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Orientation of CRP-1 Core

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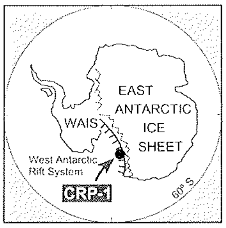
Abstract - One goal of the Cape Roberts Drilling Project is to assess the regional tectonic significance of fracture arrays within the core (CRP-1). This requires the collection of orientated intervals of CRP-1 core, but direct measurements of the orientation were precluded because of poor borehole quality. Therefore, we utilised palaeomagnetic techniques to provide an estimate of the geographical orientation of reconstructed core runs, and thus of the fracture data collected in reconstructed intervals of CRP-1. Our analysis demonstrates that palaeomagnetic reorientation of separate reconstructed core intervals results in a better clustering of drilling-induced and high-angle natural fractures, which is expected if the fractures have been rotated back to *in situ* orientations. Our results suggest that palaeomagnetic reorientation of the CRP-1 core is feasible, although possible errors are probably no less than ± 11°.



INTRODUCTION

In CRP-1, the instability of some borehole sections prevented direct orientation of core runs using a downhole orientation tool. Borehole instability and the early termination of drilling also prevented downhole logging with dipmeter and borehole televiewer tools. Fracture mapping from the orientated downhole log records would have been used to reorientate core intervals by matching fractures in the borehole wall with correlatives in the core (*cf.* Nelson et al., 1987); in particular, matching the borehole televiewer images of the borehole walls with whole-core scan images provides a robust method of core reorientation (see Schmitz et al., 1989; Weber, 1994, for methodology). In the absence of these data, other means of determining core orientation were required. Here we report the results of our efforts to reorientate the CRP-1 core using bedding dip directions and palaeomagnetism.

BEDDING DIP DIRECTIONS

In some segments of core it was possible to obtain direct measurements of bedding and cross-bedding, and it was hoped that these could be used to match a seismically-determined regional dip direction (~2° east; Cape Roberts Science Team, 1998). However, trial rotations using the bedding data revealed several problems with this technique. First, bedding planes with an appreciable dip only occurred within discrete core intervals, rather than throughout the core. The lack of dipping bedding planes prevented application of this approach to a large portion of the CRP-1 core, especially those intervals identified as of primary interest for fracture studies (see Wilson & Paulsen, this volume). Second, bedding dip-directions varied by as much as 180° and in some cases bedding was horizontal, leading to ambiguity in determining the degree of core rotation. Finally, trial reorientation of bedding to match the regional easterly dip-direction of strata at the drill site did not result in a better clustering of drilling-induced or high-angle natural fracture data. Improved clustering of fracture data is expected when fractures have been reorientated to *in situ* orientations that existed in the bedrock prior to the core entering the core barrel (*cf.* Lorenz et al., 1990; Kulander et. al., 1990; Hailwood & Ding, 1995; Hamilton et al., 1995). The overall failure of this approach may be due to local variations in bedding dip-directions within the CRP-1 sequence (*e.g.*, cross-bedding) or the possibility that the regional dip-direction of strata in the area, which is mainly constrained by two-dimensional seismic data, varies from an easterly dip-direction.

PALAEOMAGNETISM

Two palaeomagnetic methods are commonly used to orientate drillcores (*cf.* Rolph et al., 1995): 1) the viscous remanent magnetisation (VRM) method (VRM is a soft magnetisation acquired by some magnetic minerals or grain-sizes during prolonged exposure to weak magnetic fields), and 2) the stable characteristic remanent magnetisation (ChRM) method (ChRM is the component of the magnetisation that is dominant across the range of coercivity or thermal spectra for that sample). We utilize the ChRM method in this study because the VRM component of the natural remanent magnetisation (NRM) was typically over-printed by a drilling induced magnetisation. The ChRM method relies on the ability to determine an original detrital remanent magnetisation (DRM), which is acquired at the time of deposition, as the magnetic particles align with the geomagnetic field. Because the DRM directions are acquired in a relatively short time period (less than *c.* 2 k.y.), secular variation is not time-averaged within individual palaeomagnetic samples. Therefore, measurement of several samples from each reconstructed core interval is necessary to calculate an average dipole direction. This approach requires two assumptions: (1) the earth's magnetic field is time-averaged to an axial dipole field, and (2) the cored interval of strata has not been significantly deformed since deposition.

METHODOLOGY

We conducted a palaeomagnetic analysis of six reconstructed core intervals (85.08-87.92 metres below sea floor (mbsf), 102.99-114.54, 114.6-118.8, 121.14-124.17, 124.17 132.56, and 132.56-135.40 mbsf) that could be reliably reconstructed by fitting fractures together (Fig. 1a). Upon recovery and reconstruction of the core, red and blue scribe lines were drawn 180° apart along the length of the core and fracture measurements were made with reference to an "arbitrary north" defined by the red scribe line (Fig. 1a). The core was then cut into 1 m segments, studied and photographed further, and split lengthwise into two slabs, which were respectively placed into an archive box and working box (Fig. 1b).

In order to determine the magnetostratigraphy of the lower 90 m of the CRP-1 core, the Cape Roberts Science Team (1998) and Roberts et al. (this volume) drilled standard cylindrical palaeomagnetic samples every *c.* 0.5 m from the working half of the core. These were collected by placing the working half of the core face down and drilling into the back of the core, perpendicular to the slabbed face (Fig. 1b). Prior to drilling, each sample was labelled with an up-core direction. Because of differences in core-processing procedures at the drillsite laboratory, the angle between the slabbed core surface and the scribe lines varied throughout the CRP-1 core, and thus the palaeomagnetic samples could not be collected with a systematic orientation with respect to the scribe lines. Changes in orientation between the scribe lines and the palaeomagnetic samples coincide with the boundaries of the 1 m segments into which the CRP-1 core was initially cut. In order to determine the orientation of the palaeomagnetic samples with respect to the scribe lines and fractures, we measured the orientation of the scribe lines with respect to the slabbed face of the core in both the working and archive boxes.

Although both palaeomagnetic declination and inclination were routinely determined from the palaeomagnetic vector measured in each sample, only inclination was used to determine polarity because it is not affected by drilling-induced rotation of the CRP-1 core (Roberts et al., this volume). Most samples displayed a palaeomagnetic signature typical of magnetite and a stable behavior during stepwise demagnetisation, which allowed for precise measurements of declination and inclination. We have used the palaeomagnetic declination data collected by the Cape Roberts Science Team (1998) and Roberts et al. (this volume). Occasionally, stepwise demagnetisation data proved difficult to interpret; such samples were not used in palaeomagnetic reorientation analysis of the core. In order to test whether individual sample magnetisations were induced by drilling, we calculated mean vectors for each of the reconstructed core intervals. Our results showed different mean vectors for each interval, suggesting no radial overprint from drilling.

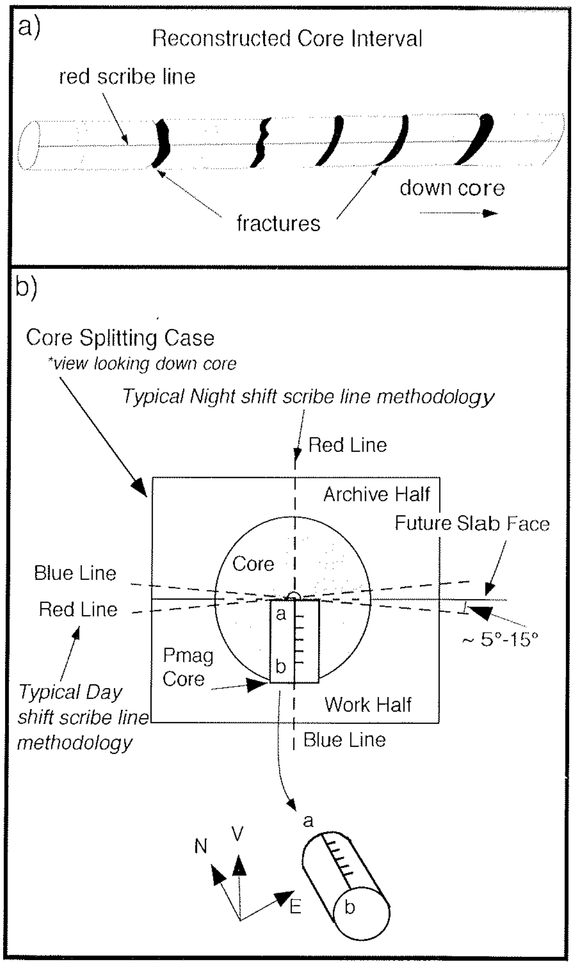


Fig. 1 - Schematic diagram illustrating typical core processing and palaeomagnetic sampling procedures. *a)* Sketch showing a typical reconstructed core interval in which core segments could be fitted together along fracture planes (modified from Hailwood & Ding, 1995). *b)* Sketch showing the CRP-1 core in the core splitting case and the relationship between the scribe lines, the working and archive halves of the core, and the palaeomagnetic samples. Core processed during the day shift was typically placed in the core splitting case with scribe lines orientated subparallel to the future slab face, whereas core processed during the night shift was typically placed in the core splitting case with scribe lines orientated perpendicular to the future slab face.

Individual palaeomagnetic declination vectors were determined relative to a common palaeomagnetic reference line. This reference line was defined along the back of reconstructed core intervals from the working half of the core, perpendicular to the split face. To calculate the mean palaeomagnetic declination direction in each of the reconstructed core intervals, we first measured the location of the red scribe line with respect to the slabbed core faces in the working or archive boxes. We then rotated each of these core segments and their corresponding palaeomagnetic vectors, so that the segments' red scribe lines matched across core segment breaks (*i.e.*, the core segments were rotated back to reconstruct their original orientations with respect to each other). Within each reconstructed core interval, we averaged 5 to 23 palaeomagnetic vectors in order to determine the mean palaeomagnetic declination direction.

It is estimated that the palaeomagnetic vectors, used to calculate a mean palaeomagnetic declination in each reconstructed core interval, span at least a *c.* 100 k.y. (Roberts et al., this volume). Therefore, secular variation is probably averaged within the mean palaeomagnetic declination direction in each reconstructed core interval. Although seismic data suggest a regional 2° eastward dip of cored strata, the lack of dipping bedding planes in numerous reconstructed core intervals and the high variance in dip-direction of some bedding planes, precludes this correction in the calculation of the mean palaeomagnetic declination directions. Our calculations also assume a vertical drillcore. The drillcore should be within 2° of vertical (pers. comm. with CRP-1 drill team), but the exact orientation of the drill hole was not directly measured. All mean palaeomagnetic directions and statistical parameters (Fisher et al., 1987) are reported with respect to the red scribe line for each of the reconstructed intervals of the CRP-1 core in figure 2.

TESTING THE RELIABILITY OF MEAN PALAEOMAGNETIC DECLINATION DIRECTIONS

The use of palaeomagnetism to orientate the CRP-1 core involves inherent difficulties because of the extreme high latitude of the drilling site (~77° S). Secular variation of the earth's magnetic field causes the magnetic pole to vary 360° around the drilling site because of its high latitude. However, the mean palaeomagnetic directions calculated for the CRP-1 core should be statistically different from mean palaeomagnetic directions expected at the geographical south pole (*i.e.*, 90° inclination, no declination). A statistical difference is expected because the drilling site is located 12° latitude away from the expected time averaged magnetic pole (*i.e.*, the geographical south pole at 90° S) and because the Antarctic continent has been in a stationary position with respect to the earth's hot spot reference frame during the time interval covered by CRP-1 strata (Quaternary-Miocene). Despite the high latitude, the mean palaeomagnetic inclinations calculated for each of the reconstructed core intervals varies from 76.8° to 86.8°. These values are expected for the CRP-1 site (77°S, Fig. 2) and suggest that mean palaeomagnetic declination values are reliable, and that there has been no detectable structural tilting of the cored strata outside of the error range calculated for the mean directions. However, given the potential uncertainties related to the high latitude of the drilling site, we conducted several tests to determine the reliability of the palaeomagnetic declination directions.

Testing for Possible Rotation Across Fracture Planes

Prior to processing the core, individual segments of the core were reconstructed by fitting fracture planes together (Fig. 1a). To further test the possibility that the distribution of individual palaeomagnetic declination vectors reflects core rotation on fractures, we grouped the vectors based on their occurrence between fractures that have a higher probability of rotation (*i.e.*, disc and torsion fractures; Fig. 3). Overall, the results show no systematic clustering pattern of palaeomagnetic vectors that can be ascribed to rotation on these fracture planes, suggesting that the observed distribution probably reflects secular variation of the earth's magnetic field. Within the 132.56-135.40 mbsf reconstructed core interval, we found one vector (no. 5 in Fig. 3) that varied 180° from four vectors that are located in a shallower core interval. Vector no. 5 is separated from the shallower vectors by a torsion fracture. Present evidence (*i.e.* the lack of clear circular grooves on the fracture surface) does not allow us to assess whether the deviation of this vector from the main cluster is due to drilling-induced core rotation or secular variation of the earth's magnetic field. However, trial calculations that excluded vector no. 5 show a negligible mean palaeomagnetic declination difference (3°), which does not significantly affect our results, although the mean

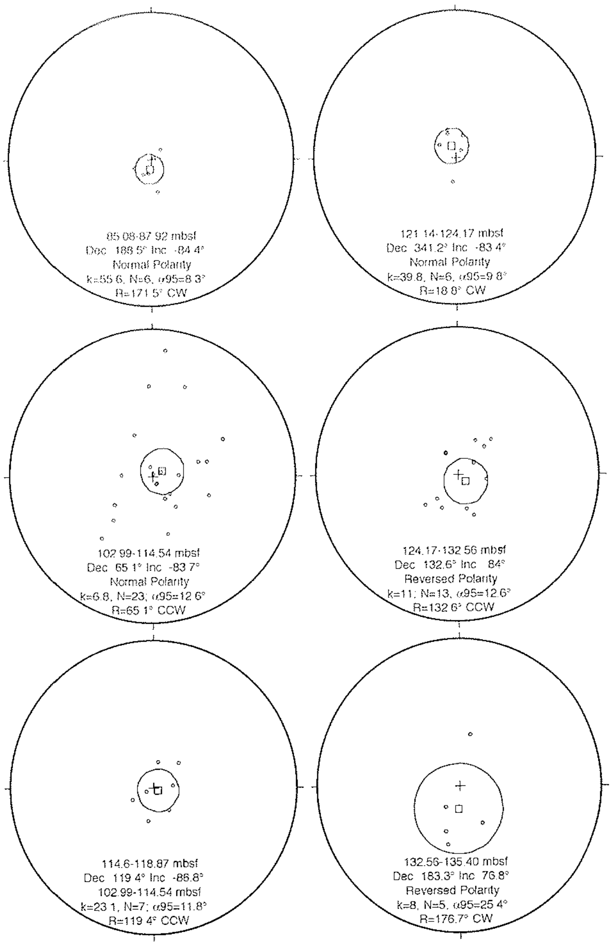


Fig. 2 - Equal area stereoplots showing individual palaeomagnetic declination vectors, calculated mean palaeomagnetic declination directions, and Fisher statistical parameters for each of the six reconstructed core intervals. R = the degree of corrective rotation applied to core based on the palaeomagnetic data; CW = clockwise; CCW = counter-clockwise.

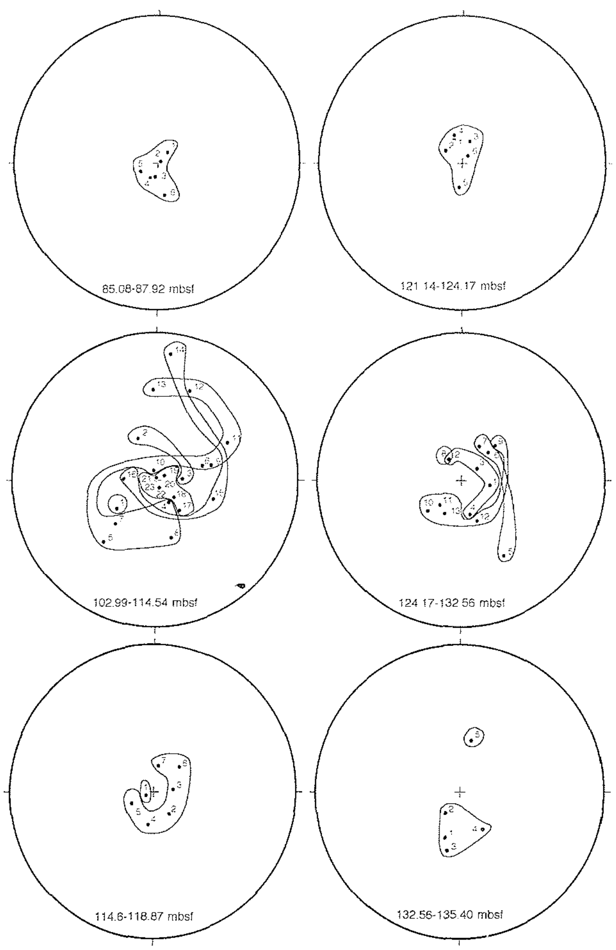


Fig. 3 - Equal area stereoplots showing individual palaeomagnetic declination vectors grouped according to core segments lacking any fractures that may have rotated during CRP-1 drilling. Individual vector numbers increase with depth of palaeomagnetic samples within each reconstructed core interval. Most vector distributions do not show systematic clustering patterns that can be ascribed to rotation on fracture planes, suggesting that the distribution probably reflects secular variation of the earth's magnetic field.

palaeomagnetic inclination and α95 calculations decrease by ~10°.

Fracture Cluster Test for Mean Palaeomagnetic Declination Directions

One method commonly used to test the reliability of mean palaeomagnetic declination directions in a drillcore is to conduct rotation cluster tests on drilling-induced and natural fractures found within a core (*cf.* Hailwood & Ding, 1995). Both fracture types should show an improved clustering upon rotation back to *in situ* orientations because they typically form with systematic orientations with respect to a regional stress field (*cf.* Lorenz et al., 1990; Kulander et. al., 1990; Hailwood & Ding, 1995; Hamilton et al., 1995; Li & Schmitt, 1997). The orientations of high-angle natural fractures and drilling-induced fractures for the six reconstructed core intervals are shown in figures 4 and 5 respectively (for discussion on fracture classification see Wilson & Paulsen, this volume). The relatively wide distribution of fracture azimuths in these core intervals reflects the fact that core segments between these reconstructed intervals could not be reliably reconstructed (*i.e.*, the reconstructed core intervals are unorientated with respect to each other).

To test the reliability of the mean palaeomagnetic declination directions, the fractures in each of the six reconstructed core intervals were rotated about a vertical axis so that original mean palaeomagnetic declination directions for normal polarity intervals were rotated to true north (000°N) and original mean palaeomagnetic declination directions for reversed polarity intervals were rotated to true south (180°S). If the mean palaeomagnetic declination directions are reliable, such rotations should convert the fracture measurements to *in situ* coordinates. Present evidence does not allow us to assess whether CRP-1 strata (and the mean palaeomagnetic declination directions) have been rotated about a vertical axis due to deformation in the western Ross Sea along the Transantarctic Mountain Front, although clockwise block rotation has been interpreted based on seismically defined fault patterns (see Hamilton et al., this volume). If block rotation has not occurred, then the overall error with our palaeomagnetic reorientation estimates should be considered no less than ± 11° and may be higher for those intervals reorientated using small palaeomagnetic datasets (Nelson et al., 1987).

Palaeomagnetic reorientation of the CRP-1 core results in a better clustering of both high-angle natural fractures (51°-80°) and drilling-induced petal-centreline fractures (Figs. 4 & 5). After reorientation, high-angle natural fractures form well-defined northeast and northwest striking conjugate sets, whereas drilling-induced petal-centreline fractures form a well-defined north-northeast striking group. Palaeomagnetic reorientation of each high-angle natural fracture set typically decreases α95 values by ~6°. α95 values for petal-centreline fractures decrease slightly after palaeomagnetic reorientation (~4°), but the α95 values remain high because of two anomalous east-west striking fractures. The anomalous east-west orientation of these two fractures may be related to their formation and propagation near pre-existing fractures. Examination of the fracture-logging notes indicates that these two fractures terminate downcore into other fractures; other core fracture studies have found that petal fractures deviate in orientation where they abut pre-existing natural fractures (*e.g.*, Hamilton et al., 1995). α95 values after eliminating these two fractures show a decrease of ~20° after palaeomagnetic reorientation. The tighter clustering of fracture orientations after corrective rotation indicates that the reorientation method has been successful. Thus, the mean palaeomagnetic declination values are probably reliable despite the high latitude of the CRP-1 site.

Low-angle natural fractures with dips of between 26° and 50° did not show better clustering after palaeomagnetic reorientation (see Wilson & Paulsen, this volume). However, this does not invalidate the palaeomagnetic reorientation estimates. Different orientations at different levels would be expected if low-angle fractures at different

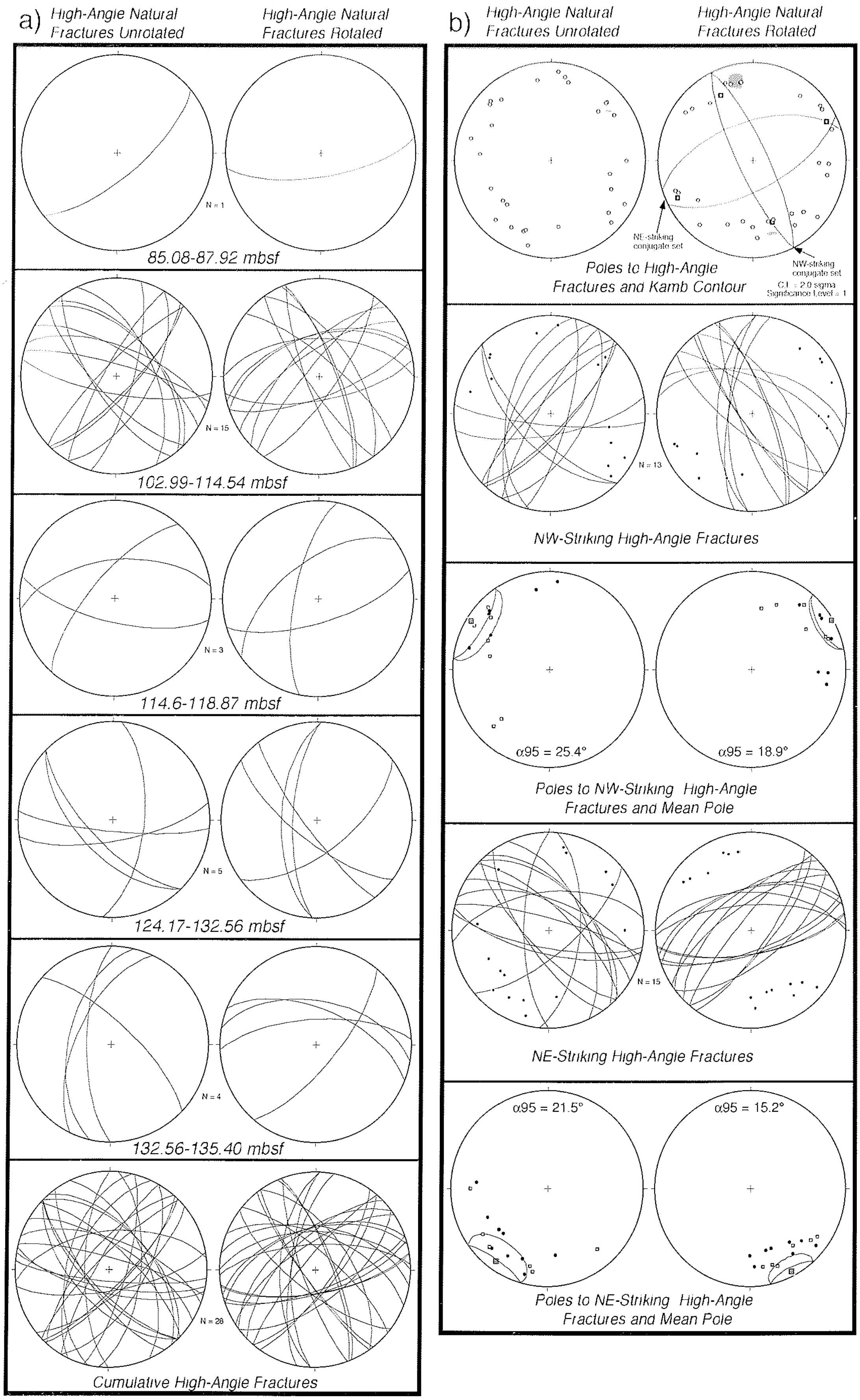


Fig. 4 - Equal area stereoplots showing the orientations of high-angle natural fractures within core intervals that were palaeomagnetically reorientated. *a)* Great-circle stereoplots of unorientated and reorientated high-angle natural fracture planes that occur within five of the reconstructed core intervals. Note that the reorientated fracture planes form two sets with similar strikes and equal but opposite dips, which is typical of conjugate shear fractures. *b)* Kamb-contour, great-circle, and scatter plots of unorientated and reorientated high-angle natural fracture planes. Note the improved clustering and α95 values after reorientation. Open squares in the α95 plots mark poles to fractures that were plotted in the upper hemisphere.

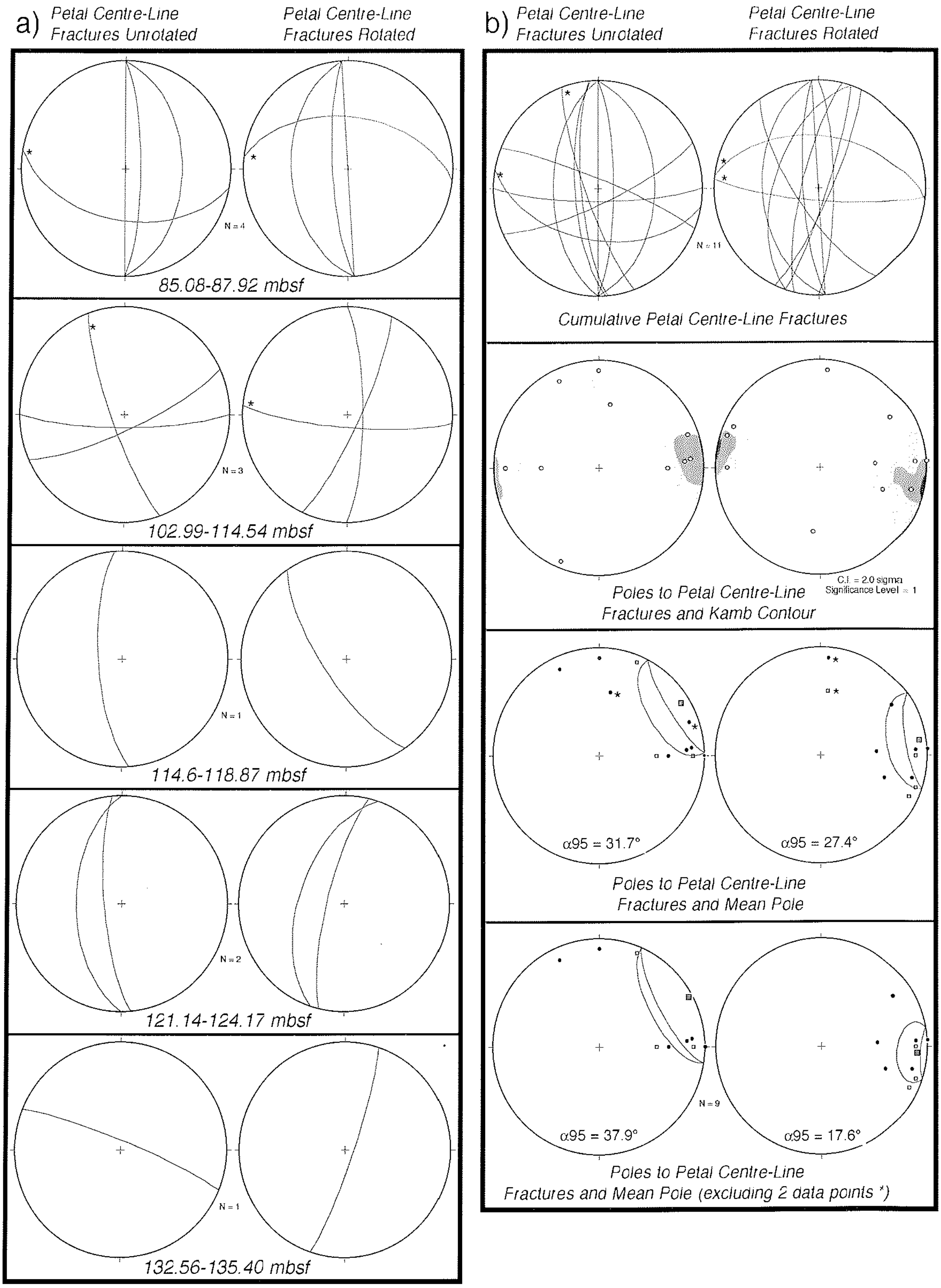


Fig. 5 - Equal area stereoplots showing the orientations of petal/petal- centreline fractures within core intervals that were palaeomagnetically reorientated. *a)* Great-circle stereoplot showing the orientations of unorientated and reorientated petal/petal-centreline fractures that occur within five of the reconstructed core intervals. *b)* Great- circle, Kamb-contour, and scatter plots of unorientated and reorientated cumulative petal/petal-centreline fractures. Note the improved clustering and α95 values after reorientation. The * marks 2 petal-centreline fractures that may have anomalous orientations due to fracture propagation near preexisting fractures. Note the improved α95 values when these fractures are excluded from the calculation. Open squares in the α95 plots mark poles to fractures that were plotted in the upper hemisphere.

depth ranges formed at different times under different stress conditions or formed as a result of glaciotectonic processes, since ice motions and related shear directions would most likely differ between glacial cycles (see Wilson & Paulsen, this volume).

CONCLUSION

This study demonstrates that palaeomagnetic reorientation of CRP-1 drillcore is feasible, although errors are probably no less than ± 11°. Palaeomagnetic reorientation of the CRP-1 core, results in a better clustering of both high-angle natural fractures and drilling-induced petal-centreline fractures. After reorientation, high-angle natural fractures form two northeast and northwest-striking conjugate sets, whereas petal-centreline fractures form a north-northeast-striking set. Low-angle natural fractures show no improvement by cluster analysis, which may reflect changing stress conditions related to their origin.

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