Structure and Composition of the Plate-Boundary Slip Zone for the 2011 Tohoku-Oki Earthquake

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Discussion

Our data suggest that multipotency is a state of multiple oscillating neurogenic and gliogenic determination factors and that cell fate choice is a process of sustained expression of a single factor. This switching may be induced by the fluctuations of Notch signaling (supplementary text). The detailed mechanism by which the oscillatory and sustained Ascl1 expression differentially regulates downstream gene expression remains to be determined. A recent report indicates that the proneural factor Ngn2 is differentially phosphorylated between NPCs and neurons and controls the expression of its target genes differently depending on its phosphorylation status (*37*). We speculate that oscillatory and sustained expression of proneural factors could be involved in the different posttranscriptional modulation that is responsible for target gene selectivity. We also demonstrated that the light-switchable gene expression system offers an efficient way to control the proliferation and differentiation of stem cells by changing the light-exposure pattern rather than using different growth factors or chemicals, showing its applicability to the regeneration technology.

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Supplementary Materials

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REPORTS

Structure and Composition of the Plate-Boundary Slip Zone for the 2011 Tohoku-Oki Earthquake

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The mechanics of great subduction earthquakes are influenced by the frictional properties, structure, and composition of the plate-boundary fault. We present observations of the structure and composition of the shallow source fault of the 2011 Tohoku-Oki earthquake and tsunami from boreholes drilled by the Integrated Ocean Drilling Program Expedition 343 and 343T. Logging-while-drilling and core-sample observations show a single major plate-boundary fault accommodated the large slip of the Tohoku-Oki earthquake rupture, as well as nearly all the cumulative interplate motion at the drill site. The localization of deformation onto a limited thickness (less than 5 meters) of pelagic clay is the defining characteristic of the shallow earthquake fault, suggesting that the pelagic clay may be a regionally important control on tsunamigenic earthquakes.

For the 11 March 2011 moment magnitude (M_w) = 9.0 Tohoku-Oki earthquake, pronounced coseismic weakening of the plate-boundary fault may explain the nearly total stress drop, the associated change from a thrust to normal faulting stress state in the wedge (*1–3*), and the large slip that breached the trench (*4–6*). Friction and other properties of faults relevant to slip behavior depend on the composition (e.g., clay content) and structure (e.g., orientation, thickness, and rock fabric) of the active slip zones.

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The Japan Trench Fast Drilling Project (JFAST), Integrated Ocean Drilling Program (IODP) Expedition 343 and 343T (1 April to 24 May and 5 to 19 July 2012) was designed to locate and directly sample the shallow, active slip zone of the M_w = 9.0 Tohoku-Oki earthquake (*7*). The JFAST drill site (C0019) is seaward of the 2011 Tohoku-Oki earthquake hypocenter and just landward of the Japan Trench, about 200 km offshore of Sendai city (Fig. 1). In this area, the earthquake exhibited relatively low speed of rupture propagation with long-period radiation akin to tsunami earthquakes (*8*, *9*), with exceptionally large slip at the trench (*4*, *10*). A predrilling multichannel seismic survey of the drill site (*11*) showed that the frontal prism of the upper plate lacks coherent reflectors. In the subducting plate below the prism and seaward to the outer rise, the basaltic crust and overlying sediments are offset by normal faults with several hundred meters throw (*11*, *12*). The drill site sits atop a horst (Fig. 1B).

The drilling vessel *Chikyu* drilled three closely spaced holes to >844 meters below the seafloor (mbsf) to reach the strong seismic reflectors thought to mark the top of the basalt of the subducting plate (Fig. 1B), thus crossing the plate boundary. We deployed logging-while-drilling tools, including natural gamma ray and multiple resistivity sensors, to record data for the entire depth of the first hole; core samples were recovered from key intervals of the second hole, and a temperature-sensing observatory was installed in the third hole (*7*). The integration of geophysical data with analyses of core samples allowed identification of the top of the geologic plate boundary at ~820 mbsf, which coincides with the seismic reflector interpreted as the plate boundary fault (*7*, *11*, *12*) that extends seaward past the horst and into the trench graben (Fig. 1C). Analysis of the temperature data recovered from the third borehole indicates the Tohoku-Oki earthquake rupture occurred at essentially the same depth as the plate-boundary fault identified in the logging and coring boreholes [fig. S1 (*13*)]. On the basis of a palinspastic reconstruction of our structural interpretation (fig. S2), we estimate that the cumulative displacement across the plate-boundary fault at the drill site is ~3.2 km.

The top of the plate-boundary fault zone is identified by changes in lithology, sediment age, log signature, and orientations of bedding determined from resistivity image logs (*7*). From 275 to ~820 mbsf, bedding is dipping ~30° to 70° with strikes normal to the plate convergence direction. Core samples from 690 to ~820 mbsf contain Pliocene to Pleistocene radiolaria. Below ~820 mbsf, the bedding uniformly dips <10° and displays high gamma ray signatures to ~835 mbsf (Fig. 2). Radiolarian microfossils in core samples confirm that the shallowly dipping, high gamma-ray strata are Late Miocene mudstones and Cretaceous pelagic clay. The transition to high resistivity and low gamma ray at ~835 mbsf represents the transition from pelagic clay to Cretaceous chert. The subhorizontal strata (below ~820 mbsf) are lithologically similar to the basal sediments documented on the outer rise of the Pacific Plate about 260 km to the northeast at site 436 of the Japan Trench transect, Leg 56, Deep Sea Drilling Project

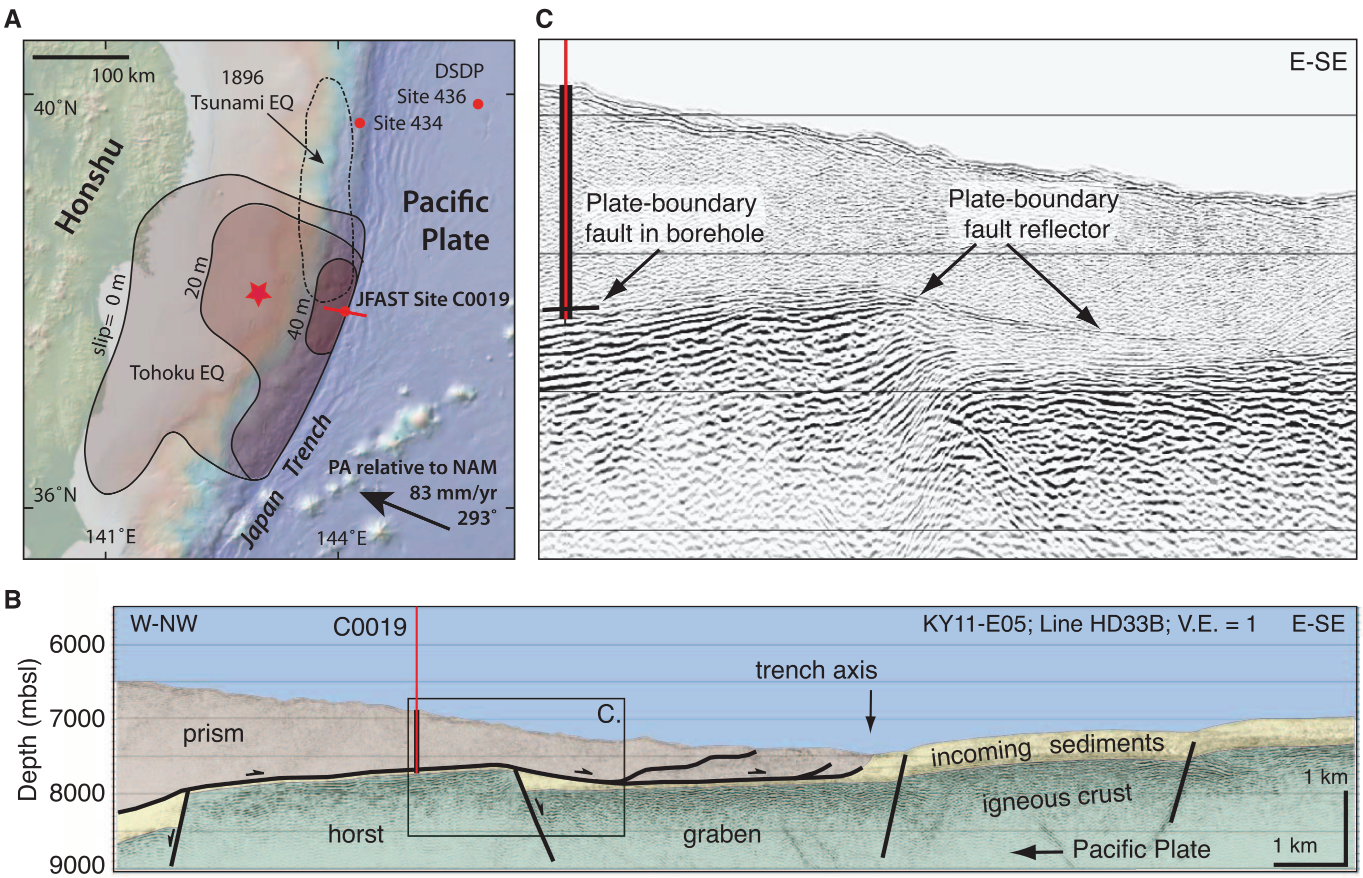

Fig. 1. Location and structural setting of the JFAST drill site. (**A**) Red dots indicate ocean drilling sites, and the red star is the epicenter of the Tohoku-Oki earthquake (EQ). Contours show the coseismic slip inferred from various data sets, and the dashed line shows the approximate rupture area of the 1896 Meiji-Sanriku tsunami earthquake (*6*, *8*, *9*, *23*). The direction of motion of the Pacific Plate (PA) relative to Honshu [North American Plate, NAM (*28*)] is shown. The red line shows the approximate orientation of the in-line seismic profile HD33B (*29*). DSDP indicates Deep Sea Drilling Project. (**B**) A portion of the in-line seismic profile (HD33B) showing the location of the boreholes, frontal prism and trench, the normal-faulted basal pelagic sediments and oceanic basalt, and the interpreted location of the plate-boundary fault and associated faults in the sediments. mbsl, meters below sea level; V.E., vertical exaggeration. (**C**) Seismic data show the presence of a faint but continuous reflector, interpreted as the plate-boundary fault [see also (*11*)] identified in the drill hole, that continues eastward above the top of the basement of the horst and cuts down into the sediment fill of the graben of the trench.

(*14*) (Fig. 1). We therefore identified the top of the plate-boundary fault at the contact between the inclined bedding of the deformed prism and the flat-lying basal sediments of the subducting plate at ~820 mbsf (Fig. 2).

The plate-boundary fault zone consists of a layer of brown clay with a unique scaly fabric not seen in any other portion of the core (Fig. 2). About 1 m of the scaly clay unit was recovered in core 17R (343_C0019E-17R-1) from the depth 821.5 to 822.65 mbsf. The contacts between the scaly clay and the bounding sediments were not recovered in cores, but, on the basis of adding the lengths of 17R and neighboring unrecovered sections, the total thickness of the scaly clay layer is less than 4.86 m (Fig. 2).

Log signature, lithology, chemical differences, and the tectonic fabric distinguish the scaly clay of core 17R as unique relative to all other sediments penetrated by the borehole (fig. S3). A greater concentration of K, Al, and Mn in the scaly clay layer relative to other core samples (fig. S3) and a comparison of the scaly clay to the basal reference section at site 436 suggest that the scaly clay is a Paleogene pelagic clay tectonically emplaced to its current position by slip within the fault zone. An increase in number of small shear bands [dark seams and bands (*7*)] and an increase in bulk density toward the scaly clay layer demarcate a ≤10-m-thick zone of fault-related deformation (Fig. 2); resistivity across the fault zone remains fairly constant, suggesting a lack of open fractures (Fig. 2 and fig. S3).

The scaly fabric defines a spaced, anastomosing foliation, dipping 0° to 30° that bounds variably shaped and sized lenses of clay (Fig. 2), similar to scaly fabrics in core recovered from other subduction thrusts (*15*). The scaly surfaces are lustrous and commonly striated, indicating distributed shear across the network of localized surfaces. The spacing of the surfaces is centimeter scale at the base of core 17R but decreases to millimeter scale near the top of the core, reflecting an increase in the magnitude of shear strain toward the upper tectonic contact. The scaly clay is bicolored (reddish-brown and dark brown to black), and the juxtaposition of the two colors of clay highlights a prominent, sharp contact in the upper, highly sheared section (Fig. 2). The contact is slightly wavy at the cm scale with amplitude less than 1 mm and truncates without deflection the foliations that are not parallel across the contact. We infer that this contact records seismic slip, although not necessarily that of the Tohoku-Oki earthquake, because the contact has characteristics similar to surfaces of large, localized slip and to surfaces of seismic rupture in other faults (*16*, *17*). Other surfaces of large, localized slip may lie within or at the boundaries of the scaly-clay layer at depth intervals that were not recovered during

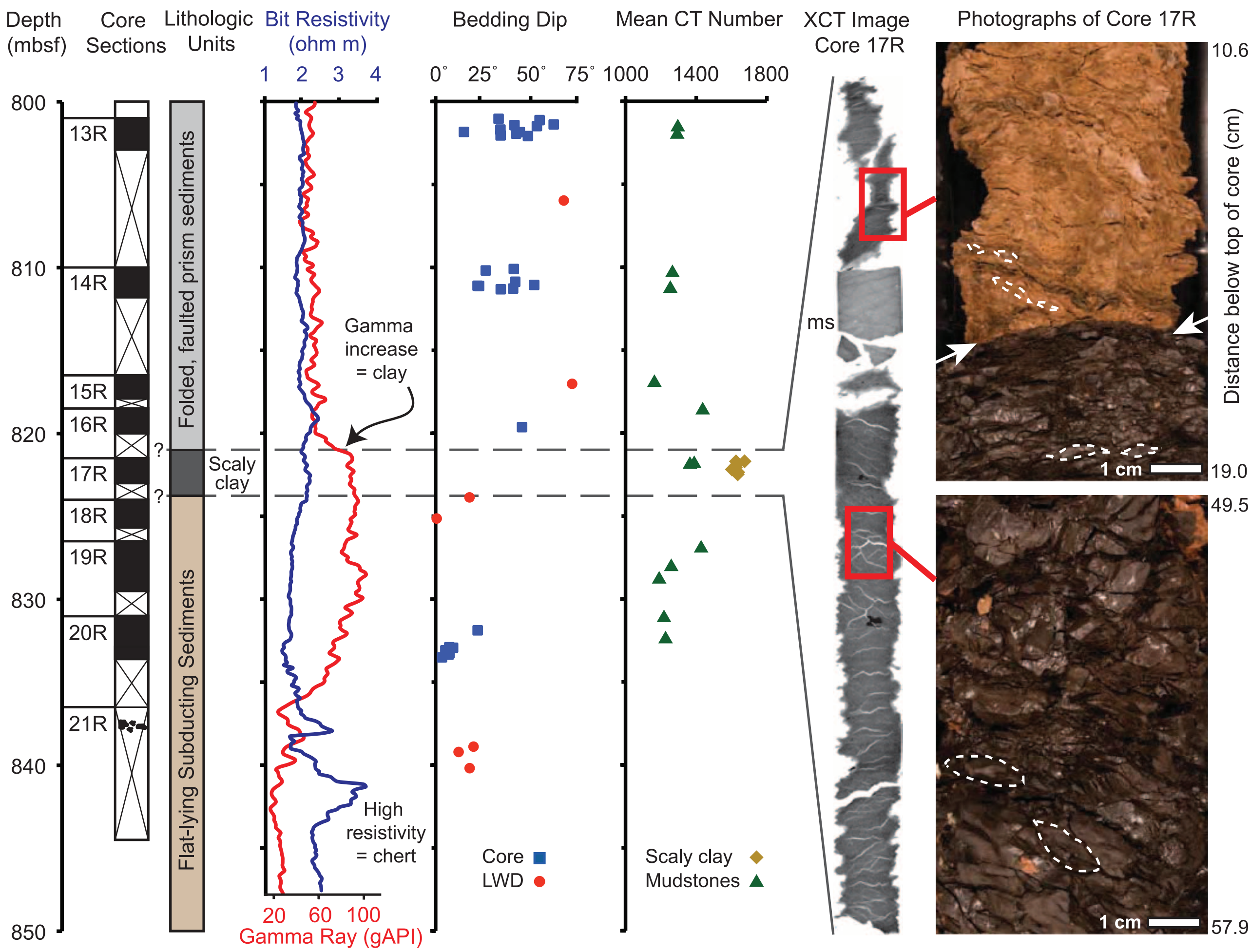

Fig. 2. Logs, core data, and images of the sampled plate-boundary fault zone. Sections of core recovery (black) and no recovery (white) for each cored interval (numbered) shown on left. Other data shown versus depth from the lower prism through the subducting sediments include lithologic units, resistivity (blue curve) and gamma ray (red curve; gAPI, American Petroleum Institute gamma ray units), bedding dip as determined from resistivity images (red circles; LWD, logging while drilling) and measured in core (blue squares), and mean computed tomography (CT) number (a proxy for density) in hanging wall and footwall mudstones (green triangles) and in the scaly clay (yellow diamonds) (*29*). The elevated CT number for the clay relative to that for the deformed mudstones likely reflects both consolidation and chemistry. X-ray CT image and core photos show scaly clay fabric. A few phacoids are outlined to demonstrate fabric scale and orientation (parallel to phacoid long axis). The sharp slip surface between red-brown and dark brown scaly clays with different fabric orientations is indicated with white arrows. Note that curvature of the surface of the core causes some planar features to appear curved.

coring and also would be candidate horizons of the Tohoku-Oki rupture.

The fault zone at the drill site is thinner with more penetrative scaly fabric and with less extensive deformation in adjacent sediments than fault zones observed in previous ocean-drilling and on-land studies (*18*, *19*). Accommodation of kilometers of shear displacement in the <5-m-thick scaly clay demonstrates marked long-term slip localization and that the clay layer has been weak relative to the bounding mudstones over the duration of fault activity (*16*, *20*). Indeed, the layer must be weaker than the surrounding sediments during periods of both seismic slip and interseismic creep. This finding is corroborated by direct laboratory measures of sliding friction for samples of the scaly clay at high shear rates (*21*) and of similar clay-rich materials at low shear rates (*22*).

Large slip during most historical earthquakes in the northwest Pacific did not extend close to the trench, but, when it has, there have been devastating consequences from unusually large tsunamis [the 1896 Meiji-Sanriku and 2011 Tohoku-Oki earthquakes (*23*, *24*)]. Similar to the shallow slip zone of the 2011 Tohoku-Oki earthquake, some other subduction zones show evidence that the lithostratigraphy of the incoming plate influences the location and the architecture of the plate-boundary fault [e.g., Barbados (*25*) and Sumatra (*26*)]. The pelagic sediments below the plate-boundary fault at the JFAST drill site are similar to those over much of the northwestern Pacific Plate (*27*). Because the site shares a history and stratigraphy with the rest of the northern Japan Trench, it is possible that the structure and relative mechanical properties observed here may be representative of the subduction thrusts throughout the region.

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29. Materials and methods are available as supplementary materials on *Science* Online.

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Supplementary Materials

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Low Coseismic Shear Stress on the Tohoku-Oki Megathrust Determined from Laboratory Experiments

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Large coseismic slip was thought to be unlikely to occur on the shallow portions of plate-boundary thrusts, but the 11 March 2011 Tohoku-Oki earthquake [moment magnitude (M_w) = 9.0] produced huge displacements of ~50 meters near the Japan Trench with a resultant devastating tsunami. To investigate the mechanisms of the very large fault movements, we conducted high-velocity (1.3 meters per second) friction experiments on samples retrieved from the plate-boundary thrust associated with the earthquake. The results show a small stress drop with very low peak and steady-state shear stress. The very low shear stress can be attributed to the abundance of weak clay (smectite) and thermal pressurization effects, which can facilitate fault slip. This behavior provides an explanation for the huge shallow slip that occurred during the earthquake.

Megathrust earthquakes commonly occur in subduction zones at depths where there is strong locking between the plates and long-term strain accumulation (*1*, *2*). In general, unconsolidated, soft sediments in the shallow region of the plate-boundary thrust (décollement) were thought to slip aseismically and have low levels of locking (*3*). The widely accepted view was that rupture during large earthquakes was unlikely to produce large slip on the shallow décollement (*1*–*3*). However, the coseismic fault slip extended all the way to the trench axis during the 11 March 2011 Tohoku-Oki earthquake [moment magnitude (M_w) = 9.0] with very large slip (~50 m), resulting in the huge tsunami that devastated much of the east coast of northern Honshu, Japan (*4*–*8*).

The Integrated Ocean Drilling Program (IODP) Expedition 343 and 343T, Japan Trench Fast Drilling Project (JFAST), provided an invaluable opportunity to investigate the plate-boundary décollement near the Japan Trench (*9*). JFAST successfully drilled the décollement at ~820 m

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