FINAL TECHNICAL REPORT

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

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ABSTRACT

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Abstract.

The Palos Verdes Fault (PVF) forms the western boundary of the Los Angeles basin, California, and has one of the highest slip rates in the region, indicating that it may be a source of future large earthquakes. Using a dense grid of petroleum industry seismic reflection data and exploration well logs, we have mapped a series of stratigraphic horizons in San Pedro Bay south of the peninsula that we use to invert for permissible underlying fault geometries and displacements. The PVF is composed of several discrete but related segments which together reflect a complex and multiphase evolution of the fault system. Directly south of the Palos Verdes Peninsula, imaged hanging wall and footwall fault cut-offs indicate that at depths below about 5km the fault dips moderately to the southwest. Furthermore, a thick sequence of eastward-thickening Miocene strata west of the fault suggests that the PVF originally formed as a normal fault during Miocene extension/transtension. Contractional folding of younger strata, as well as structural duplication of the crystalline basement surface, indicates that the normal fault was subsequently inverted during Plio-Pleistocene transpression. In the upper 3-4 km, the fault is nearly vertical, presumably accommodating right-lateral strike-slip displacement. Approximately 20 km southeast of the Peninsula, the PVF changes character across a major geometric segment boundary as a second fault segment emerges and continues trending southeast. The second segment dips northeast and shows increasing reverse displacement along strike to the southeast. Growth strata in the hanging wall and emergent sea-floor folds indicate that contractional deformation began in Pliocene time and continues to the present. The varying geometry and structural character of the PVF along strike reflect the earlier structural elements which have been reactivated to form the present fault geometry. Furthermore, the segmentation of the PVF may impact hazard estimates in one of two ways: by restricting coseismic rupture and thus limiting maximum earthquake magnitude, or by rupturing on a series of discrete but interrelated fault segments to produce a more complex rupture than current hazard models

consider. The non-vertical dip of the PVF at depth, and the dip-slip components of motion, may cause coseismic ground shaking that would differ from those produced by a simply, vertical strike-slip fault.

This research directly addresses the External Research Program Announcement for Fiscal Year 2005, 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.

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1.0 INTRODUCTION

This project investigates the structural geometry, kinematics, and earthquake potential of the Palos Verdes Fault (PVF) in southern California. Using an extensive data set of industry seismic reflection profiles and petroleum well data, the three-dimensional subsurface geometry of the fault, inc luding its dip and along-strike geometric segmentation, is being investigated to define the deformational history and kinematics of the fault, providing a basis to map slip and slip rate estimates to depth. This study also defines individual fault segments within the larger fault system, which provide constraints on the fault surface areas that might be expected to rupture during future earthquakes on the PVF. Implications of this study for earthquake hazards will be addressed by re-assessing possible magnitudes of earthquakes that rupture all or parts of the fault system, based on our improved definition of the fault size, shape, and along-strike geometric segmentation.

The PVF is recognized as a major structure in the western Los Angeles basin (Figure 1), extending over 100 km from the eastern margin of the uplifted Palos Verdes Hills southeast through the Port of Los Angeles and offshore across the San Pedro shelf. Numerous studies have focused on defining the location, activity, 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). However, there is currently no consensus about the fault's subsurface geometry, along-strike geometric segmentation, northern and southern terminations, or detailed 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.

A primary question about the PVF, and of significant relevance to earthquake hazard models in the LA Basin, 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. Along the onshore portion of the fault, 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 uplifted marine terrace remnants on the Palos Verdes Peninsula, used numerical fault models to interpret the PVF as a right-oblique reverse fault and obtained good matches to the terrace elevation data. These authors proposed that the reverse component of slip and west dipping fault segment form a restraining bend, but that the dipping fault segment is generally limited to the onshore portion of the fault.

To the south along strike, the fault has generally been considered to be vertical with purely right-lateral strike slip displacement. This is consistent with a number of steeply dipping to near-vertical faults splays that have been mapped in the offshore Beta oil field along the PVF (Kelsch et al., 1998; Rigor, 2003). In addition, shallow paleoseismic studies onshore and in the Los Angeles Harbor (Stephenson et al., 1995; McNeilan et al., 1996) interpreted near-vertical faults, with nearly pure strike-slip displacement of about 2.5-3.8 mm/year. This vertical fault model currently forms the basis for earthquake hazard estimates of the fault. However, other authors (Davis et al., 1989; Shaw and Suppe, 1996) have interpreted that at depth the PVF has a southwestern dip and a significant reverse component of displacement along its entire extent, which may significantly affect these hazard estimates.

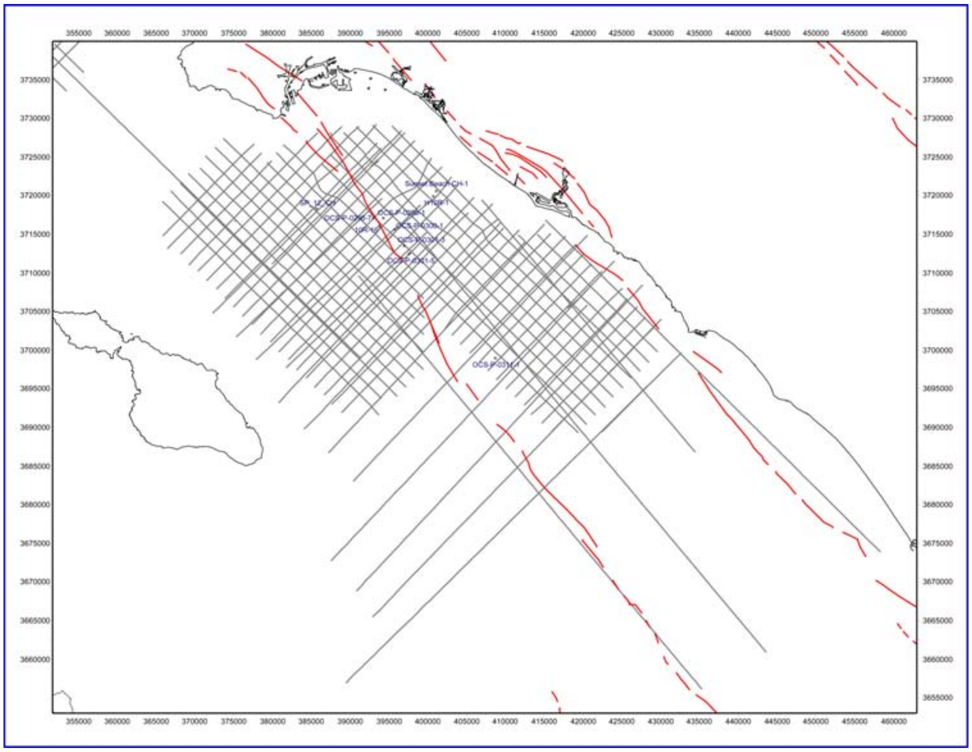

Figure 1: Location map of the San Pedro Bay region, showing the location of seismic lines used in this project. Red lines represent fault traces from Jennings (1994).

2.0 SEISMIC REFLECTION DATA

The subsurface structures along the trend of the PVF are imaged in an extensive set of 2D and 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. Eighteen seismic reflection lines, comprising approximately 800 km of data and covering the region along the PVF south of the Palos Verdes Peninsula, were digitized and vectorized. An additional several thousand kilometers of digital seismic data was obtained from the USGS through the National Archive of Marine Seismic Surveys (http://walrus.wr.usgs.gov/NAMSS). These data were imported into a PC-based seismic data project to facilitate mapping and structural interpretation (Figure 1). The data form a dense regional grid of NE-SW striking dip lines and SE-NW trending strike lines (Figure 1). 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 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.

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.

3.1 Structure of the Palos Verdes Fault in San Pedro Bay

Figure 2 shows a representative seismic line across the San Pedro Shelf, south of the Palos Verdes Peninsula, which illustrates several of the structural features that characterize this trend. At this location, the PVF in the upper 3-4 km is expressed as a near-vertical zone of incoherent and disrupted reflectors west of an undeformed basin filled with Miocene and later sediments. West of the fault, the Miocene units are deformed in contractional folds, thinning onto a prominent basement high. Within these contractional folds, the wedge of Neogene strata thickens toward the fault, and exhibits an internal fanning of limb dips that records down-to-the-fault rotation of the underlying basement block. Maximum thicknesses of units west of the fault are greater than the thicknesses of the corresponding units east of the fault. In addition, the stratigraphic horizons are structurally higher west of the fault than their corresponding horizons east of the fault. Finally, repetition and overthrusting of the basement reflector is observed at the base of the near-vertical shallow fault zone. These features are consistently observed along the PVF in the northern portion of the study area. Figure 3 shows a depth-converted seismic line with interpretation of structural and stratigraphic features.

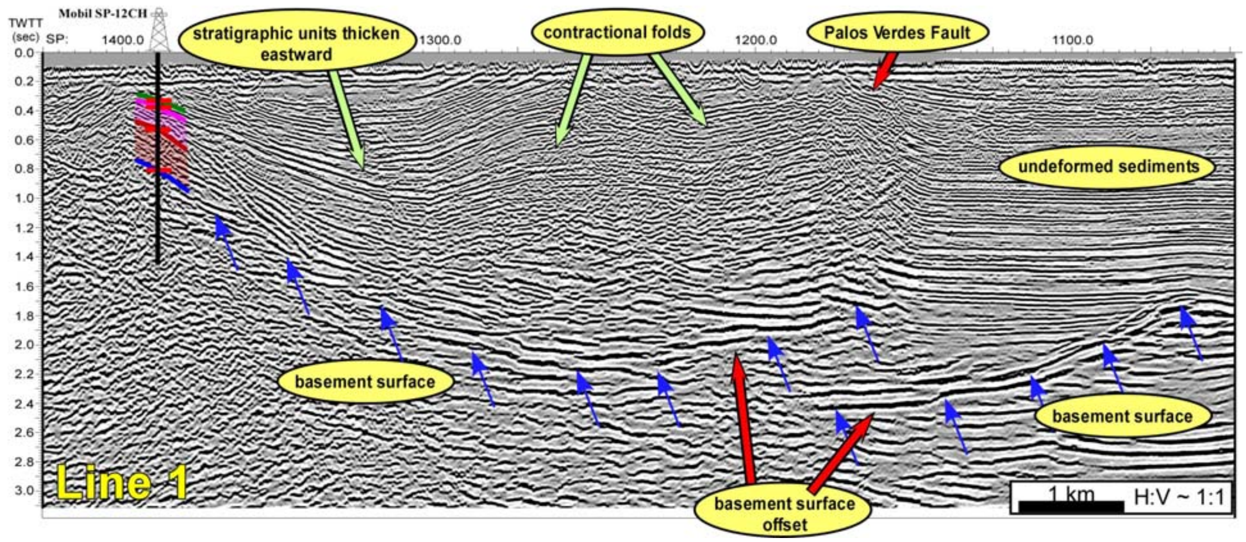

Figure 2: Seismic line (time section) showing structural and stratigraphic features which characterize the deformation surrounding the Palos Verdes Fault.

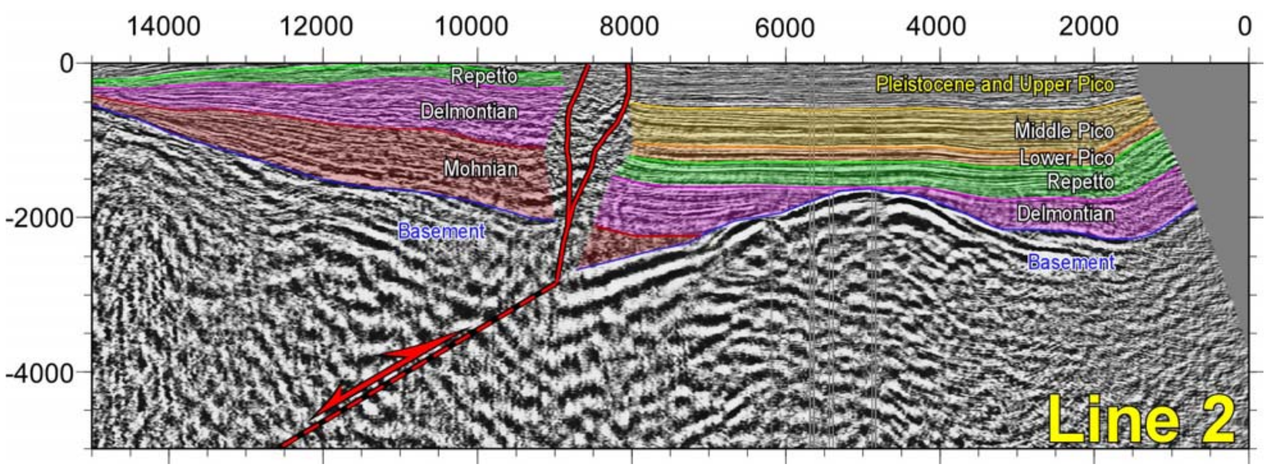

Figure 3: Seismic line (depth section) showing interpretations of stratigraphy and fault geometry in the region of San Pedro Shelf. See Figure 6 for location of line.

The geometry of sedimentary units described above is consistent with, and indicative of, deposition of growth strata in the hanging wall above a west-dipping fault with normal displacement (Hamblin, 1965; Xiao and Suppe, 1992). This interpretation is consistent with the known period of Miocene normal faulting that accommodated pure or oblique crustal extension (Crouch and Suppe, 1993; Rivero et al., 2000). Furthermore, the presence 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. 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. Thus, we interpret these structural and stratigraphic patterns to reflect that the Palos Verdes fault has reactivated a large, Miocene age normal fault. Based on the stratigraphic correlations, this inversion occurred in the late

Pliocene to Pleistocene, at the inception of the modern oblique, right-lateral reverse fault system, and appears to have generated the younger contractional folding and generated (or enhanced) the vertical fault splays.

These structural observations and their implied fault kinematics are most compatible with a southwest dip component of the Palos Verdes fault at depth in this region. This southwesterly dip is confirmed by the seismic images that show the top of basement and Tertiary strata duplicated (overthrust) by the Palos Verdes fault (Figure 2B), in a position below the imaged vertical fault splays. In depth profiles, hanging wall and footwall cut-offs constrain the fault to dip less than 55° to the southwest. Thus, the southwestern dipping portion of the Palos Verdes fault appears to extend well south of the onshore Peninsula.

3.2 Structure of the Southern Palos Verdes Fault

Farther to the south, the fault structure in the shallow subsurface changes character. Figure 4 shows a profile approximately 20 km south of the Peninsula, and shows structures and stratigraphic relationships similar to those observed in Figure 2. Eastward thickening Miocene growth strata is deformed by contractional folding, and the shallow, near-vertical fault zone is similar to that in Figures 2 and 3. However, this fault zone is located in the hanging wall of a well-imaged east-dipping reverse fault and associated anticline that accommodates a component of NE-SW contraction. The geometry of the east-dipping reverse fault, and the deformation of the Miocene growth sediments, is consistent with this fault representing either (1) a backthrust originating from the underlying west-dipping normal fault surface, which has been structurally inverted in compression; or (2) a younger reverse fault which crosscuts and offsets the earlier normal fault. In addition, a second, minor west-dipping reverse fault is present west of the PVF, and this structure dies to the north and south into an anticline-syncline pair (see Figure 6).

To the south near Lasuen Knoll, the fault system exhibits different structural details that are nevertheless consistent with reverse displacements and non-vertical fault geometries (Figure 5). The PVF is emergent at the base of the western margin of Lasuen Knoll (off the seismic section). Dip-slip components of motion result in contractional growth folding that is expressed on the east side of the Knoll. The geometry of the folded sediments on the eastern flank of the uplifted block is consistent with reverse displacement on the east-dipping reverse fault that can be traced southeast along strike from the location of Figure 3. Similar to Figure 3, this fault may be a backthrust above the inverted west-dipping normal fault, or continue to deeper levels as an east-dipping reverse fault that crosscuts the older normal fault. We prefer the backthrust/wedge interpretation as it is most consistent along the length of the PVF. These contractional growth structures are similar to structures documented above blind thrust faults elsewhere in southern California (Shaw and Suppe, 1994; 1996), and thus can be used to constrain the magnitudes and long-term rates of the contractional component of fault motion.

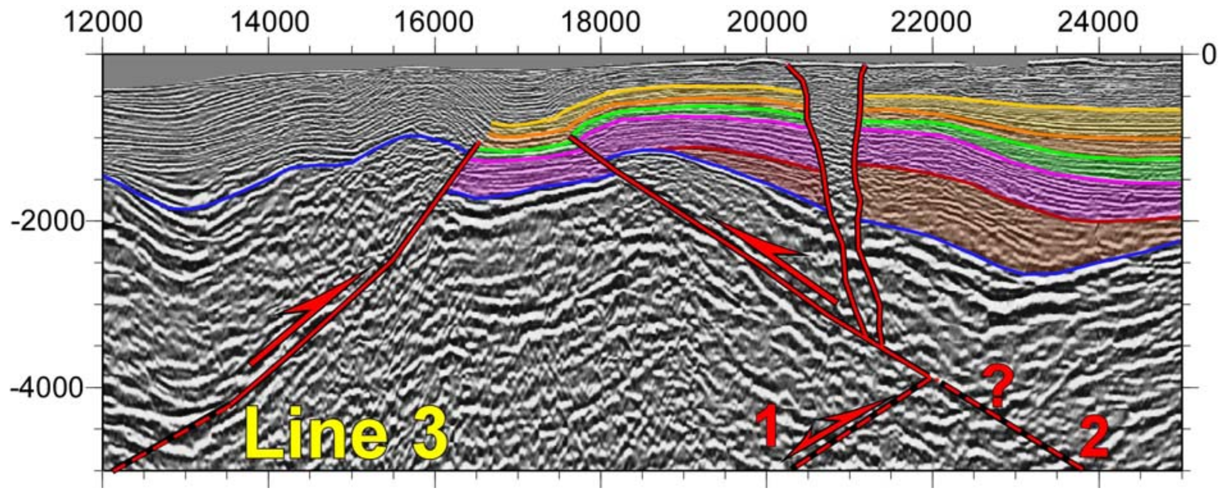

Figure 4: Seismic line (depth section) showing interpretations of stratigraphy and fault geometry and the transition to a more complex fault geometry than to the north. See Figure 6 for location of line.

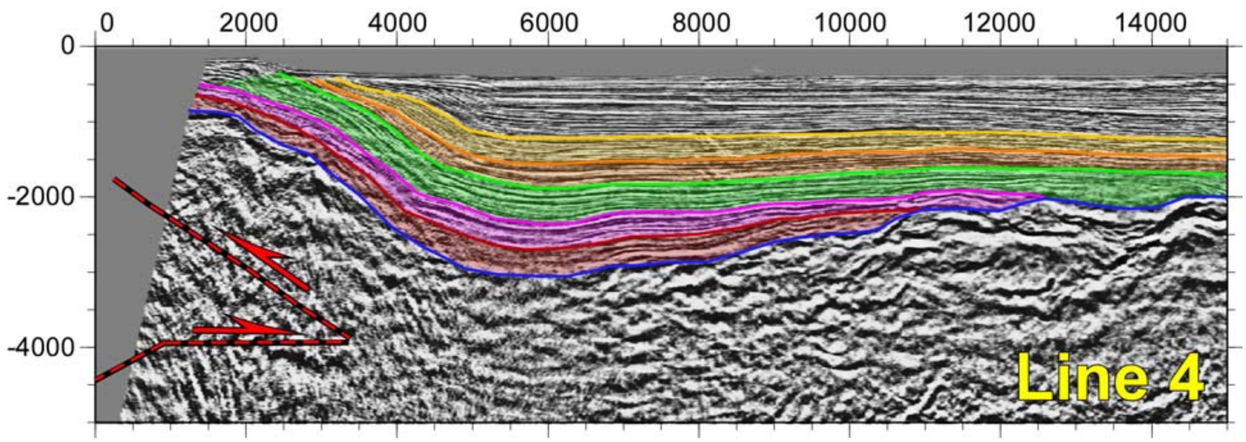

Figure 5: Seismic line (depth section) showing interpretations of stratigraphy and fault geometry in region of Lasuen Knoll. See Figure 6 for location of line.

4.0 DISCUSSION

A structure map of the region (Figure 6) and a map of the basement surface (Figure 7) show the regional character of deformation, highlighting the locations and displacements of the major segments of the PVF. At least three well-defined fault segments (informally named here F1, F2, and F3) intersect and offset the basement surface. A near-vertical, southeast-trending fault zone (F1) extends from the northern edge of the study area southwest, corresponding approximately to the mapped trace of the PVF (Jennings, 1994; Fisher et al., 2004). This fault zone is well imaged for approximately 13 km. Although the 1 km-wide fault zone corresponds to a zone of reduced seismic reflectivity and highly disrupted reflectors, the basement surface is clearly offset by up to 800m across the fault, with the west side displaced up (Figure 2). Below a depth of approximately 3km, the top of basement and Tertiary strata are duplicated (overthrust) by the Palos Verdes fault, in a position below the imaged vertical fault splays. Hanging wall and footwall cut-offs constrain the fault dip to less than 55° to the southwest. Displacement across the fault appears to decrease to the south along the fault. A second major fault segment (F2) overlaps the southern portion of F1 and continues southeast across the study region. This fault is expressed clearly along its northern extent by a southwest-vergent folding and overthrusting of basement above an east-dipping fault, locally expressed in fault-plane reflections. F2 extends southeast and bounds an uplifted block of basement that forms Lasuen Knoll. A smaller fault segment (F3) is present subparallel to the northern portion of F2 and consists of a southwest-dipping, northeast-vergent fault plane that offsets basement in a reverse sense. This fault segment appears to extend only about 10km to the south, where it terminates into an anticline-syncline pair.

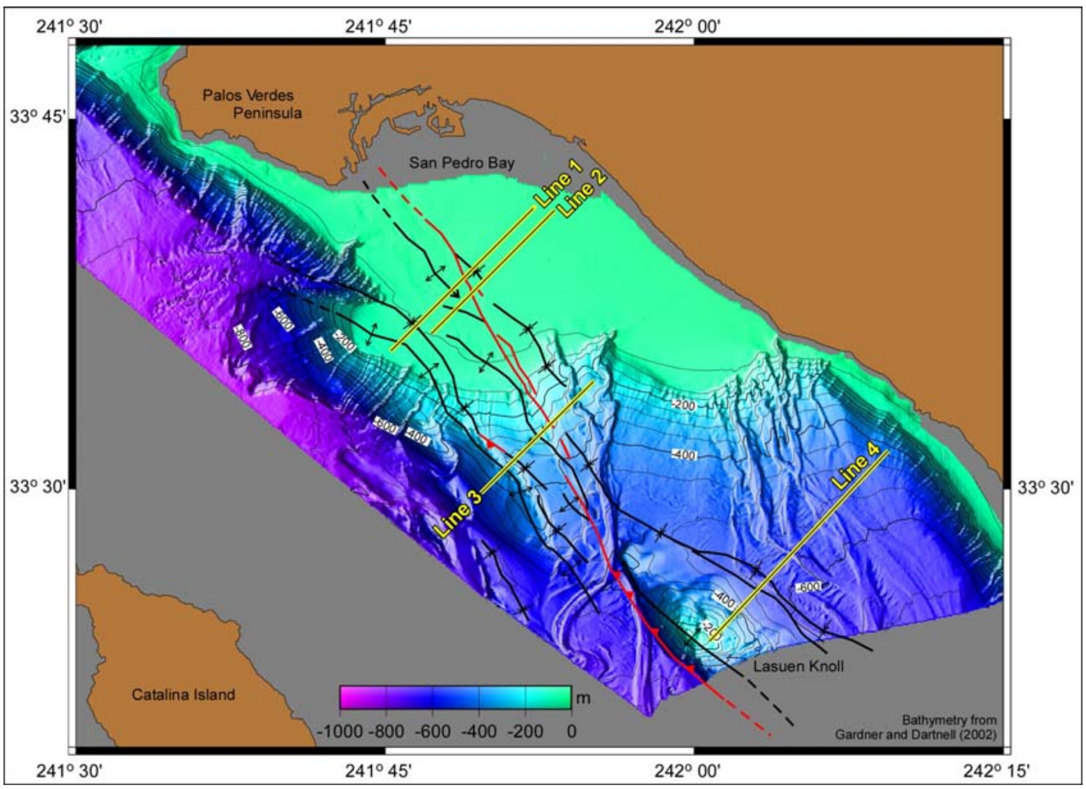

Figure 6: Map showing structures mapped from seismic reflection profiles overlaid on contours and shaded relief image of bathymetry (from Gardner and Dartnell, 2002). Locations of lines in figures 2-5 are shown.

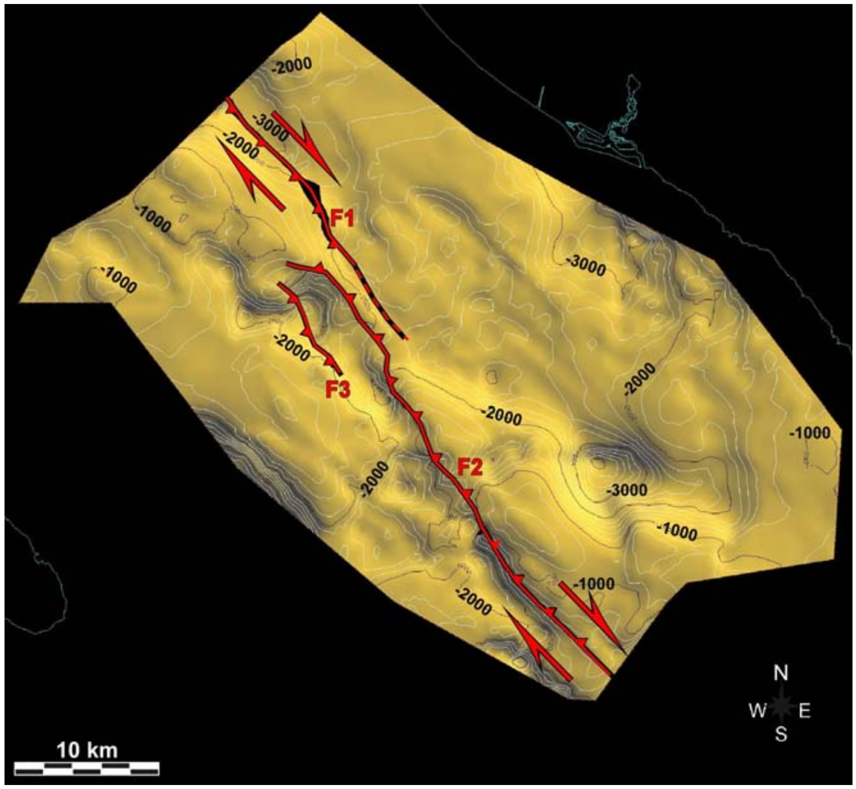

Figure 7. Contour map of top of basement, showing fault segments along the PVF. Segment F1 corresponds to the near-vertical trace of the PVF, with significant west-side-up and right-lateral strike-slip displacement. Segment F2 represents an east-dipping reverse (oblique-reverse?) fault that extends south to Lasuen Knoll. Segment F3 corresponds to a short west-dipping reverse fault that continues as an anticline north and south along strike.

All three fault segments identified above show direct indications of fault geometry in the seismic data, and two (F2 and F3) are further constrained by direct fault plane reflections. The geometry of fault F1 appears to change from near-vertical in the upper 3km to moderately west-dipping below 3km. Mapping of other stratigraphic horizons has revealed patterns of sedimentary architecture that provide indications of the fault geometry at depth, as well as its structural evolution (Figures 2 and 4). The thicknesses of the Miocene sedimentary units vary greatly across F1. East of the fault, these units are nearly flat-lying, and have uniform thicknesses to the northeast. West of the fault, however, the thickness of the units varies dramatically. Units are thin or not present on the basement high west of F1, pinching out or onlapping on to the east-dipping basement surface. In turn, the units thicken markedly to the east toward the fault.

The structural and stratigraphic observations and their implied fault kinematics are most compatible with a southwest dip component of the Palos Verdes fault at depth in this region. Thus, the southwest-dipping portion of the Palos Verdes fault appears to extend well south of the onshore Peninsula. These observations provide immediate confirmation that neither the simple vertical fault model, nor the model of the reverse fault extending only beneath the uplifted onshore Palos Verdes Hills, is accurate or sufficient for the purposes of seismic hazards estimates.

While right-lateral strike-slip motion has been documented by paleoseismic studies (Stephenson et al., 1995; McNeilan et al., 1996) and using numerical fault models (Ward and Valencise, 1994), we propose that the strike-slip displacement cannot in itself explain the structural and stratigraphic relationships observed in the seismic data. A component of dip-slip displacement is evident along the entire length imaged in the seismic data. For instance, the structural inversion of Miocene strata across the fault, the contractional folding west of the PVF, and the prominent emergent structural block of Lasuen Knoll, all argue for significant dip-slip displacements. Uplift of Lasuen Knoll has previously been explained as a pop-up structure developed by strike-slip motion through a restraining bend fault architecture (Fisher et al., 2004). However, resolving right-lateral slip on the fault trace as mapped in the seismic data (see Figure 6) results in a releasing bend geometry. Thus, we conclude that purely strike-slip motion on the PVF is not sufficient to result in the large magnitude of uplift at Lasuen Knoll. It appears that strike-slip displacement is accommodated in the discrete shallow fault traces imaged in the seismic data, while the deeper fault slips in an oblique-reverse sense.

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, in part, inherits its geometry from pre-existing structures in regions along the fault. The northern portion of the fault, in the San Pedro Shelf region, 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 inverted in the later, 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. First, 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. In addition, 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.

Ongoing regional mapping in year 2 of this grant project will refine the stratigraphic and structural relationships presented above. In addition, we will define permissible deep fault geometries, consistent with the observed shallow features, using kinematic models of growth deposition above normal faults and subsequent structural inversion. The result will be two-dimensional fault models that will then be linked into a 3D fault model that will serve as an accurate subsurface representation of the PVF.

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