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The Réunion Subchronozone at ODP Site 981 (Feni Drift, North Atlantic)

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Abstract

At Ocean Drilling Program Site 981, the Réunion Subchron is recorded from the Marine Isotopic Stage (MIS) 81/82 boundary to MIS 79 as a single normal polarity zone spanning the 2.115–2.153-Ma interval. According to the age model, produced by matching the Site 981 $\delta^{18}O$ record to an orbitally-tuned reference record, the duration of the Réunion Subchron (38 kyr) is almost four times that assumed in current geomagnetic polarity timescales. High interval sedimentation rates (18 cm/kyr) during MIS 81 at Site 981 have resulted in an unusually detailed record of the Subchron. Virtual geomagnetic poles during the onset and demise of the Réunion Subchron trace a series of mainly anticlockwise loops over eastern Asia.

Keywords: magnetic stratigraphy; isotope stratigraphy; Réunion Subchron; North Atlantic; Rockall Plateau; Feni Drift

1. Introduction

The character, duration and age of brief polarity subchrons such as the Réunion Subchron (C2r.1n) are important, not only for stratigraphic purposes, but also for understanding the geomagnetic field and its reversal mechanism. In the geomagnetic polarity timescale (GPTS) of Cande and Kent [1] for the last 80 Myr, hereafter referred to as CK95, all polarity chrons other than the Réunion Subchron have durations greater than 30 kyr. The duration of the Réunion Subchron (10 kyr) was based on astrochronological age estimates from the Singa section in Italy [2,3].

The Réunion Subchron originates from the work of Chamalaun and McDougall [4] who found both normal and reverse magnetizations in basaltic rocks yielding K/Ar ages close to 2.0 Ma from the island of La Réunion. The normal polarity directions were, at that time, considered to be coeval with those from the Olduvai Gorge documented by Grommé and Hay [5]. McDougall and Watkins [6] sampled two basaltic sections on La Réunion and clearly documented a normal polarity zone dated by K/Ar methods to the 1.95–2.04 Ma interval, corresponding to ~2.07 Ma using more modern decay constants [7]. By the early 1970s, it was realized that the Réunion 'Event' is significantly older than the Olduvai

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Subchron (C2n) that was dated at ~1.72 Ma by Grommé and Hay [8]. These authors considered, however, that a bimodal distribution of K/Ar ages for normally magnetized lavas with ages of ~2.00–2.14 Ma from a variety of locations indicated the existence of two Réunion 'Events', although there was (is) no evidence for two events within any single stratigraphic section. In their compilation of the GPTS for the last 5 Myr, Mankinen and Dalrymple [9] adopted the two Réunion Events proposed by Grommé and Hay [8] and estimated their ages as 2.01–2.04 Ma and 2.12–2.14 Ma, respectively.

Two more recent studies on La Réunion [10,11] have yielded mean $^{40}Ar/^{39}Ar$ ages of 2.14 ± 0.03 Ma for the later part of the Réunion Subchron. This estimate is almost identical to the $^{40}Ar/^{39}Ar$ age for the Réunion Subchronozone from a maar lake in France [12], when recalculated using modified decay constants [13]. At Lake Gamarri (Ethiopia), a basaltic section containing a well-defined normal polarity interval, correlated to the Réunion Subchron, yielded K/Ar ages of 2.07 ± 0.05 Ma [14]. Stratigraphically below the normal polarity interval at Gamarri, an interval within the reverse polarity Matuyama Chron of low paleointensity and high secular variation (VGP latitudes as low as 50°) has been interpreted to represent a second Réunion subchron [15]. As the K/Ar ages from Ethiopia are difficult to reconcile with the older $^{40}Ar/^{39}Ar$ age estimates if the same geomagnetic feature is being recorded, Baksi [11,13] proposed that alteration of the Ethiopian lavas may have affected the K/Ar ages.

Due to the brevity of the Réunion Subchron(s), sedimentary records are restricted to stratigraphic sections of high deposition rate. At DSDP Site 609, the Réunion Subchron is recorded by two normal polarity samples at Hole 609 and 609B [16,17], correlated to Marine Isotopic Stage (MIS) 79–81 [18]. Among the Italian sections that form the basis for the astrochronologies of Hilgen [3], the Réunion Subchron was recognized by two samples from close to the base of sapropel B5 in the Singa section [2]. The Singa section is the source of the astrochronological age (2.14–2.15 Ma) and duration estimate (10 kyr) for this subchron, as incorporated in the CK95 GPTS [1]. Oxygen isotope stratigraphy from the Singa section has placed the Réunion Subchronozone within MIS 81, and reassessment of the cyclostratigraphy and magnetostratigraphy in this section has led to a revised age span of 2.13–2.15 Ma [19].

Lacustrine sediments from Death Valley (CA) record the Olduvai and Réunion Subchrons in sediments with deposition rates of ~30 cm/kyr [20]. The two sampled sections provide evidence for a complex, perhaps doubled, Réunion Subchronozone. The Huckleberry Ridge Ash, dated at 2.06 Ma [21], lies ~10 m above the top of the Réunion Subchronozone in these sections, in an interval recording reverse polarity.

Magnetostratigraphies in Chinese loess have been interpreted to indicate a doubled Réunion Subchronozone [22,23], however, the magnetostratigraphies are difficult to interpret below the Olduvai in these sections. In addition, the loess/paleosol stratigraphy and the spacing of the normal polarity zones preclude these zones being associated with brief Réunion Subchrons. The problem of identifying short polarity subchrons in Chinese loess is compounded by the present consensus that the acquisition of magnetization in Chinese loess postdates deposition by several tens of kyr [24,25].

The magnetic polarity stratigraphy at Ocean Drilling Program (ODP) Site 981, and at the neighboring site (Site 980), has been based on shipboard long-core data and discrete samples [26]. Here we report a 'u-channel' magnetic study of the 105–146 m composite depth (mcd) interval of the composite section at Site 981. U-channel samples are encased in plastic containers that have a 2×2-cm square cross-section and a clip-on lid. Samples are the same length as the core sections (usually 150 cm) and provide continuous sampling. The u-channel samples were augmented by 180 back-to-back 1-cm^3 discrete samples collected over part of the Réunion Subchronozone, alongside the grooves from which the u-channels were collected. The composite section at Site 981 is a splice of the three holes drilled at the site [27] designed to provide an optimal record of the sediment sequence. The record of the Olduvai and Réunion Subchrons from Site 981 can be correlated to a benthic $\delta^{18}O$ stratigraphy derived from

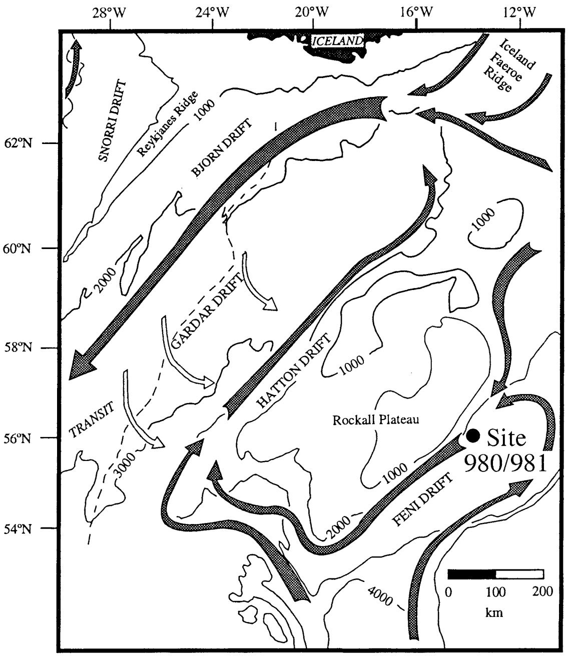


Fig. 1. Location map for ODP Site 980/981. Bathymetry in meters. Dashed line indicates crest of Gardar Drift. Arrows indicate inferred bottom current flows (after [51]).

samples taken from the working halves of the composite section. The Réunion Subchron at Site 981 is recorded over 4.75 m of the composite splice in four sections (981C-14H-2 to 981C-14H-5) from a single core. The sedimentation rates within the subchronozone are fortuitously high, reaching 18 cm/kyr. As a result, the record of the Réunion Subchron is the most detailed yet available from marine sediments, and provides improved estimates of the age, character and duration of the 'event'.

2. Lithostratigraphy and age control

ODP Site 981 was drilled in July 1995 on the Feni Drift, in 2157 m water depth, on the SE flank of the Rockall Bank (Fig. 1) at 55.48°N, 14.65°W [27]. The Holocene to Late Pliocene lithology at Sites 980/981 comprises light gray to gray nannofossil oozes intercalated with dark gray to gray nannofossil clay [27].

Oxygen isotope measurements were made on benthic foraminifera, using specimens of *Cibicidoides wuellerstorfi* and *C. kullenbergi* selected from the > 150-μm size fraction of samples collected from the composite section. The $\delta^{18}O$ data for the 105–119-mcd interval are from McIntyre et al. [28], and those for the 119–150-mcd interval were generated in the stable isotope laboratory at MIT (Fig. 2a). Analytical precision is better than ±0.1‰ for both data sets. Isotope data were calibrated using the NIST (NBS) 19 standard, and values are reported relative to PeeDeeBelemnite. Volume susceptibility for Site 981 (Fig. 2c) was determined at 1-cm intervals on u-channel samples using a susceptibility track designed for u-channels [29]. Lows in carbonate percentage [30] tend to correlate with highs in $\delta^{18}O$ and volume susceptibility (Fig. 2).

We construct the age model for Site 981 by matching the benthic $\delta^{18}O$ record to the chronology of Shackleton et al. [31] as defined by his TARGET curve (http://delphi.esc.cam.ac.uk/coredata/v677846.html) shown in Fig. 3a. The target curve comprises data from ODP Sites 677 (1.70–1.81 Ma) and 846 (1.81–2.30 Ma) [31–33]. In Fig. 3a, the Site 981 record is compared with the TARGET curve and the benthic $\delta^{18}O$ record from DSDP Site 607 [18] which was independently correlated to the Shackleton timescale used here. For Site 981, interval sedimentation rates, mean sedimentation rates between age model tiepoints, vary in the 4–18-cm/kyr range, with a maximum within MIS 81 (Fig. 3b).

3. Magnetic remanence

The natural remanent magnetizations (NRM) of u-channel samples, from the archive half of the composite section, were measured after alternating field (AF) demagnetization in nine steps in the 20–70-mT peak field interval, or 13 steps in the 0–70-mT interval. Archive halves from Holes 981A and 981B were treated shipboard at peak fields up to 25 mT [26,27] and therefore the abbreviated 9-step treatment was appropriate for these two holes. The 13-step treatment was utilized on u-channels from Hole 981C because sections from this hole were not treated shipboard.

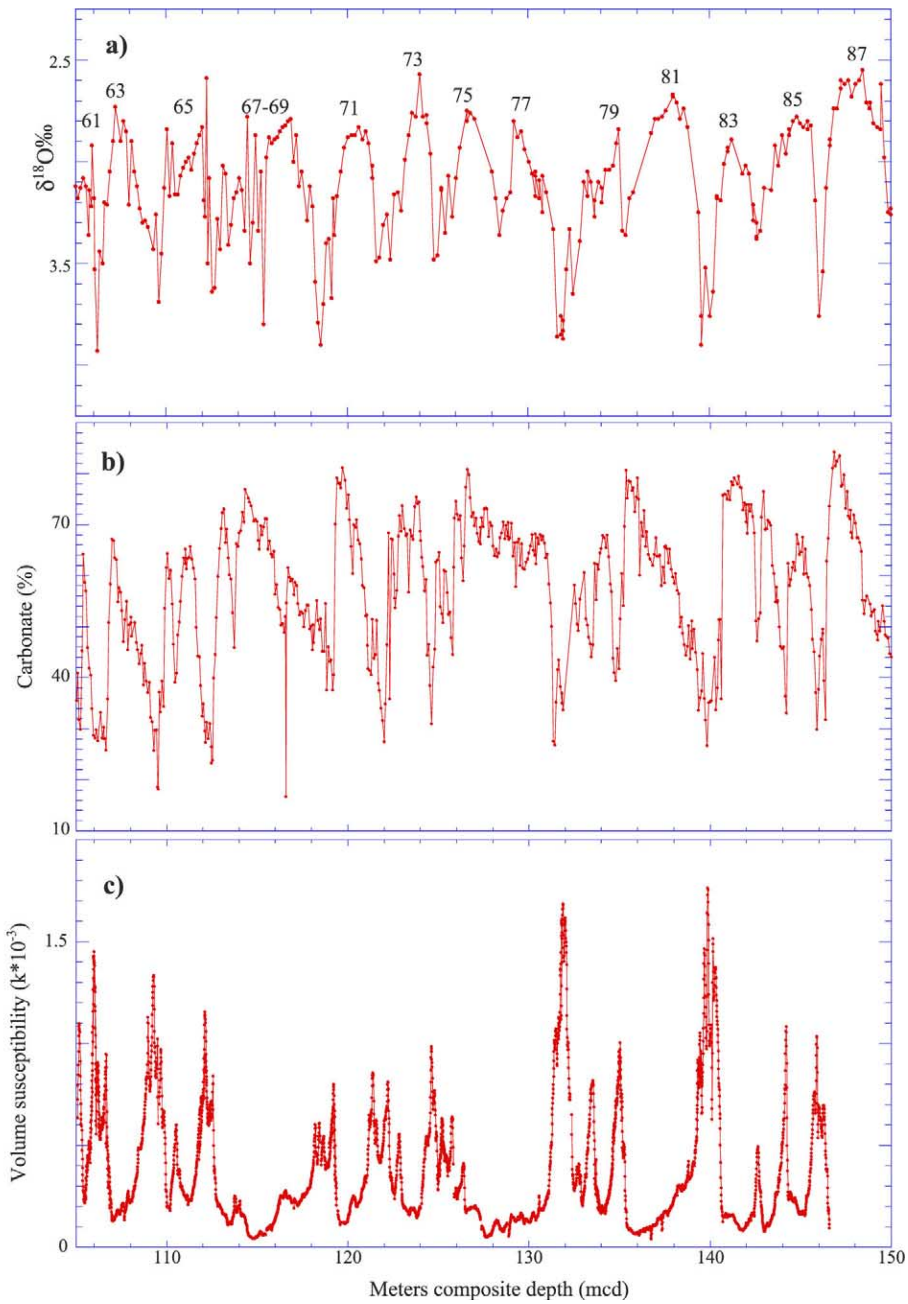


Fig. 2. ODP Site 981. (a) Benthic $\delta^{18}O$ data (partly from [28]), marine isotopic stages are numbered. (b) Percentage carbonate from [30]. (c) Volume magnetic susceptibility measured on u-channel samples.

Component magnetization directions were determined for each measurement point (at 1 cm spacing) for the 30–60-mT peak field interval using the standard least squares method [34]. Maximum angular deviation (MAD) values are generally less than 15° with elevated values close to polarity reversals (Fig. 4) and where NRM intensities are low (Fig. 5g,h). Rather than computing u-channel

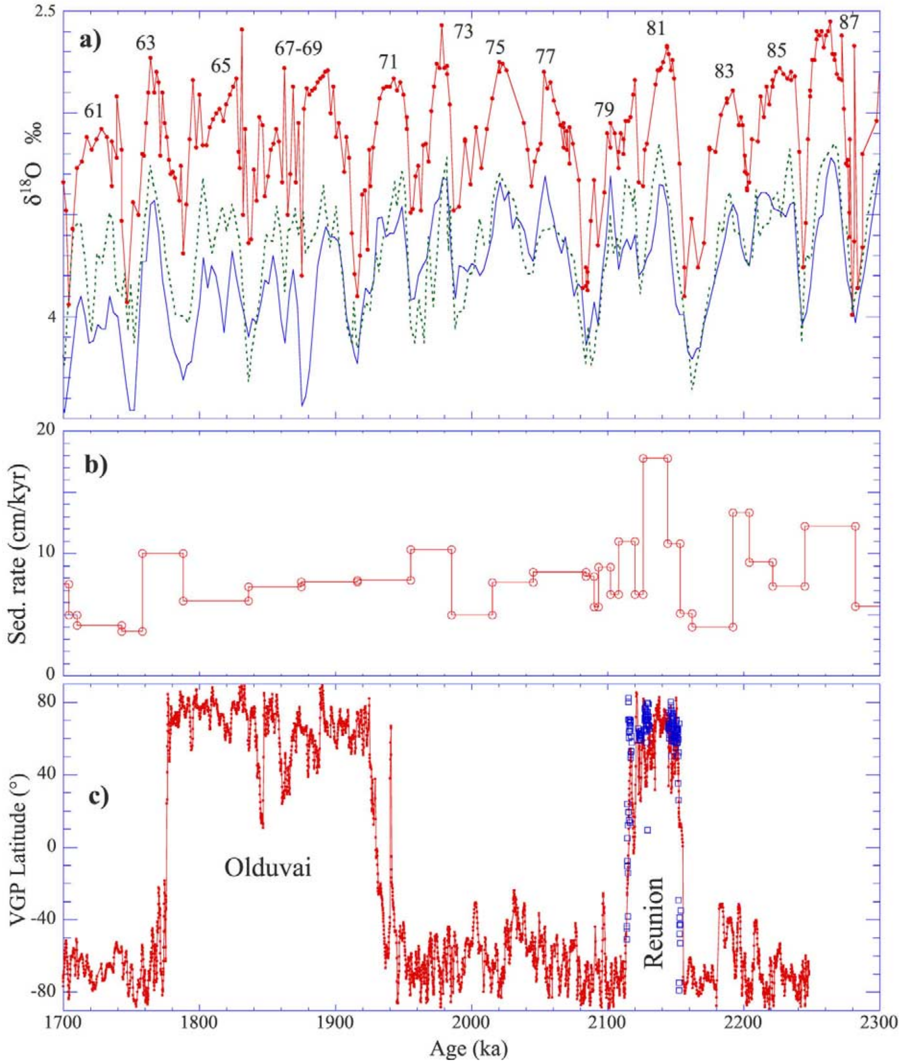


Fig. 3. (a) Benthic δ^{18}O data from ODP Site 981 (line with points) compared to the chronology of Shackleton et al. [31] as defined by his TARGET curve (http://delphi.esc.cam.ac.uk/coredata/v677846.html) (line without points), and to the benthic δ^{18}O data from DSDP Site 607 [18] set on a revised chronology (dashed line). (b) Interval sedimentation rates between tie-points linking the Site 981 record to the TARGET curve. (c) Site 981 VGP latitudes computed from component magnetizations (Fig. 4), including values computed from 1 cm^3 discrete samples for the Réunion Subchronozone (open squares).

magnetization components for a set demagnetization interval (30–60 mT), lower MAD values, and hence improved definition of magnetization components, might be achieved by individually picking components from the ∼4500 orthogonal projections.

Orthogonal projections of u-channel AF demagnetization data indicate that magnetization components are often well defined, even in the vicinity of polarity reversals. In Fig. 6, orthogonal projections are shown for the 134.24–139.54 mcd (2113–2157 ka) interval encompassing the Réunion Subchronozone. Between 139.41 and 139.20 mcd (Fig. 6), the base of the Réunion Subchron is recorded, although the two illustrated component magnetization directions are not 180° apart. Between 135.93 and 134.24 mcd (Fig. 6), lies the complex transition at the top of the Réunion Sub-

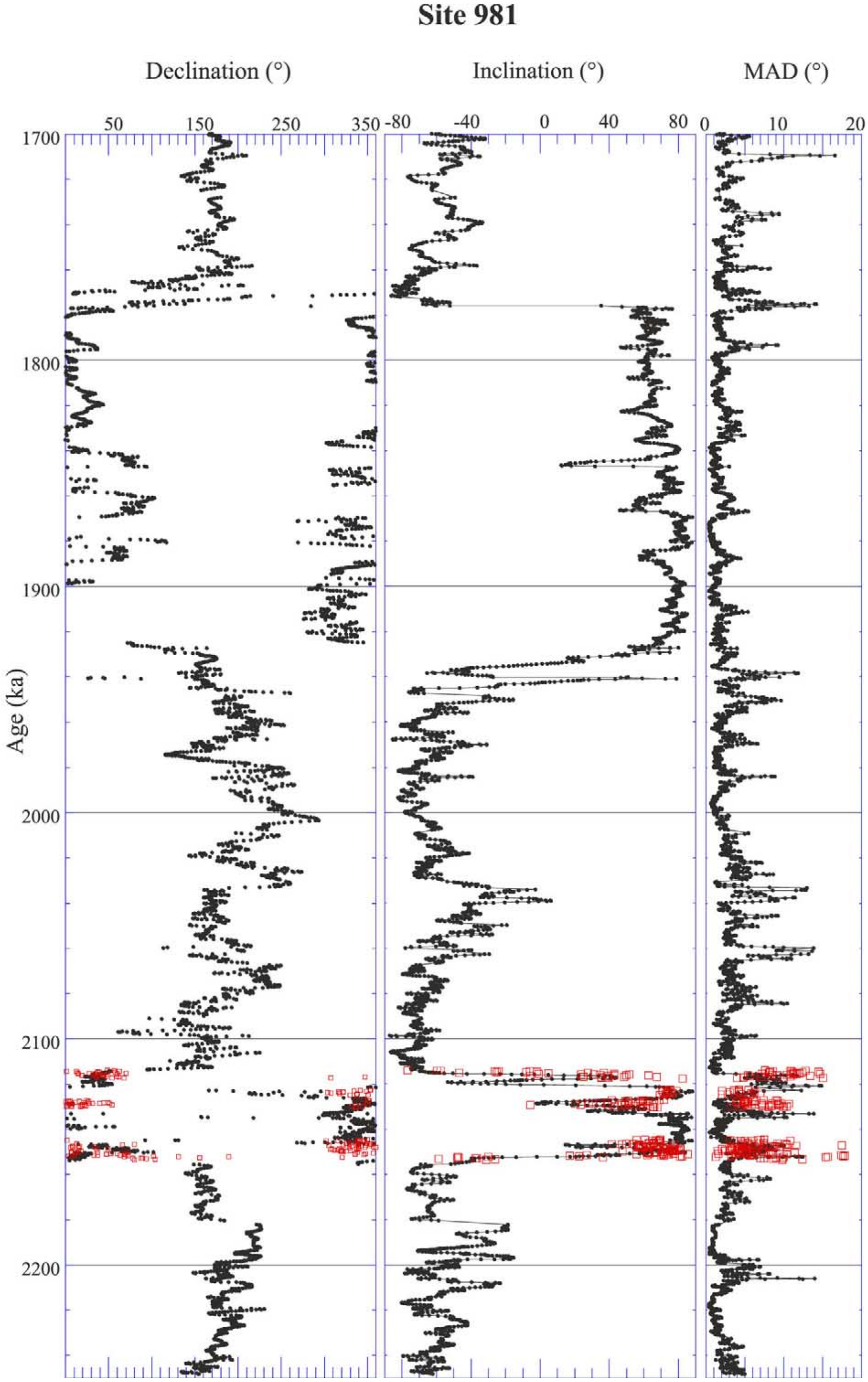


Fig. 4. ODP Site 981: component declinations and inclinations and corresponding MAD values, computed at 1 cm intervals downcore from u-channel samples for the 30–60 mT demagnetization interval using the standard least squares method [34]. Values computed from 1 cm^3 discrete samples for the Réunion Subchronozone are shown as open squares.

chronozone. As seen in Fig. 4, the inclination of the magnetization component becomes shallow, then negative, and then becomes positive again before the component direction achieves reverse polarity above 134.24 mcd.

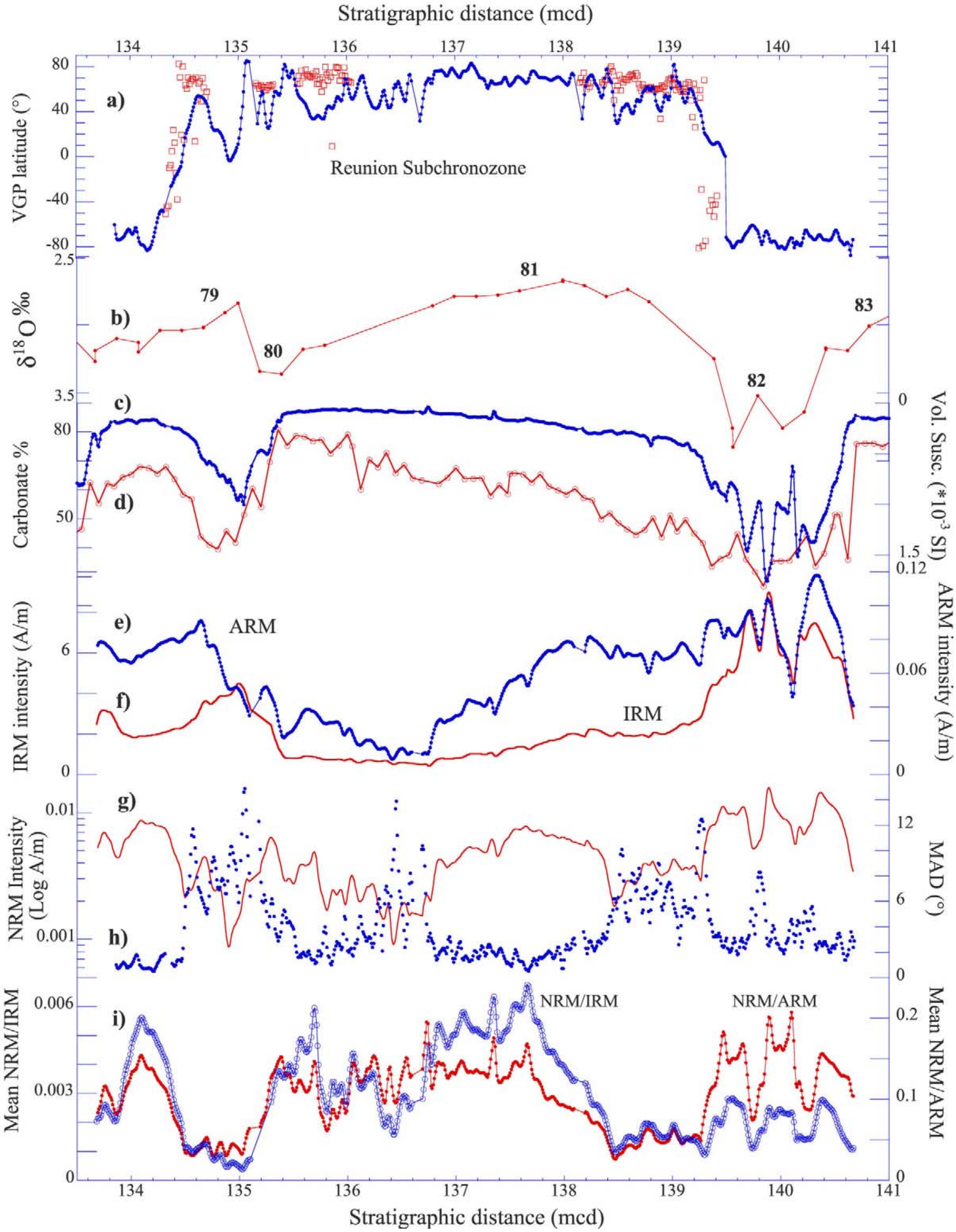
The 180 cubic (1-cm^3) samples collected back-to-back from alongside part of the u-channel groove were AF demagnetized in 15 steps at 5 mT increments in the 10–80 mT range. The small sample size was necessitated by the amount of sediment available for sampling (alongside the u-channel groove) and the desire to collect back-to-back samples for meaningful comparison with u-channel samples. For these 1-cm^3 samples, the characteristic magnetization components were picked by eye from individual orthogonal projections, and directions calculated by the standard procedure [34]. Discrete sample MAD values are often greater than MAD values obtained from u-channel samples (Fig. 4). The higher MAD values are attributed to the low magnetic moments in these small volume discrete samples, and the added difficulty of precisely orienting the small samples in the sample-holder of the magnetometer. Component magnetization directions determined from discrete samples are not always in agreement with the u-channel data (Fig. 4), but provide consistent estimates for the position of the boundaries of the Réunion Subchronozone. A small ($\sim$20 cm) discrepancy, between discrete and u-channel samples, exists for the position of the base of the Subchronozone (Fig. 5a). Sampling induced deformation close to the walls of the plastic cubes is likely to be significant for 1-cm^3 samples, and this may account for some of the discrepancy between u-channel and discrete samples.

Volume susceptibility across the Réunion Subchronozone is inversely correlated to carbonate percentage (Fig. 5c,d). Carbonate and δ^{18}O do not mirror each other perfectly (Fig. 2). For example, δ^{18}O in MIS 79–80 (Fig. 5b) appears to lead carbonate (Fig. 5d). This can be attributed to the dynamics of ice sheet calving and ice rafted debris delivery that affect carbonate percentage by both dilution and iceberg control on surface water productivity. Anhysteretic remanence (ARM) and isothermal remanence (IRM) intensities vary by about an order of magnitude across the Réunion Subchronozone (Fig. 5e,f). Mean NRM/ARM and NRM/IRM values, determined by averaging the ratios for six demagnetization steps (applied to both NRM and ARM or IRM) in the 20–45-mT peak field range, are fairly consistent across the Réunion Subchronozone (Fig. 5i). Hysteresis parameters (determined for five samples) are typical of pseudo-single domain magnetite. If magnetite in this grain size range is the only remanence carrier, the values of normalized remanence may be considered as geomagnetic paleointensity proxies. The normalized remanence data imply paleointensity lows in the vicinity of the boundaries of the Subchronozone (Fig. 5i).

4. Age and character of the Réunion Subchronozone

At Site 981, the boundaries of the Olduvai Subchronozone can be correlated to the old end of MIS 63 and to the younger part of MIS 71 (Fig. 3). These correlations are consistent with those from DSDP Site 607/609 and ODP Sites 677, 659 and 983/984 [18,31,35,36], and from Italian land sections [19].

The Réunion Subchronozone was correlated to MIS 81 in the Italian Singa section [19] and at ODP Site 984 [36], and to MIS 79/81 at DSDP Site 609 [18]. At Site 981, the old end of the Réunion Subchron correlates to the MIS 81/82 boundary, and the young end to MIS 79 (Fig. 5). The Subchron therefore spans the 2.115–2.153-Ma interval (Fig. 3c). The implied duration (38 kyr) is almost four times that estimated by Hilgen [3] and incorporated in the CK95 GPTS [1]. Sedimentation rates at eight holes from ODP Sites 981–984, calculated using the polarity stratigraphy and the CK95 GPTS, were found to be several times greater in the Réunion Subchron than elsewhere in the Matuyama Chron [26], implying that the CK95 duration for the Réunion Subchron (10 kyr) was underestimated. More uniform sedimentation rates within the Matuyama Chron at Sites 981–984 were found when the earlier CK92 [37] estimate for the duration of the Réunion Subchron (32 kyr) was assumed [26].


Stratigraphic distance (mcd)
134
135
136
137
138
139
140
141
VGP latitude (°)
a)
Reunion Subchronozone
80
40
0
-40
-80
2.5
δ18O ‰
b)
79
80
81
82
83
3.5
c)
d)
Carbonate %
80
50
Vol. Susc. (*10-3 SI)
0
1.5
0.12
e)
ARM
f)
IRM
IRM intensity (A/m)
6
0
ARM intensity (A/m)
0.06
0
g)
h)
NRM Intensity (Log A/m)
0.01
0.001
MAD (°)
12
6
0
i)
NRM/IRM
NRM/ARM
Mean NRM/IRM
0.006
0.003
0
Mean NRM/ARM
0.2
0.1
0
Stratigraphic distance (mcd)

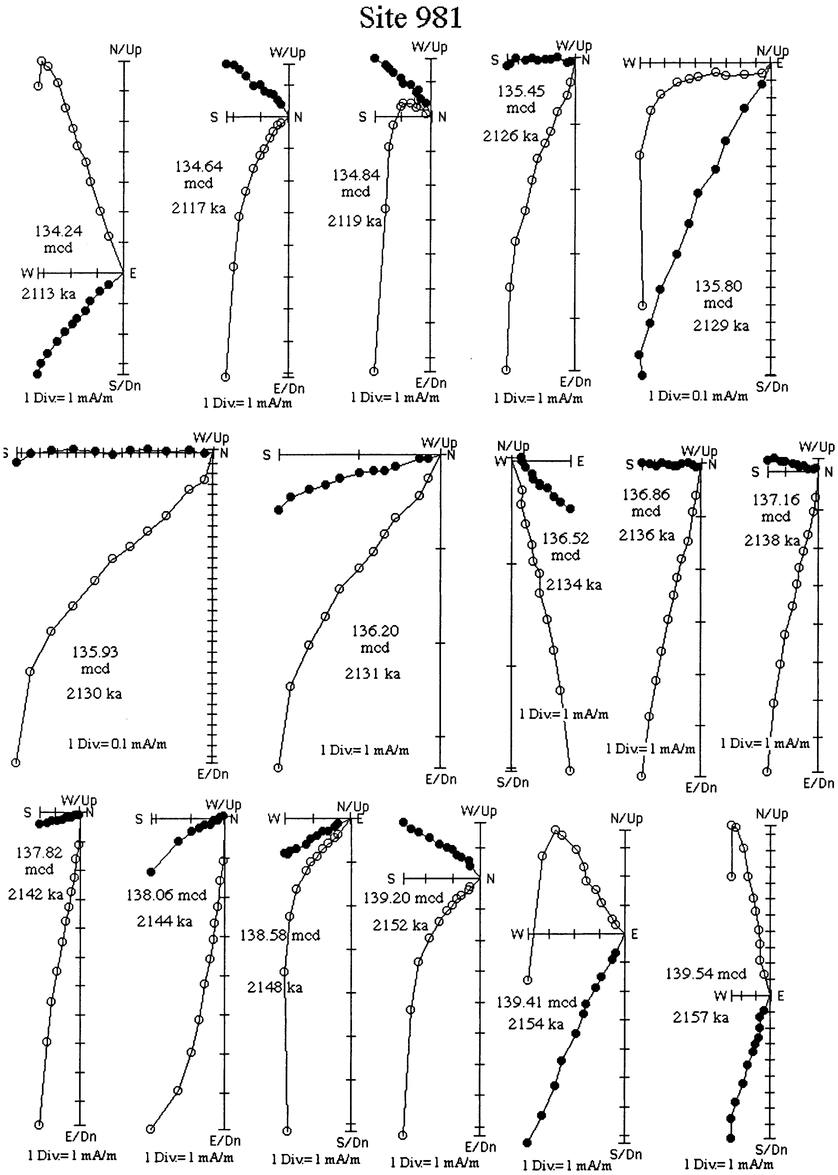


Fig. 6. Orthogonal projection of AF demagnetization data for u-channel samples from ODP Site 981 that record the Réunion Subchron. Open and closed symbols indicate projection on the vertical and horizontal planes, respectively. The positions of the samples in mcd and estimated age (ka), are indicated. The peak AFs range from 10 mT to 70 mT. Magnetization intensity (mA/m) is given for each division (Div.) on plot axes. No core reorientation applied.

←

Fig. 5. The Réunion Subchronozone (134–140 mcd) at ODP Site 981: (a) VGP latitudes for u-channel samples (points joined by continuous line) and 1-cm^3 discrete samples (open squares). (b) Benthic $\delta^{18}O$ data with MIS interpretation. (c) Volume susceptibility. (d) Percentage carbonate (from [30]). (e) ARM intensity after AF demagnetization at peak fields of 20 mT. (f) IRM intensity after AF demagnetization at peak fields of 20 mT. (g) NRM intensity after AF demagnetization at peak fields of 20 mT. (h) MAD values associated with component magnetization directions. (i) Mean NRM/IRM and mean NRM/ARM (paleointensity proxies) calculated for six demagnetization steps in the 20–45-mT peak field range.

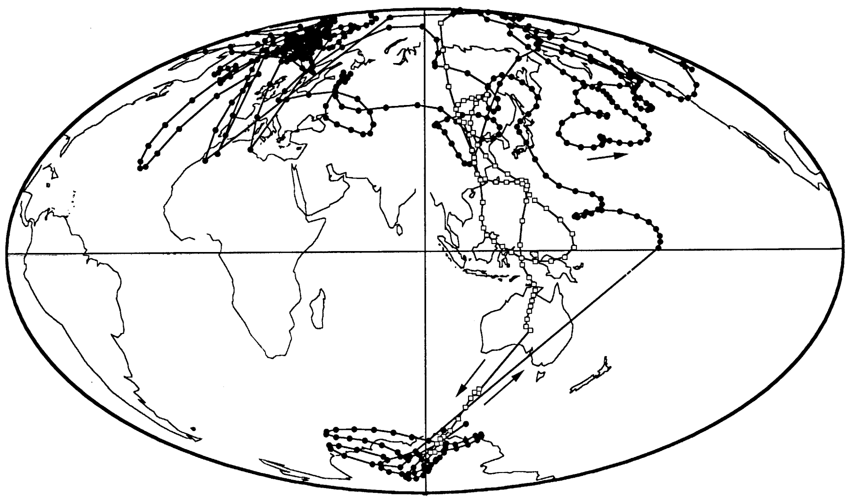


Fig. 7. VGPs for the Réunion Subchronozone at ODP Site 981 derived from u-channel samples. VGPs at the top of the Réunion Subchronozone, recording the return to reverse polarity, are shown as open symbols to permit distinction from the VGP path at the base of the Subchronozone. Hammer–Aitoff projection centered on longitude 90°E.

The age estimate for the Réunion Subchron derived from ODP Site 981 relies on the recognition of MIS 79–81 at this site (Figs. 2a and 5b), the fit of the Site 981 $\delta^{18}O$ record to the TARGET curve (Fig. 3a), and the age model for the TARGET curve [32]. The age model for the TARGET curve in the $>$1.8-Ma interval was derived by correlation of the ODP Site 846 (Leg 138) GRAPE (Gamma Ray Attenuation Porosity Evaluator) data, reflecting the ratio of calcite to biogenic opal, to the orbital insolation solution of Berger and Loutre [38]. Smoothing (reducing) the high (18 cm/kyr) sedimentation rates within MIS 81 (Fig. 3b) results in unsatisfactory fit of the Site 981 $\delta^{18}O$ data to the TARGET curve (Fig. 3a), and *greater* duration estimates for the Réunion Subchron than advocated here (38 kyr).

The u-channel record at Site 981 extends to 2250 ka and only one normal polarity zone of Réunion age is observed (Figs. 3c and 4). The $\delta^{18}O$ record (Fig. 2a) implies no stratigraphic gaps in the MIS 61–87 interval. We conclude that the Réunion Subchronozone, at ODP Site 981 and probably elsewhere, comprises a single normal polarity zone of duration $\sim$38 kyr and age limits of 2.115–2.153 Ma. The estimated duration is greater than estimates based on Italian cyclostratigraphy of 10 kyr [2,3] and 20 kyr [19], and an estimate of 15 kyr from western Pacific Core MD972143 [39]. Note that the mean sedimentation rate across the Réunion Subchronozone at ODP Site 981 ($\sim$16 cm/kyr) is about an order of magnitude greater than in the sections cited above [19,39].

At ODP Site 981, an interval of shallow inclinations (Fig. 4) and low VGP latitudes in MIS 75 (Fig. 3) at $\sim$2.04 Ma may correlated to low inclinations recorded in the Huckleberry Ridge Ash [40], dated at 2.06 Ma [21].

The virtual geomagnetic poles (VGPs), computed from Site 981 u-channel component magnetizations, track through eastern Asia both at the onset and demise of the Réunion Subchron (Fig. 7). VGP loops tend to be anticlockwise, implying westward drift according to Runcorn's rule [41]. Transitional discrete sample data (not plotted in Fig. 7) yield scattered VGPs in the eastern Asia/Indian Ocean region with no consistent VGP path, reflecting the relatively poorly defined magnetization directions in the 1-cm^3 discrete samples.

VGPs over Australia and NE Asia have been observed in both volcanic and sedimentary records of polarity transitions [42–47]. As pointed out by several authors, the NE Asian/Australian VGP clusters coincide with fast P-wave propagation in the lower mantle and with near-radial flux concentrations in the modern non-axial dipole (NAD) field (i.e. today's surface field stripped of its axial dipole). It has been inferred from the paleomagnetic record that such NAD flux concentrations may be long-standing features of the geomagnetic field [48,49], although this remains controversial [50] as analytical results are highly dependent on data selection. The fact that VGP clusters from successive reversals coincide with radial flux centers of the NAD field implies that the flux centers are persistent and influence successive polarity transitions as the axial dipole component of the geomagnetic field wanes and then strengthens during the polarity reversal process.

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