T11C-0418 0830h POSTER

High-Pressure Raman Spectroscopic Studies of FeS_2 Pyrite

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The transition metal dichalcogenide FeS_2, pyrite, is the most abundant of the sulphide minerals and common in a variety of geological environments. Strong geophysical interest in its physical and chemical properties under high-pressures and high-temperatures has arisen in the context of the F-S system's role in core formation, evolution and composition. It is known from X-ray diffraction studies that the equation of state of pyrite depends strongly on the degree of non-hydrostatic stress in the sample. In order to determine any possible influence of such intrinsic strength effects on the dynamical properties of FeS_2 we have investigated natural iron pyrite with Micro-Raman spectroscopy in the diamond-anvil cell to 55 GPa. Comparative measurements were performed under hydrostatic conditions with helium as a pressure-transmitting medium and without a pressure-medium. In fact, there have been few (if any) light scattering studies of opaque, highly reflective minerals at high-pressures. Despite the high opacity we observe (in analogy with previous work on high-pressure metallic phases) strong Raman modes at all pressures. Four out of five Raman modes are resolved with helium as a pressure-transmitting medium. The fifth mode, $T_g(2)$, is $\leq$2cm^{-1} apart from the strong A_g mode that dominates the spectrum. We observe an increase in the separation of the E_g and $T_g(1)$ mode under compression. In contrast the A_g (in-phase S_2 stretch) and $T_g(2)$ (out-of-phase S_2 stretch) mode do not separate with pressure. All observed frequencies increase continuously under compression giving no evidence for a structural phase transition in accord with diffraction and shock wave studies. The main effect of non-hydrostatic conditions on the Raman modes is a strong pressure-induced broadening; the pressure-dependence of the frequencies is not affected within the error of the measurements. The Raman data are consistent with recent bond-length *vs* pressure calculations supporting a strengthening of the S-S and Fe-S bond under pressure.

T11C-0419 0830h POSTER

Monochromatic Powder Diffraction Coupled With ^{19}F and ^{23}Na NMR: A Study of $K_{(x)}Na_{(1-x)}MgF_3$ Perovskite

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Structural phase transitions from orthorhombic (O, Pbnm) to tetragonal (T, P4/mbm) to cubic (C, Pm3m) and an increase in unit cell volume are confirmed as potassium is substituted for Na in Neighborite ($NaMgF_3$). Substitution of the 19% larger potassium ion for sodium in the A-site of the perovskite structure decreases tilting of MgF_6 octahedra. Transition from O to the T and C phases, as determined by powder XRD, occurs at ~37 and 47 mole % substitution, respectively. Superlattice reflections, expected if ordering were to occur in the A-sites, are not observed. The superlattice reflections, uniquely defining the symmetry of the O- and T-phases, broaden between each perovskite endmember, possibly indicating a conflicting coherence length between small domains of variously tilted octahedra. ^{19}F MAS NMR reveals multiple environments for fluorine that depend on the number and type of cations in the 1^{st} A-cation coordination shell, $F(Na)_y(K)_{5-y}$. At intermediate substitution levels (30 - 60%), all five of these possible fluorine coordination environments are found, but the concentration of the environments with y = 2 are much lower than expected based on random substitution of K for Na on the A cation site. This data suggests that upon substitution of 15% K into $NaMgF_3$, potassium appears to segregate into domains resembling $KMgF_3$ but smaller than the coherence length of X-rays. The ^{23}Na NMR is very sensitive to the O/T to C transition. For x > or = 0.5, a sharp resonance is observed due to sodium atoms in a cubic environment, while broader resonances are observed for x < 0.5.

T11C-0420 0830h POSTER

Thermodynamic Parameters of Uvarovite ($Ca_3Cr_2Si_3O_{12}$) from Single Crystal Raman Spectroscopy

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Garnets are ubiquitous in the crust and mantle and are key minerals in geothermometry and geobarometry as well as in the transition zone of the mantle. Uvarovites are found in nature as nearly end-member compositions in some terraines, and are significant components in diamond inclusions. They have not been studied as extensively as pyropic garnets. Raman spectroscopic studies of uvarovite provide several advantages for understanding the behavior of garnets. Thermodynamic properties, such as heat capacity and entropy, can be calculated using vibrational modeling. Using vibrational spectroscopy with cation substitution provides insight into how the properties vary with composition. The nonlinear behavior of garnet solid solutions is well-known, details of this behavior can be probed with spectroscopy (see F. Savage, A. Chopelas abstract this volume). Uvarovite is a calcic garnet with chromium at its octahedral site. It is close in volume to grossular (Al at the octahedral site), while the mass of the trivalent cation is similar to andradite (ferric iron at the octahedral site). All three have lattice parameters around 12 Å, much larger than for pyralspite garnets (lattice parameters around 11.5 Å). The samples in this study were synthetic end member uvarovite, a binary nearly halfway between andradite and uvarovite ($Uv_{59}An_{41}$), and 2 other uvarovites, one with a small pyropic content and the other with a small grossular content. Single crystal polarized spectra on the end-member revealed 23 of the 25 Raman modes expected by symmetry. The high energy modes of uvarovite closely matched those of grossular while the low energy modes more closely matched those for andradite. This is not a surprising result since the high energy modes dominated by silicate stretching and bending modes, depend nearly entirely on the lattice parameter, while the low energy modes, mainly cation translations, have a heavier dependence of the mass of the cations. Other silicate minerals exhibit this same behavior suggesting a simple treatment of the silicate modes upon substitution. Andradite's unusual intensity distribution with a very strong high energy Eg mode is repeated in end member uvarovite but not in any of the mixed uvarovites. The $Uv_{59}An_{41}$ has only a very small volume change and the lattice parameter is much closer to uvarovite's than would be expected by composition. This is reflected in the behavior of the modes, which will be further discussed. Thermodynamic calculations will also be presented.

T11C-0421 0830h POSTER

Single Crystal Raman Spectroscopy and Thermodynamics of Garnet Solid Solutions II: Pyrope - Almandine Binary

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Garnets are ubiquitous in the crust and mantle and are key minerals in geothermometry and geobarometry. Macroscopic properties , such as enthalpy and volume, exhibit non-linear behavior in solid solutions making it difficult to model their behavior. Insights into the cause of the non-linearity of such properties may be found by investigating the effects of compositional variation using a microscopic technique such as vibrational spectroscopy. A further advantage of using vibrational spectroscopy is the ability to probe the effect of small changes in the frequencies on the thermodynamic properties using vibrational modeling. Investigating the pyrope-almandine (substitution of ferric iron for magnesium) binary allows the examination of the effect of doubling the mass on the dodecahedral cation without significantly changing the cell parameter (11.45 to 11.52 A, compare to approx. 12 for Ca bearing garnets). The garnet samples here have low moisture content, eliminating a possible source of non-linear behavior. Although previous infrared data* show linear behavior across this series, our data show this not to be the case. Raman modes vary from linearity but all modes do not vary in the same way. Generally the trend is to have lower frequencies in the solid solution than expected for linear behavior, as in the andradite-grossular binary. However, a few modes at low frequencies have higher frequencies than the linear trend. Since the lowest frequency modes are most strongly affected by the divalent cation, this would suggest that the electronic and magnetic effects of iron play a role in this unexpected variation. Substitution of ferric iron into minerals raises the heat capacity above the values that can be accounted for by vibrational modeling. The effect of adjusting vibrational models for this non-linear frequency shift will be further discussed. Preliminary thermodynamic models will also be presented. *Hofmeister et al., Am. Min. 1996, 81: 418-428.

T11D MCC: Level 1 Monday 0830h

Seismotectonics of the Eastern San Francisco Bay Area I Posters *(joint with G, S)*

Presiding: **D E Moore,** U.S. Geological Survey**; D A Ponce,** U.S. Geological Survey

T11D-0422 0830h POSTER

Tectonic implications of the thermal regime, San Francisco Bay Area, California

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An integral element to understanding rheology, continental deformation, evolution and geodynamics is knowledge of the subsurface thermal regime. Five boreholes, recently drilled for strain meter emplacement along the San Andreas Fault System (SAFS) in the San Francisco Bay Area, California provided an opportunity to collect new heat flow values within this dynamic area. These new values fill gaps in existing heat flow coverage in the central and northern Bay Area, and help constrain the role of temperature in determining the spatial and temporal pattern of deformation within this plate boundary zone. The five boreholes vary in depth from 140 to 220 meters and penetrate Cretaceous and Jurassic age sedimentary, metamorphic and igneous rocks of the Franciscan and Salinian blocks. Temperature profiles were recorded in each borehole, and more than 200 thermal conductivities were measured on drill cuttings and core samples. Reliable heat flow values were acquired at four of the five sites and range from approximately 78 to 92 mW m^{-2}. The average heat flow from these four sites together with 12 previously published values from the San Francisco Bay Area west of the Calaveras fault is 87 mW m^{-2} with a standard deviation of 8 mW m^{-2}. Overall, the new data within the SAFS are consistent with elevated heat flow that characterizes the California Coast Ranges and confirm the continuation of this thermal regime along both the northern segment of the Hayward fault and the section of the San Andreas fault offshore San Francisco. Locally, variations in heat flow along the SAFS may reconcile along strike discrepancies between observed surface slip after the 1906 San Francisco earthquake and geodetic models for coseismic slip, through the influence of thermal conditions on the maximum depth of seismic moment release.

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T11D-0423 0830h POSTER

The Hayward Fault in the East San Francisco Bay Region, California: A Regional Geophysical and Geological Perspective

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Regional gravity, magnetic, and geologic data, together with sparse seismic reflection and refraction data, and drill hole logs, provide a regional tectonic perspective and context of the Hayward fault. The fault is at least 85 km long and terminates at both ends at pull-apart basins. The southeastern terminus falls near the northeastern tip of the NW-SE Evergreen basin, which likely formed in the wake of a right step between the Silver Creek and Hayward Faults as a result of large right slip. The northwestern terminus lies along the southwestern edge of the deep basin that lies beneath eastern San Pablo Bay and extends, as the East Bay Trough, both southeast and northwest. Here, a structural manifestation of the Hayward Fault (the southwestern edge of the deep basin) steps right to about trace of the Tolay thrust Fault whereas seismicity and recent movement step farther right to the Rodgers Creek Fault. The deep basin under San Pablo Bay is three times wider than the right step from the Hayward fault to the Rodgers Creek fault, suggesting that if this basin is a strike-slip pull-apart basin, then faults farther east of the Rodgers Creek fault must have been involved in its formation. The local basin that formed during the past few million years in the wake of the Hayward-Rodgers Creek right step probably is no more than 500 m deep, according to a seismic reflection profile. A continuous magnetic anomaly probably reflecting a buried volcanic body lies between the Rodgers Creek Fault and the western deep basin margin north of San Pablo Bay, continues southward to truncate against the Hayward fault beneath most of San Pablo Bay. This body is not dismembered, precluding a simple strike-slip connection between the Rodgers Creek and Hayward Faults with more than about 10 km of offset (compared to the estimated roughly 100 km of total offset across the Hayward fault). The Hayward fault separates two distinctly different crustal blocks. The Bay block to the southwest generally consists of a basement of Franciscan terranes mantled by a veneer of Plio-Quaternary deposits generally <400 m thick. One exception is the San Leandro synform west of the central reach of the Hayward fault, which contains about 800 m of folded, probably Tertiary, strata overlain by about 300 m of flat-lying younger deposits. Northeast of the Hayward Fault Franciscan terranes lie beneath Mesozoic Coast Range Ophiolite, Cretaceous Great Valley Sequence, and overlying Cenozoic deposits exposed at the surface. The Valley Sequence and younger sedimentary deposits probably reach thickness in excess of 8 km beneath Livermore Valley and San Pablo Bay, suggesting structural relief on the Franciscan basement of more than 9 km (bottom of Livermore basin to top of the Diablo Range to the south). The central reach of the Hayward Fault lies at the western base of a steeply east-dipping slab of Coast Range ophiolite, indicating that the present-day Hayward Fault is here controlled by the older Coast Range Fault, a wedge fault that regionally separates subduction-related Franciscan rocks from overlying forearc Coast Range ophiolite and Great Valley Sequence strata.

T11D-0424 0830h POSTER

Effects of Hayward fault interactions with the Rodgers Creek and San Andreas faults

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Finite-element and crustal-structure models of the Hayward fault emphasize its position within a network of interacting faults, and indicate a number of expected influences from other faults. For example, a new structural cross section across San Pablo Bay in association with potential field maps allows us to map and model detailed interactions between the Hayward and Rodgers Creek faults. The two faults do not appear to connect at depth, and finite-element models indicate growing extensional stress in the stepover between the two faults. A model consequence of extensional stress in the stepover, combined with long-term interaction with the San Andreas fault, is normal-stress reduction (unclamping) of the north Hayward fault. If this occurs in the real Earth, then substantial reduction in frictional resistance on the north Hayward fault is expected, which might in turn be expected to influence the distribution of creep. Interaction effects on a shorter time scale are also evident. The 1906 San Francisco, and 1989 Loma Prieta earthquakes are calculated to have reduced stress on the Hayward fault at seismogenic depths. Models of the 1906 earthquake show complex interactions; coseismic static stress changes drop stress on the north Hayward fault while upper mantle viscoelastic relaxation slightly raises the stressing rate. Stress recovery is calculated to have occurred by 1980, though earthquake probability is still affected by the delay induced by stress reduction. We conclude that the model Hayward fault is strongly influenced by its neighbors, and it is worth considering these effects when studying and attempting to understand the real fault.

T11D-0425 0830h POSTER

Geophysical Anomalies and Seismicity Suggest a Connection Between the Hayward and Calaveras Faults, Eastern San Francisco Bay Area, Northern California

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Gravity, magnetic, and seismicity data of the eastern San Francisco Bay Area are used to reveal the three-dimensional subsurface geologic structure of the eastern San Francisco Bay Area and its relationship to ongoing seismicity. Combined, these data suggest a connection between the Hayward and Calaveras Faults. Gravity and magnetic modeling of a tabular gabbro body near San Leandro and relocated, double-difference seismicity data along the Hayward Fault (Ellsworth et al., 2000) suggest that the Hayward Fault dips to the northeast. Further southeast, double-difference seismicity data indicate that the fault dip becomes shallower, possibly connecting the creeping surface trace of the Hayward Fault with the diverging Mission seismicity trend at depth as suggested by Manaker and Michael (2003). In the stepover region, the southern extension of the Hayward Fault is parallel to the active central Calaveras Fault for about 25 km and the 4-km wide area in between is characterized by en echelon reverse (oblique?) faults. At depths below about 5 km, seismicity appears to be continuous, connecting the Hayward fault to the left-stepping central Calaveras Fault along the Mission seismicity trend. Geophysical interpretation of offset magnetic rock units also suggests that the northern Calaveras Fault has at most a few tens of kilometers of total offset and that most slip may be transferred from the southern Calaveras Fault, with a total offset of about 175 km, along the central Calaveras, Silver Creek, Hayward, and other faults west of the northern Calaveras Fault, consistent with present seismicity. Cross-sectional and 3D visualizations of these data are used to illustrate the proposed geometry of the connection between the Hayward and Calaveras Faults.

T11D-0426 0830h POSTER

Structures in the Hayward and Calaveras Fault Zones Inferred From Relocated Seismicity

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Sixteen years of earthquakes recorded by the Northern California Seismic Net (NCSN) between 1984-2000 and relocated using the Double-Difference technique (Ellsworth and others, Eos, 2000) reveal a number of intriguing structures within the Hayward and Calaveras fault zones and a complex relationship between the main fault surfaces and secondary oblique or reverse faults. As suggested by Waldhauser and Ellsworth (2002) and Manaker and Michael (2003), the central Calaveras fault appears to connect to the Hayward fault through a volume bounded on the north by the Mission seismicity trend. As defined by seismicity below 6 km depth, the connection appears quite simple, involving several straight, near-vertical segments forming a restraining bend along the Mission seismicity trend. Above 6 km the connection is complex and not well-defined by seismicity. At the Earth's surface, the mapped creeping trace of the southern Hayward fault deviates from the eastward diverging seismicity along the Mission trend, suggesting that the fault dips to the east in this vicinity to connect with the deeper seismicity. The mapped active central Calaveras fault trace is not very linear, has several strands in many places, and deviates by 2-3 km from the upward projection of a planar fault surface at depth, beautifully delineated by seismicity. The mapped surface traces of the two faults do not connect, but run subparallel about 5 km apart for 25 km. The area of overlap is characterized by mapped reverse and oblique faults. At one location in the overlap region, seismicity suggests a dipping fault that appears to cut and offset horizontally a near-vertical Calaveras fault plane, raising the interesting possibility that seismogenic asperities are being created as the strike-slip and reverse/oblique systems interact. Intersections of this sort between two active fault systems might well explain the linear streaks of repeating microearthquakes that have been noted in a number of studies. One unanswered question is how such complex, interacting fault systems evolve in time, and whether the active creation of asperities might affect the temporal behavior of earthquakes on a fault, as may have occurred if the 1983 Coalinga event led to changes in the geometry of the San Andreas fault surface near Parkfield.

T11D-0427 0830h POSTER

Implications of Microseismicity and Earthquake-Induced Transient Fault Creep for the Earthquake Potential on the Hayward Fault, Eastern San Francisco Bay Area

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The Hayward fault is considered to be one of the primary hazards in the San Francisco Bay region. Although it is documented to undergo significant creep, with some creeping patches accommodating 50% or more of the long-term fault displacement, the fault also experiences moderate to large earthquakes (most recent M $\sim$6.8 in 1868). In order to link seismic potential to the rate at which moment accumulates on the fault plane, we need to understand the patterns and distribution of creep over time. As might be expected, the microseismicity observed on the fault produces only a negligible percentage of the seismic moment dissipated on the Hayward fault, whereas aseismic creep releases about 25% of the moment accumulating on the fault. It is also important to understand how the distribution of creep on the fault can change throughout the earthquake cycle, in particular after major seismic events. Although our creep models do a good job of representing the observed surface creep, they have not previously incorporated the effects of transient post-seismic strain recovery, which can have significant effects on creep rate. We test the temporal variation from "steady-state" creep models by incorporating an 1868-type earthquake in our model to observe changes in creep distributions and recovery rates throughout the fault plane. Both the distribution and magnitude of creep on the fault vary substantially after the simulated earthquake. Although at present the post-seismic transients have mostly decayed, the pattern of accumulated moment is significantly different when these transients are included.

T11D-0428 0830h POSTER

Investigation of Microscale Fault Textures Associated with Aseismic Creep and Coseismic Rupture in Active Fault Zones

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Micro-scale textures in poorly consolidated sand collected from active fault zones show differences between deformation fabrics produced by aseismic creep and those produced by coseismic rupture. Oriented samples of late Pleistocene to Holocene sand were collected from creeping sections of the Green Valley, Southern Calaveras, and San Andreas Faults, all parts of the San Andreas Fault system in north-central CA. Samples were also collected from two structures thought to record coseismic rupture: the McKinleyville

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_L 5.2 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.

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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.

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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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