Title	Anomalous depth dependency of the stress field in the 2007 Noto Hanto, Japan, earthquake: Potential involvement of a deep fluid reservoir
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Citation	Geophysical Research Letters, 38(6), L06306 https://doi.org/10.1029/2010GL046413
Issue Date	2011-03
Doc URL	http://hdl.handle.net/2115/57953
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Type	article
File Information	GRL_38_L06306.pdf

Anomalous depth dependency of the stress field in the 2007 Noto Hanto, Japan, earthquake: Potential involvement of a deep fluid reservoir

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Received 6 December 2010; revised 20 January 2011; accepted 21 February 2011; published 25 March 2011.

[1] We have elucidated depth variations in the stress field associated with the 2007 Noto Hanto, Japan, earthquake by stress tensor inversion using high-quality aftershock data obtained by a dense seismic network. Aftershocks that occurred above 4 km in depth indicated a strike-slip stress regime. By contrast, aftershocks in deeper parts indicated a thrust faulting stress regime. This depth variation in the stress regime correlates well with that in the slip direction derived from a finite source model using geodetic data. Furthermore, the maximum principal stress (σ_1) axis was stably oriented approximately W20°N down to the depth of the mainshock hypocenter, largely in agreement with the regional stress field, but, below that depth, the σ_1 axis had no definite orientation, indicating horizontally isotropic stress. One likely cause of these drastic changes in the stress regime with depth is the buoyant force of a fluid reservoir localized beneath the seismogenic zone. **Citation:** Kato, A., et al. (2011), Anomalous depth dependency of the stress field in the 2007 Noto Hanto, Japan, earthquake: Potential involvement of a deep fluid reservoir, *Geophys. Res. Lett.*, *38*, L06306, doi:10.1029/2010GL046413.

1. Introduction

[2] Crustal stresses are the driving force of earthquake ruptures. Although crustal stresses tend to be relatively uniform on broad scales, those associated with earthquake generation are thought to be spatially heterogeneous on length scales of several to tens of kilometers [e.g., *Abers and Gephart*, 2001; *Hardebeck and Hauksson*, 2001; *Ratchkovski*, 2003; *Kato et al.*, 2006]. The degree of heterogeneities in crustal stresses has important implications for the understanding and modeling of earthquake physics. It is therefore of crucial importance to elucidate spatial variations in crustal stresses associated with earthquake generation. However, in order to reveal fine spatial heterogeneities of the stress field, very dense seismic instrumentation is required.

[3] A shallow M_w 6.7 inland earthquake occurred along the west coast of the Noto Peninsula, Japan, on 25 March 2007, seriously damaging the surrounding areas. The focal mechanism estimated by moment tensor inversion (the National Research Institute for Earth Science and Disaster Prevention

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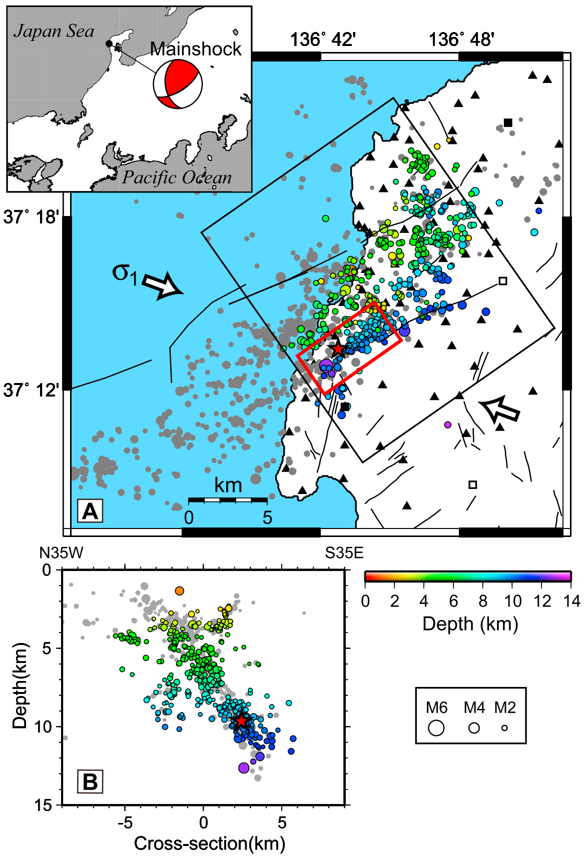

Figure 1. (a) Map of aftershocks used in the stress tensor inversion, shown in circles with radii scaled to earthquake magnitudes and colored according to depths. Aftershocks that were not used are denoted by gray circles. Red star, mainshock epicenter. Inset map, location of the studied area, and the moment tensor of the mainshock as determined by NIED. Solid triangles, temporary offline seismic stations. Solid squares, permanent online stations. Open squares, temporary online stations operated by *The Japanese University Group of the Joint Seismic Observations at NKTZ* [2005]. Solid traces, major active faults. (b) Depth profile of the relocated hypocenters of the aftershocks falling within the black rectangle shown in Figure 1a.

[NIED]) revealed an oblique slip with a dominant reverse-slip character (Figure 1). The mainshock hypocenter was located near the deepest end of the fault plane, which dipped to the southeast at a high angle of 60°. Geological and geophysical studies [e.g., *Kano et al.*, 2002; *Kato et al.*, 2008] have suggested that the mainshock thrust faulting was due to the reactivation of a steep-dipping normal fault that had been formed during the extension stage of the Japan Sea (20–15 Ma). This reactivation can be understood in terms of inversion tectonics due to crustal shortening that began in the late Miocene (~3 Ma), similar to the reactivation occurring in the Niigata region [e.g., *Kato et al.*, 2009].

[4] While online seismic networks have been put into operation on the Noto Peninsula by the NIED, the Japan Meteorological Agency (JMA), universities, and *The Japanese University Group of the Joint Seismic Observations at NKTZ* [2005], the average spacing of those stations is not enough to resolve detailed stress fields in the source region. In order to assess the stress field in more details, we deployed a dense network of temporary seismic stations immediately after the mainshock and created a high-quality aftershocks dataset [*Sakai et al.*, 2008; *Kato et al.*, 2008] (Figure 1). In this study, we first determine stress tensors using aftershock first motion data. We then discuss the relationship between the fine spatial heterogeneities of the stress field and the earthquake generation processes, with implications for the involvement of a fluid reservoir beneath the mainshock hypocenter.

2. Data and Methods

[5] We use data from 89 temporary offline stations constituting our network, 13 permanent online stations, and 5 temporary online stations operated by *The Japanese University Group of the Joint Seismic Observations at NKTZ* [2005] (Figure 1). The station spacings averaged less than 2 km. Three-component seismograms were recorded continuously at all stations at a sampling rate of either 100 or 200 Hz. We manually picked up P-wave first arrival polarities for a total of 1228 aftershocks occurring between 25 March and 22 May 2007. We then relocated the aftershock hypocenters on the basis of a three-dimensional velocity structure estimated by *Kato et al.* [2008] using local seismic tomography.

[6] Stress tensors were inverted directly from the first motion data by applying the first motion stress inversion method (called the MOTSI code) of *Abers and Gephart* [2001], without assuming prior knowledge of the focal mechanisms. The technique produces estimates of four stress parameters: the orientations of the three principal stress axes, $\sigma_1 > \sigma_2 > \sigma_3$, and the parameter $R = (\sigma_2 - \sigma_1)/(\sigma_3 - \sigma_1)$, indicating the magnitude of σ_2 relative to σ_1 and σ_3. This technique has the advantage of being able to evaluate the uncertainties in the stress tensor parameters more accurately than the more widely known stress inversion methods using focal mechanisms.

[7] In general, events with focal mechanisms that are poorly constrained because of either insufficient first motion observations or incorrect polarity determinations are not useful for constraining the stress parameters [*Abers and Gephart*, 2001]. We therefore selected 472 events with more than 20 first motion polarities (colored circles in Figure 1) on the basis of a solution quality evaluation method developed by *Hardebeck and Shearer* [2002]. For each of the selected events, the takeoff angles and azimuths were calculated using the three-dimensional velocity structure of *Kato et al.* [2008]. Since all seismic stations were located on land, details of the stress field could be resolved only on the east side of the mainshock hypocenter (Figure 1). Depth slices of *P* and *T* axis distributions have indicated that lateral variations of the stress field are relatively mild, so we mainly focus on its depth variations.

3. Results

[8] The stress fields obtained by applying the MOTSI code [*Abers and Gephart*, 2001] to different depth ranges are

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL046413.

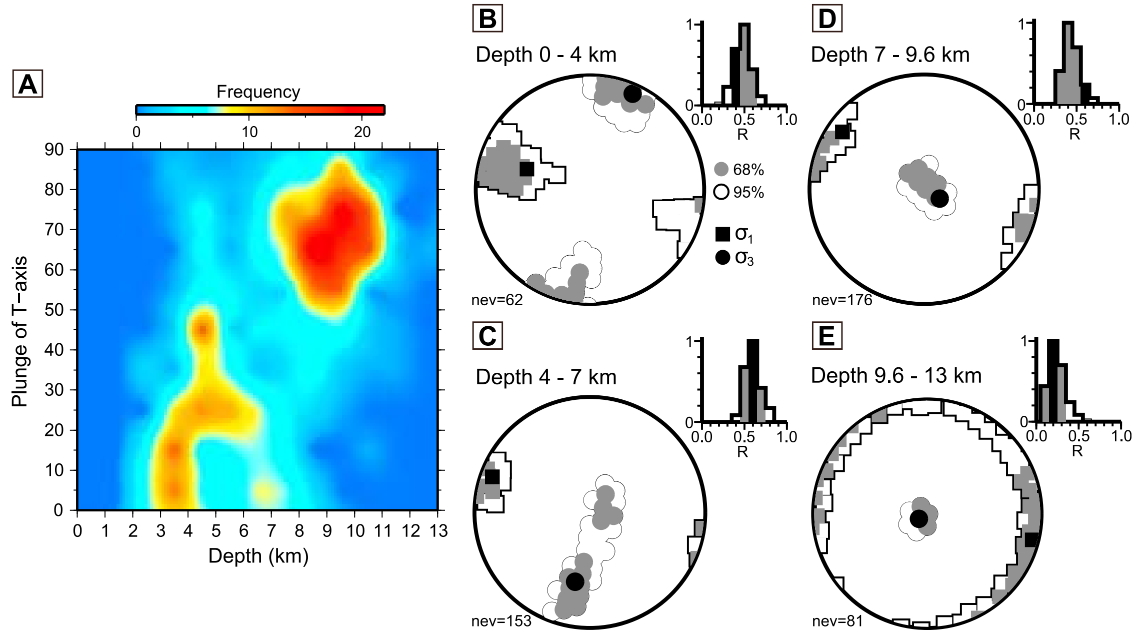

Figure 2. (a) Frequencies of T-axis plunge angles plotted against the depth. Results of first motion stress inversion (MOTSI code) for four depth ranges: (b) 0–4 km, (c) 4–7 km, (d) 7–9.6 km, and (e) 9.6–13 km, showing lower-hemisphere equal-area projections of the orientations of σ_1 (squares) and σ_3 (circles), each with their marginal confidence limits. Black-filled symbols, optimal solutions. Gray shades, 68% confidence limits. Open contours, 95% confidence limits. In the top right margins, frequency histograms of the R-values, with 68% and 95% confidence intervals denoted by gray and open bars, respectively. In the bottom left margins, the number of events is shown.

shown in Figures 2b–2e. From the surface to the depth of the mainshock hypocenter (9.6 km), the maximum principal stress (σ_1) axis was stably oriented approximately W20°N, with low plunge angles (Figures 2b–2d and Figures S1 and S2 of the auxiliary material).[1] The uncertainties in the stress tensors were relatively small. The orientation of the σ_1 axis was largely consistent with both the regional compressional strain rate axis as inferred from GPS data [*Sagiya et al.*, 2000] and the regional stress field [*Townend and Zoback*, 2006]. Curiously, the mainshock fault had a steep dip of 60°, which is far from favorably oriented for failure [*Sibson*, 1992], considering that σ_1 was nearly horizontal.

[9] Above 4 km in depth, the minimum principle stress (σ_3) axis was also nearly horizontal. The stress field in the shallow parts is therefore favorable for strike-slip faulting. By contrast, the σ_3 axis had near-vertical plunges below 7 km in depth, which indicates that the stress field is suitable for thrust faulting. Between the depths of 4 and 7 km, where the abrupt transition occurs, a composite stress field was observed (Figures 2c and S1). Figure 2a is a frequency plot of the T-axis plunge angles, showing their depth dependency. They demonstrate two clear peaks at low and steep angles, the transition occurring between 4 and 7 km in depth.

[10] Furthermore, we recognized remarkable indefiniteness in the σ_1-axis azimuths below the depth of the mainshock hypocenter, where they took all directions as long as they were perpendicular to the σ_3-axis, which remained near-vertical. This indicates a thrust-faulting stress regime that is horizontally isotropic (Figure 2e).

[11] Frequency histograms of the R-values, shown in the margins of Figure 2, indicate that, above the depth of the mainshock hypocenter, the peak frequency of R occurs around 0.5 or 0.6 (Figures 2b–2d), which means that σ_2 lies roughly halfway between σ_1 and σ_3. Below that depth, by contrast, the frequency of R peaks around 0.2, indicating that σ_2 is closer in magnitude to σ_1 than to σ_3 (Figure 2e). This is consistent with the observation that σ_1 has no definite orientation.

[12] An uncommon, near-vertical alignment of aftershocks is discerned beneath the mainshock hypocenter [*Kato et al.*, 2008; *Sakai et al.*, 2008]. Using those aftershocks (falling within the red rectangle in Figure 1), we estimated the local stress field beneath the mainshock hypocenter (Figure 3a). The σ_1 axis orientations varied significantly more than in the spatially averaged results shown in Figure 2e, and the R-values drew even nearer to zero. This atypical stress field beneath the mainshock hypocenter coincides in location with a low-V_p and high-conductivity anomaly (Figures 3b and 3c), found out by fine local tomography and a magnetotelluric (MT) survey conducted after the mainshock [*Kato et al.*, 2008; *Yoshimura et al.*, 2008].

4. Discussions and Conclusions

[13] The present study has uncovered a clear transition of the stress field from a strike-slip stress regime to a thrusting regime between 4 and 7 km in depth. This indicates that dynamic rupture propagated across both stress regimes during the mainshock (Figure 4). Indeed, a kinematic slip inversion study using GPS and InSAR data reported that dip-slip components dominated at large depths near the mainshock hypocenter, whereas right-lateral slip components became more dominant with decreasing depth [*Ozawa et al.*, 2008] (Figure S3). This depth variation in the slip direction agrees well with that in the stress regime.

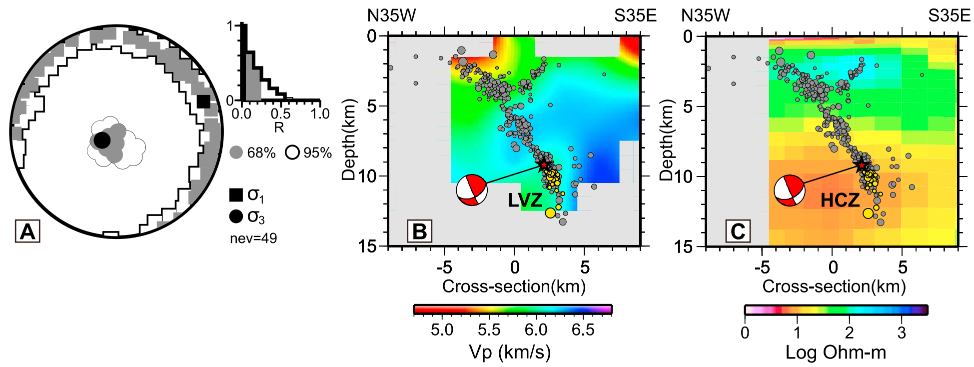

Figure 3. (a) Result of stress tensor inversion for the aftershocks aligned vertically beneath the mainshock hypocenter (falling within the red rectangle in Figure 1). (b, c) Cross sections of the V_p [*Kato et al.*, 2008] and resistivity [*Yoshimura et al.*, 2008] structures across the mainshock hypocenter.

[14] A zone characterized by both indefinite σ_1 orientations and small R-values was found in the location of a low-V_p and high-conductivity anomaly beneath the mainshock hypocenter (Figures 3b and 3c). This anomaly hints at the presence of crustal fluids [*Kato et al.*, 2008; *Yoshimura et al.*, 2008], which may be influencing the stress field in the source region.

[15] Given that σ_1 corresponds to the maximum horizontal stress (σ_h^{max}), the transition of the stress field with depth may be explained by an increase in magnitude of the minimum horizontal stress (σ_h^{min}). One simple candidate for the origin of such an increase is a hypothetical, upward flexure of the upper crust, with its hinge axis oriented parallel to the σ_1 axis (Figure 4). In shallow parts, σ_h^{min} remains smaller than σ_v (vertical stress) because of extensional stresses associated with the bending ($\sigma_v = \sigma_2$, $\sigma_h^{min} = \sigma_3$), resulting in a strike-slip regime. In deeper parts, by contrast, σ_h^{min} becomes larger than σ_v because of compressional stresses associated with the bending ($\sigma_h^{min} = \sigma_2$, $\sigma_v = \sigma_3$), which leads to a thrust-faulting regime (Figure 4). At great depths, σ_h^{min} (= σ_2) grows very close to σ_h^{max} (= σ_1), resulting in a horizontally isotropic stress field (Figures 3a and 4). A possible support for this hypothesis comes from geomorphological data, where the height profile of a marine terrace formed about 120,000 years ago [*Geographical Survey Institute*, 2007; *Ozawa et al.*, 2008] hints at the presence of a similar upward flexure in the earthquake source region.

[16] We hypothesize that the buoyant force of a fluid reservoir beneath the mainshock hypocenter is causing such an upward flexure of the upper crust. The present study has only indicated localization of fluids just beneath the mainshock hypocenter (Figure 3b), but regional (larger-scale) tomography [*Hasegawa et al.*, 2009] has suggested that fluids are apparently infiltrating into the seismogenic zone from a deeper and larger fluid reservoir, located at approximately 20 km in depth. A vertical change in the stress state from normal to strike-slip faulting has likewise been reported in the southern Taupo Volcanic Zone in New Zealand, where the seismicity is considered to be related to fluid processes [*Hayes et al.*, 2004].

[17] It has been postulated that fluids are involved in the initiation of mainshock ruptures [e.g., *Miller et al.*, 2004; *Kato et al.*, 2006]. According to the fault-valve model [e.g., *Sibson*, 1992], for example, overpressured fluids intrude episodically into the fault region, reduce shear strengths and induce mainshock ruptures. In fact, weak phases in the 2007 Noto Hanto earthquake waveforms, observed at several

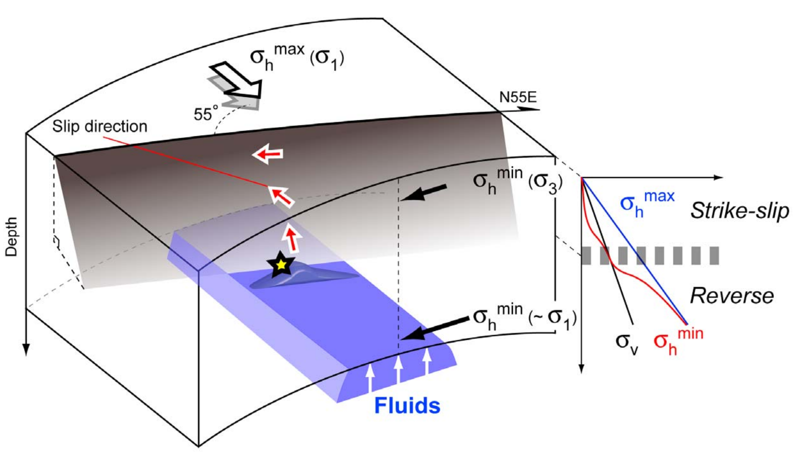

Figure 4. Schematic image of the depth variations in the stress field and a hypothetical fluid reservoir beneath the mainshock hypocenter (yellow star). The lengths of vectors are scaled to the magnitudes of the principal stresses that they represent. The fault plane is shown as a shaded, inclined surface. Red arrows, slip directions derived from a finite source model [*Ozawa et al.*, 2008] (Figure S3).

seismic stations, have revealed the occurrence of an initial breakdown rupture close to the mainshock hypocenter [*Sakai et al.*, 2008]. The initiated rupture is likely to have propagated along the structural boundary between the hanging wall and the footwall, though it was oriented unfavorably for failure. It is likely that fluid migrations, which triggered the initial breakdown, continued to proceed into broader areas along the structural boundary, reducing shear strengths and facilitating ruptures there. Given these considerations, we hypothesize that fluid migrations along the fault, along with relative mechanical weaknesses within the fault zone, were the principal factors that caused the 2007 Noto Hanto earthquake by reactivating a pre-existing normal fault created during the opening of the Japan Sea.

[18] **Acknowledgments.** We are thankful to G. Abers for allowing us to use the MOTSI code. We thank the Editor R. Harris, J. Townend, an anonymous reviewer, T. Matsuzawa, and T. Nishimura, for useful comments and suggestions. We thank NIED, JMA, and Kyoto University for allowing us to use the waveform data. This study was partially supported by the Observation and Research Program for the Prediction of Earthquakes and Volcanic Eruptions under MEXT, a MEXT Grant-in-Aid for Special Purposes 19900001, and a MEXT Special Coordination Fund for Promoting Science and Technology.

[19] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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