

Determination of three-dimensional in situ stresses from anelastic strain recovery measurement of cores at great depth

Weiren Lin ^{a,*}, Marek Kwaśniewski ^b, Tetsumi Imamura ^c, Koji Matsuki ^d

^a Kochi Institute for Core Sample Research, Japan Agency for Marine-Earth Science and Technology (JAMSTEC),
200 Monobe-otsu, Nankoku, Kochi 783-8502 Japan

^b Rock Mechanics Laboratory, Faculty of Mining and Geology,

The Silesian University of Technology, 2, Akademicka Street, PL-44-100 Gliwice, Poland

^c International Projects Division, Teikoku Oil Co., Ltd., 1-31-10 Hatagaya, Shibuya-ku, Tokyo 151-8565, Japan

^d Department of Environmental Studies, Tohoku University, Aobayama 04, Aoba-ku, Sendai 980-8579, Japan

Accepted 7 February 2006

Available online 9 August 2006

Abstract

In order to examine whether the anelastic strain recovery (ASR) method can be applied for determining the in situ stress in hard rocks at great depths, the anelastic strain recovery of oriented cores was measured in six independent directions. The core specimens were taken from four depths within the range of about 2400–4500 m MD at the METI Niitsu well in Japan; the rock materials were mudstone, dolerite, basalt and andesite. For all the rocks the expansional anelastic strains were obtained, the magnitude of the strains in various directions continuously measured for 1 or 2 weeks was of the order of 1000×10^{-6} in mudstone; in contrast, strains of the other cores did not exceed a few hundred microstrains. These strains were used for a three-dimensional analysis of the principal in situ stresses. At the third depth, the principal stress directions were considered to be affected by fractures pre-existing near the core, and showed the features of a very local stress state. With the exception of this data, the directions determined by the ASR method were in agreement with those determined using other in situ measurement methods. Based on two assumptions, i.e., (i) the rock stress in vertical direction is equal to density-related gravitational overburden stress, (ii) the ratio of anelastic strain recovery compliance of shear deformation mode and the compliance of volumetric deformation mode is equal to 2, the values of the three principal stresses were estimated. The values of the minimum principal stress in the plane perpendicular to the well axis determined in this study were in agreement with those determined based on extended leak-off tests (ELOT or XLOT) conducted at the same well. Therefore, it can be said that the ASR method is well suited for use in directly determining the directions of principal in situ stresses in three dimensions and in estimating the magnitude of the stresses in isotropic rocks at great depths, such as those encountered when drilling deep into a submarine seismic zone.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Anelastic strain recovery; In situ stress; Three-dimensional measurement; Great depth; Isotropic rock

* Corresponding author.

E-mail addresses: lin@jamstec.go.jp (W. Lin), marek.kwasniewski@polsl.pl (M. Kwaśniewski), t.imamura@teikokuoil.co.jp (T. Imamura), matsuki@mail.kankyo.tohoku.ac.jp (K. Matsuki).

1. Introduction

Great earthquakes, the magnitude of which generally reaches M8, occur repeatedly in a cycle of about 100 years in the vicinity of the Nankai Trough, Japan, which is a boundary at which the Philippine Sea Plate subducts under the Eurasia Plate. In order to understand the mechanics and dynamics of seismogenesis and rupture propagation along subduction plate boundaries or splay faults, a plan of drilling from a seafloor of about 2 km below sea level to a depth of about 6 km below the seafloor through the seismogenic zone at the Nankai Trough had been proposed within an integrated ocean drilling program (IODP). Therefore, the crustal stress should be determined for the deep drilling program, because the stress, which is considered to be the direct driving force of earthquakes, and its variation at seismogenic zone during interseismic periods, is fundamental and very important for improving our understanding of the mechanism of generation and propagation of the earthquakes and of identifying the asperities. In addition, the three-dimensional stress information is necessary because the vertical direction, which is the same as the direction of drilling axis, may not be the direction of the principal stress due to the fact that the subducting oceanic crust in the Nankai Trough region has an inclination of about 10° to the horizontal plane (Nakanishi et al., 2002).

The measurements of stress existing in rock masses of the Earth's crust, which is usually called in situ stress in stress measurement field, were attempted by various direct or indirect methods (Amadei and Stephansson, 1997). Based on a careful assessment of various existing stress measurement methods, it was concluded that there is not a perfect method by which the magnitudes and orientations of the three-dimensional in situ stresses can be reliably measured (determined) at great depth. We, therefore, suggest that combinative applications of borehole methods and core-based methods, considered both a possible and practical approach for ocean deep drilling projects, should be employed. With respect to the borehole methods, a hydraulic fracturing test or extended leak-off test would be suitable to determine the magnitude of the minimum horizontal principal stress or both the maximum and minimum horizontal principal stresses and directions of principal axes of the in situ stresses in the two-dimensional plane perpendicular to the borehole axis, if only the conceivable failure of the borehole wall does not make the tests impossible. In addition, the observation of borehole breakout and/or drilling-induced tensile wall fractures can also provide important information about in situ stresses. On the

other hand, the core-based methods can supply supplementary data to those obtained using borehole methods; these are especially suited to yield three-dimensional information. For the purpose of measuring crustal stress in seismogenic zones at depth of several kilometers, core-based methods can be considered as reasonable and easy to apply. The major merit of core-based methods is that they do not have any additional difficulty at great depth although seismogenic zones in contrast with regular condition.

One of the core-based methods is a simple and inexpensive method to determine in situ stress based on anelastic strain recovery (ASR) measurement of oriented cores, if the cost of drilling and retrieving core samples is not taken into consideration. Anelastic strain recovery measurement is a possible method to estimate the three-dimensional orientations and the ratios of three principal stress deviations when using only the anelastic strain recovery data. This method, which has a relatively explicit theoretical basis in comparison to other core-based methods, was first proposed by Voight (1968) and practically applied in petroleum engineering, etc., as a two-dimensional method by Teufel (1983). Matsuki (1991) extended the method to three dimensions. Thus, this method was chosen and employed at the Niitsu site along with other methods (ELOT and differential strain curve analysis (DSCA)). The present study was undertaken and carried out for two purposes: to verify whether the three-dimensional version of the ASR method can be applied for determining the in situ stresses in hard rocks at great depth and to determine stresses at great depth in the Niitsu region of Japan. Since in the Niitsu region an upheaval of the basement was inferred from structural observations (Fig. 1c), the objective of stress measurements at the Niitsu well was mainly to examine the conditions under which the fractured gas and oil reservoir rocks exist at depth.

2. Anelastic strain recovery method for estimating in situ stress

2.1. Previous research

Voight (1968) suggested that there is empirical justification for considering the recovered anelastic strain to be proportional to the total recoverable strain (both elastic and anelastic strains), and hence to the pre-existing state of stress in rheologically-isotropic rocks. Teufel (1982) presented an anelastic strain recovery technique as a method of determining the directions and ratio of the maximum and minimum horizontal in situ stresses from oriented cores retrieved from deep wells, and confirmed the determined directions to be consistent with the observed

orientations of hydraulic fracture. Additionally, Blanton (1983) developed a theoretical basis for calculating magnitudes of the horizontal principal in situ stresses from recovered anelastic strains, vertical stress (assumed to be equal to the overburden pressure) and Poisson's ratio based on assumptions that the rock is a linearly viscoelastic, isotropic, homogeneous material, and non-aging. According to the two-dimensional method suggested by the fundamental studies mentioned, many applications have extensively been explored in petroleum engineering, etc., for various rocks, such as volcanic tuff (Teufel, 1982), sedimentary rock e.g. sandstone, siltstone, mudstone or shale (Blanton and Teufel, 1983; Teufel, 1983; Teufel and Warpinski, 1984; Owen and Toronto, 1988; Warpinski and Teufel, 1989; Butterworth et al., 1991), limestone (Dey and Kranz, 1988), coals (Warpinski and Teufel, 1989), oceanic basaltic rocks (Brereton et al., 1992), and igneous rocks (Engelder, 1984; Wolter and Berckhemer, 1989; Butterworth et al., 1991). In these cases, vertical stress was assumed to be one of the three principal stresses, and only a two-dimensional measurement was conducted. Subsequently, this method was theoretically extended to a three-dimensional version by Matsuki (1991). However, the three-dimensional method has found few practical applications (Matsuki and Takeuchi, 1993; Ito et al., 1997; Cho et al., 2000). Although many previous studies investigated the anelastic strain and successfully provided some information on in situ stresses, the examples, such as Dey and Kranz (1988), Wolter and Berckhemer (1989), Butterworth et al. (1991), Brereton et al. (1992), Matsuki and Sakaguchi (1995) could not achieve the initial aims i.e. determining the in situ stresses for all or a part of all rocks tested because (i) the measured strains were distinctly influenced by the slow relaxation of pore pressure and/or temperature change, and this resulted in a decrease (contraction) of all or some strain components, or (ii) the quantity of anelastic strain was insufficient for accurate analysis for in situ stress. In all the applications of the ASR method mentioned above, the cores used were obtained from depths which ranged from several hundred meters to about 4 km at deep drill wells. In general, it is considered that the ASR method is more suited for great rather than shallow depth conditions, since the value of anelastic strain may be higher and can be accurately measured at great depths, i.e., at higher stress conditions.

There were many previous studies in which comparison was made between the directions or both the directions and magnitudes of in situ stresses based on ASR measurements and those obtained from hydrofracturing, differential strain curve analysis, core discing, etc., and almost all of them showed a close agreement between the ASR and the results of other methods (Teufel and

Warpinski, 1984; Owen and Toronto, 1988; Warpinski and Teufel, 1989; Perreau et al., 1989). On the other hand, examples of substantial discrepancies are also available (Engelder, 1984; Perreau et al., 1989).

With regard to the mechanism of anelastic strain recovery, Teufel (1989) and Wolter and Berckhemer (1990) found that acoustic emission (AE) accompanied the anelastic strain recovery process and that curves of the cumulative count of AE events vs. elapsed time was very similar to those of the anelastic strain vs. time. In addition, Teufel (1983) and Teufel (1989) noted interesting experimental results of seismic wave velocity which showed that the velocities decreased with the anelastic strain recovered and that amount of velocity decrease had a positive correlation with the strain, i.e. the velocity decrease revealed the maximum value in the same direction as the maximum recovered anelastic strain, and the minimum value in the direction of the minimum strain. These phenomena were interpreted as being a result of the generation of microcracks in the process of anelastic strain recovery. For the examination of mechanism and characterization of anelastic strain recovery for various kinds of rock, a few experimental laboratory studies have been reported in the literature (Rabaa and Meadows, 1986; Matsuki, 1991; Wang et al., 1997). There is no doubt, however, that these studies are neither sufficient nor satisfactory. Thus, it is desirable that more investigations are performed to quantitatively evaluate anisotropy of the anelastic strain recovery for various rock materials, to gather detailed visual evidence of the microcracking that accompanies the strain recovery process, etc.

2.2. An outline of anelastic strain recovery method

As mentioned above, Matsuki (1991) proposed a method for estimating three-dimensional in situ stresses by anelastic strain recovery measurements. For an isotropic viscoelastic material, when the in situ stresses and the pore pressure were released stepwise at $t=0$, anelastic normal strain $\varepsilon_a(t)$ recovered during the elapsed time t in an arbitrary direction, the direction cosines of which were defined as l, m, n corresponding to X, Y, Z axes, is given by the following equation:

$$\varepsilon_a(t) = (1/3) \left[(3l^2-1)\sigma_x + (3m^2-1)\sigma_y + (3n^2-1)\sigma_z \right] \\ + 6lm\tau_{xy} + 6mn\tau_{yz} + 6nl\tau_{zx} \\ \times \text{Jas}(t) + (\sigma_m - p_0)\text{Jav}(t) + \alpha_T \Delta T(t) \quad (1)$$

where $\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx}$ are components of in situ stress tensor, σ_m is constant mean normal stress, p_0 is pore pressure, α_T is linear thermal expansion coefficient, $\Delta T(t)$

is temperature change, and the $Jas(t)$, $Jav(t)$ are the anelastic strain recovery compliances of shear and volumetric deformation modes, respectively. This equation, which provides a basis for the ASR method, suggests that the anelastic strain depends on the in situ stress tensor components, pore pressure, temperature change during the measurement, expansion coefficient and the compliances of both deformation modes. Therefore, if the material constants ($Jas(t)$, $Jav(t)$, α_T), pore pressure and temperature change are known, the six stress components, i.e. three-dimensional in situ stress tensor may be obtained by measuring the anelastic normal strains in at least six independent directions.

For isotropic viscoelastic materials, the directions of the three principal axes of in situ stresses coincide with the directions of the three principal axes of the anelastic strain tensor. Thus, the directions of the three-dimensional principal in situ stresses can be determined by means of calculating the principal directions of the measured anelastic strain data of at least six independent directions. By theoretical examination, it can be proven that the ratios of the principal stress deviatoric components are given by the ratios of the principal anelastic strain deviatoric components (Matsuki, 1992). Here, the stress deviatoric components $s_{1,2,3}$ are defined as differences of principal stresses $\sigma_{1,2,3}$ and constant mean normal stress σ_m , respectively, and the strain deviatoric components $e_{1,2,3}$ are defined similarly. As a result, these principal directions and the ratios of principal stress deviatoric components can be determined without knowing the two compliances, if the rock is thermally and mechanically isotropic.

On the other hand, the magnitude of three-dimensional principal in situ stresses is given as follows:

$$\sigma_i = e_i(t)/Jas(t) + \{e_m(t) - \sigma_T \Delta T(t)\}/Jav(t) + p_0 \quad (2)$$

$$i = 1, 2, 3$$

where $e_i(t)$ denotes the principal strain deviatoric components, $e_m(t)$ is the constant mean normal strain.

Matsuki (1991) proposed a detailed procedure to determine the directions and magnitudes of the three-dimensional in situ stresses. He suggested that the two compliances which are necessary to calculate values of the principal stresses, may be determined by measuring the anelastic strain recovery of the same core sample after it was triaxially compressed and, then, unloaded in laboratory conditions. Additionally, he emphasized that because of the dependence of the shear and volumetric mode compliances on the mean normal stress, previous loading must be taken into consideration in order to ensure the accuracy of the determination of the stresses. However, precisely because of this mean stress dependence, the

calibration tests are usually very complex and require a sufficient number of specimens for the iterative method, since the stress level of the previous loading is not always equal to that of the real in situ stress. In other words, if the stress conditions used in the calibration test differ significantly from the determined stress value, the calibration test must be repeated until the applied and determined stresses become approximately equal.

In general, it is impossible to begin the anelastic strain measurements immediately after the stress release. According to Matsuki (1992), however, notwithstanding the time delay $t=t_0$, the method mentioned above can be applied if only compliances determined for the same elapsed time from t_0 instead of compliances determined for $t=0$ are used. In addition, if the temperature change is controlled within a small range during the anelastic strain recovery measurement, the term of $\alpha_T \Delta T(t)$ in the Eqs. (1) and (2) can be ignored.

3. Specimens and experimental method

3.1. Geology of Niitsu region and rock material

A deep well named METI (Ministry of Economy, Trade and Industry) Niitsu well was drilled in the Niigata Basin, Japan. A map showing the plate boundaries in the vicinity of Japan and the plate motion (Yamasaki and Seno, 2005), a geological map of the Niitsu region (Geological Survey of Japan, 1987) and a west–east cross section around the well site are shown in Fig. 1. The major geological structure and basin development of northeast Japan, including the region pertinent to the present study, has been described by Sato and Amano (1991) and Sato (1994). According to the recent researches (Henry et al., 2001; Mazzotti et al., 2001; Iio et al., 2002; Yamasaki and Seno, 2005, etc.), a deformation–concentration zone with high strain rates along the backarc side of central Honshu (the so-called Niigata–Kobe Tectonic Zone, NKTZ; shown by the shaded area in Fig. 1a) has been observed by means of GPS. The study area of this paper is located in the top portion of NKTZ. In addition, the 2004 mid Niigata prefecture earthquake (Mw6.6) occurred in October 2004; and its epicenter of the mainshock is about 65 km far from the well site. However, according to the Research Group for Active Faults of Japan (1992), there is not an active fault within an area of less than 15 km from the well site.

The maximum measured depth of the METI Niitsu well reached 5000 m MD with an inclination of about 20° and an orientation of about GN125°, and the true vertical depth at the bottom of the well was 4702 m. Where, the MD is the abbreviation of “measured depth”; and means

total length of the drilled well from the ground to the related depth. Four oriented cores were retrieved from the well at depths in a range from about 2400 m MD to 4500 m MD, and the depths will be called DP1–DP4 in

the order of depth in this paper. Using these four oriented cores, anelastic normal strain was measured in six independent directions after the release of the corresponding in situ stresses. The depth from which specimens were

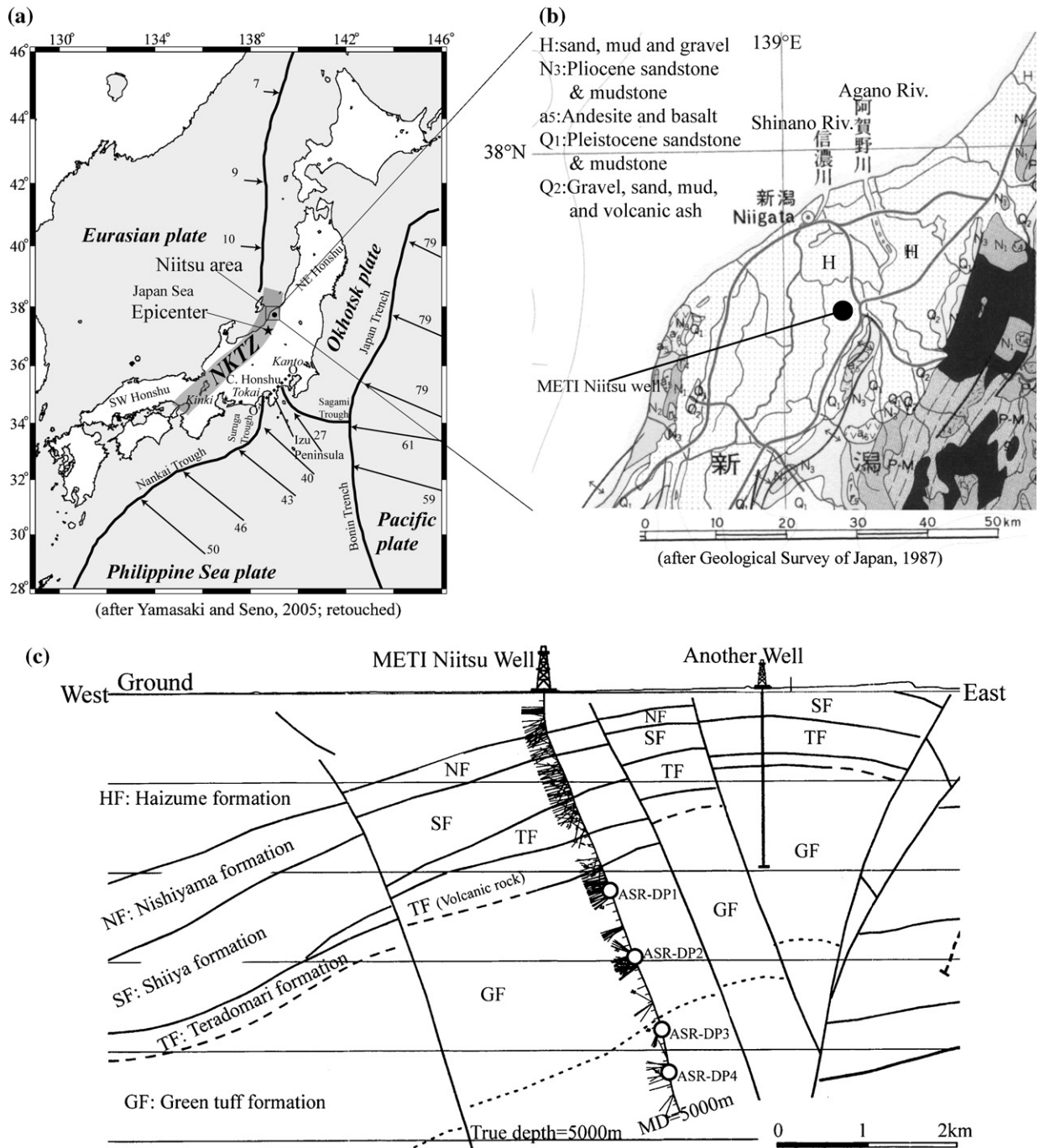


Fig. 1. Geological setting of the survey area: (a) location of the area, plate boundaries around Japan and plate motion (Yamasaki and Seno, 2005), shaded area so-called NKTZ (Niigata-Kobe Tectonic Zone) shows a deformation concentration zone with high strain rates; (b) geological map of Niitsu region (Geological Survey of Japan, 1987); (c) a west–east cross section around the Niitsu well site; circles denoted ASR–DP1, ..., ASR–DP4 show locations (depths) from which samples were taken for the ASR measurements.

taken and used for anelastic strain recovery measurements, rock type of the cores, and fundamental physical properties are listed in Table 1. The rock material taken from the depth of 2381 m MD was mudstone. Except for matrix, its major mineral components were quartz and magnetite, and the grain size was fine, usually less than 0.1 mm. The clay minerals, identified by X-ray diffraction method as being mainly smectite, accounted for about 30% of the whole of the mudstone. The rock material extracted from the depth of 3177 m MD was dolerite. Its major mineral components were plagioclase, clinopyroxenes, altered serpentine minerals and magnetite; the grain size ranged from approximately 0.1 mm to 1 mm. The rock material from 3985 m MD was altered basalt composed mainly of plagioclase, hematite and chlorite; the size of almost all the grains was less than about 0.2 mm. The rock material from the deepest location at 4544 m MD was andesite. Its major mineral components were plagioclase, enstatite, hypersthene and hematite, with the grain size not exceeding about 0.3 mm. The geological age of the four rocks is Miocene.

Dry and wet bulk densities and porosity determined using the water saturation method and the seismic wave velocities and calculated dynamic elastic constants are as shown in Table 1. The densities and porosity were measured on the specimens taken from precisely the same depth as the depth of the specimens for ASR measurements. The cylindrical or cubic specimens used for the seismic wave velocity measurements were taken from depths that were different from the depths of ASR specimens by 2–5 m, but the lithofacies of the specimens for both measurements was macroscopically the same. With respect to the anisotropy of the rocks, as an example, compressional wave velocities

measured in three directions on the cubic specimens obtained from the depth of 4542 m MD, ranged from 4.46 km/s to 4.81 km/s, and shear wave velocities were 2.69–2.96 km/s. Although a slight difference between the velocities in different directions was revealed for the depths of DP3 and DP4, distinct anisotropy of the texture of the cores could not be macroscopically observed. Additionally, in order to obtain a sense for understanding the elastic properties of the rocks, dynamic Young's modulus and Poisson's ratio values were calculated from compressional wave average velocity in three directions and shear wave average velocity using the general equations (Schon, 1998) for isotropic and elastic material. In addition, the seismic velocities were measured on wet specimens under atmospheric pressure and room temperature conditions.

3.2. Preparation of specimens for ASR measurement

At individual depths from DP1 to DP4, oriented cores of about 10 cm in diameter and of about 6–9 m in total length were obtained. As shown in Fig. 2, a homogeneous and crack-free core of 7–8 cm in length was then selected at each depth in order to prepare two specimens for ASR measurements. To shorten the time elapsed from the stress release to the beginning of the ASR measurements, the deeper part of the core was selected, but the deepest 10 cm from the bottom, approximately equal to the diameter of core, was deliberately rejected. However, the core for DP4–S1 and DP4–S2 specimens was selected at a depth separated from the bottom by about 2.5 m due to the presence of fractures and heterogeneity.

As shown in Fig. 3a, the selected core was cut in the orientations corresponding to local *X*, *Y* and *Z* axes. The *Z*

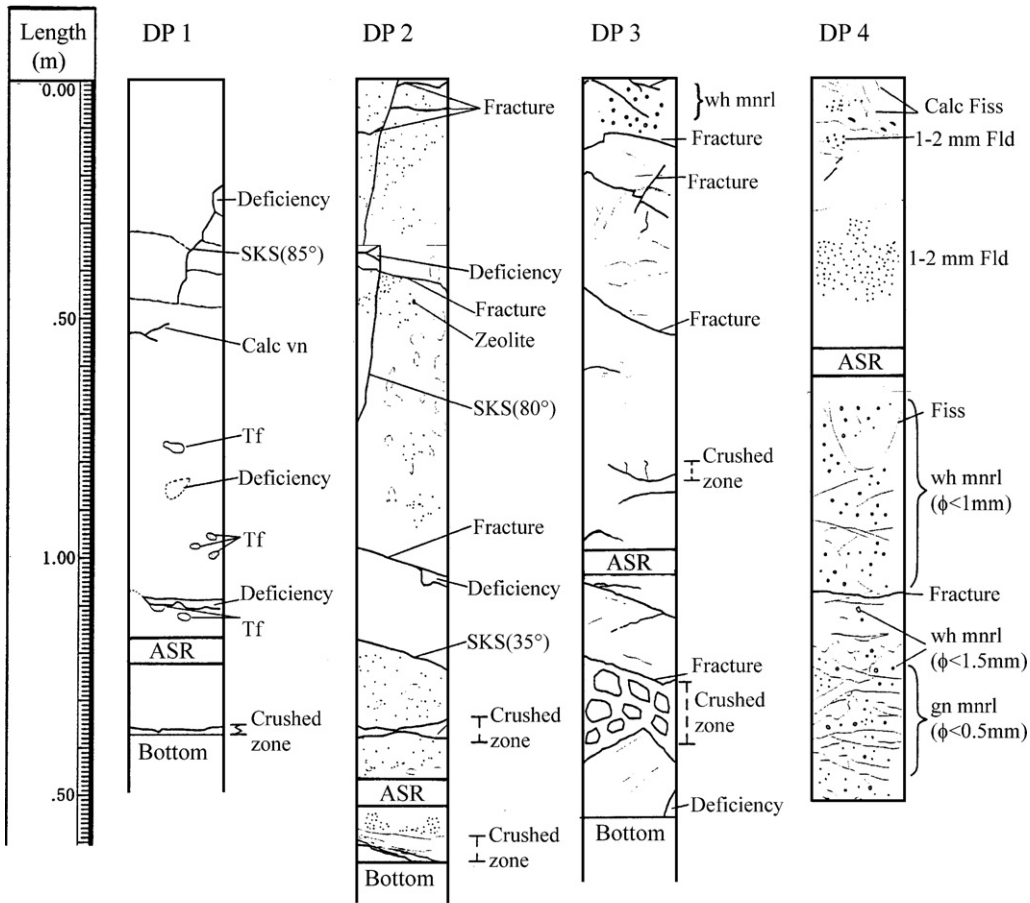
Table 1
List of specimens for ASR measurements and basic physical properties of the rocks

Measured depth of ASR specimens (m)	Symbols of ASR specimens	Rock type	Bulk density ^a (g/cm ³)		Porosity ^a (%)	Seismic wave velocities (km/s) and description of the specimen				Elastic constants calculated from velocities	
			Dry	Wet		MD ^b (m)	Shape of specimen	P-wave	S-wave ^c	Young's modulus (GPa)	Poisson's ratio
2381	DP1–S1 DP1–S2	Mudstone	2.41	2.52	10.5	2379	Cylinder	3.50	1.35	13	0.41
3177	DP2–S1 DP2–S2	Dolerite	2.64	2.74	10.4	3175	Cube	4.63–4.72	2.91–2.94	54	0.20
3985	DP3–S1 DP3–S2	Basalt	2.59	2.62	3.34	3980	Cube	4.63–4.90	2.72–2.91	52	0.25
4544	DP4–S1 DP4–S2	Andesite	2.72	2.73	0.71	4542	Cube	4.46–4.81	2.69–2.96	50	0.19

^a Density and porosity were determined using specimens taken from the same depth as those for the ASR measurements (cf. Fig. 3).

^b MD means the measured depth of the specimens taken from the same depth as those for velocity measurements.

^c Velocities at 2379 m MD were solely measured in a direction parallel to the well axis. The velocities at other depths were measured in three directions, one of which was the well axis, and the values given are the maximum and minimum velocities in three directions.



ASR: core used for ASR measurement; Calc vn: calcite vein; Tf:tuff; SKS:slickenside; Fiss:fissure; wh mnrl: white mineral grain; gn mnrl: green mineral grain; Fld:feldspar .

Fig. 2. Sketches of the cores retrieved from the well, showing the location samples used for the ASR measurements and structural features of the pre-existing fractures, etc.

axis was parallel to the well axis, and the *X* and *Y* axes were properly defined by referring to the three streaks of core-orientation tools. The flat surfaces of the three planes cut perpendicularly to each other were smooth enough,

and grinding was not necessary. In the humidity conditions of the field laboratory, surfaces of the specimens quickly dried, and attained an air-dry state, while lines were being drawn on the specimens to determine the location and

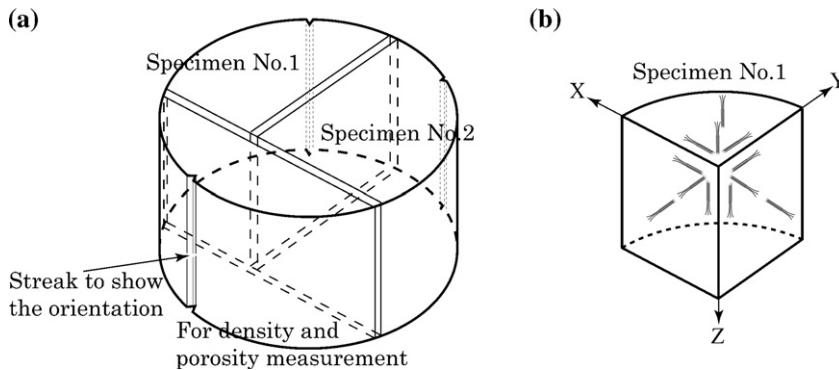


Fig. 3. Layout of specimens cut from an oriented core (a) and orientation of strain gauges mounted on a specimen prepared for the ASR measurements (b).

orientation of strain gauges, i.e. before mounting the strain gauges. A rosette type wire strain gauge and a single gauge were mounted onto each of the three perpendicular planes, i.e., for six independent directions two strain gauges were used (cf. Fig. 3b). To avoid the influence of temperature change on the resistivity of the lead wire of the gauges, three-wire gauges and a corresponding bridge circuit were employed. In addition, the strain gauges used can partially compensate for the influence of thermal expansion of measuring object for temperature change, i.e., the gauges have a negative apparent strain output of $-11 \times 10^{-6}/^{\circ}\text{C}$ (called self-compensation coefficient in this paper) as the temperature increases in non-deformation conditions.

After wrapping the specimens in vinyl sacks, the specimens were immersed in mixed silicone rubber of two-liquid type to prevent changes in the pore water content.

3.3. The anelastic strain measurement system

The apparatus for ASR measurements is schematically shown in Fig. 4. Strain data from two active specimens and a dummy granite specimen, which does not undergo any deformation except thermal expansion, for monitoring the drift of the system, were acquired. Since we had to prepare the dummy specimen before the cores for active specimens were retrieved, and did not have reliable information about the lithology of the cores beforehand, we prepared the dummy specimen using a granite the same as the expected basement rock in this area, although, no doubt, it would be better to use the same rock material as that undergoing the anelastic strain recovery. All the specimens were placed in a constant temperature chamber filled with tap water, controlled by a heater containing a water circulation system and a regulator. In this apparatus, the required or

target constant temperature must be set at a higher level than room temperature, since the apparatus does not have a cooling function.

The lead wires of the strain gauges and cables of five thermocouples (three thermocouples measuring temperature on the surface of the specimens, one measuring water temperature and one measuring room temperature) were directly connected to a data acquisition controller with a 16-bit A/D converter, and digital strain and temperature data were forwarded to a personal computer and recorded every 5 min. It took about 3–6 h to elevate the core from the depths to the surface for the different depths of DP1–DP4, and 2 h were required to prepare the specimens and set them in the apparatus. For example, the strain measurement on the DP4 specimens began about 8 h after the extraction of the core and stress release. Duration of measurements on specimens taken from the depths DP1–DP3 varied between 1 and 2 weeks, whereas the measurements on specimens DP4 (the last ones from the series of four) could be continued much longer, for about 50 days.

4. Results of the permanent strain measurement

4.1. Anelastic strain recovery

As examples of original measurement results, relations between the anelastic strain and elapsed time obtained for two DP4 specimens are shown in Fig. 5. The anelastic strains in all directions of both specimens were extensions. It should be noted however, that both specimens contracted in all directions for about 3 h after measurements began. This temporary contraction behavior can be explained by the slow relaxation of pore pressure, as suggested by Breteron et al. (1995).

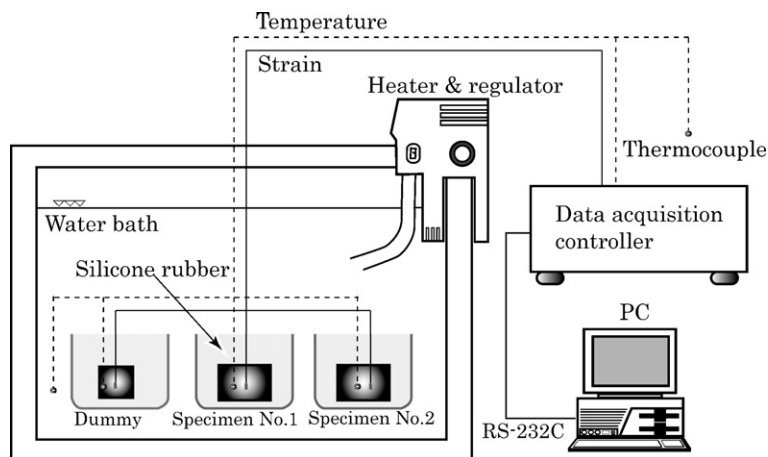


Fig. 4. Schematic diagram of anelastic strain recovery measurement system.

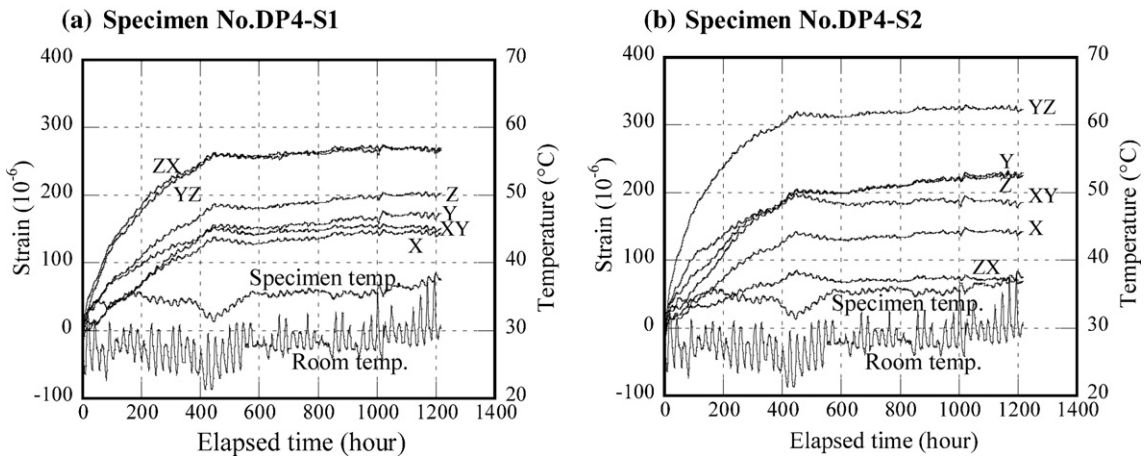


Fig. 5. Anelastic strain and temperature vs. time (letters X, Y, XY, etc., indicate the directions of strain measurement, cf. Fig. 2b).

During the experiment on the DP4 specimens, the thermostatic chamber did not work properly. As a result, the temperature of the specimen measured by a thermocouple mounted on surface of the specimen varied from approximately 32 °C to 38 °C. As shown in Fig. 6, the output of a strain gauge mounted on the dummy granite specimen which deformed solely due to thermal expansion decreased with the temperature increase, i.e., the output showed an opposite trend to the thermal expansion of the dummy specimen. This effect obviously occurred due to the fact that the self-compensation coefficient ($11 \times 10^{-6}/^{\circ}\text{C}$) of the strain gauge was larger than the linear thermal expansion coefficient of the dummy specimen used. According to Skinner (1966), the linear thermal expansion coefficient of granite was $8 \pm 3 \times 10^{-6}/^{\circ}\text{C}$; the coefficient of andesite was $7 \pm 2 \times 10^{-6}/^{\circ}\text{C}$.

Consequently, the difference in the coefficients of thermal expansion of both rocks is considered not to be

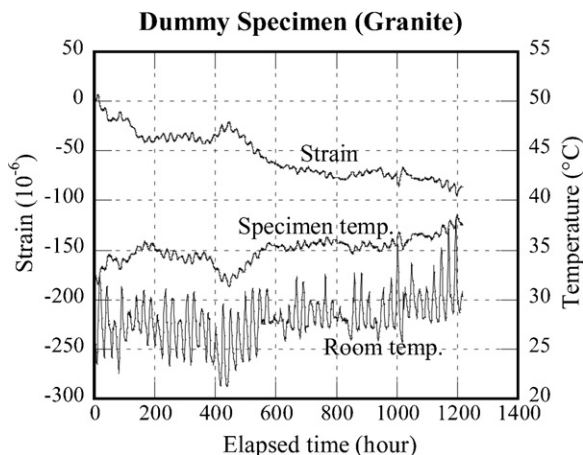


Fig. 6. Strain of a dummy specimen and temperature vs. time.

significant, and the influence of the temperature change on the anelastic strain can be corrected by subtracting the apparent strain (cf. Fig. 6) of the dummy specimen from the measured strain (cf. Fig. 5a and b) of the active specimens. As a result, the two sets of anelastic strain curves corrected are shown in Fig. 7. From a comparison of Fig. 5 with Fig. 7, it is obvious that compensation for thermal effects using the strain data from a dummy specimen could rectify somewhat distinct error, such as that encountered in the vicinity of about 450 h, but could not rectify perfectly the small variations caused by room temperature changes during a 24-h period of time. Should the lithofacies of a dummy specimen be the same as lithofacies of the core retrieved for the ASR measurements, the effect of correction for the temperature effect would be better.

While comparing the general character of the strain recovery process in the two specimens that were cut from the same core (cf. Fig. 3), it was found that the shape of strain–time curves, the magnitude of the strain in same direction and the order of the anelastic strain magnitude in the six directions, were approximately similar (cf. Fig. 7 or Fig. 5). Therefore, it is believed that the anelastic strain data were correct in a qualitative sense at least.

For the DP4 specimens, the anelastic strain recovery in all directions continued over a long period of time, although the rate of strain recovery decreased with time. The magnitude of the strains in various directions, which were continuously measured for 3 weeks or more, achieved several hundred microstrains. Of course, the magnitude of anelastic strain was dependent on the rock materials and the in situ stress level. In the four rocks tested in this study, the strains of mudstone (DP1) were the highest, reaching about 1000–3000 microstrains

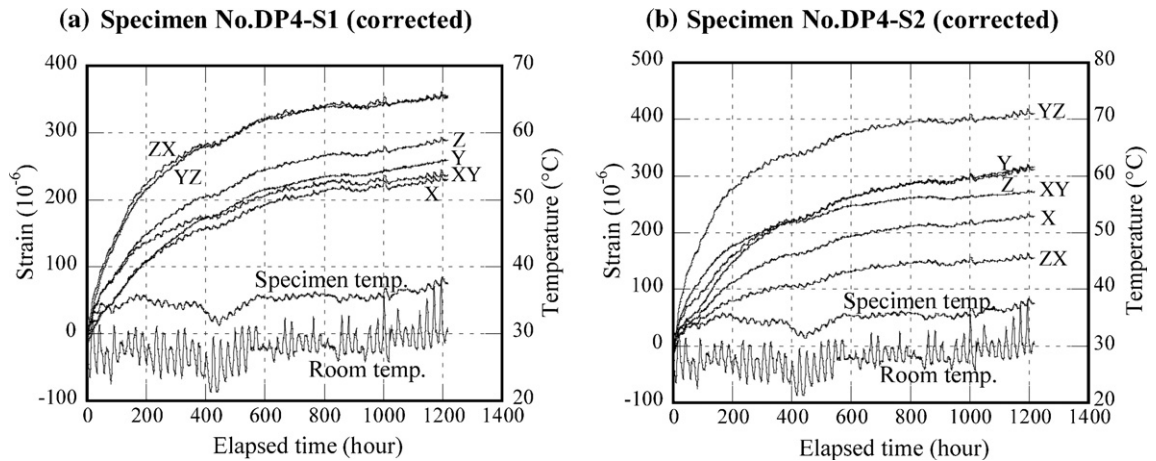


Fig. 7. Anelastic strain corrected for temperature change and temperature vs. time (letters X, Y, XY, etc., indicate the directions of strain measurement, cf. Fig. 2b). The original measured data are the same as shown in Fig. 5.

corresponding to various directions; the strains of dolerite (DP2) were 500–1000 microstrains. The anelastic strain level of basalt (DP3) was about same level as that of andesite (DP4). For the measurement accuracy of the system used, this strain level was high enough and the data could be used for a three-dimensional analysis to determine the directions of three principal axes of in situ stresses and the ratio of three principal stress deviations.

After anelastic strain measurements, the specimens used were macroscopically examined. The specimens of DP2–DP4 did not display any changes; whereas a great number of cracks were seen in the two specimens of mudstone (DP1). The photograph shown in Fig. 8 was taken while the rock was in the process of drying; the narrow cracks could therefore be distinctly

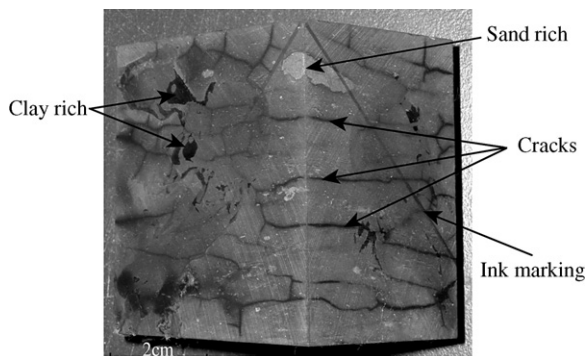


Fig. 8. Photograph of a mudstone specimen (DP1–S2) after the ASR measurement, showing the cracks which might be formed during the anelastic strain recovery. In fact, the cracks were quite narrow; however, they could not be observed on neither wet nor dry rock surfaces. This photograph was taken while the rock was in the process of drying; the narrow cracks could therefore be distinctly identified.

identified. The reason for this is that water content in the vicinity of cracks was higher than in other places, making the cracks appear wider. In fact, the cracks were quite narrow; however, they could not be observed on both wet and dry rock surfaces. This microcracking phenomenon can be explained by the mechanism that was discovered and proposed by Teufel (1989), Wolter and Berckhemer (1989), Barr and Hunt (1999).

4.2. Determination of the directions of the three principal in situ stresses

From the measured anelastic normal strains in six independent directions, the anelastic strain tensor was calculated employing least squares analysis for an arbitrary time that elapsed from the beginning of the anelastic strain measurement. Furthermore, the mean normal strain, the three anelastic principal strain deviatoric components, and a direction cosines (or trend and plunge) data set of the directions of three principal strains corresponding to the time can be determined by the same analysis procedure as described by Matsuki and Takeuchi (1993). Thus, a principal direction data series according to the elapsed time was obtained. At an early stage of the whole measurement period, the determined principal directions scattered significantly, because the ratios of the strain deviations were unstable when the major principal strain deviation, i.e. the denominator in the ratio, was small. This feature was also observed by Matsuki and Takeuchi (1993). Therefore, the average of the plunges and trends of the three principal directions were calculated using the data corresponding to only the part of the whole measurement

period where the data was stable. As previously explained, the three directions of the principal anelastic strain must be the same as the three directions of the principal in situ stresses.

The principal directions determined for the specimens retrieved from four depths are shown in Fig. 9 as a lower hemispherical projection using the equal area method. The original anelastic strains measured on DP1–DP3 were used for the analysis; whereas the strains corrected for temperature change (cf. Fig. 7) were used for DP4. In the figure, the average principal directions determined for the two specimens were plotted together with the directions determined separately for each of them at the respective depth. However, this average principal direction is not an arithmetical one of the two directions, but is a principal direction of the averaged stress tensor of the two respective stress tensors. In order to correctly average two stress tensors, these tensors must be transformed to a common set of reference axes before arithmetically averaging the components of two tensors in the same axial direction (Hudson and Harrison, 1997). Therefore, the averaged

direction does not always include the center between the two plots corresponding to the two specimens.

As shown in Fig. 9, the principal directions determined based on the results of ASR measurements carried out on specimen S1 and specimen S2 at individual depths DP1–DP4 were in agreement with each other. Therefore, it can be considered that the anelastic strain measurements had repeatability and reflected the in situ stress state of the rock cores approximately. It should be noted however, that the directions of the minor and of the intermediate principal stress at DP4 location have not been unequivocally established. The relation between the plunges of average directions of principal stresses (inclination of the stress from horizontal plane) and measured depth is shown in Fig. 10. In this figure, the trend that the plunge of major principal stress decreases as the depth increases should be noted. In other words, this trend suggests that the effect of gravity on rock stress is relatively strong at shallow depths. However, the effect of tectonic stress, thought to be mainly caused by subduction of the Pacific plate (cf. Fig. 1a), is enhanced as the depth increases.

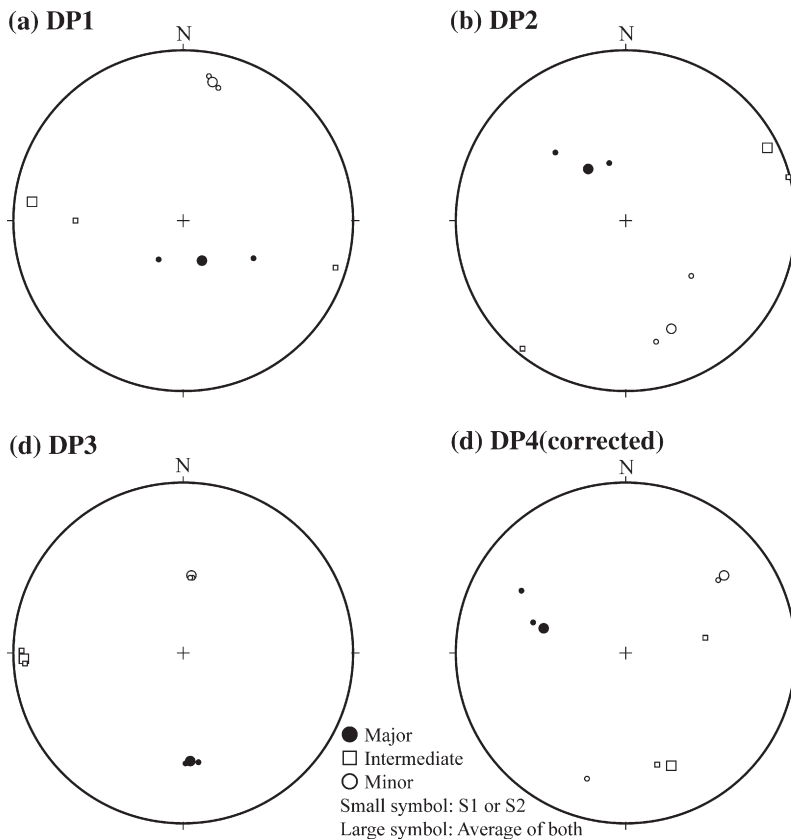


Fig. 9. Three principal directions of DP1–DP4 shown on the stereographic net of the lower hemisphere by equal area method.

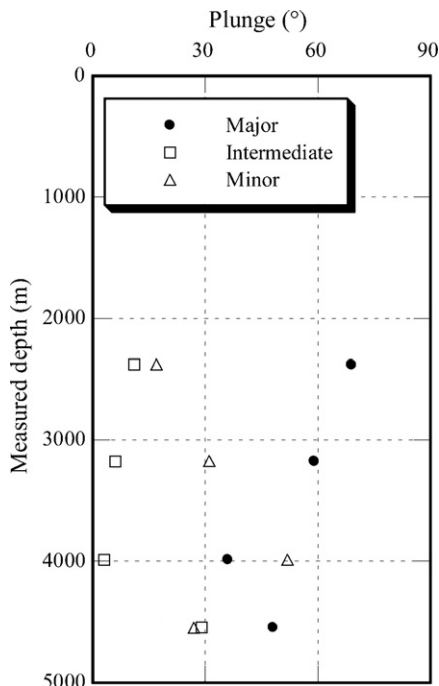


Fig. 10. Plunge of three principal stresses vs. measured depth.

It is noteworthy that published data are available on the direction of maximum horizontal compressive stress in the Niigata Prefecture or a wider region which contains the Niitsu region (the over-coring method, Kanagawa et al., 1986; the stress relief method, Tanaka, 1986; the focal mechanism, Zoback et al., 1989). The directions of maximum horizontal stress given in all these papers are almost the same, and are oriented to the northwest–west or northwest. On the other hand, the principal stress directions at DP4 determined by ASR was agreement with the sense of the fault slipped during the mainshock of the 2004 mid-Niigata prefecture earthquake which has focal mechanism of the reverse fault type with a strike of approximately N35E and a dip of approximately W50 (Kato et al., 2005). In addition, the direction of maximum horizontal stress coincides with the principal axis of horizontal tectonic contracted strain in the same region (Nakane, 1973). These features can be related to the tectonics of this region (cf. Fig. 1a). It can therefore be concluded that major principal stress at DP4 may correctly indicate the direction of the tectonic stress; whereas the principal directions calculated for DP3 may indicate a local stress state of the core and its surrounding area due to the presence of a great number of fractures at this location (cf. Fig. 2). Finally, the results obtained for DP2 and DP1 seem to be reasonable despite many fractures that existed in the vicinity of these locations.

4.3. Prediction of the magnitudes of the three principal in situ stresses

As proposed by Matsuki (1991), in order to determine correctly the magnitude of the three principal in situ stresses, anelastic strain recovery compliances of volumetric mode and of shear mode must be examined based on anelastic strain measurements taken on unloaded rock specimens that were first kept for some time under constant differential stress conditions. However, these calibration tests are very complex and require a great deal of time and effort, since the compliances depend on mean stress. Therefore, a simpler method was employed in the present study to predict the magnitude of the three principal in situ stresses.

Based on two assumptions, i.e., (i) vertical in situ stress is equal to density-related gravitational overburden stress, (ii) the ratio of anelastic strain recovery compliance of shear deformation mode and the compliance of volumetric deformation mode is a constant, the compliances can be calculated based on the measured values of anelastic strain $e_i(t)$ and $e_m(t)$ using Eq. (2) and following Eq. (3) for an arbitrary elapsed time t , if the temperature change during the anelastic strain measurement was negligible and can be ignored.

$$\sigma_v = l_p^2 \sigma_1 + m_p^2 \sigma_2 + n_p^2 \sigma_3 \quad (3)$$

where σ_v is normal stress in the vertical direction, related to the weight of the overburden, l_p , m_p , n_p are the direction cosines of vertical vector corresponding to the three coordinate axes of principal stresses. Therefore, the values of the three principal stresses can be calculated using Eq. (2) based on the estimated compliances, anelastic strain, etc.

According to the unpublished laboratory test data for various rocks of Matsuki, the ratio of shear mode compliance and volumetric mode compliance assumes values within the range of 1–3, and it was assumed to be equal to 2 in the present study. The values of the three principal stresses results estimated based on the ASR measurements carried out at four depths are listed in Table 2.

5. Discussion

5.1. Influence of temperature changes

It is important to keep the temperature constant during the anelastic strain recovery measurements. In

Table 2
Estimated values of three principal in situ stresses

Specimen	Measured depth (m)	Normal stress in vertical direction (MPa)	p_0 (MPa)	Major principal stress (MPa)	Intermediate principal stress (MPa)	Minor principal stress (MPa)
DP1–S1				50	45	41
DP1–S2	2381	48	22	49	42	37
Average				49	44	39
DP2–S1				71	59	55
DP2–S2	3177	67	30	75	74	62
Average				72	67	59
DP3–S1				134	124	64
DP3–S2	3985	88	37	118	114	66
Average				129	118	63
DP4–S1C ^a				106	105	91
DP4–S2C ^a	4544	103	43	111	101	91
Average				110	98	94

^a Results were calculated from corrected anelastic strain data (cf. Fig. 7).

general, the accuracy of estimating the in situ stresses cannot be ensured by using the apparent anelastic strain that contains some deformation due to thermal expansion. However, if the thermal properties of rock material are isotropic, the influence of thermal expansion affects only the constant mean strain and has no effect on the strain deviation tensor. As mentioned above, the directions of principal stresses are equal to those of the principal strain deviations; temperature changes have no effect on the determination of the directions of principal stresses. However, the magnitudes of the principal stresses calculated by using the absolute values of anelastic strain and two anelastic strain recovery compliances will be affected.

By using the original, measured values of anelastic strains (Fig. 5) and the data corrected for temperature variations which were obtained by subtracting the strain of a dummy specimen (Fig. 7), the directions and magnitudes of three principal in situ stresses were estimated as shown in Table 3. Notwithstanding whether original or corrected data were used, the direction parameters of trend and plunge determined for DP4–S1 and DP4–S2 specimens were

perfectly equal at the significant digit as shown in the table. Of course, this result was obtained because the corrected values of strains in all directions were calculated by subtracting the same dummy strain, i.e. it was assumed that thermal expansion would be entirely isotropic. However, it should be noted that the average directions derived from original and corrected data were different, because calculating the average was done based on the magnitudes of six stress components. On the other hand, with respect to the magnitudes of stresses of the DP4–S1, S2 specimens and the average stress magnitudes of both the specimens, the values estimated from the original and corrected strains revealed small differences. However, it can be said that the anelastic strains, the estimated directions and the magnitudes of three principal in situ stresses were not affected critically by temperature variations, since the thermal properties of the rock material tested were treated as an isotropic material and strain gauges used could automatically compensate for a part of resistance changes caused by temperature changes.

Of course, there is no doubt that keeping the temperature constant is of utmost importance. In general

Table 3
Comparison of two data sets of the principal in situ stresses calculated respectively from the original anelastic strains and the strains corrected for temperature change

Specimen	Strain data	Major principal stress			Intermediate principal stress			Minor principal stress		
		Trend (deg)	Plunge (deg)	Magnitude (MPa)	Trend (deg)	Plunge (deg)	Magnitude (MPa)	Trend (deg)	Plunge (deg)	Magnitude (MPa)
DP4–S1	Original	301	29	108	79	50	106	197	23	87
	Corrected			106			105			91
DP4–S2	Original	288	42	114	164	32	101	52	31	86
	Corrected			111			101			91
Average	Original	291	45	112	145	39	96	40	18	91
	Corrected	287	48	110	158	29	98	52	27	94

however, ASR measurement must be done at the drilling site, and the various conditions such as the thermal insulation of the laboratory, usually constructed as a temporary quarters, are unsatisfactory. Therefore, in the laboratory, the temperature in a limited space, e.g. in a chamber in which the specimens are set should be controlled constantly, and the accuracy and efficiency of temperature control in an apparatus using water as thermal exchange media would normally be better than in air. Additionally, in the case of water, concerns about the specimen drying are not warranted. Thus, a constant temperature chamber with both heating and cooling functions to control the water temperature with a high degree of accuracy (± 0.1 °C), is believed (considered) to be the best constant temperature keeping device.

5.2. Effect of assumptions about the ratio between volumetric and shear deformation mode compliances

When estimating the magnitude of principal in situ stresses without first calibrating both the anelastic strain recovery compliances of volumetric deformation mode and shear deformation mode, a simplifying assumption is needed that the ratio of the two compliances is equal to a constant ($J_{as}(t)/J_{av}(t) = \text{constant}$). In addition, an assumption is normally made that the vertical stress is equal to the overburden pressure. According to the unpublished data of Matsuki, values of the ratio of the two compliances determined based on laboratory experimental tests on seven rocks (sandstones, tuffs and granite) fall in a relatively narrow range from about 1 to 3. In general, however, the ratio is not a constant, as it may be affected by lithofacies, by mean normal stress, etc.

To examine the effect of variation of $J_{as}(t)/J_{av}(t)$ on the estimated magnitudes of principal stresses, a simulation to

obtain the relation between the stress values and the $J_{as}(t)/J_{av}(t)$ ratio was made. As an example, the simulated results on DP4–S1 and S2 specimens are shown in Fig. 11. From the results, it was found that the estimated magnitudes of principal stresses are not sensitive to the variation of the $J_{as}(t)/J_{av}(t)$ ratio. Consequently, in a case where compliance calibration test cannot be carried out, it is considered to be reasonable to use this assumption to estimate the magnitudes of in situ stresses, especially if it is taken into account that the stress state data obtained using core-based methods may be easily affected by fracture, faults, etc., existing in the vicinity of the core.

In addition, a tendency was observed based on the simulation results that the major stress decreased and the minor stress increased with an increase in $J_{as}(t)/J_{av}(t)$, i.e. the maximum shear stress $((\sigma_1 - \sigma_3)/2)$ and the principal stress ratio (σ_1/σ_3) decreased.

5.3. Comparisons between the stresses determined by ASR and other methods

At the same well site, differential strain curve analysis (DSCA) and extended leak-off test (ELOT) were applied as other in situ stress measurement methods. The first one is a core-based three-dimensional method which consists in applying hydrostatic pressure to a cubic specimen cut from an oriented core and monitoring, as the hydrostatic pressure is increased, the deformation caused by the closure of microcracks which are assumed to be generated due to the in situ stress relief. The DSCA tests were conducted on the DP1–S1 and S2 specimens used for the ASR measurements, whereas different specimens, taken from depths that were by 1–5 m apart from the location of cores used for the ASR tests, were used at DP2–DP4. Comparison of

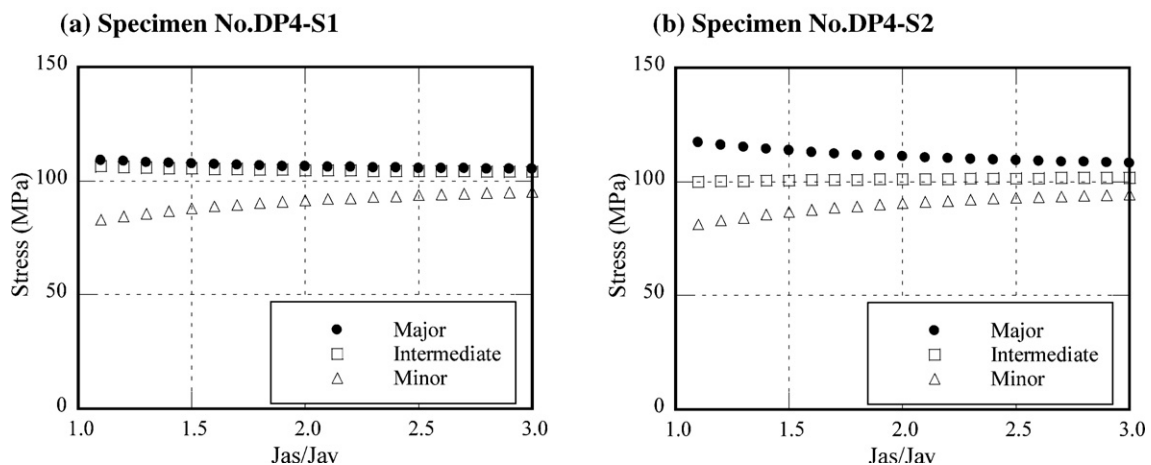


Fig. 11. Estimated in situ stress magnitude vs. the ratio of compliance of shear deformation mode and compliance of volumetric deformation mode.

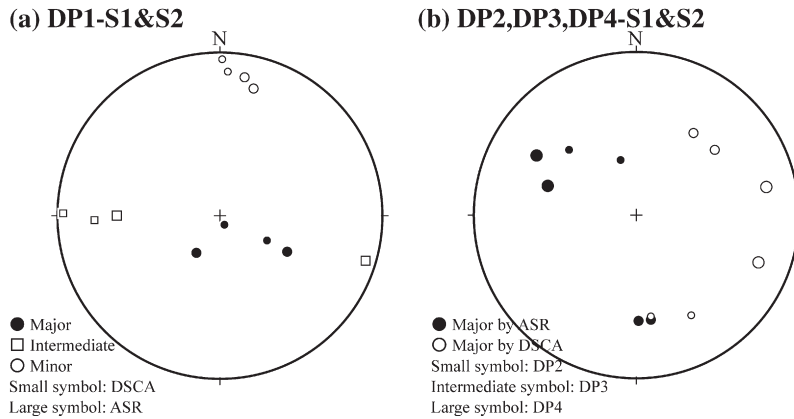


Fig. 12. Comparison of the principal directions of in situ stresses determined using ASR and DSCA methods. The results of ASR and DSCA shown in (a) were obtained using the same specimens, whereas in (b) they were obtained using different specimens taken from different depths within a distance of about 1–5 m.

the directions of three principal axes of in situ stress determined by DSCA and ASR methods on the DP1 specimens is shown in Fig. 12(a), and comparison of the directions of major stress obtained using both methods on the DP2–DP4 specimens is shown in Fig. 12(b). Both the data sets of directions at DP1 showed a very good agreement. Therefore, it can be concluded that the two measurements corroborated each other. However, at DP2–DP4 the directions determined using the two methods did not show a good coincidence. The reasons can be given as follows: (i) the results of DSCA might be affected by pre-existing microcracks unrelated to the in situ stresses, i.e. the crack-closure strains measured with the increase in hydrostatic pressure were not only those induced by the closure of microcracks corresponding to in situ stress removal but also those induced by the pre-existing microcracks (Oikawa et al., 2003) and, (ii) the specimens used for the DSCA and the ASR measurements were taken from different depths.

The extended leak-off tests were performed at the same well, and the magnitudes of minimum principal in situ stress in the two-dimensional plane perpendicular to the well axis at three depths in a range of about 1500–3700 m MD were determined. However, the orientation of fracture induced by ELOT, the normal vector of which is parallel to the direction of minimum principal stress, was not determined.

To analyze the ASR, DSCA and ELOT measurement results, Imamura et al. (2003) compared the minimum stress value obtained from the ELOT and the maximum and minimum principal stresses obtained by ASR and DSCA measurements in the same plane (Fig. 13). It can be concluded that the values of the minimum principal stress in the plane determined in the present study agree with those derived from the ELOT. Additionally, the

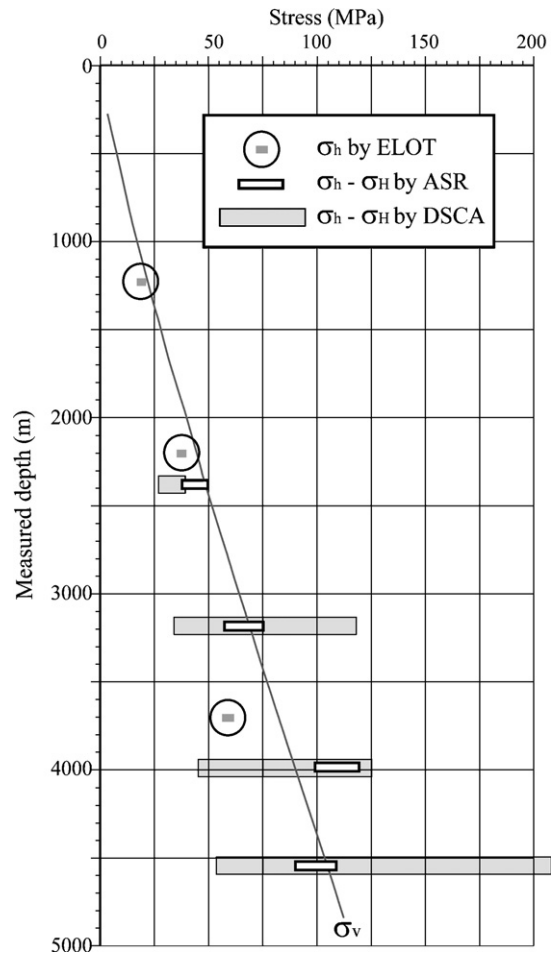


Fig. 13. Comparison of the magnitudes of in situ stresses in the plane perpendicular to the well axis obtained by ASR, ELOT and DSCA methods.

principal stress values predicted by the ASR measurements at individual depths ranged between maximum and minimum principal stresses which were independently determined by DSCA using cores extracted at nearly the same depths.

6. Conclusions

In order to determine three-dimensional in situ stresses, anelastic strain recovery was measured using wire strain gauges in six independent directions on four oriented cores after they were detached from their parent rock mass. The core specimens used were taken from depths of 2381–4544 m MD in the METI Niitsu well in Japan, and the rock materials were mudstone, dolerite, basalt and andesite. The anelastic strains obtained in all directions of all the specimens were expansional; their values were high enough for an accurate three-dimensional analysis of the principal in situ stresses.

Determined principal directions of in situ stresses at all depths, with exception of the depth at which the anelastic strain was distinctly influenced by pre-existing fractures in vicinity of the core, were reasonably consistent and in agreement with those determined for the same region based on other in situ measurements. Additionally, in the case where the same specimens were used for the ASR and DSCA measurements, the principal directions determined by both methods showed a good coincidence. The measurement results of rock stress in Niitsu region showed that the inclination of the major principal stress direction to the horizontal plane decreased as depth increased. This trend suggested that the effect of gravity on rock stress is relatively strong at shallow depths. However, the effect of tectonic stress is enhanced as the depth increases.

On the other hand, the values of the minimum principal stress in the plane perpendicular to the well axis determined in this study were in agreement with those determined based on extended leak-off tests conducted at the same well. Additionally, the predicted principal stress magnitudes by the ASR method ranged between the major and minor principal stresses that were independently determined by DSCA using cores extracted at nearly the same depths in the same well. Therefore, it can be said that the anelastic strain recovery measurement may be well suited for use to directly determine the three-dimensional directions of principal in situ stresses and to estimate the magnitude of the stresses at great depths such as those encountered when drilling deep into a submarine seismogenic zone.

At present, determination of the principal directions of in situ stresses and prediction of the magnitudes of the stresses using the ASR method are based on the

assumption of the isotropy of the anelastic strain recovery characteristics of the rock materials sampled. However, the majority of rocks, and sedimentary rocks in particular, are not completely isotropic. Therefore, it would be of the utmost importance to undertake in future experimental studies on the anisotropy of the anelastic strain recovery and develop a method that would enable this anisotropy to be taken into account when analyzing the ASR measurement results.

Acknowledgements

The authors are pleased to acknowledge the Japan Oil, Gas and Metals National Corporation (JOGMEC) for granting permission to publish this paper. We also thank T. Nakamura of Dia Consultants Co. Ltd., Japan for his assistance in the ASR measurement works, T. Yamasaki of NIPR, Japan for kindly providing of original figure used for Fig. 1(a) and Y. Oikawa of AIST, Japan, K. Yamamoto of JOGMEC, Japan for their informative discussions and helpful suggestions. In addition, a part of this work was supported by Grant-in-Aid for Scientific Research (C: 16540392) of the Japan Society for the Promotion of Science (JSPS), Japan.

References

- Amadei, B., Stephansson, O., 1997. *Rock Stress and Its Measurement*. Chapman & Hall, London.
- Barr, S.P., Hunt, D.P., 1999. Anelastic strain recovery and the Kaiser effect retention span in the Carrmenellis granite, U.K. *Rock Mech. Rock Eng.* 32 (3), 169–193.
- Blanton, T.L., 1983. The relation between recovery deformation and in-situ stress magnitudes. SPE/DOE paper 11624, SPE/DOE Symp. on Low Permeability, Denver, Colorado, pp. 213–218.
- Blanton, T.L., Teufel, L.W., 1983. A field test of the strain recovery method of stress determination in Devonian shale. SPE paper 12304, SPE Eastern Regional Meeting, Champion, Pennsylvania, pp. 71–80.
- Brereton, N.R., Chroston, P.N., Evans, C.J., Hudson, J.A., Whitmarsh, R.B., 1992. Anelastic strain recovery and elastic properties of oceanic basaltic rocks. *Proc. Ocean Drilling Program, Scientific Results*. 123, ODP, Texas A&M Univ., TX, pp. 469–491.
- Brereton, N.R., Chroston, P.N., Evans, C.J., 1995. Pore pressure as an explanation of complex anelastic strain recovery results. *Rock Mech. Rock Eng.* 28 (1), 59–66.
- Butterworth, S.R., Chroston, P.N., Davenport, C.A., Brereton, N.R., Evans, C.J., 1991. Anelastic strain recovery of rock core from the English Midlands. In: Roegiers, J.-C. (Ed.), *Rock Mechanics as a Multidisciplinary Science*. Balkema, Rotterdam, pp. 55–62.
- Cho, A., Xue, Z., Takahashi, M., 2000. In-situ stress measurements in Tsukuba deep borehole. *J. Jpn. Soc. Eng. Geol.* 41 (1), 41–47 (in Japanese, with English Abstr).
- Dey, T.N., Kranz, R.L., 1988. State of stress and relationship of mechanical properties to hydrothermal alteration at Valles Caldera Core Hole 1, New Mexico. *J. Geophys. Res.* 93 (B6), 6108–6112.

- Engelder, T., 1984. The time-dependent strain relaxation of Algerie granite. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* 21 (2), 63–73.
- Geological Survey of Japan, 1987. 1:1,000,000 Geological Map of Japan – Geological Atlas of Japan (1982). Second Printing (Copy), Geological Survey of Japan, Tsukuba, Japan.
- Henry, P., Mazzotti, S., LePichon, X., 2001. Transient and permanent deformation of central Japan estimated by GPS: 1. Interseismic loading and subduction kinematics. *Earth Planet. Sci. Lett.* 184, 443–453.
- Hudson, J.A., Harrison, J.P., 1997. In situ stress. *Engineering Rock Mechanics – An Introduction to the Principles* (Chapter 4). Pergamon, Oxford, pp. 41–70.
- Iio, Y., Sagiya, T., Kobayashi, Y., Shiozaki, I., 2002. Water-weakened lower crust and its role in the concentrated deformation in the Japanese Islands. *Earth Planet. Sci. Lett.* 203, 245–253.
- Imamura, T., Kawamoto, T., Yamamoto, T., Lin, W., Oikawa, Y., Nakamura, T., 2003. Structure interpretation using stress measurement in the METI Niitsu well. *Proc. Japan Ass. Petro. Tech. Annual Meeting Chiba, Japan*, p. 30 (in Japanese).
- Ito, H., Nishizawa, O., Xue, Z., Sano, O., 1997. Estimation of in-situ stresses from ASR and DSCA measurements on drilled cores in the 1995 Hyogoken-nambu earthquake source region. In: Sugawara, K., Obara, Y. (Eds.), *Rock Stress*. Balkema, Rotterdam, pp. 355–358.
- Kanagawa, T., Hibino, S., Ishida, T., Hayashi, M., Kitahara, Y., 1986. In situ stress measurements in the Japanese Islands: over-coring results from a multi-element gauge used at 23 sites. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* 23 (1), 29–39.
- Kato, A., Kurashimo, E., Hirata, N., Sakai, S., Iwasaki, T., Kanazawa, T., 2005. Imaging the source region of the 2004 mid-Niigata prefecture earthquake and the evolution of a seismogenic thrust-related fold. *Geophys. Res. Lett.* 32, L07307, doi:10.1029/2005GL022366.
- Matsuki, K., 1991. Three-dimensional in-situ stress measurement with anelastic strain recovery of a rock core. In: Wittke, W. (Ed.), *Proc. 7th Int. Congr. Rock Mech.*, Aachen, vol. 1, pp. 557–560.
- Matsuki, K., 1992. Theoretical examination of the method for measuring three-dimensional in-situ stresses with anelastic strain recovery of rock core. *J. Min. Mater. Process. Inst. Jpn.* 108 (1), 41–45 (in Japanese with English Abstr).
- Matsuki, K., Sakaguchi, K., 1995. Comparison of the results of in-situ stresses determined by core-based methods with those by overcoring technique. In: Matsuki, K., Sugawara, K. (Coordinators), *Proc. Int. Workshop on Rock Stress Measurement at Great Depth*, Tokyo, Japan, pp. 52–57.
- Matsuki, K., Takeuchi, K., 1993. Three-dimensional in-situ stress determination by anelastic strain recovery of a rock core. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* 30 (7), 1019–1022.
- Mazzotti, S., Henry, P., LePichon, X., 2001. Transient and permanent deformation of central Japan estimated by GPS: 2. Strain partitioning and arc–arc collision. *Earth Planet. Sci. Lett.* 184, 455–469.
- Nakane, K., 1973. Horizontal tectonic strain in Japan (II). *J. Geodyn. Soc. Jpn.* 19 (4), 200–208 (in Japanese with English Abstr).
- Nakanishi, A., Takahashi, N., Park, J.-O., Miura, S., Kodaira, S., Kaneda, Y., Hirata, N., Iwasaki, T., Nakamura, M., 2002. Crustal structure across the coseismic rupture zone of the 1944 Tonankai earthquake, the central Nankai Trough seismogenic zone. *J. Geophys. Res.* 107 (B1), doi:10.1029/2001JB000424.
- Oikawa, Y., Nakamura, T., Imamura, T., Lin, W., Yamamoto, T., 2003. Earth stress measurement of Niitsu exploratory well using DSCA. *Proc. Japan Ass. Petro. Tech. Annual Meeting Chiba, Japan*, p. 29 (in Japanese).
- Owen, L.B., Toronto, T.W., 1988. Reliability of anelastic strain recovery estimates for stress orientation in the Travis Peak Formation, Harrison County, Texas. SPE paper 18165, SPE 63rd Annual Technical Conference and Exhibition Houston, TX, pp. 1–9.
- Perreau, P.J., Heugas, O., Santarelli, F.J., 1989. Tests of ASR, DSCA, and core discing analyses to evaluate in-situ stresses. SPE paper 17960, SPE Middle East Oil Technical Conference and Exhibition Manama, Bahrain, pp. 325–336.
- Rabaa, A.W.M., Meadows, D.L., 1986. Laboratory and field applications of the strain relaxation method. SPE paper 15072 SPE 56th California Regional Meeting, Oakland, CA, pp. 259–272.
- Sato, H., 1994. The relationship between late Cenozoic tectonic events and stress field and basin development in northeast Japan. *J. Geophys. Res.* 99, 22261–22274.
- Sato, H., Amano, K., 1991. Relationship between tectonics, volcanism, sedimentation and basin development, Late Cenozoic, central part of Northern Honshu, Japan. *Sediment. Geol.* 74, 323–343.
- Schon, J.H., 1998. Elastic properties of rocks. In: Helbig, K., Treitel, S. (Eds.), *Physical Properties of Rocks – Fundamentals and Principles of Petrophysics* (Chapter 6). *Handbook of Geophysical Exploration Seismic Exploration*, vol. 18, pp. 133–282.
- Skinner, B.J., 1966. Section 6. Thermal expansion. In: Clark Jr., S.P. (Ed.), *Handbook of Physical Constants*. Geol. Soc. Am. Mem., vol. 97, pp. 75–96.
- Tanaka, Y., 1986. State of crustal stress inferred from in-situ stress measurements. *J. Phys. Earth* 34, S57–S70 (Suppl.).
- The Research Group for Active Faults of Japan, 1992. Maps of active faults of Japan, 1:1 million. In: *Maps of Active Faults in Japan with an Explanatory Text*, University of Tokyo Press, Tokyo, Japan.
- Teufel, L.W., 1982. Prediction of hydraulic fracture azimuth from anelastic strain recovery measurements of oriented core. *Proc. 23rd U. S. Symp. on Rock Mech.*, Berkeley, CA, pp. 238–245.
- Teufel, L.W., 1983. Determination of in-situ stress from anelastic strain recovery measurements of oriented core. SPE/DOE paper 11649 SPE/DOE Symposium on Low Permeability, Denver, CO, pp. 421–430.
- Teufel, L.W., 1989. Acoustic emissions during anelastic strain recovery of cores from deep boreholes. In: Khair, A.W. (Ed.), *Rock Mechanics as a Guide for Efficient Utilization of Natural Resources*. Balkema, Rotterdam, pp. 269–276.
- Teufel, L.W., Warpinski, N.R., 1984. Determination of in situ stress from anelastic strain recovery measurements of oriented core: Comparison to hydraulic fracture stress measurements in the Rollins sandstone, Piceance Basin, Colorado. *Proc. 25th U.S. Symp. on Rock Mech.* Northwestern Univ., Evanston, Illinois, pp. 176–285.
- Voight, B., 1968. Determination of the virgin state of stress in the vicinity of a borehole from measurements of a partial anelastic strain tensor in drill cores. *Felsmech. Ingenieurgeol.* 6, 201–215.
- Wang, D.F., Davies, P.J., Yassir, N., Enever, J., 1997. Laboratory investigation of controls of stress history on ASR response. In: Sugawara, K., Obara, Y. (Eds.), *Rock Stress*. Balkema, Rotterdam, pp. 181–186.
- Warpinski, N.R., Teufel, L.W., 1989. In-situ stresses in low-permeability, nonmarine rocks. *J. Pet. Technol.* 41, 405–414.
- Wolter, K.E., Berckhemer, H., 1989. Time dependent strain recovery of cores from the KTB – Deep drill hole. *Rock Mech. Rock Eng.* 22, 273–287.
- Wolter, K.E., Berckhemer, H., 1990. Estimation of in situ stresses by evaluation of time-dependent strain recovery of KTB drill cores. *Tectonophysics* 178, 255–257.

- Yamasaki, T., Seno, T., 2005. High strain rate zone in central Honshu resulting from the viscosity heterogeneities in the crust and mantle. *Earth Planet. Sci. Lett.* 232 (1–2), 13–27.
- Zoback, M.L., Zoback, M.D., Adams, J., Assumpcao, M., Bell, S., Bergman, E.A., Blumling, P., Brereton, N.R., Denham, D., Ding, J., Fuchs, K., Gay, N., Gregersen, S., Gupta, H.K., Gvishiani, A., Jacob, K., Klein, R., Knoll, P., Magee, M., Mercier, J.L., Muller, B.C., Paquin, C., Rajendran, K., Stephansson, O., Suarez, G., Suter, M., Udias, A., Xu, Z.H., Zhizhin, M., 1989. Global patterns of tectonic stress. *Nature* 341, 291–298.