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A simple method for orienting drill core by correlating features in whole-core scans and oriented borehole-wall imagery

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Abstract

Assessing the regional significance of fractures in drill cores requires the collection of oriented core intervals. Direct orientation of cores during drilling is possible, but is commonly precluded because of expense and time requirements. A simple and accurate method of core reorientation is presented where high-resolution imagery of drill cores (whole-core scans) are directly compared with oriented borehole imagery. Core intervals are reoriented by aligning features (i.e. fractures, bedding, and clasts) in whole-core scans with correlative, oriented features in borehole-wall imagery. Unlike other core orientation techniques, the direct side-by-side comparison of core scans and borehole-wall imagery can identify core segments that were mismatched due to undetected rotation between two portions of core. The combined analysis of core-based fracture data, whole-core scans and borehole imagery in this method optimizes data integration to improve structural interpretations. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Drill core; Borehole; Orientation; Imagery; Fractures

1. Introduction

Accurate orientation of fractures in drill cores can be critical for understanding neotectonic stress, structural history, and reservoir productivity (Davison and Haszeldine, 1984; Nelson et al., 1987). Direct orientation of cores during drilling can be achieved by continuously scribing the core within an oriented core barrel (Kulander et al., 1990). However, this method is expensive, time consuming, and cannot detect instances where core pieces rotate due to motion of the drill bit before they are scribed upon entering the core barrel (Nelson et al., 1987; Hailwood and Ding, 1995). Similarly, in cases where an orienting tool is run, there may be twists in the core or poor quality control by the operator that make the orientation of the core dubious (Shipton et al., 2001). In the absence of direct measurement, other indirect means of determining core orientation are required.

Indirect methods, such as paleomagnetism, have been successful, but challenge geologists because method-specific problems both limit use and restrict confidence in core-orientation results (Kulander et al., 1990; Lackie and Schmidt, 1993; Hailwood and Ding, 1995; Rolph et al., 1995; Paulsen and Wilson, 1998; Paulsen et al., 2000; Payenberg et al., 2000). A particularly promising indirect orientation technique is based on correlating fractures, bedding, or other features in unoriented drill cores to oriented borehole images (e.g. Mathis et al., 1995; Paulsen et al., 2000; Payenberg et al., 2000; Jarrard et al., 2001). Common approaches include use of mechanical goniometers to measure core structures, or use of manual and photocopy-based techniques to produce images of drill core for measuring structure orientation (Schmitz et al., 1989; Weber, 1994; Paulsen et al., 2000; Payenberg et al., 2000). Another method used in industry is based on scanning acetate-peel overlays with manual tracings of core features, digitally joining them into continuous core images, then orienting them using dipmeter or borehole image data (Lawrence Bourke, pers. comm.). However, these techniques are time consuming, may produce low-resolution drill-core imagery, and do not always yield accurate correlations of drill core and borehole-wall features (Weber, 1994).

In this paper, we describe an orientation technique that applies recently developed core-scanning technology to provide a simple and quick means of acquiring high-resolution imagery of drill cores (whole-core scans). The acquisition of high-resolution whole-core scans allows accurate measurement of feature orientation and unambiguous

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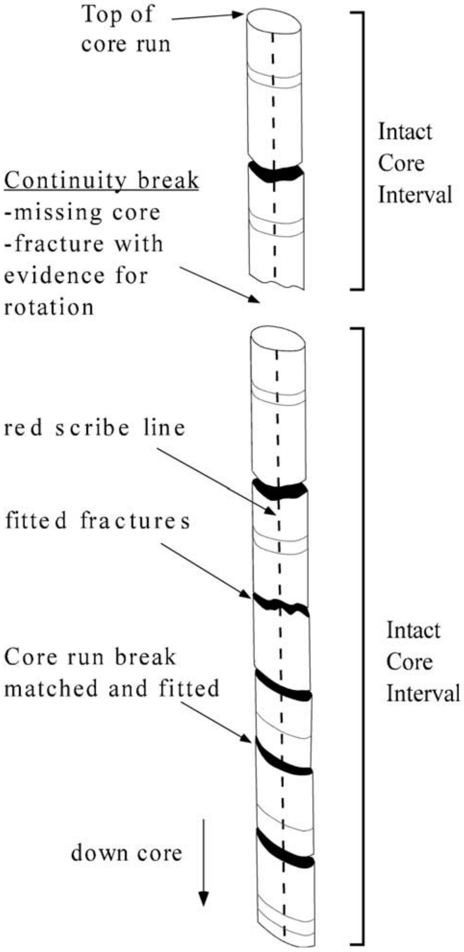

Fig. 1. Sketch showing a typical intact core interval with fitted core segments within a core run or at run breaks (modified from Hailwood and Ding, 1995). The upper and lower boundaries of intact core intervals are where core could not be fitted together because of core loss or rotation on fractures. Fracture orientation was measured with respect to an arbitrary 'north' defined by a red scribe drawn along the length of each core run.

correlation to borehole-wall imagery. This technique does not eliminate the need for traditional core-based observations, such as logging fracture orientation and fractographic features to establish mode of origin. However, the technique does provide a more robust matching of features, which lends greater confidence in core reorientation. Thus, this core-reorientation technique, when combined with traditional observations about core properties (e.g. fault kinematic or paleomagnetic analysis), provides a powerful tool for constructing spatial data sets in drill cores, which may then be applied to solving a variety of geological problems. We illustrate the application and effectiveness of this technique with a drill core from the Cape Roberts Drilling Project (e.g. Cape Roberts Science Team, 2000).

2. Core-processing procedure and image collection

Key initial steps in the drill-core reorientation process occur during core logging. These steps include identification of core runs that can be matched and fitted together across run breaks, refitting core across fracture breaks, and logging all fractures where spinning of the core between drilling and entry into the core barrel disrupted the continuity of the core (Figs. 1 and 2). This systematic logging of all core breaks allows the core to be partitioned into intact intervals without rotations (Fig. 1). Each intact core interval must be reoriented independently, because rotations between intervals may have occurred. Partitioning core into intact intervals has two advantages. First, fewer intervals of drill core need to be reoriented. Second, identifying fractures or zones where core spinning occurred is critical to preventing incorrect fracture reorientation, which introduces error and scatter into structural analysis.

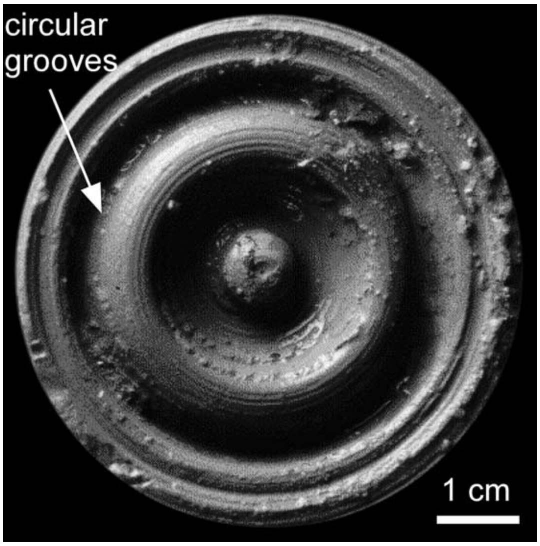

Fig. 2. Photo of subhorizontal fracture with circular grooves indicating drill-core rotation. Photo is from the first drill core retrieved by the Cape Roberts Drilling Project in Antarctica.

Upon recovery and reconstruction of the core, red and blue scribe lines are drawn 180° apart along the length of the core. The dip and dip direction of planar structures are measured with respect to an arbitrary north defined by the red scribe line. Scribe-line straightness and parallelism to the core axis is essential to prevent the introduction of error and scatter into structural measurements. For example, a ca. 4 mm deviation in parallelism of the red scribe line on core of 45 mm diameter (NQ) results in a 10° angular difference for dip direction measurements. For long intact intervals, the cumulative deviation effect can have a large angular significance.

After planar structures are described and measured, the core is cut into 1 m segments. Where core integrity permits, the core surface is scanned using Corescan® equipment leased from DMT, Germany (Fig. 3). Other devices, like the Autocar® system, can also be used to image the outer surface of a drill core (see Mathis et al., 1995). The Corescan® obtains high resolution digital images (5 pixels/mm;

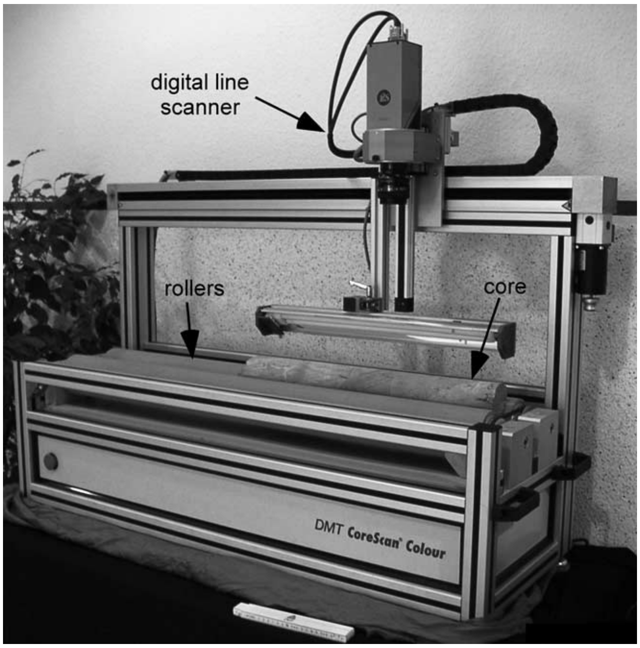

Fig. 3. Photo of the Corescan® machine.

Fig. 4) by rotating the whole core on rollers, scanning segments up to 33 cm in length using a digital line-scanner, and digitally joining these segments into 'unrolled' core images up to a maximum length of 100 cm. Planar features such as beds and fractures have sinusoidal shapes on these images because the three-dimensional core surface has been 'unrolled' into a two-dimensional image (Fig. 4). The scanning process is quick and can be conducted at a drill-site science lab as part of a core processing procedure (e.g. Cape Roberts Science Team, 2000). In the Cape Roberts Project, where Cenozoic sedimentary rocks were drilled, we could scan ~85% of the cores. Most segments that we did not scan were from shallow depths where poor lithification caused poor core integrity.

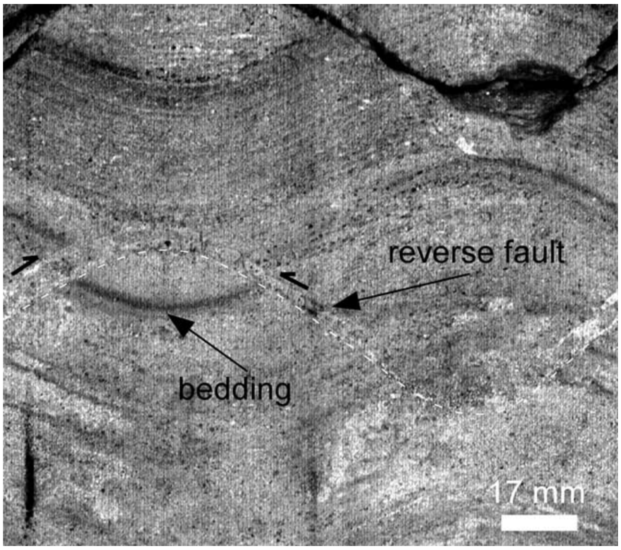

Fig. 4. Example of high-resolution (5 pixels/mm) Corescan® image of well-bedded Devonian sandstone near base of the third Cape Roberts drill core. Planar features such as the reverse fault and beds appear as sinusoids on the unrolled image.

Corescan® images of core segments within an intact core interval can be digitally stitched together using software, either on-site or during post-field processing, to correct differential rotations of adjacent segments and merge images into a single restored (pre-break) image. We used DMT Corelog® software leased from DMT, Germany, but other software packages, like the Elf Aquitaine Diamage® software, can also be used for the digital-stitching process (see Mathis et al., 1995). The hand-drawn scribe lines are an invaluable guide for reconstructing drill-core continuity during the digital 'stitching'. However, the scribe lines may have 'mismatches' across core fractures due to incorrect refitting of core during initial logging. The digital stitching process allows any 'mismatches' to be identified and then corrected by digitally cutting, rotating to correct the mismatch and then restitching. This improves core continuity and also allows core-based measurements made with respect to the misfitted red scribe line to be corrected. Another advantage of stitching is that it can be used to identify and measure drift in the scribe line from parallelism with the core axis. These results can be used to correct core-based directional measurements made with respect to the scribe line and thus, refine the accuracy of results. In the Cape Roberts drill core, scribing errors resulted in a 90° shift in a 12 m intact interval (2.92 mm/m change in line position) and a 145° shift in a 25 m intact interval (2.28 mm/m change in line position). Such errors are not easily recognized by other core reorientation techniques because most do not permit visualization of long sections of a core and its scribe line with respect to a fixed reference line (i.e. the left or right sides of stitched Corescan® imagery). The digitally-stitched whole-core scan imagery permits identification and accurate removal of scribing errors.

In the Cape Roberts drilling project, we compared Corescan® images to oriented borehole televiewer (BHTV) logs to determine core orientation. The BHTV is an active remote sensing device that fires sound pulses at the borehole wall and measures the return signal to detect surface roughness changes, which can be associated with stratigraphic changes (i.e. bedding) and fractures (e.g. Moos et al., 2000). The BHTV data are oriented magnetically and can be processed to provide oriented images of the surface reflectivity of the borehole wall (Zemanek et al., 1970). In drillholes from some other regions, oriented Formation MicroScanner® (FMS) logs have been run instead of BHTV logs, providing downhole images that can be used instead of BHTV for matching to core images (Haggas et al., 2001).

3. Reorientation of drill core

To reorient the core, BHTV and Corescan® imagery are

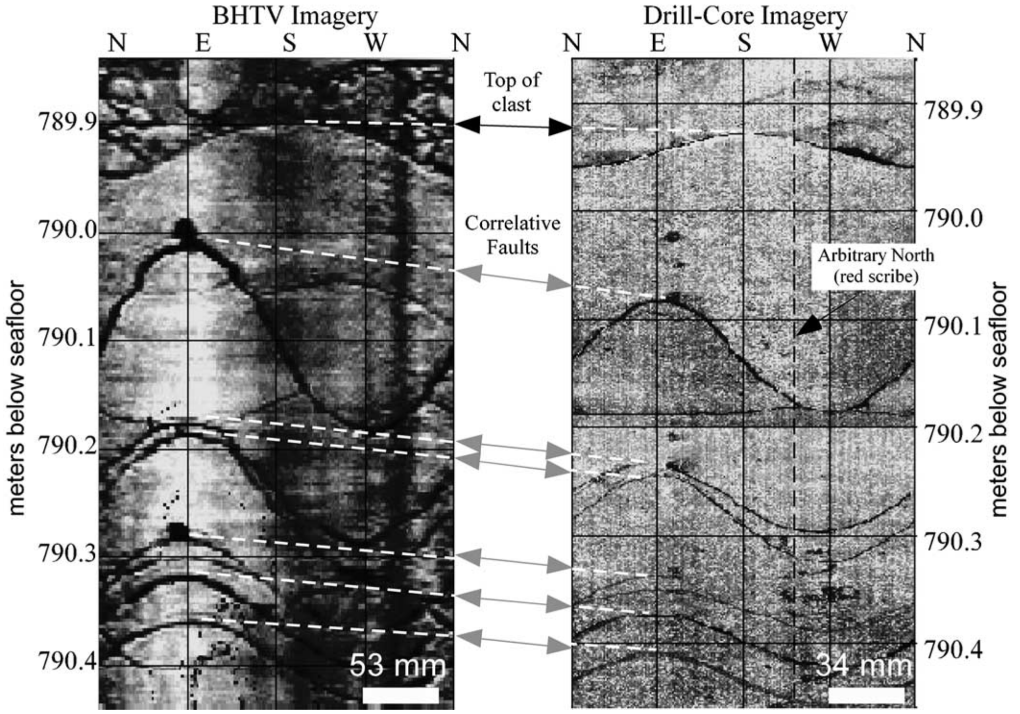

Fig. 5. Example of matching features between drill core and borehole wall to reorient drill core from the third Cape Roberts drill core. Note that the scribe line does not coincide with North after the whole core scan image is rotated to match the BHTV image. The sinusoids have larger amplitudes on the BHTV image because it has a larger diameter than the whole-core image.

imported into WellCAD® software (Advanced Logic Technology; www.alt.lu) and displayed as unrolled 0–360° azimuth images for direct side-by-side comparison (Fig. 5). True north is on the left side of the oriented BHTV image and initially the arbitrary 'north' defined by the red scribe line is also revolved to the left side of the unrolled core image. Because the BHTV and Corescan® imagery are imported into WellCAD® at a comparable resolution (1 mm vertical resolution for Corescan® imagery and 3 mm vertical resolution for BHTV imagery), correlative features can be identified. Feature matching is used initially to correct any depth shift between the BHTV logs and the core depths, which is typically caused by stretch of the logging cable. This step is critical in the orientation process because minor depth discrepancies between core depths and borehole image logs can lead to incorrect feature correlation. Other software packages, like the Elf Aquitaine Diamage® software, can also be used to correct for such depth shifts (see Mathis et al., 1995).

After depth correction, the stitched core and BHTV imagery is examined for features that provide an unambiguous template for drill-core reorientation (Fig. 5). For the sedimentary rocks cored in the Cape Roberts Project, we matched fractures, bedding, and clasts. The most accurate azimuth determination and resulting core orientation is provided by steep fractures and bedding, whereas beds with dips of <10° do not provide useful matches. In principle, an intact core interval is reoriented by rotating core features to match correlative structures in the oriented BHTV image (Fig. 5). Feature orientations can be picked in WellCAD® by identifying single-points (e.g. a fracture top or a clast center) and sinusoids (e.g. planar features such as fractures or beds). The angular difference for each as measured on stitched-core and BHTV is plotted vs. depth for each stitched core, and this plot is examined to identify and exclude any strongly anomalous picks. All angular differences are then used to calculate a single average rotation angle to restore the entire stitched-core interval to true geographic coordinates. Because the rotation angle is referenced to the red scribe line on the core, any core structures or samples measured with respect to the red scribe can also be reoriented to North using this rotation angle.

Unlike other core-orientation techniques, the side-by-side comparison of drill core and borehole-wall imagery can easily detect a mismatch of adjacent core segments due to unrecognized rotation between two portions of core (cf. Kulander et al., 1990; Lackie and Schmidt, 1993; Hailwood and Ding, 1995; Rolph et al., 1995; Paulsen and Wilson, 1998; Paulsen et al., 2000; Payenberg et al., 2000). In cases where core-BHTV feature matching detects a core mismatch, then core intervals above and below the break can be reoriented independently based on rotation angles calculated for each interval. In the Cape Roberts drill cores that we have reoriented by this method to date (~231 m), we identified sudden breaks, or offsets, of core-BHTV correction angle, in about one-fourth of the intact intervals. Such undetected rotations could introduce significant scatter into structural analysis by applying a single

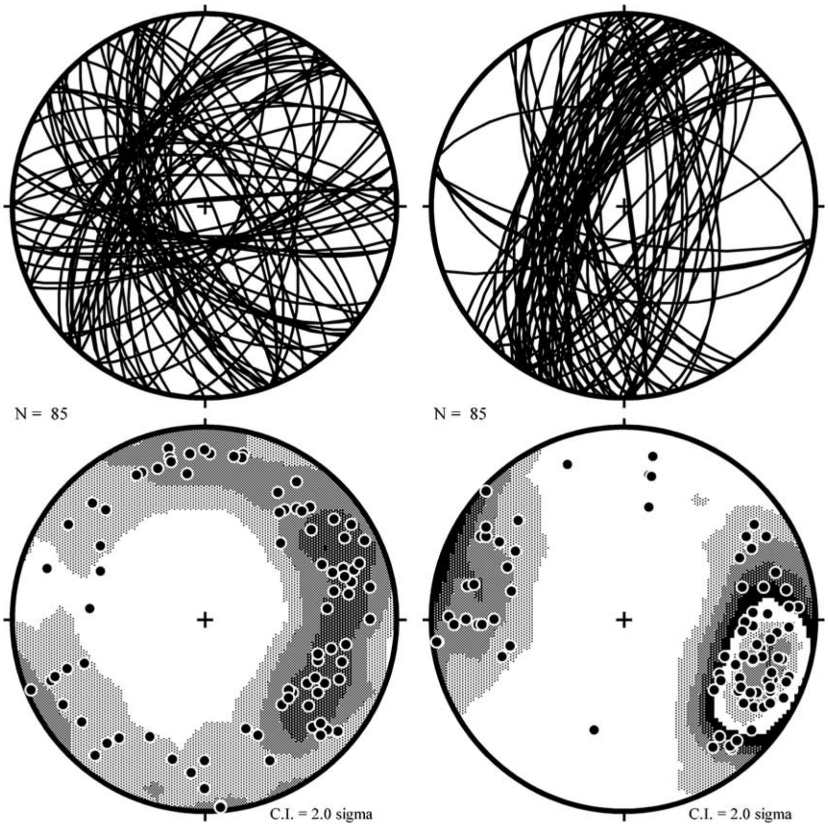

Fig. 6. Equal-area stereoplots (great circle and Kamb-contoured scatter plots) showing fault orientations within core intervals before (left) and after (right) reorientation. Data are from three different intact core intervals from the third Cape Roberts drill core (404–413 m below seafloor (mbsf), 693–706 mbsf, and 707–723 mbsf).

reorientation angle to an incorrectly logged 'intact interval'. Thus, this reorientation method provides greater confidence in core reorientation because previously described techniques do not permit clear identification of such breaks.

4. Testing the reliability of the orientation technique

Like other core-orientation techniques, the reliability of this reorientation method can be tested by conducting rotation cluster tests on natural fractures in the core (e.g. Hailwood and Ding, 1995). Fractures should show an improved clustering after rotation because they typically have systematic orientations (e.g. Kulander et al., 1990). Our reorientation of the Cape Roberts drill core produces a significant improvement in fracture clustering (Fig. 6), indicating successful reorientation.

How accurate is the reorientation process? Typical 95% confidence limits based on all feature matches for a single stitched core are 5–10°, but other sources of error are present. Overall, we estimate an orientation uncertainty of ±10° for entire stitched core intervals and ±15° for individual features such as a single fracture. Some of the error results from standard limits in accuracy associated with each step of a typical reorientation process (e.g. Nelson et al., 1987). For example, the internal BHTV magnetometer has an accuracy of ±2° and ±2° for local deviation at the Cape Roberts drill site (Jarrard et al., 2001). We estimate ±10° accuracy for fracture measurements that we made with a mechanical goniometer with respect to the red scribe, and ±2° accuracy for later picking of the red scribe orientation on the stitched core images (for details see Jarrard et al., 2001). We presently attribute a large source of the error in reorientation of the Cape Roberts drill core to an enigmatic third-order drift error of <20° of core-BHTV correction azimuth that occurs within some intact core intervals. Slight misalignment within the Corescan® equipment could have imparted gradual rotations into the imagery. We have not corrected for these drifts, because they cannot be determined accurately. If this apparent drift can be identified and corrected, our error estimates will diminish substantially. If Corescan® equipment alignment is calibrated upon set up and intermittently checked during the scanning, this source of error might be removed.

Does Corescan® imagery eliminate the need for traditional core-based observations like logging fracture orientation and fractographic features? Trial measurement of fracture orientations using Corescan® imagery indicates that the software-based technique does not sacrifice data accuracy for ease of measurement. However, elimination of core-based observations would restrict the ability of the observer to recognize as many features. In many cases, we found that very fine hairline veins and faults are difficult to see or are not visible on the Corescan® imagery. In addition, BHTV and FMS images also commonly miss features in the borehole walls (Payenberg et al., 2000). Corescan® imagery allows identification of faults by bedding offsets, but cannot provide information on fractographic features, such as measured slickenlines, or on fracture fill material, which may be critical for understanding structural history. Combining core fracture logging and Corescan® image analysis provides an optimal integration of core, image and borehole data for robust structural interpretations.

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