Three-Dimensional Splay Fault Geometry and Implications for Tsunami Generation

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leave meters of dust and sand. The accumulation of meters of sediments suggests that the non-ice component of an ice-rich MFF deposit may be larger than the maximum 10% estimated for the south polar layered deposits (SPLD) (*25*). This, in turn, suggests a higher modeled real dielectric constant than that of pure ice.

Although the real dielectric constant and dielectric losses may be consistent with an ice-rich material, the existing data do not exclude the possibility that the MFF deposits are an anomalously low density, ice-poor material. In either case, these deposits appear to have unique characteristics from other martian deposits studied to date by radar sounding. An ice-rich MFF raises the intriguing possibility of a large volume of water ice in the equatorial zone of Mars beneath a veneer of dust and sand. MARSIS observations suggest that the total volume of ice in the SPLD is ~1.6×10^6 km^3 (*25*). If the MFF deposits are ice-rich, estimates of their total volume suggest a volume of water comparable to that in the SPLD.

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Three-Dimensional Splay Fault Geometry and Implications for Tsunami Generation

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Megasplay faults, very long thrust faults that rise from the subduction plate boundary megathrust and intersect the sea floor at the landward edge of the accretionary prism, are thought to play a role in tsunami genesis. We imaged a megasplay thrust system along the Nankai Trough in three dimensions, which allowed us to map the splay fault geometry and its lateral continuity. The megasplay is continuous from the main plate interface fault upwards to the sea floor, where it cuts older thrust slices of the frontal accretionary prism. The thrust geometry and evidence of large-scale slumping of surficial sediments show that the fault is active and that the activity has evolved toward the landward direction with time, contrary to the usual seaward progression of accretionary thrusts. The megasplay fault has progressively steepened, substantially increasing the potential for vertical uplift of the sea floor with slip. We conclude that slip on the megasplay fault most likely contributed to generating devastating historic tsunamis, such as the 1944 moment magnitude 8.1 Tonankai event, and it is this geometry that makes this margin and others like it particularly prone to tsunami genesis.

Most of Earth's largest and most destructive earthquakes and tsunamis occur along the global belt of subduction zones (*1*–*4*). Great (moment magnitude > 8.0) earthquakes are generated when large areas of the subduction megathrust rupture, a process that often generates large tsunamis such as those produced by the 2004 Sumatra and 2006 Java earthquakes (*5*, *6*). The size and destructive power of tsunamis that often accompany great subduction earthquakes is determined largely by the amount and area of vertical uplift of the sea bed, and these factors are especially sensitive to the geometry of the slipping fault as the earthquake rupture approaches the sea floor (*7*–*9*). Very long thrust faults that rise from the plate boundary megathrust and intersect the sea floor along the lower slope of the margin—known as out-of-sequence or megasplay faults and recently identified as first-order features in the Nankai Trough (*10*, *11*)—are also common in other subduction zones such as Alaska (*12*, *13*), Sunda (*14*), and Colombia (*15*). These megasplay faults have been hypothesized to efficiently transfer displacement to the near surface, fostering tsunami genesis, but owing to the lack of resolution of the shallow structure of these faults, the capability of the megasplay in enhancing tsunami generation has been controversial (*16*, *17*). Moreover, an earthquake that ruptures up to (or near) the surface (i.e., one with a slip distribution skewed to the updip end) has an enhanced tsunamigenic potential (*18*).

The Nankai Trough is characterized by destructive earthquakes that occur repeatedly along the plate boundary megathrust (*19*). A large out-of-sequence thrust (OOST), first recognized as a strong seismic reflection (*10*), branches from the megathrust fault ~50 km landward of the trench south of Kii Peninsula, where it forms the trenchward boundary of Kumano Basin (Fig. 1). Swath-bathymetric and seismic reflection data show a pronounced, continuous outer ridge of topography that extends more than 120 km along the strike (Figs. 1 and 2) and is related to the splay fault slip. This fault, termed the "megasplay" (*11*), is a fundamental structural element of the margin. Substantial long-term slip is documented by sequence boundaries and progressive landward tilting of the strata in Kumano Basin (*3*).

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Moreover, the megasplay separates rocks with considerably higher seismic velocity on its landward side from rocks of lower seismic velocity toward the trench (*20*), indicating that it represents a major mechanical discontinuity and leading Wang and Hu (*21*) to hypothesize that the megasplay is the boundary between two distinct structural wedges: (i) a stronger "inner wedge" on its landward side overlying the seismogenically active part of the megathrust and (ii) a weaker "outer wedge" on the seaward side overlying the aseismic frontal décollement.

Many authors have speculated that coseismic slip is concentrated along the Nankai megasplay (*8*, *10*, *16*, *17*), but earthquake and tsunami inversions lack the resolution to distinguish between slip that has been diverted up the megasplay and slip along the frontal décollement segment of the plate boundary megathrust. What has been missing is evidence that the megasplay has recently been active and may thus have been responsible for the tsunami caused by the 1944 Tonankai earthquake. Mechanical arguments further suggest that the megasplay has participated in great subduction earthquakes (*21*, *22*). Wang and Hu (*21*) proposed that the accretionary prism (the outer wedge) can be described as a "dynamic Coulomb wedge," whose compressive deformation intensifies at the time of a great earthquake because of coseismic velocity-strengthening of the aseismic frontal décollement. The strengthening of the frontal décollement promotes slip upward along the megasplay.

Here, we present the results of two- and three-dimensional (2D and 3D) seismic reflection surveys across the Nankai Trough subduction complex south of central Honshu, Japan (Fig. 1). These new seismic data, acquired using a commercial seismic vessel towing four hydrophone streamers and two airgun source arrays (table S1), image the subduction plate boundary megathrust and the subsidiary megasplay (Figs. 2 to 4 and movie S1) that have caused great earthquakes and tsunamis in the past (*17*, *23*). The streamers recorded the reflected seismic wave field generated from the active seismic source directed into the sub–sea floor, and this wave field was then migrated to form the seismic images with 3D prestack time migration (table S1), typical for industrial seismic imaging (*24*). These images reveal the scale, continuity, and degree of geologically recent near-surface activity of the megasplay fault system, supporting the

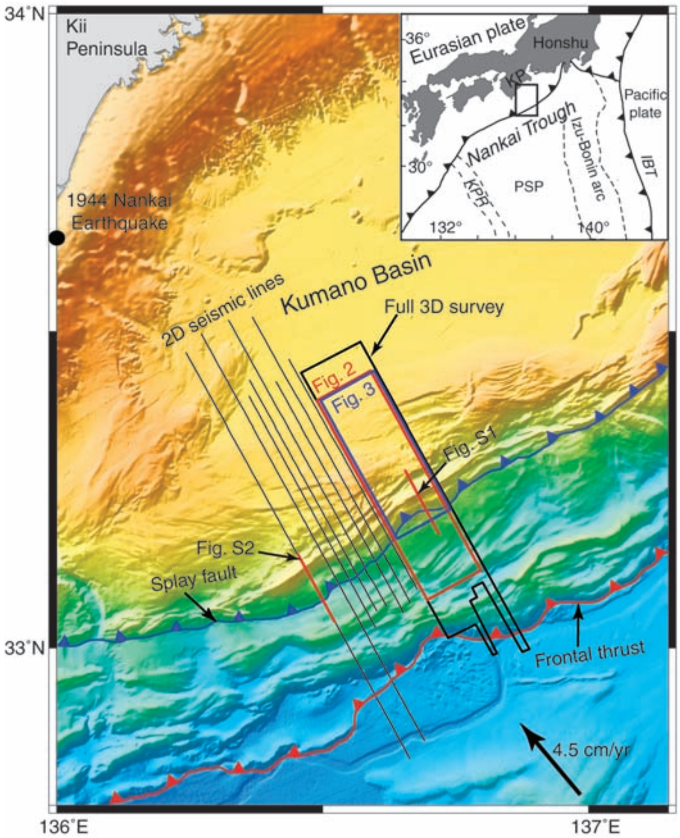

Fig. 1. Location map showing the regional setting of the Nankai Trough (upper right inset). PSP, Philippine Sea Plate; KPR, Kyushu-Palau Ridge; IBT, Izu-Bonin Trench; KP, Kii Peninsula. Convergence direction between the Philippine Sea Plate and Japan is shown at the lower right.

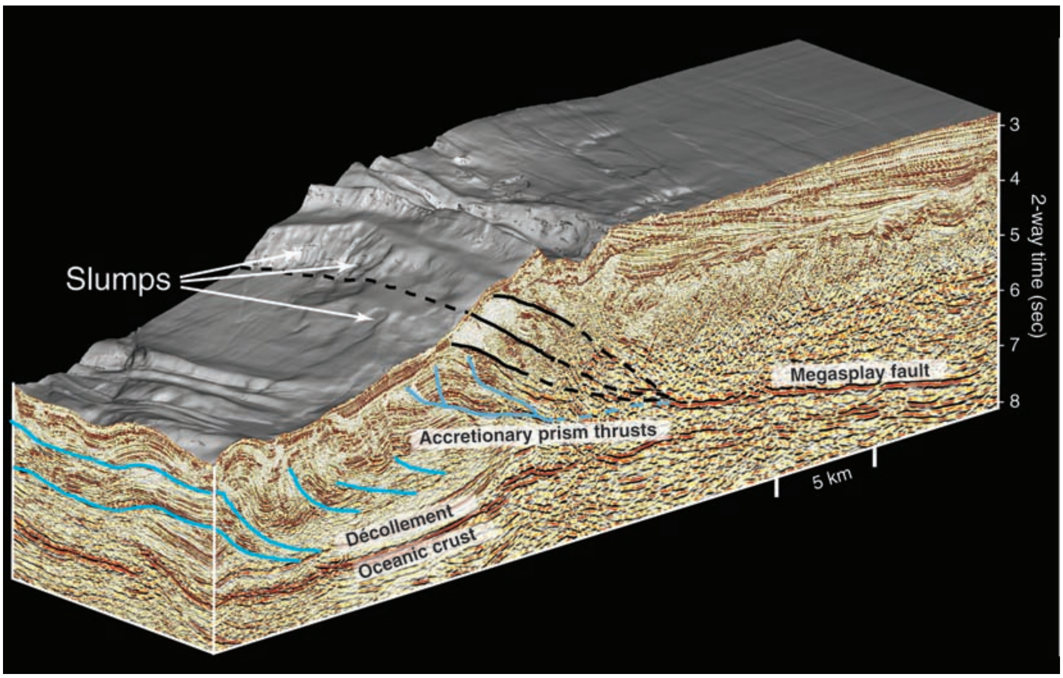

Fig. 2. 3D seismic data volume depicting the location of the megasplay fault (black lines) and its relationship to older in-sequence thrusts of the frontal accretionary prism (blue lines). Steep sea-floor topography and numerous slumps above the splay fault are shown.

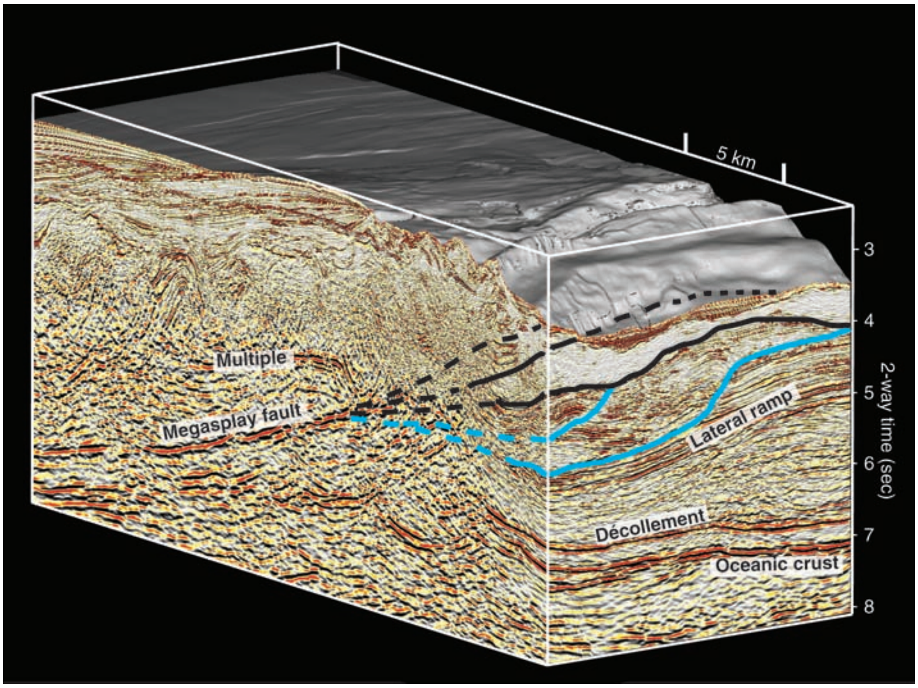

Fig. 3. 3D data volume showing relations of in-sequence thrusts of the frontal accretionary prism (blue lines) and the younger out-of-sequence branches of the splay fault (black lines). The top of a thrust sheet that has been folded above a lateral ramp in the frontal prism is cut off by the younger megasplay fault.

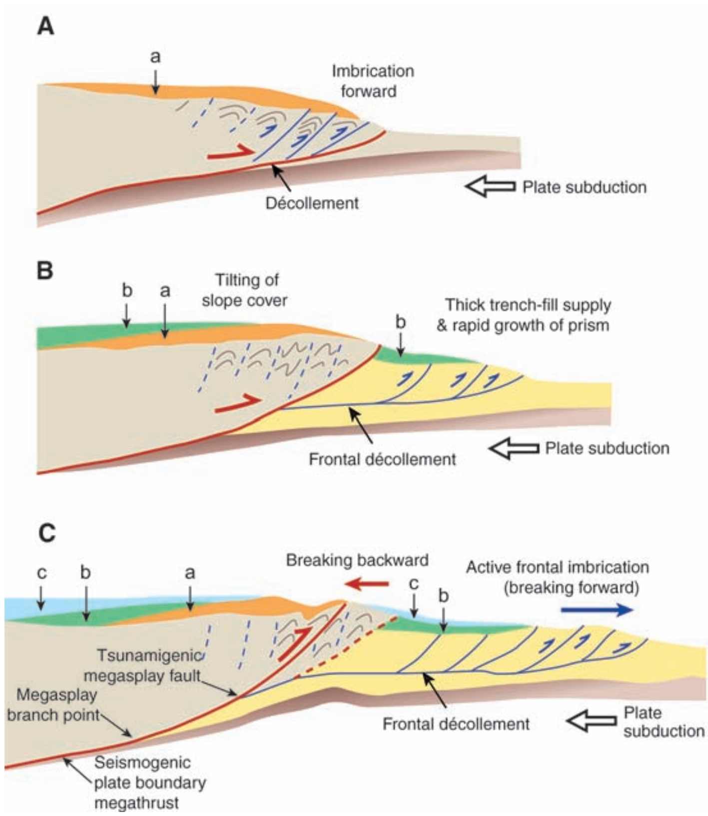

Fig. 4. (**A** to **C**) Summary diagram showing the development of the Nankai accretionary prism in the Kumano Basin area. After "normal" in-sequence thrusting and building of an accretionary prism, an out-of-sequence (splay) fault system broke through at the back of the prism. a, b, and c refer to sequential sedimentary sequences.

hypothesis that it is a first-order feature and a key part of the coseismic, tsunamigenic slip system. This detailed picture of the megasplay offers a key to link slip within the megathrust seismogenic zone up to the sea floor, the likely locus of tsunami generation. Our data thus demonstrate the connection between the regional megasplay fault that originates within the shallow portion of the seismogenic zone and the near-surface region. Slip directed along the megasplay to the sea floor, or near to it, could have generated the 1944 tsunami (Figs. 2 and 3).

The 3D geometry of the megasplay system shows that it has two branches, with the upper branch being younger (Fig. 2). Both branches truncate (and hence are younger than) the thrust faults within the accretionary prism. The top of the landward-most thrust package of the frontal accretionary zone (Figs. 2 and 3 and fig. S1) is cut off by the lower splay fault (Fig. 4B). This thrust package is deformed over a lateral ramp (Fig. 3), a branch off of an underlying thrust that dips to the southwest, perpendicular to the main direction of thrusting. If the overlying fault were older than the underlying fault, it would be carried "piggyback" on the underlying thrust and would also have been deformed by motion up the lateral ramp, but it is not. This observation further indicates that the thrusts are breaking backward (away from the deformation front) (Fig. 4C) in an OOST mode (*25*), rather than breaking forward (toward the deformation front) in an in-sequence mode that dominates the frontal part of this and other accretionary prisms (Fig. 4, A and B). In addition, a substantial amount of sediment has accumulated on top of the underlying thrust sheet and has been overridden by the advancing splay fault (fig. S1), indicating that the underlying thrust sheet was inactive before being overridden by the splay fault. Furthermore, the higher splay fault is clearly younger than the lower fault, because it has not yet overridden a substantial amount of slope sediment and the overall slope sediment cover is thinner than that covering the older fault.

Direct fault intersections with the sea floor are rare; however, a portion of a 2D line southwest of the 3D survey area illustrates clear propagation of the splay fault to the sea floor (fig. S2). This fault connects laterally to the lower splay fault shown in fig. S1, perhaps indicating that slip along the lower fault is still occurring in the southwest region. Thus, the fault does not everywhere propagate all the way to the surface; however, the displacement of this older thrust block during a great earthquake would generate a large tsunami, even without a sea-floor break (*9*).

A key to understanding the generation of tsunamis during great earthquakes is determining exactly where slip is apportioned on the splay/frontal décollement system. The amount of motion along the megasplay may control the magnitude of tsunami generation, and we presented several lines of evidence to indicate that the megasplay system is actively accommodating an appreciable component of plate boundary motion. The most compelling evidence connecting the megasplay to the recent tsunamigenic slip is the geographical coincidence with the updip termination of slip during the 1944 Tonankai event, as inferred from tsunami (*17*, *26*) and seismic (*27*) waveform inversions and recent structural studies. These studies all suggest that the megasplay may have experienced coseismic slip, so our discovery of recent movement along a strand of the megasplay system is strong evidence that lends support to this interpretation.

Inversion of earthquake seismicity data shows that rupture in the Tonankai earthquake initiated near the downdip end of the slip area and propagated updip (*23*). Inversion of tsunami data (*17*) cannot adequately distinguish contributions to wave generation from interplate slip along the décollement or along the splay fault during the Tonankai earthquake, but results favor slip along the splay fault. Because of the modeling techniques employed, the vertical resolution of the updip extent of both coseismic slip and tsunami source area is relatively poor. The horizontal resolution is better, however, and the slip inversions suggest that rupture did not propagate to the trench but terminated close to where the megasplay intersects the surface (*17*, *23*). As rupture approached the surface, it could have (i) continued along the basal décollement, dying out in soft sediments of the outer accretionary wedge, or (ii) propagated up the megasplay. Kame *et al*. (*22*) modeled this scenario using an elastodynamic fault formulation and concluded that coseismic slip on the megasplay branch is favored over the basal décollement and that simultaneous slip on both is unlikely. This mechanical argument, combined with the tsunami source modeling and our current observations, suggests that the megasplay thrust system is presently a part of the "plate boundary fault," as defined by megathrust earthquake rupture (Fig. 4C).

We have shown that the most active fault in the prism is the megasplay and that there is less activity on the frontal décollement. This splay fault represents one single fault that is continuous from the deep seismogenic zone up to the surface. This observation supports the suggestion by Wang and Hu (*21*) that the velocity-strengthening behavior of the frontal décollement causes the slip to concentrate along the megasplay during great earthquakes. As the mechanical boundary between the inner and outer accretionary wedge (*21*), the megasplay could thus be seen as producing a (deformable) backstop for the outer wedge. Major slip along a fault with the geometry of the megasplay during great earthquakes thus increases the potential for tsunamis and explains why this and some other margins foster tsunami generation whereas still others do not.

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Supporting Online Material

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Figs. S1 and S2
Table S1
Movie S1

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Rise and Fall of Species Occupancy in Cenozoic Fossil Mollusks

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In the time between speciation and extinction, a species' ecological and biogeographic footprint—its occupancy—will vary in response to macroecological drivers and historical contingencies. Despite their importance for understanding macroecological processes, general patterns of long-term species occupancy remain largely unknown. We documented the occupancy histories of Cenozoic marine mollusks from New Zealand. For both genera and species, these show a distinct pattern of increase to relatively short-lived peak occupancy at mid-duration, followed by a decline toward extinction. Thus, species at greatest risk for extinction are those that have already been in decline for a substantial period of time. This pattern of protracted rise and fall stands in contrast to that of incumbency, insofar as species show no general tendency to stay near maximal occupancy once established.

Every biologic group, at species rank and higher, varies over time in the size of its footprint on Earth. For example, *Homo sapiens* has spread from a minor species occupying a spot on the globe to complete dominance in many environments, whereas the phylum Brachiopoda has declined in species richness, numerical abundance, and range of occupied environments since the Paleozoic Era. Such observations are part of the basic narrative of the history of life. What is virtually unknown, however, is whether there is any overarching regularity to the waxing and waning of species, although a number of models, with varying predictions, have been proposed on the basis of limited available evidence [summarized in (*1*, *2*)].

Within marine invertebrates over the Phanerozoic Eon, species richness, frequency of occurrence, and geographic range increase and decrease nearly symmetrically on average over the duration of a genus (*3*), although certain subsets of genera show asymmetrical patterns (*3*, *4*). The pattern of regular increase in geographic range has also been demonstrated for Ordovician marine invertebrate genera (*5*). A survey of Late Cretaceous mollusks from the Gulf and Atlantic coasts of the United States found that geographic range and geologic longevity are correlated and that species originating

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