma. However, the palaeomagnetic sampling interval in that zone was larger than elsewhere and the HRT itself was not sampled there due to its highly friable nature.

Within the Turkana Basin, northern Kenya, surprisingly old ages of 2.27 \pm 0.04–2.19 \pm 0.04 Ma and 2.15 \pm 0.04–2.11 \pm 0.04 Ma have been associated with the RU-1 and RU-2 events, respectively (McDougall *et al.* 1992). Although undetected varying sedimentation rates could have biased these ages, it is clear from these records that two geomagnetic events have existed in this late Matuyama interval.

In southern Ethiopia, Kidane *et al.* (2007) present a palaeomagnetic record within the Shungura formation where two N polarity episodes have been recognized. By correlation with tephra layers dated by $^{40}\text{Ar}/^{39}\text{Ar}$ (McDougall & Brown 2006), ages of 2.06 \pm 0.01–2.08 \pm 0.01 Ma, 2.15 \pm 0.01–2.20 \pm 0.01 Ma, relative to 28.1 for Fish Canyon sanidine (FCs) (Spell & McDougall 2003), have been proposed for these events, hence correlated to the RU-2 and RU-1 events, respectively (Kidane *et al.* 2007).

South of Iceland, a well-defined N polarity interval spanning the 2.153–2.115 Ma interval has been recorded at ODP site 981, and a marked inclination shallowing (from about -70 – $+10^\circ$) between 2.08 and 2.02 Ma (Channell *et al.* 2003). Comparable features have also been observed in nearby ODP sites 983 and 984 (Channell *et al.* 2002).

A similar episode of unusually large inclination variations has been recorded in the western Philippine Sea around oxygen isotopic stage 78, at about 2.05 Ma (Horng *et al.* 2002). It occurs about 1.5 m above a clearly identified N polarity event identified as the Réunion event *s.s.* and astronomically dated there between 2133 \pm 5 and 2118 \pm 3 ka (Horng *et al.* 2002).

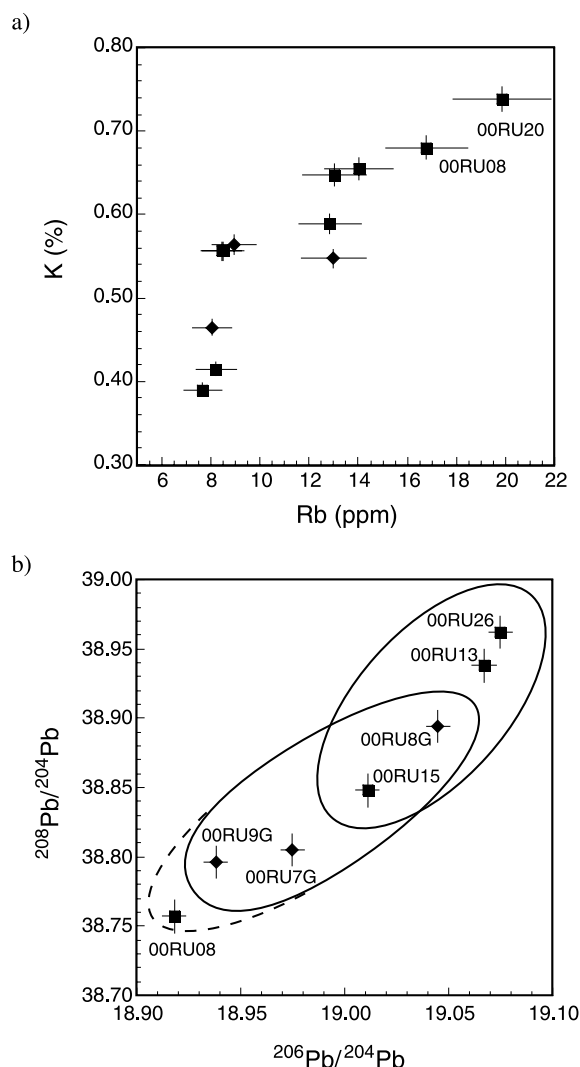


Figure 6. (a) K content (in percentage) as a function of Rb concentration (in ppm). (b) $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{208}\text{Pb}/^{204}\text{Pb}$ (Bosch *et al.* 2008) for some of the lava flows dated here. Field A highlights 2.15 Ma Rivière St Denis (RSD) samples (00RU26, 00RU13 and 00RU15), while field B is for samples from the 2.04 Ma Grande Chaloupe (GC) section (00RU8G, 00RU7G and 00RU9G). Note that 00RU08, although from the RSD section, lies on the low radiogenic side of the GC samples field B. Same symbols as in Fig. 2(a)

5.5 Structure of the Réunion events

Our K/Ar ages of 2.15 ± 0.02 and 2.04 ± 0.02 Ma, obtained here for RU-1 and RU-2 from seven and two dated lava flows, respectively, are distinct at the 2 sigma level, strongly suggesting that two independent N polarity episodes have been recorded in the Réunion Island.

As mentioned, the RU-1 event, which is the Réunion event *s.s.*, has been found in many deep-sea and lacustrine sedimentary sections, while the RU-2 event, which can be related to the Huckelberry Ridge event, is not always recorded in the same sections (Table 4). This can be explained by the fact that RU-1 is a true, albeit short, N polarity event (or subchron), while RU-2 is rather similar to a magnetic field excursion. RU-2 is most probably associated with a low dipole field, which did not succeed in reversing polarity. During RU-2, the dominant magnetic field displayed a complex and rapidly changing non-dipolar geometry, which explains why the

RU-2 event is not globally observed as a full polarity episode, therefore making its use for magnetostratigraphy purposes problematic. Effectively, it has been recommended that only correlation between sites of less than 30° on the Earth's surface should be attempted for the excursions (Merrill & McFadden 2005).

This hypothesis is further supported by deep-sea sedimentary records. In the equatorial Pacific (Valet & Meynadier 1993), palaeointensity records display two intensity minima that can be related to RU-1 and RU-2 recorded at La Réunion Island. It can be noted that RU-2 displays a somehow lower intensity decrease, which could explain why it is not globally recorded as a full N polarity event, but appears at some location as only an episode of intense secular variation with large departures from the expected geocentric axial dipole directions (Carlut *et al.* 1999). Finally, note that related features (i.e. a stable N polarity event followed by an episode of unstable polarity) have also been recorded in North Atlantic (Channell *et al.* 2002) and Philippine Sea (Horng *et al.* 2002) at the same ages as the RU-1 and RU-2 events recorded at the Réunion Island sections we studied.

6 CONCLUSIONS

Overall, our new K-Ar ages performed on separated groundmass show a rather good coherence with most flows previously dated at La Réunion despite the fact that the previous analyses were whole-rock analyses performed for K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dating. The confusion regarding the existence of one or two N polarity events recorded at La Réunion Island within the 2.2–2.0 Ma interval might have originated by (1) the difficulty of fully assessing the continuity of volcanic sections, (2) the use of whole-rock material in the earlier studies, which for a few flows, led to significantly younger ages and (3) the presence of valley fill flows inferred here from major and trace elements data and available Pb isotopic analyses.

When all previous sedimentary and volcanic records are considered together with the new volcanic ages obtained at La Réunion Island, it can be confidently proposed that two palaeomagnetic events occurred within the 2.2–2.0 Ma interval. The first (Réunion 1; RU-1) is associated with a large dipole intensity decrease at 2.15 ± 0.02 Ma, and hence is globally recorded, while at 2.04 ± 0.02 Ma, the dipole intensity decrease was not as pronounced, making the Réunion 2 (RU-2) event not present as a full directional change in many sections worldwide.

Finally, the comparison with globally distributed records assesses that RU-2 can be confidently associated to the Huckelberry Ridge event, while RU-1 is the Réunion event *s.s.*, as originally identified in the Réunion Island (McDougall & Watkins 1973).

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Table 4. New and previously published ages derived for the RU-1 and RU-2 events. Mineralogical phases used for radiometric dating; Gm.: groundmass; Wr.: whole-rock; Feld.: feldspar. Flux monitor name and age used for $^{40}\text{Ar}/^{39}\text{Ar}$ analyses is given in italics; TCR: Taylor Creek Rhyolite; FCb: Fish Canyon Tuff biotite; FCs: Fish Canyon Tuff sanidine. Note that relative to 28.02 Ma for FCs, an age of 28.34 Ma has been proposed for TCR (Renne *et al.* 1998).

Age RU-1 (in Ma)	Age RU-2 (in Ma)	Dating method	Type/place	Reference
2.15 ± 0.02	2.04 ± 0.02	Gm. K-Ar	La Réunion Island	This study
2.089 ± 0.02 ^a (2.02 ± 0.02)	2.075 ± 0.02 ^a (2.02 ± 0.02)	Wr. K-Ar	La Réunion Island	(McDougall & Watkins 1973)
2.14 ± 0.02		Wr. $^{40}\text{Ar}/^{39}\text{Ar}$ <i>FCb; 27.95 Ma</i>	La Réunion Island	(Baksi & Hoffman 2000)
2.15 ± 0.03 ^c (2.14 ± 0.03)		Wr. $^{40}\text{Ar}/^{39}\text{Ar}$ <i>TCR; 28.06 Ma^c</i> <i>(TCR; 27.92 Ma)</i>	La Réunion Island	(Baksi <i>et al.</i> 1993)
2.09 ± 0.06	2.03 ± 0.08	Gm. K-Ar	Gamarri (Ethiopia)	(Carlut <i>et al.</i> 1999; Kidane <i>et al.</i> 1999)
	2.086 ± 0.016 ^b (2.059 ± 0.004)	Feld. $^{40}\text{Ar}/^{39}\text{Ar}$ <i>TCR; 28.34 Ma</i> <i>(TCR; 27.92 Ma)</i>	Yellowstone (WY, USA)	(Lanphere <i>et al.</i> 2002)
2.13 ± 0.05 ^b (2.10 ± 0.01)		Feld. $^{40}\text{Ar}/^{39}\text{Ar}$ <i>FCs; 28.02 Ma</i>	Senèze maar (France)	(Roger <i>et al.</i> 2000)
2.137 ± 0.016		Gm. $^{40}\text{Ar}/^{39}\text{Ar}$ <i>TCR; 28.34 Ma</i>	Cerro Fraile (Argentina)	(Singer <i>et al.</i> 2004)
2.12 – 2.15		Magnetostratigraphy and HRT age	Death Valley (CA, USA)	(Holt & Kirschvink 1997)
2.27 ± 0.04 – 2.19 ± 0.04	2.15 ± 0.04 – 2.11 ± 0.04	Interpolated from K/Ar dated tuffs	Turkana Basin Ethiopia	(McDougall <i>et al.</i> 1992)
2.15 ± 0.01 – 2.20 ± 0.01	2.06 ± 0.01 – 2.08 ± 0.01	Interpolated from $^{40}\text{Ar}/^{39}\text{Ar}$ dated tuffs	Omo Valley Ethiopia	(Kidane <i>et al.</i> 2007)
2.118 ± 3 – 2.133 ± 5		$\delta^{18}\text{O}$ and astronomical cal.	MD972143 (Philippine Sea)	(Hornig <i>et al.</i> 2002)
2.115 – 2.153		$\delta^{18}\text{O}$ and astronomical cal.	ODP 981 (North Atlantic)	(Channell <i>et al.</i> 2003)

Notes: ^aAges recalculated using Steiger & Jäger (1977) decay constants or ^brecalculated by (Singer *et al.* 2004) or ^cby (Baksi & Hoffman, 2000). Originally published ages are given in parentheses.

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