Origin and evolution of a splay fault in the Nankai accretionary wedge

Michael Strasser¹*, Gregory F. Moore^{2,3}, Gaku Kimura^{3,4}, Yujin Kitamura⁵, Achim J. Kopf¹, Siegfried Lallemant⁶, Jin-Oh Park^{3,7}, Elizabeth J. Screaton⁸, Xin Su⁹, Michael B. Underwood¹⁰ and Xixi Zhao¹¹

Subduction zones are often characterized by wedge-shaped sedimentary complexes—called accretionary prisms—that form when sediments are scraped off the subducting plate and added to the overriding plate. Large, landward-dipping thrust faults can cut through such a prism: these faults, known as 'megasplay faults'^{1,2}, originate near the top of the subducting plate and terminate at the shallow, landward edge of the prism^{1,3-6}. Megasplay faults have been the subject of numerous geological and geophysical studies⁴⁻¹⁵, but their initiation and evolution through time remains poorly constrained. Here we combine seismic reflection data from the Nankai accretionary wedge with geological data collected by the Integrated Ocean Drilling Program (IODP) and find that the splay fault cutting this wedge initiated \sim 1.95 Million years (Myr) ago in the lower part of the prism as an out-of-sequence thrust (OOST). After an initial phase of high activity, the movement along the fault slowed down, but uplift and reactivation of the fault resumed about 1.55 Myr ago. The alternating periods of high and low activity along the splay fault that we document hint at episodic changes in the mechanical stability of accretionary prisms.

Great earthquakes and tsunamis along subduction zones are generated when large areas of the megathrust rupture and slip propagates along faults, transferring displacement close to the sea bed. For example, the devastating wave generated by the 2004 Sumatra earthquake¹⁶ showed us this hazardous force of nature quite plainly. Many studies have inferred that coseismic slip along splay-faults provides a mechanism by which earthquakes generate tsunamis^{1,3-5,9,10}. On longer timescales, 'geologically' active splay faults may accommodate a significant portion of plate convergence stresses⁶. The geological history of such faults thus has important implications for the structural evolution of accretionary margins, as well as for the related tectonics of the seismogenic zone, and its geohazard potential. Conceptually, a splay fault may evolve from reactivation of preexisting faults or discontinuities, such as when the basal décollement is strengthening and its shear strength approaches the value of internal friction of the prism, or by readjustment of the wedge taper angle owing to a décollement step down and accompanied underplating^{12,13}.

For the Nankai Trough, where the Philippine Sea plate is subducting below south west Japan and repeatedly producing destructive earthquakes¹⁷, reflection seismic images have been used to identify such a splay fault as a first-order margin-dominating structure that extends more than 120 km along the strike^{4,5}. Mechanical arguments^{15,18}, seismic⁸ and tsunami^{9,10} waveform inversions, and reflection seismic data that image the splay fault–seafloor intersection⁵ strongly suggest that this fault, termed 'megasplay'², is the primary coseismic plate boundary near the up-dip terminus of slip and contributed to generating devastating historic tsunamis.

In the Kumano Basin area, the megasplay branches from the plate boundary thrust \sim 50 km landward of the trench⁴ (Fig. 1). Substantial long-term slip is documented by sequence boundaries and progressive landward tilting of strata in the forearc basin^{5,19}. The shallow part of the megasplay is a complex thrust system with backwards-breaking branches that truncate the imbricate thrust faults within the accretionary prism^{5,19}. This observation, along with the fact that slope sediments overlying the thrust sheet have been overridden by the megasplay, led to the conclusion that after 'normal' in-sequence thrusting and building of an accretionary prism, the out-of-sequence megasplay fault broke through at the back of the prism⁵. New results from the IODP Expedition 316 drilling the shallow portion of the megasplay and an adjacent slope basin partly overridden by the fault (Sites C0004 (ref. 20) and C0008 (ref. 21); Figs 1 and 2) allow us to test this interpretation, assign age control on the conceptual prism-development model, and explore the splay-fault origin and evolution and its relation to the structural evolution of the Nankai margin through time.

Coring at Site C0008A recovered the full slope-basin stratigraphic succession and the top of the underlying accretionary prism²¹. The boundary between older accreted sediments (unit II; maximum age 2.87 Myr (Fig. 3)) and the overlying slope-basin sediments (unit I) correlates to a high amplitude, landward-dipping seismic reflection, indicating that the accommodation for slopebasin sediments was created behind anticlinal structures related to in-sequence forward-propagating thrusts.

The lowermost part of the slope-basin stratigraphic succession consists of a 40-m-thick mass transport complex (MTC; ref. 21). In seismic data, the MTC corresponds to a package characterized by

¹MARUM, Centre for Marine Environmental Sciences, University of Bremen, 28359 Bremen, Germany, ²Department of Geology and Geophysics, University of Hawaii, Honolulu, Hawaii 96822, USA, ³Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science Technology, Kanazawa-ku, Yokohama, Kanagawa 2360001, Japan, ⁴Department of Earth and Planetary Science, The University of Tokyo, Tokyo 113-0033, Japan, ⁵IFM-GEOMAR, The Leibniz-Institute of Marine Sciences at University of Kiel, 24148 Kiel, Germany, ⁶Geosiences & Environment Cergy, University of Cergy-Pontoise, 95031 Cergy-Pontoise, France, ⁷Ocean Research Institute, The University of Tokyo, Tokyo 164-8639, Japan, ⁸Department of Geology, University of Florida, Gainesville, Florida 32611, USA, ⁹School of Marine Geosciences, China University of Geosciences, Beijing 100083, China, ¹⁰Department of Geological Sciences, University of Missouri, Columbia, Missouri 65211, USA, ¹¹Department of Earth and Planetary Sciences, University of California, Santa Cruz, California 95064, USA. *e-mail: mstrasser@marum.de.

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ETTERS



Figure 1 | **Geological setting of the Nankai accretionary wedge. a**, Shaded relief map of the Nankai Trough showing the regional setting of the IODP NanTroSEIZE (Nankai Trough Seismogenic Zone Experiment) drilling transect^{2,19}. The red line through IODP drill Sites C0002, C0004 and C0008 shows the location of the seismic cross-section in Fig. 1b. The inset is a tectonic map of the Philippine Sea region. b, Interpreted composite seismic line of the NanTroSEIZE transect, after Moore *et al.*¹⁹. VE = 2X: twofold vertical exaggeration.



Figure 2 | Data compilation across the shallow megasplay system. Detail and interpretation of the seismic inline IL 2675 crossing IODP Sites C0004, C0008A and C0008C. The location is shown in Fig. 1b. Overlain are lithostratigraphic sections of drill sites (see Fig. 3 for the symbol legend) and age constraints for key stratigraphic horizons^{20,21}.

low amplitude, fuzzy reflections of low lateral continuity. This body thickens towards the northwest where it has been fully overridden by the splay fault, which indicates that the fault has been active almost since the onset of MTC formation. The low content of calcite leads us to conclude that in its early stage, the basin was in deep water below the calcite compensation depth (CCD (ref. 22); Fig. 3). Magnetostratigraphy shows that the whole MTC was deposited during times of continuously positive polarities correlated to the Olduvai subchron (1.95–1.77 Myr; Fig. 3). We thus interpret the occurrence of older nanofossil assemblages within the lower part of the MTC as being reworked (Fig. 3) and assign an age of \sim 1.95 Myr to the base.

This date further provides a minimum age for accretion. It follows that Site C0008 was at a frontal-prism-toe position sometime between 2.87 and 1.95 Myr. This relatively large time span suggests a stratigraphic hiatus and that the MTC does not

conformably overlie the prism. Similarly, maximum and minimum accretion ages for the prism now uplifted in the hanging-wall block of the splay fault can be constrained from age control over the lithological boundary between overlying slope-apron sediments and underlying accreted strata at Site C0004. In the core, this boundary corresponds to a sharp angular unconformity with a hiatus spanning between 1.46-1.6 and 2.06 to 2.512 Myr, and between 1.77 and 1.95 Myr, as derived from nanofossil biostratigraphy and magnetostratigraphy, respectively²⁰ (Fig. 3). There is some discrepancy between the age models, but we know that the accretion age has to be older at Site C0004 than at Site C0008, as reasoned by geometrical arguments within the splayfault thrust system. We use the overlap range for maximum and minimum accretion ages at both sites to conclude that there is no major discontinuity in accretion age even where the splayfault system is crossed. Hence, our data document that sometime

LETTERS

NATURE GEOSCIENCE DOI: 10.1038/NGEO609



Figure 3 | **IODP Sites CO004 and CO008; core data.** Compilation of the magnetostratigraphy, biostratigraphy, lithostratigraphy and content of calcite values for Sites C0004 (ref. 20) and C0008 (ref. 21). Blue boxes in the nanofossil event column indicate likely reworking due to mass movements. The dashed vertical line in the content of calcite plot marks the interpreted threshold condition for deposition below or above the calcite compensation depth CCD (\sim 4.0 ± 0.6 km; ref. 22). Note that we have interpreted this value as 10% calcite, which still accounts for some (10%) calcite reworking by downslope sediment transport processes. The magnetostratigraphy abbreviations are: B: Brunhes chron, M: Matuyama chron, Ga: Gauss chron, Gi: Gilbert chron, J: Jaramillo subchron, CM: Cobb Mountain subchron, O: Olduvai subchron, E: Emporer event.

between 2.512 and 1.95 Myr (with an older age within this age range being more likely) the tectono-stratigraphic system was in a frontalprism-toe position with a forward-propagating deformation front at a nearly steady rate of accretion (Fig. 4d). At \sim 1.95 Myr, what is now the shallow portion of the megasplay initiated as an OOST that overrode mass-wasting deposits accumulating in the slope basin situated in a lower prism position below the CCD (Fig. 4c).

The subsequent evolution of the splay-fault system is reconstructed by back-stripping fault movements in seismic data (Fig. 4, Supplementary Fig. S1). Along the transect studied, the fault zone is bounded by an upper and a lower fault²⁰ (Fig. 2), the lateral extent of which, however, is small, suggesting an anastomosing pattern of the shallow part of the megasplay fault system¹⁹. The lower fault does not cut the shallow slope sediments younger than 1.46-1.6 Myr but the upper fault cuts them and thus is younger. Back-stripping movement along the lower branch, which our data show to have been active between \sim 1.95 and \sim 1.55 Myr, reveals horizontal throw rates of \sim 8.6 m kyr⁻¹ between 1.95 and 1.8 Myr, 2.5 m kyr⁻¹ between 1.8 and 1.7 Myr, and 1.93 m kyr⁻¹ between 1.7 and 1.55 Myr (Fig. 4, Supplementary Fig. S1). This suggests that after an initial high-activity phase, movement along the lower fault continuously decreased. During its initial phase between 1.95 and 1.8 Myr the OOST accommodated ~15-22% of the estimated plate convergence during that time, as inferred by relating the reconstructed horizontal throw rate along the fault to mean plate motions of between 4 cm yr^{-1} (ref. 23) and 6 cm yr^{-1} (ref. 24). This relatively high value suggests that during that time, prism forward growth was probably diminished or temporarily ceased (Fig. 4c). Since ~1.8 Myr, the initial high-activity period then was followed by ~250 kyr of decreased rate of outof-sequence thrusting, most likely accompanied by more efficient transfer of the plate convergence to the frontal prism, resulting in forward propagation of the deformation front and accretion by in-sequence thrusting (Fig. 4b).

This reconstruction does not support the previously held hypothesis that onset of movement along the splay-fault system and associated uplift of the hanging-wall block caused formation of the forearc high, thereby creating accommodation and favouring onset of rapid sedimentation in the Kumano Basin⁵. Results from IODP Expedition 315 (ref. 25) coring at Site C0002 (Fig. 1) integrated with three-dimensional seismic interpretation¹⁹ indicate that rapid forearc-basin deposition started around 1.56-1.67 Myr, and thus \sim 400 kyr after our inferred age of splay-fault origin. One possible explanation for this discrepancy would be a time delay between creation of accommodation and the reorganization of sediment-delivery systems²⁵. Alternatively, as suggested by our analysis, this discrepancy can be explained by interpreting thrusting along the lower splay-fault branch as corresponding to activity along the initial OOST in a frontal-prism setting. Formation of the forearc high and subsequent onset of rapid forearc-basin sedimentation then links to uplift and reactivation of this OOST as a 'megasplay' system ~1.56-1.67 Myr ago. This interpretation is reinforced by low concentration of calcite in the underthrust section at Site C0004 (Fig. 3), revealing that at least until 1.56-1.61 Myr, deposition occurred below CCD and uplift thus has to be younger. Similarly, the increase of content of calcite in the slope sediment strata at Site C0008A between \sim 160 and 40 m below the seafloor (mbsf) suggests that the tectono-stratigraphic system became shallower at some time between \sim 1.6 and \sim 1.24 Myr (Fig. 3).

Reconstruction of throw rates along the upper megasplay fault since 1.55 Myr cannot be constrained because no tie-points are available. But owing to the significant age reversal of more than 1 Myr over the fault drilled at Site C0004 (ref. 20) (Fig. 3), throw is expected to be large. Along the IODP drilling transect studied it

NATURE GEOSCIENCE DOI: 10.1038/NGEO609

LETTERS



Figure 4 | Summary diagram showing the splay-fault origin and evolution

in the Nankai accretionary wedge. a-d, Left and right panels show overall sketches of accretionary prism scale and close-up views on the shallow megasplay system, respectively, for different time steps. The sizes of the red and blue arrows indicate the relative activities of the splay fault and prism forward growth, respectively. The dashed horizontal line shows the approximate depth of the carbonate compensation depth (CCD). The splay-fault system initiated ~1.95 Myr ago as an OOST in the lower part of the accretionary wedge. From ~1.55 Myr, this initial OOST has been uplifted and became reactivated, favouring ongoing 'megasplay' slip along it. Alternating periods of high and low splay-fault activity are linked in an out-of-phase mode to accretionary prism forward growth and in-sequence frontal imbrications.

seems that displacement along this short segment of the megasplay fault ceased at \sim 1.24 Myr, suggesting that it only experienced a relatively short period of high activity between \sim 1.55 and 1.24 Myr. This interpretation is supported by high sedimentation rates in the slope basin and the occurrences of age reversals within the time-correlative section at Site C0008 (ref. 21; Fig. 3) that reflect a highly dynamic sedimentation and mass-wasting regime during this period of high splay-fault activity. This was followed by a phase during which activity decreased or dislocated through backward branching in the shallow part of this fault segment, as demonstrated by Moore and colleagues⁵. However, seismic data clearly show that the megasplay truncates very young sediments near the seabed adjacent to the drilling transect, revealing that various small segments of the fault system are moving independently and that the megasplay system in general is thus still highly active^{5,19}.

In summary, our results present a dynamic picture beginning with the birth and the early evolution of the Nankai megasplay fault system, which records out-of-sequence thrusting in the lower part of the accretionary prism starting at ~1.95 Myr, followed by uplift and ongoing/reactivated activity as megasplay fault since ~1.55 Myr. Our most significant conclusion is that splay-fault activity varies through time, with alternating high-activity periods during which splay-fault thrusting accommodates a large part of the plate convergence and phases, with a decrease of throw along the OOST but more efficient transfer to the deformation front resulting in in-sequence frontal imbrication. This implies alternating overall accretionary prism mechanical stability, the forcing factor(s) of which remain to be discovered. Possible candidates are roughness changes on the incoming plate (for example, ridges or seamounts) or changes in trench sedimentation influencing pore-pressure evolution and mechanical stability of the sedimentary section on the subducting oceanic plate. Both processes have been documented and proposed to affect the evolution of the Nankai accretionary prism and the seismogenic zone^{26–30}. Future studies using new IODP samples and data from deep drill holes² will yield the means to explore whether and how they may control the observed alternating splay-fault activity, and its relation to the onset of forearc-basin sedimentation and changes in rate of prism forward growth.

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LETTERS

NATURE GEOSCIENCE DOI: 10.1038/NGEO609

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Author contributions

M.S., paper writing, lithostratigraphy, data integration, conceptual model; G.M., paper writing, seismic stratigraphy, conceptual model, project planning; G.K., E.J.S., project planning, data integration, J.-O.P., seismic data processing, conceptual model; A.J.K., S.L., conceptual model; Y.K., X.Z., magnetostratigraphy, X.S., biostratigraphy, M.B.U., lithostratigraphy, mineralogy, data integration.

Additional information

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SUPPLEMENTARY INFORMATION

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Suplementary Figure S1: Back-stripping of seismic data and reconstruction of splay-fault development

The figures shows Interpretation of seismic inline 2675 crossing Sites C0004, C0008A and C0008C, and age constraints of key horizons from borehole data²¹, that was used as basis for back-stripping displacement along the splay fault. VE = vertical exaggeration. Location is shown in Fig. 1B. Table below shows reconstructed throw estimates as inferred from the back-stripping. Note that the horizontal throw rate reconstructed for the time period between 1.95 and 1.8 Ma may only represent an approximate value, because extrapolation of isochron 1.95 Ma down to depth of >3.5km may not be unique (dashed red line) and part of the horizontal throw may have been accommodated by secondary faults shown by the thin blue lines.