FINAL TECHNICAL REPORT

Subsurface geometry and segmentation of the Palos Verdes Fault and their implications for earthquake hazards in southern California

Principal Investigator:

John H. Shaw

Department of Earth and Planetary Sciences
Harvard University
20 Oxford Street, Cambridge, MA 02138
phone: 617-495-8008 fax: 617-495-7660
email: shaw@eps.harvard.edu
webpage: http://structure.harvard.edu

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ABSTRACT

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John H. Shaw

Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138; phone: 617-495-8008; fax: 617-495-7660; email: shaw@eps.harvard.edu

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<u>Abstract.</u>

We define the three-dimensional subsurface geometry and long-term slip history of the Palos Verdes fault using an extensive database of seismic reflection profiles and well logs acquired by the petroleum industry. The Palos Verdes fault is an active geologic structure along the western margin of the Los Angeles Basin and Inner Continental Borderland which represents a significant seismic source, and about which much debate has centered regarding its sense of slip and subsurface fault geometry, including its segmentation. In most hazard compilations, the Palos Verdes fault has been generally considered to be a vertical, predominantly right-lateral, strike-slip fault system that extends continuously from the Santa Monica thrust south across Santa Monica Bay and the Inner Borderlands to the area of Coronado Banks, with a restraining bend where the fault dips steeply to the southwest generates uplift and folding of the Palos Verdes Peninsula. In contrast, our analyses of industry seismic reflection data indicate that the fault has a significant component of reverse slip and southwesterly dip at depth along a significant portion of its length, and that much of the current fault architecture is inherited from Miocene rift structures. Mapping of a regionally extensive set of stratigraphic marker horizons and interpretation of fault surfaces throughout the seismic data indicates that the deformation along the PVF is strongly heterogeneous and reflects a complex, multiphase history of deformation that varies along the length of the fault. In the region of the San Pedro Shelf, we interpret that the currently active PVF reactivates a pre-existing Miocene age normal fault, uplifting a sequence of originally down-dropped Miocene syn-rift sediments. Oblique displacement appears to be partitioned at shallow levels into nearly pure right-lateral strike slip on near-vertical faults and contractional folding above gently dipping blind-thrust fault splays. In contrast, further to the south the PVF does not utilize pre-existing structures, and appears to dip steeply to the east below the uplifted Lasuen Knoll structural block. Slip here appears to be dominated by right-lateral strike-slip motion, perhaps with modest amounts of reverse motion.

The transition between the two portions of the fault is complex and clearly represents a major geometric segment boundary. Thus, we suggest that earthquake ruptures may terminate at the juncture, thereby limiting earthquake magnitude and reducing their average repeat times. Moreover, our analysis indicated that ruptures on the segment of the fault that extends from the San Pedro Shelf across Long Beach Harbor may include a significant component of reverse motion, which may increase some components of hazardous ground shaking in future earthquakes.

This research directly addresses the External Research Program Announcement for Fiscal Year 2006, Element I (National and regional earthquake hazards assessments), which states an interest in "supporting research that contributes to … assessing earthquake hazards and reducing losses in urban areas." In particular, this project supports the Priorities in Southern California to "…improve our estimates of fault characteristics…" and to "…quantify known and speculative faults in 3D space." The constraints on the geometry of the Palos Verdes fault in the offshore region will contribute to these goals and greatly reduce uncertainty in the estimates of earthquake hazards from this fault.

TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

The Palos Verdes fault (PVF) is a major, active geologic structure that forms the western boundary of the Los Angeles basin, and has long been considered a potential source of large earthquakes. The fault extends over 100 km from the Gulf of Santa Catalina northwest across the San Pedro shelf (Figure 1). Onshore, the PVF bounds the eastern margin of the uplifted Palos Verdes Hills, and extends offshore at the Port of Los Angeles southwestward into San Pedro Bay. The PVF continues across the San Pedro shelf and into deeper water, where it bounds the western margin of Lasuen Knoll. Numerous studies have been focused on defining the activity, map trace, and slip rate of the fault (e.g. Woodring et al., 1946; Yerkes et al., 1965; Wright, 1991; Dibblee, 1999; Marlow et al., 2000; Bohannon et al., 2004; Fisher et al, 2004). Estimates of the Holocene slip rate, based on uplift of the Palos Verdes Peninsula and offset channels onshore and in the outer harbor, range from 2.5-3.8 mm/year (Stephenson et al., 1995; McNeilan et al., 1996). Slip rates of this magnitude define the PVF as one of the fastest slipping and largest faults in the basin. Despite this, the subsurface geometry, segmentation, and detailed kinematics of the PVF are largely unknown, and there is currently no consensus about the fault's subsurface geometry, along-strike geometric segmentation, northern and southern terminations, or precise sense of slip. In addition, the relationship of the PVF to many of the adjacent, and potentially active, fault systems (e.g., THUMS and Compton faults), is not well understood.

The importance of improved understanding of the PVF is underscored by its close spatial proximity to crucial infrastructure and lifeline facilities along the southern California coast. The trace of the PVF passes through the Port of Los Angeles on the southern end of the Palos Verdes Peninsula, cutting through the Outer Harbor and crossing the Pier 400 Site and Terminal Island before passing between the support towers of the Vincent Thomas Bridge (McNeilan et al, 1996). The Port of Los Angeles is the busiest port facility in the United States, handling over 190 million metric tons of cargo, with a value of over $200 billion, in 2006 (Port of Los Angeles, 2007). Crucial facilities, including large petroleum storage tanks, pipelines, and chemical facilities, are located along the trace of the PVF. A large earthquake on the PVF would undoubtedly have a major impact on these facilities.

One of the primary questions about the PVF is whether the fault is a near-vertical, right-lateral strike-slip fault, or if it dips more gently and accommodates a significant component of dip slip. Wright (1991) documented a 1200 m vertical offset of the top of basement across a west-dipping fault surface that bounds the northeast side of the Palos Verdes Peninsula. Consistent with this interpretation, Ward and Valensise (1994), in a study of marine terrace remnants on the Palos Verdes Peninsula, used a numerical fault model to interpret the PVF as a right-oblique reverse fault and obtained good matches to the marine terrace elevation data. These authors proposed that the reverse component of slip and west dipping fault segment form a restraining bend and are generally limited to the onshore portion of the fault. To the north and south along strike, the fault has generally been considered to be vertical with purely right-lateral strike slip. This is consistent with steeply dipping faults splays mapped in the offshore Beta oil field (Kelsch et al., 1998; Rigor, 2003). However, other authors (Davis et al., 1989; Shaw and Suppe, 1996) have implied that the fault at depth might have a southwestern dip and reverse component of motion along its extent.

The southern termination of the fault, and its along strike segmentation, have also been interpreted differently. Jennings (1994) shows a relatively simple fault trace, consisting of several linear segments, that extends from the center of Santa Monica Bay southward to Lasuen Knoll, where it extends southward as the Coronado Bank fault zone. More detailed studies have interpreted a highly segmented fault trace, with major offsets in the vicinity of Lasuen Knoll. Bohannon et al. (2004) used reflection seismic and high resolution bathymetric data to investigate the tectonics of the offshore continental borderland region, including the offshore structure of the PVF. They documented a highly variable and complex fault geometry along strike, including both east- and west-dipping portions as well as near-vertical segments bounding areas of large bathymetric relief as well as regions of negligible relief. They conclude that the PVF is primarily a strike slip fault that bounds a region of compressional deformation to the west. Fisher et al (2004) explain the wide variety of deformational features along the PVF as the result of small scale fault variability along a master strike-slip fault zone, using high resolution seismic reflection data.

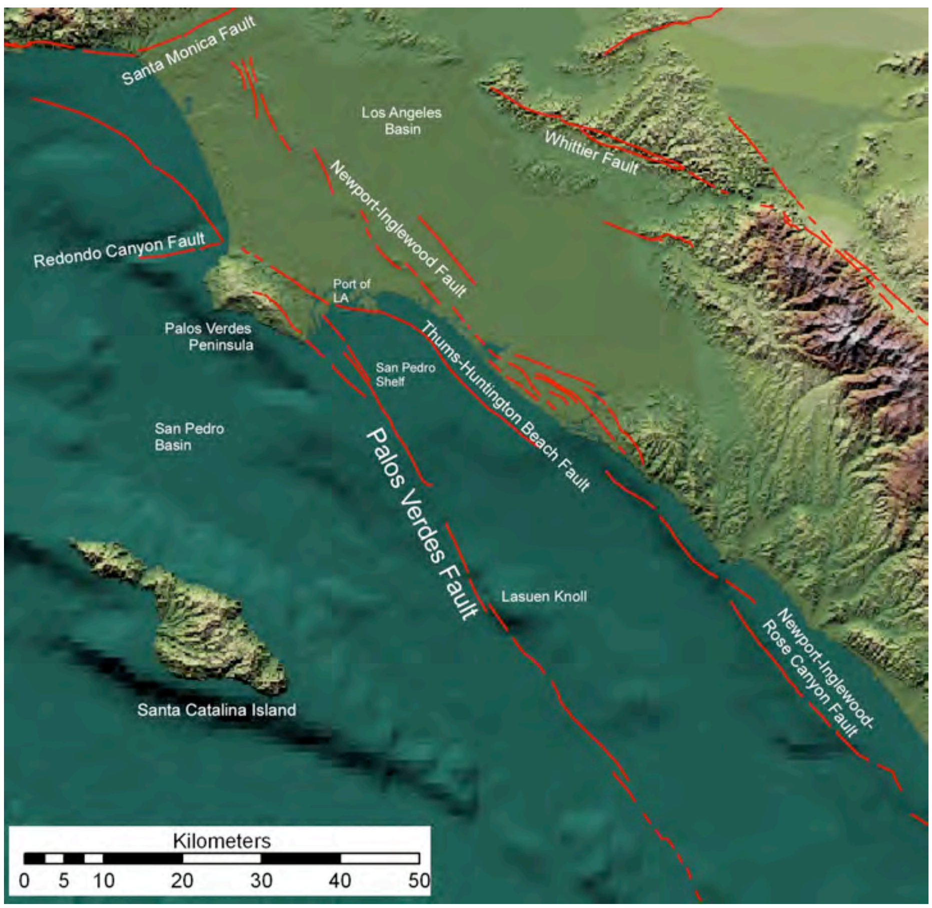

Figure 1: Location map of the Los Angeles Basin and Continental Borderland regions, showing locations of major faults and physiographic features. Fault locations from Jennings (1994), Wright (1991), and Dolan et al. (2000).

In terms of slip sense, several workers have proposed that the PVF has displayed primarily strike-slip displacements in the Holocene to late Quaternary. Detailed geomorphic mapping by Stephenson et al (1995) defined several lineaments that were interpreted as traces of the PVF, and two high resolution seismic reflection profiles across the lineaments constrained the faults to be dipping from 50° southwest to vertical. They also interpreted a 300 m right lateral offset of a paleochannel of the Los Angeles River across the trace of the PVF, estimated to be approximately 120-80 ka. From this evidence, they conclude that the Holocene slip on the PVF has been primarily strike-slip. Similarly, McNeilan et al (1996) used a dense grid of geotechnical borings and high resolution shallow seismic reflection lines to assess the near-offshore of the PVF in the Los Angeles Harbor area. They interpret the PVF as a 100-300 m wide zone of vertical to steeply east-dipping faults, with primarily right lateral offsets and minor west side up (normal) dip slip displacement. They estimate strike-slip to dip-slip ratios of approximately 7:1 to 8:1.

The basis of our current investigations was the observation that strike-slip displacements on a purely vertical fault do not satisfactorily explain the prominent contractional folding and structural relief across the fault imaged in offshore seismic reflection profiles well to the south of the onshore restraining bend (Figure 2). These data define near-vertical faults splays, but also resolve up to a kilometer of structural relief of basement and Tertiary horizons across the fault zone. In addition, we interpret the stratigraphic and structural evidence to indicate that the deeper fault inherited its structural geometry, in at least some portions along its length, to Miocene rift structures. This implies that the fault at depth has some component of non-vertical dip. Our investigations seek to resolve the complex, three-dimensional fault geometry and reconcile the various observations of structures along the fault with a coherent structural architecture and sequence of fault evolution that explains the observed structures.

2.0 SEISMIC REFLECTION DATA

The subsurface structures along the trend of the PVF are imaged in an extensive set of 2D and 3D seismic reflection data collected and processed by the petroleum industry in the 1970s and 1980s. The industry seismic reflection profiles have been made available to us for this study through partnerships with various oil companies, as well as through publicly accessible data resources, including the USGS National Archive of Marine Seismic Data. Our data include more than 10,000 kilometers of offshore 2D profiles as well as 3D surveys from the Beta and Wilmington oil fields. The data form a dense regional grid of NE-SW striking dip lines and SE-NW trending strike lines (Figure 2). The 2D line spacing is about 5 km for the dip lines, and between 9 and 10 km for strike lines, with considerably higher line density in some areas. Most lines are 40-120 fold, and record to 5-6 seconds two-way time (TWTT), generally corresponding to imaging depths well in excess of 5 km. The 3D seismic survey is a 1980s-vintage volume collected during exploration and development of the Beta oil field, and covers approximately 270 km^2 of the San Pedro Shelf and adjacent slope regions. The industry seismic lines overlap the coverage shown in Bohannon et al. (2004) and Fisher et al. (2004), but generally image deeper and extend about 50 km farther south in the Inner Borderlands. This data coverage is well suited to investigating the entire, along strike extent of the fault. The data provide good constraints on aspects of the fault geometry at depth, and serve as the basis for our analysis of subsurface fault geometry and kinematics.

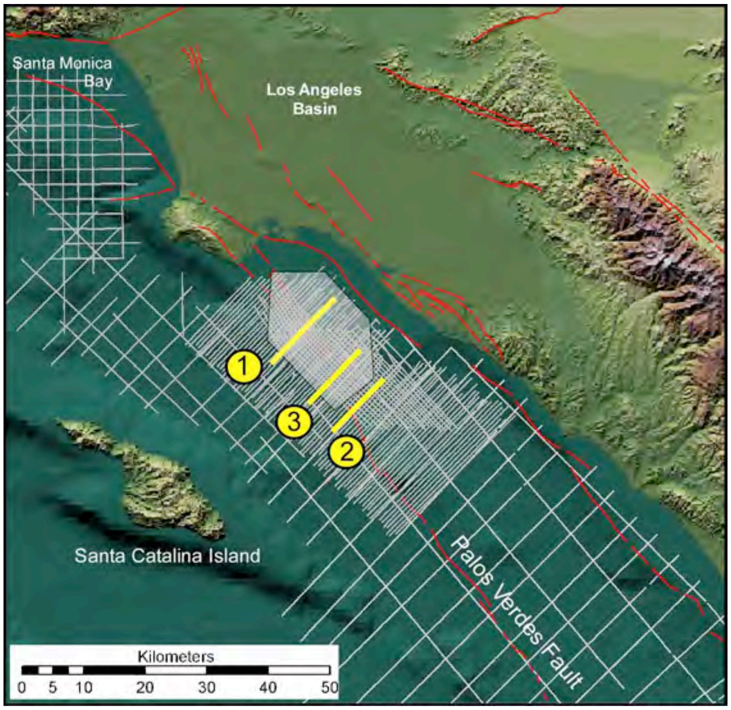

Figure 2: Location map showing extent of seismic reflection data used in this study. Highlighted lines (1-3) are shown in figures 3, 5, & 9. Light grey box denotes coverage area of 3D seismic survey.

3.0 STRUCTURAL AND STRATIGRAPHIC SEISMIC MAPPING

We performed a systematic mapping of the stratigraphic units and structural features in the Inner Borderlands region south of the Palos Verdes Peninsula. Eighteen 2D seismic lines, comprising approximately 800 km of data and covering the region along the PVF south of the Palos Verdes Peninsula, were digitized and vectorized. These data were imported into a workstation-based seismic data project to facilitate mapping and structural interpretation. We also recently were granted access to a digital 3D seismic volume encompassing the San Pedro Bay region. Additional non-digitized seismic lines were used as checks for the digital data in confirming stratigraphic correlations. In addition, stratigraphic and velocity data from several petroleum industry exploration wells in the area were incorporated into the project to facilitate interpretation of stratigraphic surfaces. Stratigraphic picks from the wells included the top of crystalline basement (Catalina schist), and a series of regionally extensive sedimentary units including Mohnian; Delmontian; lower and upper Repetto; lower, middle, and upper Pico; and top Pleistocene where imaged. These stratigraphic tops were correlated throughout the extent of our data, allowing for detailed mapping of folded and faulted strata. The loop-and-tie method of mapping ensured consistent interpretation of all surfaces throughout our study area.

Sedimentary Basin Fill

The San Pedro Shelf region is underlain by a sequence of Miocene through Recent sediments up to 3000m thick, unconformably overlying crystalline basement rocks. Basement in the area consists of the Catalina schist, a Mesozoic complex of metasediments of blueschist- and amphibolite-facies (Wright, 1991; Fisher et al., 2004). The overlying sediments comprise late-Miocene through Pliocene sediments of the Monterey (Mohnian and Delmontian) and Repetto Formations, late Pliocene through Pleistocene Pico Formation, and Holocene through recent sediments. Figure 3 shows a representative seismic line from the San Pedro Shelf which illustrates the major stratigraphic and structural features.

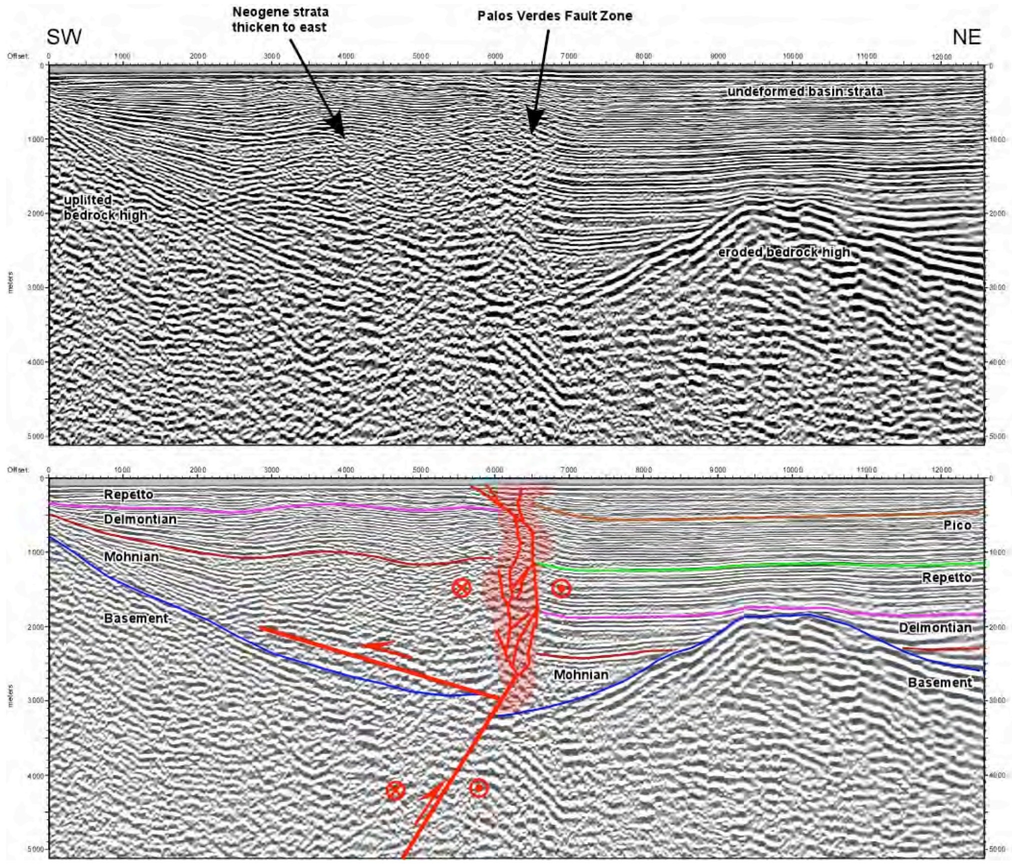

Figure 3: Seismic line #1 (location in figure 2), showing characteristic features present along the PVF in the San Pedro shelf region. West-dipping fault at depth is inferred on the basis of Mohnian-Delmontian syn-rift growth strata and from structural duplication of basement surface. Dip of deep fault may dip to the west shallower than shown. Data courtesy of Texaco, Inc.

The basement-sedimentary contact is most easily identified in the seismic data and is manifested as a high amplitude reflection and a marked transition from coherent, uninterrupted reflectors to largely scattered and inconherent reflections. This contact is recognizable throughout the dataset and allows for the high precision mapping of the basement surface. A contour map of the basement surface (figure 4) shows that the top basement unconformity surface has a large amount of relief, which includes both eroded bedrock highs as well as structurally-controlled relief along faults. Offsets of the top basement surface highlight the locations and displacements of the major segments of the PVF (see discussion below).

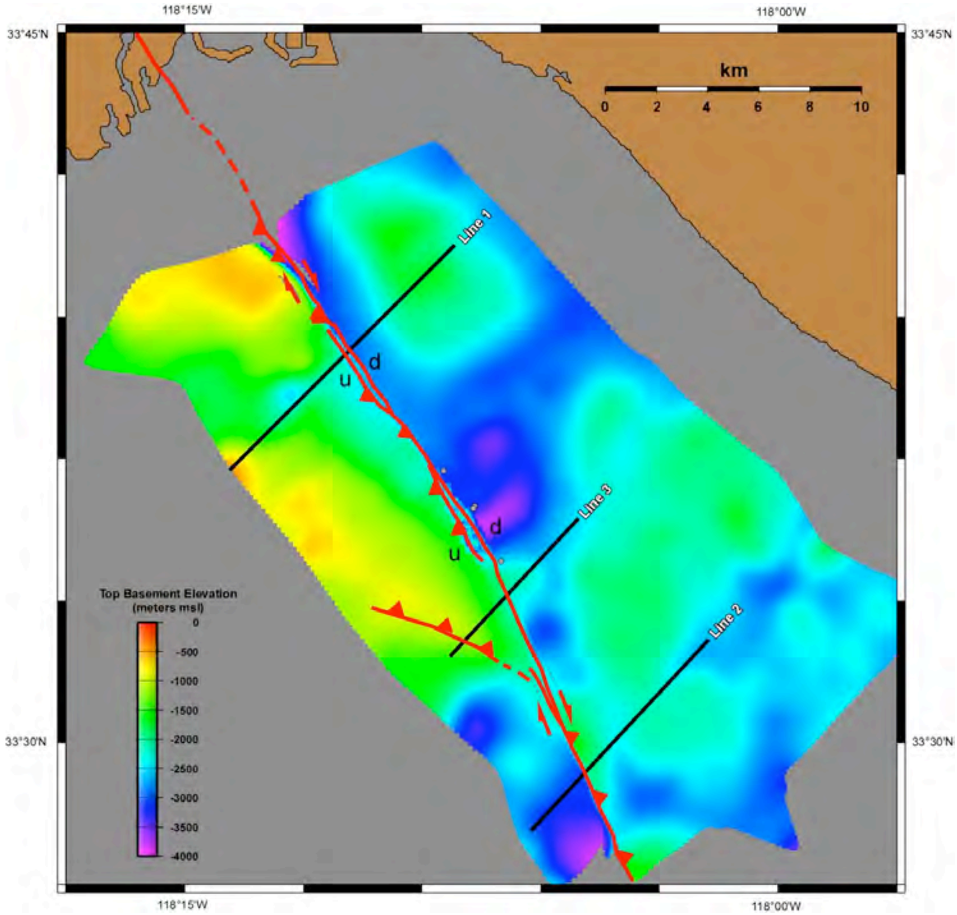

Figure 4. Contour map of the top-of-basement surface (Catalina Schist) along the Palos Verdes Fault (PVF) south of the Palos Verdes Peninsula. Mapped traces of the PVF, bounding regions of uplifted basement, are shown. Datum is msl.

The stratigraphic character of the overlying Neogene strata differs fundamentally on either side of the main trace of the PVF (Figure 3). East of the fault, the entire sedimentary section is virtually undeformed, with only minor drape folding over basement highs associated with compaction. In the seismic data, reflectors corresponding to these strata are horizontal, continuous, and of large amplitude. In contrast, west of the fault the section differs in several respects. First, the Delmontian and Mohnian strata is considerably thicker than the correlative units east of the fault, and the section thins considerably onto a bedrock high at the southwest margin of the shelf. In particular, these units are thickest where they are offset by the PVF, and thin to the west onto the bedrock high, forming an eastward-expanding stratigraphic section. Second, the overlying Pico Formation and Pleistocene strata are largely missing in the northern portion of the shelf. Where they are preserved, they are typically thinner than to the east of the fault. Finally, the entire section west of the PVF is structurally higher than the equivalent units to the east; in the northern portion of the shelf, the Pico and Pleistocene have been eroded away. These observations are discussed below in the context of the structure of the PVF.

The current deposition on the San Pedro Shelf is confined primarily to east of the PVF. Active uplift of the shelf bathymetric surface west of the PVF exposes Plio-Pleistocene strata (Repetto and Pico Formation)

South of the shelf-slope transition, the stratigraphic character changes dramatically (Figure 5). At this location, the same units as to the north are present, however, the dramatic thickness changes of the Delmontian is not observed. Rather, thickness of the Delmontian and overlying Repetto Formations are relatively constant across the PVF. East of the PVF, the Pico Formation thins slightly towards the fault, constraining the initiation of fault activity on this segment of the PVF (see discussion below).

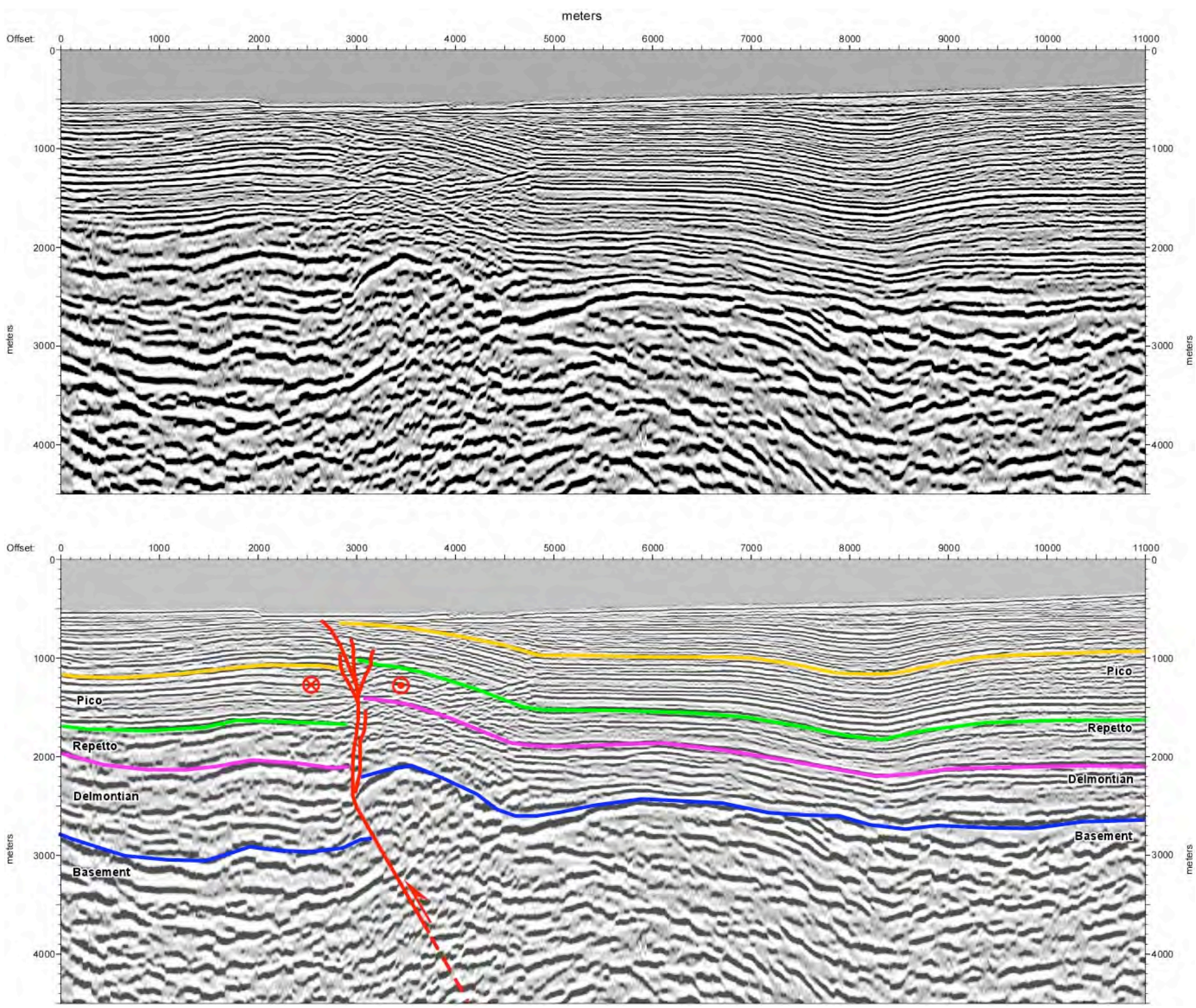

Figure 5: Seismic line #2 (location in figure 2), showing characteristic features present along the PVF in the southern portion of the study area. Data courtesy of Texaco, Inc.

Structure of the Palos Verdes Fault and Related Deformation

Deformation along the PVF is complex and variable, suggesting a multi-phase history of deformation of the fault system and the inherited geometry of pre-existing structures along the fault. At the larger scale, this composite fault zone corresponds generally to the previously mapped trace of the PVF (Fischer et al., 1987; Jennings, 1994; Fisher et al., 2004). The styles of deformation vary greatly between the northern and southern portions of the PVF

In the region of the San Pedro shelf, the northern fault segment extends for approximately 20 km from the northern extent of our data to the present day shelf edge. Deformation is concentrated to the southwest of the trace of the PVF (Figure 6). Deformation is manifested as a series of en echelon anticlines and synclines which intersect the fault zone at acute angles, consistent with a component of right-lateral slip along the PVF. These folds deform the sea floor west of the PVF, indicating their recent activity and demonstrating an active component of shortening across the PVF and well south of the onshore anticline on the Palos Verdes Peninsula. East of the fault, the only major structure is a synclinal fold axis which bounds the active fault zone and defines the eastern limit of deformation. In this northern portion of the PVF, the shallow fault zone is marked by an approximately 1-km-wide near-vertical region of disrupted reflectors and scattered, incoherent seismic energy extending from the seafloor to about 3 km depth (Figure 3). Within this fault zone, numerous steeply dipping to vertical, anastamosing fault surfaces form small scale stepovers and restraining and releasing bends within the larger fault zone.

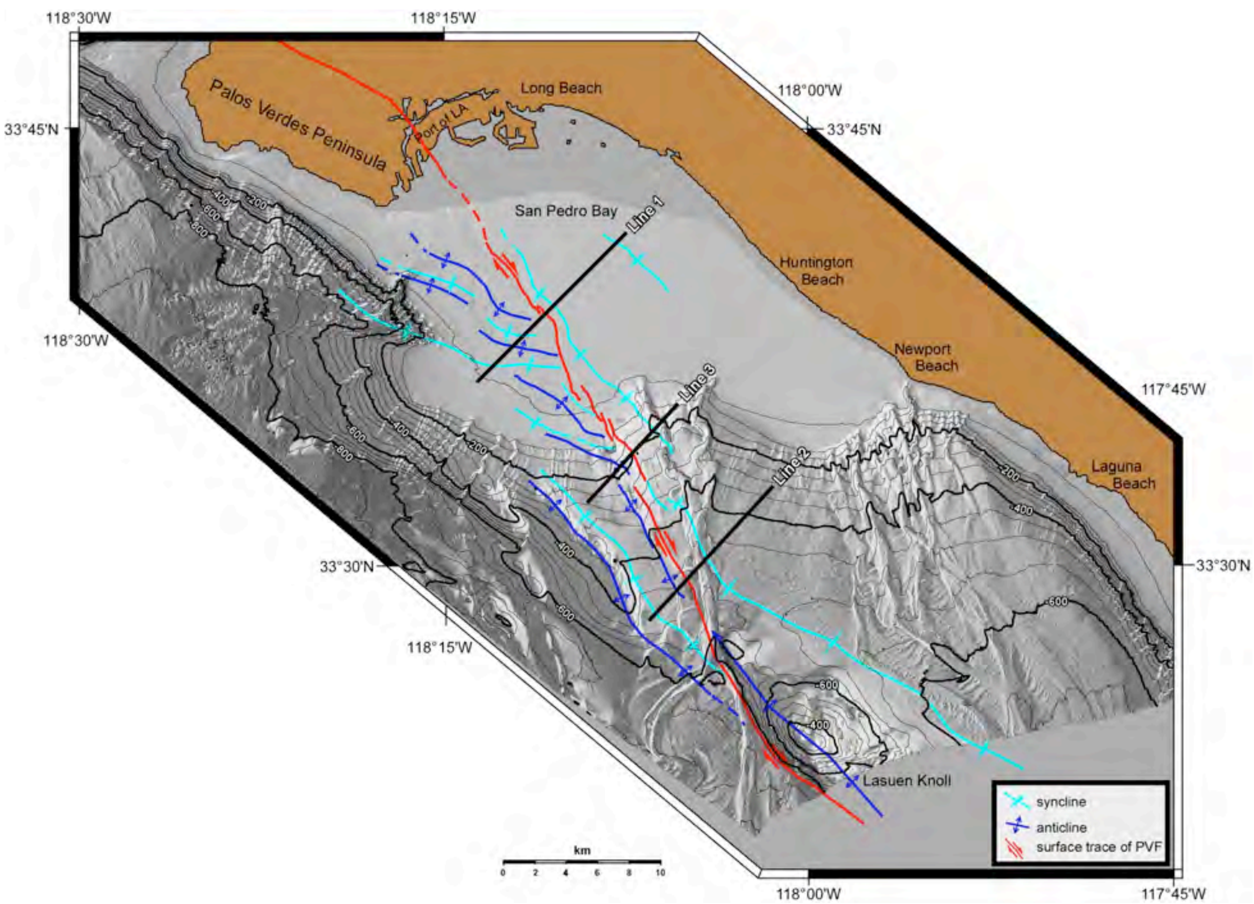

Figure 6: Structure map of the Palos Verdes Fault in the San Pedro Shelf region.

At depths below about 3km, however, the seismic data show evidence that the fault does not continue vertically to depth, but rather shallows in dip to the southwest. In particular, structural duplication of the prominent basement surface precludes a vertical continuation of the shallow

PVF to depth. The basement surface is clearly offset by up to about 900m across the fault, with the west side displaced up. The deeper fault is not directly imaged; however the overthrusting of the basement surface and the structural relief of Neogene strata indicate that the deep fault must dip moderately to the southwest. Structural relief across the fault decreases to the south along the fault (Figures 4 and 7). The composite geometry of the PVF in this location thus includes a shallow vertical fault zone extending from the surface down to approximately 3km depth, below which the fault dips moderately to the west. This west dip is consistent with the west dipping geometry of the PVF onshore below the Palos Verdes Peninsula, and implies that this dip is not confined solely to the onshore portion of the fault.

South of the shelf margin, the overall style of deformation along the PVF transitions from concentrated deformation west of the PVF to uplift and folding primarily east of the fault. The sense of offset of the basement surface, as well as the overlying sediments, changes polarity, transitioning from west-side-up below the San Pedro shelf, to east-side-up below the slope and further south (Figures 4 and 7). This becomes more pronounced to the south, with the emergence of Lasuen Knoll as a bedrock high east of the southern PVF.

The shallow fault zone along the southern segment of the PVF is imaged as a relatively narrow zone of discrete subvertical and anastamosing fault surfaces extending from the surface to approximately 2-3 km depth. Basement is vertically offset with the east side up. Overthrusting of the basement surface demonstrates that the deeper fault dips to the east. However, the magnitude of dip is not well constrained; east dips of between 55° (shown in Figure 5) to as shallow as 30° are consistent with the observations of basement offset and folded strata. A well-defined narrowing-upward kink band within the Pico interval constrains the onset of activity on this fault segment, and indicates a component of shortening across this portion of the PVF. This fold limb becomes more pronounced to the south, representing the greater magnitude of structural relief across the fault to the south and the emergence of Lasuen Knoll.

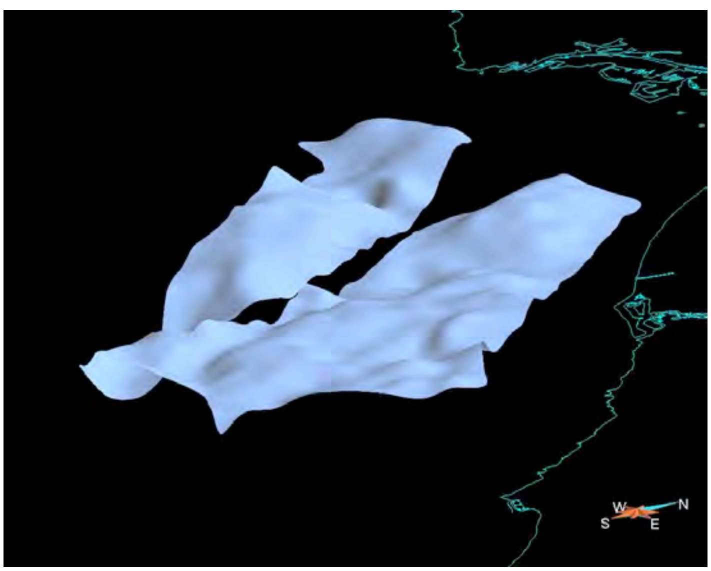

Figure 7: Perspective view (view towards NW) of the top basement surface offset by the Palos Verdes Fault in the San Pedro Shelf region. Note the change in polarity of fault displacement, from west side up to east side up.

4.0 INTERPRETATIONS

The contrasting structural and stratigraphic features observed in the San Pedro Shelf region are interpreted to be indicative of a fundamental change in the underlying structure of the PVF. In particular, we propose that the current geometry of at least portions of the PVF is inherited from structures originating from an earlier, Miocene phase of extensional deformation.

Northern PVF

Several lines of evidence indicate that the PVF shallows in dip at depth, and does not maintain a nearly vertical orientation. Most dramatic is the variation in unit thicknesses across the fault, which can be understood in terms of the evolution of a Miocene rift basin through time, and which controlled the deposition of the syn-rift and later sediments. West of the fault, the geometry of the Delmontian and Mohnian units, with eastward thickening strata and an internal fanning of bed dips, is consistent with and indicative of deposition of sediments above a Miocene-age, west-dipping fault during normal (west-down) displacement. Fault slip on a listric (shallowing down-dip) normal fault causes hanging wall block rotation and creates accommodation space during deposition, and results in hanging-wall sections which thicken towards the fault (Figure 8; Hamblin, 1965; Xiao and Suppe, 1992). In this model, the Delmontian/Mohnian interval represents sediments deposited during active normal faulting. These older strata likely record a period of basin deposition during regional extensional and transtensional faulting, associated with the opening of the Inner California Borderlands and associated rotation of the Western Transverse Ranges (Luyendyk and Hornafius, 1987; Crouch and Suppe, 1993; Nicholson et al., 1993; Rivero et al., 2000). In this case, this likely reflects that the proto-PVF originated as a west dipping rift-bounding normal fault which accommodated a component of pure or oblique extension in the Miocene and early Pliocene.

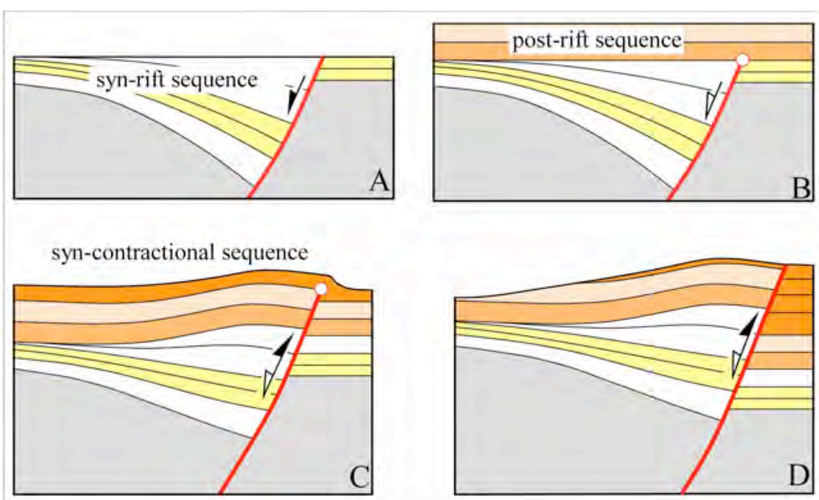

Figure 8: Schematic model of growth deposition during normal faulting and subsequent inversion of fault system. After Rivero (2004).

The variations in thickness of the Delmontian unit provide insight into the geometry of the normal fault. An isopach map of the Delmontian interval (Figure 9) shows that the thickness varies dramatically across the region, and in particular across the trace of the PVF. We interpret the Delmontian interval to represent sediments infilling a Miocene basin which is actively extending through slip on a series of NW-SE striking normal faults. The location of one such fault can be interpreted using the transition between the thickened section in the hanging wall and the thinner equivalent units in the footwall at the present location of the PVF. The locus of deposition was clearly influenced by the normal fault, as indicated by the thickened section west of the fault. The along-strike termination of this normal fault is unclear; however, the decrease in unit thickness to the south in both the hanging wall and footwall of the PVF, indicates that the normal fault does not continue south of approximately the present day shelf-slope transition. Seismic lines from this region (e.g. Figure 4) show that there is no change in Delmontian thickness, such as we observe to the north. Clearly, then, the pre-existing normal fault system either died out to the south or transitioned across a linkage to another fault segment not imaged in the seismic data.

Furthermore, the apparent right-lateral offset of the depocenter by approximately 5 km (in the future, you must think of ways to graphically document this with annotations on the figure, and offer a range) provides a potential control on the magnitude of post-extension displacement on the PVF. Based on this offset, we calculate a minimum post-Delmontian right-lateral slip rate of 1.1 mm/yr. This is considerably lower than slip rates constrained using paleoseismic and numerical modeling techniques (Ward and Valensise, 1994; Stephenson et al., 1995; McNeilan et al., 1996); however, our rate is clearly a minimum, largely owing to the fact that we cannot precisely date of onset of the strike-slip faulting as this may not have directly followed the deposition of the Delmontian, and an accurate estimate of the age of the top Delmontian surface, as these units are defined by biostratigraphy and may be somewhat time-transgressive (Wright, 1991).

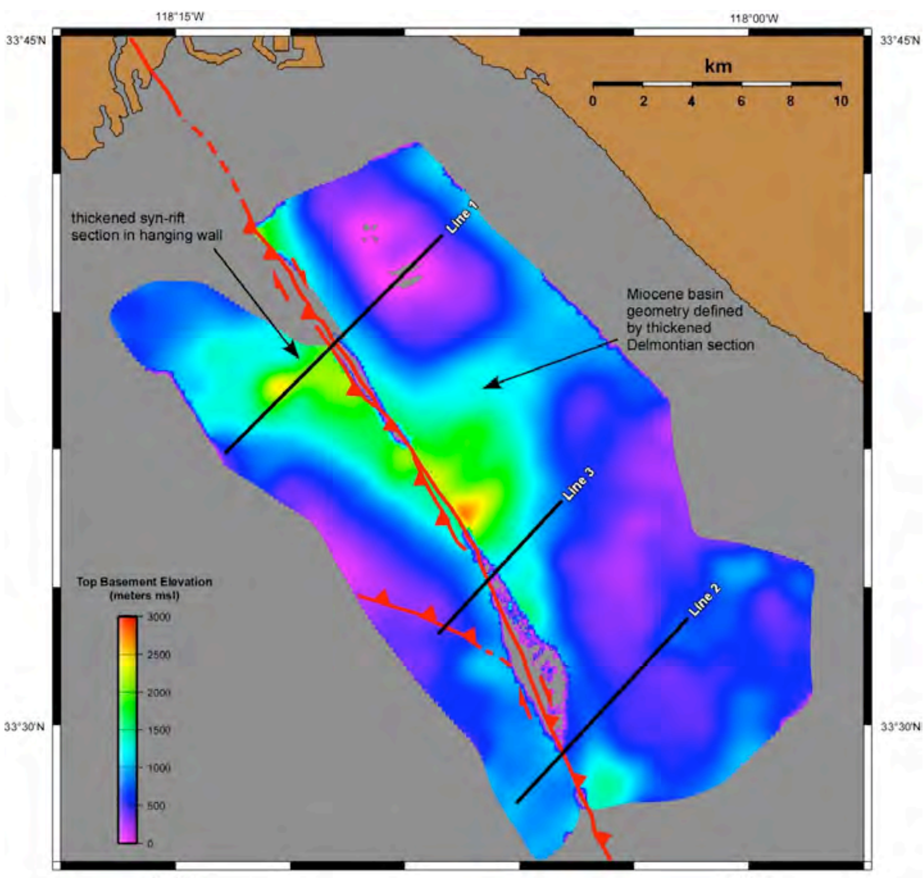

Figure 9: Isopach map of syn-rifting (Mohnian and Delmontian) strata in the San Pedro Shelf area.

The observation of structurally higher horizons west of the fault indicates that these units must have been structurally inverted, or uplifted, in a contractional phase of deformation subsequent to the extension. We can directly observe this reverse offset by correlation of horizons across the fault (Figure 3). The deformation is also manifested in the contractional folding of the uplifted hanging wall into a series of anticlines and synclines west of the PVF. At least one of these folds is cored by a backthrust originating from the base of the shallow, vertical fault zone (see Figure 3), which can be identified in the seismic on the basis of downward-terminating fold limbs and dip discordances within the fold. Late Pliocene reactivation of the fault, currently manifest by active oblique, right-lateral reverse motion, has generated the younger contractional folding and generated (or enhanced) the shallow vertical fault splays. This contractional deformation is consistent with the overthrusting (structural duplication) of the basement surface by east-directed reverse faulting as imaged in the seismic data (Figure 3). Thus, we interpret these structural and stratigraphic patterns to reflect that the Palos Verdes fault has reactivated a large, Miocene normal fault. Based on the stratigraphic correlations, this inversion occurred in the early to mid-Pliocene at the inception of the modern oblique, right-lateral reverse fault system.

Estimation of long-term (post-rifting) fault slip rate on the PVF is possible using the mapped vertical displacements of the faulted stratigraphic units. Using an uplift of 1300m on the top Delmontian surface (Figure 3), we calculate a post-early-Pliocene uplift rate of 0.3 mm/yr. Using an estimated maximum deep fault dip of approximately 60° results in a dip-slip slip rate of about 0.35 mm/yr. Combining this with the long-term strike-slip slip rate of 1.1 mm/year (estimated above) gives an oblique fault slip rate of about 1.16 mm/year. We note that this is a minimum dip-slip rate because we use the steepest fault dip that is compatible with the stratigraphic and structural observations (see above). Shallower fault dips result in slightly higher slip rates; for example, a 45 fault dip results in an oblique slip rate of about 1.19 mm/yr.

Southern PVF

The changes in stratigraphy and style of deformation indicate that the southern portion of the PVF did not reactivate a Miocene rift structure, as seen in the northern PVF, but rather is a primary strike-slip fault (Figure 5). This transition from primary strike-slip fault to inverted rift basin is manifest in the trace of the fault across the Miocene depocenter in Figure 9. To the north, the PVF occupies the northeastern side of the basin coincident with the Miocene normal fault. To the south the PVF diverges from the rift margin and extends through the center of the Miocene basin (see both Figures 9 and 10). We interpret this as indicative of the modern PVF utilizing the pre-existing normal fault structures to the north, but not to the south (see below).

The change in the style of deformation along strike on the PVF is another indication that the pre-existing normal fault system is not present along the PVF to the south. South of the shelf-slope transition, deformation becomes concentrated on the east side of the PVF, and the offset of basement changes polarity to become east side up, as opposed to west side up to the north (Figure 8). The geometry of the basement uplift indicates a deeper fault that dips steeply to the east, in contrast with the west-dipping geometry interpreted in the northern portion of the PVF. The constant unit thicknesses within the Delmontian interval indicate that this southern segment was not active during Miocene extension, as to the north. Similarly, the Repetto shows constant thickness across the PVF. However, the overlying Pico strata thin onto the uplifted block east of the PVF, indicating that slip on the southern segment initiated during the late Pliocene.

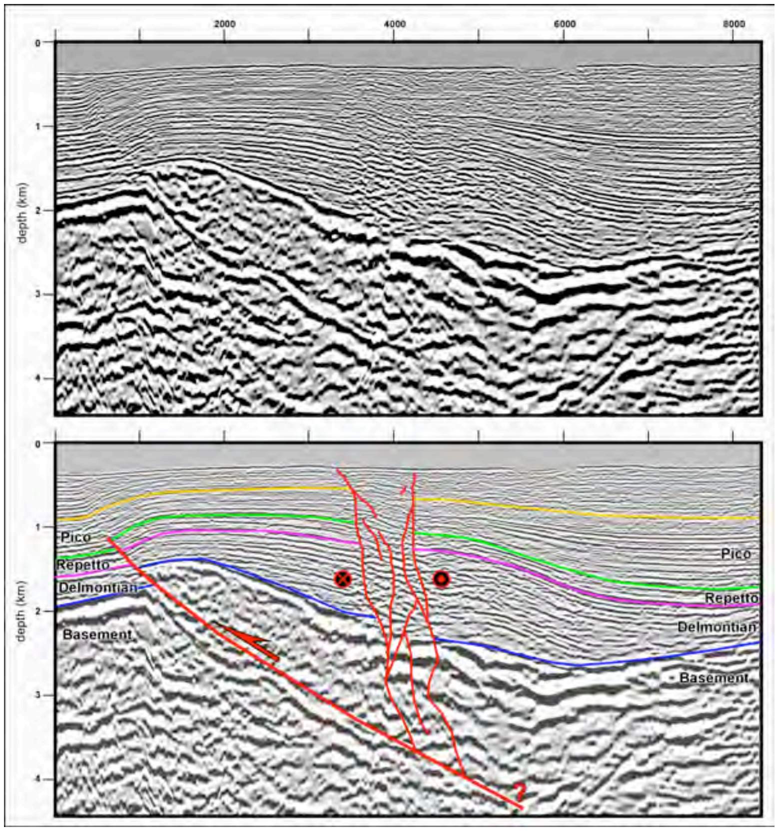

Figure 10: Seismic line showing the transition between northern and southern portions of the Palos Verdes Fault, south of the San Pedro Shelf. At this location, the thickened Delmontian section indicates that the deposition in this region was influenced by the Miocene normal fault, but shallow vertical PVF does not reactivate the normal fault as to the north. Rather, the shallow fault cuts through the hanging wall strata and interacts with a deeper, east-dipping reverse fault. Data courtesy of Texaco, Inc.

Fault slip rates on the southern PVF are limited due to a lack of piercing points such as the Miocene rift basin identified along the northern segment of the PVF. However, vertical displacement of strata across the fault can provide constraints on the dip-slip component of fault slip rates. Vertical displacement of the top Delmontian and top Repetto surfaces is about 700m, and assuming a post-Repetto initiation of faulting at this location (as indicated by the Pico growth strata) gives a vertical uplift rate of about 0.28 mm/yr, which is virtually identical to the uplift rate calculated on the northern segment. Because the deep fault geometry is unconstrained at this point, we calculate a dip-slip slip rate of 0.34-0.56 mm/yr based on the range of potential fault dips of 30°-55°.

This style of deformation continues to the south, where the PVF bounds the western margin of Lasuen Knoll, which forms a prominent uplifted basement block up to 500m above the surrounding bathymetry. Progressively increasing structural relief to the south along Lasuen Knoll suggests that the contractional component of fault displacement increases to the south along this fault segment. The uplifted block has been interpreted previously as due to a restraining bend along the PVF (Fisher et al., 2004). However, the magnitude of uplift is difficult to reconcile with a purely restraining bend structure based on our definition of the fault surface and magnitudes of slip. Thus, we suggest that the uplift of Lasuen Knoll is a result of at least a component of contractional deformation on the southern PVF.

5.0 CONCLUSIONS

Our investigations of the Palos Verdes Fault indicate that the complex stratigraphic patterns and deformational features are consistent with an active fault that inherits its geometry from pre-existing structures in regions along the fault. The northern portion of the fault, in the region underlying the San Pedro Shelf, originated as a Miocene-age, west-dipping normal fault which accumulated a thick sequence of Mohnian and Delmontian strata in its hanging wall. This sequence was subsequently inverted in the current phase of transpression, which uplifted and folded the syn-rift strata. This transition to transpression likely began in the mid- to late-Pliocene, as shown by thin to absent post-rifting strata west of the PVF. In contrast, the southern portion of the PVF exhibits strikingly different behavior. Stratigraphic patterns indicate that the normal fault did not extend south to this region, and thus the active PVF is interpreted to have formed here as a primary transpressional structure accommodating both strike-slip and significant contractional deformation. The currently active PVF underlies and defines the western margin of the uplifted Lasuen Knoll, and based on the fold geometry and basement repetition dips steeply to the east, in contrast to the northern PVF's west dip at depth. This change in the character of deformation appears to form a major geometric segment boundary that may limit the extent, and thereby magnitude, of earthquakes on this fault system. Moreover, the dip and reverse component of motion on the PVF may impact the style, magnitude, and distribution of hazardous ground shaking in future events.

Our findings have important implications for characterization of seismic hazards associated with the PVF:

1) The potential segment boundary between the northern and southern portions of the PVF, as described above, indicates that the lateral extent of coseismic rupture of the PVF, and thus the maximum earthquake magnitude, may be limited and smaller than earlier estimates which generally consider full rupture of the fault to or past Lasuen Knoll.

2) The west dip of the deep PVF in San Pedro Bay, and in particular the component of dip slip that is resolved on the fault, indicates that coseismic rupture of the PVF will have a component of reverse displacement. This may increase the impact on the Los Angeles Basin in the form of greater vertical ground motions and focusing of seismic energy towards the coastline.

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