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Three-dimensional Stress Orientations Determined by Anelastic Strain Recovery Measurements and their Comperison with Borehole Breakouts

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Summary

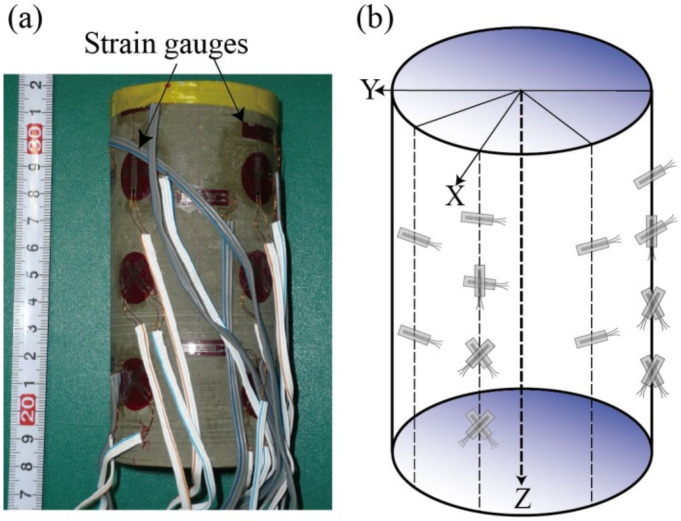
To determine three-dimensional stress orientation, anelastic strain recovery (ASR) measurements were carried out by using drill core samples taken from a scientific ocean deep drilling project. The lithology of the core samples is mudstone or siltstone with larger porosities ranged from 35 % to 45 %. I glued strain gauges on their cylindrical surface, and successfully obtained high quality anelastic strain data in at least six directions. And then, I determined the three-dimensional stress orientations by the strain-time curves. The stress orientations obtained from the ASR core measurements were consistent with those from drilling induced borehole breakouts observed in electrical image of borehole logging.

Introduction

As an Integrated Ocean Drilling Program (IODP) scientific deep drilling project, Nankai Trough Seismogenic Zone Experiments (NanTroSEIZE) is being conducted in the southwest Japan subduction zone to understand the physics of an active fault. Determination of in situ stress state is an important and necessary research item in such scientific drilling projects. Unfortunately, there is no foolproof method by which magnitudes and orientations of three-dimensional in-situ stress can be reliably measured at large/great depth, although various field and laboratory measurement techniques have been proposed. In cases of scientific deep drillings, I suggest that a combined application of borehole method (s) and core-based method (s) be employed. As one of them, a simple and inexpensive method to determine in-situ stress from anelastic strain recovery (ASR) measurement of oriented cores can be considered as having a relatively explicit theoretical basis in comparison to other core-based methods. Three-dimensional ASR measurements have been carried out in several continental drillings (Matsuki & Takeuchi, 1993; Lin et al., 2006; Lin et al., 2007). Recently, we successfully applied the ASR measurements in NanTroSEIZE project to determine three-dimensional stress orientations as the first time in scientific ocean drillings (Byrne et al., 2009). Hereafter, I report an example of ASR measurements and its comparison with borehole breakout results in the NanTroSEIZE drilling site C0002 to show measurement techniques applied in drilling project.

Anelastic Strain Recovery Method

The principle idea behind the ASR method is that stress-induced elastic strain is released first instantaneously (i.e., as time-independent elastic strain), followed by a more gradual or time-dependent recovery of anelastic strain. The ASR method takes advantage of the time-dependent strain. Voight (1968) first proposed that anelastic strain could provide constraints on in situ stress; and then Teufel (1983) applied this in some petroleum industry as a two-dimensional method. Matsuki (1991) showed that the method could be extended to three-dimensional stress and that it could constrain stress magnitudes. In principle, the anelastic strain is induced by stress release of the core sample accompanying drilling. Therefore, the stress constrains obtained by ASR measurement are of the stress state just before the drilling. Matsuki (1991) showed that the orientations of the three principal in situ stresses coincide with the orientations of the three principal anelastic strains for isotropic viscoelastic materials. Thus, the orientations of the principal in situ stresses can be determined by calculating the orientations of principal anelastic strain data measured in at least six independent directions. In this study, the ASR experiments are based on the basic principle suggested by Matsuki (1991) and by the same test procedures and apparatuses as Lin et al. (2007).



Drilling Site: C0002
Depth: 912 mbsf

Diameter: 50-60 mm
Length: 100-150 mm

Figure 1: (a) A photograph of the ASR core sample taken from 912 mbsf in drilling site C0002, (b) and its schematic illustrations of the X, Y, Z axes of a local coordinate system and the layout of the strain gauges glued on the surface of a cylindrical core sample.

ASR Measurements were conducted onboard the drilling vessel *D/V Chikyu*. During the measurements, the bagged samples were placed in a constant temperature chamber filled with tap water, in which the temperature was controlled by the circulator with heating and cooling functions. The strain gauges and two high-resolution thermistor thermometers (one measuring water temperature and the other room temperature) were connected directly to the data logger, and the digital data were recorded every 10 minutes. In general, the anelastic strain continuously recovers over several days or several weeks after the stress release. Usually, ASR measurement over a period of about one week is sufficient. After the ASR onboard measurements, sub-samples were made from the used ASR samples in shore-based laboratory. By using them, the core samples were successfully reoriented to a geographic reference frame with paleomagnetic data.

An Example of ASR results

As an example, raw data of anelastic strain in nine directions of a core sample taken from 912 mbsf (meter below seafloor) depth in C0002 site is shown in Figure 2. The duration of the measurement period was approximate 8 days. During the experiment, the constant temperature chamber worked correctly, so the temperature change was less than ±0.1 °C. As a result, the anelastic strains in all directions were extensional; all of the curves varied smoothly and similarly with increasing time. It is clear that the anelastic strain recovery continued in all directions for a period more than the measurement duration 8 days.

The values of the strain in the various directions, continuously measured for about 8 days depended on the orientation, the largest one (Z direction) reached more than 300 microstrains (0.03%). These suggest that ASR method is suitable to such lithology and such deep drillings. Thus, these data could be used for the three-dimensional analysis to determine the orientations of principal strains. From the measured anelastic normal strains in nine directions, which included six independent directions, the anelastic strain tensor including orientations of the three principal strains can be determined by least-squares analysis (Figure 2 and 3(a)). The orientations of the three principal anelastic strains must be the same as the orientations of the three principal in situ stresses.

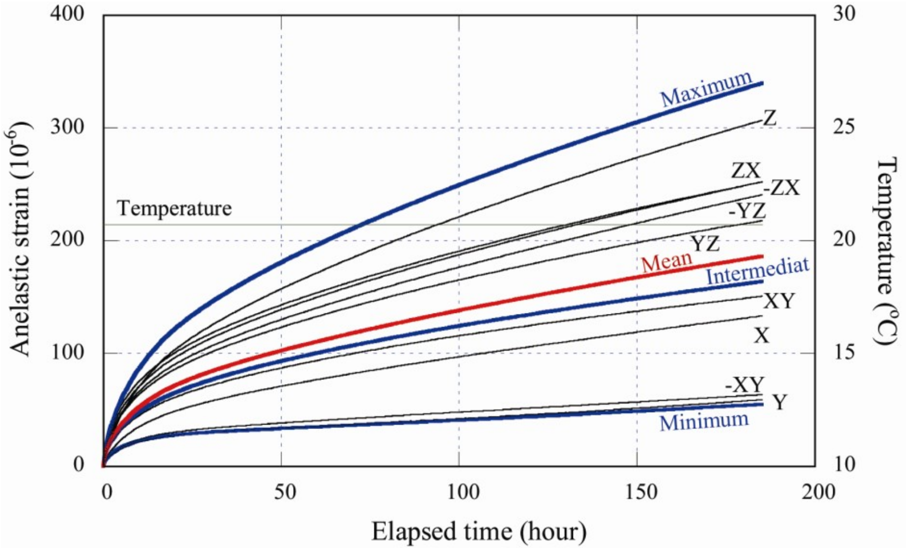


Figure 2: As an example of anelastic normal strain recovery raw data, strain curves (thin curves labeled by X, Y, Z etc showing its measurement direction) measured in nine directions during approximate 8 days of a core sample taken from 912 mbsf in drilling site C0002. Four thick curves (three principal strains, i.e. Maximum, Intermediate and Minimum strains, and the Mean principal strain) were calculated from the nine anelastic strain raw data.

In NanTroSEIZE drilling site C0002 where the ASR measurements were conducted, two boreholes were drilled at almost same location. In the first borehole, LWD (logging while drilling) was carried out without coring. Then, the core samples including ASR samples were retrieved from the second borehole. From the very clear borehole wall electrical images, a lot of drilling induced borehole breakouts (compressive failures) were recognized. Therefore, the orientations of principal horizontal stresses at the drilling site were determined from the borehole breakouts. Here, we show some breakouts in LWD borehole image corresponding to the approximately same depth range with the ASR core sample for a comparison of the horizontal stress orientations with the ASR result (Figure 3(b)). The breakout analysis is a two-dimensional method, i.e., having principal horizontal stress orientation data only; whereas ASR is a three-dimensional method. Because the stress regimes at the depth of ASR core sample are almost normal stress regime, i.e., the vertical stress is almost the same as the three-dimensional maximum principal stress σ_1, and the two-dimensional maximum and minimum principal horizontal stresses are almost the same as the intermediate stress σ_2 and minimum stress σ_3, respectively. Therefore, the results indicate that stress orientations independently determined by ASR measurements and breakout analyses are consistent with each other (Figure 3(b)).

Conclusions

To determine three-dimensional principal stress orientations, ASR measurements were applied by using drill core samples in the scientific ocean deep drilling project NanTroSEIZE. The lithology of the core samples is mudstone or siltstone with larger porosities ranged from 35 % to 45 %. High quality anelastic strain data in at least six directions was successfully obtained. The three-dimensional stress orientations were determined by the strain-time curves. The stress orientations by the ASR measurements were consistent with those obtained from drilling induced borehole breakouts analyses. Therefore, it can be said that the ASR method is well suited for the applications in directly determining the directions of principal in-situ stresses in three dimensions in deep drillings.

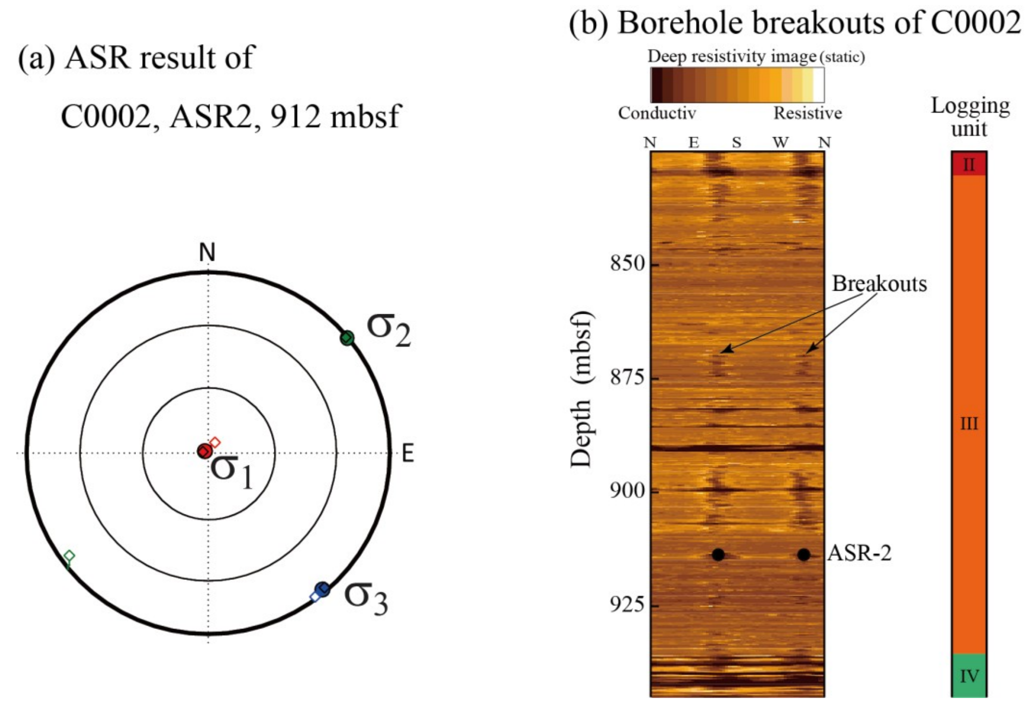


Figure 3: (a) Stereo projections (lower hemisphere) of orientations of three-dimensional principal stresses which are same as those of the principal anelastic strains from ASR measurements with respect to the true north coordinate system at C0002. (b) An unrolled borehole electrical image (left) in a depth range from 825 mbsf to 950 mbsf at C0002 obtained by LWD (Logging While Drilling) and lithologic unit column (right) defined by the logging data (Expedition 314 Scientists, 2009). Breakouts which show the azimuth of minimum principal horizontal stress were intermittently recognized. The circle plots are the azimuth of the minimum principal stress determined by the measurements of ASR-2 core sample.

Acknowledgements

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