

Variable crustal structure of strike-slip fault zones as observed on deep seismic reflection profiles

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ABSTRACT

Seismic reflection profiling across strike-slip faults has revealed a distinct variation in deep crustal structure. Profiles across the San Andreas, Great Glen, and Bray faults depict a near-vertical, reflection-free zone that appears to truncate and in some cases offset reflections interpreted to have originated from the base of the crust. A near-vertical, crustal-penetrating fault zone is suggested for these continental transform faults. In contrast, reflection profiles across intra-plate strike-slip fault systems such as the northern Walker Lane and Garlock faults suggest that they are decoupled in the middle crust by subhorizontal detachments. These detachments are inferred from reflections that are traceable below the surface faults without disruption. Such detachments in the middle crust may act to ease the rotation of upper-crustal blocks adjacent to strike-slip fault zones, as observed in paleomagnetic studies. Furthermore, moderately dipping reflections, interpreted to be from the fault zone, project to the surface traces of the northern Walker Lane faults and the frontal faults of the Wichita Uplift, indicating that these strike-slip faults with large components of dip-slip displacement are not vertical but dip moderately into the mid-crust. Although the available data sets are still few, they suggest that there is a primary variation in fault geometry that is related to the different behavior of transform versus intra-plate strike-slip fault systems.

INTRODUCTION

Over the past 30 yr, numerous geological and geophysical studies have addressed the geometry and kinematics of strike-slip fault zones (Sylvester, 1984). Yet the nature of strike-slip faulting at depth is still poorly understood. Current ideas about the deep crustal structure of strike-slip faults have been developed from teleseismic P-wave travel-time residuals, deep seismic sounding, fault-zone mechanics, and earthquake focal mechanism studies (Zandt, 1981; Daignieres and others, 1982; Sibson, 1983; Webb and Kanamori, 1985; Yeats, 1981). Now, a number of deep seismic reflection profiles have been collected by the Consortium for Continental Reflection Profiling (COCORP), the British Institute Reflection Profiling Syndicate (BIRPS), Etude de la Croute Terrestre en France par Methode Sismique (ECORS), the University of California at Berkeley, and the United States Geological Survey. In spite of the difficulties inherent in using the reflection technique to probe steeply dipping structures, these profiles provide a fresh look into the nature of major strike-slip fault

zones at depth. In this study, we review these various deep seismic reflection profiles in an attempt to identify significant distinctions, if any, with regard to the deep structure of strike-slip fault zones.

Many examples of the shallow structural geometries across strike-slip fault zones are available from industry reflection profiles and drill data (Harding, 1983, 1985; Harding and others, 1983). The studies often indicate an upward-branching pattern of faults that originate from a steeply dipping strike-slip zone of deformation. Harding and Lowell (1979) refer to this upward-branching geometry as a "flower" structure. Figure 1 is a seismic profile across a convergent strike-slip fault zone in the Ardmore basin (Harding and Lowell, 1979). Convergence across the fault zone is suggested by the reverse stratigraphic separations on the outward-branching faults. In general, these outward-branching faults may show a change in fault offset with depth, perhaps even a reversal, but they all appear to merge at depth with a central strand that is thought to be near vertical (Harding, 1985). Deep seismic reflection profiles discussed in this paper provide a clue to the possible continuation of the main fault strand into the deep crust.

Although steeply dipping faults are difficult to image on seismic reflection profiles (Lynn and Deregowski, 1981), they are frequently detectable by indirect means. For example, a lateral change in reflection character, perhaps associated with data degradation, can betray the presence of steep structures. Unfortunately, the complex geology often associated with strike-slip fault zones might also result in severe seismic velocity variations and resultant ray-path distortion, as well as high seismic energy attenuation, in such a manner as to obscure or mask structural characteristics associated with the deeper portions of such faults. Yet, as seen in Figure 1, when layered reflections are disrupted by a strike-slip fault, abrupt changes in dip, terminations, and diffractions can help pinpoint steeply dipping subsurface faults. Furthermore, shallow fault traces can often be recognized on unstacked data (for example, shot-point gathers) by both changes in refraction velocities and offsets in refracted arrivals. Although actual fault-zone reflections are rare, processing of reflection results can be oriented to detect steep dips by testing higher velocities that more effectively stack steeply dipping reflections (Telford and others, 1978). Migration and three-dimensional control are also of particular importance in estimating true structural geometries near a strike-slip fault.

Processing of the deep seismic reflection data examined here occurred at different times and by different groups. Therefore, the seismic sections represent various processing sequences, with interpretations relying primarily on available stacked sections. Unless otherwise indicated, both sections and line drawings are here displayed in unmigrated form and without vertical or horizontal exaggeration, assuming an average crustal velocity of 6.0 km/sec. Thus, one second of two-way travel time corresponds to a depth of 3.0 km. Details of the data processing may be found in the original reports (Brewer and others, 1983; Hall and others, 1984;

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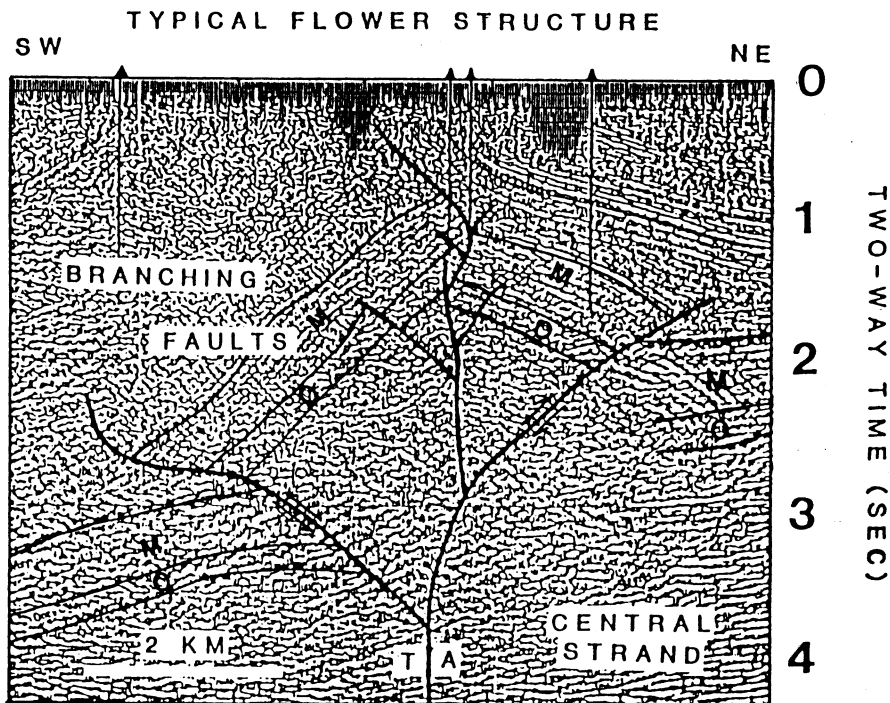


Figure 1. Example of a "typical" flower structure from a seismic profile within the Ardmore basin (from Harding and Lowell, 1979). Note that other geometries have been observed, such as one-sided flower structures (T. P. Harding and A. C. Tuminas, unpub. data) and simple single fault strands. M = Mississippian, O = Ordovician, T = toward, A = away.

Bois and others, 1986; Cheadle and others, 1986; McBride and Brown, 1986; Kneuper and others, 1987).

SAN ANDREAS FAULT

The most important and intensively studied strike-slip fault zone in the United States is the San Andreas. Extending for more than 1,100 km, this right-lateral fault is considered a transform boundary between the North American and Pacific lithospheric plates (Atwater, 1970). As such, it is presumed to represent a steeply dipping zone of decoupling through the lithosphere. Since the Miocene, at least 300 km of right-lateral displacement has been estimated from offset sedimentary and volcanic units (Crowell, 1962; Matthews, 1976). Three deep seismic reflection profiles cross the San Andreas near the seismically active Parkfield region in central California (Fig. 2). Aftershock studies from the 1966 Parkfield earthquake suggest a near-vertical fault extending from the surface to about 15-km depth (Eaton and others, 1970). Geophysical anomalies such as gravity, electrical resistivity, and seismic velocity lows parallel the fault zone and have been cited as additional evidence of a near-vertical fault extending to a depth of 10 to 15 km (Wang, 1984). The anomalies probably result from the existence along the fault zone of saturated, clay-rich fault gouge like that exposed at the surface (Wang, 1984).

The San Andreas fault zone in central California consists of numerous strands, trending about N40°W, which juxtapose the Salinian block to the west against the Franciscan terrane to the east. Seismic refraction profiling suggests crustal thicknesses beneath the Salinian block averaging 22 to 26 km (Healy, 1963; Stewart, 1968; Walter and Mooney, 1982), versus 27 to 31 km beneath the Franciscan terrane (Stewart, 1968; Warren and Healy, 1973; Walter and Mooney, 1982; Eaton and others, 1970). The change in crustal thickness across the San Andreas fault zone provides further evidence of the juxtaposition of distinctly different crustal units.

The two most informative deep seismic reflection profiles across the central segment of the San Andreas fault zone are shown in Figure 3. The sections displayed here and in subsequent figures were produced using a

coherency filter to enhance small-scale reproducibility. Interpretations of McBride and Brown (1986) and those elaborated upon here, however, are based on careful analysis of several versions of the seismic section. Profile A, collected by COCORP in 1977, crosses the fault zone near Parkfield (McBride and Brown, 1986). Data quality is relatively poor, and some of the features described below may appear subtle at best, even with coherency-enhanced sections. In this region, at least three separate fault strands define the 3-km-wide fault zone at the surface. Below the surface strands, there are numerous short reflection and possible diffraction events (D) between 0.2 to 6.0 sec. Some of the more continuous reflections

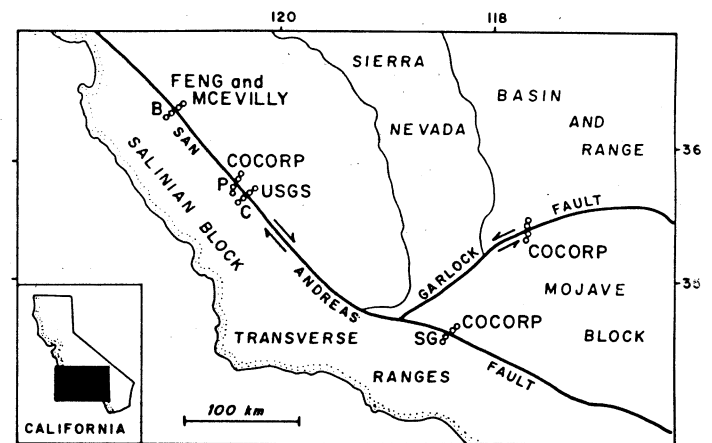


Figure 2. Generalized map of southwestern California with locations of seismic profiles across the San Andreas and Garlock fault zones. Solid circles are surveys discussed in text. Surveys indicated by open circles are not considered in this review because data quality is too poor to contribute significantly to discussion on deep structure. B = Bear Valley, P = Parkfield, C = Chalome, SG = San Gabriel Mountains.

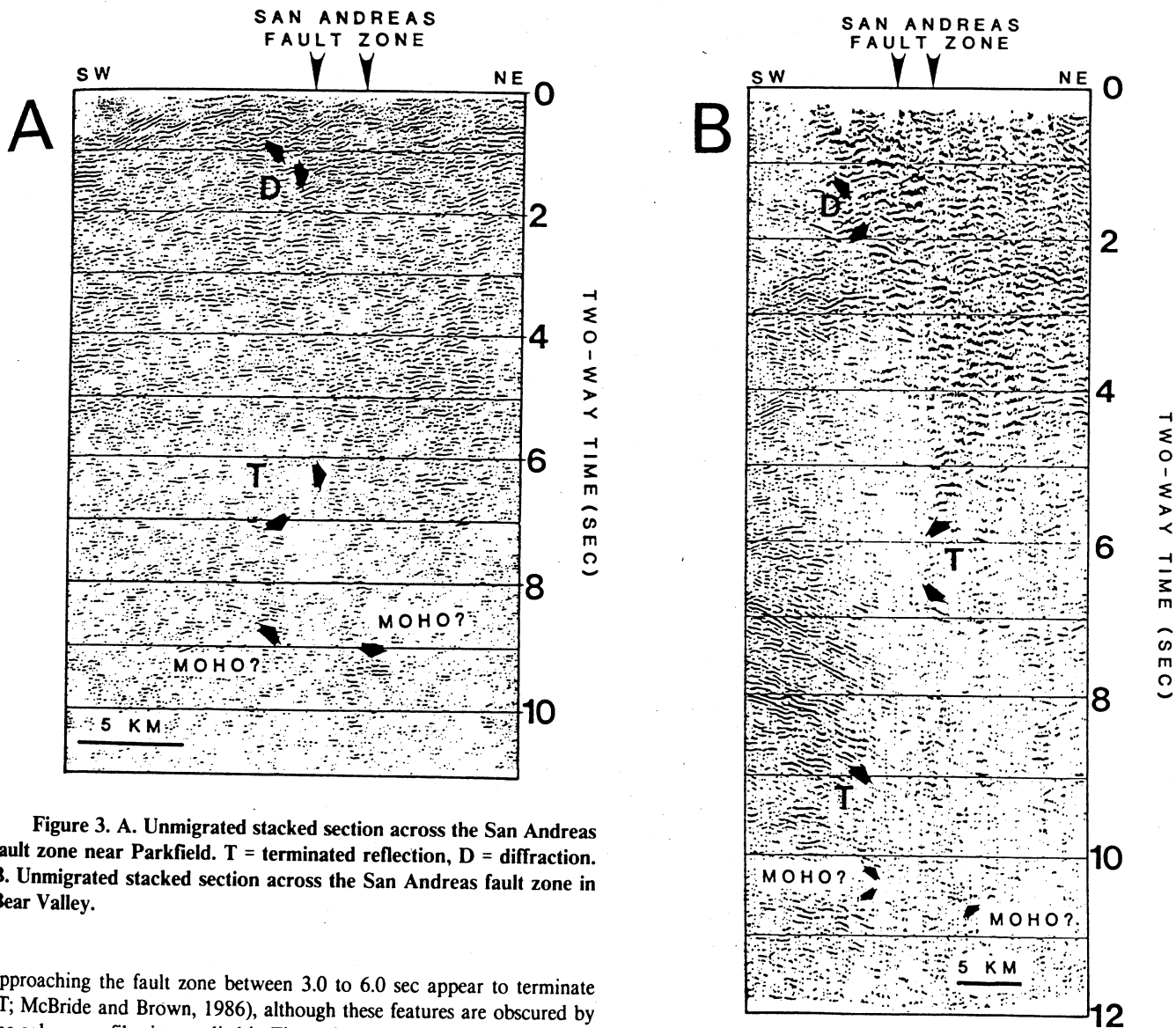


Figure 3. A. Unmigrated stacked section across the San Andreas fault zone near Parkfield. T = terminated reflection, D = diffraction. B. Unmigrated stacked section across the San Andreas fault zone in Bear Valley.

approaching the fault zone between 3.0 to 6.0 sec appear to terminate (T; McBride and Brown, 1986), although these features are obscured by the coherency filtering applied in Figure 3. The increased disruption and termination of reflections below the fault zone is presumably due to faulting, but it may also reflect the difficulty of imaging beneath structural complexity. Ray-path distortion by lateral velocity variation may well reduce the effectiveness of the common-depth-point technique in enhancing crustal reflections beneath the shallow part of the fault.

At travel times longer than 6.0 sec, a significant change in the reflection character occurs beneath the surface traces of the fault zone (Fig. 3A). A near-vertical, reflection-free zone is outlined by the apparent termination of reflections on either side (McBride and Brown, 1986). Some of these "truncated" reflections appear to be "pulled-down" as they approach the zone directly under the fault. This pull-down effect is consistent with the inferred reduction in P-wave velocities within the fault zone (McNalley and McEvilly, 1977). A lack of reflections corresponding to the lower crust beneath the fault may indicate that the fault zone itself contains no coherent reflectors, or it may be an artifact of near-surface geological complexities reducing signal penetration and coherence. Detailed analysis (McBride and Brown, 1986) failed to resolve this basic ambiguity. It can be argued that the existence of reflections above 6.0 sec attest to some degree of signal penetration and could be cited in support of the reality of the deeper reflection-free zone. The inference of a near-vertical fault in the

lower crust, however, is not wholly dependent upon the existence of a reflection-free zone at depth.

Reflections interpreted as originating from the base of the crust appear, upon careful examination, to be well defined adjacent to, but differ across, the San Andreas fault zone (McBride and Brown, 1986). Beneath the Salinian block, there are multicyclic reflections between 7.8 and 10.2 sec. The upper part of these reflections correspond to refraction Moho depths of 22 to 26 km. Conversely, beneath the Franciscan terrane, simpler two- to three-cycle reflections are concentrated at 9.4 sec, which correspond to the Moho depths of 27 to 31 km estimated by refraction profiling. Thus, there is an apparent change in Moho reflection character as well as depth across the San Andreas fault, with a laminated zone in the southwest and simpler reflections in the northeast (McBride and Brown, 1986). There may be some ambiguity as to the identification of specific reflections with the Moho; nevertheless, there is a change in reflection character at the base of the crust beneath the fault zone. The central reflection-free zone itself continues past travel times corresponding to refraction Moho depths. Thus the data for all of its ambiguities still suggest that the San Andreas penetrates through the entire crust as a steeply dipping fault.

Feng and McEvelly (1983) presented a 20-km-long deep seismic reflection profile across the San Andreas fault zone in Bear Valley (Figs. 2 and 3B). The dominant characteristics of this previously unpublished version of the profile is an abrupt change in apparent frequency and data quality across the fault. Higher frequencies and more definitive reflections appear southwest of the fault. A substantial variation in source coupling, such as described by De Voogd and others (1986), is suspected but cannot be established on the basis of the data available at this time. The following discussion and interpretation of this section should be considered with this unresolved issue in mind.

Between 0.0 to 3.5 sec on the seismic section below the fault zone, there are numerous short, discontinuous reflection segments and diffraction hyperbolas (D). The diffractions indicate an average rock velocity of 1 to 2 km/sec within the fault zone, which is 0.3 to 0.4 km/sec less than adjacent rock velocities (Feng and McEvelly, 1983). A number of short reflections approaching the fault zone from the northeast between 5.0 and 7.0 sec appear to terminate below the fault zone (T). Deeper beneath the Salinian block on the southwest side of the fault zone, there are a number of semi-continuous horizontal and east-dipping reflections. These reflections lose their coherency as they are traced below the fault zone and are not evident within the Franciscan terrane. The loss of reflection coherency below the fault zone may again indicate deformation at depth within this region or imaging limitations (Feng and McEvelly, 1983). Subhorizontal reflections within the Salinian block between 9.5 to 10.8 sec are deeper than previously estimated Moho depths and are interpreted to be from the base of the crust. They appear to be absent within the fault zone and are obscure within the Franciscan terrane to the northeast. This change in character of the lower crustal reflections adjacent to the fault zone suggests that the fault zone extends steeply through the entire crust.

GREAT GLEN FAULT

The Great Glen fault zone trends northeast across Scotland, dividing the northern from the central Highlands (Fig. 4). Kennedy (1946) was the first to suggest as much as 100 km of left-lateral strike-slip motion across the fault during the late Paleozoic, based upon the offset Caledonian age Strontian and Foyers igneous complexes. Disagreement continues, however, regarding the history and magnitude of movements along the Great Glen fault zone. Van der Voo and Scotese (1981) used paleomagnetic data to suggest as much as 2,000 km of lateral displacement, but most estimates agree with left-lateral displacements on the order of a few hundred kilometres (Holgate, 1969; Garson and Plant, 1973; Winchester, 1974; Storetvedt, 1974; Mykura, 1975; Smith and Watson, 1983; Soper and Hutton, 1984). Plate-tectonic reconstructions of the late Paleozoic treat the Great Glen fault zone as part of a continental transform system which accommodated plate readjustments in the Pangea megacontinent (Dewey, 1982; Badham, 1982). Upper crustal offshore strands of the Great Glen fault zone appear to have been reactivated as normal faults during the Cenozoic extension of northwestern Europe (McQuillin and others, 1982; Naylor and Shannon, 1982; Hall and others, 1984).

Seismic refraction and wide-angle seismic reflection studies that cross the Great Glen fault in north-central Britain have found considerable lateral variation in crustal layering (Blundell, 1981). P-wave velocities from the upper crust as well as wide-angle reflections from the middle crust may indicate a disruption in velocity horizons across the fault zone (Bamford and others, 1978). Wide-angle reflections from the Moho indicate a 25- to 30-km depth in the region of the Great Glen fault zone. A deep seismic reflection profile (WINCH) collected by BIRPS crosses the southwest seaward extension of the Great Glen fault zone between Britain and Ireland (Fig. 4; Matthews and Cheadle, 1985; Hall and others, 1984). Here the fault zone is ~5 km wide and is bounded by the Dubh Artach

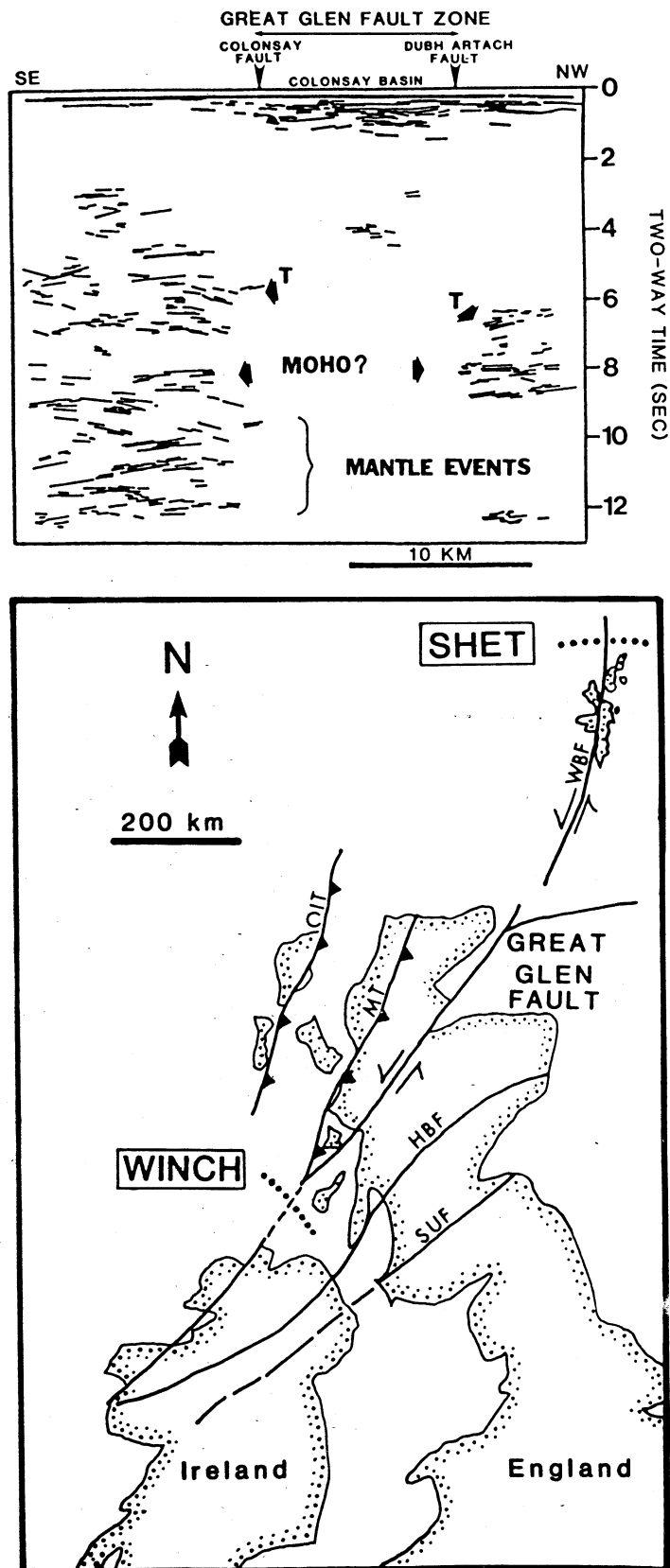


Figure 4. Interpretive line drawing of the WINCH unmigrated stacked section across the Great Glen fault accompanied by a generalized map depicting the location of the WINCH and SHET seismic surveys.

and Colonsay faults. These are normal faults active during the Tertiary opening of the Colonsay basin (Hall and others, 1984).

A line drawing of the major reflections abstracted from the WINCH seismic section is shown in Figure 4. The reflection sequence between 0.2 and 1.3 sec has been interpreted as sedimentary strata within the Colonsay basin that postdate strike-slip movement on the Great Glen fault (Hall and others, 1984). Nearly flat-lying Quaternary sediments overlie more disrupted Tertiary volcanic and sedimentary units, underlain by Mesozoic deposits covering the basement surface at about 1.3 sec (Hall and others, 1984; Naylor and Shannon, 1982). The reflection patterns combined with gravity modeling suggest that the Dubh Artach and Colonsay normal faults dip toward the center of the basin (Hall and others, 1984; Naylor and Shannon, 1982). Between 2.0 and 4.0 sec, the seismic section consists of relatively few reflections, which prohibits the downward extrapolation of the basin-bounding normal faults. Refraction data in the area demonstrate that low velocities are associated with the fault zone down into the basement, suggesting that the rock is a low-density fault gouge (Hall and others, 1984). Unfortunately, between 4.0 and 15.0 sec, diffraction "side-swipe" from prominences on the fault at shallow depth was recorded, which deteriorates the data quality below the Great Glen fault (Hall and others, 1984). The line drawing depicts the seismic section without these artifacts.

Beneath the surface traces of the Great Glen fault zone, the reflections from the lower crust appear to be interrupted by a near-vertical reflection-free zone (Fig. 4). A highly reflective lower crust is a pervasive feature on the BIRPS profiles around southwest Great Britain, but its continuity is broken beneath the fault (Matthews and Cheadle, 1986). Both horizontal and dipping reflections terminate abruptly on either side of this reflection-free zone (T). Furthermore, prominent Moho reflections evident along much of the WINCH survey at ~8.0 to 9.0 sec (Powell and Sinha, 1986) are absent within this reflection-free zone. Interpreted upper-mantle reflections between 10.0 and 12.5 sec within the southeast block also terminate below the Great Glen fault outlining the reflection-free zone and are less prevalent toward the northwest. These deep reflections attest to sufficient signal penetration in the area as well as a difference in reflection character across the fault zone. The Colonsay basin may be producing this artifact of a crustal blank zone, but it would more likely misplace lower crustal reflections in the area as a result of velocity variations and not totally eradicate them.

More recently BIRPS collected the SHET survey across the Walls Boundary fault, which is the northern continuation of the Great Glen fault in the Shetlands (Fig. 4). The pervasive lower crustal reflections on the BIRPS profiles are less prevalent on the SHET profile. Furthermore, McGeary and others (1986) suggest that the Walls Boundary fault appears to penetrate the entire crust, with the Moho showing an offset of at least 1.5-sec two-way travel time. Therefore, the truncated reflections seen on the Great Glen fault profile may be a preserved Paleozoic feature. This raises questions about the relationship between extension and the reflective lower crust (Warner and Peddy, 1986) and suggests that Paleozoic features of the lower crust may not be completely erased by younger tectonic events.

BRAY FAULT

The Bray-Vittel fault zone extends over 500 km under the central Paris basin in northwestern France (Fig. 5). The Bray fault is considered part of a set of northwest-trending faults which have undergone right-lateral strike-slip motion during the middle to upper Paleozoic (Badham and Halls, 1975; Arthaud and Matte, 1977; Badham, 1982; Matthews, 1984). Oblique plate convergence during the Hercynian orogeny in southern Europe caused the development of a continental transform fault system

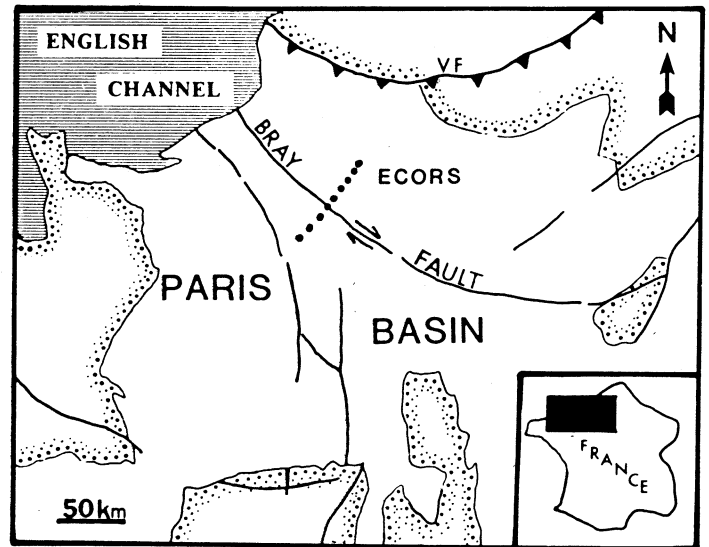
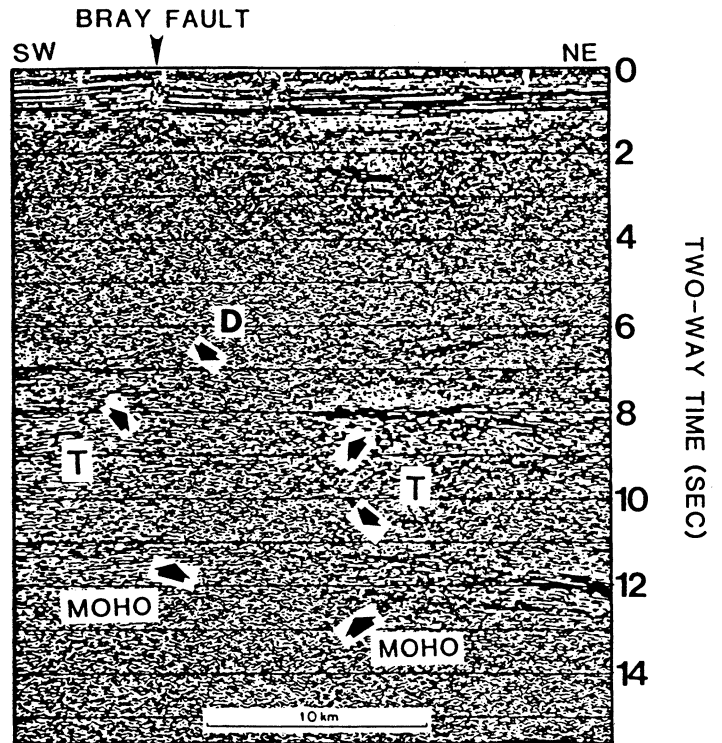


Figure 5. Unmigrated stacked section across the Bray fault (from Bois and others, 1986) with a generalized map depicting the location of the ECORS survey. VF = Variscan Front; dotted pattern outlines Paleozoic massifs.

which accommodated the Appalachian and Uralian shortening (Arthaud and Matte, 1977; Dewey, 1982). Although concealed beneath the Paris basin, the Bray fault is marked by a surface anticline and by both magnetic and gravity anomalies (Debeglia and Weber, 1985). Unfortunately, lack of exposures precludes any estimate on the total amount of right-lateral displacement. It is also believed that the Bray fault zone was reactivated as a normal fault during the Mesozoic and Tertiary extension that affected the region (Ziegler, 1982).

The ECORS group collected a 230-km-long deep seismic reflection profile across the Bray strike-slip fault zone in the Paris basin (Fig. 5). The

results provide the most succinct picture yet of the crustal geometry of such a fault zone. The laterally continuous reflections between 0.1 and 1.0 sec are correlated with Mesozoic strata encountered in drill holes (Bois and others, 1986). The reflections between 0.5 and 1.0 sec are slightly down-dropped to the northeast in the location of the Bray fault. This apparent normal fault has produced a drape-anticline in the overlying sedimentary units which is the surface expression of the fault zone. Unfortunately, the lack of reflections from 1.0 to 7.0 sec precludes any interpretation of the upper-crustal geometry of the fault zone. An obvious disruption, however, occurs in the abundant reflections which characterize the lower crust in this area (Bois and others, 1986). Reflections from both the southwest and northeast appear to terminate against this 6-km-wide reflection-free zone (T). Some of the truncations are associated with diffractions (D). The blank zone lies slightly north of the surface location of the Bray fault; if correlated, an apparent dip of 75°NE is suggested. The top of the reflective lower crust appears to be relatively well defined here and shows an apparent vertical offset of 1.0 sec, or 3 to 4 km, depending upon the seismic velocities at depth.

The base of the lower crustal reflections occurs at about 11.5 sec within the southwest block and is interpreted as the crust/mantle interface (Bois and others, 1986). These strong Moho reflections also appear to be 1.0 sec deeper northeast of the reflection-free zone, suggesting that the Bray fault offsets the Moho. It seems unlikely that the shift in the lower crustal reflections across the fault zone has resulted from an overlying low-velocity anomaly. The significance of this apparent Moho offset, however, has been called into question (Cazes and others, 1986). Wide-angle recordings across the Bray fault near the reflection line indicate a relatively continuous Moho reflection (Hirn and others, 1987), although the nature of many offsets of overlying crustal reflections is less clear from the auxiliary experiment. This apparent contradiction between the two techniques has yet to be unambiguously resolved.

If an apparent 1.0 sec of normal offset at depth is indeed real, it is much greater than any offsets in the overlying Mesozoic deposits. Therefore, the apparent offset of the lower crustal reflections may have resulted from strike-slip motion displacing an interface with a dip that is oblique to the strike of the fault plane. Unfortunately, a lack of three-dimensional control precludes further analysis of such a possibility. Regardless, this observation suggests that pre-Mesozoic deformation has been preserved and questions the relationship between extension and a reflective lower crust. The preservation of these offsets over such a long period has important implications for lower-crustal rheology with regard to creep processes (Meissner and Kusznir, 1986; Kusznir and Meissner, 1986).

In summary, the reflection profiles across the San Andreas, Great Glen, and Bray strike-slip fault zones have very similar characteristics: a steeply dipping, reflection-free zone cutting through the crust that separates distinctly different crustal blocks. All three fault zones have been interpreted as major transform faults, although only the San Andreas fault zone is presently active. Both the Great Glen and Bray fault zones were active strike-slip faults during the Paleozoic but may have been reactivated during more recent tectonism. Reactivation has perhaps helped to preserve their structural geometry against overprinting by younger tectonism.

GARLOCK FAULT

The Garlock fault zone is a 265-km-long, east- to northeast-trending, left-lateral, strike-slip fault zone in southern California (Fig. 2). It separates the northwest-trending, right-lateral, strike-slip faults in the Mojave block to the south from the north-south-trending structures in the Basin and Range and Sierra Nevada regions to the north. Although little is known about total displacement on the western segment (LaViolette and others,

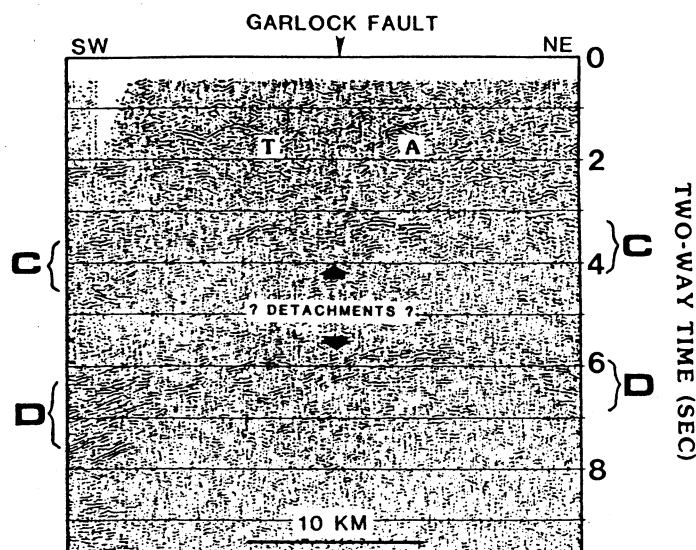


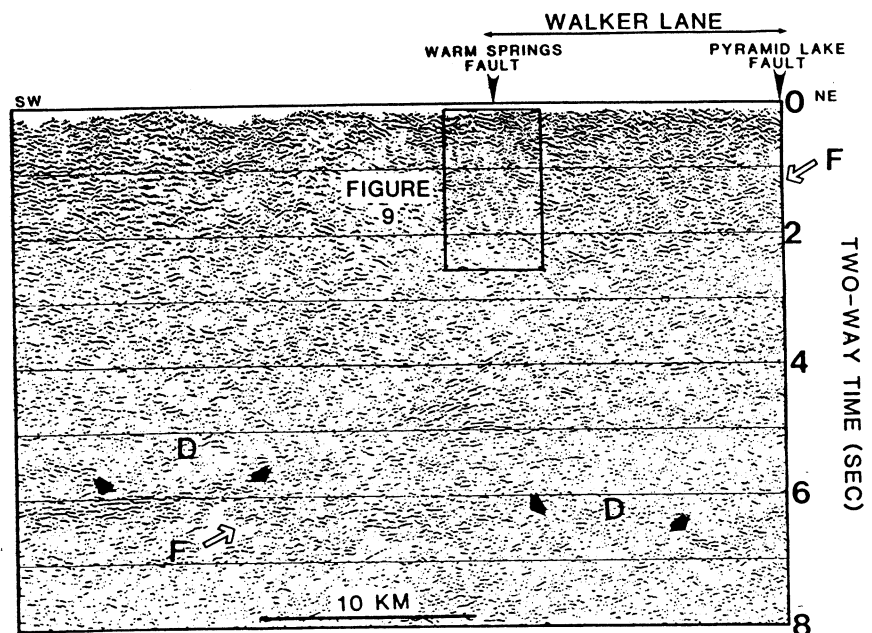
Figure 6. Unmigrated stacked section across the Garlock fault in the Mojave Desert. T = toward, A = away. See Figure 2 for location.

1980), early Tertiary activity along the eastern half of the fault is indicated by a dike swarm offset, in a left-lateral sense by as much as 64 km (Smith, 1962; Smith and Ketner, 1970). More recently, stratigraphic offsets identified by Carter (1982) led him to suggest that about 43 km of displacement has occurred along the eastern segment of the fault since the middle Pliocene. Recent seismicity and ground cracking are also associated with the Garlock fault zone (Zellmer and others, 1985; Astiz and Allen, 1983).

The eastern Garlock fault segment is generally a single fault trace consisting of both gouge and small slivers of rock. All evidence suggests that the near vertically dipping fault zone has predominantly left-lateral offsets with only minor amounts of dip-slip displacement (Dibblee, 1967, 1980). Earthquake focal mechanism studies indicate a near-vertical fault zone within the upper crust undergoing left-lateral movement (Astiz and Allen, 1983). Most earthquakes occur at ~7.5-km depth with a few estimated to be as deep as 15 km. Other than a few earthquake focal mechanism depths, little is known about the subsurface geometry of the fault zone.

A portion of the COCORP deep seismic reflection profile collected across the Garlock fault zone is shown in Figure 6. The profile crossed a single strand of the fault zone where it divides recent basin sediments from exposed Tertiary volcanic units. No fault plane reflections, diffractions, or terminated reflections are evident on the seismic section from 0.5 to 3.0 sec, so that the upper crustal geometry of the Garlock fault is unclear (Cheadle and others, 1986). A relatively continuous band of reflections at 3.3 sec travel time, however, is identifiable beneath the surface trace of the Garlock fault (C; Fig. 6). Beginning at ~8 km to the northeast of the fault, these events can be traced below the fault zone. Directly beneath the fault, however, the reflections appear to be slightly pulled down, which may be a low-velocity effect from the overlying low-density fault-zone gouge. Cheadle and others (1986) correlated these reflections over 100 km on the seismic section. They appear to have a general dip toward the southwest and exhibit a ramp and flat geometry down to ~7.0 sec (Cheadle and others, 1986). Below C, there is an arcuate band of reflections labeled D at ~6.0 sec, which also passes relatively undisturbed beneath the fault zone (Cheadle and others, 1986). These events are traceable from the northeast end of the seismic section ~45 km to the southwest where they merge into interpreted Moho reflections at about 9.8 sec (Cheadle and others, 1986).

Figure 7. Unmigrated stacked section across the northern Walker Lane and location map for the COCORP survey. WSF = Warm Springs fault, PLF = Pyramid Lake fault, WSV = Warm Springs Valley. Dotted pattern outlines ranges.

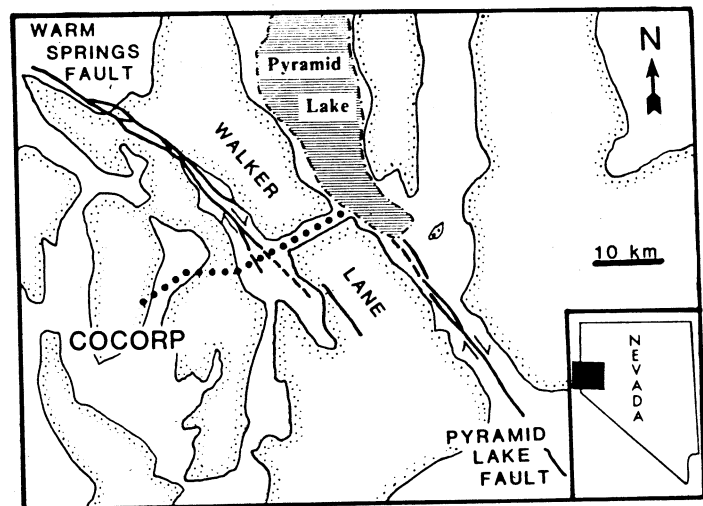


Although neither C nor D can be explicitly related to surface features, they clearly limit the depth to which the Garlock fault can extend. As argued by Cheadle and others (1986), left-lateral displacement along the Garlock fault will create an apparent vertical offset on any dipping plane which it cuts, if that plane has a strike which is not parallel to the strike of the fault. The three-dimensional geometries of reflection bands C and D determined from crossing COCORP California Lines 3 and 5 indicate that the Garlock fault would obliquely cut the dipping features represented by these reflections. Although the age and origin of these features are not known, a pre-Pliocene age seems reasonable considering both the Mesozoic compressional and Cenozoic extensional tectonic history of the region (Burchfiel and Davis, 1981). Therefore, analysis shows that even in the absence of a dip-slip component the 43 km of post-Pliocene, left-lateral displacement on the Garlock fault should yield a 2.0-sec apparent vertical offset on band C and 3.0- to 4.0-sec apparent vertical offset on band D. Yet, no such large vertical offsets are observed on these reflection sequences (Fig. 6). This implies that the Garlock fault does not offset them and must be a relatively shallow feature confined to the upper 9 km of the crust (Cheadle and others, 1986). If these reflection sequences are imaging detachments, then this would support the conjecture that strike-slip displacement can be limited to the upper crust by deeper detachments (Nicholson, 1986).

NORTHERN WALKER LANE

The Walker Lane (Fig. 7) is a northwest-trending system of right-lateral, strike-slip faults located in western Nevada and eastern California (Locke and others, 1940). In southwestern Nevada, there is evidence for up to 190 km of right-lateral displacement since the late Miocene (Stewart and others, 1968). The Walker Lane can be divided into three main segments based upon the distribution of surface faults, with the northernmost segment comprising the Pyramid Lake and Warm Springs fault zones (Bell, 1984). This segment of the Walker Lane is considered the transition zone between the Sierra Nevada province to the west and the Basin and Range province to the east. Recent seismicity and landforms along the faults indicate that both right-lateral, strike-slip faulting and normal faulting are taking place contemporaneously (Bell, 1984; Bonham, 1969).

The COCORP profile crosses the northern Walker Lane in the vicin-



ity of a left step from the Pyramid Lake fault to the Warm Springs fault (Fig. 7; Knuepfer and others, 1987). Exposures in the region consist of Cretaceous granitoids of the Sierran Arc overlain by Tertiary volcanics related to Basin and Range extension (Bonham, 1969). As a result of the complex volcanic stratigraphy, precise estimates of right-lateral and normal displacements in this divergent strike-slip fault setting are lacking (Bonham, 1969). Some workers, however, have estimated right-lateral displacements between 16 and 32 km within the whole northern Walker Lane segment (Bonham, 1969; Bell, 1984). Basin-bounding normal faults have vertical offsets averaging 1 km (Bonham, 1969).

Two prominent reflection sequences are evident on the COCORP profile (Fig. 7; Knuepfer and others, 1987). The first is a semi-continuous band of southwest-dipping reflections extending from 1.5 to 6.5 sec two-way time (F). These reflections are most continuous from 3.5 to 5.5 sec beneath the Warm Springs fault. The crooked aspect of the seismic line provided control for the three-dimensional geometry of F, yielding a true strike and dip of N40°W 45°SW. At approximately 6.0 sec, the F events intersect with a prominent band of subhorizontal reflections, D, which is correlative across much of the profile (Knuepfer and others, 1987).

Toward the northeast, these D reflections appear to cap the reflective lower crust of the Basin and Range province (Knuepfer and others, 1987). Migrated stacks confirm that F does not cut across D. The surface projection of F is less certain because of poor data quality at two-way times of less than 1.0 sec. These reflections could project to the surface trace of the Pyramid Lake fault or perhaps to a fault hidden beneath Pyramid Lake. Knuepfer and others (1987) have suggested that both strike-slip and normal displacement are being accommodated by a southwest-dipping master fault (F) which merges into a subhorizontal detachment zone (D) at 18- to 22-km depth.

The seismic section also constrains the upper crustal geometry of the Warm Springs fault (Knuepfer and others, 1987). Although no fault-plane reflections are apparent on the seismic profile (Fig. 8), near-vertical faults are suggested by the termination of subhorizontal basin reflections (T) and diffractions (D). In addition, shot-point gathers pinpoint these two covered fault traces within Warm Springs Valley (Fig. 9): a change in refraction velocity, a slight offset of refraction arrivals, as well as a reversed moved-out reflection are all associated with the mapped faults. These faults cannot be traced deeper than about 1.0 sec. A pair of 45° east-dipping reflections (B₁ and B₂) project to the fault bounding the west side of the basin,

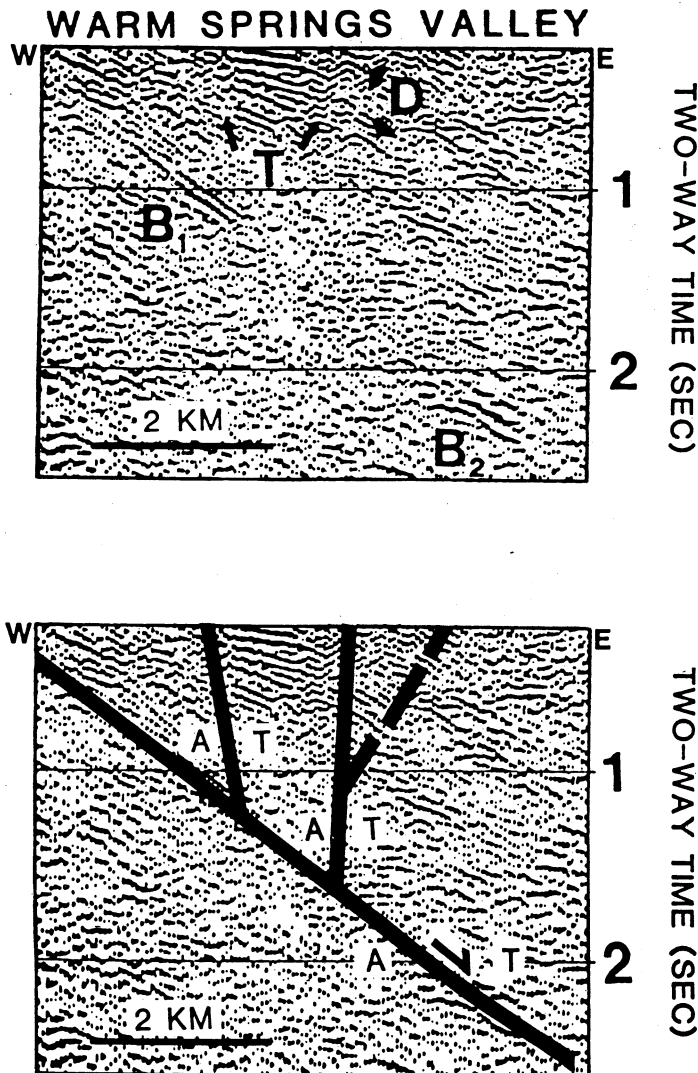


Figure 8. Unmigrated stacked section and interpreted stacked section across the Warm Springs Valley fault. Displayed at 1:1 at 4 km/sec. T = toward, A = away. See Figure 2 for location.

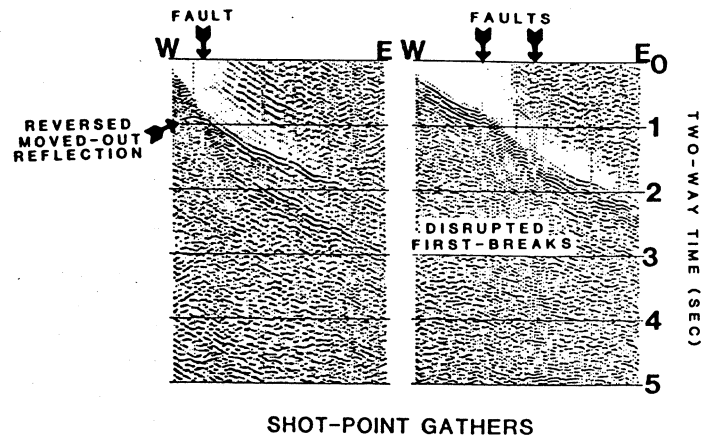


Figure 9. Shot-point gathers from Warm Springs Valley showing features indicative of surface faulting.

however, (Fig. 8; Knuepfer and others, 1987). Although the relationship is not clear, these eastward-dipping reflections appear to merge with the more prominent reflection band F at ~2.3 sec. It is not known whether the lack of continuity of events B₁ and B₂ beneath the Warm Springs fault is a result of the near-vertical faults cutting through this region, or a result of signal disruption due to the increased structural complexity as the near-vertical faults merge into the east-dipping fault. Assuming the latter case, the interpreted seismic section (Fig. 8) depicts a new flower structure variety comprised of a set of steeply dipping strike-slip faults soling into a moderately east-dipping fault undergoing divergent strike-slip motion.

WICHITA FAULT SYSTEM

The northwest-trending frontal fault zone of the Wichita Mountains is the central part of a 500-km-long fault system that extends from the Arbuckle Mountains in southern Oklahoma to the Amarillo Uplift in the Texas panhandle (Ham and others, 1964). Both strike-slip and reverse faulting occurred along this fault system during the late Paleozoic Ouachita orogeny (Wielchowsky and Gilbert, 1982). Stratigraphic markers in the Arbuckle Mountains indicate as much as 100 km of cumulative left-lateral displacement across the entire fault zone (Tanner, 1967; Wickham, 1978; Wielchowsky and Gilbert, 1982). Using well logs, Budnick (1986) has also suggested as much as 120 km of left-lateral displacement along faults of the Amarillo Uplift. Although poor exposures preclude an estimate of displacement along the frontal faults of the Wichita Uplift, which is nested between the areas of these two estimates, structural analysis does indicate at least two periods of convergent strike-slip faulting (Donovan, 1985). It therefore appears that the frontal faults of the Wichita Uplift may also have up to 100 km of left-lateral displacement.

The Meers fault and Mountain View fault are the two main structures of the northern frontal fault system of the Wichita Uplift (Fig. 10, Ham and others, 1964). At the surface, the Meers fault dips steeply to the southwest and juxtaposes the Cambrian igneous complex of the Wichita block against the highly deformed Anadarko basin deposits. Estimates of vertical offsets along the Meers fault range from 5 to 8 km (Donovan, 1985; Ham and others, 1964), based upon stratigraphic and structural analyses in the region, to 10 to 15 km (Brewer and others, 1983), determined from COCORP seismic reflection data. The Mountain View fault deforms the Precambrian to Early Permian stratigraphy of the Anadarko basin by thrusting and folding (Harlton, 1972). The deformed basin deposits are overlain by flat-lying, post-orogenic, Permian strata which are now being eroded to expose the late Paleozoic topography. A pronounced fault-line scarp associated with the Meers fault has renewed interest in

possible recent activity (Tilford and Westen, 1985; Ramelli and Slemmons, 1985). The fault, however, appears to be seismically quiescent (Lawson, 1985).

The northern half of COCORP's Oklahoma Line 2/2A crosses this convergent strike-slip fault zone (Fig. 10). The most prominent reflections on the seismic section dip south between two-way times of 2.0 to 5.5 sec (F). These events project to the subsurface position of the Mountain View fault and are considered fault-plane reflections from this structure (Brewer and others, 1983). A true dip of 30° to 40° southwest was determined based on the surface trend of the fault zone and apparent dip from the seismic section using the techniques of De Voogd and others (1986). These F reflections are not traceable past 5.5 sec, and so their lower crustal geometry is uncertain.

Reprocessing of the seismic section has been unsuccessful in obtaining any reflections that can be correlated with the Meers fault (J. Huang, 1986, personal commun.). The geometry of the Meers fault in the upper crust, however, is suggested by the termination of short discontinuous reflections and a diffraction (Fig. 10). For example, an arcuate band of reflections (D) between two-way times of 2.6 and 3.5 sec is a diffraction perhaps originating off a truncated feature along the Meers fault at depth. A pair of discontinuous reflections at a two-way time of 2.5 and 3.0 sec, interpreted as complexly deformed Anadarko basin deposits (Brewer and others, 1983), terminate below the surface trace of the Meers fault (T; Fig. 10). Such terminations can be used to trace the approximate position of the Meers fault at depth. Migration tends to collapse the diffraction and shift the truncated reflections in such a way as to imply an apparent dip of at least 70° S for the Meers fault between 0.5 and 3.0 sec (Fig. 10). The data, however, do permit the possibility of much steeper dips.

The lack of reflected energy later than 4.5 sec obscures the relationship between the Meers fault and Mountain View fault in the middle crust, but extrapolating both faults downward at constant dip leads to their intersection at ~ 15 km (Fig. 10). Unfortunately, deeper crustal structure cannot be deciphered due to the general lack of reflections recorded throughout the Wichita block, which may suggest either a signal penetration problem or a nonreflective igneous complex. The reprocessed section, however, does suggest that the convergent strike-slip offsets along the frontal fault zone of the Wichita Uplift occurred along moderately to steeply dipping faults in the upper crust.

DISCUSSION

Strike-slip faults have been identified in a wide range of tectonic provinces. Analysis of the present plate framework suggests that strike-slip tectonics is an important component of more than half of plate-boundary-related orogens (Woodcock, 1986). Deep seismic reflection profiling across strike-slip fault zones has produced mixed results in portraying their deep crustal geometry. Although imaging difficulties must be considered, some strike-slip fault zones appear to be near vertical and penetrate deeply into, if not completely through, the crust, whereas others are confined to the upper crust above detachment horizons (Fig. 11). The San Andreas, Great Glen, and Bray fault zones are all examples of the former. It is perhaps significant that each has been a part of a major transform system, the San Andreas being presently active.

Continental transform fault systems can dominate the development of structures over a wide region. If energy penetration is not a problem, then the absence of Moho reflections beneath the transform faults examined indicates that the faults are also significant crustal structures at depth. Although the deformation mechanisms may change with depth from a brittle to quasi-plastic response, the fault zones appear to be relatively continuous, throughgoing features. Their near-vertical crustal geometry suggests that a significant amount of coupling occurs along the fault zone between the brittle upper and ductile lower crustal regimes. Even given

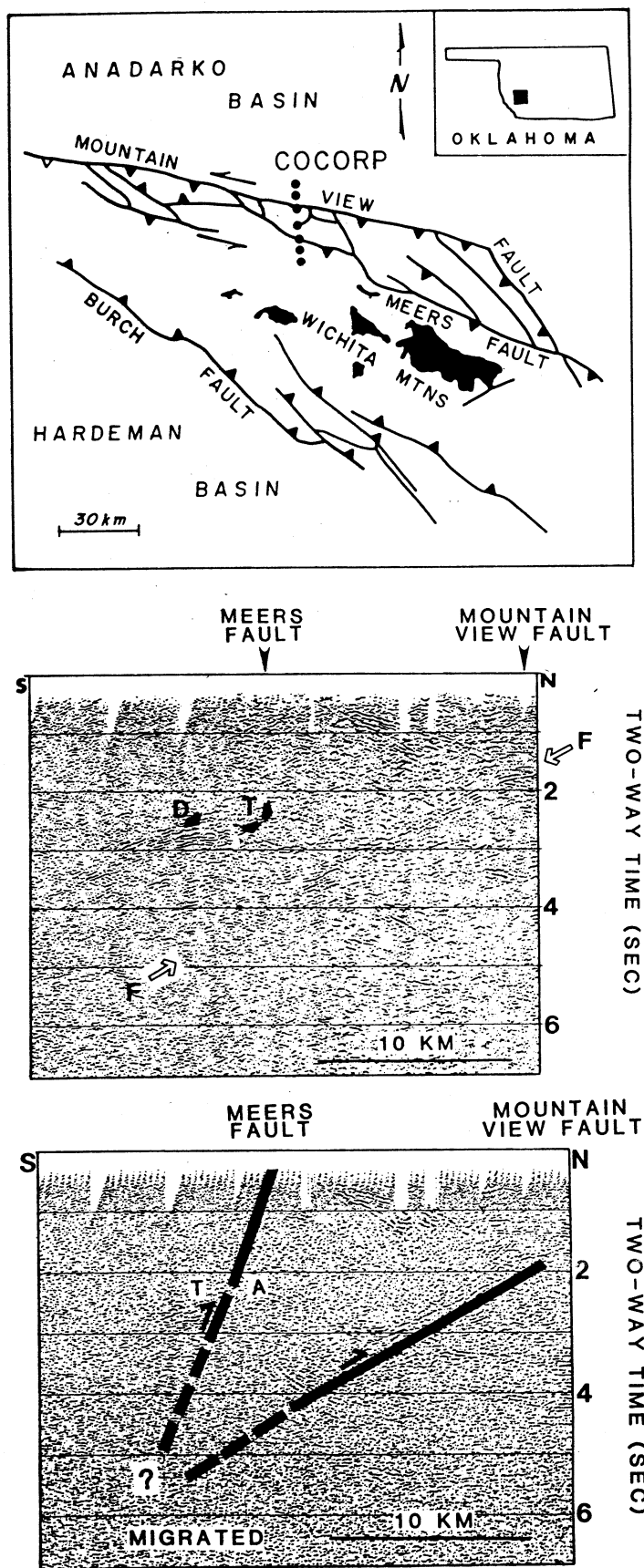


Figure 10. Location map with unmigrated and interpreted migrated stacked section across the frontal faults of the Wichita Uplift. T = toward, A = away.

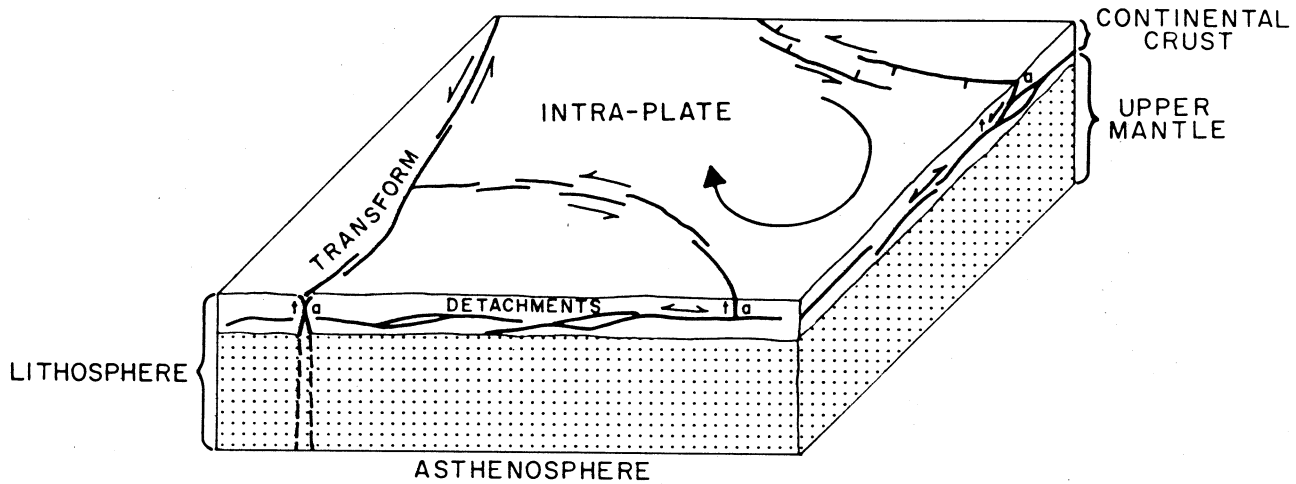


Figure 11. Schematic block diagram depicting the fundamental differences between the crustal structure of transform versus intraplate, strike-slip fault zones as observed on the deep seismic reflection profiles. T = toward, A = away.

their crustal reflection character, however, it is still unclear how transform faults continue through the lower continental lithosphere or how they merge into the asthenosphere (Zandt, 1981).

Another strike-slip fault exhibiting prominent Moho offsets is the North Pyrenean fault in southern France. Plate reconstructions treat the fault as Mesozoic transform between the European and Iberian plates with up to 400 km of left-lateral displacement (Choukroune and Mattauer, 1978). Although near-vertical reflection profiles across the Pyrenees are not yet available, wide-angle experiments recorded reflections from the base of the crust which suggest as much as 10 km of vertical offset beneath the surface fault trace (Daignieries and others, 1982). The data are consistent with a model of a near-vertical, crustal-penetrating, strike-slip fault juxtaposing crustal blocks of different thicknesses (Daignieries and others, 1982).

A continuing uncertainty is whether the vertical reflection-free zones on a seismic section are artifacts resulting from data acquisition, processing techniques, and/or the effects of near-surface geological complexity on deeper images. It can be argued that the blank zones beneath the transform faults are not artifacts because the acquisition and processing methods used were different in each survey and because they do not occur beneath every strike-slip fault studied. Furthermore, it is unsatisfactory to simply attribute these zones to surface geological effects, because the shallow geology varies so considerably among these examples, from the complex structure in the Salinian and Franciscan terranes in California, to the undeformed basin strata in France, and to the un lithified marine sediments in the west Scottish basins. To have similar results from such vastly different regions lends strong support to the interpretation that these blank zones are not completely artifacts. The general absence of reflections is quite consistent with expected complex deformation adjacent the fault zone as well as its steeply dipping attitude, which would tend to scatter reflected energy in various directions and thus reduce the effectiveness of the common-depth-point method. Nevertheless, blank zones on a seismic section need to be carefully analyzed with regard to acquisition techniques and local geology before attributing any geological significance to them (De Voogd and others, 1986).

In contrast to these deeply penetrating strike-slip fault zones are the intra-plate strike-slip faults which appear to be decoupled by mid-crustal detachments (Fig. 11). Reflection profiles across the Garlock fault and the northern Walker Lane, for example, suggest that these fault zones only displace shallow crustal blocks. Inferred detachment horizons in the middle crust confine the faulting to the upper crust. Considering the tectonic history of both regions, detachment horizons could have developed during either Mesozoic compressional or Cenozoic extensional tectonic events (Burchfiel and Davis, 1981; Oldow, 1984; Bonham, 1969). Low-angle crustal detachments related to extensional tectonics have been interpreted from reflection profiles throughout much of the Basin and Range region (Cheadle and others, 1986; Hauser and others, 1986; Okaya and Frost, 1986; Morris and others, 1986; Smith and Bruhn, 1984; Allmendinger and others, 1983; Hamilton, 1982). The high heat flow associated with regions of extension may contribute to the development of subhorizontal detachments. In addition, a reflection profile in the Vienna basin, Czechoslovakia, has similarly led Royden (1984) to suggest that both normal and strike-slip faults of the basin merge at depth into a gently southeast-dipping detachment horizon. The Brevard zone of the southern Appalachians may be a strike-slip fault detached and reactivated by thrusting (Edelman and others, 1987).

The hypothesis of mid-crustal detachments is not new in the southern California area, where motion along the San Andreas transform fault has produced a broad area of strike-slip faulting. Displacement along strike-slip fault systems is considered responsible for the rotation of adjacent crustal blocks (Ron and others, 1984; Garfunkel and Ron, 1985). Garfunkel (1974) presented a model for the late Cenozoic tectonic history of the Mojave Desert region that involved the counterclockwise rotation of major crustal blocks. Subsequently, paleomagnetic investigations throughout southern California have documented both clockwise and counterclockwise rotations (Luyendyk and others, 1980, 1985; Bogen and Seeber, 1986). Rotation of large crustal blocks implies the existence of a lower bounding detachment zone that would allow the blocks to rotate freely (Nicholson and others, 1986; Terres and Luyendyk, 1985). The COCORP reflection profiles within the Mojave Desert and Death Valley regions

suggest that these detachments occur within the upper and middle crust (Cheadle and others, 1986; L. Serpa and others, unpub. data).

By using earthquake arrival times, Nicholson and others (1986) have interpreted a low-velocity zone beneath the San Bernardino Mountains as a detachment horizon that allows the overlying crustal block to rotate due to strike-slip faulting. Focal mechanisms from the Eastern Transverse Ranges indicate a detachment between 13- and 15-km depth (Hadley and Kanamori, 1978; Webb and Kanamori, 1985). The lateral extent of this detachment horizon is poorly constrained, but it appears to terminate beneath the San Andreas fault (Webb and Kanamori, 1985). In addition, the upper boundary to the highly reflective lower crust in France and Britain has been interpreted as a crustal detachment zone (Matthews and Cheadle, 1986; Bois, 1986), yet it also appears to be truncated against the Great Glen and Bray transform fault zones. Although the detachments occur beneath intraplate strike-slip faults, they are truncated by transform faults. Continued analysis of the kinematic differences between these two classes of strike-slip faults may explain their different crustal behaviors (Freund, 1974).

The seismic sections across the divergent strike-slip fault zone of the northern Walker Lane and the convergent strike-slip fault zone of the Wichita Uplift frontal fault system both suggest that strike-slip faults with a relatively large component of dip-slip offset, at least at the surface, may dip moderately at depth (Fig. 11). In particular, the northern Walker Lane strike-slip fault system appears to merge at depth with a 45° southwest-dipping master fault that accommodates both strike-slip and dip-slip displacement. Earthquake focal mechanism studies from western Nevada indicate that both strike-slip and normal faulting is occurring throughout the upper crust (Vetter and Ryall, 1983; Vetter, 1984). The range of fault plane dips between 20° to 60° southwest determined from the earthquake data is consistent with the interpretation of the seismic reflection data from the northern Walker Lane, which suggests that divergent strike-slip displacement is occurring along a moderately dipping fault that extends to ~20 km depth.

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REFERENCES CITED

- Allmendinger, R. W., Sharp, J. W., Von Tish, D., Serpa, L., Brown, L., Kaufman, S., and Oliver, J., 1983, Cenozoic and Mesozoic structure of the eastern Basin and Range province, Utah, from COCORP seismic reflection data: *Geology*, v. 11, p. 532-536.
- Arthaud, F., and Matte, P., 1977, Late Paleozoic strike-slip faulting in southern Europe and northern Africa: Result of a right-lateral shear zone between the Appalachians and the Urals: *Geological Society of America Bulletin*, v. 88, p. 1305-1320.
- Astiz, L., and Allen, C. R., 1983, Seismicity of the Garlock fault, California: *Seismological Society of America Bulletin*, v. 73, p. 1721-1734.
- Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: *Geological Society of America Bulletin*, v. 81, p. 3513-3536.
- Badham, J.P.N., 1982, Strike-slip orogen—An explanation for Hercynides: *Geological Society of London Journal*, v. 139, p. 493-504.
- Badham, J.P.N., and Halls, C., 1975, Microplate tectonics, oblique collisions and the evolution of the Hercynian orogenic systems: *Geology*, v. 3, p. 373-376.
- Bamford, D., Nunn, K., Prodehl, C., and Jacob, B., 1978, LISPB IV crustal structure of northern Britain: *Royal Astronomical Society Geophysical Journal*, v. 52, p. 43-60.
- Bell, E. J., 1984, Overview of late Cenozoic tectonics of the Walker Lane, Guidebook for selected Nevada earthquake areas: *Geological Society of America Annual Meeting, Field Trip 18*, p. 407-413.
- Blundell, D. J., 1981, The nature of the continental crust beneath Britain, in Illing, L. V., and Hobson, G. D., eds., *Petroleum geology of the continental shelf of north-west Europe*: London, England, Heyden and Son, p. 58-64.
- Bogen, N. L., and Seeber, L., 1986, Neotectonics of rotating blocks within the San Jacinto fault zone, southern California [abs.]: *EOS (American Geophysical Union Transactions)*, v. 67, p. 1200.
- Bois, C., Cazes, M., Damotte, B., Galdeano, A., Hirn, A., Mascle, A., Matte, P., Raolt, J. F., and Torrelles, G., 1986, Deep seismic profiling of the crust in northern France: The ECORS project, in Barazangi, M., and Brown, L., eds., *Reflection seismology: The continental crust*: American Geophysical Union Geodynamic Series, Volume 14, p. 21-29.
- Bonham, H. F., 1969, *Geology and mineral deposits of Washoe and Storey Counties, Nevada*: Nevada Bureau of Mines and Geology Bulletin, v. 70, 140 p.
- Brewer, J. A., Good, R., Oliver, J. E., Brown, L. D., and Kaufman, S., 1983, COCORP profiling across the southern Oklahoma aulacogen: Overthrusting of the Wichita Mountains and compression within the Anadarko basin: *Geology*, v. 11, p. 109-114.
- Budnick, R. T., 1986, Left-lateral intraplate deformation along Amarillo-Wichita Uplift, Texas panhandle and Oklahoma [abs.]: *Oklahoma Geology Notes*, v. 46, p. 68.
- Burchfiel, B. C., and Davis, G. A., 1981, Mojave desert and environs, in Ernst, W. G., ed., *The geotectonic development of California*: Englewood Cliffs, New Jersey, Prentice-Hall, p. 218-252.
- Carter, B., 1982, Neogene displacement on the Garlock fault, California [abs.]: *EOS (American Geophysical Union Transactions)*, v. 63, p. 1124.
- Cazes, M., Mascle, A., Torrell, X., Bois, C., Damotte, X., Matte, P., Raolt, X., Pham, V. N., Hirn, A., and Galdeano, X., 1986, Large Variscan overthrusts beneath the Paris basin: *Nature*, v. 323, p. 144-147.
- Cheadle, M. J., Czuchra, B. L., Byrne, T., Ando, C. J., Oliver, J. E., Brown, L. D., Kaufman, S., Malin, P. E., and Phinney, R. A., 1986, The deep crustal structure of the Mojave desert, California, from COCORP seismic reflection data: *Tectonics*, v. 5, p. 293-320.
- Choukroune, P., and Mattauer, M., 1978, Tectonique des plaques et Pyrenees: sur le fonctionnement de la faille transformante nord-Pyreneenne; comparaisons avec des modeles actuels: *Geologic Society of France Bulletin*, v. 20, p. 689-700.
- Crowell, J. C., 1962, Displacement along the San Andreas fault, California: *Geological Society of America Special Paper* 71, 57 p.
- Daignieres, M., Gallart, J., Banda, E., and Hirn, A., 1982, Implications of the seismic structure for the orogenic evolution of the Pyrenean range: *Earth and Planetary Science Letters*, v. 57, p. 88-100.
- Debaglia, N., and Weber, C., 1985, Geologic mapping of the basement of the Paris basin (France) by gravity- and magnetic-data interpretation, in Hinze, W. J., ed., *The utility of regional gravity and magnetic anomaly maps*: Society of Exploration Geophysicists, p. 154-163.
- De Voogd, B., Brown, L., and Mery, C., 1986, Nature of the eastern boundary of the Rio Grande Rift from COCORP surveys in the Albuquerque Basin, New Mexico: *Journal of Geophysical Research*, v. 91, p. 6305-6320.
- Dewey, J. F., 1982, Plate tectonics and the evolution of the British Isles: *Journal of the Geological Society of London*, v. 138, p. 371-412.
- Dibblee, T. W., Jr., 1967, *Areal geology of the western Mojave desert, California*: U.S. Geological Survey Professional Paper 522, 153 p.
- , 1980, Geologic structure of the Mojave desert, in Fife, D. L., and Brown, A. R., eds., *Geology and mineral wealth of the California Desert*: Santa Ana, California, South Coast Geological Society Guidebook, p. 69-100.
- Donovan, R. N., 1985, The Meers fault as a hinge to the Wichita frontal fault zone [abs.]: *Earthquake Notes*, v. 55, p. 1.
- Eaton, J. P., O'Neill, M. E., and Murdock, J. N., 1970, Aftershocks of the 1966 Parkfield-Chalome, California, earthquake: A detailed study: *Seismological Society of America Bulletin*, v. 60, p. 1151-1197.
- Edelman, S. H., Liu, A., and Hatcher, R. D., Jr., 1987, The Brevard in South Carolina and adjacent areas: An Alleghanian orogen-scale dextral shear zone reactivated as a thrust fault: *Journal of Geology*, v. 95, p. 793-806.
- Feng, R., and McEvilly, T. V., 1983, Interpretation of seismic reflection profiling data for the structure of the San Andreas fault zone: *Seismological Society of America Bulletin*, v. 73, p. 1701-1720.
- Freund, R., 1974, Kinematics of transform and transcurent faults: *Tectonophysics*, v. 21, p. 93-134.
- Garfunkel, Z., 1974, Model for the late Cenozoic tectonic history of the Mojave desert, California, and for its relation to adjacent regions: *Geological Society of America Bulletin*, v. 85, p. 1931-1944.
- Garfunkel, Z., and Ron, H., 1985, Block rotation and deformation by strike-slip faults 2. The properties of a type of macroscopic discontinuous deformation: *Journal of Geophysical Research*, v. 90, p. 8589-8602.
- Garson, M. S., and Plant, J., 1972, Possible dextral movements on the Great Glen and Minch faults, Scotland: *Nature*, v. 240, p. 31-32.
- Hadley, D., and Kanamori, H., 1978, Recent seismicity in the San Fernando region and tectonics in the west-central Transverse Ranges, California: *Seismological Society of America Bulletin*, v. 68, p. 1449-1457.
- Hall, J., Brewer, J. A., Matthews, D. H., and Warner, M. R., 1984, Crustal structure across the Caledonides from the 'WINCH' seismic reflection profile: Influences on the evolution of the Midland Valley of Scotland: *Royal Society of Edinburgh Transactions*, v. 75, p. 97-109.
- Ham, W. E., Denison, R. E., and Merritt, C. A., 1964, Basement rocks and structural evolution of southern Oklahoma: *Oklahoma Geological Survey Bulletin* 95, 302 p.
- Hamilton, W., 1982, Structural evolution of the Big Maria mountains, northeastern Riverside county, southeastern California, in Frost, E. G., and Martin, D. L., eds., *Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada*: San Diego, California, Cordilleran Publishers, p. 1-27.
- Harding, T. P., 1983, Divergent wrench fault and negative flower structure, Andaman Sea, in Seismic expression of structural styles—A picture and work atlas: *American Association of Petroleum Geologists Studies in Geology* 15, v. 3, p. 4.2-1-4.2-8.
- , 1985, Seismic characteristics and identification of negative flower structures, positive flower structures, and positive structural inversion: *American Association of Petroleum Geologists Bulletin*, v. 69, p. 582-600.
- Harding, T. P., and Lowell, J. D., 1979, Structural styles, their plate tectonic habitats, and hydrocarbon traps in petroleum provinces: *American Association of Petroleum Geologists Bulletin*, v. 63, p. 1016-1058.
- Harding, T. P., Gregory, R. F., and Stephens, L. H., 1983, Convergent wrench fault and positive flower structure, Ardmore basin, Oklahoma, in Seismic expression of structural styles—A picture and work atlas: *American Association of Petroleum Geologists Studies in Geology* 15, v. 3, p. 4.2-13-4.2-17.
- Hartlon, B. H., 1972, Faulted fold belts of southern Anadarko basin adjacent to frontal Wichitas: *American Association of Petroleum Geologists Bulletin*, v. 56, p. 1544-1551.
- Hauser, E. C., Barnes, A., Gephart, J., Latham, T., Lundy, J., Brown, L., and Oliver, J., 1986, COCORP deep reflection transect in Arizona: Across the transition zone from Colorado plateau to core complexes [abs.]: *EOS (American Geophysical Union Transactions)*, v. 67, p. 1096.
- Healy, J. H., 1963, Crustal structures along the coast of California from seismic-refraction measurements: *Journal of Geophysical Research*, v. 68, p. 5777-5787.
- Hirn, A., Damotte, B., Torrelles, G., and ECORS Scientific Party, 1987, Crustal reflection seismics: The contributions of oblique, low frequency and shear wave illuminations: *Royal Astronomical Society Geophysical Journal*, v. 89, p. 287-296.
- Holgate, N., 1969, Paleozoic and Tertiary transcurent movements on the Great Glen fault: *Scottish Journal of Geology*, v. 5, p. 97-139.
- Kennedy, W. Q., 1946, The Great Glen fault: *Geological Society of London Quarterly Journal*, v. 102, p. 41-72.
- Knaeuper, P. L., Lemiszki, P. J., Hauge, T. A., Brown, L. D., Kaufman, S., and Oliver, J. E., 1987, Crustal structure of the Basin and Range-Sierra Nevada transition from COCORP deep seismic reflection profiling: *Geological Society of America Bulletin*, v. 98, p. 488-496.
- Kuszmir, N. J., and Meissner, R., 1986, Moho topography decay and its isostatic consequences [abs.]: *Terra Cognita*, v. 6, p. 343.
- LaViolette, J. W., Christenson, G. E., and Stepp, J. C., 1980, Quaternary displacement on the western Garlock fault, southern California, in Fife, D. L., and Brown, A. R., eds., *Geology and mineral wealth of the California Desert*: Santa Ana, California, South Coast Geological Society Guidebook, p. 449-456.
- Lawson, J. E., Jr., 1985, Seismicity at the Meers fault [abs.]: *Earthquake Notes*, v. 55, p. 2.

- Locke, A., Billingsley, P. R., and Mayo, E. B., 1940, Sierra Nevada tectonic patterns: *Geological Society of America Bulletin*, v. 51, p. 513-540.
- Luyendyk, B. P., Kamerling, M. J., and Terres, R. R., 1980, Geometric model for Neogene crustal rotations in southern California: *Geological Society of America Bulletin*, v. 91, p. 211-217.
- Luyendyk, B. P., Kamerling, M. J., Terres, R. R., and Hornfau, J. S., 1985, Simple shear of southern California during Neogene time suggested by paleomagnetic declinations: *Journal of Geophysical Research*, v. 90, p. 12,454-12,466.
- Lynn, H. B., and Deregowski, S., 1981, Dip limitations on migrated section as a function of line length recording time: *Geophysics*, v. 46, p. 1392-1397.
- Matthews, D. H., and Cheddie, M. J., 1986, Deep reflections from the Caledonides and Variscides west of Britain and comparison with the Himalayas, in Barazangi, M., and Brown, L., eds., *Reflection seismology: The continental crust*: American Geophysical Union Geodynamic Series, Volume 14, p. 5-19.
- Matthews, S. C., 1984, Northern margins of the Variscides in the North Atlantic region: Comments on the tectonic context of the problem, in Hutton, D. W., and Sanderson, D. J., eds., *Variscan tectonics of the North Atlantic region*: Geological Society of London Special Publication 14, p. 71-85.
- Matthews, V., III, 1976, Correlation of Pinnacles and Neenach volcanic formations and their bearing on San Andreas fault problem: *American Association of Petroleum Geologists Bulletin*, v. 60, p. 128-141.
- McBride, J. H., and Brown, L. D., 1986, Reanalysis of the COCORP deep seismic reflection profile across the San Andreas fault, Parkfield, California: *Seismological Society of America Bulletin*, v. 76, p. 1668-1686.
- McGeary, S., and BIRPS Group, 1986, Profiling a major continental strike-slip fault: The SHET survey [abs.]: Second International Symposium on Deep Seismic Reflection Profiling of the Continental Lithosphere, p. 13.
- McNally, K. C., and McEvilly, T. V., 1977, Velocity contrast across the San Andreas fault in central California: Small-scale variation from P-wave modal plane distortion: *Seismological Society of America Bulletin*, v. 67, p. 1565-1576.
- McQuillin, R., Donato, J. A., and Tulstrup, J., 1982, Development of basins in the Inner Moray Firth and the North Sea by crustal extension and dextral displacement of the Great Glen fault: *Earth and Planetary Science Letters*, v. 60, p. 127-139.
- Meissner, R., and Kuszniir, N. J., 1986, Continental crustal rheology and the reflectivity of the lower crust [abs.]: *Terra Cognita*, v. 6, p. 347.
- Morris, R. S., Okaya, D. A., and Frost, E. G., 1986, Multiple deformational events evident in the regional crustal structure of southeast California from industry seismic profiles [abs.]: EOS (American Geophysical Union Transactions), v. 67, p. 1109.
- Mykura, W., 1975, Possible large scale sinistral displacement along the Great Glen fault in Scotland: *Geological Magazine*, v. 112, p. 91-93.
- Naylor, D., and Shannon, P., 1982, *Geology of offshore Ireland and West Britain*: London, England, Graham and Trotman, 161 p.
- Nicholson, C., 1986, Seismic evidence for conjugate slip and block rotation within the San Andreas fault system, southern California: *Tectonics*, v. 5, p. 629-648.
- Nicholson, C., Seeber, L., Williams, P., and Sykes, L. R., 1986, Seismicity and fault kinematics through the eastern Transverse Ranges, California: Block rotation, strike-slip faulting and low-angle thrusts: *Journal of Geophysical Research*, v. 91, p. 4891-4908.
- Okaya, D. A., and Frost, E. G., 1986, Regional tectonic implications of the CALCRUST seismic profiling southwest of the Whipple mountains, southeast California [abs.]: EOS (American Geophysical Union Transactions), v. 67, p. 1109.
- Powell, C.M.R., and Sinha, M. C., 1986, The PUMA seismic experiment west of Lewis, U.K. [abs.]: *Terra Cognita*, v. 6, p. 344.
- Ramelli, A. R., and Slemmons, D. B., 1985, Surface offsets and scarp morphology, Meers fault, Oklahoma [abs.]: *Earthquake Notes*, v. 55, p. 1.
- Ron, H., Freund, R., and Garfunkel, Z., 1984, Block rotation by strike-slip faulting: structural and paleomagnetic evidence: *Journal of Geophysical Research*, v. 89, p. 6256-6270.
- Royden, L., 1984, Thin-skinned extension of Vienna basin [abs.]: *American Association of Petroleum Geologists Bulletin*, v. 68, p. 523.
- Sibson, R. H., 1983, Continental fault structure and the shallow earthquake source: *Geological Society of London Journal*, v. 140, p. 741-767.
- Smith, D. I., and Watson, J., 1983, Scale and timing of movements on the Great Glen fault, Scotland: *Geology*, v. 11, p. 523-526.
- Smith, G. I., 1962, Large lateral displacement on the Garlock fault, as measured from offset dike swarm: *American Association of Petroleum Geologists Bulletin*, v. 46, p. 85-104.
- Smith, G. I., and Kettner, K. B., 1970, Lateral displacement on the Garlock fault, southeastern California as suggested by offset section of similar metasedimentary rocks: U.S. Geological Survey Professional Paper 700-D, p. D1-D4.
- Smith, R. B., and Bruhn, R. L., 1984, Intraplate extensional tectonics of the eastern Basin-Range: Inferences on structural style from seismic reflection data, regional tectonics and thermal-mechanical models of brittle-ductile deformation: *Journal of Geophysical Research*, v. 89, p. 5733-5762.
- Soper, N. J., and Hutton, D.W.H., 1984, Late Caledonian sinistral displacements in Britain: Implications for a three plate collision model: *Tectonics*, v. 3, p. 781-794.
- Stewart, J. H., Albers, J. P., and Poole, F. G., 1968, Summary of regional evidence for right lateral displacement in the western Great Basin: *Geological Society of America Bulletin*, v. 79, p. 1407-1414.
- Stewart, S. W., 1968, Preliminary comparison of seismic travel times and inferred crustal structure adjacent to the San Andreas fault in the Diablo and Gabilan Ranges of central California: Stanford University Publications, *Geological Sciences*, v. 11, p. 218-230.
- Storevedt, K. M., 1974, A possible large-scale sinistral displacement along the Great Glen fault in Scotland: *Geological Magazine*, v. 111, p. 23-30.
- Sylvester, A. G., compiler, 1984, *Wrench fault tectonics*: American Association of Petroleum Geologists Reprint Series 28, 374 p.
- Tanner, J. H., III, 1967, Wrench fault movements along Washita Valley fault, Arbuckle Mountains area, Oklahoma: *American Association of Petroleum Geologists Bulletin*, v. 51, p. 126-141.
- Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A., 1978, *Applied geophysics*: New York, Cambridge University Press, 860 p.
- Terres, R. R., and Luyendyk, B. P., 1985, Neogene tectonic rotation of the San Gabriel region, California, suggested by paleomagnetic vectors: *Journal of Geophysical Research*, v. 90, p. 12,467-12,484.
- Tilford, N. R., and Weston, D. P., 1985, Morphological evidence for recent multiple surface ruptures along the Meers fault, southwestern Oklahoma [abs.]: *Earthquake Notes*, v. 55, p. 1.
- Van der Voo, R., and Scotese, C., 1981, Paleomagnetic evidence for a large (2000 km) sinistral offset along the Great Glen fault during Carboniferous time: *Geology*, v. 9, p. 583-589.
- Vetter, U. R., 1984, Focal mechanisms and crustal stress patterns in western Nevada and eastern California: *Annals Geophysica*, v. 2, p. 699-710.
- Vetter, U. R., and Ryall, A. S., 1983, Systematic change of focal mechanisms with depth in the western Great Basin: *Journal of Geophysical Research*, v. 88, p. 8237-8250.
- Walter, A. W., and Mooney, W. D., 1982, Crustal structure of the Diablo and Gabilan Ranges, central California: A reinterpretation of existing data: *Seismological Society of America Bulletin*, v. 72, p. 1567-1590.
- Wang, C., 1984, On the constitution of the San Andreas fault zone in central California: *Journal of Geophysical Research*, v. 89, p. 5858-5866.
- Warner, M., and Paddy, C., 1986, Is lower crustal reflectivity related to extension? [abs.]: *Terra Cognita*, v. 6, p. 347.
- Warren, D. H., and Healy, J. H., 1973, Structure of the crust in the conterminous United States: *Tectonophysics*, v. 20, p. 203-213.
- Webb, T. H., and Kanamori, H., 1985, Earthquake focal mechanisms in the eastern Transverse Ranges and San Emigdio Mountains, southern California and evidence for a regional decollement: *Seismological Society of America Bulletin*, v. 75, p. 737-757.
- Wickham, J. S., 1978, The southern Oklahoma aulacogen, in Wickham, J. S., and Denison, R. E., eds., *Structural style of the Arbuckle region*: University of Oklahoma Guidebook for Geological Society of America South-Central Section Annual Meeting, Field Trip 3, p. 9-41.
- Wielchowsky, C. C., and Gilbert, O. E., 1982, Style, timing and mechanism of basement-involved versus detached Paleozoic deformation southeastern Oklahoma and northern Texas [abs.]: *Geological Society of America Abstracts with Programs*, v. 14, p. 140.
- Winchester, J. A., 1974, Great Glen Fault—Reply (to K. M. Storevedt): *Nature*, v. 249, p. 777.
- Woodcock, N. H., 1986, The role of strike-slip fault systems at plate boundaries: *Royal Society of London Philosophical Transactions*, ser. A, v. 317, p. 13-27.
- Yeats, R. S., 1981, Quaternary flake tectonics of the California Transverse Ranges: *Geology*, v. 9, p. 16-20.
- Zandt, G., 1981, Seismic images of the deep structure of the San Andreas fault system, central Coast Ranges, California: *Journal of Geophysical Research*, v. 86, p. 5039-5052.
- Zellmer, J. T., Roquemore, G. R., and Blackerby, B. A., 1985, Modern tectonic cracking near the Garlock fault, California: *Geological Society of America Bulletin*, v. 96, p. 1037-1042.
- Ziegler, P. A., 1982, *Geological atlas of western and central Europe*: New York, Elsevier, 130 p.

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