NEW CONSTRAINTS ON THE LOCATION, GEOMETRY, SLIP RATE, AND SEISMIC POTENTIAL OF THE PALOS VERDES FAULT ZONE, SOUTHERN LOS ANGELES BASIN, CALIFORNIA BASED ON STUDIES FOR THE PROPOSED NEW EFFLUENT OUTFALL TUNNEL THROUGH THE PALOS VERDES PENINSULA

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ABSTRACT

1. New high-resolution 2-D seismic reflection data were collected for the Sanitation Districts of Los Angeles County’s proposed Joint Water Pollution Control Plant Effluent Outfall Tunnel across the Holocene-active Palos Verdes fault zone (PVFZ) in the eastern Palos Verdes Peninsula (PVP). These data were used in conjunction with digital renderings of early 20th-century topography and borehole data to refine the location, geometry and kinematics of shallow (< 2,000 meters) faulting and folding along one of the highest-slip-rate structures in the greater metropolitan Los Angeles area. The onshore PVFZ is approximately 2,000 meters wide and consists of four principal strands, referred to herein as the northern, middle and southern splays (PFVN, PVFM and PVFS, respectively), and an unnamed blind backthrust. PVFN bounds the northeastern range front of the PVP, and is interpreted as a 75-degree, southwest-dipping blind reverse fault. PVFM is interpreted as an 80- to 85-degree, southwest-dipping, right-oblique fault, whereas the PVFS is interpreted as a vertical strike-slip fault based on the down-dip trajectory of reflection terminations, an abrupt

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juxtaposition of contrasting reflection sequences and, as visible in the early 20th-century topographic data, aligned linear drainages, slope breaks and channel deflections. Reassessment of offsets of the ancestral LA River canyon suggests that the total late Quaternary slip rate is 3-3.5 mm/year at this location. Approximately 2 mm/year of slip is accommodated on the middle splay and 1 mm/year on the southern splay. The fault zone geometry and kinematics arise from a 20-degree restraining bend in the fault. Probabilistic and deterministic fault displacement hazard assessment results are presented in a companion paper by Kocijan et al. [1] and have been incorporated into the design of the new effluent outfall tunnel. Numerous other critical lifelines also cross the PVFZ, and should be considered in resiliency planning and future seismic retrofits.
New constraints on the Location, Geometry, Slip Rate, and Seismic Potential of the Palos Verdes Fault Zone, Southern Los Angeles Basin, California based on studies for the proposed new Effluent Outfall Tunnel through the Palos Verdes Peninsula

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ABSTRACT

New high-resolution 2-D seismic reflection data were collected for the Sanitation Districts of Los Angeles County’s proposed Joint Water Pollution Control Plant Effluent Outfall Tunnel across the Holocene-active Palos Verdes fault zone (PVFZ) in the eastern Palos Verdes Peninsula (PVP). These data were used in conjunction with digital renderings of early 20th-century topography and borehole data to refine the location, geometry and kinematics of shallow (< 2,000 meters) faulting and folding along one of the highest-slip-rate structures in the greater metropolitan Los Angeles area. The onshore PVFZ is approximately 2,000 meters wide and consists of four principal strands, referred to herein as the northern, middle and southern splays (PFVN, PVFM and PVFS, respectively), and an unnamed blind backthrust. PVFN bounds the northeastern range front of the PVP, and is interpreted as a 75-degree, southwest-dipping blind reverse fault. PVFM is interpreted as an 80- to 85-degree, southwest-dipping, right-oblique fault, whereas the PVFS is interpreted as a vertical strike-slip fault based on the down-dip trajectory of reflection terminations, an abrupt juxtaposition of contrasting reflection sequences and, as visible in the early 20th-century topographic data, aligned linear drainages, slope breaks and channel deflections. Reassessment of offsets of the ancestral LA River canyon suggests that the total late Quaternary slip rate is 3-3.5 mm/yr at this location. Approximately 2 mm/yr of slip is accommodated on the middle splay and 1 mm/yr on the southern splay. The fault zone geometry and kinematics arise from a 20-degree restraining bend in the fault. Probabilistic and deterministic fault displacement hazard assessment results are presented in a companion paper by Kocijan et al. [1] and have been incorporated into the design of the new effluent outfall tunnel. Numerous other critical lifelines also cross the PVFZ, and should be considered in resiliency planning and future seismic retrofits.

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Introduction

The proposed tunnel will carry secondary treated effluent from the JWPCP, located in Carson, under the Palos Verdes Peninsula (PVP) where it will tie into an existing manifold structure at White Point (Figs. 1 & 2). The tunnel alignment crosses the Palos Verdes Fault Zone (PVFZ) bounding the northern side of the PVP. Two-dimensional (2D) onshore seismic reflection data were collected at the intersection(s) of the proposed tunnel alignment with the PVFZ (Fig. 2). The PVFZ is of particular importance to tunnel design because it is a known Holocene-active structure with the potential to generate earthquakes of magnitude Mw=7.0 to 7.8 [2][3][4]). The onshore PVFZ consists of a complex zone of right-lateral, reverse-oblique and reverse fault splays that accommodates up to 4 mm/yr of the relative Pacific-North America plate motion [2][5][6]), making it one of the highest-slip-rate faults in the Los Angeles Basin. Historically, there has been significant uncertainty and disagreement regarding the location, number of individual faults, style, and activity level of the PVFZ in the PVP. Much of this uncertainty arose because the tectonic geomorphic expression of the fault zone has been heavily altered by extensive urban development in the PVP, which began in the mid-20th century. The PVFZ has a well-documented history of Holocene displacement in the nearby Port of Los Angeles, where displacement of an approximately 8ka paleochannel yields an average slip rate of 2.7 to 3 mm/yr [2]. In the Outer Harbor area, Fugro [7] used seismic reflection and geotechnical data to derive a Holocene slip rate of 3 mm/yr and a relative horizontal-to-vertical slip ratio of 7:1. Near Vincent Thomas Bridge, the dip of the PVFZ is well-constrained at 70° to 75° to the west; the width of the fault zone is ~400m [3]. Offshore on the San Pedro Shelf lateral offsets of the Miocene depocenter across the PVFZ have been used to estimate a longer-term slip rate of 4 +/- 0.3 mm/yr [6]. To the southeast on the offshore San Pedro Slope, previous work has [8] established a preferred slip rate of 1.6-1.9 mm/yr over the
last 17 to 31 ka based upon a dated offset landslide headscarp and associated debris flow deposits. This study used subsurface seismic reflection and historical digital elevation data to better constrain the locations of fault splays along the tunnel alignment. The seismic reflection data were integrated with proprietary project geotechnical and geospatial data as well as publicly-available geologic and oil and gas exploration well records to characterize the style, sense of motion and slip rates of faults crossing the tunnel alignment. These data were also used to aid in understanding structural relationships and stratigraphic contacts in the subsurface. Better constraints of the fault splay locations were used to assess possible impacts of fault displacements and folding on the proposed tunnel.

**Methodology**

**Technical Approach**

This study integrated seismic reflection data collected for the final tunnel design with public and private topographic, geologic and geotechnical data. These latter datasets were used to guide and inform interpretation of the seismic reflection data. The seismic reflection data were used primarily to locate fault splays, characterize the structural geometry, and evaluate Quaternary activity based on subsurface cross-cutting relationships.Geomorphic data were used primarily to evaluate recency of activity and sense of slip. Numerous datasets were compiled and managed using IHS Kingdom and ArcGIS software platforms, including: 2D seismic reflection data acquired by Fugro for the project, geologic map of the Palos Verdes Peninsula [9], Subsurface geologic mapping and observations from the Whites Point outfall tunnel, Geotechnical borehole data acquired for the project, Oil and gas well records, and Digital Elevation Model (DEM) derived from historical topographic maps of the PVP.

![Figure 2. Map showing historical DEM of the Palos Verdes Peninsula and location of Seismic Profile 1. PoLA=Port of Los Angeles. JWPCP=Joint Water Pollution Control Plant. Inset view is towards the northwest.](image-url)
Data Summary

Geologic Mapping of the Palos Verdes Peninsula

The structural and stratigraphic framework used for interpreting subsurface contacts in the seismic reflection is based on Dibblee (1999). Surface stratigraphic contacts, structural features, and strike-and-dip measurements were used in conjunction with the reflection fabric to develop geologically-informed interpretations of the subsurface.

Stratigraphy

At the broadest level, the stratigraphy of the PVP can be subdivided into five lithologic assemblages. From oldest to youngest, these are: (1) Mesozoic basement rock; (2) Miocene bioclastic and marine sedimentary and volcanic rocks; (3) Miocene to Pliocene terrigenous marine sedimentary rocks; (4) semi-consolidated Pleistocene strata; and (5) Quaternary surface deposits. Catalina Schist forms the basement rock of the PVP and consists primarily of greenschist, epidote-blueschist and possibly amphibolite [10]. Surface exposures of basement rock occur along the crest of the PVP. Catalina Schist was encountered during excavation of White Point Tunnel and was identified in numerous oil and gas exploration wells near the Alignment. Basement rock is unconformably overlain by an approximately 950m-thick sequence of Miocene to Pliocene sedimentary and volcanic rocks [3, 11-13]. From oldest to youngest, these strata include the San Onofre breccia, Monterey Formation, Malaga Mudstone, and Fernando Formation. Quaternary stratigraphy of the PVP can be divided into an older sequence of consolidated to semi-consolidated Pleistocene marine strata, and a younger sequence of various unconsolidated mostly terrestrial surficial deposits. The younger Quaternary sequence in the PVP includes deposits associated with elevated flights of emergent marine terraces, deep-seated landslide deposits, older and younger generations of alluvium, older and younger generations of eolian dunes, and beach deposits [9]. Alluvial deposits rest on the eroded surface of the underlying Pleistocene sediments and older strata. Beneath the Torrance Plain they are primarily stream-deposited sand, silt and clay with some gravel in the Lakewood Formation, which underlies younger fluvial, estuarine and lacustrine floodplain deposits that are essentially undeformed by tectonic processes. Along Gaffey Street, the alluvial deposits are associated with incision and infilling of the paleo Los Angeles River channel. This channel coincides with the parts of the proposed tunnel alignment along Gaffey Street. The channel incises marine terrace deposits dated to be as young as 120 to 80 Ka and was subsequently abandoned due to uplift of the Gaffey Anticline across the PVFZ [5, 14]).

Subsurface Geology from White Point Tunnel, Wells, and Boreholes

The two existing effluent outfall White Point Tunnels were excavated across the PVP in 1935 and 1936. The tunnel exposures provided direct observations of structure, stratigraphy and engineering geologic behavior of the rock mass in the subsurface [11]. To integrate the Whites Point tunnel data with the seismic reflection data in this study, the line location and tunnel stations were imported into IHS Kingdom software, and then projected along strike (where applicable) onto the seismic profile. The existing and proposed new White Point Tunnel alignments are shown on Fig. 2. Data from oil & gas wells and boreholes drilled along the
existing and new tunnel alignments provide information on the lithology, depth, and location of stratigraphic contacts in the subsurface. They also provide a means of correlating seismic stratigraphic packages and individual reflections observed in the seismic data to the lithostratigraphic framework [9].

**Digital Elevation Model**

identified in the seismic reflection data were evaluated with respect to a digital elevation model (DEM) generated from 5-foot contour maps made by the USGS in 1925, 1928 and 1934 (Fig. 2). This DEM data set is significant because it depicts the topography of the Palos Verdes Peninsula prior to the extensive urban development that characterizes the area at present. The DEM data were used to generate derivative hillshade and slope maps, which were manipulated to accentuate potential tectonic geomorphic features.

**Results**

The seismic profile (profile) trends north-south and spans the entire mapped width of the PVFZ and clearly images the subsurface to a depth of ~1.4km (Figs. 2 and 3).

**Geomorphic Setting and Surface Geology Along Profile**

The seismic reflection profile follows Gaffey Street through a canyon incised into a narrow piedmont separating the northeastern Palos Verdes Hills from the Torrance Plain and the Port of Los Angeles (Fig. 2). The piedmont is bound on the northeast and southwest sides by geomorphic features indicative of faults such as aligned linear valleys, offset drainages and topographic escarpments (Fig. 4). The canyon traversed by the seismic line was carved by the Los Angeles River, and

![Figure 3. Uninterpreted and interpreted Seismic Reflection Profile along Tunnel Alignment beneath Gaffey Street. See Figure 1 for profile location. PVFS=South Splay PVFZ; F2=Unnamed Blind Backthrust; PVFM=Middle Splay PVFZ; PVFN=North Splay PVFZ (Blind). Unit descriptions and provided below.](image-url)
was abandoned in the Late Pleistocene [5] due to uplift of the Palos Verdes Hills along the PVFZ.

The surface geology along Profile 1 consists of Quaternary alluvium (Qa) with isolated exposures of the underlying Quaternary San Pedro Sand (Qsp) (Fig. 5b). Both units are gently folded into the Gaffey Syncline and Gaffey Anticline. Qsp strata along the Profile dip consistently at 5 to 6° [9], except along the crest of the Gaffey anticline and range front of the PV Hills, where they dip 9° to 10° to the north (Figs. 3 and 5). Exposures immediately to the northwest of the profile indicate that the Middle Pleistocene San Pedro Sand is underlain by more-deformed Pliocene- to Miocene-aged strata of the Fernando Formation, Malaga Mudstone and Monterey Formation.

**Seismic Stratigraphy of Profile**

Figure 3 shows uninterpreted and interpreted seismic reflection data along the Profile. Subsurface seismostratigraphic units mapped along the profile are described from youngest to oldest.

**Undifferentiated Middle and Late Quaternary Units (Qu):** Unit Qu includes Holocene and Late Pleistocene alluvium, channel fill deposits, and San Pedro Sand. This sequence is variably expressed in the seismic data as acoustically transparent (both the younger and older alluvium); wavy, low amplitude reflectors with moderate to poor lateral continuity (Lakewood Formation); and planar to slightly wavy, high-amplitude reflections with strong lateral continuity. As a seismic stratigraphic package, the Middle and Late Quaternary units form a continuous capping sequence that spans the length of Profile 1. Base of Qu was identified in geotechnical boreholes, and is defined by angular unconformity. This unit has less internal deformation relative to underlying sequences.

**Early and Middle Pleistocene San Pedro Formation (Qsp):** Unit Qsp consists of wavy, moderate- to high-amplitude reflections with poor to moderate lateral continuity. Lithologic descriptions for this depth interval provided in the Palos Verdes No. 1 exploration well log record include sand, gravel and boulders, with minor shale intervals. The base of Qsp is defined by up to 20° of angular discordance with underlying reflections. In the Palos Verdes No. 1 well,
this depth coincides with a change to predominantly shale. Based on the wavy nature and poor lateral continuity of the reflector fabric, Qsp is interpreted as a fluvial and/or deltaic sequence from the ancestral Los Angeles River.

Pliocene Fernando Formation (Tfp/Tfr): The Fernando Formation is subdivided into two members: Pico (Tfp) and Repetto (Tfr)[9]. Tfp is expressed in the seismic reflection data as an approximately 485m-thick sequence of planar, moderate to high amplitude reflectivity with strong lateral continuity. Unit Tfr is significantly thinner in the south, where it forms discontinuous outcrops on the PVP west-northwest of the profile. It is expressed in the seismic data by reflections that are wavy, low amplitude, and of low lateral continuity. The base of Tfr south of station 4,000 is defined by a distinct, 45m-thick pair of high-amplitude reflectors that discordantly overlie more steeply dipping reflection sequences. To the south of the southern strand of the PVFZ, the base of this unit paraconformably overlies Malaga Mudstone and Monterey Formation.

Undifferentiated Miocene-Pliocene Malaga Mudstone and Monterey Formation (Tmg/Tm): Unit Tmg/Tm is expressed in the seismic data as an approximately 970m-thick (maximum) sequence of reflections that vary from planar to wavy, and moderate to high amplitude with poor to strong lateral continuity. At the south end of the line the inclination of the reflection fabric becomes progressively steeper with depth (i.e., it fans to the north). The base of Tm is defined by an abrupt decrease in both the lateral continuity and amplitude of seismic reflections. The reflective fabric below these depths is typically chaotic and is interpreted as acoustic basement. Farther north, the Keck Syndicate well (Figs. 3 and 4) never encountered basement, indicating that the Monterey Formation thickens considerably from south to north.

Mesozoic Catalina Schist (sc): Unit sc is expressed in the seismic reflection data by reflective fabrics that vary from very low amplitude (i.e., acoustically transparent) with poor lateral continuity, to high amplitude with strong lateral continuity. In both cases, the fabric is typically folded and non-parallel to overlying sequences.

Fault Location and Geometry Along Profile

Two different classes of faults are interpreted along this profile: (1) Primary faults, which are

[Figure 5. Paleo-LA River Thalweg Profile with projected base Qoa surface and piercing points of primary splays of the PVFZ. Profile location, primary fault locations, and surface geology map [9] shown on lower panel.]
considered seismogenic and capable of generating significant subsurface or surface deformation potentially on the order of meters; and (2) secondary faults (Fig. 3b). Primary and secondary faults are differentiated from one another based on down-dip extent of reflection terminations, juxtaposition of disparate seismic reflection domains and stratigraphic units, and geomorphic expression. Four primary faults and numerous secondary faults are mapped. Only the primary faults are described in this paper. The four primary faults are labeled F1, F2, F3, and F4 (Figs. 3b and 4). Faults F1 and F4 correlate to the mapped traces of the PVFZ by Fugro in 2010 [15], and F3 correlates to a fault identified by previous workers [5]. Fault F2 is newly identified in this study.

**South Splay PVFZ (PVFS)** is defined in the seismic data by a subvertical alignment of truncated and folded reflections that can be traced to a depth of at least 1.4km. The fault juxtaposes a planar, north-dipping reflection fabric on the south from a more deformed sequence of wavy reflections on the north. PVFS geomorphic expression is characterized by aligned linear valleys, topographic saddles and deflected drainages, and is nearly coincident with the Gaffey Syncline (Fig. 4).

**Unnamed F2 Blind Backthrust Fault** is defined by an 80-degree, northeast-dipping alignment of truncated and offset reflections that can be traced from depth to an elevation of ~212m (~150m below the tunnel zone), where it terminates in a series of unfaulted reflections. While there is no obvious geomorphic expression of a fault in the DEM at this location, the tipline of F2 corresponds with a southwest-side-down step or fold in the base of the 120,000-year-old marine terrace and an inflection point in the thalweg of the paleo-LA River channel (Fig. 5a), and is structurally linked to the other primary faults of the PVFZ (Fig. 3). Faults F2 and F3 lie near the center of the Profile, and define an upward-branching geometry. They bound a buried bedrock anticline.

**Middle Splay PVFZ (PVFM)** is expressed in the seismic data by an 80- to 85-degree southwest-dipping alignment of truncated and offset reflections. The fault juxtaposes wavy and folded seismic reflection fabric from a more planar, broadly folded reflection fabric to the north (Fig. 3). The walls of the former Los Angeles River canyon—estimated to be no older than 120,000 to 80,000 years—are right-laterally offset by the PVFM (Figs. 4 and 5). This fault (1) bounds the thickest stratigraphic section of the Monterey Formation, (2) emplaces Miocene strata (Monterey Formation) over Pliocene and Pleistocene strata to the north (Fernando Formation and San Pedro Formation), (3) has generated an ~15m down-to-the-northeast step in the base of the

![Figure 6. Palinspastic Restoration of LA River Channel across southern and middle splays of the PVFZ based on channel wall piercing points. Panel A) Present Day, B) PVFM Restoration, C) PVFS Restoration.](image-url)
undifferentiated Middle to Late Pleistocene sequence (unit Qu), and (4) corresponds to a large northeast-side-down step in the top of basement rock (Catalina Schist). Based on thickness trends of the Monterey Formation and Fernando Formation, the PVFM is interpreted as an inverted normal fault. This interpretation is consistent with the presence of the buried anticline, which lies in the hangingwall of this structure and formed during the inversion process. Vertical offset on the base of the Qu sequence across the PVFM is estimated to be ~15m, whereas the right-lateral offset on the Late Pleistocene canyon carved by the Los Angeles River may be as great as ~340 m (Figs. 5a and 6). Previous workers [5] estimated ~300 m dextral offset along this fault splay.

North Splay PVFZ (PVFN). Based on aligned reflection truncations at depth, this fault dips approximately 75° to the south-southwest. The tipline is well constrained at depth by an unfaulted angular unconformity at an elevation of ~450m (Fig. 3). This fault is thus blind, and does not offset near-surface geologic units. The fault tip terminates within a prominent synformal hinge, which is most obviously expressed within a sequence of planar and laterally-continuous reflections (Fig. 3), which correspond to the Pliocene Fernando Formation. Folding above the blind fault involves the Middle Pleistocene marine sequence as well as both the Late Pleistocene marine terraces and thalweg of the abandoned course the Los Angeles River. The location of the fault tipline defines the range-front fold scarp and topographic uplift boundary.

Discussion

Age Constraints and Kinematics of Faulting Along Profile

The four primary splays which comprise the PVFZ crossed by the tunnel alignment define an ~2km-wide zone (Fig. 4). Two of the splays are blind faults and do not rupture to the surface. Geomorphic and geophysical data suggest that the most active strands showing evidence for surface rupture and strike-slip displacement of Late Pleistocene strain markers are the PVFS and
PVFM faults. Significant shortening and uplift appear to be accommodated by fault-propagation folding that begins directly above the blind tipline of the PVFN fault (Fig. 7). The four primary fault splays unequivocally offset or fold the ~120,000-year-old oxygen isotope stage 5e marine abrasion platform and thalweg of the abandoned Los Angeles River. All four primary faults are considered Holocene-active and capable of producing permanent ground deformation within the tunnel envelope. Based on tectonic geomorphic features observed along the fault, such as aligned linear valleys and saddles, and deflected drainages (Fig. 4), and the sub-vertical fault dip (Fig. 3), motion along the PVFS is predominantly right-lateral strike-slip. Motion along PVFM is predominantly right-lateral strike-slip with the potential for minor south-side-up reverse slip (i.e., reverse-oblique motion). This is based on dextral offset of the abandoned channel margin of the Los Angeles River [5](Fig. 6), and the relatively minor vertical offset of the base of the Qu sequence interpreted in the seismic reflection data (Fig. 5a). Motion along PVFN is purely dip-slip based on the lack of resolvable lateral offset of the abandoned LA river channel where it crosses the fault. This is further supported by the relationship between the blind fault and the overlying fault-propagation fold, and the spatial association with the topographic uplift boundary (Fig. 7). The canyon formerly occupied by the Los Angeles River crosses the fold scarp of the PVFN and, within the resolution of the DEM, shows no horizontal offset (Fig. 6). As stated above, this fault is blind and does not directly cross-cut the tunnel zone. Ground deformation above the unnamed F2 blind backthrust is anticipated to be expressed by only minor folding.

**Slip Rate Estimates**

Geomorphologic and structural relationships suggest distributed faulting and strain partitioning across the entire PVFZ. Based on interpretation of a 300-m deflection of the ancestral LA River Channel, and an estimated age of the MIS Stage 5e and/or 5c terrace into which the channel is incised is 80,000 to 120,000 years [14], resulting in previous estimates of the slip rate for the middle strand of the fault at 2.5 to 3.8 mm/year [5]. In the Port of Los Angeles, a paleochannel (~8 ka) offset across the PVFZ yields a Holocene slip rate of 2.7 to 3.0 mm/yr [2]. The latter is significant because the PVFZ at the Port of Los Angeles consists essentially of a single strand or narrow zone. This slip rate, therefore, provides a “slip budget” for assessing relative activity levels elsewhere along the fault zone. Based on geomorphic analysis of the historical DEM, measured dextral offsets across the PVFM identified in this study suggest a range of ~160 to ~330 m of offset of the eastern and western channel walls along Gaffey Street (Figure 6). Based upon an offset range of approximately 200 to 300 m and an estimated age of 100,000 +/- 20,000 years, the estimated slip rate for the PVFM is 1.7 to 3.8 mm/yr. Using a preferred offset of 250 m and preferred age of 115,000 years yields a slip rate of 2.17 mm/yr. The southern strand exhibits approximately 95 m +/- 10 m of offset of the eastern channel margin, and 110 m +/- 10 m of offset of the western channel margin along Gaffey Street, suggesting a dextral (right-lateral) rate of approximately 0.7 to 1.5 mm/yr over the past 100,000 +/- 20,000 years. Using a preferred offset of 105 m and preferred age of 115,000 years yields a slip rate of 0.91 mm/yr. Geomorphic interpretations of channel alignments across the northern splay suggest no detectable dextral offset on this splay within the resolution of the existing DEM. The geometry of the channel margins across the fault-propagation fold above the northern splay suggest pure reverse faulting
at depth, with folding and associated uplift at the surface. Interpretation of the seismic reflection and geomorphic data likewise suggests deformation at the location of the northern splay is dominated by a sharp flexure and folding, with no significant lateral displacement. The thalweg profile down the LA River Channel (Fig. 5a) shows >4.5m of distributed vertical flexure across the PVFZ, which is interpreted to have occurred since channel abandonment approximately 45-50ka (MIS stage 3). A topographic profile of the base of the uplifted older Quaternary Alluvium (Qoa) surface [9], which represents the MIS Stage 5e marine terrace [14], projected onto the thalweg profile illustrates ~35m of uplift and distributed flexure over the past ~115,000 years. The vertical uplift starts above the tipline of the northern fault splay, and tapers off to the south of the southern fault splay. Inflection points along the profile of the paleo-LA river thalweg coincide with each of the four major strands of the PVFZ (Fig. 5a). The total combined preferred dextral slip across the PVFZ based on the measured channel offsets of the middle and southern fault splays along Gaffey Street as presented in this study is 3.08 mm/yr, within a range of 2.0 to 5.6 mm/yr. Lower confidence is placed on the upper bound slip rate estimate than the lower bound limit. High confidence is placed on the preferred slip rate for the middle and southern fault splays. Additional slip may be accommodated by motion on the blind northern fault splay, the unnamed F2 blind backthrust, off-fault deformation, and minor slip on secondary fault strands. Presuming the observed channel deflections reflect dextral slip over the past 80-120 ka, the distribution of right-lateral displacement across the primary middle (PVFM) fault strand is about double that on the southern (PVFS) fault strand.

Conclusions

Slip partitioning and distribution may result in the total displacement across the PVFZ being distributed across several fault strands during individual earthquakes. It is possible, however, that all of the strike-slip displacement in a single event will occur on one fault strand, as is commonly observed on other major strike-slip faults with multiple, parallel fault strands in Southern California. The available data for the PVFZ along the Gaffey Street section of the JWPCP alignment show that the dominant mode of surface deformation, and thus hazard, to the tunnel crossing of the northern strand and the unnamed F2 blind backthrust is distributed tilting or flexure. Conversely, the available data show that the dominant sense of slip on the middle and southern fault strands is strike-slip, with only very minor vertical motions. Over a time scale of ~100 ka, it appears that approximately twice as much slip has occurred on the middle splay relative to the southern splay; however, there are no data to suggest whether this ratio may persist for individual fault ruptures, or whether it characterizes the most recent behavior on the fault. Thus, for design considerations of the new tunnel, it would appear that displacement values approaching ~90% of the total dextral slip derived from either probabilistic or deterministic assessments [1] of the PVFZ should be considered credible at both the middle and southern splay fault crossings. Numerous other critical lifelines also cross the PVFZ, and should be considered in resiliency planning and future seismic retrofits.

References


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