T41A MC: Hall D Thursday 0830h

Nankai Seismogenic Zone: Results from ODP Coring and Logging, Experiments, and Submersibles *(joint with OS, S)*

Presiding: **A Klaus,** Texas AM**; J ashi,** Univ. of Tokyo

T41A-0847 0830h POSTER

Deformation, Structure, and Hydrogeology in the Nankai Accretionary Prism, Japan: Initial Results of ODP Leg 196 Logging While Drilling and Installation of Long-term Hydrogeological Observatories

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Leg 196 was the second of a two-leg program of coring, logging, and installing advanced CORK (ACORK) long-term hydrogeological observatories in the Nankai Trough, the type example of a convergent margin accreting a thick section of clastic sediments. The two-leg program was built on results from Leg 131 and was designed to define the interrelationship of deformation, structure, and hydrogeology in the Nankai accretionary prism. Leg 196 focused on logging while drilling (LWD) and installation of ACORKs at two sites near the toe of the Nankai prism: Site 808, cored during Leg 131 at the deformation front, and Site 1173, cored during Leg 190 as a reference site 12 km seaward.

At Hole 1173B we collected LWD data to basement at 737 meters below seafloor (mbsf). Here the LWD data verify a subtle porosity increase with depth from 122 to 340 mbsf, followed downhole by a sharp decrease in porosity and return to a normal consolidation trend. The sharp decrease in porosity correlated with the diagenetic transition from cristobalite to quartz and is marked by a strong seismic reflector that is reproduced well by a synthetic seismogram based on the LWD data. Resistivity-at-the bit (RAB) images of the borehole show no evidence of a propagating protodecollement but, rather, reveal a basinal state of stress dominated by steeply dipping fractures and normal faults of variable strike.

In Hole 808I we acquired LWD data to just below the decollement (1035 mbsf); poor drilling conditions precluded further penetration. Borehole Resitivity At Bit (RAB) images provide unparalleled structural and stratigraphic detail across the frontal thrust and decollement that indicate northwest-southeast shortening consistent with the seismic reflection data. RAB images also document borehole breakouts that show a northwest-southeast oriented maximum principal in situ stress direction, nearly parallel to the maximum principal stress direction inferred from microfaults in cores and from the plate convergence direction. Resistivity curves suggest that the frontal thrust zone has compacted, presumably due to faulting. In contrast, the resistivity data suggest that the decollement zone is dilated. These resistivity anomalies in the frontal thrust and decollement zones cannot be explained by variations in pore water composition and need to be verified by the density and porosity logs, after careful correction for borehole washouts.

In Hole 1173B, a four-packer, five-screen ACORK installation was successfully emplaced. It was configured for monitoring the hydrogeological state and processes in basement and the stratigraphic projection of the decollement in the Lower Shikoku Basin formation. The ACORK in Hole 808I was configured with two packers and six screens and was intended to penetrate just to the dcollement, with an emphasis on determining the hydrogeological state and processes at the frontal thrust, a fractured zone 160 m below the frontal thrust, and the decollement. Owing to extreme deterioration of drilling conditions and underreamer failure, actual penetration concluded ∼36 m short of the target depth.

T41A-0848 0830h POSTER

Compaction and deformation in frontal thrust zone in Nankai Accretionary prism

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During Ocean Drilling Program Leg 196, logging-while-drilling (LWD) operations were conducted at Sites 1173 and 808 in the Nankai Trough. The LWD tool consists of RAB, ISONIC, and AND, which provides continuous borehole data of resistivity, azimuthal resistivity images, natural gamma ray, P-wave velocity, density, and neutron porosity. High quality data across the frontal thrust and decollement zones were acquired from Hole 808I. Especially, resistivity and density data are useful parameter to interpret in-situ physical properties and structure in the fault zones in the accretionary prism. The frontal thrust zone is characterized by high density and high resistivity, which suggest compactive deformation. The LWD profiles across the frontal thrust zone demonstrate repeated stratigraphic packages in the section by using layer-by-layer correlation method. A detailed correlation between hangingwall and footwall documents that a stratigraphic package is duplicated and the high resistivity zone in the frontal thrust is a repetition of resistive part in the footwall. Therefore, high resistivity in the frontal thrust zone is due to both compactive deformation and lithological effects. The correlation also suggest that most of the fractures in the frontal thrust zone are repeated section in the lowermost part of hanging wall. The thickness and density of the hangingwall and foot wall shows almost same value, which suggest that dewatering process is slow and pore pressure is relatively high in the footwall.

T41A-0849 0830h POSTER

From Protodecollement to Incipient Plate Boundary - Physical Property Characteristics of Nankai and Barbados Decollement Zones Compared

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The Nankai Trough and Barbados Ridge accretionary prisms represent the two different end member situations of sediment accretion. The Nankai Trough is an example for convergent margins characterized by a high input of terrigeneous clastic sediment, while the Barbados accretionary complex is dominated by hemipelagic sediments. Both settings have been successfully drilled and cored by the Ocean Drilling Program (ODP). Core derived physical property data from Barbados (Legs 110, 156) and Nankai (Legs 131, 190) were supplemented by high resolution Logging-While-Drilling (LWD) data in Leg 171 and more recently Leg 196. In both areas the position of major thrust and decollement zones could be identified through core-based structural and geochemical evidence. LWD measurements however provided density and resistivity data of much higher resolution reflecting the in-situ stress and fluid regime from incipient to well developed decollement at the toe of both prisms.

Combining core and LWD data the changes in physical properties during transition from proto- to well developed decollement during approach and frontal thrusting can be documented in detail. At Nankai LWD data showed little evidence for a propagating protodecollement in the reference site 1173, but rapid loading of the section combined with limited dewatering causes the development of a strong density inversion across the decollement below the frontal thrust at site 808. In contrast the Barbados transect shows a gradual transition from a primary density anomaly across the protodecollement at site 1044 to a broad low porosity decollement zone at site 948 several km behind the frontal thrust. Here the base of the decollement is marked by an offset to higher densities, whereas in Nankai the top of the underthrust sediments shows an offset to lower densities. Based on this comparison the influence of sediment properties and loading history for the localization and evolution of both types of decollements are discussed.

T41A-0850 0830h POSTER

Physical Properties Changes of Sediment Packages Determined from Logging-While-Drilling Data at Nankai Trough/Japan (ODP Leg 196)

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Physical properties of sediments entering the Nankai Trough subduction complex play an important role in the development of this accretionary prism. During May-July 2001 Ocean Drilling Program (ODP) Leg 196 investigated the relationship between deformation, physical properties, and fluid flow in the toe of the Nankai Trough accretionary prism. Previous drilling during ODP Legs 131 and 190 has already focused on the change of index properties around the dcollement zone in detail. One of the key questions of ODP Leg 196 was to determine the porosity or fluid content of incoming sediments, accretionary prism, and underthrust sediments. Logging-While-Drilling (LWD) data of high quality exist at two sites: Site 1173 is located seaward of the frontal thrust to provide information on physical properties of the incoming sediments, Site 808 examined the sediments within the protothrust zone. These two sites allow new insights in the physical properties of the development in this sand-rich end member accretionary prism. The LWD data of ODP Leg 196 enable to correlate sediment packages among the two drill sites using the parameters gamma ray, density and magnetic susceptibility. This correlation quantifies the changes of bulk density between Sites 1173 and 808, and estimates the change of water content/porosity within each site. A detailed log analysis of LWD data enables to reconstruct lithologies in sections with no or low core recovery (especially at Site 808). Thus, the lithology-dependent variation of sediment compaction can be characterized.

T41A-0851 0830h POSTER

Geological Structure Of The Nankai Accretionary Prism Determined From Logging-While-Drilling Data: Results From ODP Leg 196

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The objective of ODP Leg 196 was to clarify deformation behavior and fluid flow in the Nankai accretionary prism. Leg 196 was the 3rd deep-sea drilling investigation of the Nankai accretionary prism following Legs 131 and 190. In order to measure the physical properties of the decollement zone, a special method

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was designed which uses LDW (Logging-While-Drilling) tools. During LWD, the logging machine is located just above the drill bit. The attached logging tools measure resistivity, density, porosity and velocity of the stratum. For the first time in deep-sea drilling history, resistivity borehole images (RAB images) of the decollement zone were obtained.

In Leg 196, drilling in two sites the decollement zone and the proto-decollement region of the accretionary prism was carried out in order to obtain information about the early deformation style during the compressional phase. Site 808 and Site 1173 were selected where the decollement is still forming and has not advanced into the accretionary wedge. The contrast between each site was clear. The decollement zone was characterized seismically as a high-amplitude, reversed-polarity reflection, which corresponds to a high-porosity, low-density layer. However, core samples recovered on Leg 131 suggests low-porosity and high-density in the decollement zone. Because core recovery in the decollement zone was 20% or less, sequential data by logging was required. From the result of logging in the decollement zone which is filled with fluids, we would like to make clear deformation process.

T41A-0852 0830h POSTER

Ship Heave Effects on ODP Drilling Dynamics: analysis of MWD data in the Nankai Trough

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Characterization of the dynamics of ship heave and its effect on downhole drilling and coring has been long sought after in the Ocean Drilling Program. Operating in the Nankai trough region, the JOIDES Resolution acquired new data of downhole parameters using commercially-available Measurement-While-Drilling (MWD) tools at two drilling sites. Our objective during ODP Leg 196 was to record weight-on-bit, rate of penetration, torque, and pump pressure near the bit as drilling proceeded. Digital instruments installed on the rig floor simultaneously acquired vital surface information of the drilling parameters. Although the sampling rate afforded by the downhole tools is insufficient to resolve wave periods of 8-10 seconds, longer wavelength changes are clearly observed. Wavelet transform analysis was used to eliminate window length restrictions with conventional Fourier analysis and to retain the time-specific information recorded in the raw signal. The integration of the uphole and downhole data sets and subsequent wavelet analysis show less variation with heave than in previous experiments near Antarctica where sea states reached 4 meters. The ratio of surface to downhole weight-on-bit for the two data sets in the >30 second spectral window varies systematically with changes in sea state, water depth, pipe depth and driller input. We are thus able to study the effects and drilling dynamics in changing sea states and in water depths up to 4800 meters and to evaluate the operation of the shipboard heave compensation systems. As a result of these analyses, ODP is deriving an empirical approach for operational use to describe downhole and uphole drilling parameters under a variety of conditions and in different geological environments.

T41A-0853 0830h POSTER

Experimental Investigation of Decollement Zone Mechanics and Consolidation State

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Studies on accretionary prism decollement fault zones show them to be very weak structures, with pore pressures close to the lithostatic overburden stress. We have designed a series of experiments to address whether high strains and retained high porosity can coexist in such decollement zones. The experiments will also document the stress paths to obtain these conditions, as well as the microstructures that are developed. We are deforming artificial analogs of decollement lithologies (35% silt sized quartz, 50% montmorillonite, 15% kaolinite) in a high-pressure ring shear device mounted on an MTS torsion-testing device. Experiments were conducted with a normal stress of 9 MPa, a shear strain rate of ca. $7 \times 10^{-4} s^{-1}$ to a shear strain of ca. 40 (360° rotation in 16 days). Fluid pressures of 7 MPa and 8.8 MPa were used. Experiments were conducted on samples which were normally consolidated and overconsolidated (compacted and then subject to a decrease in effective stress). Experimental conditions, are such, that they simulate in situ conditions from currently sampled decollement zones (e.g. Barbados and Nankai). A normally consolidated sample shows a shear stress of ca. 2.5 MPa (normal stress 9 MPa, fluid pressure 7 MPa, normally consolidated); the overconsolidated samples are expected to be stronger and the samples with a higher fluid pressure are expected to be weaker. We are also able to measure fault-parallel and fault-perpendicular P and S wave seismic velocity. These results will allow comparison with seismic observations. Preliminary results indicate a reduction of Vp and Vs on the order of 5-8% with the reduction occurring with a shear stress of less than 15. The results of these experiments will allow us to explore the fundamental processes of fault mechanics and the significance of the seismic response. These results can be directly compared to existing geophysical and geologic information from decollement zones.

T41A-0854 0830h POSTER

Modeling of Coseismic Pore Pressure Changes and Fluid Flow: An Example from the Nankai Subduction Zone

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Fluid flow in subduction zones has received attention because fluid flow, fluid pressures, and the earthquake cycle are interrelated. Fluid expulsion affects thermal and geochemical transport and influences the material properties of sediments. Furthermore, pore fluid pressures are thought to facilitate fault movement. In turn, as stresses in sediments and crustal rock redistribute, pore fluid pressure variations are induced during earthquake cycles. Accordingly, the monitoring of fluid pressures and flow indicators will be an important component of seismogenic zone investigations. Despite indications of episodic flow in subduction zones, the coupling between fluid flow and seismic events at subduction zones has not yet been fully explored. In this study, we modeled coseismic deformation during subduction zone events to better understand what patterns of pore pressure response may be observed in shallow portions of subduction zones. In the hanging wall seaward of the rupture zone, a zone of pore pressure increase is indicated, whereas directly above the rupture zone, a zone of decreased pore pressures results. Although the seismic effect on the fluid flow field will depend on the magnitude relative to the pre-existing excess pore pressures, the pore pressure changes due to coseismic deformation appear large enough to be observable.

T41A-0855 0830h POSTER

Permeability Measurements and Implications for Generation of Overpressures at the Nankai Accretionary Prism, ODP Leg 190 Sites 1173 and 1174

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Permeability is an important hydrologic component in quantitatively evaluating sediment consolidation and pore pressures. In clay rich sediments, the intrinsic permeability generally decreases with decreasing porosity. In this study we used core samples from the Ocean Drilling Program (ODP) Leg 190 Sites 1173 and 1174 from the upper and lower Shikoku Basin facies of the Nankai accretionary prism. Both sites were drilled along the Muroto Transect through the decollement zone or its equivalent. Site 1173 is located 11 km seaward of the deformation front and it represents the undeformed incoming sediments, whereas Site 1174 represents sediments within the proto-thrust zone. Although the Nankai accretionary complex is characterized by turbidite-rich sediments, the core samples from the Shikoku Basin facies are composed of hemipelagic muds. To measure the vertical permeability of the sediments, constant flow tests were conducted on core samples by inducing a hydraulic gradient across the samples. The highest permeability is $5x10^{-17}$ m^2 at a porosity of 66% in the upper Shikoku Basin facies, and permeability tends to decrease with decreasing porosity. Rapid loading rates and shipboard porosity data at the toe of the Nankai accretionary complex suggest the likelihood of overpressures. To examine the generation of overpressures at the toe of the prism we incorporate the measured permeability values in a prism growth/fluid flow model. This model builds the accretionary prism through time and thus allows us to view the pore pressures and porosities at various stages during the evolution of the toe of prism.

T41A-0856 0830h POSTER

Diagenesis at the Nankai Trough: Implications for Mechanical Properties and Updip Limit of the Seismogenic Zone

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The updip limit of the seismogenic zone at the Nankai Trough, southwest Japan, has been shown to generally coincide with the thermal regime associated with the completion of the smectite-to-illite transition. Furthermore, this diagenetic reaction not only affects the frictional strength of the sediment, it contributes fresh water to the fluid budget of the accretionary prism. The scientific objectives of ODP Leg 190 include examination in three dimensions of the interrelations among lithology, deformation, diagenesis, and fluid flow in an accretionary prism. To this end, reference Sites 1173 and 1177 were drilled outboard of the deformation front to provide baseline data of sediment properties and composition. Site 1174 penetrated the prisms protothrust zone just seaward of ODP Site 808. Bulk powder XRD reveals that an average of 45-60% of the bulk sediment at all three sites consists of clay minerals. Within the <2um fraction, illite comprises the greatest proportion of clay minerals, followed by smectite and chlorite. Both Sites 1173 and 1174 along the eastern Muroto transect show a downhole increase in relative abundance of smectite to a maximum of 45%, followed by a decrease. There is a nearly-monotonic downhole increase in the proportion of illite in mixed-layer I/S clay. These trends are consistent with results from ODP Site 808. At Site 1777 along the western Ashizuri transect, smectite increases steadily downward and reaches a higher relative abundance than at the other sites. Furthermore, mixed-layer clays do not show a strong downward trend in %-illite. These results are consistent with the expected diagenetic trends based on a relatively higher geothermal gradient at the Muroto transect area, and will contribute to understanding three-dimensional variations in prism structure, deformation, and fluid flow.

T41A-0857 0830h POSTER

Magnetic Fabric Analysis of Proto Decollement Zone at the toe of the Nankai Accretionary Prism

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Deformation and fluid flow processes across the Nankai Trough accretionary prism were investigated during Ocean Drilling Program (ODP) Leg 190, and sedimentary cores through decollement zone were successfully recovered at the deformation front of the prism (Site 1174). Two reference sites for define all features of sedimentary components, physical and chemical properties on sedimentary sections were drilled at the seaward ends of the Muroto (Site 1173) and Ashizuri Transect (Site 1177). Seismic reflection profiles and results of several measurements for sedimentary sections on board indicate proto decollement zone at both reference sites present along a stratigraphic unit (5.9-7.0Ma) within upper part of the lower Shikoku Basin facies. At Site 1177, proto decollement zone within hemipelagic mudstone unit laid above thick Miocene turbidite unit. However, such turbidite unit can not have been identified below the proto decollement zone at Site 1173. Generally, localization of decollement in sediments at the toe of prism is considered to relate with stratigraphic boundary and with taper angle of prism wedge. From observation during the cruise, localization and development mechanisms of the decollement zone at the Nankai prism still remain questions. To understand reason for presence of proto decollement zone within hemipelagic mudstone unit, magnetic fabric analysis based on anisotropy of

magnetic susceptibility using a large number of discrete samples taken from both reference sites were carried out. Magnetic anisotropy across the proto decollement zone increase its degree along the depth. Shape parameter of magnetic tensor ellipsoid indicates those increase of the anisotropy degree reflects gradual increase of compaction effect on sediments. As an important notice, some characteristic spikes showing low magnetic anisotropy were observed around the proto decollement zone at both sites. These low anisotropy spikes indicate magnetic particles keep random fabrics against sedimentary compaction, and their depth are also corresponding with similar spikes on results of P-wave velocity measured on shipboard. Based on these magnetic and physical properties, hemiperagic mudstone unit at Site 1177 initially has characteristic random grain fabric, and possibly spans to the Muroto Transect. Then, compressive strain during accretion causes destruction of sediments like decollement zone easily within the sedimentary sections consisting of random grain fabric.

T41A-0858 0830h POSTER

Origin and Evolution of the Decollement Zone in the Nankai Trough Accretionary Prism

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Origin and evolution of a plate boundary decollement zone remain a big puzzle. Ocean Drilling Program (ODP) Legs 190 and 196 performed coring and logging while drilling near the toe of the Nankai Trough accretionary prism. Here, the decollement zone is well expressed on seismic profiles. We examined the nature of the decollement zone using samples and data collected during Legs 190 and 196.

At reference site (Site 1173), structural features on cores and resistivity-at-the bit (RAB) images of the borehole show no clear evidence for the proto-decollement zone. However, magnetic fabrics indicate the age equivalent decollement is located at the bottom of the domain marked by weakly developed compaction fabric. Below the decollement horizon, the degree of compaction increases with depth. Vertical anisotropy data of P-wave velocity and resistivity reflects change in compaction state across the decollement horizon

The decollement zone at the toe of the prism (Site 1174) is marked by the breccia zone in which the mudstone is broken into mm- to cm-scale coherent fragments bounded by discrete slip surfaces. Based on microstructure, magnetic fabric, and vertical anisotropy data of P-wave velocity and resistivity, random fabric with small pore space characterizes coherent fragments, while preferred orientations of clay minerals develop along discrete slip surfaces. These features suggest the unique deformation history and stress path of the decollement zone: undrained deformation followed by isotropic consolidation and shearing under drained condition. Consequently, core samples from the decollement zone have lower porosities than those from above and below.

RAB images at Site 808 located 1 km landward of Site 1174 suggest dilated horizons in the decollement zone. Dilated horizons correspond to the horizons where cores were not recovered during previous leg. Dilated horizons may result from shear failure under the critical state that is expected after shearing under drained condition. Presumably, dilated horizons are filled with high-pressured fluid, resulting in strain decoupling across the decollement zone.

T41A-0859 0830h POSTER

Structure and cold seep of the Nankai accretionary prism off Kumano

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Seafloor survey by submersible was conducted on the slope of the Nankai accretionary prism off Kumano. The Nankai Trough extends about 700 km from the Izu-collision zone to the northern end of the Kyushu-Palau Ridge. The eastern and western parts of the Nankai Trough have been well investigated by the KAIKO projects since 1984, dense seismic survey and the deepsea drillings. In contrast, only few studies have so far been made at the Kumano area located at the central part of the Nankai Trough. The epicenter of the 1944 Tonankai earthquake is estimated north of this area. Our survey using submersible "Shinkai 6500 (JAMSTEC)" was conducted to understand relationship between fluid circulation, prism growth and seismogenic zone development. Recent seismic reflection studies off Kumano indicates development of a large out-of-sequence thrust at the upper slope and two large thrust faults at the toe and the middle slope of the prism (Park, unpublished data). Chemosynthetic biological communities were observed along these major fault scarps suggesting fluid expulsion along the fault planes. The exposures of the scarp are mainly composed of highly tilted siltstone, alternations of sandstone and siltstone, and light-colored tuff. These sequences are regarded as accreted trench-fill sediments by offscraping based on the seismic reflection profile. However, the rock collected from the toe has porosity of 45 percent, which correspond to the deepsea drilling sample off Shikoku at the depth of 500 meters below the seafloor. It is inferred that the prism toe off Kumano is suffered from active erosion after frontal accretion.

T41B MC: Hall D Thursday 0830h

Viscoelastic Deformation of the Earth: Observations and Models I

(joint with G, S, DI, MR)

Presiding: **J X Mitrovica,** University of Toronto**; S Zhong,** University of Colorado

T41B-0860 0830h POSTER

Earth's Potentiosphere

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Viscoelastic fluid theory suggests that Earth's upper mantle and transition zone comprise a coherent thermomechanical boundary layer. Based on the remarkable correspondence between theoretical predictions and observable seismic features in the upper mantle, this finding has important ramifications for global tectonics. The theory, parameterized in terms of Weissenberg number (Wi) and scaled using the average thickness of the mechanical lithosphere (about 100km), is a logical extension of mantle convection theory based on the Rayleigh-Benard problem. Wi is a dimensionless measure of residual normal stress, assumed to be inversely proportional to temperature. The theory predicts a significant potential component for mantle flow above a depth of 693 km, with essentially dissipative conditions below. Thus the terms potentiosphere and rheosphere are coined for the mantle shallower and deeper than 693 km, respectively. Also predicted is a characteristic spatial dimension for inertial rupture, on the order of 10 km. Together, these concepts provide a simple physical explanation for the globally observed seismicity cutoff at the base of the upper mantle, implicitly tied to thermal state. Seismically observed reflectors in the mantle correspond to intrinsic boundary conditions, either coupled or uncoupled. An energy minimum, associated with uncoupling, is predicted at a depth of 666 km. This implies that the equilibrium phase change commonly associated with the 660-km seismic discontinuity actually might be mediated by localized shear near that depth. Similar situations, although associated with coupled conditions, are predicted at 400 and 324 km depths. The latter might represent the X reflector observed in subduction environments. The theory also predicts a change in the character of deformation from distributed and isotropic below a depth of about 200 km to localized and anisotropic above, generally consistent with the Lehmann discontinuity. A fundamentally weak zone, associated with uncoupling, is predicted at a depth of 173 km. Finally, another coupled flow boundary is predicted immediately beneath the assumed mechanical lithosphere at a depth of 124 km, consistent with the controversial 125-km constant temperature boundary condition of Parsons and Sclater (1977). Thus, the new theory satisfies both seismic and thermal observations critical for global tectonics.

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Transition Wavelength Theory

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Viscoelastic single-layer folding theory predicts a transition from distributed to localized deformation at a specific normalized wavelength - transition wavelength - as a function of the competence contrast at the layer boundaries. This transition is independent of stabilizing forces such as gravity and surface energy. The effect of viscoelasticity, compared to the viscous case, is to destabilize folds at wavelengths shorter than the transition wavelength, and stabilize those at longer wavelength. Transition wavelength theory, therefore, not only provides an explanation for the common observation of thrust faults cross-cutting fold hinges in fold-thrust belts, but also the generally short normalized wavelengths of observed natural folds. Fold-wavelength frequency distributions of natural folds, normalized to layer thickness, display marked skewness, with an overall range from about 3 to 35 and modes in the range 4 to 7. Comparison of these data with the theory suggests that competence contrasts attending deformation in fold-thrust belts range from about 10 to 36. This conclusion stands in contrast to those drawn from dominant wavelength theory for both Newtonian and power law viscous rheologies, which suggest competence contrasts in the range of 500 to 1000 or more. Note that the predicted 10 to 36 range is consistent with the classic analysis of Sherwin and Chapple (1968), and well below those values at which Lan and Huddleston (1995)demonstrated the formation of a finite neutral surface in single-layer buckle folds using power law viscous rheology. Observed natural folds generally lack a finite neutral surface. These findings demonstrate the importance of viscoelasticity for fold formation, and raise the often ignored question of extrapolating empirical relationships based on rock mechanics data to deformation at tectonic strain rates. While the power law viscous and Maxwell viscoelastic rheologies are useful for modeling observable time dependencies, mathematically they cannot capture deformation in deep time. However, other more general constitutive models such as used in the present theory can.

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Postseismic Reloading: A Mechanism for Temporal Clustering of Major Earthquakes on Individual Faults

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On a single fault segment, geologic and paleoseismic evidence from locations such as the Basin and Range [Friedrich et al. JGR, submitted] and Dead Sea Transform [Marco et al., JGR, 1996] indicate that occurrence of major earthquakes in time is often extremely heterogeneous and may, in fact, exhibit temporal clustering. We consider major earthquake clustering as the occurrence of multiple event sequences with intra-cluster inter-event times much shorter than the average time between clusters. Many factors may contribute to temporal clustering of major earthquakes. Over multiple event time scales, time-dependent postseismic stress transfer may play an important role.

After major earthquakes, time-varying deformation transients occur. These transients result from diffusion of stress away from zones of stress concentration generated during the coseismic rupture. As a consequence, the coseismic fault is reloaded at a rate that is initially much higher than the background rate derived from far-field plate motions. On a given fault, earthquake recurrence intervals are moderated by various sources of system noise, including stress perturbations due to neighboring earthquakes, crustal heterogeneity, and fault evolution. Depending on the relative timing and magnitude of earthquakes in a sequence, therefore, the postseismic stress available for transfer to the coseismic fault may be greater or less than average. This may lead to a situation in which postseismic stress transfer becomes a significant factor in controlling the time to the next event.

To investigate these longer-term postseismic processes, we develop a spring-dashpost-slider model of time-dependent stress transfer in the earth. With this tool, we gain an understanding of how variations in rheology, fault slip-rate, and system noise affect a fault's behavior. In tectonic environments with a weak lower crust/upper mantle, we find that small random variations in the fault failure criteria generate temporally clustered earthquake sequences. This effect is enhanced as the geologic slip-rate on the fault decreases. By analogy, areas such as the Basin and Range are particularly susceptible to clustering induced by long-term postseismic stress effects.