DAVID BLOOM

Displacements on late Cenozoic strike-slip faults of the central Mojave Desert, California

began late as Pliocene or Quaternary time— early stage of development.

p308.

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ABSTRACT

Field studies demonstrate that displacements on northwest-striking wrench faults of the central Mojave Desert are too small to support hypotheses suggesting large interior translations and associated rotation of the province during late Cenozoic time. The margin of an early Miocene structural belt provides the marker with which to establish lateral displacement on individual faults. Displacement values for faults are as follows: Lenwood fault = 1.5–3 km, Camp Rock Fault = 1.6–4.0 km, Calico fault = 8.2 km, and Rodman-Pisgah faults = 6.4–14.4 km. Cumulative displacement on all the major northwest-striking faults of the Mojave Desert is about 26.7–38.4 km. Most, if not all, regionally distributed right shear (presumably related to Pacific–North American plate interaction) developed in the central Mojave Desert after 20 m.y. B.P. Right shear was preceded by significant amounts of kinematically unrelated northeast-southwest crustal extension.

INTRODUCTION

Reconstruction of the Mojave Desert region in light of late Cenozoic deformations is critical if we are to understand fully the tectonic evolution of the southwestern United States. Previous regional syntheses have misjudged the degree of continental extension that occurred in the Mojave during the early Miocene and have overestimated the amount of late Cenozoic right strike-slip displacement. This paper attempts to document the movement along these later faults and discusses the viability of hypotheses for the tectonic evolution of this province in light of these new constraints.

The Mojave Desert block of southern California is defined here as a triangle-shaped structural province bounded on the north by the Garlock fault and on the south by the San Andreas fault system (Fig. 1). Its eastern limit is considered to be a north-trending line defined by geophysics (i.e., Bouguer gravity and seismicity), crustal thickness, and physiography (Dokka, 1980). The dominant, active structural elements of the Mojave Desert block are northwest-striking wrench faults that are responsible for the neotectonics and present-day physiography. This fault system consists of at least seven major strands that include (from west to east) the Helendale, Lenwood, Camp Rock, Calico, Rodman-Pisgah, Ludlow, and Bristol Mountain faults (Fig. 1). They are high-angle, display dominantly right slip, and are composed of anastomosing and en echelon segments. These faults are best seen on aerial photographs where they form topographic lineaments defined by fault scarps, aligned truncated spurs, and fault-line scarps.

The late Cenozoic tectonic history of the central Mojave Desert block is marked by several periods of different faulting styles (Dokka, 1979, 1980, 1983) that were initiated near the beginning of the Miocene. Prior to this time, the central Mojave region was of low relief and served as a sediment source for basins to the south and west (Hewett, 1954). This low-relief surface was disrupted during a short-lived interval of detachment faulting and high-angle normal faulting that was probably related to intraplate extension (Dokka, 1980; Dokka and Glazner, 1982). Chaotic monolithologic breccias and conglomerates as well as newly erupted volcanic rocks and their detritus were deposited in rapidly evolving tectonic basins within and peripheral to the extending terrane (Dokka,

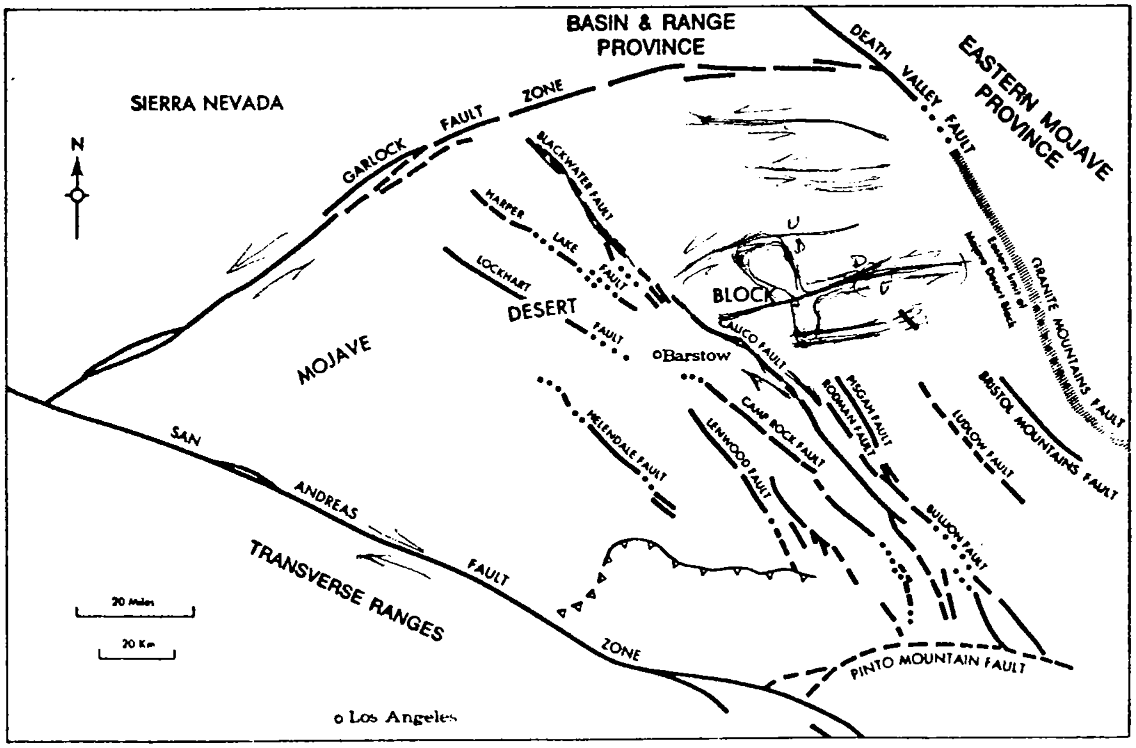


Figure 1. Index map for central Mojave Desert.

1979, 1980; Dokka and Glazner, 1982). This deformation is important to the study of later northwest-striking strike-slip faulting because it created a regional marker (terrane margin) that allows one to determine amounts of strike-slip displacements of younger faults.

The origin of late Cenozoic strike-slip faulting in the central Mojave Desert has been speculated upon by several workers. Dibblee (1961) first recognized the presence of wrench faults on the basis of their geometry and associated structures and suggested that they were related to movement along the San Andreas fault. Garfunkel (1974), on the basis of Dibblee's data, proposed that these intraprovince faults developed because of broadly distributed shear induced by local geometric irregularities along the Pacific and North American plate boundary. Movement between individual fault slices was thought to be accompanied by the counterclockwise rotation of both slices and faults. Garfunkel predicted that rocks of the Mojave block may have been rotated as much as 30°. Luyendyk et al. (1980) proposed a tectonic model for southern California that predicted tens of kilometres of slip on each of the Mojave faults. Their slip estimate (their Fig. 3) was based on a paleomagnetic reconstruction of the region. Hadley and Kanamori (1977) suggested that the faults of the central Mojave may be the surface expression of the mantle transform boundary between the North American and Pacific plates, a boundary that is inboard (northeast) of the crustal transform boundary at the San Andreas fault. These conclusions were based on the northeast termination of an east-northeast–trending high-velocity ridge in the upper mantle centered beneath the Transverse Ranges.

KINEMATICS

Previous estimates of movements on central Mojave Desert strike-slip faults have generally not been based on dated offset geologic features. Garfunkel (1974) suggested, on the basis of offsets of the pre-Tertiary–early Miocene "unconformity" (of Dibblee, 1971), that the Lenwood, Camp Rock, and Calico faults have slipped 15–20 km, 10 km, and 20 km, respectively. Hawkins (1975) recognized the nondepositional nature of that contact and concluded that the strike slip on the Camp Rock was only 1.5 km, occurring between early Tertiary and late Holocene time. Hawkins was not able to find evidence of latest Holocene displacement. S. Miller (1980) determined by correlating offset volcanic strata that 3.75 km of slip had occurred on the Camp Rock fault since the early Miocene. Additional northwest-striking faults lie east of the Ludlow fault, between the Bristol and Granite Mountains. Davis (1977) considered and dismissed the hypothesis of Hamilton and Myers (1966) that this fault was the southern extension of the recently active Death Valley fault zone. Davis found no evidence to support the existence of a through-going strike-slip fault of Quaternary age. Pre-Quaternary movement, however, was not ruled out. Farther south along this trend, Miller et al. (1982) have documented >6 km of right separation for a fault system along the southwest border of the Bristol Mountains. This fault cuts the lower beds of Pleistocene(?) alluvium. The region east of the Bristol Mountains fault is tectonically and seismically inactive (Hileman et al., 1973; Carr and Dickey, 1976).

The once continuous southern edge of the early Miocene detachment fault terrane provides a regional marker with which to determine lateral displacements (Fig. 2) on late Cenozoic strike-slip faults of the central Mojave Desert. This edge is a high-angle fault and is named the Kane Springs fault for exposures in the southern Newberry Mountains (Dokka, 1980). The Kane Springs fault originated as a transform structure, accommodating the differential extension of regions within the central Mojave detachment terrane (Dokka, 1980; Dokka and Glazner, 1982; Dokka, 1983). In the Newberry and Rodman Mountains, the fault separates the extended terrane from a region of no extension. However, east of the Rodman Mountains, the Kane Springs fault becomes intraterrane, dividing two oppositely tilted half-grabens (Dokka, 1983).

Although no piercement points required for net slip determination were found, strike-separation values presented here are considered to be close approximations because (1) kinematic indicators along faults suggest dominantly horizontal movements; (2) fault trace geometry (straight, narrow fault zone with anastomosing strands) and associated structures (folds, other faults) are similar to known strike-slip zones (e.g., Wilcox et al., 1973); and (3) displaced planes (faults) are high-angle and are oriented nearly perpendicular to the faults.

Table 1 summarizes the post-20-m.y.-ago strike separations on wrench faults of the central Mojave Desert as determined from this study and from other sources. An undetermined but probably minor amount of strain in the form of drag can also be observed along some of the faults. For example, along one part of the Calico fault (Fig. 2b), the early Miocene marker (detachment terrane margin) and nearby rocks are bent to an extent (shear strain = 1.73) that suggests that an additional 1.4 km of distributed right shear has occurred.

The finite slip and the time of initiation of right-slip faulting in the central Mojave Desert are difficult to determine because of the lack of narrowly constrained dated crosscutting relationships. Relations along the Camp Rock fault, however, suggest that the displacement of Mesozoic and older rocks is similar to the post-20-m.y.-ago slip. Miller and Carr (1978) correlated two distinctive stratigraphic sections across the fault in the central Rodman Mountains area. These rocks occur as roof pendants in Upper Cretaceous biotite quartz monzonite and consist of a sequence of quartzite, calc-silicate rocks, carbonates, and volcanic-

TABLE 1. ESTIMATES OF SLIP ON NORTHWEST-STRIKING WRENCH FAULTS OF THE CENTRAL MOJAVE DESERT

Fault	Garfunkel (1974)	This Paper
Helendale	10-15	3.0 *
Lenwood	15-20	1.5-3
Camp Rock	10	1.6-4.0†§
Calico	10-20	8.2 #
Rodman-Pisgah	20-40	6.4-14.4
Bristol Mountains	-----	6.0 **
Ludlow	-----	Small?
Cumulative	65-105	26.7-38.4

Note: All estimates are kilometers.

*Based on estimate (Miller and Morton, 1980) of 3 km of net slip.

†Hawkins (1975) estimated 1.5 km of strike separation.

§S. Miller (1980) estimated 3.75 km of strike separation.

#Does not include an additional 1.4 km of right shear expressed as strain.

**D. Miller et al. (1982).

clast conglomerates. Miller and Carr's (1978) mapping indicates that the two sections have been laterally displaced 3–5 km from each other along a straight, vertical segment of the Camp Rock fault. Although the available data are not well constrained enough to suggest that the fault was initiated after 20 m.y. ago, it does strongly indicate that most of the movement did occur after that time. Determination of the lower limit of initiation is even more elusive. Pleistocene(?) sedimentary deposits are only partially displaced along the Camp Rock, Lenwood, and Calico faults (Hawkins, 1975; Dokka, unpub. mapping). Thus, field relations suggest that most if not all displacements along active northwest-striking right strike-slip faults occurred and probably began between early Miocene (post–20 m.y. ago) and Pleistocene(?) time.

DISCUSSION

Two important points emerge from the study of late Cenozoic northwest-striking wrench faults of the central Mojave Desert block. The first is that most if not all right-slip movements in this region (presumably related to distributed transform shear) began *after* the area had undergone an intense interval of regional extension (northeast-southwest–directed detachment faulting). This reinforces the notion put forth by several authors (e.g., Davis and Burchfiel, 1973; Proffett, 1977; Zoback and Thompson, 1978; Dokka and Merriam, 1982) that regional strike-slip faulting associated with the Pacific–North American transform boundary cannot be dynamically related to major extension of western North America (Great Basin, proto-Gulf of California, Rio Grande Rift, etc.) during the late Cenozoic. In addition to timing problems, transform-related extension models (e.g., Carey, 1958; Wise, 1963; Hamilton and Myers, 1966; Atwater, 1970; Livaccari, 1979) predict that dilation was directed parallel to the strike of the transcurrent faults (northwest-southeast, in this case). These hypotheses, therefore, cannot explain the geometries and kinematics of the structures produced during the earlier events in the central Mojave Desert. One

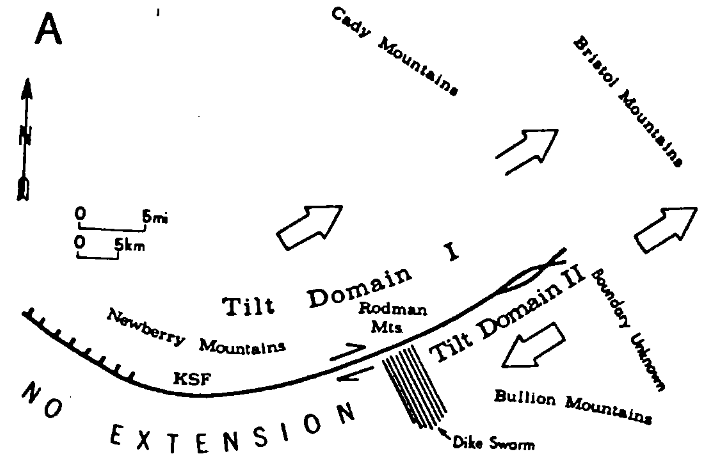
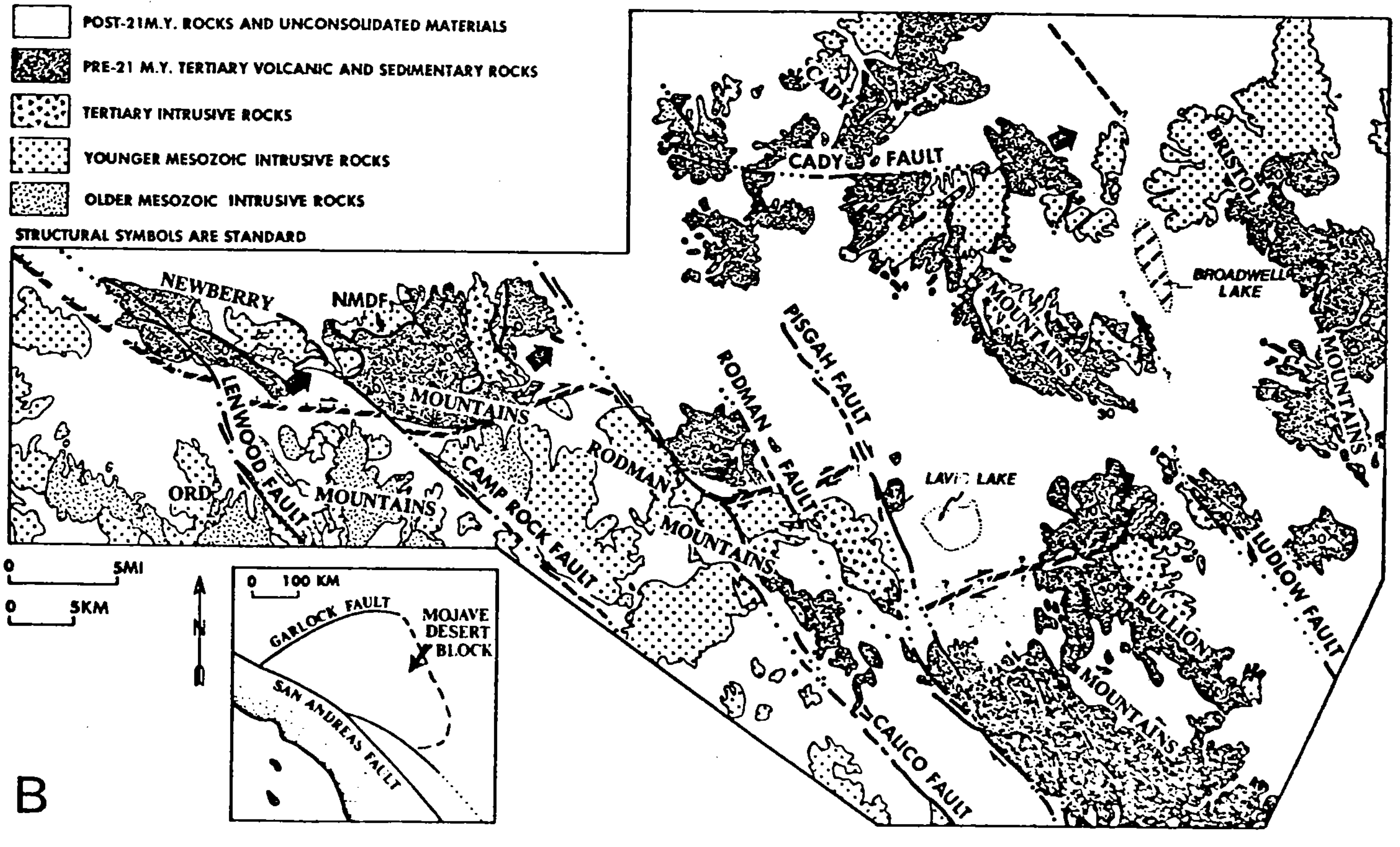


Figure 2. (A) Pre–strike-slip faulting (ca. 20 m.y. ago) configuration of central Mojave Desert. Structure symbols are standard. Kane Springs fault (KSF) is major accommodation structure that separates regions that extended differently during early Miocene detachment faulting interval. (B) Present-da, geology of central Mojave Desert. Broken line segments are Kane Springs fault. Displacements along individual faults are given in Table 1.



might argue that these earlier deformations were related to northwest-southeast extension but were subsequently rotated clockwise to their present position in a manner such as has been suggested by Garfunkel (1974). Such rotations of early formed structures are not uncommon in wrench fault terranes (e.g., Tchalenko, 1970). However, Garfunkel's model is untenable because it requires that strike-slip faults of the Mojave have lateral displacements of up to ten times greater than can actually be demonstrated. This leads to the second point regarding a more realistic estimate of the cumulative and individual slip on faults of the Mojave. The once continuous edge of the early Miocene detachment fault terrane provides a unique marker with which to determine displacements. About 26.7–38.4 km of cumulative right slip has occurred on the strike-slip faults of the central Mojave (Table 1) since 20 m.y. ago. Pre-20-m.y.-ago displacements, if any, must be regarded as extremely small. The upper limit on the time of fault inception is poorly constrained by the lack of offset pairs of rocks along the faults. It is conceivable, however—and very probable, in my opinion—that faulting began later, perhaps as late as Pliocene or Quaternary time. This speculation is founded on the overall geometric arrangement of structures and the high ratio of fault length to slip. These observations, coupled with displacement data, suggest that the central Mojave Desert strike-slip faults may be in an early stage of development. More detailed study is needed.

SUMMARY AND CONCLUSIONS

The amount of slip on individual faults is determined to be 3.0 km for the Helendale, 1.5–3.0 km for the Lenwood, 1.6–4.0 km for the Camp Rock, 8.2 km for the Calico, 6.4–14.4 km for the Rodman-Pisgah, and small for the Ludlow. Cumulative right slip on northwest-striking wrench faults of the central Mojave from Helendale to the Granite Mountains is 26.7–38.4 km, on the basis of the restoration of the high-angle southern margin of an early Miocene detachment fault terrane. This value is about five times less than some previous speculations and therefore invalidates models that propose large interior translations of the Mojave Desert block. Large rotations of the block as a whole, however, cannot be ruled out. Distributed right shear probably did not develop in the central Mojave Desert before 20 m.y. ago. Strike-slip faulting in this region was preceded by significant amounts of kinematically unrelated northeast-southwest-directed crustal extension.

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trend. Subordinate and older N-S to NE-SW striking normal faults cut these volcanic units.

A series of rhyodacite to rhyolite domes and associated air-fall tuffs covering 40 km^2 postdating the faulting were erupted .15±.006 m.y.a. at the western edge of the center. Present-day geothermal activity is spatially linked to the older rhyolites and is virtually absent in the zone of the younger silicic volcanics, since movement of fluids in the geothermal field is strongly controlled by the fault sets. Fault movement between .37 and .15 m.y.a. may be due in part to the emplacement of a high-level silicic magma chamber which would serve as a heat source for the active geothermal system as well as a magma reservoir for the younger rhyolite domes.

NEW OCCURRENCES OF SCHALLERITE AND BAFERTISITE IN MN-RICH ROCKS AND IMPLICATIONS FOR FUGACITY GRADIENTS DURING METAMORPHISM

Nº 32015

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The rare minerals schallerite - $Mn_{16}Si_{12}As_xO_{30+2x}(OH)_{20-x}$ and bafertisite - $Ba(Mn,Fe)_2TiSi_2O_7(OH,F)_2$ occur in metamorphosed Mn-rich rocks from W. Massachusetts. Schallerite occurs with barite, rhodochrosite, tephroite, pyrophanite, fluoro-sonolite, jacobsite, arsenopyrite, pyrrhotite, and fluorite. The As content of schallerite varies between 6 and 13 wt. % between grains but is constant within individual grains. Bafertisite occurs with the above minerals excepting barite, and in addition coexists with alabandite. Ignoring minor solid solution in the minerals ($Ca\overline{Mn}$, $Fe\overline{Mn}$ exchanges) calculated phase relations imply an increase in fO_2 and possibly a minor decrease in fS_2 between the two assemblages. No As-poor schallerite occurs in the previous assemblages. This suggests that schallerite may be stabilized by its As content. Using the As exchange proposed by Dunn, et al (1981), a possible reaction explaining the occurrence of schallerite is:

$$2FeAsS + 3/2\ O_2 = 2AsO_2(\overline{OH)\lambda\square}_{schall} + 2FeS + H_2O$$

In addition, a reaction for the disappearance of bafertisite might be:

$$BaMn_2TiSi_2O_7(OH)_2 + 3MnS + 7/2\ O_2 = BaSO_4 + MnTiO_3 + 2Mn_2SiO_4 + H_2O + S_2$$

DOLOMITIZATION, AN HYPOTHESIS OF THE PROCESS

Nº 30132

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Preservation within a dolostone of undistorted ghosts of the primary rock fabric dictates that dolomitization is a volume for volume replacement of calcite by dolomite, and the volumetric rate of dolomite precipitation must equal the rate of calcite dissolution. Geochemical conditions within the pore system prerequisite to dolomitization are therefore very limited, yet the volume of dolomitized calcite in the stratigraphic record implies that the process is a common event. It is hypothesized here that the pore system chemistry has only an indirect effect on the process in that it serves as a source and sink for the ions involved in the reaction and that the physical-chemical process of dolomitization is described by the conditions that exists within a narrow boundary zone located between the dissolving calcite crystal and precipitating dolomite. Within this zone the concentrations of dissolved ions approximate that of the pore system but the pressure of the fluid within the zone is drastically different due to a greater volumetric potential for dolomite growth relative to the potential for calcite dissolution. The potential growth rate differential attempts to reduce the volume of the zone hence distance between the growth surface of the dolomite and dissolution surface of the calcite. This reduction in width of the boundary zone is resisted by molecular attraction of the solution to the crystal surface. Reduction in width therefore must be accompanied by an increase in pressure within the zone in order to force the water out. Since reaction rates are a function of pressure the physical-chemical condition of dolomitization is established by adjustments to the boundary zone width. Dolomitization therefore proceeds as a combination of "pressure solution" and "force of crystallization" in a wide range of chemical environments limited only by the mechanical strengths of the dolomite and calcite crystal lattices.

SHEAR INSTABILITIES AND GLACIAL SURGES

Nº 27533

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It seems generally accepted that the high rates of motion observed during glacial surges must be the result of sliding. Several authors have proposed mechanisms for surging, based on a instability at the base of the glacier. However, surges are accompanied by thickness changes. Analysis of the shearing which must accompany these changes suggests an instability mechanism occurring within the ice, that may make a major contribution to glacial surges.

As a glacier thickens prior to surging, shearing characteristic of compressive flow will occur. The shearing will cause the ice to recrystalize with basal planes parallel to the direction of shear, reducing the resistance to shear, and increasing the rate of shear. Eventually, this may result in fracturing and the formation of discrete shear zones. The shear zones will curve upward from the base of the ice to the surface and basal debris will be carried upward within these zones. The accumulation of debris within the shear zones, in conjunction with melting, will create a situation where shearing is taking place between wet rocks, rather than within glacial ice. At this point the glacier will slide quite rapidly, until the driving forces drop below the frictional forces. Then the ice will stagnate, the shear zones will refreeze, and the whole process will begin another cycle.

This model provides a mechanism for instability in glacier flow and also allows for the spatial variations in velocity observed in surging glaciers. Furthermore, the shearing mechanism will produce large quantities of englacial and supraglacial debris, which may remain after glacial retreat, as evidence of surging glaciers in the past.

A NON-UNIFORM EXTENSION MODEL FOR CONTINENTAL RIFTING

Nº 18993

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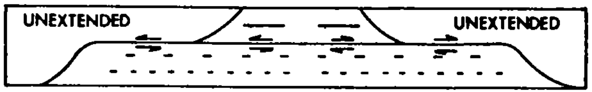
We propose a model to reconcile geophysical observations with field structural studies of ancient continental rifts. Extension develops in two major mechanical domains within the lithosphere. The upper domain ($\ll$15km) extends by brittle processes which are concentrated in a relatively narrow zone in comparison with deeper levels. In the lower domain, extension is accomplished by flow and occurs over a broader area, reaching beyond the limits suggested by surface rupture. The geometry of the extended lithosphere is probably temperature-controlled, and thus related to earlier thermal events. Extension within each domain is also non-uniform. Although the displacement field is inhomogeneous, the integrated strain at all levels is equal (see figure below).

Decoupling within the lithosphere along detachment faults is the result of abrupt changes in the displacement field and/or transition from one mode of extension to another (e.g., brittle to ductile). Thus, a section of extended lithosphere should be expected to contain low-angle normal faults at upper levels and ductile shear zones at deeper levels. A major detachment would be expected to form at the transition from the upper to the lower domain. Beneath the upper domain, the detachment serves to accommodate distension and rotation of crustal blocks by high-angle normal faulting. The detachment continues to deeper levels (thereby rooting), separating the moderately extended lower crust from unextended portions of the upper crust.



LENGTH OF LINES PROPORTIONAL TO STRAIN RATE

COASTAL HAZARDS MAPPING

Nº 24164

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In 1979 we reported on rates of shoreline change along the mid-Atlantic coast. Since then, under sponsorship of the U.S. Geological Survey, we have assembled data on shoreline changes for the remainder of the United States, including Chesapeake Bay, Delaware Bay, and the Great Lakes. The information is presented on a 1:7,500,000 scale map for the National Atlas and as a series of 1:2,000,000 maps for regional planning applications. The data are contained in a user-oriented computerized information system (CEIS)

The data base has been expanded to include coastal hazards information. Eleven process and response variables were defined as posing a risk to coastal inhabitants, including shoreline rates of change, overwash, storm surge, storm frequencies, tsunami frequency, seismic and tectonic activity, ice and permafrost cover, and tendency for subsidence and slope failure. Factors contributing to risk mitigation or intensification, such as relief and stabilization, are also included. Data were compiled from primary sources using the sampling base developed for the erosion map series. An overall "risk factor" was determined statistically for each 3' (latitude or longitude) segment of the coast. These data are presented on a 1:7,500,000 scale map for the National Atlas and are included in the information system (CEIS). Prototypes of a 1:2,000,000 hazard map series have also been designed.