the inner core, is of primary importance. Studies include first-principle calculations [1-5] and x-ray radial diffraction measurements [6], but the results show general disagreement, not only in magnitude, but in direction as well.
We will report new inelastic x-ray scattering (IXS) data on polycrystalline hcp-iron as a function of pressure, complementing and extending previous IXS data [7]. The derived longitudinal and transverse sound velocities will be compared with the calculations and the experimental results present in literature.
Furthermore, the issue of elastic anisotropy will be addressed. Taking advantage of the texturing developed by uniaxially compressed hcp-metals [8], and making use of a properly designed diamond anvil cell characterized by an angular aperture of more than 90^o, we measured the sound velocity at 22 and 112 GPa in two different geometries with respect to the compression axis, probing the longitudinal sound propagation at 50^o and 90^o with respect to it. A difference in acoustic sound velocity of about 5% has been detected at the highest pressure. This effective anisotropy on a textured polycrystalline sample is comparable with the one observed in the Earth, further relaxing the requirement of a nearly perfect alignment of iron crystal grains sustained by previous theoretical investigations [1,4].
[1] L. Stixrude, R.E. Cohen, Science 267, 1972 (1995). [2] P. Soderlind et al., Phys. Rev. B 53, 14063 (1996). [3] R. E. Cohen et al., Phys. Rev. B 56, 8575 (1997). [4] G. Steinle-Neumann et al., Phys. Rev. B 60, 791 (1999). [5] G. Steinle-Neumann et al., Nature 413, 57 (2001). [6] H.K. Mao et al., Nature 396, 741 (1998); correction Nature 399, 280 (1999). [7] G. Fiquet et al., Science 291, 468 (2001). [8] H. R. Wenk et al., Nature 405, 1044, (2000).

T21F-05 1120h

Chemical relaxation and seismic attenuation across a phase transition

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Values of mantle thermodynamic properties are often deduced indirectly through seismological and geodynamical experiments that cover a large range of characteristic times. We show that due to phase transitions, the incompressibilities obtained by these experiments could be very different. Experimental probes faster than phase transformation kinetics sample unrelaxed properties at constant compositions. On the contrary, slow experiments sample relaxed properties at compositions maintaining thermodynamic equilibrium. We illustrate these concepts by using the example of the olivine-wadsleyite phase change that takes place around 410 km depth. We compute the incompressibility, attenuation and Bullen parameter as a function of kinetic rate of the transformation. We show that the compressional quality factor Q_K of mantle material undergoing a phase change can be as low as 0.6 when characteritic times of the phase kinetics and geophysical probes are comparable. Assuming that the characteristic time of olivine to wadsleyite transformation under average mantle temperatures is between 3 hours and 3 months, we show that the chemical relaxation can be a significant source of dissipation and of energy sink for slow processes (normal modes, tides or Chandler wobble). Using the example of normal modes we show that the compressional quality factor can be significantly low (Q_K ∼100) even if the sampled values of K_S are close to the unrelaxed ones. If the phase change kinetics is faster than 3 hours, the chemical dissipation can significantly affect probes even on seismic periods.

T21F-06 1135h INVITED

Seismological Constraints on Mantle Structure and Composition

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Results of travel time tomography suggest that some slabs of subducted lithosphere are severely deformed between 400-1000 km depth - which is loosely referred to as the transition zone (Layer "C" according to Bullen's classification) - and that beneath some convergent margins subducted slab material has sunk to larger depths in the mantle, some perhaps to near the CMB. The transition zone may be marked by enhanced levels of anisotropy. These inferences all suggest that mantle convection is more complex than suggested by the canonical end-member models of either convective stratification at 660 km or unhindered whole mantle overturn. Over the past 5 years the emphasis has shifted from mapping wavespeed patterns to constraining spatial variations in temperature and composition, and there is now mounting seismological evidence for the existence of compositional heterogeneity in the deep mantle. P and S wave travel times suggest that the ratio of relative variations in shear- and compressional wavespeed (R=dlnVs/dlnVp) increases more rapidly with depth than can be explained by temperature effects alone, in particular away from major convergent margins (i.e., in the regions with the lowest wavespeeds). Furthermore, combined with constraints from mineralogy, normal mode studies based on full model space searches indicate that in the deep mantle the most likely ratios between variations in elastic parameters and density require variable composition. Both lines of study suggest that variations in perovskite and iron are needed to explain the seismological data. These inferences are qualitatively consistent with main aspects of the thermo-chemical mantle model proposed by Kellogg et al. (Science, 1999), but lack of observations of scattering off the implied interface (e.g., Castle & Van der Hilst, JGR, 2003) renders existence of a distinct layer in the deep mantle unlikely. Diffuse boundaries due to hitherto unknown phase transitions or gradual, pressure induced changes in composition cannot yet be ruled out, however, and in thermo-chemical convection vertical mixing gradients may exist over long periods of geological time, with rapid recycling in the shallow mantle and a lowermost mantle that is much less often involved in convective overturn. We will speculate on the possible origin of the compositional heterogeneity in the mantle beneath 1000 km depth.

T21F-07 1150h

Diamond Formation in Core Segregation Experiments : a key for Estimating the Carbon Content of Planetary Cores

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High-pressure experiments were performed in a multi-anvil press at 1700 °C and pressures between 10 and 25 GPa on assemblages of iron carbonate (siderite) and silicon. The relative proportions of the two phases were varied in order to investigate different conditions of oxygen fugacities in the run products. The relevance of the investigated experimental conditions to core formation models is discussed. Samples were studied by Raman spectroscopy, electron microscopy, ion and nuclear microprobes. In all samples, siderite was reduced to (Fe,Si) metallic alloy and to diamond whereas silicon was partially oxidized to stishovite. The diamonds formed are euhedral crystals with characterisitc sizes of 20 micrometers. The carbon content in the metal phase equilibrated with those diamonds (diamond saturation) has been measured by ion microprobe to be of 1.5 wt %. This number would be an upper bound for the carbon content of planetary cores formed under such conditions. This suggests that the carbon content in the Earth's core is low when compared to the cosmic abundance of this element, but large enough for the inner core to be constituted of iron carbide (see Wood et al 1993, Earth and Planetary Science Letters, 117, 593-607). Moreover, this study brings new constraints on the relative position of silicon-stishovite and carbon-carbonate buffers at high pressure and provides experimental evidence of diamond formation from reduction of carbonates by reaction with Fe-Si alloys.

T21F-08 1205h

Some Geochemical Implications of the Mantle Transition-Zone Water-Filter Model

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Geochemical observations are usually interpreted in terms of the Earth's initial composition and subsequent differentiation, including (1) core-mantle separation, (2) continental crust formation and (3) partial melting at mid-ocean ridges and/or subduction-zone upper mantle. In this traditional picture, significant chemical differentiation occurs only in the shallow upper mantle [process (3)], in which case it is difficult to reconcile geochemical evidence for isolated mantle reservoirs with geophysical evidence for mantle-wide convective circulation. However, we recently proposed [Bercovici and Karato, Nature, Sept 4, 2003] that dehydration-induced partial melting at 410km will act as a filter for incompatible elements which are extracted into a dense melt that is then returned to the deep mantle; the trace-element circulation is thus partially decoupled from the convective circulation of the bulk of the mantle which occurs at the whole-mantle scale. In this model, the OIB source materials are drawn directly from the undepleted and heterogeneous deep mantle (deeper than 410km), while the MORB source materials are processed through the putative 410km dehydration-melting "filter". The separation of MORB and OIB source materials is thus assumed to occur at 410km and therefore it is important to examine if our hypothesis is consistent with observations of isotopes with very slow radioactive decays (i.e., $^{87}Sr/^{86}Sr$, $^{143}Nd/144Nd$). The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios are distinct between OIBs and MORBs (i.e., OIBs have a wider distribution than MORBs, and MORB isotopic ratios correspond to "depleted" chemistry). These isotopic ratios are controlled by (i) the chemical composition (Rb/Sr and Sm/Nd, respectively) and (ii) the long-term radioactive decay (half-life of 48 and 106 Gyrs, respectively). A simple analysis was made to calculate the contrast in the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios between OIBs and MORBs corresponding to our model. Two factors control these isotopic ratios in our model: (i) chemical differentiation at 410km between Rb/Sr and Sm/Nd and (ii) the volume fraction of OIB sources with different isotopic ratios (and the degree of mixing of these materials in the 410km dense melt layer). We find that the observed isotopic ratios are consistent with our model if (i) the source region of OIBs is volumetrically dominated by materials with isotopic ratios similar to Hawaii or FOZO source regions (but not EM1 or HIMU), (ii) significant chemical fractionation occurs by partial melting at 410km for Rb/Sr but not for Sm/Nd and (iii) the mixing at 410km is extensive. Implications for other geochemical signatures including isotopic ratios of rare gas elements and their volumetric amounts and the trace element distribution pattern will also be discussed.

T22A MCC: Level 1 Tuesday 1330h

Development of Fault Systems Through Time: Process and Rates III Posters

Presiding: **P Cowie,** Edinburgh University**; N Dawers,** Tulane University

T22A-0487 1330h POSTER

A High Resolution Geophysical Study of the Offshore Western Gulf of Corinth Rift

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The western Gulf of Corinth has generated recent debate in terms of distribution of extensional strain, interactions between active faults and fault geometry. Onshore data suggest that faults do not accommodate extensional strain of the magnitude suggested by geodetic measurements. Recently acquired high resolution

geophysical data in the western Gulf of Corinth, including Reson Seabat 8160 50 kHz multibeam bathymetry (with sidescan collected simultaneously) and sparker and boomer seismic profiles, will allow a detailed study of faulting relationships, fault propagation history and associated sedimentological processes. Multibeam data indicate the complex axial and tributary channel pattern of the gulf as well as revealing the surface expression of active faults on both margins and within the basin centre. Several fault tips are evident, including the Aigion fault which has been surveyed in great detail with boomer lines spaced between 25-100 m. The fault tip is complex with multiple synthetic and antithetic splays. The post-lowstand transgressive surface is clearly imaged and therefore fault growth rates can be established. Gas-related features are common, including pockmarks and mud volcanoes. To the east, displacement on the eastern tip of the Eliki fault decreases rapidly offshore and a splay of the Derveni fault is observed. A major S-dipping antithetic fault opposite the Eastern Eliki fault has clear bathymetric expression and is locally associated with a prominent basement ridge. This fault may make a significant contribution to extensional strain in this part of the rift. In the centre of the basin, sediments are deformed by multiple minor faults with seafloor displacement. Ultimately, high resolution offshore interpretations can be integrated with regional datasets and existing data (e.g., geomorphic, paleoseismological and sedimentological) onshore and used to better assess rift deformation models, rift evolution and local seismic hazards.

T22A-0488 1330h POSTER

Control of Fault Segmentation and Seismicity by Inherited Cross-strike Fabric in the Corinth Rift (Greece)

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Fault growth occurs in crust that is often strongly heterogeneous. Lateral variations of geometrical and mechanical properties are more difficult to recognize and model than simple horizontal layering, but they play an important role, especially in domains of superposed deformation. The Corinth Rift (Greece) is an ideal setting for analysing dimensions and displacement of seismically active normal faults that since the early Pleistocene propagated at right angles to the Neogene Hellenic thrust belt. The largest historical earthquakes of the last two centuries and 6 shocks within the last 30 years with 6<M<6.7 are evenly distributed along N-dipping faults that bound the southern margin of the Corinth Rift. However, the western regions of the rift (from Patras to Egion) differ from the eastern regions (from Dervenion to Corinth) in terms of extensional strain (15 mm/year versus 10 mm/year of N-S extension from GPS), dip of seismic fault planes (30°N versus 50°N) and maximum depth of seismic activity (8-11 km versus 12-15 km). New mapping along the southern shore of the rift documents different thickness and facies of the Pliocene-Pleistocene clastic sequence in two distinct sub-basins (Egion to the west and Dervenio to the east), separated by a N-S elongated ridge. This ridge is an inherited culmination of the Neogene thrust belt that exposes a stack of folded carbonate units basally detached above a low-grade metamorphic basement. The contour map of the basal detachment depicts the structural high as a large scale, N-plunging antiform truncated by E-W and N-S normal faults. Segmentation of the Quaternary syntectonic basins on the southern margin of the rift is a consequence of the lateral decay in offset of the largest E-W faults that have controlled the northward progradation of the sedimentary sequence in the basins. Both the Egion, Eliki and Pirgaki fault in the west and the Xilokastron fault in the east display a progressive tapering of their total throw, dying out laterally against the N-S structural high. A longitudinal crustal cross section along the southern margin of the rift shows lateral segmentation of the E-W normal faults with a wavelength comparable to the folding of the basal detachment surface and suggests that fault segmentation at the surface reflects structural heterogeneity at depth. Geometrical discontinuities inherited from the compressional thrust belt interfere with present-day kinematics and ultimately control individual seismic ruptures and the long-term growth of the normal faults.

T22A-0489 1330h POSTER

Three-dimensional Structure of the Cinarcik Basin from a Densely Spaced Grid of Seismic Reflection Profiles, SEISMARMARA Experiment

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The North Anatolian Fault (NAF) has been responsible for the earthquakes of Izmit and Duzce in 1999. The presence of a seismic gap in the Sea of Marmara has led an extensive marine research in recent years. The SEISMARMARA survey was carried out in 2001 as a combined seismic reflection, refraction and earthquake experiment in the Marmara region. R/V Le Nadir was equipped with a 4.5 km long streamer and a large single-bubble airgun source. During Leg 2, about 2300 km of seismic data were acquired in the Cinarcik Basin and its margins, using a 2900 cu.in. source and a shooting interval of 37.5 m. The dataset comprises 82 lines shot at N13 azimuth (approximately at right angle to the basin margins) and spaced 600 to 900 m apart, and one strike line perpendicular to these dip lines. Processing of this homogeneous, high-quality dataset was achieved, including detailed velocity analyses, multiple suppression - taking advantage of the larger offsets available - and post-stack time migration. The resulting sections provide insight into the structure and tectonic activity of the Cinarcik Basin. Imaging of active normal faults along the NNE and SSW margins of the basin indicate that this basin can be viewed as a releasing, underlapping side-step governed by two strike-slip segments, the Izmit fault being the eastern segment. These bounding faults seem to have had a complex geological evolution, both in space and time. The top of the basement appears as a high-amplitude reflector and can be traced mainly in the eastern and southern parts of the basin. Sedimentary infill consists of two major sedimentary units, previously called the upper and lower sequences, and which may be related to two different tectonic stages. The westward thinning of the upper sequence suggests that the basin is propagating eastward. A rough estimate of the maximum sedimentary thickness is about 5 km. We present here the 3-D geometry of the Cinarcik basin and discuss its evolution in space and time, and its relationship with the rest of the Marmara Sea and the North Anatolian fault system.

T22A-0490 1330h POSTER

Submarine faults activities in the Gulf of Izmit and Gemlik Bay, NW Turkey: high-resolution shallow seisemic survey and earthquake recurrence studies

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The Gemlik Bay is located in the southeast part of Marmara Sea, where is one of the major active-faulting features seen in the NAF Zone. There are three sets of faults in and aroud the Gemlik Bay: 1) several south-dipping normal faults along southern coast of the Armtlu Peninsula 2) several continuous north-dipping normal faults along the southern coast of Gemlik Bay 3) small basin bounded two sets of normal fault. These three features of faults can explain right-stepping strike-slip faulting opening the bay by pull-apart mechanism. Almost major faults show that vertical rate of displacement is over than sedimentation rate. In order to evaluate fault activities (time and displacement amount), we tried coring about one of the faults in the bay. After several analysis <ETH> magnetic susceptibility, grain fraction and C14 dating, we found two seismic events among the cored interval. After the same method was tried in the Eastern Basin of Izmit Bay, three seismic events are reconstructed. Another way to evaluate seismic activities, we tried to take cores from the deepest (-208m) Central Basin in Izmit Bay. We recognized seimo-turbidites occurred periodically, and can be seen over twenty layers by high-resolution seismic profiling. Among the four meters cored samples (1000-1700 years BP) from the basin, we detected five seimo-turbidite layers. Seismic events and average intervals reconstructed from two different way <ETH> fault coring and seismo-turbidite- are well consistent with each other.

T22A-0491 1330h POSTER

Active interplay between strike-slip and extensional structures in a Back-Arc environment, Bay of Plenty, New Zealand

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Active continental back-arc tectonics associated with the oblique Hikurangi subduction zone, North Island, New Zealand, is characterized by (1) extensional deformation distributed across a 40-50 km-wide zone, but presently concentrated in the east within the 20 km-wide, NE-striking Taupo Fault Belt (TFB) and Whakatane Graben (WG); (2) c. 12mm/yr extension rate at the Bay of Plenty coast; (3) 1-3 mm/yr subsidence in the WG; and (4) a seismogenic zone estimated to be 6-9 km thick. A component of the oblique convergence within the plate boundary is partitioned to the east onto the adjacent North Island Dextral Fault Belt (NIDFB), a large NNE-trending strike-slip fault system traversing the entire North Island. At the Bay of Plenty coast, the NIDFB strikes north, with an estimated strike-slip rate of at least 1 mm/yr. Both normal and strike-slip fault systems extend beneath the continental shelf in the Bay of Plenty, and because of differences in their strike, they converge and interact. Detailed mapping of faults using marine seismic reflection profiles and multibeam bathymetry data reveals the structure of the WG. Tilted basement blocks are associated with large west-dipping faults, numerous antithetic secondary faults, and domino-style fault arrays. Eastward migration of the principal extension zone during the last c. 1 Myrs has resulted in the encroachment and oblique overprinting of the NIDFB by the WG. The structure and geometry of the White Island Fault (WIF), currently the principal fault along the eastern margin of the graben, results from interaction and linkage of the two fault systems. The displacement profile of this fault reveals relatively young NE-striking sections that obliquely link more northerly-striking, inherited components of the NIDFB. Understanding of the fault structure and evolution may have implications for the interpretation of earthquake potential close to urban centres.

T22A-0492 1330h POSTER

Displacement Accumulation in a Linked Segmented Normal Fault over the last 18 ka Within the Whakatane Graben, New Zealand.

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The Whakatane Graben is a young (<2 Ma) and highly active structure situated on the New Zealand continental shelf where the sediment supply has been sufficient to infill accommodation space created by the rapidly displacing faults, thus providing a complete record of past fault motions. The shallow water (up to 200 m depth) of the graben on the continental shelf means it is well placed for acquisition of high-resolution seismic data and core samples. One of the most active faults in the Whakatane Graben is the Rangitaiki Fault, a 20 km long linked, segmented, normal fault. The central 9 km of the Rangitaiki Fault is imaged by over 97 closely spaced chirp sonar, 3.5 kHz and Boomer profiles covering an area approximately 5 km by 9 km, the outer sections of the fault are imaged by 12 more widely spaced high-resolution profiles. These data provide excellent quality high-resolution images of the top 50 - 60 m of sediments which include the post-glacial (< 18 ka) transgressive sequence. Within the post-glacial sequence there are several strong and laterally continuous reflectors displaced by active extensional growth faults. Displacements on four of these horizons, dated 17 ± 1, 13.3 ± 1, 11.1 ± 1 and 9 ± 1 ka, are used to create displacement profiles and to calculate displacement rates. The segments of the Rangitaiki Fault are hard-linked throughout the last 18 ka, but the post-glacial

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displacement accumulation is still dominated by the location of the relict segment boundaries. The maximum displacement rate observed on the Rangitaiki Fault is 4.6 ± 2.3 mm/yr measured over 2 ka, a maximum of 3.4 ± 0.2 mm/yr measured over 18 ka. Displacement profiles of the last 9 ka of fault movement are regular and similar to profiles showing the last 300 ka of fault movement. In contrast, profiles showing only 2 ka of fault movement are highly irregular and show points of zero displacement on the larger faults. The variability of fault displacement rates over short (< 2 ka) timescales suggests that fault activity rates measured from geodetic surveys may not be adequately sampling the fault activity, and longer timescale estimates of displacement rate, such as are presented here, are more reliable an indicator of seismic risk and earthquake recurrence intervals.

T22A-0493 1330h POSTER

Oblique Strike-Slip Faults and Structural Geomorphology: new Insights From the Plate Boundary Transfer Zone, NE South Island, New Zealand

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Temporal and spatial variations in topographic loading directly affect near-surface stress field perturbations controlling fracture propagation and orientation, as well as fault zone behaviour and evolution. While some end-member styles of transpressional deformation are well documented by laboratory modelling and from field examples, fault-slip is often complex, and invariably accompanied by progressive uplift and mountain building. There are few field studies documenting the critical interdependence of fault zone evolution and tectonically-driven mountain building. Under transpressive conditions a combination of compressive loads generated by the regional stress field coupled with the asymmetric additional loading created by the uplifted topography tends to extrude a wedge of material out of range front shear zones producing an anomalous sense of normal surface displacement. The combination of footwall splays and partitioning of strike-slip on the steep hanging wall side of the whole fault zone, creates a wedge of weakened rock dominated by inclined shear zones dipping into the hillside. Conversely if conditions give rise to a relaxation and a change to extension, the pre-existing steep reverse faults are optimally oriented to reverse slip and act as normal faults so that the whole wedge slides in under the hanging wall. The development of an inclined wedge on non-vertical faults is specific to this mode of deformation. Integration of structural geometry and geomorphic evolution in the analysis of tectonically active regions has pragmatic implications for paleoseismic studies, where surface displacements are only indirectly related to actual slip components at seismogenic levels. A further question is how does geomorphic evolution of a fault-driven landscape (e.g. valley incision, large deep-seated landsliding) influence upper crustal fault zone architecture and visa versa. Detailed field observations from the plate boundary transfer zone in NE South Island has formed the basis of related structural models. These illustrate the way in which slip along range front fault zones is distributed in complex 3D deformation both within segments and at segment boundaries, and the way topography influences these processes.

T22A-0494 1330h POSTER

Quantifying the Growth History of an Ancient Border Fault System, and the Role of Normal Fault Growth on Sedimentation During Basin Formation: a Case Study from the Late Cambrian Owen Conglomerate, West Coast Range, western Tasmania, Australia

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The stratigraphic and depositional architecture of evolving extensional basins is principally controlled by normal fault growth through the generation of accommodation space. The history of border fault systems therefore controls the evolution of internal drainage patterns and basin facies distributions. Despite recent advances in the understanding of present-day normal fault growth, quantifying the effect of normal fault evolution on the architecture of ancient sedimentary basins has been largely obscured by post-rift deformation and erosion. The Late Cambrian Owen Conglomerate along the West Coast Range of western Tasmania, Australia, includes thick fluvial sandstone and marine turbidite sequences, as well as fluvial and marine conglomerates. The accumulation of this formation provides excellent insights into the rift-fill history of an ancient extensional basin, due to rugged, glaciated topography and exceptional outcrops, and the typically overfilled nature of the basin, which preserves the fault displacement history. Structural traverses have delineated the geometry of the extensional fault system active during deposition of the Owen Conglomerate. The fault system comprises a segmented array of border faults with variable along-strike polarity. Minimum displacements were calculated from present-day stratigraphic thicknesses, and define a roughly symmetric displacement-length profile that resembles that of a single, isolated fault, with maximum displacement (Dmax) located at the centre of the fault array, and decreasing displacement toward the distal segments. Displacement along the fault system, however, indicates a varied growth history through time. Isolated faulting (Stage 1) occurred during the early stages of rifting, when small fault segments grew in isolation. Stage 1 faults exhibit a Dmax at the centre of each individual segment. Rapid propagation of fault segments to maximum strike length occurred early in the basin history, with only limited interaction and feedback between individual segments. Continued growth faulting (Stage 2) resulted in migration of the locus of maximum displacement as individual segments began to interact and link. Eventual linkage of fault segments (Stage 3) occurred during the final stages of rifting, where the overall system exhibits a characteristic, through-going, displacement-length profile. Integration of lithofacies distributions, isopach maps and palaeocurrent data with the structural dataset shows that the stratigraphic architecture is strongly coupled with the development of the border fault system, and offers a high resolution model for fault development. While the generation of accommodation space adjacent to footwall scarps facilitated the development of a hanging-wall, dip-slope fluvial catchment and axial-through drainage networks, tectonic subsidence also provided a crucial trigger for the onset of isolated marine sedimentation where accommodation space generated by the localised accumulation of displacement on individual segments outpaced sediment supply.

T22A-0495 1330h POSTER

Paleoseismicity on the Dense Network of Holocene Submarine Faults in Beppu Bay, Southwest Japan

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Beppu Bay, approximately 30 km by 15 km in size, contains a complex network of Holocene submarine faults whose total length amounts to 230km. They are normal dip-slip fault with left-lateral strike-slip component. The maximum vertical offset accumulated in the past 7,300 years exceeds 20 m. A detailed study on paleoseismicity on one of the faults shows a feature of the time-predictable recurrence, i.e., the larger the vertical offset, the longer the following inter-event time. Branching features can be often recognized near the end of fault and the consistency in branching direction of neighboring faults suggest repeated rupture propagation in the same direction. A detailed examination of high-resolution seismic profiling of branch indicates a repeat of old branching and a slow transition of rupture from an old branch to a new one. The central Beppu-Bay fault running WNW to ESE in the center of the bay forms the northern boundary of the major graben structure of the bay. The Asamigawa fault in the west of the bay, running parallel to the central Beppu-Bay fault, has been considered as the southern boundary, but its eastern continuation was not clear. Recent seismic profiling carried out by Chida et al. (2003) showed an existence of Holocene normal fault beneath the city of Oita whose population is 440,000 and interpreted it as a part of the southern boundary. Our high-resolution shallow-water profiling survey revealed the submarine portion of the southern boundary fault, filling a gap between two subaerial faults. We continuously sample marine sediments down to a subbottom depth of 20m by piston coring and correlate specific features of sediment, 20 volcanic ash layers, a few features of magnetic susceptibility and coarse fraction together with C-14 ages of echinoids, pelecypods, and plant remains on the both sides of a targe fault to estimate the date and vertical offset of paleoearthquakes.

T22A-0496 1330h POSTER

Recovering the Linkage History of Large Faults from the Sediments of the Gulf of California Extensional Province

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Analysis of the stratigraphy of sedimentary basins bounded by normal faults yield a wealth of information about how these brittle structures evolve through time forming array systems. However, mostly due to large uncertainties in the dating of sediments, little can be said about slip rates and how slip is accommodated during the interaction and linkage of normal faults. Cyclicity in sediments induced by Milankovitch climatic changes can be used as a very precise high-resolution stratigraphic chronometer, eliminating the problem of uncertainties in the dating. Therefore, the slip history of faults can be inferred with high accuracy. Here we present a cyclicity analysis of gamma-ray log from a borehole drilled in the Laguna Salada basin, a transtensional basin located in the Gulf of California extensional province. This has allowed us to establish its chronostratigraphy with a resolution of 50 kyr, from which the subsidence history of the Laguna Salada fault and its interaction with neighboring faults is recovered. We find that the long-term subsidence rate of the Laguna Salada basin has remained constant during the last 1.65 Ma (1.4 mm/yr) in agreement with observations documented by other authors. However, our analysis reveals that at shorter timescales the subsidence history is composed of pulses lasting on average 500 kyr. Subsidence rates during these pulses can vary by a factor of two with respect to the long-term subsidence rate. These pulses correlate with the breaking of the Laguna Salada Fault and the breaking of the Cañon Rojo fault, a releasing stepover that links the Laguna Salada fault with the Cañada David detachment to the south.

T22A-0497 1330h POSTER

Episodic Accelerations in Extensional Fault Displacement Rate Determined From Reconstructed Delta Architectures: Loreto Basin, Baja California Sur, Mexico.

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The Pliocene Loreto basin is a fault-bounded half graben situated on the western margin of the obliquely extending Gulf of California. The 35 km long, basin-bounding Loreto fault has 1500m of throw and has accommodated largely east-west bulk extension. Episodic displacement accumulation on the Loreto fault has been proposed by previous authors to be the controlling factor on the development of 16 cycles of coarse-grained delta progradation. They showed that the frequency of progradation cycles was too rapid to be explained by Pliocene eustatic fluctuations. Here we present a high-resolution study of the facies architecture to show that previously unrecorded systematic variations in depositional architecture of individual cycles of progradation can characterise the temporal variations in fault-displacement rate. Our analysis provides reconstructions of the depositional architecture of 11 cycles of delta progradation, of which 7 exhibit a transition from a shoal-water to Gilbert-type delta with increasing foreset height and thickness when traced palaeoseaward. We show that the geometry, and specifically the nucleation of Gilbert-type deltas and basinward thickening of foresets cannot be generated by eustatic fluctuations, but that they are tectonically controlled. Furthermore, the geometry of a single cycle of delta progradation requires a continued basinward increase

in bathymetry that can only be generated by an acceleration in the rate of tectonically-controlled basin subsidence along the basin-bounding Loreto fault. This transition in delta morphology plus the subsequent drowning of the delta tops requires an acceleration in fault displacement rate over a time period of 5-20 kyr. A physical explanation for this acceleration is that fault rupture is controlled by time-dependent damage accumulation, where the damage accumulation rate depends on applied stress. Finally, we hypothesise that the recurring episodes of movement on the Loreto fault are characteristic of strain partitioning between extensional and strike-slip faults in the Gulf of California, i.e., the degree of partitioning is time-varying.

T22A-0498 1330h POSTER

Active Extensional Faulting at the Southern Half-Graben Belt of the Tepic-Zacoalco Rift, Western Mexico

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In the past decade much debate has centered upon the kinematics and the mechanism of continental deformation in western Mexico and the motion of the Jalisco block relative to North America. Two distinct models have been proposed. The first one suggest a NW-motion of the Jalisco block that would implies a right-lateral faulting along the Tepic-Zacoalco rift (TZR). More recently others authors have documented a N-NE extensional tectonics active since late Miocene and suggested that the continental boundaries of the Jalisco block, are older structures reactivated by plate boundary forces. Studies on the crustal seismicity and the kinematics of Quaternary faults provide another constraint on the direction of motion between the Jalisco block and North America. On November 4, 5, 6, and 7, 1995, one month after the October 09, 1995, Manzanillo earthquake (Mw = 8.0), a swarm of small events was felt in the Amatlan de Cañas half-graben and recorded by the regional seismic network of Comision Federal de Electricidad. The coda magnitude of the largest event was Mc = 2.5-3.6 and the events were located depth ranging from 6 to 10 km. This seismic activity provoked that people from Pie de la Cuesta and Yerbabuena villages were evacuated. After that a seismic station equipped with an analogic seismograph MEQ-800 at Pie de la Cuesta was installed for three months. During the same time, October, 1995, some houses distributed along a WNW trend in Ameca city underwent severe damages, they are. The digital elevations model of the Ameca city suggest that several structures tectonics are shorter than 2 km are present in the area. The present direction of motion of the Rivera plate relative to North America plate along Middle America Trench has been estimated between N19°E to N48°E (e.g. Bandy et al., 1996). During the October 09, 1995, subduction-related earthquake (Mw = 8.0) a GPS network recorded a SW motion of the Jalisco block which could be associated to an elastic deformation (Melbourne et al., 1996. Our results suggest that (1) the southern half-grabens are the most active structure of the TZR and (2) They are related to a N-NE extensional tectonics as previously reported. We speculate that the seismic activity recorded at the Amatlan de Cañas region is related to a long-term deformation associated with the SW motion of the Jalisco block.

T22A-0499 1330h POSTER

Syn-Rift Stratigraphic Architecture Reveals the Growth History of a Sub-basinal Fault Population in the Outer Moray Firth, North Sea

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Processes of normal fault propagation and linkage are recorded in the stratigraphic record by syn-rift sedimentary deposits that fill the generated accommodation volume. Using 3D seismic stratigraphic analysis, supported by well log and core interpretation, we investigate how the growth of an intrabasinal fault population led to the progressive development of an extensional sub-basin in the Moray Firth rift arm of the North Sea. The North Halibut Graben sub-basin has an E-W to WNW-ESE orientation and formed through the interaction of two main structural trends during late Jurassic rifting. E-W trending structural barriers bound the sub-basin to the north (Tartan and Petronella Ridges) and south (Halibut Horst Spur) whilst major NE-SW trending structures occur at the eastern margin. Spatial and temporal changes in syn-rift stratigraphic architecture reflect the history of faulting within the North Halibut Graben sub-basin. Fault parallel seismic profiles and intra-syn rift isochron maps demonstrate how faults initially developed as separate segments and subsequently linked to form longer strands through progressive growth and propagation. They also provide clear evidence that a major change in the structural framework occurred during rifting, supporting earlier studies advocating sequential rather than synchronous normal fault activity. The syn-rift sequence can be divided into at least two phases based on shifts in sedimentary packages and reorganistation of sequence thicknesses. Isochron maps illustrate that from late Oxfordian times (syn-rift phase I), early syn-rift sedimentation was controlled solely by NE-SW trending faults at the eastern margin of the basin. Strain was initially accommodated across several distributed, highly segmented faults but, with progressive linkage, stress became localised on one or two major through-going fault strands whilst shorter surrounding segments were switched off. From early-mid Volgian times we observe a progressive switch of extensional activity from NE-SW trending faults to newly generated E-W trending structures that suggests a rotation of the prevailing stress field. The syn-rift phase II isochron map (early-mid Volgian - Base Cretaceous) demonstrates how the linearly focused, NE-SW oriented thick deposited during syn-rift phase I is succeeded by a more distributed E-W trending depocentre. A detailed study of the depositional patterns of the Claymore Sandstone Member, a late Kimmeridgian to mid-Volgian syn-rift turbidite lobe system, reveals that migratory changes in dispersal patterns can be directly related to the structurally controlled modifications in basin-floor topography. Observations of turbidite distribution through time comply with and further enhance the model of structural reconfiguration developed through seismic analysis. Subtle changes in depocentre location and facies distribution document segmentation and linkage along individual fault strands. Our observations indicate that the growth history of a normal fault population can be reconstructed through the analysis of depositional systems of the syn-rift sequence. Lateral shifts in depocentre location, changes in thickness of sedimentary deposits, and facies transitions reflect propagation and linkage along individual fault arrays and, more significantly, the switch of activity from one fault set to another.

T22A-0500 1330h POSTER

Displacement Addition on Linking Extensional Fault Arrays in the Canyonlands Graben, Utah

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Studies of brittle fault populations over the past decade have revealed that large extensional faults grow by the lengthening, interaction and physical linkage of en echelon fault segments. However, the temporal evolution of displacement accumulation during segment interaction and linkage is difficult to unravel due to a lack of direct observation during each stage in the fault array development. The process of profile re-adjustment prevents reconstruction of the growth history of a fault from its final configuration, and as a result, several models for the growth trajectory of a fault array undergoing linkage are possible. Observational data with which to constrain the relative timing and mode of displacement accumulation during the linkage process are currently lacking. We use the deformation of late Pleistocene-Holocene stream systems by the growth of a active normal faults in The Grabens, Canyonlands National Park, Utah to constrain the mode of growth of fault arrays. Coupling fault displacement data with geomorphic analysis of deformed present-day and palaeostreams, permits sequential reconstruction of both simple 2-segment fault arrays and complex multi-segment populations from their initial component segments to the present day displacement geometry. In particular, these data provide information on the relative rates of displacement addition. For example, the presence of waterfalls where streams cross fault scarps indicates abrupt rates of displacement accumulation which we can relate to the hard linkage process. The reconstruction of both three- and six-segment faults reveal common aspects of displacement distribution through time: (1) Displacement accumulation occurs almost entirely in the interaction and linkage phase. (2) Interaction between segments causes enhanced displacement addition in overlap zones. (3) Despite interaction in the soft-linkage stage, faults do not achieve a characteristic profile during this phase (4) Displacement accrues rapidly immediately following linkage, and recovery to a standard D-l profile is gained through this process. (5) The locus of displacement accumulation is not fixed in time; the central fault segment does not always experience the greatest displacement enhancement. Preliminary results of cosmogenic 10Be exposure dating of bedrock with quartz from the Permian Cedar Mesa Sandstone indicate recent (<10ka) timing of rapid displacement addition on linking faults.

T22A-0501 1330h POSTER

Secondary Normal Faulting Near the Terminus of a Strike-Slip Fault Segment in the Lake Mead Fault System, SE Nevada

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The 95 km long Lake Mead Fault System (LMFS), located about 50 km east of Las Vegas and about 100 km west of the relatively undeformed Colorado Plateau, consists of a group of NE/SW-trending Miocene left-lateral strike-slip faults with a total offset of 65-110 km. Previous work suggests that the LMFS acted as a transform zone to accommodate differential extension between the southern Basin and Range to the north and the metamorphic core complexes of the Colorado River extensional corridor to the south. Studies of individual faults of the LMFS have shown that strike-slip faulting was the dominant mode of deformation while normal faulting, pull-apart basins, and push up structures formed as localized secondary structures related to strike-slip faults. This study focuses on the portion of the LMFS west of the Overton Arm of Lake Mead, which consists of the Bitter Spring Valley Fault (BSVF) and the Hamblin Bay Fault (HBF). Both faults have estimated offsets of 20-60 km, but past mapping efforts have been inconsistent with respect to the BSVF trace locations and degree of fault complexity. In order to demonstrate that the apparent complexity of the BSVF is the result of segmentation and secondary normal faults associated with individual segments, we focused field mapping efforts on an apparent segment of the BSVF near Pinto Ridge, located southwest of the Echo Hills and about 5 km NW of the more prominent HBF. We have identified nine normal faults that initiate near the SW tip of a segment of the BSVF and die out to the south before reaching the HBF. The offset on all these faults is a maximum at their northern intersection with the BSVF, then steadily decreases to zero away from the BSVF. These normal faults range from 0.6 km-2.25 km in length and have variable fault trace patterns. The normal fault originating closest to the SW tip of the BSVF segment curves with increasing distance away towards parallelism with the BSVF. The eight other normal faults are all oriented approximately N/S. These secondary faults all intersect the BSVF at angles of 40-60 degrees and the intersection angles typically decrease away from the BSVF segment tip. Linear elastic fracture mechanics predicts that when a mode II fault slips, it causes stress concentrations near the tips of the sliding fault. Furthermore, resultant secondary tensional fracturing is predicted to be oriented at 70.5 degrees to the main fault in the extensional quadrant. This angle can be larger or smaller for mixed mode cases and is also affected by the frictional properties of the fault. Typically, these features are referred to as tailcracks, and have mostly been documented at the cm to m scale as mode I joints. Given strike-slip faults like the BSVF where cumulative slip is on the order of tens of km, large-scale tailcracks can be manifested as normal faults. We thus interpret these normal faults to be tailcracks that formed in a locally perturbed stress field near the SW tip of a segment of the BSVF. We conclude that in the vicinity of Pinto Ridge, the left-lateral BSVF is less complex than has been previously mapped, occurring as a strike-slip fault segment flanked by secondary normal faults near the SW tip.

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T22A-0502 1330h POSTER

Owens Valley fault kinematics: Right-lateral slip transfer via north-northeast trending normal faults at the northern end of the Owens Valley fault

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The occurrence of several northeast trending normal faults along the eastern margin of the Sierra Nevada escarpment are evidence of right-lateral slip transfer across northern Owens Valley from the Owens Valley fault to the White Mountains fault zone. Interaction between the Sierran frontal normal fault and these two fault zones has created a transtensional tectonic environment, which allows for right-lateral slip transfer via a population of northwest dipping normal faults within the Late Quaternary-Holocene alluvial valley fill of northern Owens Valley. A component of normal movement within the valley floor has been documented along fifteen faults. This includes the Tungsten Hills fault, two faults near Klondike Lake, and twelve or so, some possibly linked, small NNE trending scarps southeast of the town of Bishop. One fault segment, located just past the tip of the 1872 earthquake rupture, reveals a minimum of 3.2 meters of normal throw along much of its length. This fault shows evidence for at least three large ruptures, each exhibiting at least one meter of vertical slip. In addition, a large population of normal faults with similar orientations is mapped within the immediate vicinity of this scarp segment. These faults accommodate a substantial amount of normal movement allowing for eastward right lateral slip transfer. With the exception of the Tungsten Hills fault, they are primarily concentrated along a segment of the Sierran Escarpment known as the Coyote Warp. The pre-existing normal fault geometry along this segment acts to block the northward propagation of right-lateral movement, which is consequently forced across the valley floor to the White Mountain fault zone.

T22A-0503 1330h POSTER

Unravelling the Post-glacial History of Faulting on Reykjanes Peninsula, SW Iceland

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The Reykjanes Peninsula, in southwest Iceland, is a complex tectonic system which includes the transition zone from an off-shore to an on-shore spreading segment. At the same time it exhibits many characteristics of a transform-type plate boundary. As the ridge comes onshore at the Reykjanes Peninsula it bends sharply to the east, becoming approximately 30 degrees oblique to the direction of plate motion. Because of its highly oblique geometry with respect to the NUVEL 1A spreading direction, it experiences both extension and shear which may be partitioned in both time and space. The peninsula is characterized by arrays of eruptive fissures, spaced on average approximately 5 km apart, and having an average strike of N40E. These have been described in the literature as comprising either five or four distinct volcanic systems each with their own magma supply, high temperature geothermal system, and clusters of closely spaced fractures referred to as fissure swarms. The fissure swarms are comprised of shear fractures (mainly normal faults), extension fractures (mainly gaping fissures with no shear displacement) and hybrid fractures which exhibit components of both shear (vertical offset parallel to the fracture plane) and extension (opening perpendicular to the fracture plane). Still unclear are the dynamics of this zone, how faulting and magmatism are related in time and space on the peninsula. This study presents a preliminary map of faults and open fractures for all of Reykjanes Peninsula. The map is compiled from new field data and new mapping from high-resolution, digital orthophotos. The map is contained within a GIS and overlain on both air photos and digital geologic maps. Local bedrock geology consists of Plio-Pleistocene lavas and sub-glacially erupted hyaloclastites, as well as lava flows dating from earliest post-glacial times up until 725 ybp. This study examines in particular the development of fractures in post-glacial lavas.

T22A-0504 1330h POSTER

Lost in Iceland? Fracture Zone Complications Along the Mid-Atlantic Plate Boundary

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The mid-Atlantic plate boundary breaks up into a series of segments across Iceland. Two transform zones, the South Iceland Seismic Zone (SISZ) and the Tjörnes Fracture Zone (TFZ) separate the on land rift zones from the Reykjanes Ridge (RR), and the Kolbeinsey Ridge (KR), offshore N-Iceland. Both are markedly different from fracture zones elsewhere along the plate boundary. The 80 km E-W and 10–15 km N-S SISZ is made up of more than 20 N-S aligned, right-lateral, strike-slip faults whereas the TFZ consists of a broad zone of deformation, roughly 150 km E-W and 75 km N-S. The over-all left-lateral transform motion within the SISZ is accommodated by bookshelf faulting whereas the right-lateral transform motion within the TFZ is incorporated within two WNW-trending seismic zones, spaced ~40 km apart, the Grímsey Seismic Zone (GSZ) and the Húsavík-Flatey fault (HFF). Recently collected EM300 and RESON8101 multibeam bathymetric data along with CHIRP subbottom data has unveiled some tectonic details within the TFZ. The GSZ runs along the offshore extension of the Northern Volcanic Rift Zone (NVRZ) and is made up of four left-stepping, en-echelon, NS-striking rift segments akin to those on land. Large GSZ earthquakes seem to be associated with lateral strike-slip faulting along ESE-striking fault planes. Fissure swarms transecting the offshore volcanic systems have also been subjected to right-lateral transformation along the spreading direction. As the Reykjanes Peninsula, the on land extension of the RR, the GSZ bears the characteristics of an oblique rift zone. The plate boundary segments connecting to the RR and KR are thus symmetrical with respect to the plate separation vector (105°) and orientation of individual volcanic systems. The HFF has an overall strike of N65°W and can be traced continuously along its 75–80 km length, between the Theistareykir volcanic system within the NVRZ, across the central TFZ-graben, the Skjálfandi bay, and into the largest and westernmost graben, Eyjafjardaráll (EG). Four pull-apart basins occur along the fault, the largest at the intersection with the EG, the southward magma-starved, continuation of the KR. Dikes, parallel to the HFF bear witness to it being a leaky transtensional feature. RESON8101 maps expose the tectonic fabric along the tidally swept shoreline adjacent to the main fault. The southwesternmost margin of the fault is characterised by NE-striking lavas which, along the coast, dip steeply (30–50°) westwards, towards the EG. The lavas are dissected by en echelon arrays of minor strike-slip faults intersecting the main fault at angles of N20°–30°W and N20°E. Some can be traced onto land where they exhibit complicated flower patterns. Destructive earthquakes occurred on the HFF in 1755, 1867 during an eruption offshore Tjörnes, i.e. north of the fault, and in 1872. The 1867 earthquakes where most likely associated with rift-transform interaction on the easternmost section of the fault. An intense earthquake sequence on April 17, 1872 culminated with two ~M6.5 earthquakes at 10 a.m. and 11 a.m. the next day. Based on intensity and damage reports, the ~M6.5 earthquakes originated at different segments of the HFF, near Húsavík and Flatey.

T22A-0505 1330h POSTER

Neotectonic Geomorphology of the Owen Stanley Oblique-slip Fault System, Eastern Papua New Guinea

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Previous GPS studies have shown that the Australia-Woodlark plate boundary bisects the Papuan Peninsula of Papua New Guinea and that interplate motion along the boundary varies from about 19 mm/yr of orthogonal opening in the area of the western Woodlark spreading center and D'Entrecasteaux Islands, to about 12 mm/yr of highly oblique opening in the central part of the peninsula, to about 10 mm/yr of transpressional motion on the western part of the peninsula. We have compiled a GIS database for the peninsula that includes a digital elevation model, geologic map, LANDSAT and radar imagery, and earthquake focal mechanisms. This combined data set demonstrates the regional importance of the 600-km-long Owen Stanley fault system (OSFS) in accommodating interplate motion and controlling the geomorphology and geologic exposures of the peninsula. The OSFS originated as a NE-dipping, reactivated Oligocene-Early Miocene age ophiolitic suture zone between an Australian continental margin and the Melanesian arc system. Pliocene to recent motion on the plate boundary has reactivated motion on the former NE-dipping thrust fault either as a NE-dipping normal fault in the eastern area or as a more vertical strike-slip fault in the western area. The broadly arcuate shape of the OSFS is probably an inherited feature from the original thrust fault. Faults in the eastern area (east of 148°E) exhibit characteristics expected for normal and oblique slip faults including: discontinuous fault traces bounding an upthrown highland block and a downthrown coastal plain or submarine block, transfer faults parallel to the opening direction, scarps facing to both the northeast and southwest, and spatial association with recent volcanism. Faults in the western area (west of 148°E) exibit characteristics expected for left-lateral strike-slip faults including: linear and continuous fault trace commonly confined to a deep, intermontane valley and sinistral offsets and deflections of rivers and streams by 0.5 to 1.2 km. The northern edge of the OSFS merges with the Ramu-Markham strike-slip fault near Lae. SW tilting of the footwall block (Papuan Peninsula) is responsible for the asymmetrical topographic profile of the peninsula and drowned topography along the southern coast of the peninsula.

T22B MCC: Level 1 Tuesday 1330h

Development of Fault Systems Through Time: Process and Rates IV Posters

Presiding: **L McNeill,** Southampton Oceanography Centre**; S Gupta,** Imperial College

T22B-0506 1330h POSTER

Mechanical controls on the spatial and temporal variability of faulting mechanisms in sandstone along the Moab normal fault, Utah

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Segmentation is a fundamental characteristic of faults. However, the effect of segmentation on the process of fault development, the architecture of the fault zone, and the properties of faults are poorly understood. Along the Moab fault, a basin scale normal fault with 1 km of throw in SE Utah, segmentation is associated with localized changes in the density and types of structures associated with faulting in sandstone. Changes in the types of structural elements are associated with fault development by two different mechanisms in sandstone: (1) cataclastic shear failure that produces deformation bands and (2) the repeated formation and subsequent shearing of joints that leads to the formation of a brecciated fault zone. Deformation bands are prevalent along the entire length of the fault system and band density is greatest within relays between normal fault segments that are subjected to a component of strike-parallel contraction. The joints and sheared joints only occur at intersections between normal fault segments and relays that are subjected to strike-parallel extension where they overprint deformation bands. We contend that spatial variation of the faulting mechanisms in sandstone is associated with the stress perturbation around the fault. We used the geometry and kinematics of the fault segments and an estimated burial depth of 2 km to simulate the mechanical behavior of the fault system in linear elastic boundary element models using Poly3D. We looked specifically for changes in the stress state that would cause a transition from deformation band formation to joint formation because joints are the youngest structural elements wherever they occur. Joints form normal to the least compressive principal stress when this stress exceeds the tensile strength of the rock. We also note