New Technology; New Geological Challenges

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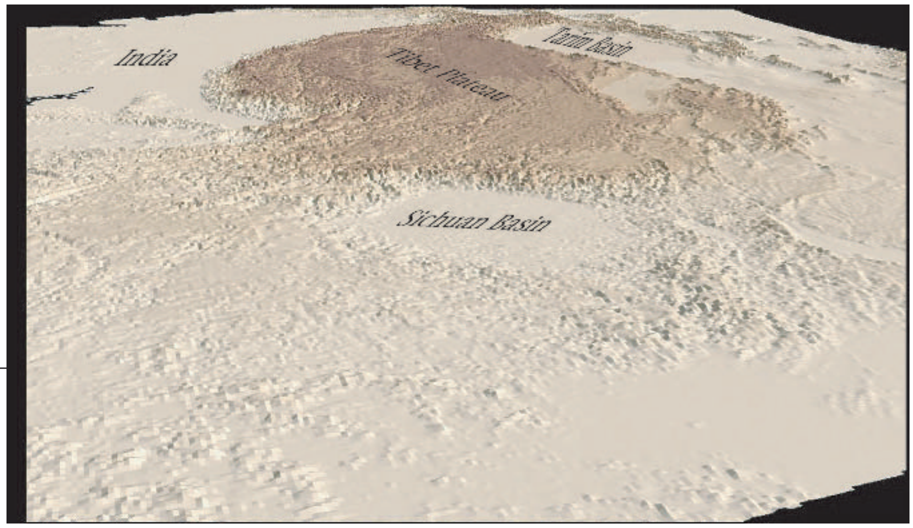

Figure 1. Looking west into the eastern part of the Tibetan plateau. This digital elevation model image shows the very different topography of the eastern margin of the plateau compared to the steep topographic fronts that form the northern and southern boundaries of the plateau.

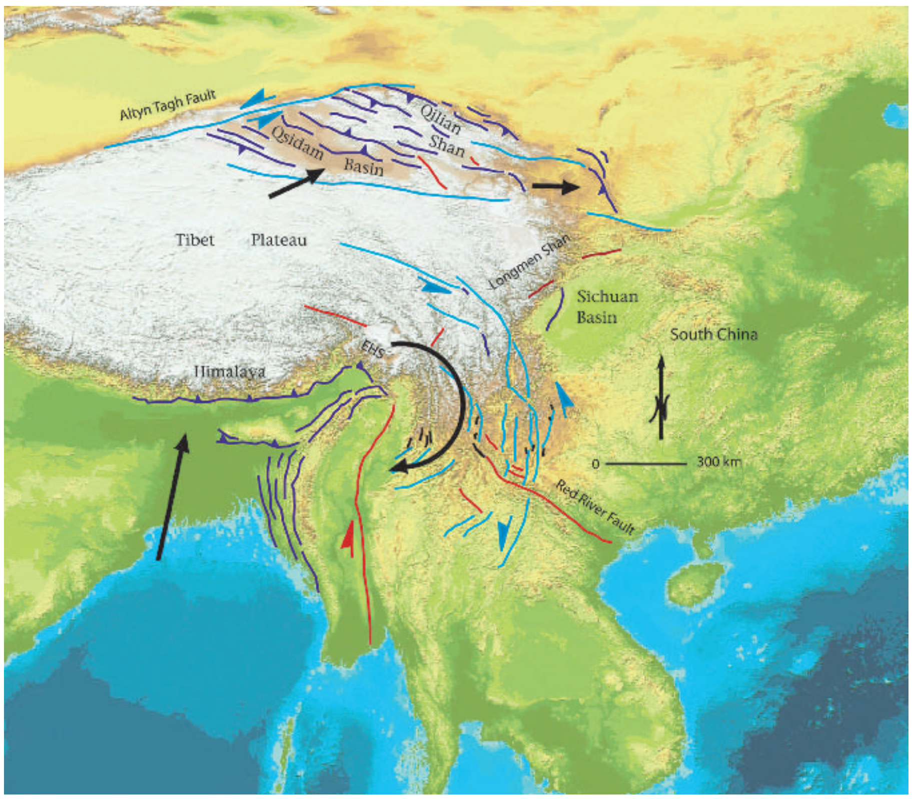

Figure 2. Generalized tectonic map of the eastern part of the Tibetan plateau and adjacent areas for late Cenozoic to Recent time. Black arrows show movement of crustal fragments relative to Eurasia for India and in the northeast part of the plateau, and relative to South China in the southeastern part of the plateau. Left-lateral strike-slip faults shown in blue, right-lateral strike-slip faults shown in red, shortening structures shown in purple, and extensional structures shown by short black lines. EHS—Eastern Himalayan syntaxis.

New technologies applied to geoscience yield new scientific data that permit us to advance our understanding of geological processes. At the same time, new technologies often yield data that challenge the ways in which we interpret geological processes and force us to examine these processes in new and different ways. Here, I want to discuss some data that, as a field geologist, I only partially understand and that remain a topic of active investigation. This is really a work in progress, but potentially also has produced results that will force us to look at shallow crustal structures and their relationship to deeper lithospheric processes in new ways. The technology is Global Positioning Systems (GPS), and the data come largely from China, but similar problems of data analysis are known from other places.

During our cooperative field geological studies with the Chengdu Institute of Geology and Mineral Resources (CIGMR) from l986 to about 1995, we developed a hypothesis for the late Cenozoic to Recent tectonic framework of the eastern Tibetan plateau. I must acknowledge here my long time colleague at CIGMR, Chen Zhiliang, with whom I have worked continuously for the past 17 years. The hypothesis contains interpretations that we believed to be new and unconventional. GPS studies were considered to be a new technology at that time, because their use was still finding new applications. It took only a few years of campaign GPS to produce preliminary results.

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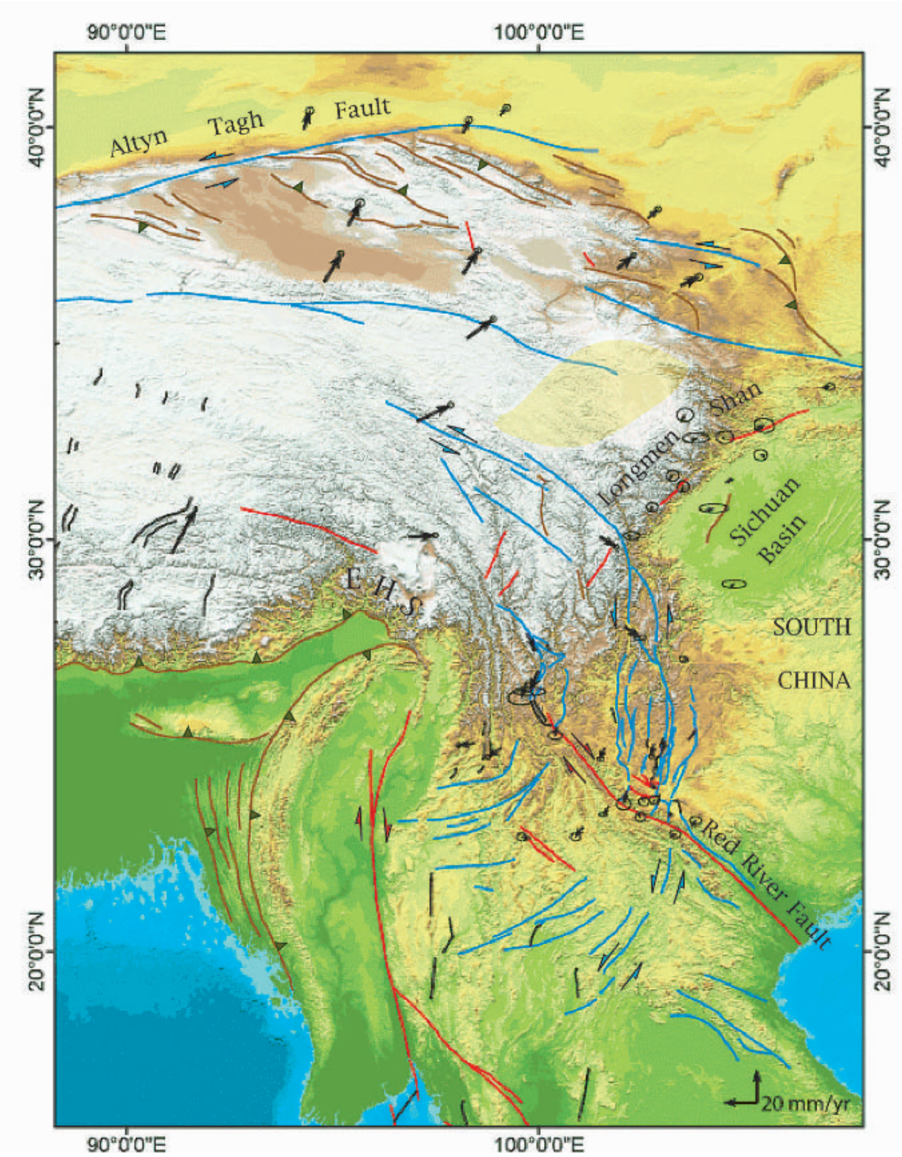

Figure 3. Global Positioning System (GPS) velocities within the eastern part of the Tibetan plateau and its adjacent foreland relative to South China superposed on tectonic map of Figure 2. The GPS velocities show that the Longmen Shan part of the Tibetan plateau moves with South China and that there is no shortening within error along the steep topographic front of the Longmen Shan. These GPS data indicate a velocity gradient west of the Longmen Shan that has no apparent surface structure related to it (region shown in yellow). Color code on structures are the same as in Figure 2. EHS—Eastern Himalayan Syntaxis.

The first areas I will discuss come from the eastern Tibetan plateau. The topography of the eastern part of the plateau is very different from the northern and southern boundaries of the plateau, which have steep continuous topographic fronts (Fig. 1). The eastern part of the plateau has two areas of long continuous slopes with no definable topographic boundaries and is separated by the very steep topographic front of the Longmen Shan west of the Sichuan basin. Our tectonic hypothesis, developed largely by field studies, indicated that the tectonic framework of the eastern Tibetan plateau consisted of three regions of different late Cenozoic and active deformation (Fig. 2). In the northeast region, displacement along the sinistral east-northeast–striking Altyn Tagh fault is transferred to northeast-southwest–shortening in the Qilian Shan. Eastward, the shortening direction becomes more east-west where east-west–striking left-lateral strike-slip faults are transferred into north-south–shortening on north-south–trending structures. In the central region, the Longmen Shan rise to more than 6 km above the Sichuan basin, forming one of the steepest mountain fronts along any margin of the Tibetan plateau. Field studies show that this mountain front and the high plateau to the west were not formed by significant upper crustal shortening and that the eastern part of the plateau in this area moves with its foreland to the east at a slow rate (Burchfiel et al., 1995; Chen et al., 2000). Finally, in the southwest region, there is no prominent topographic break that defines the eastern margin of the plateau. Here, the crust contains active, convex-east, left-lateral strike-slip faults, and the crust west of these faults rotates clockwise around the eastern Himalayan syntaxis relative to South China (Wang et al., 1998).

Our GPS studies in the eastern part of the Tibetan plateau have supported and modified our general tectonic interpretations (Chen et al., 2000) and have forced us to look for new structural interpretations. Here, I must acknowledge the outstanding work of our geodetic colleagues, Bob King of MIT, and Xuanyang Zhang of the Chengdu Institute. These GPS data are valid for time scales of years or decades, but our geological studies indicate that the present system has been active for at least the past 4–6 m.y. and perhaps longer in some places. What is of particular interest, and the focus of this presentation, are the implications of the combined GPS and geological data.

In the central Longmen Shan region, geology and GPS data, in a South China reference frame, indicate the coupled eastward movement of a segment of the plateau with South China and virtually no shortening to account for formation of a high plateau west of the topographic margin (Fig. 3). This was not at all the interpretation we initially proposed to test when we went into this area. Based largely on work by Royden (1996) we have developed the interpretation that eastward lower crustal flow, driven by gravitational potential energy of the central plateau, created the high topography of the eastern part of the Tibetan plateau by inflational thickening of the lower crust. A cross section through the southern Longmen Shan also shows the small magnitude of late

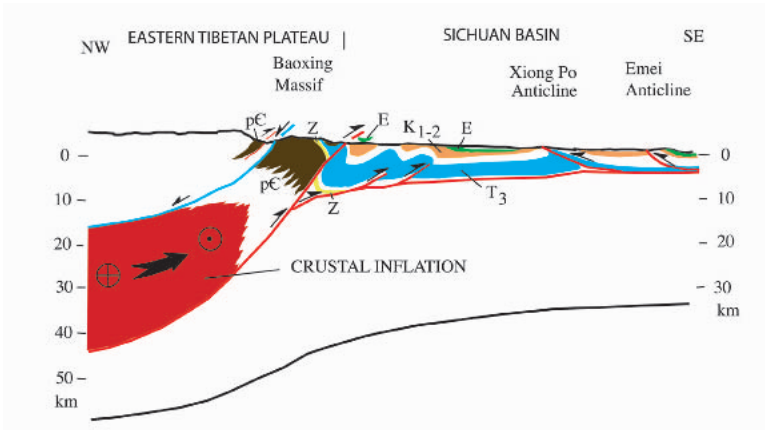

Figure 4. Generalized cross section from the Tibetan plateau across the very southern part of the Sichuan basin. Shows the interpretation of thickening of the crust below the plateau by lateral eastward crustal flow of ductile middle to lower crust causing thickening by crustal inflation. Eastward flow from the central part of the plateau encounters less ductile crust beneath the Sichuan basin and flows around the Sichuan basin forming the gently inclined plateau surface to the north and south of the Sichuan basin (see Figure 1).

Cenozoic shortening within and east of the Longmen Shan front (Fig. 4). The steep topographic front of the Longmen Shan results from resistance to eastward crustal flow because of a strong, less ductile crust underlying the adjacent Sichuan basin. The ductile lower crust appears to upwell at the plateau edge producing uncompensated local relief. Most of the lower crust flows laterally around the less ductile crust below the Sichuan basin to form broad areas with more gentle topographic gradients to the north and south (Clark and Royden, 2000) (Fig. 1). Recent work on mantle tomography by Lebedev and Nolet (2003) shows the Sichuan basin to be underlain by high velocity, presumably cold and less ductile lithosphere to depths of 150 km and possibly to more than 350 km.

But here is where the challenge comes in. If this interpretation is correct, there are few data from surface geology to provide direct evidence for the deformation occurring at depth or to analyze past changes in plateau elevation. We find evidence from the work of Kirby et al. (2002), and Clark (2003) that the eastern plateau was elevated in the past ~5–12 m.y., and our structural and geochronological studies along the steep Longmen Shan front have shown that the faults here have mainly vertical displacements during late Cenozoic time (Burchfiel et al., l995). However, if we were dealing with an older mountain system where data from topography, young or active structures, and GPS were not available, would we be able to identify such important tectonic processes and provinces?

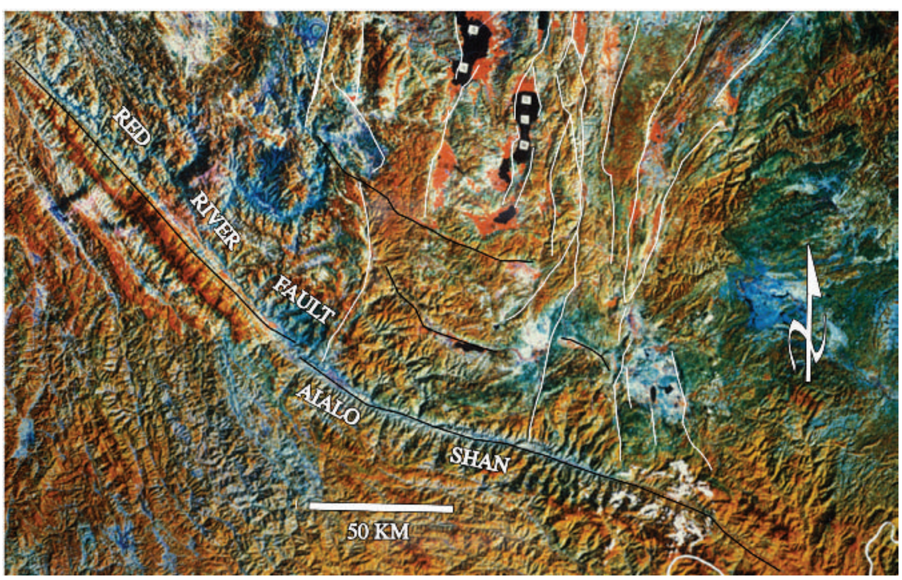

Figure 5. Landsat image of the central part of the Red River area where the left-lateral displacements on faults of the north-south striking Xianshuihe-Xiaojiang fault system, shown in white, die out, but the shear continues across the Red River fault (shown in black), Ailao Shan and structures farther south, bending the these features without being marked by prominent surface structures. Two prominent active right-lateral faults north of the Red River fault are also shown in black.

The GPS data from the northeastern part of the plateau have also revealed an additional, previously unrecognized problem (Fig. 3). Where is the western boundary for the part of the Longmen Shan plateau that moves with South China? This was a question we never considered until the GPS data began to show the need for a possible western boundary within the eastern plateau. West of the Longmen Shan, preliminary GPS data show a boundary, trending approximately northeast, with ~8–15 mm/yr active right shear. Because this result was not anticipated, we did not design our network to constrain the location of this boundary. We have now densified the network in this area to define more clearly where this boundary may be, but the results are not yet available. These data also presented another challenge for the field geologist: there were no structures on any Chinese map, or evident from the topography or from satellite imagery, that would lead one to hypothesize the existence of such a boundary. It raises the questions of how much strain the continental crust can absorb without developing throughgoing structures and whether we would recognize such strain in the older geological record.

A related problem is present in the southeastern region of the plateau where the convex-east faults define crustal fragments that rotate clockwise around the eastern Himalayan syntaxis at ~10 mm/yr relative to South China, as described by Wang (1994), and verified by GPS measurements (King et al., l997; Chen et al., 2000). The left-lateral fault system that bounds this zone of rotating crustal fragments on the east is well defined, but to the southeast the fault splays into several branches that are marked by numerous extensional pull-apart basins (Wang et al., l998; Fig. 3). Total displacement on the fault system is ~60 km throughout. About 100 km north of the Red River, the total displacement is still ~60 km but occurs on numerous splays instead of a single fault as it does farther north. However, within ~100 km north of the Red River, left-slip displacements on these splays decreases southward, and only a few of these faults reach the northwest-trending right-lateral Red River fault (Wang et al., 1998); none of them displaces it as shown by the recent work of Schoenbohm et al. (2003). Yet, although these individual faults lose displacement to the south, the portion of the Red River fault that lies across the geographic limits of the north-south–striking left-lateral system displays a prominent left-lateral bend with ~60 km of apparent deflection (Fig. 5). In the Landsat image, not only is the Red River fault bent, but the Ailao Shan range and other tectonic units farther south are also bent. Still farther south, a series of northeast-striking left-lateral faults and a few northwest-striking right-lateral faults appear and become more prominent southward into Indochina (Fig. 2). It thus appears that the shear that is bounding the clockwise rotating crust within the southeastern part of the plateau continues across the Red River fault and into Indochina, but the character of this upper crustal deformation changes along strike from discrete faults, to a broad zone of lesser faults, to a broad shear zone without faults, and finally to a broad region of northeast-striking left-lateral faults with some conjugate right-lateral faults.

Our most recent GPS results confirm this interpretation of the active deformation in the region (Fig. 3), and our geological studies suggest that this pattern of deformation is at least 4–6 m.y. old (Wang et al., 1998). The challenge presented by these data is to understand how the crust accommodates the broadly distributed shear that bends the Red River fault and adjacent rocks without discrete faults, obvious fractures, or other structures that absorb the deformation. It is in the deflected segment that the Red River fault shows its most prominent active right-slip. Thus, the counterclockwise rotation within the north-south shear zone increases right-lateral slip on the northwest-trending Red River fault and forms a discrete crustal boundary within a zone of the crust that otherwise behaves as if it is affected by a uniform homogenous shear. From surface geology, it has been proposed that the Red River fault is a major active right-lateral strike-slip fault in the tectonic scheme of southern China, but our studies show that most of the right-lateral activity may be related to counterclockwise rotation within the north-south–trending shear zone. Field geology and GPS data are in agreement with this interpretation, but the processes of how crustal bending is accommodated remains unresolved. Thus, the challenge for field geology is whether such relationships would be recognized in older orogens. Perhaps if the proper rocks are present within such regions, paleomagnetic studies might be useful to determine how the rotation was accomplished. A further question is presented. What would these structures look like at depth in more deeply eroded orogens?

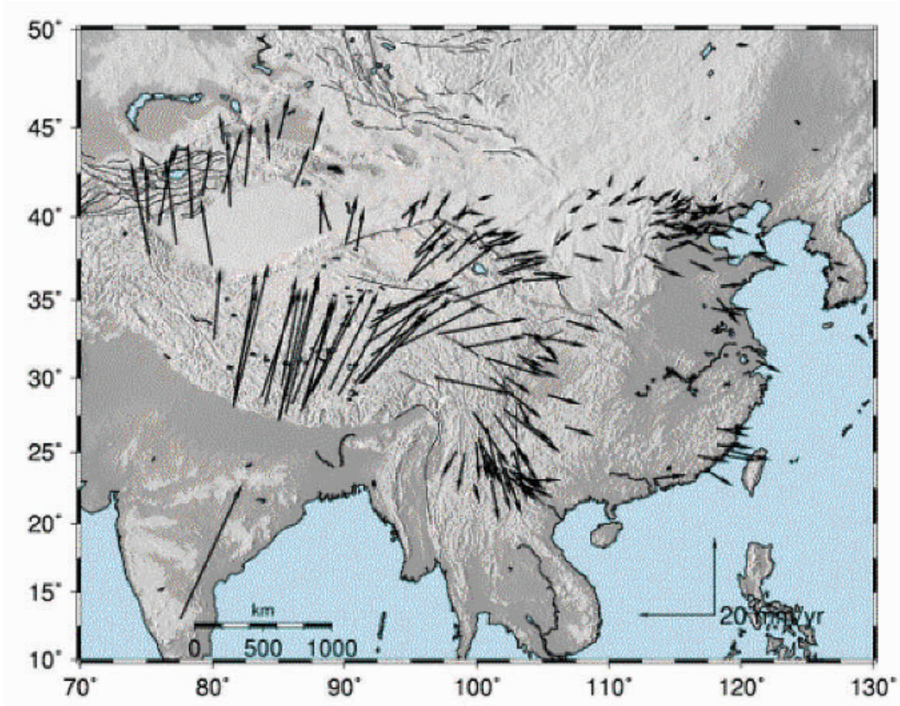

Figure 6. Compilation of Global Positioning System data for China and Nepal in a Eurasian reference frame. Shows the general ESE movement at about the same velocity of the eastern part of the Tibetan plateau (Longmen Shan area) and the clockwise rotating crustal fragment in the SE part of the plateau along with eastern China. Data from Abdrakhmatov et al. (1996), Chen et al. (2000), T. Herring (2003, personal commun.), Shen et al. (2000), and Wang et al. (2001).

If the results of tectonic and GPS analyses are viewed more broadly, additional challenges present themselves. When the GPS results are viewed in a fixed Eurasian frame of reference, all of the eastern part of China, including the Longmen Shan part of eastern Tibet, moves east-southeast about a pole of rotation far from eastern China (Fig. 6). Our preliminary interpretation is that the rotation of the crust around the eastern Himalayan syntaxis is driven by the northward indentation of India into Eurasia and gradients in gravitational potential energy from the central high Tibetan plateau. However, to the south, crustal motions are increasingly influenced by pull from the IndoBurman subduction zone and extensional structures within the upper crust become progressively more abundant. We suggest that such movements indicate that upper crustal structures and motions observed are decoupled from deeper lithospheric motions. The east-southeast motion of South China relative to Eurasia may be the result of deeper lithospheric motion, and the upper crustal structures are carried along with the deeper lithosphere. Tests of these

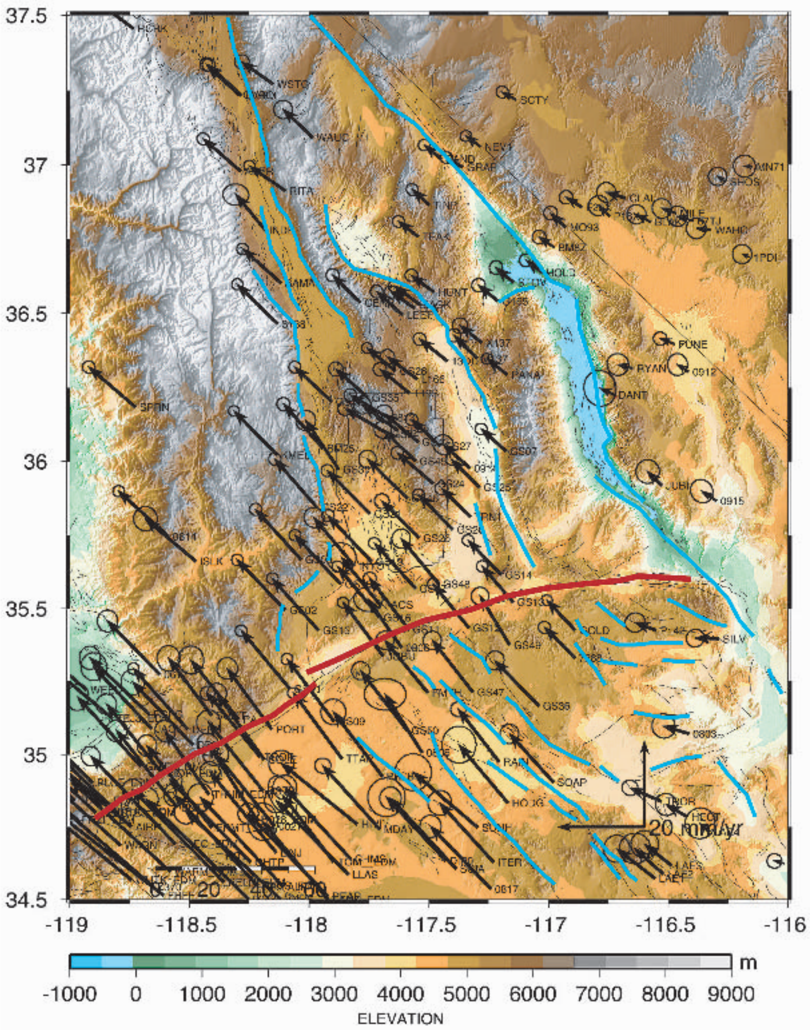

Figure 7. Global Positioning System velocity field relative to North America in southern Nevada and southeastern California (S.C. McClusky, 2003, personal commun.). Garlock fault shown in red; some of the major active NNW-striking right-lateral faults shown in blue.

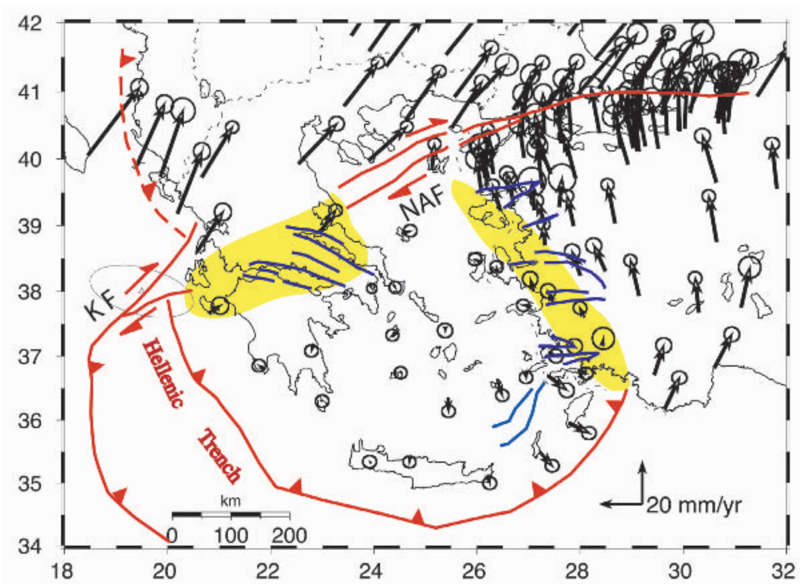

Figure 8. Global Positioning System (GPS) velocities plotted relative to minimized velocities in the area of the Aegean Sea. Hellenic trench and right-lateral Kefalonia (KF) and North Anatolian fault (NAF) zones shown in red. Yellow areas are diffuse boundaries defined by GPS velocity gradients. Blue lines are normal faults.

interpretations are possible and are in progress now by an aerial broadband seismic network we have deployed with our Chinese colleagues in southeast Tibet and its southeastern foreland. When viewed within the Eurasian reference frame, the east-southeast motion is toward the complex Pacific–southeast Asian plate boundary and may be driven to some degree by the dynamics of that boundary. At this scale, the entire complex region of offshore southeast Asia, a site of extensional oceanic and continental basins and irregular subduction zones, is as large as or larger than the region of intercontinental convergence north of the India-Eurasia collision zone. These two regions probably define different but interconnected regions of "push" and "pull." The boundary between them is complex, is very diffuse, and lies on-land within southeast Asia.

The challenge that faces us from the use of new GPS technology includes addressing the following problems. First, in the region of southeastern Tibet, we can determine the rates and directions of crustal movements, but we have difficulty in explaining how upper crustal deformation is accommodated by local areas of continuous shear strain without mappable structures. Second, what does the deeper crustal structure look like in such areas? Third, without GPS data, it would be difficult to determine that the local upper crustal domains are moving east-southeast, decoupled from deeper lithospheric motion.

Problems such as the ones I have covered here take many different expressions. Similar shear and bending of fault traces and adjacent crustal rocks are known from other areas. For example, the north-northwest–trending right-shear that passes through the eastern Mojave and east of the Sierra Nevada in the western United States is bending the eastern part of the east-striking left-lateral Garlock fault (Miller et al., 2001) at about ~11 mm/yr of right shear as shown in the compilation of GPS velocities by McClusky et al., (2001; Fig. 7). The bending here is much like that of the Red River fault region in that most of the north-northwest–striking right-slip faults, except for the southern Death Valley fault zone, do not cut the Garlock fault. Here, paleomagnetic studies have been very useful in defining how the deformation has been accommodated (see, for example, Schermer et al., 1996), but the mechanism of crustal shear remains unclear.

A different surface expression of upper crustal shear occurs in Greece and western Turkey. Recent GPS data by McClusky et al. (2000) have defined the crustal velocities in the eastern Mediterranean region. The GPS velocities in the Aegean Sea region are all about the same within error and indicate that the Aegean Sea crust moves as a single small crustal fragment without significant internal deformation (Fig. 8). Its boundaries on the northwest and northeast are expressed differently: on the west by a zone of horizontal shear and extension within the Greek mainland and in the east by a zone of mixed horizontal shear and extension as shown by the GPS velocity gradients. The North Anatolian fault zone bounds the Aegean crust in the north and is a well-defined fault zone in the northern Aegean Sea and along its apparent western continuation in the Kefalonia fault zone in the Ionian Sea. Right-shear along this fault system is ~25 mm/yr, but where it crosses the Greek mainland, there is no single continuous fault system. Instead, major west-northwest to east-west–trending en echelon grabens, such as the Corinth graben, form a belt ~100 km wide and trend at an oblique angle to the projection of the main shear zone (McKenzie, l978; Goldsworthy et al., 2003). The eastern boundary of the Aegean crust lies in western Turkey in a northwest-trending belt of east-west–trending grabens, but no through-going zone of transtensional left-lateral shear is present. A recent interpretation by Dimitris Papanikolaou and Leigh Royden (2003, personal commun.), based on geological mapping in Peloponnesus, suggests that movement of the Aegean as a single crustal fragment is young, probably Pliocene-Quaternary, and disrupts a long Cenozoic history of more typical back-arc extension above a subducting slab. The challenge for field geology here is to determine how surface structures in this part of Greece and Turkey would have been recognized as the expression of a major through-going shear without GPS and seismic data. Geologists mapping these surface structures might have struggled with the importance of these complex structures without a good regional framework within which to work. The expression of these structures at depth where they cross the Greek and Turkish mainlands remains a tectonic problem to be investigated.

In older orogens, can connections be made between broad regional shear, locally complex structure, and surficially discontinuous shear zones without the availability of GPS data? My answer is "yes," but only if we systematically study the upper crustal expressions and mode of deformation of modern shear zones of the type discussed here. It is also necessary to know what the deeper crustal expressions of these zones of active shear might be, so that structures related to such shear in older, more deeply eroded orogens can be recognized. Such data will come from combined geodetic, geological, geophysical, and paleomagnetic studies. Conversely, field studies of former deep crustal shear zones that are now exposed in older orogens can supply insights into active deep crustal processes discerned primarily by GPS-related investigations of the type described here.

We all know that GPS has become an increasingly important tool for a wide variety of geological research. My point here is that it is an extremely important tool for the field geologist as well. It yields a new type of data that needs to be integrated with field studies to solve not only local, but also regional problems. It is a new technology that presents us with new and significant geological challenges.

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