Paleomagnetic inclinations in DSDP Hole 417D reconsidered: Secular variation or variable tilting?

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[1] In Deep Sea Drilling Program (DSDP) Hole 417D in the western central North Atlantic, dips of pillow margins measured in the upper and lower part of basement correlate with tilts predicted from paleomagnetic inclinations in the corresponding parts of the hole. A ~40° westward dip of the seafloor around 417D matches the tilt predicted from inclinations and pillow margin dips in the uppermost lavas. The correlation suggests that most of the large long-wavelength inclination variation in Hole 417D is caused by variable tilting about an axis more or less parallel to the paleo rift rather than by secular variation. The variable tilt in Hole 417D is interpreted as the sum of rotation due to lava loading along the Mesozoic paleo rift and a later block rotation of ~40° in the rift valley walls. This interpretation allows a reconstruction of the paleo rift environment in which the 417D upper crust formed. INDEX TERMS: 3035 Marine Geology and Geophysics: Midocean ridge processes; 1527 Geomagnetism and Paleomagnetism: Paleomagnetism applied to geologic processes

1. Introduction

[2] The argument of rotation (tilting) versus secular variation as the cause of variable paleomagnetic inclination in ocean crust drill holes has existed since the beginning of ocean crust drilling. Drill core samples measure inclination without azimuth which makes it difficult to test the tilting hypothesis. Furthermore, inclinations, even in adjacent holes, do not show a systematic variation with depth and the inclinations indicate tilts that are both toward the spreading axis and away from it. In the seventies, the leading paradigm was tilting of the lavas toward the axis due to lava loading or lava burial [e.g., Palmason, 1973; Cann, 1974]. In the eighties, block rotation along listric normal faults causing tilting away from the axis [e.g., Versub and Moores, 1981] became the leading paradigm. Neither tilt paradigm has been able to provide a satisfactory explanation for the variable inclination in ocean crust drill holes.

[3] The lack of independent information on the tilt of lavas in the holes and of a satisfactory paradigm to explain the tilt variations has suggested that either upper ocean crust is too randomly tilted or that secular variation dominates the variable inclination in the holes. In either case the magnetic inclinations in ocean crust drill holes have eluded meaningful interpretation.

[4] Recent studies of the Troodos ophiolite, Cyprus, where offset Holes CY-1 and CY-1A penetrated most of the volcanic sequence, show that tilts of lava flow surfaces and dice margins in outcrop match the large long-wavelength inclination variation in the holes [Schouten and Denham, 2000]. This implies that the contribution of secular variation to the long-wavelength inclination variation in Holes CY-1 and CY-1A must be comparatively small. Schouten and Denham [2000] explain the long-wavelength tilt variation using a combination of the two tilt paradigms: differential rotation of the lavas due to lava loading in the inner rift valley followed by block rotation in the rift valley walls. Accordingly, block rotation should equal rotation in the shallowest lavas where lava loading is zero. Tilting caused by lava loading increases from zero in the uppermost lavas at the top (no loading) to ~50° in the deepest part of composite hole CY-1/1A (maximum loading). Later block rotation added a uniform 20° tilt in the opposite direction. Magnetic inclinations in Hole 504B, Costa Rica Rift, eastern equatorial Pacific, indicate a tilt increase from ~zero at the top to ~50° in the bottom of the lava pile. The progressive tilt with depth is toward the Costa Rica spreading axis, which suggests the tilt variation would be caused by lava loading. The ~zero tilt of the uppermost lavas in Hole 504B is interpreted to indicate ~zero block rotation. In both the Costa Rica Rift and Cyprus holes, the sheeted dikes and lowermost lavas appear untilted relative to the uppermost lavas suggesting that the synrift deformation in the sheeted dikes and lowest lavas was by cataclastic faulting (i.e., no rotation) while in the rest of the lava pile that deformation was by cataclastic flow (i.e., rotation) [Schouten and Denham, 2000].

2. Paleomagnetic Inclinations and Pillow Margin Dips in Hole 417D, Western North Atlantic

[5] DSDP Hole 417D was drilled in Mesozoic ocean crust in the western central North Atlantic, almost 1000 km SSW of Bermuda. Paleomagnetic inclinations measured on basement core samples show considerable variation with depth in the hole (Figure 1a). The upper 150-m of basement in the hole has a stable inclination averaging ~66° ± 8°, significantly steeper than the average paleo field inclination for this site (~35°, vertical line in Figure 1a). Below 150 m and above a breccia zone with widely scattered inclinations, the mean inclination is ~23° ± 9°, while below the breccia zone the inclination is ~43° ± 12°. This large variation, with steeper inclinations in the top 150 m and shallower inclinations closer to the predicted value in the lower 200 m of the hole, has been attributed to variable tilting by the paleomagnetists of Leg 51. The Leg 52 shipboard party mostly favor secular variation to explain the inclinations [Shipboard Scientific Parties, 1980].

[6] Pillow margin dips were measured in cores marked by the brackets shown in Figure 1a. The data survive only in the form of histograms of pillow margin dip angles [Robinson et al., 1980] shown in Figures 2c and 2d. In the ODP archives there is no record of the individual measurements and the original measurements are presumed lost (ODP data librarian, personal communication, 2001). Because it was noticed that the paleomagnetic inclinations in the upper part of Hole 417D are much steeper than those in the lower part, the measured pillow dips were presented in two separate histograms [Robinson et al., 1980]. The two data sets (Figures 2c and 2d) are clearly different. In the upper sequence, pillows have a well-defined maximum at about 40 degrees (median 35°) and in the lower sequence most of the dips are less than 20°.

[7] We model the measurements in Figures 2c and 2d with pillow shapes that have a gaussian distribution of dip angles and a tilt. The measurements in the upper and lower lavas are best modeled respectively with standard deviations (s.d.) 20° and 10° and tilts 35° and 10° (thin bell curves in Figures 2c and 2d). The corresponding gaussian pillow shapes are shown in Figures 2a and 2b.
the tilt is 17° toward WNW. Due to lava loading followed by uniform block rotation of 40° shaded line in (b). Model assumes variable rotation toward ESE horizontals (thin lines) in the hole (bold vertical bar) conforms to nearly 55°. Diamond shows interpillow limestone stratification now inclined measured in the cores there are two solutions for post-depositional with error bars in Figure 1b). Estimated tilt in the upper 150 m of choose the solution with the lower tilt estimate (small open circles ±1sigma error bars; alternative solution: small crosses. Large open circles and crosses are alternative tilt solutions ±35° and ±10° from pillow margin dips in Figures 2c and 2d. Hexagon shows 41°WNW tilt of seafloor from Figure 3. Diamond shows interpillow limestone stratification now inclined nearly 55° [Shipboard Scientific Parties, 1980], (c) Tilt of paleo horizontals (thin lines) in the hole (bold vertical bar) conforms to shaded line in (b). Model shows variable rotation toward ESE due to lava loading followed by uniform block rotation of 40° toward WNW.

2b. The rounder shapes of the upper pillows (Figure 2a) suggest pillow flows although they appear somewhat flatter than the common pillow (s.d. >30°–40°). The flatter shapes of the lower pillows suggest lobate flows (Figure 2b). The modeling demonstrates that the histograms in Figures 2c and 2d conform to acceptable pillow margin shapes and that in the upper lavas the median value represents the mean dip of the flattened top of the pillows; the lobate lower lavas are subhorizontal (tilt 10° ± 10°).

We re-examine the correlation between paleomagnetic inclinations and pillow margin dips in Hole 417D. We assume that post-depositional rotation of the lavas in the hole was about an axis parallel to the paleo spreading center, or, about a horizontal axis trending 035°, which trend is at right angles to the paleo spreading direction at this site [e.g. Klitgord and Schouten, 1986]. The only other assumption we make is that at deposition the lavas acquired a stable magnetization parallel to the paleomagnetic field. We use a reversed Cretaceous North America field inclination (−35°) and declination (145°) predicted for this site. For each inclination measured in the cores there are two solutions for post-depositional rotation (tilt) of the lavas in 417D. One of the solutions has very high values of tilt (>70°NW, small crosses in Figure 1b). We choose the solution with the lower tilt estimate (small open circles with error bars in Figure 1b). Estimated tilt in the upper 150 m of basement is −34° ± 9°. Below 150 m and above the breccia zone the tilt is 17° ± 17°, while below the breccia zone it is −12° ± 8°.

A reason for choosing the solution with the lower tilt is the corresponding low values of the dips of pillow margins measured in the cores (Figures 2c and 2d). Like the magnetic inclinations, pillow margin dips measured in cores have no azimuth. For an assumed horizontal rotation axis, tilt equals dip angle and can be positive or negative. We plot in Figure 1b the positive and negative tilt solutions from the pillow margin dip distributions with large open circles and crosses, respectively ±35° and ±10°. The preferred solution from the magnetic inclinations (small open circles with error bars in Figure 1b) shows a satisfactory correlation with one of the solutions (large open circles) from pillow margin dips. Histograms of the inclinations from the same cores inverted for tilt and rectified (Figures 2e and 2f) show similar correlations. The correlation between inverted inclinations and pillow margin dips then suggests that the large inclination variation down Hole 417D reflects mostly variable tilt in the lava pile (assuming that a common horizontal axis describes all rotation in the hole). This correlation also indicates that the average pillow margin dip angle is close to the dip of the paleo horizontal.

3. Discussion

Paleomagnetic inclinations and pillow margin dips measured in drill cores have undetermined azimuths. We overcome this problem by assuming that post-depositional rotation (tilt) of the lavas is about an axis parallel to the paleo-spreading center. This provides two possible tilt solutions for each inclination and average pillow margin dip measured in the cores. One of the solutions for average pillow margin dip matches one of the solutions for the average magnetic inclination in the cores. For an interpretation of the tilt variation with depth in Hole 417D we make a further assumption that most of the rotation of large crustal blocks postdates lava deposition [Schouten and Denham, 2000]. This will allow estimation of block rotation from the tilt of the uppermost lavas. This assumption is not unreasonable.

![Figure 1](image1.png)

**Figure 1.** (a) Paleomagnetic inclinations in Hole 417D (open circles). Brackets indicate cores where pillow margin dips were measured shown in Figures 2a and 2b. (b) Inclinations (25-m core length averages) inverted for tilt (Cretaceous field inclination: −35°; declination: 145°; trend rotation axis: 035°). Preferred tilt solution: small open circles with ±1sigma error bars; alternative solution: small crosses. Large open circles and crosses are alternative tilt solutions ±35° and ±10° from pillow margin dips in Figures 2c and 2d. Hexagon shows 41°WNW tilt of seafloor from Figure 3. Diamond shows interpillow limestone stratification now inclined nearly 55° [Shipboard Scientific Parties, 1980], (c) Tilt of paleo horizontals (thin lines) in the hole (bold vertical bar) conforms to shaded line in (b). Model shows variable rotation toward ESE due to lava loading followed by uniform block rotation of 40° toward WNW.

![Figure 2](image2.png)

**Figure 2.** Gaussian pillow shapes and histograms of pillow margin dips and inverted paleomagnetic inclinations in the upper lavas (cores 22–42) and lower lavas (cores 52–56 and 62–66) of Hole 417D. (a,b) Gaussian pillow shapes described by bell curves in Figure c,d. (c,d) Histograms of pillow margin dip angles [Robinson et al., 1980] and best-fit gaussian model distributions (thin bell curves). (e,f) Histograms of the paleomagnetic inclinations in the same cores inverted for tilt (from Figure 1b) and rectified. Median values are indicated with a dashed line.
as the flow of lava from the ridge crest usually will be stopped by the first inward-facing fault scarp nearest to the axis while rotation of fault-bounded crustal blocks is typically just beginning at that fault. Progressive increase in dip with depth observed in the sediments on top of the Troodos ophiolite, implies that significant block rotation occurred after lava deposition had ceased. The same conclusion can be drawn from the progressive increase in normal-fault throw with distance to the EPR far beyond the reach of lavas flowing from its axis [Macdonald et al., 1996].

[12] If most of the rotation of large crustal blocks postdates lava deposition, then the tilt recorded in the uppermost lavas should approximate that of block rotation, because uppermost lavas cannot be tilted by lava loading (no load). The estimated tilt of the uppermost lavas in 417D is close to 40° toward WNW (Figure 1b) suggesting block rotation (back tilt) of that order. The contribution of lava loading to the tilt then is defined by the estimated tilt of the lavas in the hole, minus the block rotation (the tilt of the uppermost lavas). The model for this interpretation is shown in Figure 1c for 40°-block rotation toward WNW. Tilt of the paleo horizontals (thin lines) in the hole (heavy vertical bar) conforms to the preferred tilt in the eastern flank where 417A was drilled was dipping 78° toward east which is close to the shallow inclinations (i.e., low tilts) found only in the lower part of 417D above the breccia zone (Figure 1a).

[15] The model of a back-tilted block predicts that Hole 417D entered the crust at the top of the lava pile whereas Hole 417A was tilted by lava loading that affected mostly the lower lavas. The 206 m of basaltic ocean crust in 417A has been severely affected by low-temperature alteration whereas the basalts in 417D are generally weakly to moderately altered (Figure 1c). Besides for the uppermost 150 m [Shipboard Scientific Parties, 1980], we suggest the rubble may indicate a fault zone. The paleomagnetic inclinations in 417A average −22° ± 6° which is close to the shallow inclinations (i.e., low tilts) found only in the lower part of 417D above the breccia zone (Figure 1a).

[16] The inferred 417D structure shown in Figure 1c can be read as follows. Initially, lava accumulation in the rift valley generated a sequence of overlapping flows that were progressively tilted with depth toward the spreading axis depending on the average vertical cross section of the flows. Near the spreading axis, that cross section was relatively uniform, short and thick resulting in rather uniformly steeply dipping lower lavas. Farther from the axis, the average cross section of the overlapping flows was longer and thinner, resulting in upper lavas that were tilted only slightly. The sharp change in tilt between upper and lower lavas suggests a sharp change from short thick flows accumulating near the axis to longer thinner flows farther away. The gradual change in tilt in the lowest part of the hole lies in the lava-dike transition where 540B and CY-1/1A exhibit similar changes, which Schouten and Denham [2000] interpret to reflect a change in style of deformation from cataclastic flow to faulting. Alternatively, the gradual change in tilt in the lowest lavas in Hole 417D could reflect secular variation. Following deposition of the latest and uppermost lavas, an outward block rotation caused the whole section to tilt more than 40° away from the axis, resulting in the present structure sampled in Hole 417D. The significant (50°) rotation due to lava loading of the lower lavas and the associated deformation forms an explanation for slickenlides occurring only in the 417D lower lavas. A lack of slickenlides in the upper lavas agrees with the lack of significant rotation in those lavas prior to the block rotation. Intercalated limestones in the upper lavas attest to an infrequent accumulation of those lavas farther from the axis. An absence of intercalated limestones in the lower lavas suggests rapid lava accumulation nearer to the spreading axis. We suspect from the way the slickenlides are distributed in 417D that the slickenlides are not related to block rotation involving the whole section but to the severe differential rotation due to lava loading that affected mostly the lower lavas.

4. Conclusions

[17] Paleomagnetic inclinations match tilts from pillow margin dip angles in Hole 417D drill core samples when inclination is
inverted for rotation about a NNE-trending axis parallel to the paleospreading center. The match of two independent sets of observations suggests that most of the large inclination variation in 417D is due to post-depositional rotation of the lavas and therefore not the effect of secular variation.

[18] The variable rotation with depth in the 417D lava pile is explained by progressive rotation due to lava loading in the Mesozoic rift valley, followed by block rotation in the rift valley walls. Rotation due to lava loading increases from zero in the uppermost lavas (no load) to ~50° in the lower lavas, as found in Holes 504B and CY-1/1A. Later block rotation in the opposite direction added a uniform rotation of ~40° to the whole section.

[19] Hole 417D was drilled into the western slope of a back tilted block, which dips 41° toward 295°. The correlation with a similar rotation of the paleomagnetic vector in the uppermost lavas in the hole suggests that this seafloor was subhorizontal when the youngest lavas accumulated. Hole 417A was drilled only 600 m away into the eastern slope of the block, which dips 37° toward 115°. This slope probably is the normal-fault face that bounds the block to the east and that was unroofed by the severe block rotation. The latter would explain a 10-m rubble zone on top of 417A basement, the pervasive low-temperature alteration throughout the hole, and its shallow paleomagnetic inclinations (i.e., low tilts) that match those only in the lower part of Hole 417D.

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References


