NEOTECTONICS

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Contents

Summary

Neotectonics is the study of recent or active crustal deformation (rates, geometries, and kinematics), the forces that are responsible for the state of stress in the earth's crust and its relation to processes at plate boundaries or in the interior of plates. In addition, neotectonic studies are concerned with the impact of ongoing deformation with respect to topography and the resulting erosion and deposition observed at the surface, and its expression in the geologic record. Neotectonic activity in a considered region may have

started a very long time ago, but corresponding deformation has continued into the present. Neotectonic deformation in different regions may thus have started diachronously, and a phase of neotectonic deformation is defined by the onset of changing tectonic boundary conditions and its relevance to present processes.

1. Neotectonics as An Integral Part of Geosciences

Neotectonics characterizes recent or active crustal deformation (rates, geometries, and kinematics), its relation to processes at plate boundaries and in the interior of plates (as well as its impact on topography and the resulting erosion and deposition observed at the surface), and its expression in the geologic record. “Recent” deformation has been variously interpreted, depending on the problems of interest. Obruchev introduced the term neotectonics into the scientific literature, and characterized neotectonics as crustal deformation spanning the last 35 Ma. Other authors associate “neotectonics” with deformation in post-Miocene time, the last major plate-tectonic reorganization in a structural province, the ultimate 3 Ma , or the Quaternary Period. Stewart and Hancock defined neotectonics as "the branch of tectonics concerned with understanding earth movements that both occurred in the past and are continuing at the present day". According to Wallace, active tectonics involves the study of those tectonic movements that "are expected to occur within a future time span of concern to society". This definition of young tectonic features has far reaching societal implications concerning risk assessment, land and urban planning, and hazard mitigation. Accordingly, depending on acceptable levels of risk for humans and infrastructure in a densely *vs.* sparsely populated region, faults with various ages have qualified as active structures, even including features active within the last tens- to hundreds of thousands of years. Neotectonic structures related to the current stress regime in a lithospheric plate may thus record a much longer period of tectonic activity than envisioned in the original definition. Slemmons cautioned that neotectonic deformation is not automatically caused by seismicity and neotectonic structures may no longer continue to be active. Confusion regarding the usage of the term neotectonics has increased in the past decade because many studies have employed this, and the seismicity-related terms “active tectonics” and “seismotectonics” interchangeably. Although closely related, these fields should be considered a subset of neotectonics, as they specifically include seismic analysis and hazards of currently active faults. Neotectonic studies in active plate boundary environments therefore provide clear benefits for society, because they help risk mitigation. However, increasing evidence from the interiors of stable cratons and regions with infrequent seismicity, low deformation rates, and inferred low risk potential demonstrates that such environments are also subject to neotectonic deformation. The time scales of these events may be much longer, with earthquake-recurrence intervals in excess of hundreds to thousands of years. The cause, recurrence, and seismic hazard of earthquakes and their geomorphic expression in the interior of continents are still poorly understood phenomena. In addition, the recognition and characterization of seismogenic faults that may potentially generate destructive future earthquakes in areas previously considered at low risk are important in densely populated regions. Unrecognized seismogenic faults with long recurrence intervals are thus an increasingly important topic of international research. The need for a better understanding of this aspect of neotectonics is underscored by seismic hazard assessments that mainly rely on data sets of historic seismicity and instrumentally recorded events. As neotectonics is the study of active deformation, it spans many different disciplines of the geosciences depending on the spatial and temporal scales of the problems investigated. Remote sensing assessments, traditional structural geologic studies coupled with fault-slip analysis, and geophysical investigations can constrain the degree of deformation and stress or paleo-stress patterns in a region; analyses of landforms and long-term landscape development, paleoseismologic investigations, and geodetic studies can be utilized to define the geometry and kinematics of recent deformation in an area and the amount of potential seismic activity. In the following sections, the field of neotectonics will be discussed in light of several related disciplines that help understand phenomena caused by young deformation of the earth's crust.

2. Remote Sensing Methods

Remote sensing aids identification of active geologic structures and anomalies in landform development, river courses, and/or vegetation. When used in conjunction with detailed field mapping, these types of images may help extrapolate local field observations to infer regional trends (Figure 1). Early LANDSAT 7 studies combined with field mapping in the regions affected by the India-Eurasia collision led to an understanding of processes and associated structural patterns characteristic of mountain building in the course of continental collision. Analysis of higher resolution SPOT imagery coupled with ground-truth, geodetic and geochronologic information confirmed these interpretations and further helped constrain the kinematics and offset magnitudes of important strike-slip fault systems in Central Asia. Mapping on remotely-sensed data bases may be combined with topographic maps and/or Digital Elevation Models (DEM) to constrain the geometry of structures in an area. In addition, many alteration products associated with active faulting emit or reflect different frequencies of radiation that are sensed by satellite-borne multispectral instruments. By analyzing the measured frequencies of radiation, the type of alteration product and its concentration may be inferred. Therefore, the alteration products associated with active faulting, and hence the location of active faults, may be identified using space-borne instrumentation. Multispectral satellite imagery or aerial photographs depicting various spatial resolutions may be used in concert to identify regional trends and local anomalies to these trends.

3. Structural Field Studies

Structural investigations in a neotectonic context are carried out to determine and/or confirm the geometry, kinematics, and relative age of apparently active structures. Fault geometry, slip direction, mineral-lineation measurements, and microstructures can be used to deduce stress and deformation fields, and cross-cutting field relations may be used to determine how these fields may have changed over time. A classic study of the structural neotectonic inventory near El Asnam, Algeria, and coseismically generated structures during a M = 7.3 earthquake in that region emphasizes the need to analyze and compare structural phenomena at various length and time scales when neotectonic assessments are made with inferences based on the character of the coseismic stress field. The El Asnam earthquake (Figure 2) was related to a reverse fault, which caused folding and coeval shallow normal faulting along the thrust-parallel anticlinal axis. Similar faults were associated with the 1988 Spitak earthquake (M_s 6.9) of Armenia.

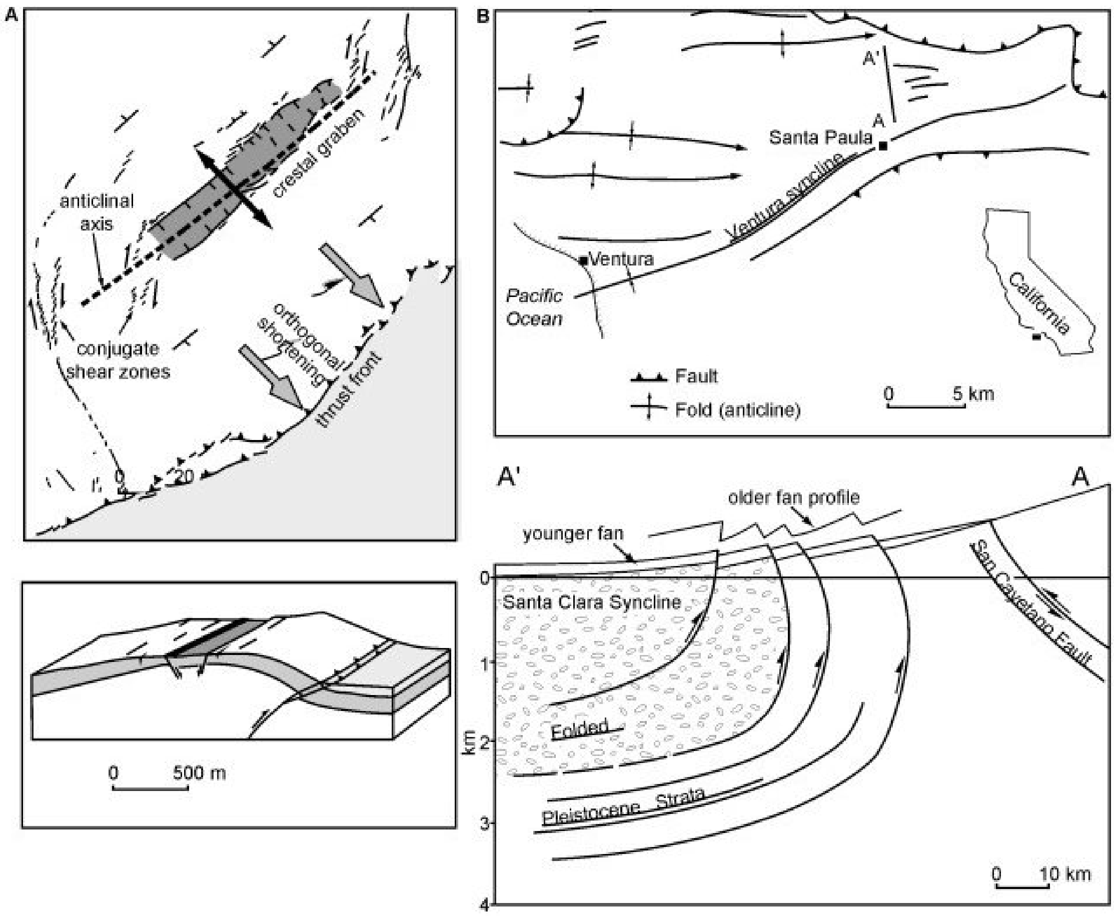

Figure 1: A) Bending-moment fault with folding and coeval normal faulting in the hangingwall during the El Asnam earthquake, Algeria (after Philip and Meghraoui, 1983). In this case orthogonal shortening results in a graben parallel to the anticlinal axis. During oblique shortening, en echelon graben are formed. B) Flexural-slip fault. Shallow, secondary faulting during layer-parallel slip causes rupture in unconformably overlying deposits with diminishing throw toward synclinal axis, Santa Clara syncline, Ventura Basin in southern California (after Rockwell, 1983; Yeats, 1986).

Analogous to bending of an elastic layer around a fold axis, which results in tension and normal faulting on the convex, and contraction and thrusting on the concave sides, Yeats defined these faults as *bending-moment faults* (Figure 2). In contrast, *flexural-slip faults* are reverse faults generated during flexural-slip folding (Figure 2); they rupture along the limbs of synclines and lose their structural expression in the fold hinges. Activity along these structures is documented through unconformities with overlying sediments and associated landforms such as pediments and terraces.

Cross-section balancing in these environments is useful in order to decipher long-term contraction rates and evaluate faults that have only partially surfaced or are still hidden in the subsurface and may represent important seismic hazards. Burbank *et al*. used a combination of structural field observations and cross-section balancing to define spatial and temporal sequences of asymmetric fold growth and reverse faulting.

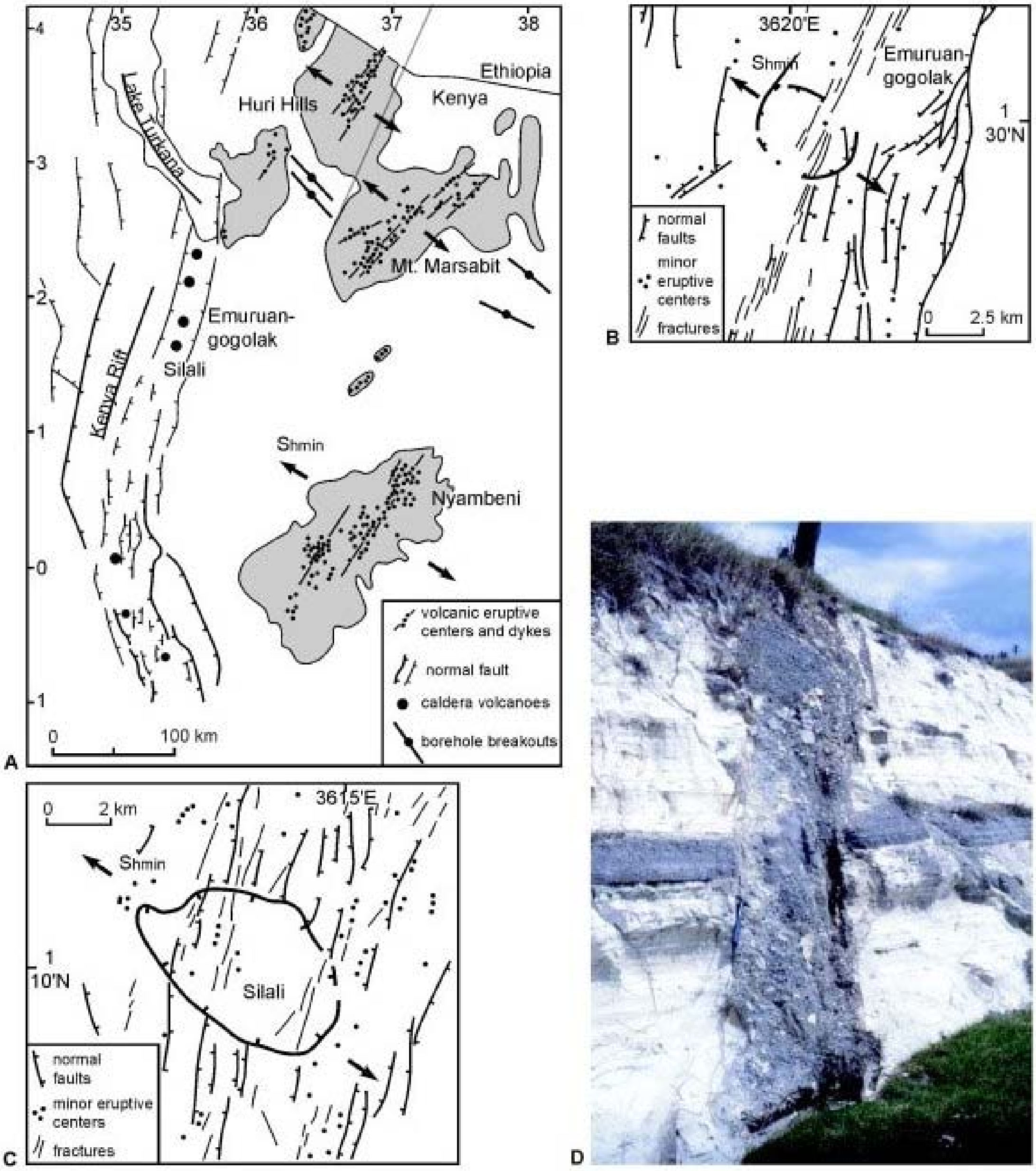

Figure 2: Various structural phenomena in the Kenya Rift region indicating the orientation of the least compressive horizontal stress (Shmin). A) Orientation of Quaternary dyke systems and associated volcanic eruptive centers on the northeastern shoulder of the Kenya Rift (after Strecker and Bosworth, 1991; Haug and Strecker, 1995; Bosworth and Strecker, 1997; Bosworth et al, 2001). Arrows depict orientation of Shmin. B) and C) Elongated late Quaternary caldera collapses, faults, and extension fractures at Silali and Emuruangogolak volcanoes in the northern Kenya Rift. Preferred caldera elongation is NW-SE and is interpreted to represent elongation of a once circular caldera due to shear fracturing, similar to a giant borehole breakout. Two kinds of failure may occur around a circular caldera collapse. If magma pressure (Pf) is high enough, the tensile strength of the caldera-wall rocks will be exceeded and hydrofractures parallel to SHmax form. If Pf is low, SHmax will increase and the shear strength is exceeded resulting in spalling of caldera walls parallel to Shmin (arrows). D)

NE-SW oriented Neptunic dyke in the central Kenya Rift in the vicinity of Lake Elmenteita. Numerous Quaternary lake deposits in the rift spanning the ultimate 300,000 years (Trauth et al., 2001) are affected by clastic dykes of similar orientation and document mid-Pleistocene to Recent NW-SE to WNW-ESE oriented extension (Strecker et al., 1989). Clastic dykes are related to water saturated, liquefied sediments that are injected into overlying sediments during an earthquake (Obermeier, 1996). Clastic dykes are thus similar to artificially induced hydrofracturing in boreholes (Hickman et al., 1985), which results in tension fractures at right angles to Shmin.

They documented the role of active tectonism in partitioning of intramontane basins and influencing drainage networks as well as associated changes in erosional and depositional patterns in the Tien Shan of Central Asia.

At the scale of mountain ranges, regional compilation of fault-slip data has helped to infer the state of stress, the level of tectonic activity, the character of neotectonics in different altitudinal sectors of orogens, and large-scale plate kinematic changes. In extensional settings the orientation of dyke systems (Figure 3) can be used to characterize the orientation of the least compressive horizontal stress (S_{hmin}) when these features are not parallel to pre-existing anisotropies such as faults, foliation or joint systems.

In addition, the orientation of Neptunic dykes and aligned volcanic eruptive centers or the systematic elongation of collapse calderas (Figure 3) have been used to infer the orientation of S_{hmin}. Structural analysis of well dated volcanic dyke systems, aligned volcanic edifices, meso-scale faults, and striations on fault surfaces has been used in rifting environments in North America, East Africa, Central Asia, and Europe to define the character of neotectonic deformation and changes in the kinematic evolution of rift-bounding faults related to changes in the tectonic stress field.

4. Geophysical Investigations

Analysis of focal mechanism solutions, microseismicity arrays, and seismic tomography studies aid in deciphering the present tectonic character of a structural province and help to understand and evaluate geologic phenomena in the framework of present geodynamic boundary conditions.

For example, seismic tomography has revealed the character of the active Altyn Tagh Fault along the northern margin of Tibet as a major, localized shear zone of lithospheric scale. Seismic tomography, gravity measurements, and microseismicity arrays together may help to explain patterns of young regional uplift, subsidence and deformation, and the spatial-temporal migration, as well as compositional variations of volcanism in regions underlain by anomalously hot asthenosphere.

This includes large-scale anomalies such as the trace of the Yellowstone hotspot, the East Africa Dome or the Altiplano/Puna plateau of the southern central Andes. Smaller mantle anomalies known as hot fingers such as in the Massif Central of France or the Eifel Plume area in Germany may have comparable neotectonic effects on surface uplift and surficial processes.

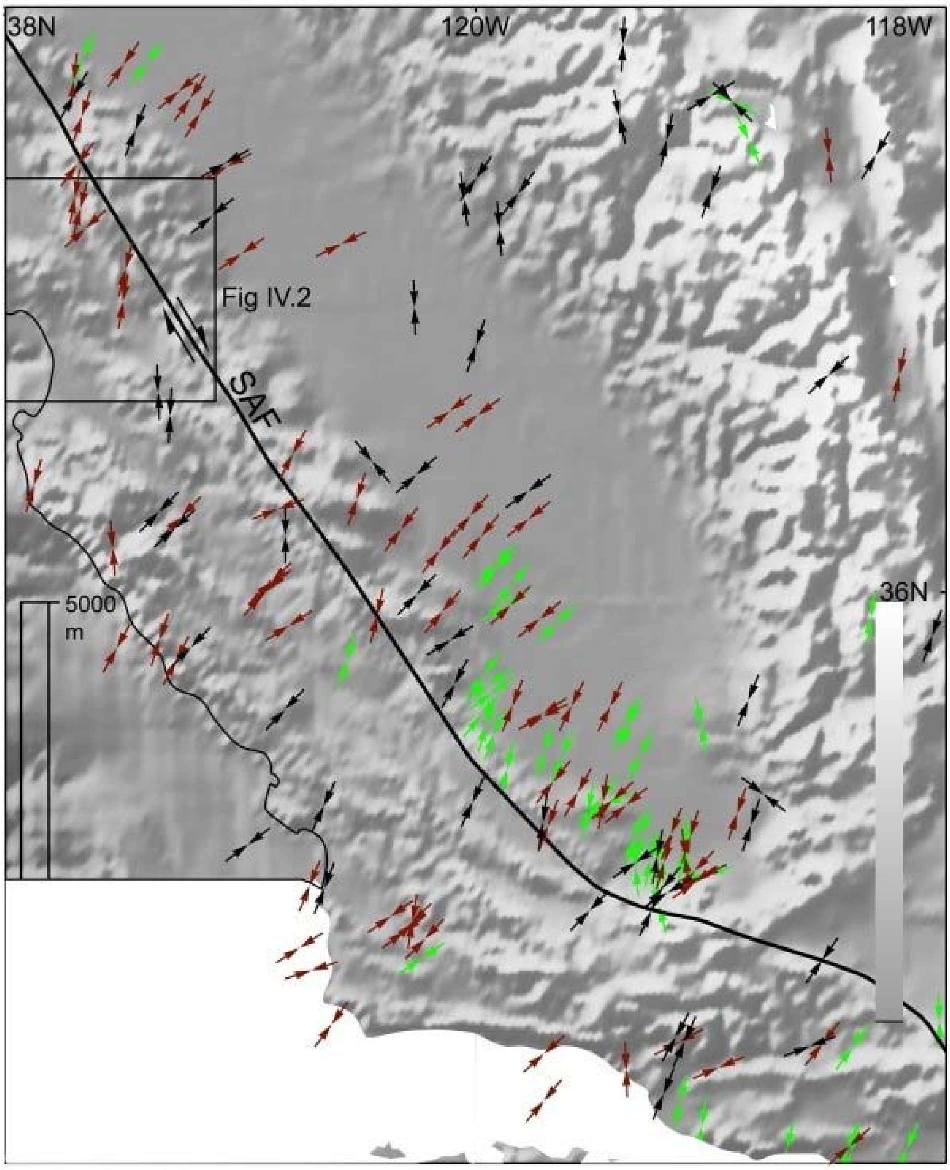

Figure 3: Composite stress map of California showing the directions of maximum horizontal compressive stress (SHmax) determined from borehole breakouts, overcoring, focal mechanisms, fault slip, and in-situ measurements. Colors represent quality ranking of stress - measurement data (after Zoback and Zoback, 1991; Zoback, 1992). SAF denotes San Andreas Fault, inset shows location of geologic map in Fig. 4. The different data sets indicate compression perpendicular to the San Andreas Fault in the immediate victinity of the fault.

In addition to imaging the density and velocity structure of the crust, determination of the regional stress field is an important component of neotectonic studies. Various techniques for determining *in situ* stresses have been developed and can be divided into three groups: surface, near-surface, and deep measurements. This includes, for example, the analysis of borehole breakouts (Figure 3 and 4) of scientific or commercial wells, hydrofracturing experiments or flatjack and doorstopper techniques. Seismic reflection experiments and seismic stratigraphic studies have been used to constrain long-term tectonic deformation to depths of several kilometers. In regions of low tectonic activity these studies may help better understand the occurrence of earthquakes and associated surface deformation, such as in paleo-rift zones in the interior of tectonic plates (e.g., New Madrid seismic zone, U.S.A.). Finally, ground-penetrating radar surveys have been used to visualize structures in unconsolidated materials at a depth of a few meters. The latter method has proven useful in reconnaissance investigations to detect covered fault offsets along active faults in humid climate environments characterized by pronounced soil creep or solifluction during colder climate conditions in the past. The use of geophysical and structural data sets to understand neotectonic processes is best demonstrated along the San Andreas Fault system in California.

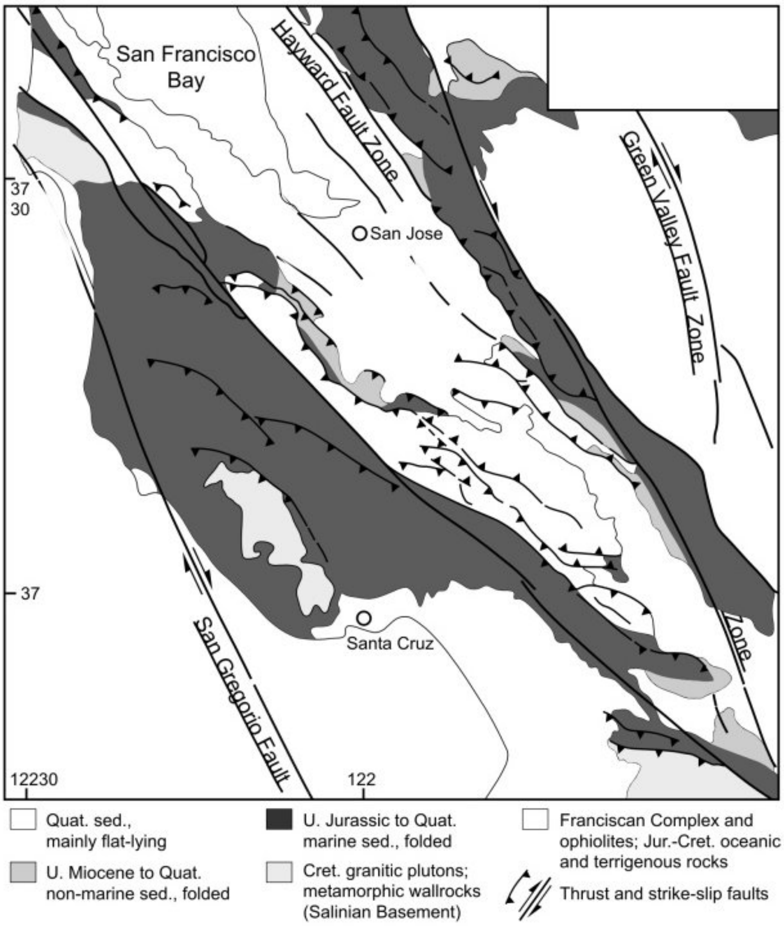

Figure 4: Simplified geologic map of the San Francisco Bay area showing thrust faults parallel to the San Andreas Fault system (after Aydin and Page, 1984; Arrowsmith et al., 2000). See Fig. 3 for location.

Structural investigations documented fault-normal orientation of the greatest horizontal stress (S_{Hmax}) making the fault poorly oriented relative to the regional stress field around the fault. Seismic reflection surveys, analysis of earthquake focal mechanisms, and borehole-breakout studies confirmed active fault-normal compression. From this, it was inferred that the fault system must have a low shear strength, causing the tectonic stress field to change its orientation near the fault (Figure 4 and 5).

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Biographical Sketches

Manfred R. Strecker is professor of geology at the University of Potsdam in Germany. He has worked with his colleagues on young crustal movements and their effects on erosion, sedimentation and climate change in the Pamir, the Andes, the Himalaya and the Baikal and Kenya rifts.

Peter M. Blisniuk is assistant professor at the University of Potsdam. He has worked on rift and foreland deformation in Kenya and Pakistan, respectively. In recent projects, he has investigated the structural evolution of orogenic plateaus and long-term climate changes in Tibet and the Patagonian Andes using stable isotopes, radiometric dating methods and sedimentological observations.

George E. Hilley was a Humboldt Fellow at the University of Potsdam, he held a postdoctoral research position at UC Berkeley and is now assistant professor at Stanford University. He focuses on geomorphic modeling of orogenic belts and plateaus. He also has interest in investigating the erosional and topographic response to rock uplift.

Claus-Dieter Reuther is professor of geology of the University of Hamburg in Germany. His research interests focus on neotectonic problems in the interior of continents (Central Europe) and active margins (Chile), determination of tectonic stress fields (Mediterranean region), and paleoseismology (Central Europe).