Iio *et al. Earth, Planets and Space (2018) 70:97*
https://doi.org/10.1186/s40623-018-0869-6

Earth, Planets and Space

PREFACE Open Access

Crustal dynamics: unified understanding of geodynamic processes at different time and length scales

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Keywords: Crustal dynamics, Tohoku-oki earthquake, Stress, Strength, Deformation, Fault zone, Friction, Rheology, Crustal fluid, Materials science

The 2011 Tohoku-oki earthquake occurred on an unexpected scale, which made us realize that the generation mechanisms of earthquakes are poorly understood. To provide a unified view of the geodynamic processes including earthquake generation processes in the Japanese arc–trench system, it is necessary to clarify the absolute values of crustal stresses, the stress–strain field, and the basic properties of the island arc crust and mantle, in particular, those of fault zones. This special issue includes 22 papers, and they are divided into several categories: (1) crustal stress and overpressured fluids, (2) stress and rupture heterogeneity, (3) large-scale deformation in the Japanese Island Arc, (4) shear zone detected by Satellite Geodesy, (5) rheology of crustal fault zones, (6) materials science of rock deformation.

Several papers analyzed spatiotemporal changes in crustal stress related to earthquake generation and volcanic eruption and discussed involvement of overpressured fluids in seismogenesis and fault zone properties related to overpressure. Hardebeck (2017) investigated coseismic and postseismic rotations of principal stress axes caused by three $M > 8.8$ subduction megathrust ruptures. The largest coseismic stress rotations occur just above the Moho depth of the overriding plate where large continuous slip patches appear (from seismological studies) to coincide with areas of intense fluid overpressuring inferred to promote near-complete shear stress drop. Modeling the full spatial distribution of static stress changes during the mainshock is probably needed to account for the spatial complexity of coseismic stress rotations. Otsubo et al. (2018) employed the multiple inverse method (MIM) to demonstrate significant variations in the normal faulting stress state around Iwaki City, Japan, over a period of a few years prior to the 2011 Mw 9.0 Tohoku megathrust earthquake. Such variations in stress state require a low differential stress state which they attribute to overpressured fluids in the focal regions. Terakawa (2017) analyzed slip plane diversity within microearthquake swarms around Mt. Ontake stratovolcano to make the case that local swarm activity is driven by regions where pore fluids are overpressured by 10–30 MPa. Matsumoto and Shigematsu (2018) reported measurements of fault zone permeability from borehole intercepts along the Median Tectonic Line (MTL) in Mie Prefecture, SW Japan, finding values more than 100–700 times the permeability of the surrounding protolith assemblage of crystalline rocks. While reported permeabilities (5×10^{-16} m$^2 > k > 3 \times 10^{-19}$ m^2) are generally too high to contain overpressured fault fluids at depth, it has to be kept in mind that the measurements were made under low confining pressure at depths of only a few hundred meters. Sibson (2017) advanced the hypothesis that the local attainment of the tensile overpressure state ($P_f > \sigma_3$) is associated with the formation and activation of fault–fracture meshes distributed throughout tabular volumes. Except in the near surface this generally requires near-lithostatic fluid overpressures. Interlinkage of shear fractures with fluid-saturated extension fractures

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slows slip transfer, allowing such mesh structures to function as rheological units incorporating viscous dashpots capable of giving rise to a variety of anomalous slow-slip phenomena.

Full understanding of crustal dynamics requires clarification of stress and strength heterogeneities, and rupture heterogeneity. Yukutake and Iio (2017) conducted a precise analysis of hypocenters and focal mechanisms of upper crustal aftershocks from the 2000 Mw 6.6 Western Tottori, Japan, earthquake which involved predominantly sinistral strike-slip along a NNW–SSE fault structure disrupted by a conjugate set of dextral cross-faults. Aftershocks around the mainshock rupture plane occur within a tabular zone 1.0–1.5 km thick, significantly broader than the likely damage zone, with diverse mechanisms. The aftershocks apparently represent rupture of fractures surrounding the mainshock rupture rather than reshear of the primary rupture, caused by stress changes arising from heterogeneous slip distribution along the mainshock rupture. Iio et al. (2017) employed a high-density seismological network in western Nagano Prefecture. Focal mechanisms were inverted to show that the crustal stress field can generally be regarded as uniform at a scale of 1 km throughout the study region, but that strength is heterogeneous, varying over comparatively short distances (~ 100 m). Ando et al. (2017) analyzed complex patterns in the wave radiation and surface displacement of the 2014 Mw 6.2 northern Nagano earthquake sequence which involved predominantly reverse slip on an irregularly segmented rupture. Observations include foreshock occurrence, large differences between the first-motion focal mechanisms and the CMT, and along-strike variations in surface displacement. Aftershocks reveal a more complex geometry in the northern half of the focal area, correlated with along-strike variation of fault activity and maturity. Dynamic rupture simulations took account of the observationally determined regional stress field and fault geometry. The observed complexity is explained as the effect of non-planar fault geometry with a number of branch faults and bends. Maeda et al. (2018) explored the spatial relationship between upper crustal structure and seismicity in the Kii Peninsula of southwest Japan, where the stress field and the predominant focal mechanism change with depth. They attribute this stress heterogeneity to localized thermal stress from a buried heat source in the lower crust.

Deformation occurs in response to stress and/or stress changes, and it reflects material properties where the deformation occurs. Thus, it is crucial to measure deformation and/or deformation rate in the Japanese Island Arc. Sueoka et al. (2017) employed (U-Th)/He thermochronometric analyses across southern Tohoku in the Japan arc to reconstruct the long-term uplift and denudation history of the region. Distinct morphostructural provinces defined by apatite He ages are distinguished, the Abukuma Mountains on the fore-arc side (64.3–49.6 Ma), the Ou Backbone Range along the volcanic front (11.4–1.5 Ma), and the Asahi Mountains on the back-arc side (< 10 Ma). Denudation rates of < 0.1 mm/year are estimated for the Abukama Mountains, 0.1–1.0 mm/year for the Ou Backbone range, and 0.1–0.3 mm/year for the Asahi Mountains. These techniques could be extended across other segments of the arc, but possible thermal effects of magmatism need to be carefully considered.

Finer-scale deformation is estimated by Satellite Geodesy along major fault zones in Japan. Nishimura and Takada (2017) used GNSS velocity data to define the San-in dextral shear zone with a width of c. 50 km accommodating c. 5 mm/year of dextral shearing along the northern coastline of southwest Japan. Major recent earthquake ruptures appear to follow anticipated trajectories of conjugate Riedel shears within the shear zone. Takada et al. (2018) employed Satellite Geodesy (InSAR and GNSS) to define a sharp velocity gradient across the Ushikubi fault within the dextral Atotsugawa fault system in central Japan. Analysis of InSAR data shows interseismic deformation to be spatially heterogeneous within the strain concentration zone.

Rheology of large-scale crustal fault zones is essential in the crustal dynamics, because it can control deformation in the whole crust in island arcs. Nakajima and Matsuzawa (2017) used high-quality waveform data from a dense seismic network to explore the three-dimensional P-wave attenuation structure at depth along the Niigata–Kobe Tectonic Zone (NKTZ) in central Japan. The study confirms spatial relationships between attenuation structures and surface deformation along the NKTZ. Anelastically weakened lower crust west of the Itoigawa–Shizuoka Tectonic Line (ISTL) promotes surface contraction over a region about 100 km wide while anelastic deformation in the thick, shallow sedimentary basin east of the ISTL restricts surface deformation to a narrow region (25–40 km). These observations account qualitatively for regional variations in the width of the high-strain-rate zone across the ISTL, placing constraints on the character of deformation in the subsurface. Dojo and Hiramatsu (2017) used the spatial distribution of coda Q from the analysis of waveform data to investigate a high-strain-rate region in the northeastern part of the Niigata–Kobe Tectonic Zone (NKTZ). Coda Q in the 2–3 Hz frequency band correlates spatially with S wave velocity at 25 km depth, while Coda Q in the 4–8 Hz band correlates with S wave velocity perturbations at 10 km depth. Results indicate that a combination of deformation in the upper crust as well as ductile deformation in the lower crust may contribute to the high strain rate in the northeastern NKTZ. Zhang and Sagiya (2017) modeled strain concentration in two dimensions within the lower crust, assuming steady fault sliding in the upper crust and ductile flow in the lower crust according to laboratory-derived power-law rheology with a yield threshold at the brittle–ductile transition. Possible physical mechanisms for strain concentration in the lower crust are investigated including frictional and shear heating, grain size, and power-law creep, taking account also of the role of water in promoting crystal plasticity.

Materials science of rock deformation is fundamental for not only the crustal dynamics but also all the studies in solid earth sciences. Consequently, its progress is crucial for our understanding of crustal dynamics. Fukuda et al. (2018) showed how the addition of small amounts of water to polycrystalline anorthite under high temperature induces a change from distributed fracturing to plastic flow promoting grain-size-sensitive creep in the lower middle crust. Kameda et al. (2017) investigated the alteration and dehydration of subducting oceanic crust, specifically pillow basalts within the Shimanto belt showing how the saponite–chlorite conversion within mixed layer C/S minerals may contribute fluid to plate boundary fault systems with consequent mechanical effects. Kuwatani and Toriumi (2017) employed a new forward modeling technique for analyzing retrogressive hydration reactions. Results indicate that changes in mineral composition are mainly controlled by pressure and temperature, but that changes in mineral modes are controlled by the degree of water infiltration. Matsumura et al. (2017) statistically analyzed two probability density functions to evaluate a microboudin paleopiezometer applied to stretched tourmaline grains within Archean metacherts from the East Pilbara Terrane in Western Australia. They found that an elastic matrix model is preferable to a Newtonian viscous model for analyzing the stresses involved in microboudinage of columnar tourmaline grains within the quartz matrix of the metamorphic tectonite. Tsubokawa and Ishikawa (2017) reported on the preparation of submicron polycrystalline olivine and clinopyroxene by sintering. Incorporation of trace amounts of graphite allows experimental investigations into the influence of graphite on mantle rheology and seismic velocity.

Authors' contributions

All authors of this article are guest editors for this special issue. All authors read and approved the final manuscript.

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Acknowledgements

We express our sincere gratitude to the authors who contributed to this special issue and the reviewers who evaluated the contributions and gave thoughtful comments and suggestions.

Competing interests

The authors declare that they have no competing interest.

Funding

This study was partly supported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, under the Earthquake and Volcano Hazards Observation and Research Program, and KAKENHI Grant Numbers 26109001-26109007, and 15K21755.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 5 June 2018 Accepted: 6 June 2018
Published online: 20 June 2018

References

Ando R, Imanishi K, Panayotopoulos Y, Kobayashi T (2017) Dynamic rupture propagation on geometrically complex fault with along-strike variation of fault maturity: insights from the 2014 Northern Nagano earthquake. Earth Planets Space 69:130. https://doi.org/10.1186/s40623-017-0715-2

Dojo M, Hiramatsu Y (2017) Spatial variation in coda Q in the northeastern part of Niigata–Kobe Tectonic Zone, central Japan: implication of the cause of a high strain rate zone. Earth Planets Space 69:76. https://doi.org/10.1186/s40623-017-0663-x

Fukuda J, Muto J, Nagahama H (2018) Strain localization and fabric development in polycrystalline anorthite + melt by water diffusion in an axial deformation experiment. Earth Planets Space 70:3. https://doi.org/10.1186/s40623-017-0776-2

Hardebeck JL (2017) The spatial distribution of earthquake stress rotations following large subduction zone earthquakes. Earth Planets Space 69:69. https://doi.org/10.1186/s40623-017-0654-y

Iio Y, Yoneda I, Sawada M, Miura T, Katao H, Takada Y, Omura K, Horiuchi S (2017) Which is heterogeneous, stress or strength? An estimation from high-density seismic observations. Earth Planets Space 69:144. https://doi.org/10.1186/s40623-017-0730-3

Kameda J, Inoue S, Tanikawa W, Yamaguchi A, Hamada Y, Hashimoto Y, Kimura G (2017) Alteration and dehydration of subducting oceanic crust within subduction zones: implications for décollement step-down and plate-boundary seismogenesis. Earth Planets Space 69:52. https://doi.org/10.1186/s40623-017-0635-1

Kuwatani T, Toriumi M (2017) Thermodynamic forward modeling of retrogressive hydration reactions induced by geofluid infiltration. Earth Planets Space 69:18. https://doi.org/10.1186/s40623-017-0607-5

Maeda S, Matsuzawa T, Toda S, Yoshida K, Katao H (2018) Complex microseismic activity and depth-dependent stress field changes in Wakayama, southwestern Japan. Earth Planets Space 70:21. https://doi.org/10.1186/s40623-018-0788-6

Matsumoto N, Shigematsu N (2018) In-situ permeability of fault zones estimated by hydraulic tests and continuous groundwater-pressure observations. Earth Planets Space 70:13. https://doi.org/10.1186/s40623-017-0765-5

Matsumura T, Kuwatani T, Masuda T (2017) Statistical model selection between elastic and Newtonian viscous matrix models for the microboudin palaeopiezometer. Earth Planets Space 69:83. https://doi.org/10.1186/s40623-017-0669-4

Nakajima J, Matsuzawa T (2017) Anelastic properties beneath the Niigata–Kobe Tectonic Zone, Japan. Earth Planets Space 69:33. https://doi.org/10.1186/s40623-017-0619-1

Nishimura T, Takada Y (2017) San-in shear zone in southwest Japan, revealed by GNSS observations. Earth Planets Space 69:85. https://doi.org/10.1186/s40623-017-0673-8

Otsubo M, Miyakawa A, Imanishi K (2018) Normal-faulting stress state associated with low differential stress in an overriding plate in northeast Japan prior to the 2011 Mw 9.0 Tohoku earthquake. Earth Planets Space 70:51. https://doi.org/10.1186/s40623-018-0813-9

Sibson RH (2017) Tensile overpressure compartments on low-angle thrust faults. Earth Planets Space 69:113. https://doi.org/10.1186/s40623-017-0699-y

Sueoka S, Tagami T, Kohn BP (2017) First report of (U–Th)/He thermochronometric data across Northeast Japan Arc: implications for the long-term inelastic deformation. Earth Planets Space 69:79. https://doi.org/10.1186/s40623-017-0661-z

Takada Y, Sagiya T, Nishimura T (2018) Interseismic crustal deformation in and around the Atotsugawa fault system, central Japan, detected by InSAR and GNSS. Earth Planets Space 70:32. https://doi.org/10.1186/s40623-018-0801-0

Terakawa T (2017) Overpressurized fluids drive microseismic swarm activity around Mt. Ontake volcano, Japan. Earth Planets Space 69:87. https://doi.org/10.1186/s40623-017-0671-x

Tsubokawa Y, Ishikawa M (2017) Sintering polycrystalline olivine and polycrystalline clinopyroxene containing trace amount of graphite from natural crystals. Earth Planets Space 69:128. https://doi.org/10.1186/s40623-017-0717-0

Yukutake Y, Iio Y (2017) Why do aftershocks occur? Relationship between mainshock rupture and aftershock sequence based on highly resolved hypocenter and focal mechanism distributions. Earth Planets Space 69:68. https://doi.org/10.1186/s40623-017-0650-2

Zhang X, Sagiya T (2017) Shear strain concentration mechanism in the lower crust below an intraplate strike-slip fault based on rheological laws of rocks. Earth Planets Space 69:82. https://doi.org/10.1186/s40623-017-0668-5

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