Fault, CA, an active thrust fault in the forearc of the Cascadia Subduction Zone, and the hypothesized New Madrid North fault, MO, a possible active strike-slip fault in the New Madrid Seismic Zone. Samples were cemented with low-viscosity epoxy and examined using image analysis of photomicrographs and SEM images. Fault zone sediment samples from the active faults studied share several textural characteristics at the microscopic scale. Fault zone samples from both coseismic slip and creeping faults have finer grain size and less pore space than sediments outside of (>10 cm from) the fault zone, as well as some degree of preferred grain orientation. These textures record a combination of fault zone kinematics (translation, rotation, strain history of sediments) and authigenic processes. Of particular interest to paleoseismologists are textural characteristics that differ between fault zones with histories of coseismic slip and those experiencing fault creep. One such texture in the coseismic slip examples studied is a pronounced anastomosing shear zone structure consisting of relatively undeformed sand lenses surrounded by fine-grained shear zones. Grains within lenses in the McKinleyville fault deformation band appear undamaged, while those in the New Madrid North fault show some grain size reduction relative to sand several meters from the fault zone. Abrupt decrease in grain size at the boundaries of these lenses suggests that grain size reduction accompanied concentration of shear in localized shear zones. This texture may be an indicator of velocity weakening, potentially unstable stick-slip behavior. Another textural characteristic that differs between the samples studied is the orientation of elongate grains relative to the fault. In the McKinleyville and New Madrid North fault samples, preferred grain orientation is oblique to the fault. In contrast, in samples from creeping segments of the Southern Calaveras Fault at Costa Ranch, and San Andreas Fault at Flook Ranch, the highest concentration of elongate grains is oriented parallel to the fault. Factors other than the creep vs. stick-slip history of these faults may influence preferred grain orientation in fault zone sand. Possible factors include differences in sense of motion, mechanics of fracture initiation, interplay between fault strands, etc. We plan to extend our studies to additional sites in order to investigate further the relationships between fault texture and slip history.

T11D-0429 0830h POSTER

The West Napa Fault as defined by gravity and magnetic data, northern California

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The north-northwest-striking West Napa Fault is mapped along the western margin of Napa Valley, California. The epicenter of the 2000 M_L5.2 Yountville earthquake occurred 5 km west of the surface trace of the West Napa Fault as defined by Helley and Herd (1977), and thus the source of the earthquake was assigned to an unmapped fault. Here we argue based on recently acquired geophysical and geologic data that the earthquake may have occurred on a strand of the West Napa Fault. A linear aeromagnetic anomaly along strike with the Holocene West Napa Fault extends northwest 30 km from just north of the Napa County Airport to the latitude of the town of Rutherford. North of Rutherford, another linear aeromagnetic anomaly can be traced 20 km north to Calistoga. The source of the anomalies resides within the pre-Cenozoic basement rocks, most likely unexposed ophiolitic basement rocks of the Great Valley sequence. Both of the aeromagnetic anomalies occur near the base of a linear east-facing gravity gradient. The gravity gradient is caused by the juxtaposition of Great Valley and Franciscan rocks to the southwest with less dense Cenozoic Sonoma volcanics and alluvium to the northeast, although this relationship is completely buried by Sonoma volcanics at the surface north of the town of St. Helena. The correlation of the potential-field anomalies suggests that a steeply west-dipping reverse fault bounds the western margin of the Napa Valley basin. The alignment of the reverse fault with the Holocene mapped West Napa Fault suggests that they are related. The focal mechanism of the Yountville earthquake, which occurred at a depth of about 10 km, indicates slip occurred on a steeply southwest-dipping, northwest-striking fault plane. Projection of this fault plane to the surface coincides closely with the location of the geophysically defined fault bounding the western margin of the Napa Valley basin and the surface trace of the West Napa Fault as mapped by Fox (1983) and Graymer and others (2003). Although the focal mechanism indicates nearly pure right-lateral slip, aftershocks of the event include both right-lateral and reverse mechanisms. Despite the relatively small magnitude of the Yountville earthquake, it probably occurred on a fault capable of much larger earthquakes. Given the length of the geophysically defined West Napa Fault, it may be capable of producing a **M** 6.8-7.1 earthquake. An unusual characteristic of the Yountville earthquake was more extensive damage in the city of Napa than in communities more proximal to the epicenter. A preliminary inversion of the gravity data indicates that the Cenozoic basin fill is as much as 2 km thick beneath the town of Napa and substantially thinner beneath Yountville. The variation in thickness of the basin fill may be one of the factors that contributed to unusually strong ground accelerations recorded at Napa and the lack of damage to older buildings at Yountville during the 2000 earthquake.

T11E MCC: 3005 Monday 1020h

Structure and Evolution of Nonvolcanic Rifted Margins I

Presiding: **B E Tucholke,** Woods Hole Oceanographic Institution**; J Sibuet,** Ifremer Centre de Brest

T11E-01 1020h INVITED

Nucleation of an Oceanic Spreading Center in a Continental Rift: The Northern Red Sea

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The northern Red Sea is an active amagmatic continental rift in which a mid-ocean ridge spreading center is beginning to develop. The morphology of the Red Sea consists of very narrow continental shelves and a main trough with depths of 400-1200 m. The main trough consists of a series of fault bounded terraces 20-30 km wide, stepping down to a 15-30 km-wide axial depression. Free-air gravity anomalies form a pattern of elongate high-amplitude (50 mGal) highs and lows oriented subparallel to the trend of the rift and located on the seaward edges of the bathymetric terraces. Gravity anomalies are systematically terminated or offset across NE-SW trending zones at which the bathymetric contours are also offset. The gravity anomalies display the basement relief under the main trough, interpreted as a series of tilted fault blocks 15-30 km across and roughly 60 km long, separated by accommodation zones. A new data compilation and synthesis shows that the accommodation zones extend continuously across the entire width of the Red Sea. Where accommodation zones have been mapped in the rift mountains on-shore, the off-shore accommodation zones appear to continue into them. However, the trends on land and at sea tend to be different. Accommodation zones in the low-to-moderately extended rift mountains are controlled by pre-existing Precambrian structures, while those in the highly-extended offshore area are oriented parallel to the opening direction. The axial depression is marked by a free-air gravity low with a relative amplitude of 30-60 mGal and by very high heat flow (300-600 mW/m^2). The axial depression often appears to be fault bounded. Sediment deformation is more intense and concentrated there than in the rest of the main trough. The axial depression is not only the locus of recent deformation, but is the location of a series of small axial deeps, 1400-1600 m deep and associated with large-amplitude dipolar magnetic anomalies. A deep is located near the midpoint of each segment, approximately halfway between the accommodation zones. Water depth and the amplitude of the gravity low decrease away from the deeps toward the accommodation zones. The gravity lows over the axial depression within each segment are offset or overlap without intersecting at accommodation zones. The large-amplitude normally-magnetized dipolar magnetic anomalies at the deeps appear to result from recent volcanic activity. Small volcanoes (a few km across and several hundred m high) can be identified at several deeps. In most cases, the magmatic activity does not occur in the deep itself, but rather immediately adjacent to it along the faults bounding the axial depression. Extension in the northern Red Sea, which has been amagmatic, has reached the point where melt is beginning to be produced. The melt is focused at the center of rift segments where it ascends along faults bounding the axial depression. By analogy with the central and southern Red Sea, it is hypothesized that, with continued intrusion, the deeps will develop into small seafloor spreading cells that propagate and grow together to form an oceanic spreading center. The initial segmentation of the newly formed mid-ocean ridge is thus directly inherited from the rift geometry established early in continental rifting.

T11E-02 1035h INVITED

The Rifting-to-Spreading Transition in the Woodlark Basin

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The Woodlark Basin-Papuan Peninsula region exemplifies a continuum of active extensional processes, laterally varying from continental rifting to seafloor spreading at 2-6 cm/yr. There, we have previously shown that continental breakup proceeds by successive phases of rifting localization, spreading center nucleation, spreading center propagation (sometimes stalling), and then an en echelon offset to the next site of localized rifting. The breakup has been centered within thickened orogenic crust that includes a Neogene volcanic arc west of 153E built on Paleocene ophiolite, resulting in a first order asymmetry between the stratigraphy and structure of the conjugate margins (forearc and backarc). The rifted margins are about 100 km wide and the transition from stretched continental to oceanic crust is very sharp (less than 5 km wide). Using swath bathymetry, magnetization and seismic reflection data, we illustrate the breakup of conjugate margins of varying ages (3.2, 1.9, 0.8, and 0 Ma) and involving multiple generations of normal faults (both high- and low-angle). Rifting continues for up to 1 m.y. after seafloor spreading initiates. Ridge jumps produced multiple ocean/continent boundaries within one transect. ODP-calibrated margin subsidence data reveal that focused faulting is accompanied by more regional lower crustal flow prior to breakup.

T11E-03 1050h INVITED

On-land Exposures of Ocean-Continent Transitions: A Window for Understanding Rifting and Slow Sea-Floor Spreading Processes

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Direct observations and nearly unlimited sampling in ancient margins and ocean-continent transitions exposed in the Alps combined with drill-hole and geophysical data from the present-day Iberia margin result in new concepts of how magma-poor passive continental margins evolve towards (ultra?-) slow seafloor spreading systems. We review data from both the shallow and deep structure of magma-poor passive margins and propose that three temporal and spacially different fault systems are sufficient to explain the overall evolution from continental extension to early seafloor spreading. (1) During an initial stage of rifting the architecture and rift structures are controlled by inherited heterogeneities in the intermediate and lower crust which lead to a different response of the future distal and proximal margins. Future proximal margins are characterized by frequent normal faulting soling out at approximately 10km, while future distal margins show little evidence for early rift-related normal faults. However, the deep structure underneath the future distal margin is controlled by crustal-scale faults which thinned the crust to about 10km by excising up to 20 km of intermediate to lower crust. Thus we prefer the hypothesis of a 'within crust decoupling' of deformation and suggesting that boudinage of the lower crust is an important process during early rifting. A second important aspect is that after the initial stage of rifting mantle rocks are accessible for serpentinization. (2) Late-stage rifting is controlled by detachment faults. The most compelling evidence are extensional allochthons of upper continental crust emplaced on exhumed mantle rocks and tectono-sedimentary breccias covering detachment faults. Strain is extremely localized and leads to the formation of characteristic black fault gouges which are documented in ocean-continent transitions. Low angle detachment faults cut accross the entire, previously thinned continental crust and provide a mechanism for exposure of subcontinental mantle and rarely lower continental crust at the seafloor. The exhumed mantle rocks and the associated mafic crust show mineralogical and geochemical characteristics that are spatially corrrelated with their distance to the continental margin. (3) The transition from late rifting to the onset of seafloor spreading is most probably controlled by the interactions of rising asthenospheric mantle with concave downward faults. Such faults exhume deeper (and hotter) mantle oceanwards and are temporaly and spatially juxtaposed with the onset of magmatic activity. Evidence from Alpine ophiolites and from Iberia suggest regional-scale melt

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infiltration and melt/rock reaction which is most obviously expressed by the widespread formation of plagioclase peridotites in zones of exhumed continental mantle. Whether or not rift-related melt infiltration and heating is recorded by exhumed mantle rocks depends on the relative position to the underlying upwelling asthenosphere. Thus during final breakup the rheology of the extending lithosphere seems to be controlled by the competing effects of heating of the lithospheric mantle by ascending magmas from the underlying hot asthenosphere and conductive cooling and hydrothermal alteration by exhumation.

T11E-04 1105h

Rolling Hinge Formation of S and Overlying Crustal Blocks at the Galicia Rifted Margin

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The last stage of continental breakup in the Galicia Bank Basin and Iberia Abyssal Plain appears to have involved “rolling hinge” style extension in forming the S detachment and the allocthonous continental blocks that overly S. We support this assertion using seismic examples from the Iberia Seismic Experiment, conducted in 1997 by U.S., German, Portuguese, and Spanish scientists, using the R/V Ewing’s 4 km streamer and deep penetration airgun array. Profile ISE-5 is a north/south strike line across the Galicia Bank basin and over the area where S is well developed and studied. S is clearly seen, but is not the relatively simple, laterally continuous, reflector seen in dip lines. It is offset by one or more north-dipping mantle-penetrating faults and its reflection character changes at several points along the profile. Fault bounded blocks interpreted to consist of continental crust, prerift sediments, and postrift sediments overly S. In one location it appears that S may be directly overlain by postrift sediment. In strike cross-section, the continental blocks have a “pod-like” shape, thick (1-3 km) in the center and pinching out to both sides. The continental crustal section over S varies laterally and consists of a stack of one to three of these overlapping pods. In dip-section these blocks are bounded top and bottom by down-to-the-west normal faults that sole into S. We suggest that this geometry is consistent with margin formation as a rolling hinge detachment. The detachment had two major parts. To the west, the detachment fault dipped at high angle to the west into the upper mantle. The roughly horizontal detachment, imaged as the reflector S, is the continuation of this fault to the east. The upper mantle rocks forming the footwall of the detachment fault were pulled to the east, out from under the hanging wall along the high angle portion of the fault. They were then flexed and rotated so that the detachment became roughly horizontal. As substantial extension was accommodated by this system, blocks of continental crust and sediment were periodically transferred from the hanging wall to the footwall. They were then carried, as on a conveyor belt, to the east. In this system, a given area of the hanging wall might be covered by one or several allocthonous blocks, or might be left entirely uncovered. The later would be a zone of exhumed continental mantle. We believe that the pod-like blocks we image along profile ISE-5 are produced in this way. They are in a sense, “flakes” of continental crust plucked from the hanging wall. The reflection character of S varies along strike because different portions of the fault have moved at different times and are covered by different hanging wall material. The continuous segments of S, like the allocthonous crustal blocks, have greater dip extent than strike extent. The relative rates of extension and of plucking crustal blocks from the hanging wall controls the thickness of the crust over the detachment.

T11E-05 1120h

ODP Leg 210 Drills the Newfoundland Margin in the Newfoundland-Iberia Non-Volcanic Rift

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The final leg of the Ocean Drilling Project (Leg 210, July-September 2003) was devoted to studying the history of rifting and post-rift sedimentation in the Newfoundland-Iberia rift. For the first time, drilling was conducted in the Newfoundland Basin along a transect conjugate to previous drill sites on the Iberia margin (Legs 149 and 173) to obtain data on a complete non-volcanic’ rift system. The prime site during this leg (Site 1276) was drilled in the transition zone between known continental crust and known oceanic crust at chrons M3 and younger. Extensive geophysical work and deep-sea drilling have shown that this transition-zone crust on the conjugate Iberia margin is exhumed continental mantle that is strongly serpentinized in its upper part. Transition-zone crust on the Newfoundland side, however, is typically a kilometer or more shallower and has much smoother topography, and seismic refraction data suggest that the crust may be thin (about 4 km) oceanic crust. A major goal of Site 1276 was to investigate these differences by sampling basement and a strong, basinwide reflection (U) overlying basement. Site 1276 was cored from 800 to 1737 m below seafloor with excellent recovery (avg. 85%), bottoming in two alkaline diabase sills >10 m thick that are estimated to be 100-200 meters above basement. The sills have sedimentary contacts that show extensive hydrothermal metamorphism. Associated sediment structural features indicate that the sills were intruded at shallow levels within highly porous sediments. The upper sill likely is at the level of the U reflection, which correlates with lower Albian - uppermost Aptian(?) fine- to coarse-grained gravity-flow deposits. Overlying lower Albian to lower Oligocene sediments record paleoceanographic conditions similar to those on the Iberia margin and in the main North Atlantic basin, including deposition of black shales’; however, they show an extensive component of gravity-flow deposits throughout.

T11E-06 1135h

On the formation of ultra-thick sedimentary basins on rifted margins: a comparison of the Scotian and Labrador margins

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Sedimentary basins that form on rifted continental margins exhibit a great variety of shapes and sizes. In particular, the total sediment thickness can vary significantly and in certain sub-basins can approach 15-20 km. The deeper structure of these ultra-thick basins is typically not well resolved by seismic reflection profiles due to poor penetration within the thickest parts of the basin. Wide-angle seismic reflection/refraction profiles can help resolve these deeper features. We compare two such sub-basins that occur on the eastern Canadian margins, where reflection and refraction profiles are able to define the complete sedimentary and crustal structures: the Sable sub-basin on the northeast Nova Scotian margin and the Hopedale sub-basin on the central Labrador margin. We compare the development of these basins by converting the sediment refraction velocities to density and back-stripping assuming local isostasy. Although these basins formed during completely different episodes of rifting on different types of continental crust, we find a surprising similarity in the characteristics of crustal thinning across each margin, especially for the lower crust. Initial thinning of the crust by 50-60% occurs within 50 km followed by more gradual thinning over the subsequent 100 km. This leaves a tongue of lower continental crust extending 150 km seaward of the unstretched continental crust. This outer region becomes the location of the thickest initial sediment deposition, followed by up-building and out-building of the shelf. The local form of this deposition differs between the two margins: with much larger syn- and immediately post-rift sediments on the Scotian margin and thicker recent deposition on the Labrador margin, probably controlled by the local availability of sediment fill. Comparison with previous models of rifting based on borehole observations for the Scotia margin compare well with the overall width of the rifting (150 km), but our results suggest more rapid initial crustal thinning. By comparison, the conjugate margins of SW Greenland and Morocco are much narrower, do not have the broad region of thinned lower continental crust and have much smaller sediment thicknesses primarily located seaward of the continental shelf and slope. These features are all evidence for asymmetric rifting during late stages of extension.

T11E-07 1150h INVITED

The Formation of Non-Volcanic Rifted Margins by the Progressive Extension of the Continental Lithosphere

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Rifted margins include two main end-members: those termed ”Volcanic Rifted Margins - VRMs” where magmatism is much more voluminous than predicted by passive asthenospheric upwelling (e.g. White et al., 1989), and those where magmatism is consistent or even less than the same predictions. The latter are termed ”Non-Volcanic Rifted Margins - NVRMs” to emphasise the contrast with the VRMs: the name does not exclude the presence of minor amounts of magmatic activity. The NVRMs are typified by the North Biscay, south Australian, SW Greenland, and the West Iberian margins, which share a number of common characteristics: - extreme crustal thinning, increasing towards the ocean; - presence of well-defined rotated fault blocks. However at the feather edge of the continent there is an extension discrepancy: the amount that can be inferred from the geometry of these faults is far less than that indicated by the crustal thinning observed; - presence in places of a detachment fault at the base of the fault blocks; - little evidence for synrift magmatism; - the presence of a broad zone of partially serpentinised mantle (Boillot et al., 1988; Whitmarsh et al., 1996; Krawczyk et al., 1996; Pickup et al., 1996), both occurring beneath the highly thinned and faulted continental crust, and as a zone of exhumed continental mantle, now largely buried by postrift sediments. We show that such margins are the logical result of progressive extension of continental lithosphere above cool sub-lithospheric mantle. The key factors controlling the development of the margin are the rheological evolution of the crust (explaining the serpentinisation of the mantle), the occurrence of multiple phases of faulting (explaining the apparent extension discrepancy), and the temperature structure of the sub-continental mantle (explaining the lack of magmatism).

T11E-08 1205h

Modeling of the Role of Serpentinization and Magmatism at the Transition From Rifting to Seafloor Spreading

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Observations from magma-poor rifted margins exposed in the Alps and drilled and seismically imaged in Iberia show that at the transition from rifting to seafloor spreading the fault geometry change from upward to downward concave. Observations and data from these to margins suggest that the fault geometry is controlled by serpentinization processes and the emplacement of igneous rocks, which are the results of temperature and reaction dependent processes and decompression melting. Here, we present 2D numerical models of the extension of a visco-elasto-plastic lithosphere. We study the effect of serpentinization and magmatism on both the evolution of strain and the force necessary to breakup the continent and form a new ocean. The brittle parts of the lithosphere are modeled as a frictional and cohesional material. The ductile lithosphere is modeled as a non-Newtonian Maxwell visco-elastic material. Faults in the brittle parts of the model are formed by locally decreasing the cohesion as a function of plastic strain. The rheological structure of the model is controlled by the initial temperature distribution and the temperature boundary conditions.To study the transition between ”listric concave upward” to ”concave downward” normal faulting, we start the model with a 10 km thick brittle crust and 90 km thick mantle. The serpentinized layer is modeled as a weak plastic layer. The mantle is inferred to be dominated by olivine rheology and the crust by diabase rheology. In a first set of model we study the effect of a serpentinized layer below the brittle crust on the style of faulting and the tectonic force. With no weak serpentinized layer the deformation leads directly to the formation of large offset normal fault. Moreover the force needed to extend the lithosphere is higher than what can be expected from ridge push or slab pull. We find that the presence of a serpentinized layer leads to the localization of multiple normal faults in the brittle layer rooted in the weak serpentine and a large decrease in the tectonic force necessary to rift the layer. We then study the possible interaction between the ascent and melting of the mantle with faulting in the brittle layer. We model magma percolation and accumulation using a Darcy’s law approach. The main role of melting is to help focus the area of necking and accelerate the rate of deformation. It also substantially decreases the force necessary to rift the modeled layer.