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ACTIVE TECTONIC DEFORMATION AT THE EASTERN MARGIN OF THE CALIFORNIA COAST RANGES RESULTS OF THE BASIX AND CALCRUST PROGRAMS

By

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Abstract

Investigation of the neotectonics of the Sacramento Delta area along the eastern margin of the Coast Ranges has located several active near-surface compression-related structures along a 40 km long east-west transect: The Pittsburg/Kirby Hills fault (renamed from Kirby Hills or Montezuma fault), a portion of the Midland fault, and a splay of the Los Medanos thrust running beneath Ryer Island. Interpretation of crustal-scale geology is based on integration of multichannel marine seismic profile data, high-resolution shallow seismic profiles, velocity modeling from wide-angle refraction, (data generated from BASIX, Bay Area Seismic Imaging eXperiment); seismicity data from the Northern California Seismic Network, subsurface geologic data, and surface geology. Tectonic wedges beneath active reverse faults are moving relatively east over a crystalline basement on a mid-crustal decollement, at depths averaging about 15 km beneath the study area and shallowing to the east. Depth and location of earthquake hypocenters indicates additional deformation at 16 to 24 km depth, within the crystalline basement.

INTRODUCTION

Recognition that thrust-related earthquakes are an integral component of deformation within the predominantly strike-slip San Andreas fault system has sparked a search for potentially destructive thrust faults throughout the California Coast Ranges. The 1983 M_L 6.7 Coalinga, 1989 M_L 7.1 Loma Prieta, and 1994 M_L 6.7 Northridge earthquakes occurred on previously unknown compressive structures related in some way to displacement along the San Andreas fault system. One aim of the Bay Area Seismic Imaging eXperiment (BASIX) program was to locate and characterize active and potentially active buried thrust faults, thereby aiding assessment of seismic hazards as well as building an understanding of transpressional fault dynamics. BASIX was a project conducted by a consortium of research groups involving acquisition, processing and interpretation of seismic reflection and refraction data across the central California Coast Ranges using marine geophysical techniques along the course of the Sacramento River through San Francisco Bay and offshore. This paper presents an interpretation of crustal structure in the eastern Coast Ranges in the Sacramento River delta area (Fig. 1 & 2) as synthesized from BASIX and complementary geologic data (expanded from Karageorgi et al., 1992 and Band et al., 1993).

An unforeseen outgrowth of the investigation was recognition of very deep seismicity occurring beneath surface-mapped faults (25 km compared to an average 10 km in the Coast Ranges), in the basement. Realization that such deep deformation is occurring within the crystalline basement led geologists to reconsider the tectonic models applied to the Coast Ranges (Furlong et al., 1989; Jones et al., 1994).

Geologic Setting

The California Coast Ranges are an amalgam of accretionary prism material (Franciscan Assemblage) added to the western margin of North America during late Jurassic through early Tertiary subduction of the Farallon Plate. Adjacent to the Coast Ranges (Fig. 1) lies the Central Valley, an asymmetrical syncline comprised of Upper Jurassic and Cretaceous strata (known as the Great Valley Sequence) and Tertiary clastics originally deposited on a crystalline basement. Originally flat-lying Great Valley Sequence is now exposed in an east-dipping homocline along the eastern margin of the Coast Ranges as well as being folded and faulted into the Coast Ranges themselves. The nature of the structure responsible for the homocline is thought to be either an ancient subduction zone (Dickinson, 1981) or an east-moving tectonic wedge of Franciscan rocks (Wentworth et al., 1984; Jones et al., 1994).

Since the conversion of this margin to largely transform motion, beginning about 8 Ma (Atwater, 1970), strike-slip faults (Fig. 1) sliced through the Coast Ranges, cutting older faults and folds (Irwin, 1990). While right-lateral strike-slip is the dominant style of geodetically determined deformation, geologic evidence for young (≤3.5 Ma) deformation along the eastern margin of the Coast Ranges is compressive. Examples of young compressive deformation are the active folds at Coalinga Anticline (Wentworth et al., 1983; Wentworth and Zoback, 1989), Kettleman Hills (Bloch et al., 1993) and Rumsey Hills (Unruh and Moores, 1992). Additionally, tilted and offset Pleistocene and younger units are observed in outcrop (Harwood and Helley, 1987) and on seismic reflection profiles all along this margin. Occurrence of large earthquakes with no apparent surface rupture suggests seismogenic blind thrusting is taking place beneath the folds (Wong et al., 1988; Wong, 1992). Similar fault associations in New Zealand (Cashman et al., 1992) are interpreted as examples of strain partitioning of far-field stresses where weak strike-slip faults accommodate the shear component, and folds and thrusts accommodate the normal component of deformation in an area of oblique tectonic convergence. However, unlike New Zealand, the latest plate motion models based on geodetics show no active convergence between the plates across the boundary marked by the San Andreas fault system, (DeMets et al., 1990).

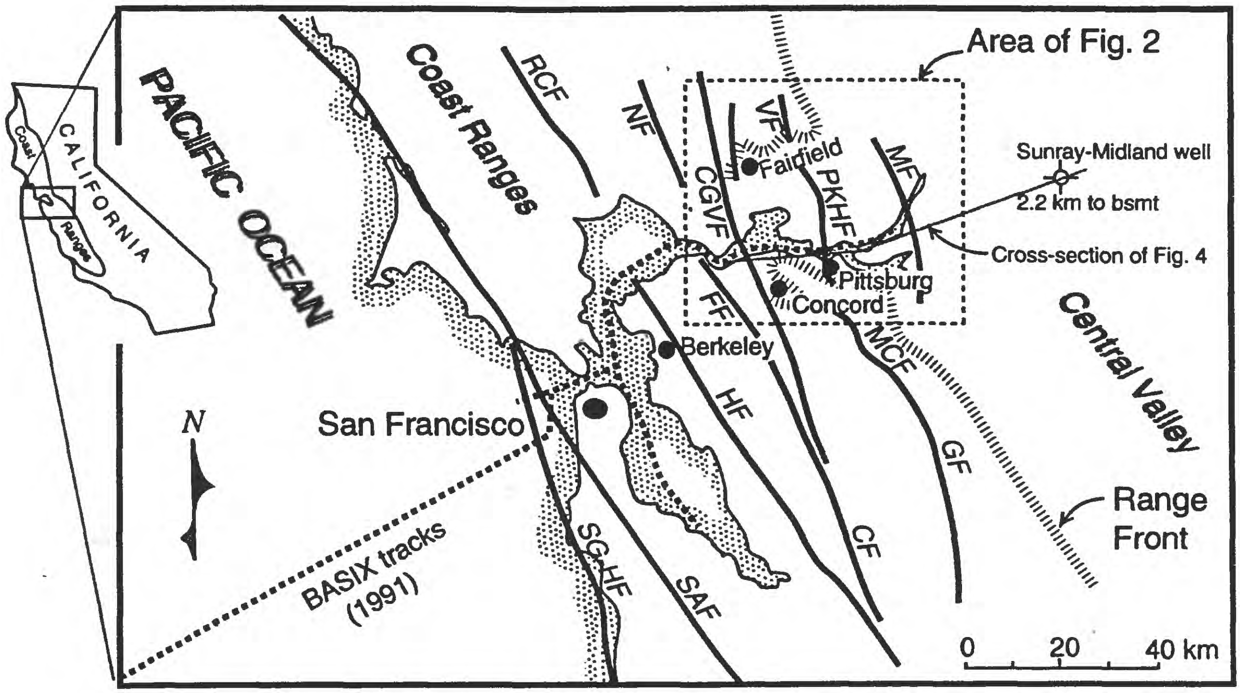


Figure 1: Regional map and study area showing BASIX cruise track and study area centered on the Sacramento Delta. Bold lines mark major faults: CGVF = Concord/Green Valley fault, VF = Vaca fault, SAF = San Andreas fault, HF = Hayward fault, CF = Calaveras fault, MCF = Marsh Creek fault, GF = Greenville fault, SG-HF = San Gregorio-Hosgri fault, PKHF = Pittsburg/Kirby Hills fault, MF = Midland fault. Note how the line marking the eastern topographic margin of the Coast Ranges "bays" in at the delta; the topography in this case in structurally controlled.

The BASIX Experiment

The BASIX program was prompted by the 1989 Loma Prieta earthquake to search for similar thrust-type structures associated with East Bay faults (Hayward, Calaveras & Greenville faults). The BASIX profiling cruise took place in 1991; details are described by McCarthy and Hart (1993). The specific objective was to image the entire crust to define the geometry of crustal-scale faults and their apparent relationship. Three complementary methods were used: Multichannel seismic profiling (McCarthy and Hart, 1993), wide-angle reflection/refraction profiling (Brocher and Moses, 1993; Brocher and Pope, 1994), and high-resolution seismic profiling (Anima and Williams, 1991; Anima et al., 1992). However, data quality of the multichannel seismic profile was compromised by noise and other problems associated with acquisition in a high-current channel setting (described by McCarthy and Hart, 1993). The multichannel profile, designed to reveal structure to 6-10 sec two-way travel time, recovered useful data to only about 4 sec twtt, and that only east of Suisun Bay (Figure 2). The multichannel data were processed at the U.S. Geological Survey (McCarthy and Hart, 1993) (Fig. 3).

The same source used for multichannel profile was recorded along a wide-spaced refraction array reaching from San Francisco to the Sierra Foothills on portable 3- and 5-component seismometers (described in Brocher and Moses, 1993). These data provide reliable velocity information to depths of about 5 km, deeper data are less well-defined. High-resolution reflection data (Anima and Williams, 1991) image strata to depths shallower than 200 m.

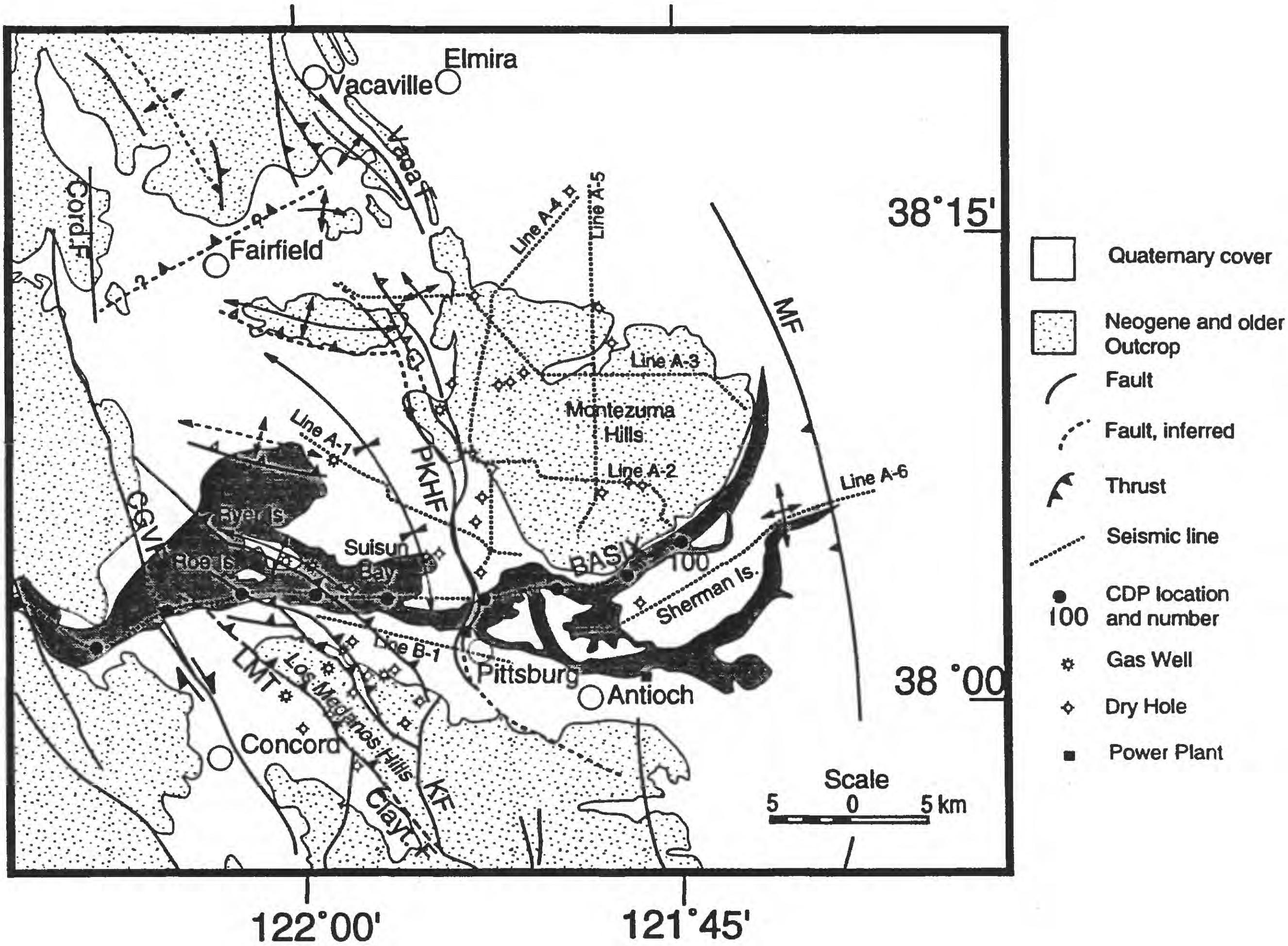


Figure 2: Sacramento Delta area location map showing seismic lines, some of the wells used for structural control, and major faults in the study area. Fault labels as for Fig. 1 with the following additional faults: Cord. F = Cordelia fault, KF = Kirker Pass fault, LMT = Los Medanos thrust. The Pittsburg/Kirby Hills fault is imaged on Lines B-1, BASIX, A-1 and A-3; partially on A-2. Only the BASIX reflection line in shown in this paper.

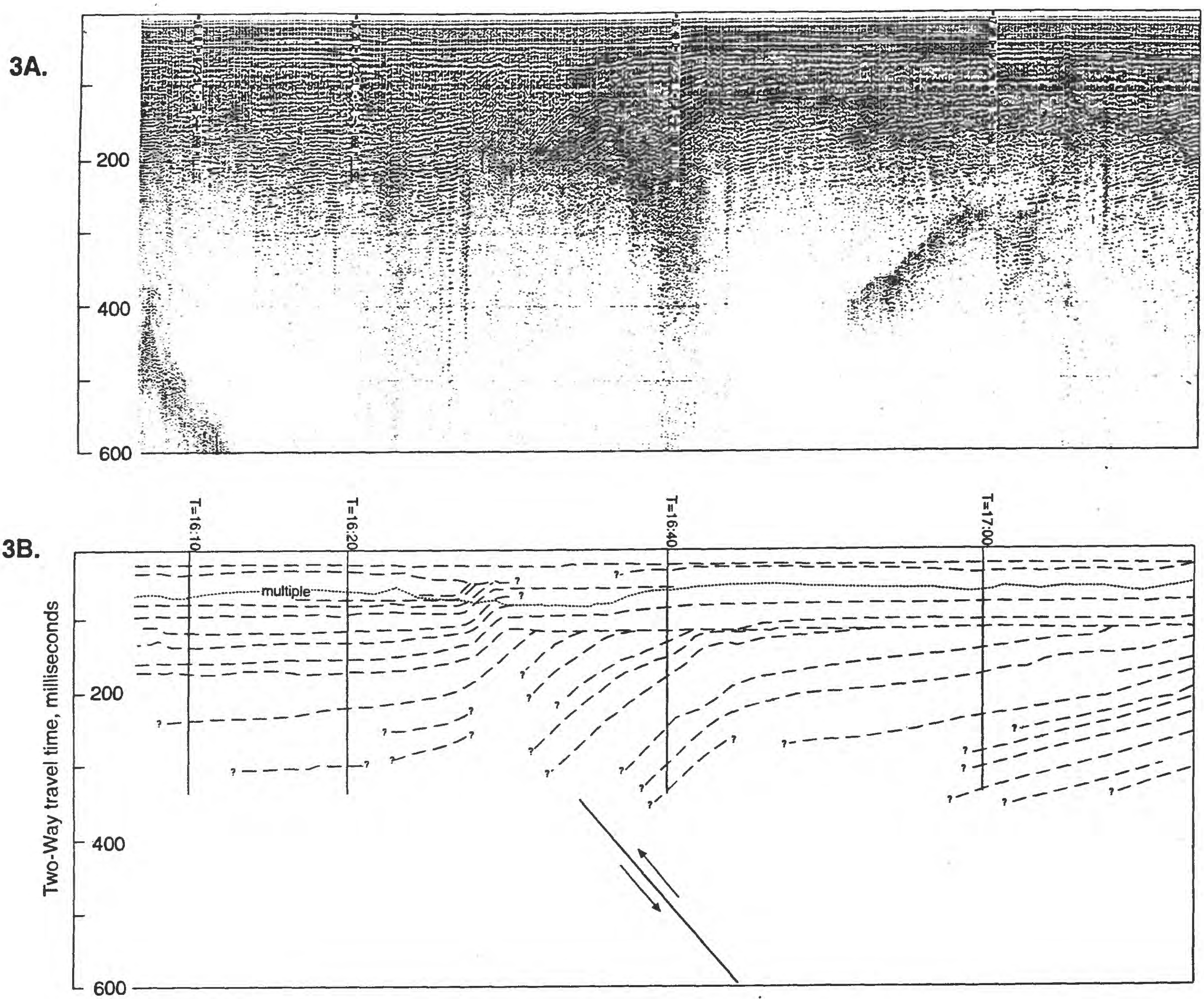
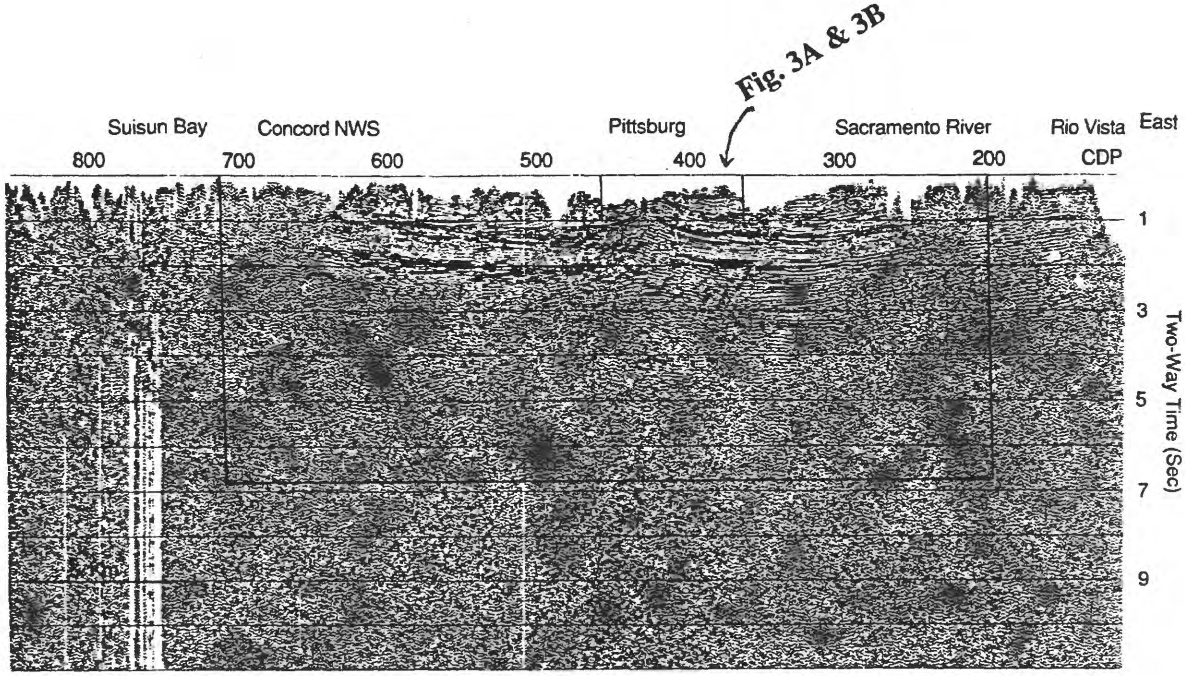


Figure 3: High-resolution profiling of Anima and Williams (1991) and BASIX line processed by McCarthy and Hart (1993). 3A: Uninterpreted version of high-resolution line centered on a folded, shallow unconformity over a west-dipping monocline. 3B: Line-drawing of reflection line with location of fault.

3C.



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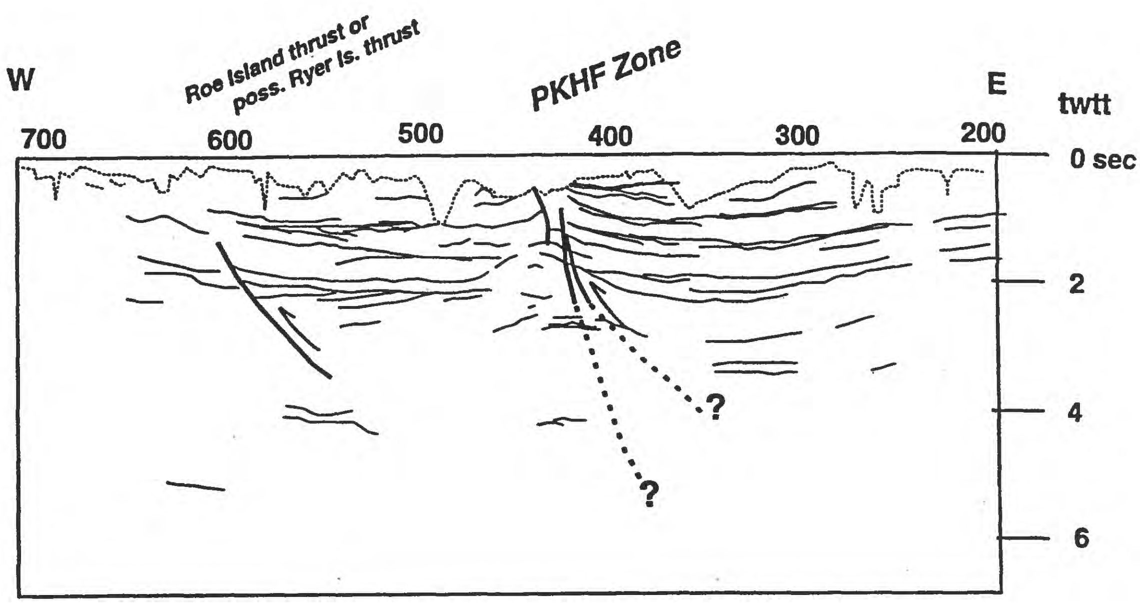

3C: Uninterpreted version of the BASIX multichannel reflection profile through the study area. The Pittsburg/Kirby Hills fault (PKHF) lies at about CDP 420. Small box shows the area of Fig. 3A & 3B where the high-resolution data overlap. Note loss of reflector coherency west of CDP 650; this is where the steeply dipping beds strike nearly parallel to the BASIX track. 3D: Line-drawing of 3C with two possible interpretation of fault location shown.

Method of Present Study

The Sacramento Delta is a region of active petroleum exploration and production. Numerous wells provide excellent subsurface geologic information to a few km depth. Local stratigraphy and history of movement of the main faults within the study area are thoroughly reviewed by MacKevett (1992) and Krug et al. (1992). Through Calcrust (an NSF-funded program to determine crustal structure in California and the western United States), we acquired 155 km of petroleum industry seismic reflection profiles (Fig. 2) to show structure deeper than wells penetrate. Reflection profiles were tied to each other where possible, and correlated to well and outcrop data, providing dense control over some structures. Additionally, gravity and magnetic data of Jachens et al. (1995), and Wentworth et al.'s (1995) depth-to-basement map were used to constrain major physical crustal units. Location and style of seismic deformation were determined by analysis of earthquake hypocenters and focal mechanisms. These data formed the basis of a new regional structural map of the Sacramento Delta area (simplified version in Figure 2).

ACTIVE DEFORMATION

Two active structures cross the BASIX line in the Sacramento Delta, the Pittsburg/Kirby Hills fault and a splay of the Los Medanos thrust zone (Figs. 2 & 3). Another active structure, the Midland fault, occurs 10 km east of the eastern end of the BASIX line and is seen on a land-based industry line. All three active structures are shown in the cross-section of Fig. 4.

The Pittsburg/Kirby Hills fault, is herein renamed from 'Kirby Hills fault' shown on the fault map of Jennings (1994) and older maps. Although it occupies the same location north of the Sacramento River, its expression on line B-1 south of the river establishes that it tracks south through the town of Pittsburg rather than southeast through Antioch (Fig. 2). This fault also does not join the Vaca fault northward as inferred in Jennings (1994). In order to distinguish the new map trace of the fault from older, incorrect traces, it is renamed the Pittsburg/Kirby Hills fault (PKHF in the figures). MacKevett (1992) described the Pittsburg/Kirby Hills fault north of the Sacramento River as a flower structure. The fault is composed of several strands dipping towards each other with reverse offsets, yet the overall structure shows little, if any, strike-slip offset (MacKevett, 1992, p. 73). Line A-3 shows the northern end of the fault rolls over into an east-dipping thrust fault that cuts the eastern nose of the Potrero Hills (an E-W anticline south of Fairfield, Fig. 2).

High resolution profiling in the Sacramento River (Anima and Williams, 1991; Anima et al., 1992) near Pittsburg reveals shallow deformation associated with the Pittsburg/Kirby Hills fault. Holocene (?) beds are folded and tilted westward (Fig. 3A & 3B). Interpretation of reflection data indicates the presence of a fault-propagation fold above the termination of a steeply east-dipping reverse fault. Distributed deformation imaged in the marine sections consists of a one-km-wide, west-facing monocline centered on the town of Pittsburg, uplift and erosional truncation of beds east of the monocline, and subsidence and sediment accumulation to the west. In cross-section, fold axes are narrow; beds within and beside the monocline are essentially planar. An abrupt change of attitude at the axes suggests faulting is taking place along an axial surface. Beds are traceable through the western limb, but the eastern limb may be faulted subsequent to folding. Fold geometry is consistent with reverse movement on an east-dipping fault.

Apparent dip of Plio-Pleistocene sedimentary layers adjacent and outside the shallow fold is 0.5 to 2°W. Within the monocline, apparent dips of these same beds average 11 to 13°W, reaching a maximum of 17°. In the hanging wall, the Pleistocene beds thin and truncated by two unconformities, the youngest of which we interpret to be the base of the Holocene. At least 80±10 m of Pleistocene (?) strata have been removed from the eastern limb of the fold through erosion between unconformities.

Deeper data from the multi-channel BASIX survey (Fig. 3C & 3D) corroborate the high-resolution interpretation of fault geometry. At least one steeply east-dipping fault cuts through the upper 2 s (two-way travel time) of reflectors but noise and structural

Crustal-Scale Cross-Section, Sacramento Delta

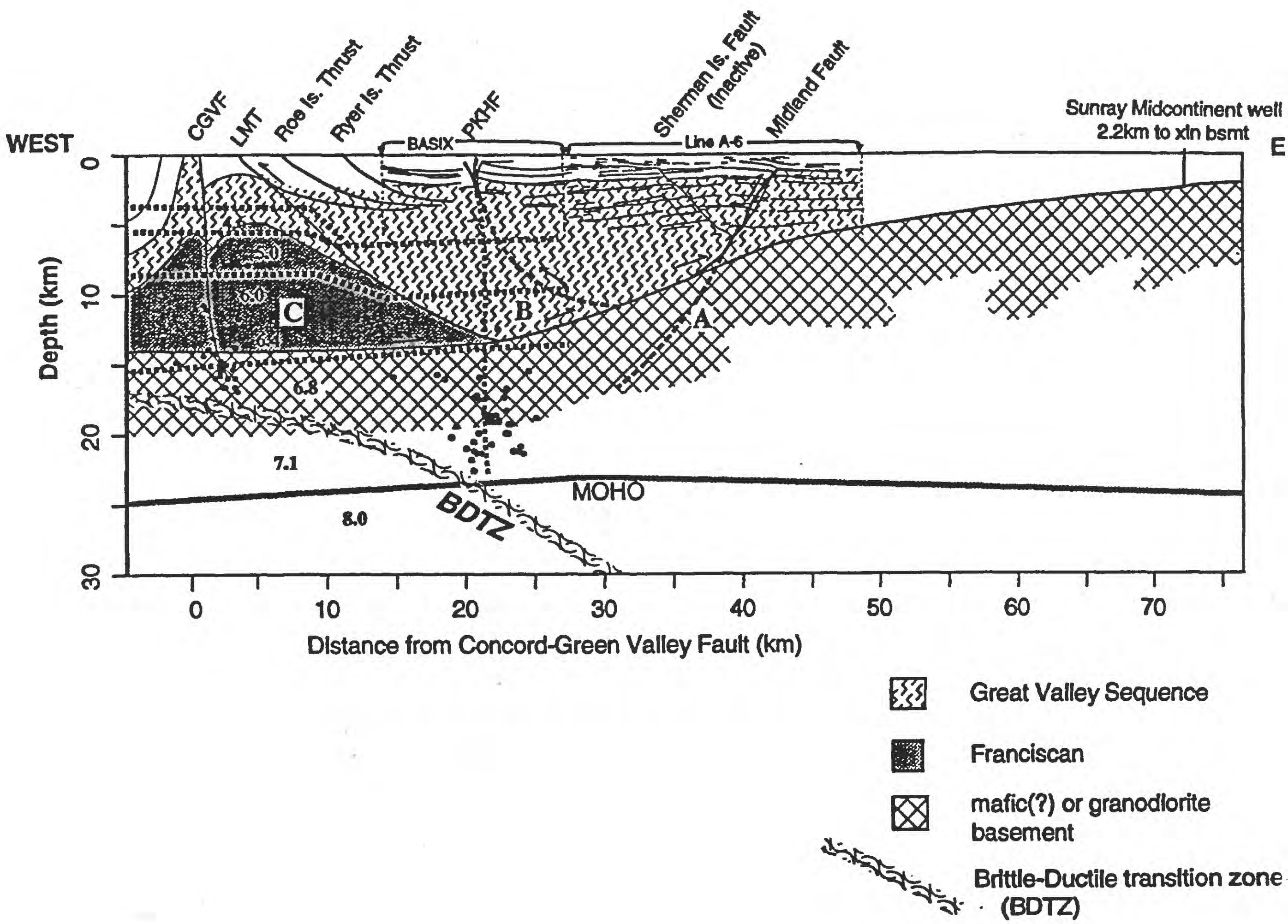

Figure 4: Crustal Scale cross-section, no vertical exaggeration. Seismicity plotted in small dots is also shown in Fig. 5. Shallow geology is projected from BASIX, Line A-6 and subsurface geology. Wide-hachured lines on the west half of the cross-section correspond to a velocity model derived by Hole et al (1993) from wide-angle refraction data. Numbers refer to velocities (km/s) within the modeled units. Note increase in velocity going west across the Los Medanos thrust, corresponding to presence of a tectonic wedge of Franciscan rock. The Los Medanos thrust was a major attenuation fault in Early Tertiary now behaving as a thrust fault.

complication directly beneath the surface trace of the Pittsburg/Kirby Hills fault make it difficult to identify exact fault planes at depth. McCarthy et al. (1994) projected a straight fault from the surface trace to seismicity at depths of 17-24 km. In contrast, we interpret an east-dipping fault with a probable listric geometry based on evidence from: 1) deformational style in adjacent sedimentary panels, 2) the faulting style of the Pittsburg/Kirby Hills fault on lines A-1, A-2, A-3 to north of the river, B-1 south of the river, and 3) subsurface mapping of well data (MacKevett, 1992). Stratigraphic relations and thicknesses of correlative units across the Pittsburg/Kirby Hills fault as expressed in the well data and on seismic profiles that cross the fault show that this was an east-dipping normal fault during early Tertiary and probably through Miocene. Displacement reversed sometime in the Pliocene, continuing apparently to the present. Age-dating of displaced Holocene (?) peat beds may provide more information as to the recency and frequency of activity of this fault.

The Midland fault, 22 km east of where the Pittsburg/Kirby Hills fault crosses the Sacramento River, is another fault that behaved as a normal growth fault from late Cretaceous through the early Tertiary. Post-Miocene motion is reversed on this fault in the same manner as the Pittsburg/Kirby Hills fault, though without development of flower-structure (Line A-6 in Figs 2 and 4). The Midland fault occurs near a steepening of the basement slope (Wentworth et al., 1995). The old growth-fault may have rooted on, and perhaps into, the basement at the slope break (Fig. 4).

Topmost reflectors on line A-6 bend and dip eastward over the Midland fault, indicating reverse displacement on the west-dipping fault, exactly opposite of deformation at the Pittsburg/Kirby Hills fault. The block between the two faults (called the Montezuma Block) now behaves as a pop-up. The force driving the uplift must come from generally E-NE to W-SW directed compression, because the Pittsburg/Kirby Hills fault and active part of the Midland fault trend N-S. Compression oriented more N-S would produce uplift on the Midland fault further north where the fault curves to the west, but this is not observed. Compression and uplift of the pop-up block is probably driven by an east-moving tectonic wedge beneath the deep Pittsburg/Kirby Hills fault. The geometry that best fits the observations is that of a single tectonic wedge riding up over basement.

The Los Medanos thrust (LMT in the figures) is a complex of NE-dipping faults that elevates the Los Medanos Hills east of Concord (Fig. 2). The main fault crosses the BASIX line just west of Roe Island, the small island SW of Ryer Island (Fig. 2) and apparently merges with, or is cut by, the strike-slip Concord/Green Valley fault. The reflection line becomes nearly parallel to the strike of steeply dipping beds here, so reflector coherency is lost and the detailed relationship of thrust fault with strike-slip fault is not seen. Southward, the Los Medanos thrust joins the Marsh Creek fault, a seismically active fault with primarily strike-slip mechanisms. Numerous oil and gas exploration wells have been drilled on both sides of the LMT, providing excellent subsurface control. Hoffman's (1992) cross-sections and subsurface maps across this structure show a northwest plunging anticline in the footwall, which we project onto the cross-section of Figure 4. Hoffman (1992) also documents the unconformity at the top of the Pliocene is offset by over 610 m (2000 ft), with the Pleistocene Montezuma Formation is fully involved and overturned in the footwall of the main fault, indicating a very young structure. A subsidiary thrust that forms the ramp for the Ryer Island anticline is imaged on the western end of the BASIX line (Fig. 3C). High resolution profiling was undertaken in this region to look for shallow deformation, but the data have not yet been fully processed and analyzed.

SEISMICITY

Several large historical earthquakes have occurred in the study area. The oldest known event occurred May 19, 1889 near Antioch with an estimated M_L of 6.0 (Wong et al., 1988). Near the towns of Vacaville and Winters (11 and 37 km north of Fairfield, respectively; Fig. 2), two large earthquakes occurred in 1892. Based on reported damage and area affected, Dale (1977) and Wong (1984) estimated magnitude of the main shock as 7.0, and that of the aftershock as 6.75. These earthquakes were felt over a large area, causing one death, numerous casualties and destruction of buildings. A M_L 6 event occurred on May 18, 1902 east of Vacaville near Elmira. Since modern seismic recorders have been installed, no earthquakes larger than about M4.5 have occurred in the area, but clearly the potential exists for events with magnitudes greater than 6.0 in the study area.

No surface ruptures were reported in association with those earthquakes, suggesting the faults were deep or blind. The Vacaville-Winters earthquakes probably took place on a buried thrust that is present only north of the BASIX transect and so does not appear on Figure 4. While the 1889 Antioch earthquake may have resulted from motion on the deep part of the Pittsburg/Kirby Hills fault or Midland fault.

Contemporary microseismic activity indicates where deformation is presently taking place. Earthquakes recorded by the Northern California Seismic Network (NCSN) from 1980 to 1995 are shown in Figure 5. Events are filtered to accept only those with a range distribution of receiving stations ≥240° (azumuthal gap ≤120°), M≥2.0, and a root-mean-square (rms) error ≤ 0.20 s. Map and cross-sectional plots are shown in Figure 5. P-wave first motion mechanisms of events related to the Concord fault indicate right-lateral strike-slip motion for those events north of the cluster at Alamo. Right-lateral and thrust events predominate along the Pittsburg/Kirby Hills fault trend but a few normal events are also observed.

The most interesting aspect of the seismicity beneath the Pittsburg/Kirby Hills fault trend is that all sampled seismic activity occurred at depths greater than 14 km. North of the Marsh Creek cluster (labeled **a** on Fig. 5C), events are mainly restricted to below 15 km, with many deeper than 20 km. Even with the formal uncertainty associated with depth assignments of ±1 to 3 km, these events are clearly located within the basement (discussed in next section); lack of shallower events suggests decoupling from surface structures. Concord fault seismicity also occurs very deep, mostly between 14 and 17 km depth, partly within the basement. Focal mechanisms determined for events north of Pittsburg, near -15 km (lateral) and -20 km (depth) on profile B-B' (labeled **b** on Fig. 5C), are thrust events and may indicate south vergence based on the overall deepening of seismicity towards the north. Profiles A-A' and B-B' project events occurring within the boxes onto a plane. Direct projection causes earthquake hypocenters along the Concord fault to plot about 2 km closer to the Pittsburg/Kirby Hills fault trend than their actual fault-position due to the oblique intersection of the fault with the line of A-A'. So that earthquake locations would relate to the fault and geology as presented on the cross-section of Figure 4, we projected the Concord fault seismicity along the local trend of the fault so that on the cross-section events are shifted about 2 km west in Figure 4 from direct projection in Figure 5B.

Maximum depth of seismicity, related to the depth of the brittle-ductile transition, deepens eastward in the study area. Two possible reasons for eastward deepening: 1) the 350° isotherm, that marks the brittle-ductile transition zone, may become deeper this direction (Jones et al., 1994), or 2) increasing mafic content of lower crust increases rock strength, requiring higher temperature, hence greater depth, for ductile behavior (Sibson, 1982).

CRUSTAL SCALE CROSS-SECTION

Construction of the cross-section (Fig. 4) incorporated all available surface and subsurface geology and geophysical data sets. On the east end we plotted the deepest drilled well that reaches crystalline basement in the northern Central Valley, the Sunray Midcontinent Shell-Brovelli #1 (7298' to basement; Schilling, 1962). At the west end is the Concord/Green Valley fault (CGVF on the Figure), documented by Sharp (1973) as an active strike-slip fault. Stratigraphy and structures known from seismic profiling and well data constrained the upper 3-5 km. Plunging structures defined on geologic maps were

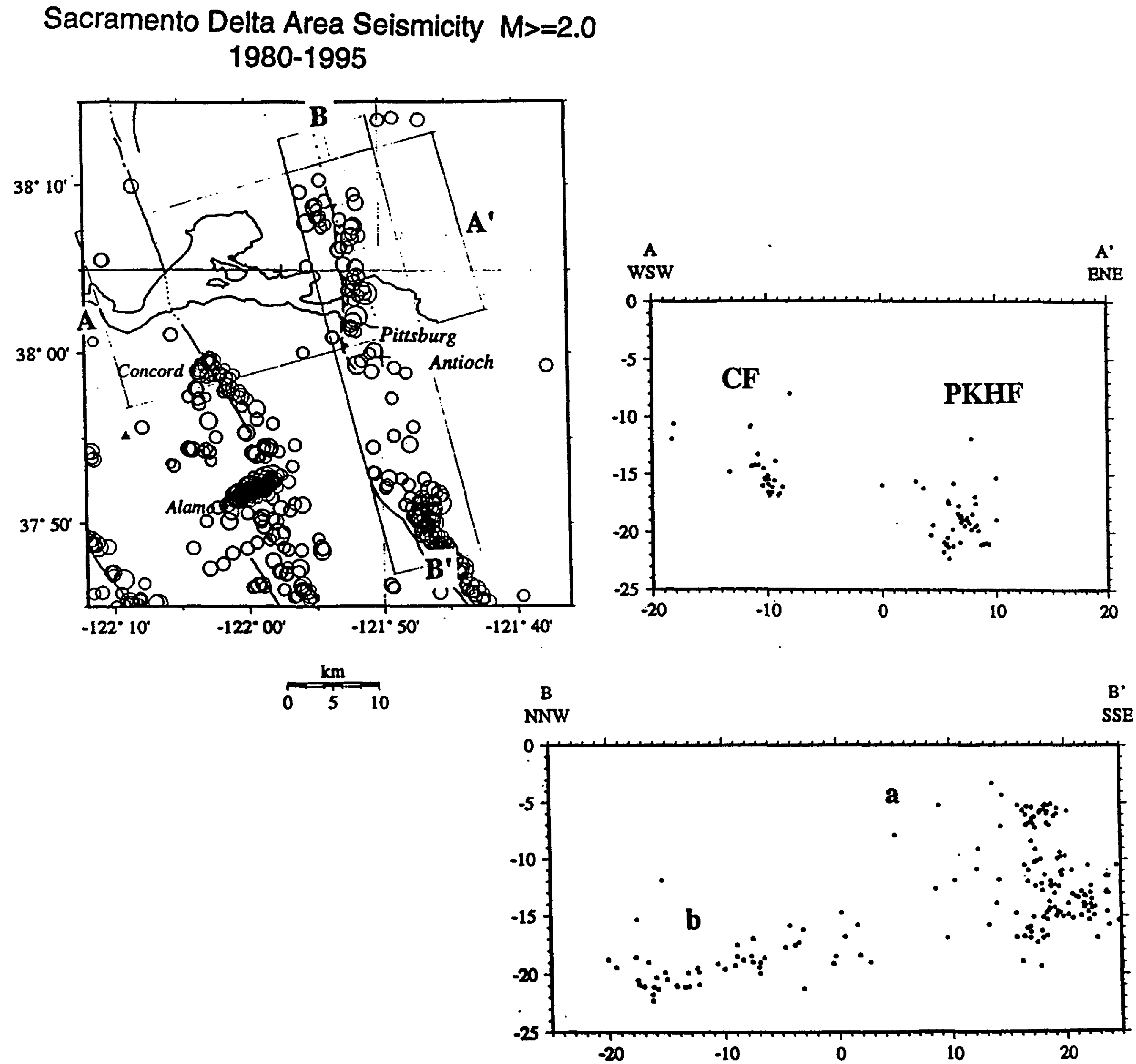

Figure 5: Area map with quality-selected epicenters of earthquakes plotted from the Northern California Seismic Network catalog. Events in section A-A' (5B) and B-B' (5C) were projected onto a vertical plane within the boxes indicated on 5A. Events clustering near Alamo occur on a step-over from the Calaveras fault to the Concord fault. Region A on 5C groups events related to strike-slip motion on the Marsh Creek-Grenville fault, the southern extension of the Los Medanos thust. Region B indicates a cluster possibly north-dipping thrust events in the deep Pittsburg/Kirby Hills fault trend.

projected into the subsurface to constrain the geology between the Concord/Green Valley fault and the Los Medanos thrust. Geophysical data aided in interpreting deeper features.

Beneath the Great Valley Sequence strata in the Central Valley lies a crystalline basement which has been penetrated by the drill in numerous locations on the eastern side of the Central Valley (Schilling, 1962; Wentworth et al. 1995). Where described in western penetrations, basement rocks consist of granite, diorite, and quartz diorite. This basement dips westward and becomes too deeply buried to be reached by exploration wells, though the regional trend as mapped by Wentworth et al. (1995), places it between 11 and 14 km beneath the study area (deeper to the west). A steepening of the dip of the basement surface (labeled **A** on Fig. 4) is based on well data projected from the southern Central Valley (Wentworth et al. 1995).

Jachens et al. (1995) interpret a homogeneous, west-dipping magnetic body (ophiolite) to lie beneath the Central Valley, beginning just west of the deepest well to reach basement and continuing westward beneath the Coast Ranges. Depth to the top of the magnetic body (which we interpret to correspond to basement) is between 13 and 15 km beneath the study area. The BASIX wide-angle reflection/refraction data (Brocher et al., 1993a & b, 1994; Brocher and Moses, 1993; Holbrook et al., 1995) identified such a reflector beneath San Francisco Bay that continues eastward at least as far as the Hayward fault, and perhaps as far as the study area. An increase to Moho velocities (8.0 km/s) occurs along a more or less flat boundary at about 25 km depth (Brocher et al., 1993b) beneath the study area (Fig. 4).

The Midland fault separates Great Valley Sequence and younger strata that unconformably overlie basement from a detached block to the west. We infer the Midland fault roots along the surface of the basement in a detachment, but it could also be interpreted to continue through the basement, perhaps relating to an old attenuation fault that cut basement. An old normal fault could account for steepening of the basement slope but can only be conjectured. The Pittsburg/Kirby Hills fault is steep at the surface, but shallows eastward to root along probably the same detachment as the Midland fault since ancient activity of the Pittsburg/Kirby Hills fault mirrored that of the Midland fault (Krug et al., 1992). Such a geometry defines a tectonic wedge west of, and beneath the Pittsburg/Kirby Hills fault (**C** on Fig. 4). Based on velocities modeled by Brocher et al. (1993b), we interpret block **C** to consist of Great Valley Sequence overlain by Tertiary strata.

Another reactivated, reversed normal fault is observed in the Los Medanos thrust. Geologic relations across the southern extension of this fault (Graymer et al., 1994) show that it was a major east-dipping attenuation fault in early Tertiary (?), cutting out its original basement of Coast Range Ophiolite, and juxtaposing Great Valley Sequence against Franciscan. The velocity model of Hole et al. (1993) requires a similar structure to bring up higher velocity rocks, possibly Franciscan, on the west as shown by the east-dipping velocity discontinuities at **D** on Figure 4 (Holbrook and Mooney, 1987; Fuis and Mooney, 1990). As noted above, recent motion on this structure is reverse. Detailed subsurface mapping in the region between the Pittsburg/Kirby Hills fault and Los Medanos thrust (Weber-Band et al., manuscript in preparation) reveals a shallow, imbricate style of the Roe and Ryer Island thrust faults (above **C**, Fig. 4), apparently detached along a shallow decollement that projects onto Figure 4 at about 5 km depth, and is unrelated to the deeper, ancient structure.

DISCUSSION & CONCLUSIONS

Seismic reflection profiling data from the BASIX program, together with seismic profiles acquired through the Calcrust program, permit identification of two active tectonic wedges beneath the Sacramento delta area. One of the wedge-defining faults may have been responsible for the 1889 M_L6 earthquake near Antioch. The potential of a high-magnitude earthquake in proximity to an area unprepared for large earthquakes necessitates documentation of these structures and review of the seismic hazard.

Geophysical data suggest a continuous basement extends westward from beneath the Central Valley to beyond the Hayward fault. Above this basement occurs a major strike-slip fault (Concord/Green Valley) and active compression-related structures (Los Medanos thrust, Pittsburg/Kirby Hills fault, Midland fault). In the study area, contemporary seismogenic deformation appears concentrated in the basement where fault mechanisms are primarily strike-slip while upper crustal structures are clearly compressional. We interpret faults at the surface to be independent, separated from basement deformation by tectonic wedges and decollement structures.

Significance of deep seismicity in the study area can be interpreted in two ways. First, that it is the continuation of a general trend of eastward deepening base of the seismogenic zone caused by lowering of the geothermal gradient (Jones et al., 1994). Or, that eastward deepening occurs in response to an increasingly mafic middle crust which is stronger at the same temperature (Sibson, 1982), causing the brittle-ductile transition zone to be depressed as it encounters increasing mafic content. In either case, the middle crust deforms in a strike-slip fashion while the upper crust deforms in compression. How is such vertical partitioning accomplished? We find the tectonic model involving a broad decollement beneath the Coast Ranges (Jones et al., 1994) offers the best mechanism, allowing transmission of shear stress to basement rocks at 25 km depth to cause earthquakes while leaving upper crustal blocks independent.

Compression between the Pittsburg/Kirby Hills fault and the Midland fault (occurring within the upper crust) can be generated in several ways: Westward movement of the Sierran Block against the Coast Ranges (Wright, 1976; Wong and Ely, 1983; Hill, 1982), a component of motion normal to the San Andreas fault system (Wong et al., 1988; Harbert and Cox, 1989; Page and Brocher, 1993; Jones et al., 1994), or local changes in stress field generated by the bounding geometry of moving crustal block (Hill, 1982; Wang et al., 1995). The solution could be determined through modeling (Wang, in progress), or through long-term observation and analysis of geodetic information.

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