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Deep Drilling and Current Models of Cenozoic Crustal Deformation in Western United States

Seismic reflection, heat-flow, earthquake, gravity, and magnetic data have been interpreted in recent years to suggest that the crust of the actively deforming Basin and Range province may consist of two layers that have contrasting physical properties and mechanical behavior. The boundary between them, a subhorizontal zone of decoupling to weak coupling, is pictured as a thin zone of decollement. Above this zone the crust fails in extension through the formation of listric faults tangential to it. Below it, the crust dilates horizontally through the injection of dikes of basalt from the mantle. The boundary is pictured as inherited from master thrusts that formed during Mesozoic and Paleogene compressional regimes. The upper crustal layer is essentially brittle; the lower layer is relatively ductile.

This model, if correct, has implications for a wide variety of matters of practical interest. Prominent among them are: the design of strategies for oil and gas, geothermal energy, and mineral resources exploration; the underground storage of hazardous wastes; and the occurrence and surface effects of regional earthquakes.

The model is amenable to testing by drilling to depths of 16,000 to 40,000 ft (5 to 12 km). Outcrops of subhorizontally foliated metamorphic rocks as young as Miocene have been interpreted as locally uplifted with exposed parts of the zone and may provide information on its lithologic characteristics; however, deep drilling (and attendant in-situ testing of rock and fluid properties, measurements of stress and their variation with depth, and surface-to-borehole geophysical communication) offers the only viable means for determining the state of the crust and for testing the postulated dynamic processes associated with it.

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Lebensspuren of Dysaerobic, Bathyal Basin, California Borderland

The low oxygen waters and bathyal depths of Santa Cruz basin provide harsh conditions for marine life, yet the basin supports a surprisingly high density and diversity of macrofauna. In contrast, biogenic sedimentary structures are low in density. Bottom photographs from 117 stations show a biogenically produced micro-hummocky topography with few resolvable biogenic traces. Recognizable lebensspuren are of three main classes: tracks and trails, depressions, and fecal matter. Echinoderms, the most abundant epifauna on the slope and adjacent basin floor, produce most of the large tracks and trails. Significantly, many tracks and trails are less distinct than similar markings of the abyss owing to the soupy, thixotropic nature of the basinal sediment. Depressions made by asteroids, regular urchins, and bottom-dwelling fish are most common at relatively shallow depths. A characteristic, circular depression made by a feeding, tubicolous polychaete is restricted to the lowermost slope and adjacent basin floor. Holothurian fecal strands dominate the photographically resolvable feces of this bathyal environment. These holothurian feces take the "clothes-line" form common to the abyss.

X-ray radiography and photography of box-core sediment slabs reveal an indistinct burrow mottling resulting from the thixotropic response of the sediment to biogenic disturbance and lack of density contrast for radiography. Although open burrows are common in bottom photographs, few are recognizable in box-core slabs. Similarly, surface lebensspuren have poor preservation potential. When lithified, this bathyal sediment will probably be bioturbate-textured.

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Growth Faulting and Sedimentation in Upper Wilcox Delta System, South Texas

Well logs from the deep Wilcox trend of south Texas delineate the upper Wilcox Rosita delta system which comprises three locally developed delta complexes comparable in scale to deltas in the lower Wilcox Rockdale delta system of middle and upper Texas Gulf Coast.

Each delta comprises several lobes, some of which can be traced across the deep zone where they thicken as much as tenfold, owing to progradation over a series of active growth faults. Characteristic upward-coarsening progradational units are interpreted to include prodelta, delta-front, distributary-channel, and interdistributary facies. There is an overall change from delta-plain to prodelta facies basinward across the growth-fault zone.

Growth faults are large-scale slumps formed by basinward gravity gliding of huge masses of deltaic sediments. Faulting was initiated and maintained as sand and mud of the delta front prograded over previously deposited prodelta mud. The growth faults influenced the thickness of sediment which accumulated on each side of the fault by controlling the relative rates of subsidence (growth ratio). Constant growth ratios for a series of consecutive progradational sequences indicate that rates of subsidence were insensitive to local fluctuations in sedimentation. Log patterns suggest that sedimentary processes were continuous across fault traces; no important surface expression of faults is evident.

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Tertiary Structural Development of Selected Valleys Based on Seismic Data—Basin and Range Province, Northeast Nevada

Reflection seismic data in Railroad, Diamond, Mary's River, and Goshute Valleys provide information on their structural development that cannot be deduced solely from outcrop and well data.

These valleys contain Tertiary sediments which, in dip section, define an asymmetrical basin bound along the eastern flank by a major listric normal fault with about 10,000 to 15,000 ft (3,048 to 4,572 m) of displacement. The west flank is defined by a gentle east-dipping ramp. Seismically the trace of the listric fault is interpreted to dip westward and sole into the Paleozoic section exploiting regionally recognized Mesozoic decollement surfaces. The Tertiary depocenter, adjacent to this fault, shifted from west to east with continued slippage through time, the greatest movement occurring in Miocene and post-Miocene. In the strike direction, the valleys are separated into at least two subbasins by an east-west structurally high axis. The axis is postulated to be the result of a tear fault associated with movement along the listric normal fault.

Tertiary stratigraphy varies between valleys and between subbasins in a given valley. All the valleys contain Miocene and younger rocks; however, not all subbasins contain the pre-Miocene section suggesting a complex scheme of structural development.

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Trace Fossils and Stagnation of Deep-Sea Basins

The patterns and intensity of bioturbation of marine sediment are useful indicators of the response of benthic organisms to fluctuating oxygen levels in the bottom water. Trace fossil assemblages in mid-Cretaceous (Barremian-Albian) DSDP core sections from the central and southern Atlantic were examined to document the activities of burrowing infauna relative to episodes of stagnation in deep Atlantic basins during that time.

The mid-Cretaceous anoxic horizons in DSDP cores typically are dark, homogeneous or laminated, organic muds, which alternate with moderately to heavily burrowed facies containing less organic carbon. Bioturbation intensity and trace fossil diversity appear to correlate inversely with the amount of unoxidized carbon in the sediment, suggesting that the more organic-rich facies were deposited under conditions where oxygen was a limiting factor for benthic macro-organisms.

The ichnogenus *Chondrites* commonly occurs, sometimes to the exclusion of all other kinds of burrows, immediately above and/or below unburrowed, laminated mud. It also occurs in heavily burrowed limestones containing rich trace fossil faunas, including *Zoophycos*. Therefore, mid-Cretaceous *Chondrites* apparently were created by animals possessing broad oxygen tolerances; the presence of *Chondrites* alone in an organic-rich deposit probably indicates dysaerobic conditions.

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How do Thrust Belts Form?

Thrust belts form at converging plate margins and straddle both sides of a hinterland occupied by a calc-alkaline arc. There are two competing theories for thrust belts and each implies a distinctly different behavior at the plate margins. The two theories, stated in oversimplified form, claim that thrust belts are created by either a horizontal push, or by the gravity-driven spreading of an elevated hinterland. In response to modern geometrically based structural interpretations the two theories have changed and developed over the past decade. Thrust toes are clearly dominated by a compressive push from the rear, but for larger parts of a thrust the gravitational terms are more significant. However, on the scale of an entire thrust belt, are rocks sufficiently weak for the gravitational terms to dominate? One of the principal differences between the two theories boils down to the question of rock strength. Certain simple structures provide a key to this impasse. One is listric normal and growth faults which develop without any push from the rear. Because of their high degree of symmetry, opposed-dip thrust complexes, such as triangle zones and pop-ups, also provide information. By working on these structures with limit analysis, a method recently developed in soil mechanics, we can estimate upper and lower bounds which bracket rock strengths under long term geological conditions. These bounds to rock strength can be directly applied to the two theories for the formation of thrust belts.

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A Test of the Melanoidin Hypothesis

Marine and terrestrial humic acids are thought to differ in structural composition owing to differences in precursors and formation pathways. It has been proposed that marine humic acids are formed by the polymerization of sugars and amino acids (the melanoidin pathway) while terrestrial humic acids result primarily from the condensation of lignin-derived phenols and amino acids. In this study, four marine and three terrestrial humic acids have been isolated, and a series of polymers have been made by the reaction of either glucose or catechol with alanine or ammonia. Chemical and spectroscopic measurements of the natural and synthetic polymers have been made, including elemental analysis, carbon isotope ratios and IR, UV-visible, UV-fluorescence, and ESR scans. In addition, degradative analyses of marine and terrestrial humic acids together with the synthetic polymers have been performed to determine (1) if characteristic structural differences exist between marine and terrestrial humic acids and (2) if similarities between the degradative products of synthetic and natural polymers reflect biologic precursors and reaction pathways.

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Carbon Flux from Ocean to Biosphere—Chemical Evidence from Deep-Sea Cores

The ocean is the major carbon reservoir in the ocean-atmosphere-biosphere system. Depending upon the demands of the biosphere, the ocean alternately acts as a source or sink of carbon. Because organic carbon has a δC^{13} composition of approximately -25 ppm (PDB), a 15% variation in the size of our modern biosphere (living and humus) would result in a 0.2 ppm δC^{13} variation in the CO_2 of the world ocean. A -0.4 ppm δC^{13} variation in modern surface water has been measured in a 200-year-old coral. Carbon-14 measurements in the same coral confirm that the cause of the δC^{13} variation