LETTERS
PUBLISHED ONLINE: 16 AUGUST 2009 | DOI: 10.1038/NGEO609
nature geoscience

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

Michael Strasser[1]*, Gregory F. Moore[2,3], Gaku Kimura[3,4], Yujin Kitamura[5], Achim J. Kopf[1], Siegfried Lallemant[6], Jin-Oh Park[3,7], Elizabeth J. Screaton[8], Xin Su[9], Michael B. Underwood[10] and Xixi Zhao[11]

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 studies[4–15], 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 ∼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 earthquake[16] 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 stresses[6]. 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 pre-existing 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 earthquakes[17], 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], seismic[8] and tsunami[9,10] waveform inversions, and reflection seismic data that image the splay fault–seafloor intersection[5] 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 ∼50 km landward of the trench[4] (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 prism[5]. 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 prism[21]. 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 slope-basin 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

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

© 2009 Macmillan Publishers Limited. All rights reserved.

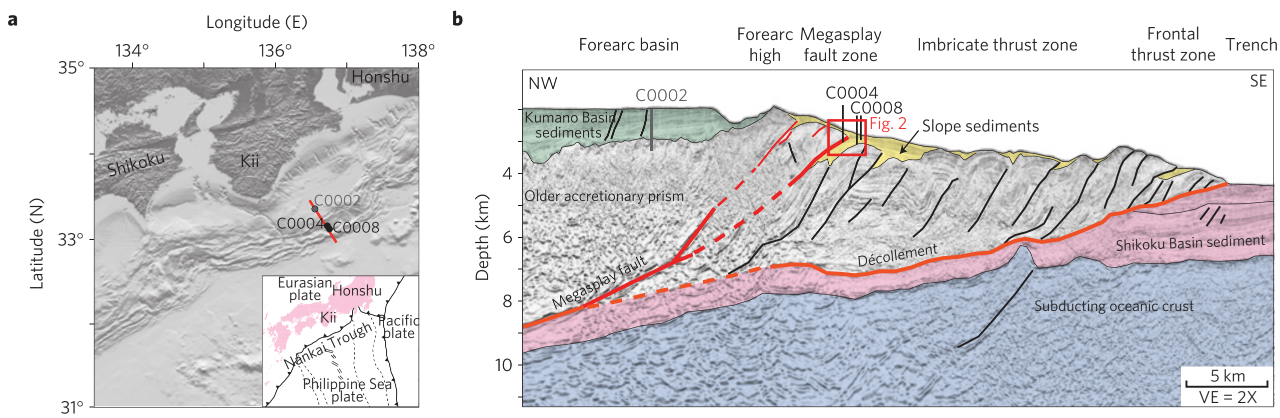


Figure 1 | Geological setting of the Nankai accretionary wedge. a, Shaded relief map of the Nankai Trough showing the regional setting of the IODP NanTroSEIZE (Nankai Trough Seismogenic Zone Experiment) drilling transect[2,19]. The red line through IODP drill Sites C0002, C0004 and C0008 shows the location 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.

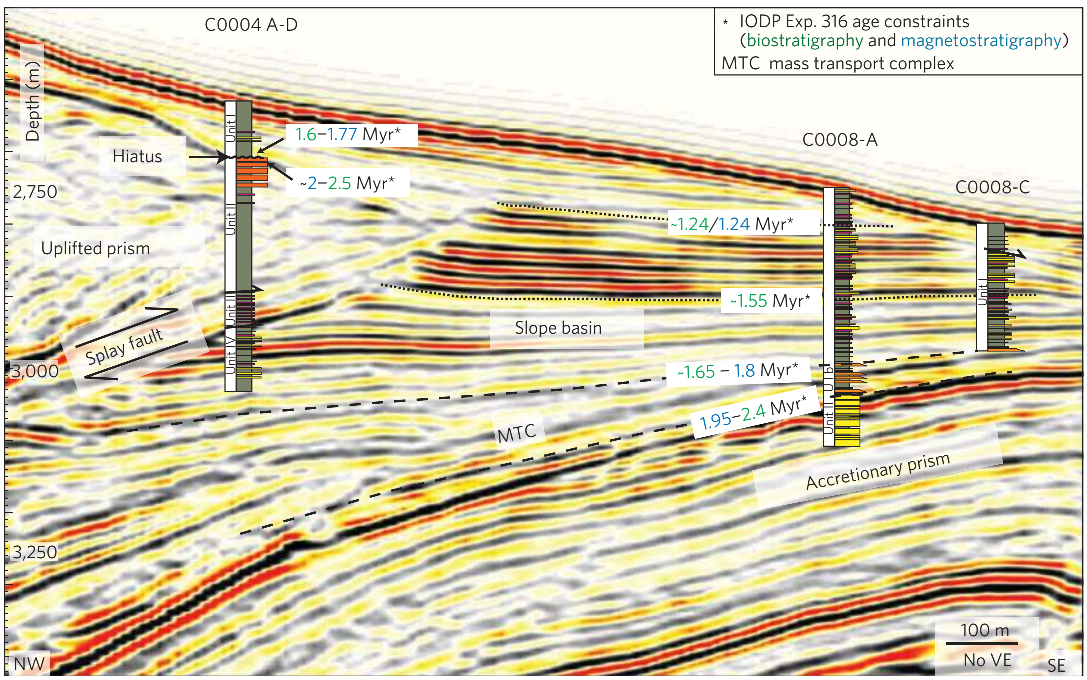


Figure 2 | Data compilation across the shallow megasplay system. Detail and interpretation of the seismic inline IL 2675 crossing IODP Sites C0004, C0008A and C0008C. The location is shown in Fig. 1b. Overlain are lithostratigraphic sections of drill sites (see Fig. 3 for the symbol legend) and age constraints 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 ~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, respectively[20] (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 splay-fault 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 splay-fault system is crossed. Hence, our data document that sometime

© 2009 Macmillan Publishers Limited. All rights reserved.

NATURE GEOSCIENCE DOI: 10.1038/NGEO609

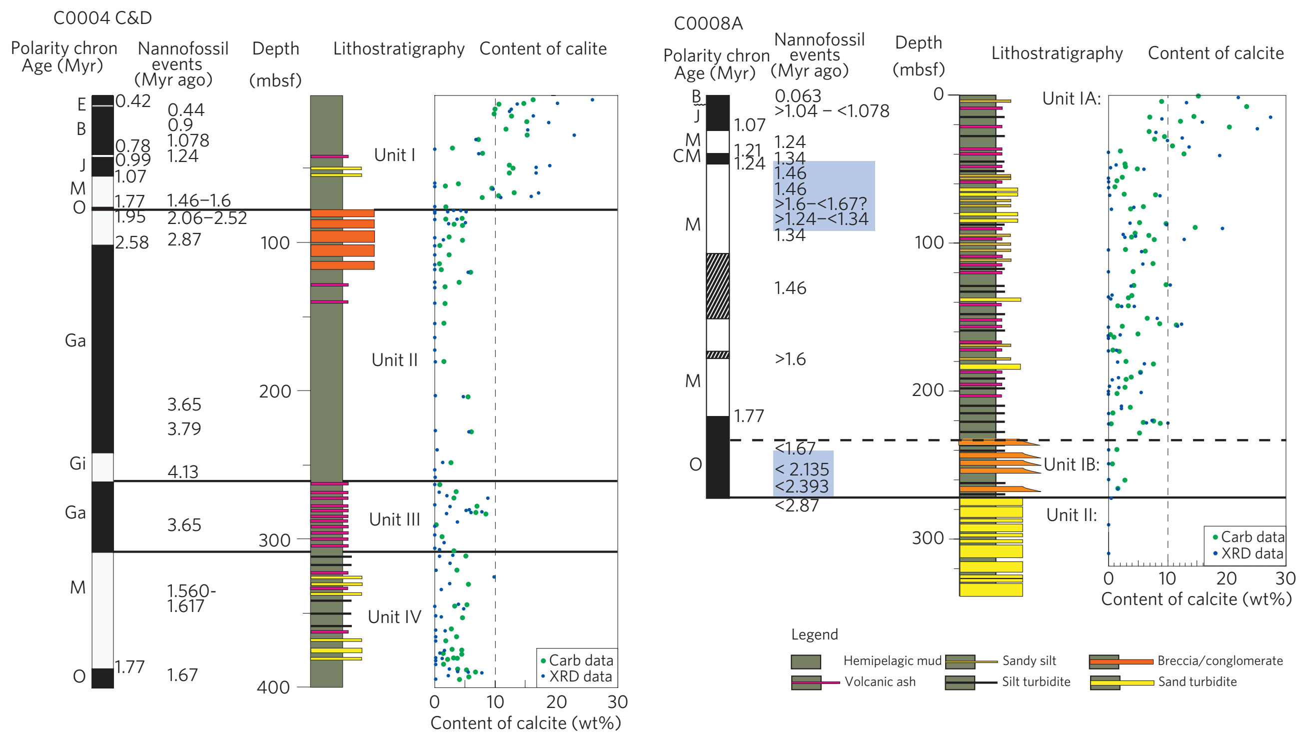


Figure 3 | IODP Sites C0004 and C0008; core data. Compilation of the magnetostratigraphy, biostratigraphy, lithostratigraphy and content of calcite values for Sites C0004 (ref. 20) and C0008 (ref. 21). Blue boxes in the nanofossil event column indicate likely reworking due to mass movements. The dashed 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 $\pm$ 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 frontal-prism-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 fault[20] (Fig. 2), the lateral extent of which, however, is small, suggesting an anastomosing pattern of the shallow part of the megasplay fault system[19]. 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 $\sim$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 $\sim$1.8 Myr, the initial high-activity period then was followed by $\sim$250 kyr of decreased rate of out-of-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 Basin[5]. Results from IODP Expedition 315 (ref. 25) coring at Site C0002 (Fig. 1) integrated with three-dimensional seismic interpretation[19] 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 systems[25]. 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 $\sim$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

© 2009 Macmillan Publishers Limited. All rights reserved.

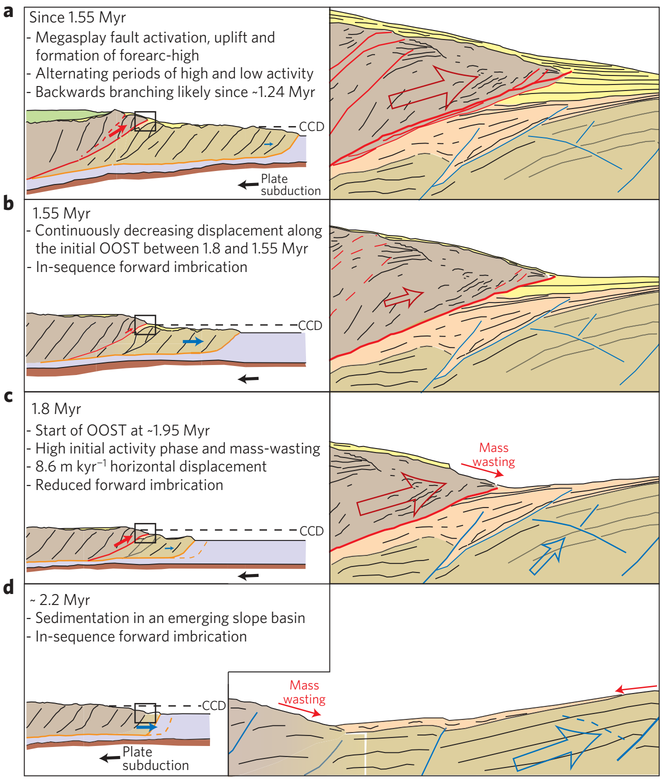


Figure 4 | Summary diagram showing the splay-fault origin and evolution in the Nankai accretionary wedge. a–d, Left and right panels show overall sketches of accretionary prism scale and close-up views on the shallow megasplay system, respectively, for different time steps. The sizes of the red and blue 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 ~1.24 Myr, suggesting that it only experienced a relatively short period of high activity between ~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 colleagues[5]. 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 holes[2] 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.

Received 6 April 2009; accepted 22 July 2009; published online 16 August 2009

References

1. Fukao, Y. Tsunami earthquakes and subduction processes near deep-sea trenches. *J. Geophys. Res.* **84,** 2303–2314 (1979).
2. Tobin, H. J. & Kinoshita, M. NanTroSEIZE: The IODP Nankai trough seismogenic zone experiment. *Sci. Drill.* **2,** 23–27 (2006).
3. Plafker, G. Alaskan earthquake of 1964 and Chilean earthquake of 1960: Implications for arc tectonics. *J. Geophys. Res.* **77,** 901–925 (1972).
4. Park, J.-O., Tsuru, T., Kodaira, S., Cummins, P. R. & Kaneda, Y. Splay fault branching along the Nankai subduction zone. *Science* **297,** 1157–1160 (2002).
5. Moore, G. F. *et al.* Three-dimensional splay fault geometry and implications for tsunami generation. *Science* **318,** 1128–1131 (2007).
6. Collot, J. Y., Agudelo, W., Ribodetti, A. & Marcailou, B. Origin of a crustal splay fault and its relation to the seismogenic zone and underplating at the erosional north Ecuador—south Colombia oceanic margin. *J. Geophys. Res.* **113,** B12102 (2008).
7. Bangs, N. L. *et al.* Broad, weak regions of the Nankai Megathrust and implications for shallow coseismic slip. *Earth Planet. Sci. Lett.* **284,** 44–49 (2009).
8. Kikuchi, M., Nakamura, M. & Yoshikawa, K. Source rupture processes of the 1944 Tonankai earthquake and the 1945 Mikawa earthquake derived from low-gain seismograms. *Earth Planets Space* **55,** 159–172 (2003).
9. Baba, T., Cummins, P. R., Hori, T. & Kaneda, Y. High precision slip distribution of the 1944 Tonankai earthquake inferred from tsunami waveforms: Possible slip on a splay fault. *Tectonophysics* **426,** 119–134 (2006).
10. Tanioka, Y. & Satake, K. Detailed coseismic slip distribution of the 1944 Tonankai earthquake estimated from tsunami waveforms. *Geophys. Res. Lett.* **28,** 1075–1078 (2001).
11. Katsumi, K. Out-of-sequence thrust of an accretionary complex. *Mem. Geol. Soc. Jpn* **50,** 131–146 (1998).
12. Kimura, G. *et al.* Transition of accretionary wedge structures around the up-dip limit of the seismogenic subduction zone. *Earth Planet. Sci. Lett.* **255,** 471–484 (2007).
13. Morley, C. K. Out-of-sequence thrusts. *Tectonics* **7,** 539–561 (1988).
14. Gutscher, M.-A., Kukowski, N., Malavieille, J. & Lallemand, S. Cyclical behavior of thrust wedges: Insights from high basal friction sandbox experiments. *Geology* **24,** 135–138 (1996).
15. Wang, K. & Hu, Y. Accretionary prisms in subduction earthquake cycles: The theory of dynamic Coulomb wedge. *J. Geophys. Res.* **111,** B06410 (2006).
16. Lay, T. *et al.* The great Sumatra–Andaman earthquake of 26 December 2004. *Science* **308,** 1127–1133 (2005).
17. Ando, M. Source mechanisms and tectonic significance of historical earthquakes along the Nankai trough, Japan. *Tectonophysics* **27,** 119–140 (1975).
18. Kame, N., Rice, J. R. & Dmowska, R. Effects of prestress state and rupture velocity on dynamic fault branching. *J. Geophys. Res.* **108,** B5-2265 (2003).
19. Moore, G. F. *et al.* in *Structural and Seismic Stratigraphic Framework of the NanTroSEIZE Stage 1 Transect: Proc. IODP 314/315/316* (eds Kinoshita, M. *et al.*) (Integrated Ocean Drilling Program Management International, 2009).
20. Kinoshita, M. *et al.* (eds) *Expedition 316 Scientists. Expedition 316 Site C0004: Proc. IODP 314/315/316* (Integrated Ocean Drilling Program Management International, 2009).
21. Kinoshita, M. *et al.* (eds) *Expedition 316 Scientists. Expedition 316 Site C0008: Proc. IODP 314/315/316* (Integrated Ocean Drilling Program Management International, 2009).
22. Van Andel, T. H. Mesozoic/Cenozoic calcite compensation depth and the global distribution of calcareous sediments. *Earth Planet. Sci. Lett.* **26,** 187–194 (1975).

© 2009 Macmillan Publishers Limited. All rights reserved.

23. Seno, T., Stein, S. & Gripp, A. E. A model for the motion of the Philippine sea plate consistent with Nuvel-1 and geological data. *J. Geophys. Res.* **98,** 17941–17948 (1993).
24. Miyazaki, S. I. & Heki, K. Crustal velocity field of southwest Japan: Subduction and arc–arc collision. *J. Geophys. Res.* **106,** 4305–4326 (2001).
25. Kinoshita, M. *et al.* (eds) *Expedition 315 Scientists. Expedition 315 Site C0002: Proc. IODP 314/315/316* (Integrated Ocean Drilling Program Management International, 2009).
26. Kodaira, S. *et al.* Cyclic ridge subduction at an inter-plate locked zone off central Japan. *Geophys. Res. Lett.* **30,** 1339 (2003).
27. Park, J.-O., Moore, G. F., Tsuru, T., Kodaira, S. & Kaneda, Y. A subducted oceanic ridge influencing the Nankai megathrust earthquake rupture. *Earth Planet. Sci. Lett.* **217,** 77–84 (2003).
28. Bangs, N. L. B., Gulick, S. P. S. & Shipley, T. H. Seamount subduction erosion in the Nankai Trough and its potential impact on the seismogenic zone. *Geology* **34,** 701–704 (2006).
29. Screaton, E. J., Saffer, D., Henry, P. & Kunze, S. Porosity loss within the underthrust sediment of the Nankai accretionary complex: Implications for overpressures. *Geology* **30,** 19–22 (2002).
30. Saffer, D. & Bekins, B. A. Hydrologic controls on the morphology and mechanics of accretionary wedges. *Geology* **30,** 271–274 (2002).

Acknowledgements

This research used samples and data provided by the Integrated Ocean Drilling Program (IODP). This work was supported by fellowship grants from the Swiss National Science Foundation (Grant No PBEZ2-118865) and the DFG-Research Centre/Cluster of Excellence 'The Ocean in the Earth System' (to M.S.), the US National Science Foundation to the University of Hawaii (G.M.) and the Japanese Ministry of Education, Culture, Science, Sports, and Technology to JAMSTEC.

Author contributions

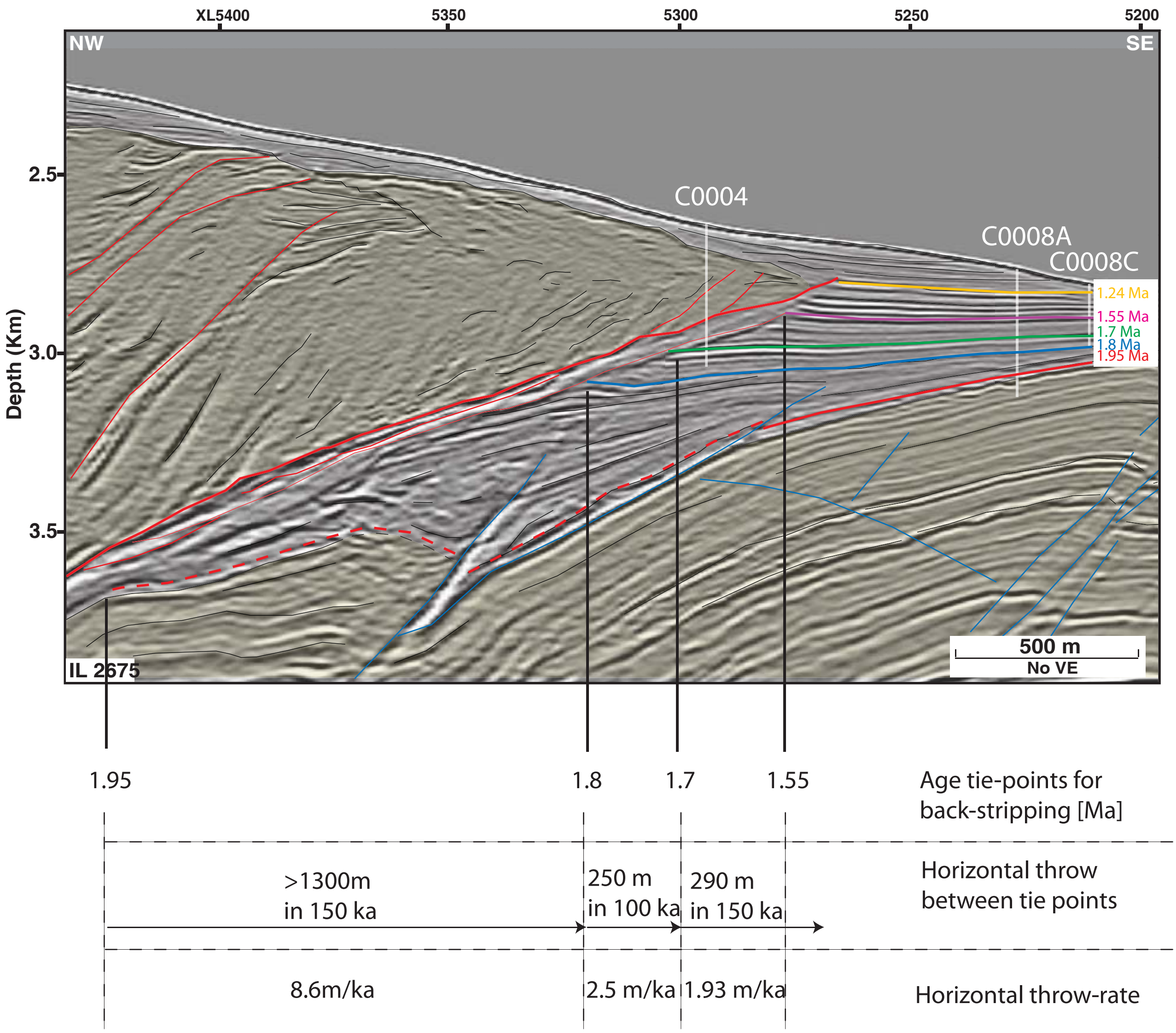
M.S., paper writing, lithostratigraphy, data integration, conceptual model; G.M., paper writing, seismic stratigraphy, conceptual model, project planning; G.K., E.J.S., project planning, data integration, J.-O.P., seismic data processing, conceptual model; A.J.K., S.L., conceptual model; Y.K., X.Z.,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

Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to M.S.

© 2009 Macmillan Publishers Limited. All rights reserved.

nature geoscience
SUPPLEMENTARY INFORMATION
DOI: 10.1038/NGEO609



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 data[21], 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.