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FINAL TECHNICAL REPORT

Project Title:

Subsurface Characterization of the Potrero-Ryer Island Thrust System, Western Sacramento-San Joaquin Delta, Northern California

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ABSTRACT

The western Sacramento-San Joaquin Delta region is bounded on the west by the dextral Concord-Green Valley fault system, and on the east by the dextral Pittsburg-Kirby Hills fault zone. Based on analysis of drill hole and seismic reflection data, we interpret that the geologic structure between these two major fault systems is characterized by a series of east-west to WNW-ESE-trending anticlines, most of which coincide with developed gas fields. From south to north, the major folds include: the Los Medanos Hills anticlinorium; Roe Island and Ryer Island anticlines; the Honker-Van Sickle anticlinorium; the Suisun-Grizzly Island anticline or anticlinorium; and the Potrero Hills anticline. Drill hole data and seismic reflection profiles confirm that several of the anticlines in the western Delta region are underlain by blind thrust faults, indicating that they have formed as fault-bend or fault-propagation folds.

The anticlines in the western Delta region are part of a contractional belt that extends southward to the northern Diablo Range, and which includes the late Cenozoic Mt. Diablo anticline. For convenience, we refer to these structures collectively as the Mt. Diablo fold-and-thrust belt. South of the Delta, major structures of the Mt. Diablo fold-and-thrust belt include: the Williams and Verona thrust faults; Tassajara anticline; and Mt. Diablo anticline. The Los Medanos Hills anticlinorium and northwest-southeast-trending folds in the western Delta represent the northward continuation of the Mt. Diablo fold-and-thrust belt. The contractional structures in this belt trend more westerly and exhibit a right-stepping, en echelon geometry with respect to the Greenville and Concord strike-slip faults. South of the Sacramento River, the asymmetric folds consistently verge to the southwest and underlying thrust faults dip northeast. This pattern changes north of the Sacramento River and Suisun Bay, where the Suisun-Grizzly anticline, Honker-Van Sickle anticline and the Potrero Hills anticline verge to the northeast and are underlain by southwest-dipping thrust faults.

The Pittsburg-Kirby Hills fault zone passes through the Kirby Hills, intersects the eastern margin of the Potrero Hills anticline, and forms an eastern tectonic boundary to the contractional domain in the western Delta region. Structure contours on the Eocene Domengine sandstone, a prominent stratigraphic marker and producing gas horizon, document the absence of comparable west-northwest-trending folds east of the Pittsburg-Kirby Hills fault zone. These observations suggest that the Pittsburg-Kirby Hills fault zone accommodates the differential shortening between the western and eastern Delta regions, probably as a strike-slip fault. This structural interpretation is consistent with focal mechanisms for small earthquakes whose epicenters lie along the map trace of the fault, which indicate primarily right-lateral slip on north-northwest-striking nodal planes. The hypocenters for these events are located at depths of 18 km or greater, which we interpret to show that the Pittsburg-Kirby Hills fault is a deeply rooted, steeply dipping to subvertical strike-slip fault zone. Shallow high resolution seismic reflection profiles strongly suggest that Holocene deposits in the channel of the Sacramento River are deformed above the Pittsburg-Kirby Hills fault, presumably by fault rupture associated with one or more earthquakes.

Based on the orientation of the fold-and-thrust structures and their spatial association with strike-slip faults, we interpret that shortening in the western Delta region primarily is driven by distributed northwest-directed dextral shear between the Concord-Green Valley fault system on the west and the Pittsburg-Kirby Hills fault zone on the east. Patterns of microseismicity, particularly along the Pittsburg-Kirby Hills fault zone, and the occurrence of at least one historical earthquake (i.e., the M6 1889 Antioch earthquake) indicate that the region is seismically active. Potential sources of moderate to large magnitude earthquakes in the western Delta region include the Los Medanos Hills thrust fault (blind); the Roe Island thrust fault (blind); the Pittsburg-Kirby Hills fault; and the Potrero Hills thrust fault (blind). Based on analysis of open-hole logs, seismic reflection profiles, and on construction of restorable cross sections, we conclude that the thrust

faults beneath the Suisun-Grizzly and Honker-Van Sickle anticlines are not deeply rooted (i.e., do not extend to depths at which moderate to large magnitude earthquakes nucleate in western California), and thus are unlikely to be independent seismic sources.

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1.0 INTRODUCTION

The purpose of this study is to identify and map potentially active faults in the western Sacramento-San Joaquin Delta region, northern California. For the purposes of this report, boundaries of the western Delta region include the Concord-Green Valley fault and the Carquinez strait on the west; the Pittsburg-Kirby Hills fault and the Montezuma Hills on the east; the Los Medanos Hills on the south; and the Potrero Hills anticline on the north (Figure 1). Thus defined, the western Delta region includes Suisun Bay, Grizzly Bay, Grizzly Island, as well as several smaller islands within the Sacramento River. The majority of the reclaimed Delta islands, as well as the extensive Delta levee system, lie directly east of the detailed study area (Figure 1).

Our technical approach consists of using subsurface mapping techniques, including detailed analysis of open-hole logs and interpretation of seismic reflection profiles, to construct a series of structure contour maps and cross-sections through the western Delta region. Through this analysis, we seek to identify major contractional structures, evaluate the dimensions of late Cenozoic folds, and infer the geometry of hidden or "blind" thrust faults that underlie the folds. The subsurface analysis was augmented by kinematic modeling of focal mechanisms from small and moderate magnitude earthquakes in the study region to evaluate seismogenic strain and assess the role of structures identified in this study in accommodating active deformation.

In the following report, we describe the tectonic setting of the western Sacramento San Joaquin Delta region (Section 2); present the results of our subsurface data analysis (Section 3) and inversion of seismicity data (Section 4); and develop a tectonic model for the western Delta (Section 5), with emphasis on evaluating the down-dip geometry of thrust faults west of the Pittsburg-Kirby Hills fault zone.

1.1 Acknowledgments

We thank Mr. Louis Klonsky (Chevron, Bakersfield) for permitting us to examine proprietary seismic reflection profiles from Suisun Bay in the western Delta region. Gary Drilling Company (Davis office, northern California) generously provided access to its library of open-hole logs in the Delta for our use in developing the maps and cross-sections in this report. Also, we gratefully acknowledge discussions with Mr. Steve Muir (WZI, Lodi, California), Dr. Patrick Williams (Lawrence Berkeley Laboratory) and Dr. Janine Weber-Band (UC Berkeley) regarding the structure and tectonics of the study region.

1.2 Publications Supported by This Research

Unruh, J.R., Hector, S.T., Williams, P.L., and Rector, J.W., 1997, Transpressional tectonics of the western Sacramento-San Joaquin delta, eastern San Francisco Bay region, California: EOS (Transactions, American Geophysical Union), v. 78, no. 46, p. F631-F632.

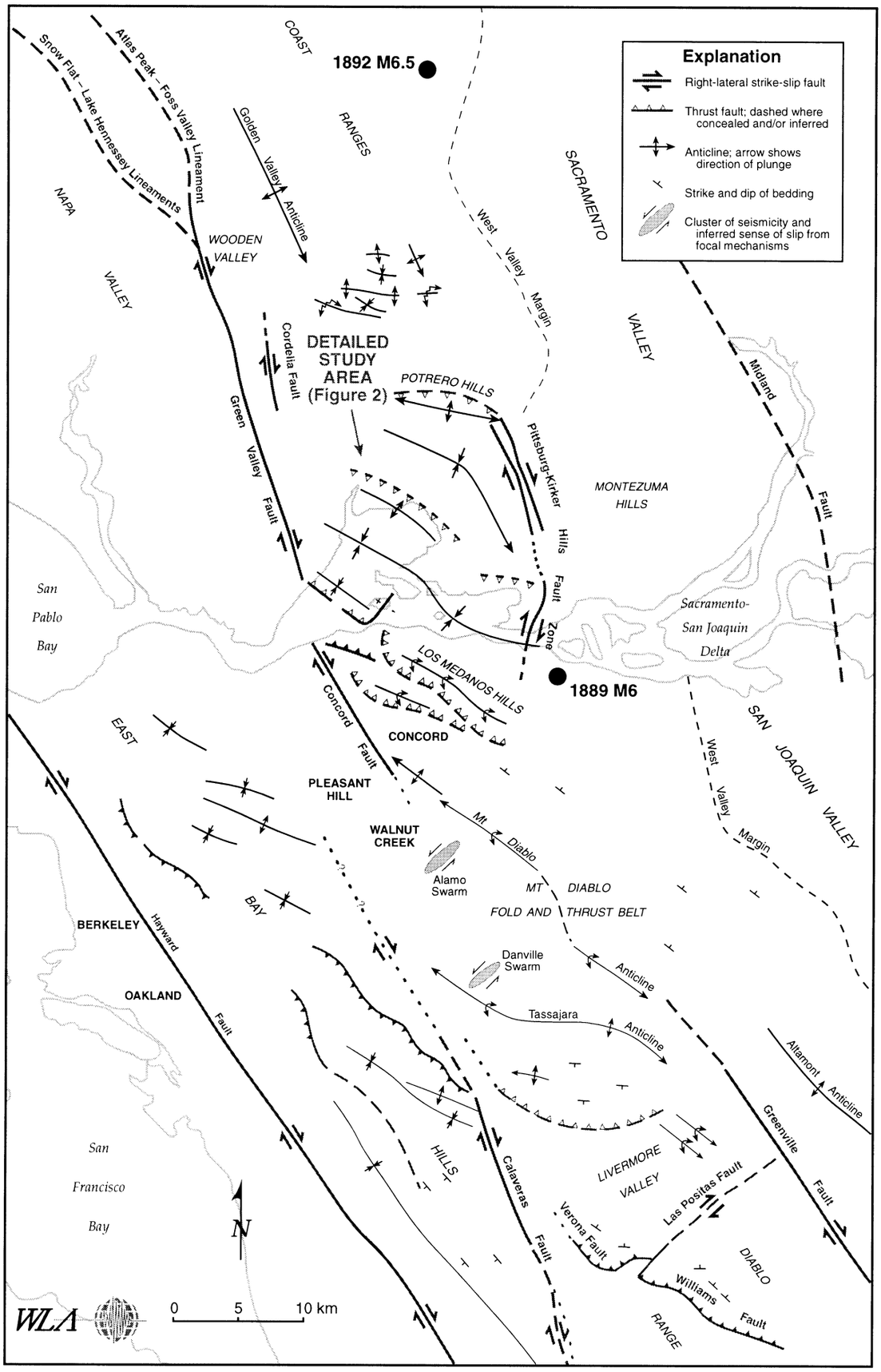

Figure 1. Generalized tectonic map of the eastern San Francisco Bay area, northern California. The box shows the location of the western Sacramento-San Joaquin Delta study region.

2.0
REGIONAL TECTONIC SETTING

The western Sacramento-San Joaquin Delta study area lies at the northern end of a belt of contractional structures that can be mapped continuously for about 60 km north of the Diablo Range and Livermore Valley (Figure 1). On the west, this contractional belt is bounded by the Concord-Green Valley fault system. On the east, the belt is bounded by the Greenville fault, Pittsburg-Kirby Hills fault, and the western San Joaquin Valley. South of the Delta, the contractional belt is associated with an area of high, youthful topography that includes the 1173-m-high peak of Mt. Diablo. Following Unruh and Sawyer (1997), we refer to this group of contractional structures as the Mt. Diablo fold-and-thrust belt.

The contractional structures in the Mt. Diablo fold-and-thrust belt exhibit a well-defined right-stepping, en echelon geometry with respect to the major dextral faults of the eastern San Andreas system. Starting in the Diablo Range south of Livermore and moving north, the en echelon pattern is defined by the following structures (Figure 1): the Williams and Verona faults; the Tassajara anticline; the Mt. Diablo anticline; the Los Medanos Hills anticlinorium; west-northwest-trending folds in the western Delta; and the east-west-trending Potrero Hills anticline. The maximum structural relief within this contractional belt occurs across the Mt. Diablo anticline.

Unruh and Sawyer (1995; 1997) proposed that crustal shortening in the Mt. Diablo fold-and-thrust belt is "transpressional" in nature, and driven primarily by a restraining left-stepover or transfer of dextral slip from the Greenville fault southeast of Mt. Diablo to the Concord fault northwest of Mt. Diablo. In this model, most of the dextral slip is transferred from the Greenville fault to the Concord fault across the Mt. Diablo anticline, but west-northwest-trending folds in the Tassajara Hills and Livermore Valley south of Mt. Diablo, as well as the Los Medanos Hills anticlinorium and folds in the western Delta region to the north, indicate that dextral shear probably is distributed across a broad north-south zone between the Greenville and Concord faults that is approximately centered on the Mt. Diablo anticline. This model is consistent with: (1) the oblique trends of the contractional structures relative to the major strike-slip faults; (2) the right-stepping, en echelon geometry of the contractional structures; and (3) the observation that the maximum structural relief in the belt occurs across Mt. Diablo anticline.

Unruh and Lettis (1998) attributed the distinctive pattern of "transpressional" deformation in the Mt. Diablo fold-and-thrust belt to a more northward orientation of macroscopic dextral shear east of the Hayward fault, as originally discussed by Gilbert et al. (1994). Major strike-slip faults east of the Hayward fault, including the Greenville and Concord faults, are parallel to the local direction of macroscopic dextral shear but are oblique to the general northwest-southeast orientation of the Pacific-Sierra Nevada plate boundary. In order to maintain continuity and conserve slip along strike, the dextral faults preferentially form contractional left stepovers. These stepovers in turn generate localized zones of crustal shortening like the Mt. Diablo fold and thrust belt (Figure 1).

3.0 IDENTIFICATION AND DOCUMENTATION OF SEISMIC SOURCES

3.1 Rationale and Methodology

Previous workers (Hector and Unruh, 1992; Hoffman, 1992; MacKevett, 1992; Crane, 1995a; Unruh et al., 1997a; Weber-Band, 1998) have recognized that the major gas-producing structures in the western Delta region are a series of northwest-southeast- to WNW-ESE-trending folds. Extremely generalized structure contour maps published by the Division of Oil and Gas (1982) indicate that individual gas fields in the western Delta are formed by anticlines or faulted anticlinoria. Although these maps are useful for identifying potentially significant folds in the western Delta region, detailed maps are necessary to constrain the geometry of the folds for the purposes of drawing restorable cross sections. An integrated structural map of the western Delta region also is necessary to assess the lateral extent of the folds and provide a basis for evaluating the dimensions of blind thrust faults beneath the folds to estimate maximum earthquake magnitudes. We thus undertook a systematic program of subsurface analysis to prepare maps that can be used to evaluate contractional structures in the Delta as potential seismic sources.

Structure contour maps of individual gas fields were constructed by interpreting key stratigraphic contacts identified on open-hole well logs. The majority of the well data used in this effort were provided by Gary Drilling Company (Davis office, northern California); in several cases, we purchased open-hole logs from data brokers to fill gaps in Gary Drilling Company's well log library. We selected the Eocene Domengine sandstone, a laterally-extensive stratigraphic horizon that is relatively easy to identify on electric logs, for drawing detailed structure contour maps. Where readily discernible, we also picked the tops of the Nortonville shale and the Capay shale, which are stratigraphically above and below the Domengine sandstone, respectively (detailed descriptions of these Eocene units are provided by MacKevett, 1992). For deviated wells, the true horizontal positions and vertical depths to the tops of stratigraphic units were calculated using directional surveys. The measured depth and true vertical depth for the Domengine sandstone and other stratigraphic markers are tabulated for each well in Appendix 1.

After interpreting stratigraphy on the e-logs, we prepared a map of the depth to the top of the Domengine sandstone at 1:12,000 scale for each of the major gas fields in the western Delta region. To supplement the contour mapping, we constructed shallow cross-sections across each of the major gas fields by correlating Eocene stratigraphic units among wells. Interpretations of well data and seismic reflection profiles from the western Delta region published by Hoffman (1992) and MacKevett (1992), as well as original analysis of proprietary seismic reflection profiles for this study, were useful for constraining our map interpretations of the structure of individual fields.

We compiled the maps of individual gas fields at a smaller scale to generate a regional map of structure on the top of the Domengine sandstone in the western Delta region (Figure 2). We incorporated extensive subsurface mapping by Hoffman (1992) of the Domengine sandstone in the vicinity of the Los Medanos Hills and the city of Concord in this map to show that structural trends discussed in Section 2.0 can be traced with confidence from the Mt. Diablo and Concord areas northward into the western Delta region. Also, we reviewed proprietary seismic reflection profiles of varying vintage and quality to interpolate structure contours in synclinal regions between the major antiformal gas fields. We acknowledge that the structure contours are less well constrained in these regions; however, we believe that the general depiction of structural trends is correct, and that the dimensions of the folds are sufficiently well constrained by the available data to develop models for blind thrust faults beneath the folds.

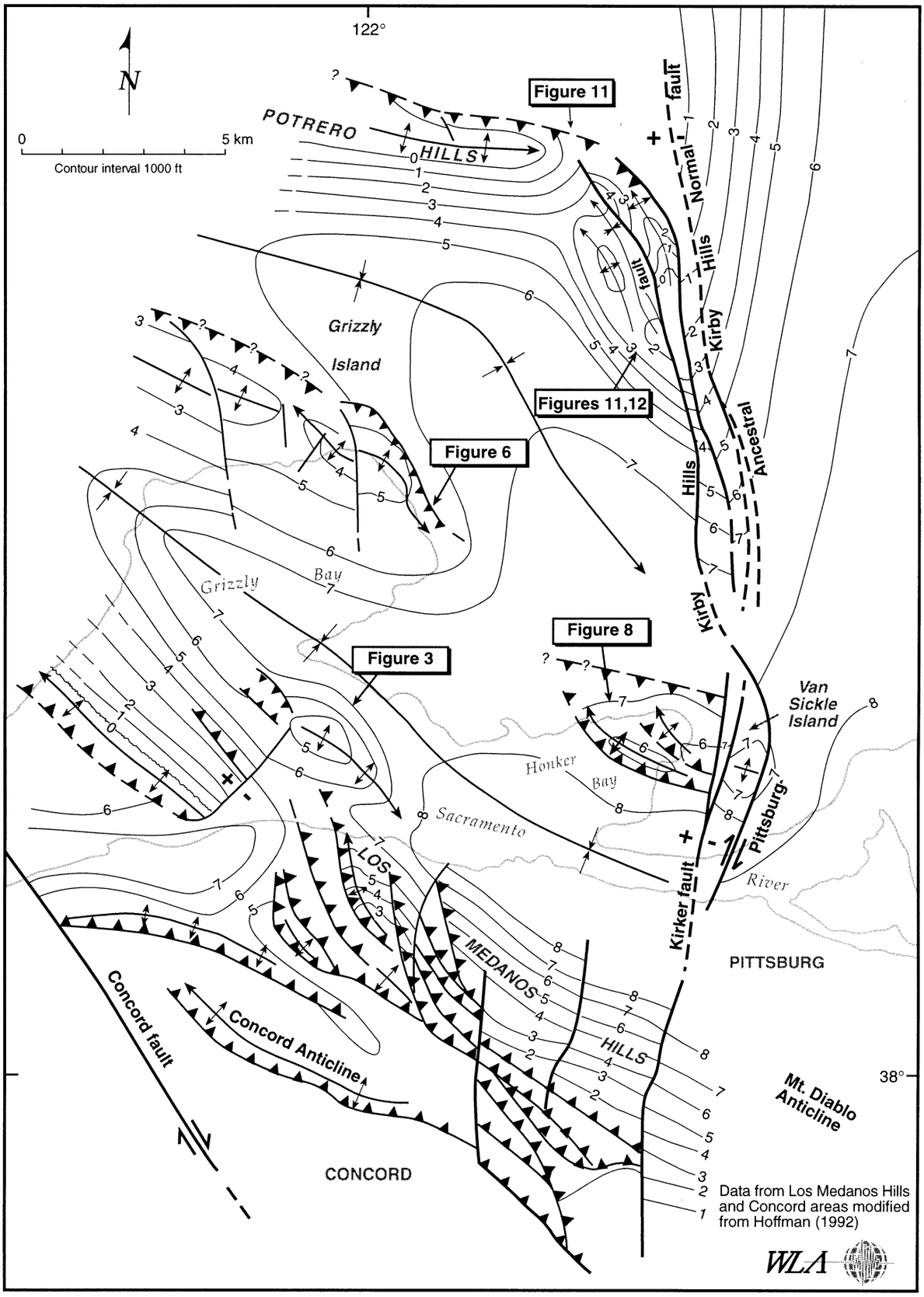

Figure 2. Structure contour map on the top of the Eocene Domengine sandstone in the western Delta study area. Contour interval is 1000 feet. Data from the Los Medanos Hills and Concord areas are modified from Hoffman (1992). See indicated figures for detailed maps of individual gas fields.

In the following sections, we describe the structure of individual gas fields in the western Delta study region.

3.2 Los Medanos Hills Anticlinorium

The Los Medanos Hills anticlinorium underlies the low hills north of the town of Clayton and east of the town of Concord (Figure 2) (Hoffman, 1992). The structure either plunges steeply to the northwest and southeast, or it is truncated at both margins by northeast-striking high-angle faults (Hoffman, 1992). Based on detailed analysis of the drill hole data, Hoffman (1992) interpreted that the Los Medanos Hills anticlinorium consists of three distinct folds or fold structures, segmented by northeast-striking high-angle faults that form structural boundaries of individual gas fields. From southeast to northwest, these structures include the Mulligan Pass, Willow Pass and Los Medanos anticlines (Hoffman, 1992). The crest of each structure is cut by a somewhat different pattern of closely-spaced thrust and reverse faults. We interpret these folds to be a single anticline or anticlinorium because they lie along a common trend, have a similar southwest-vergent geometry, and exhibit roughly similar amounts of structural relief. Total northwest-southeast length of the Los Medanos anticlinorium is approximately 10 km, and total northeast-southwest width of the structure is approximately 4.5 km (Figure 2).

Wells drilled to the west of the Los Medanos Hills anticlinorium penetrated a series of lower amplitude folds called the Concord anticline and the City of Concord anticline (Hoffman, 1992). The folds are associated with low hills southwest of the Los Medanos hills. These structures are parallel to the Los Medanos trend, and as they approach the Concord strike-slip fault they either die out or are truncated by the fault (Figure 2).

Gas exploration wells document uplift, folding and local repetition of the Eocene Domengine sandstone by thrust faulting beneath the Los Medanos Hills anticlinorium and folds to the southwest (Hoffman, 1992). Minimum structural relief on the Domengine sandstone across the main antiformal axis is approximately 1400 m. Structural relief on the Domengine sandstone across the smaller Concord and City of Concord anticlines to the west is approximately 600 m or less. Based on line-length restoration of the Domengine sandstone in Hoffman's cross sections, total post-Eocene horizontal shortening across the Los Medanos Hills anticlinorium and folds in the Concord area is about 2.2 km to 2.5 km. Based on analysis of drill hole data, Hoffman (1992) inferred that the Pleistocene Montezuma Formation is involved in the folding of the Los Medanos Hills anticlinorium, implying that at least some growth of the fold occurred during the Quaternary.

3.3 Roe Island and Ryer Island Anticlines

Roe Island and Ryer Island are located within the Sacramento River channel south of Grizzly Bay and east of the Carquinez strait (Figures 2 and 3). The islands are associated with Ryer gas field, which is formed by northwest-trending anticlinal traps (Division of Oil and Gas, 1982). Crane (1995a) interpreted that the fold structures are underlain by northeast-dipping thrust faults on his compilation maps.

Roe Island is associated with an asymmetric, southwest-vergent anticline, herein referred to as the Roe Island anticline, that is at least 4 km long (Figure 3) and may be up to 8 km long if the fold axis extends as far northwest as the Green Valley fault (Figure 2). Minimum structural relief of about 1740 m across the fold is documented by two wells: (1) the State 3743.1, #48-2 well, which encountered the Domengine sandstone at about 1740 m (5703 ft) near the base of the backlimb of the fold; and (2) the State 3742.1, #47-2 well, which was drilled near the crest of the fold and encountered the Domengine at a depth of about 93 m (304 ft) (Figure 4). Total relief across the structure probably is greater than 1740 m because the Domengine sandstone is

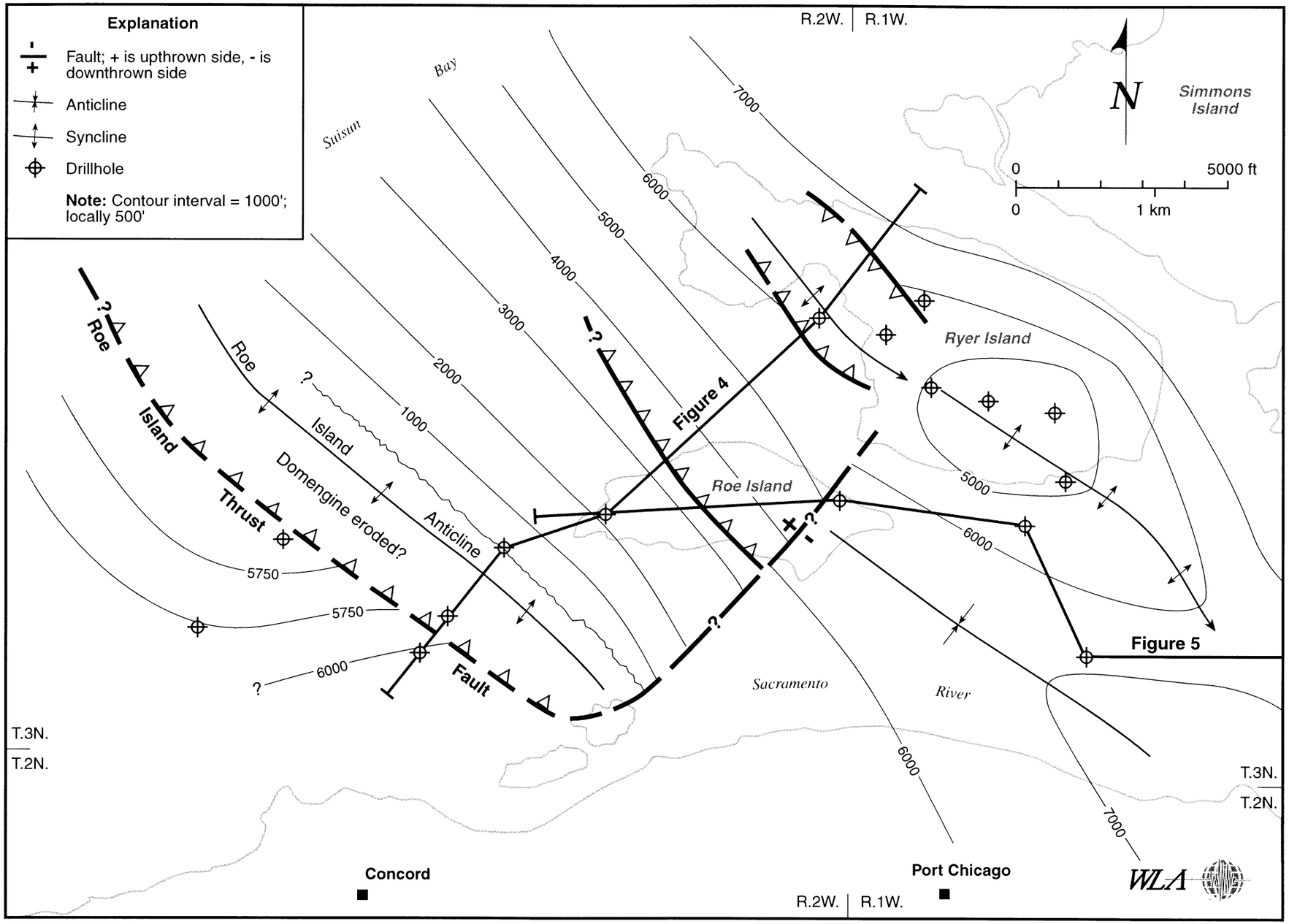

Figure 3. Structure contour map on the top of the Eocene Domengine sandstone, Roe Island and Ryer Island gas fields (see Figure 2 for location in the western Delta study region).

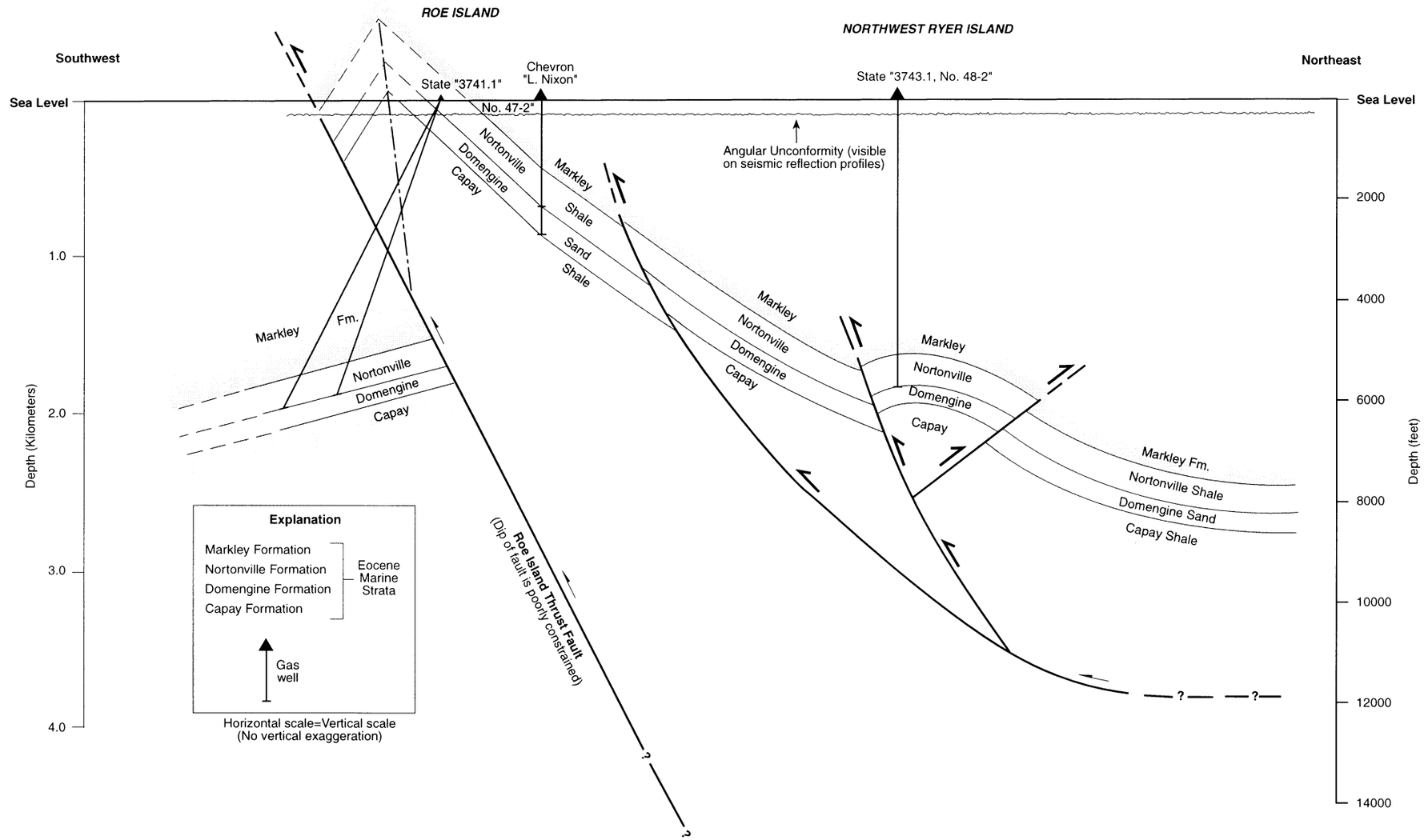

Figure 4. North-south cross-section across the Roe Island and Ryer Island gas fields showing the geometry of the south-vergent Roe Island anticline (see Figure 3 for location of section line). The locations of the Roe Island thrust fault and shallow thrust faults beneath northwest Ryer Island are inferred primarily from analysis of proprietary seismic reflection profiles.

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eroded across the crest of the anticline, and because the State 3743.1, #48-2 well is located southwest of the hinge at the base of the backlimb and thus does not constrain the maximum depth of the Domengine sandstone in Suisun Bay north of the anticline. We estimate that the total structural relief may be about 2450 m (8000 ft).

Based on our analysis of the available dry hole and gas well data from the Roe and Ryer fields (Figures 3 and 4), as well as inspection of proprietary seismic reflection data acquired and processed by Chevron, we concur with Crane's (1995a) interpretation that the Roe Island anticline overlies a blind, northeast-dipping thrust fault. Seismic reflection profiles acquired by Chevron confirm the southwest vergence of the fold, and reveal that northeast-dipping reflectors associated with the backlimb are juxtaposed at depth against subhorizontal or less steeply dipping reflectors by a poorly imaged, northeast-dipping feature that we interpret to be a thrust fault. The thrust fault appears to extend from the bottom of the time-migrated seismic sections (about 3.0 seconds, two-way travel time) to the upper 0.6-1.0 seconds depth. We have incorporated our interpretation of this thrust fault in the cross-section across the Roe Island anticline (Figure 4).

Based on analysis of available data, we interpret that the Ryer Island gas field north of Roe Island is associated with two different contractional structures. From analysis of seismic reflection profiles, we infer that the structural high associated with the northwest end of Ryer Island is a small, 1-km-wide antiformal fold bounded on both the northeast and southwest margins by inwardly dipping thrust or reverse faults. This fold or "pop-up" block is developed on the back limb of the much larger Roe anticline (Figure 4). Based on analysis of drill hole data (i.e., the State 3743.1, #48-2 well; Ryer #4 wells) and proprietary seismic reflection lines, we estimate that total relief on the Domengine sandstone across the pop-up block is about 100 m or less. The thrust faults bounding the pop-up block appear to converge at relatively shallow depths (i.e., 2.0 seconds two-way travel time or less), indicating that the "pop-up" structure is not deeply rooted.

In contrast to the "pop-up" structure that forms the northwest end of the Ryer Island gas field, proprietary Chevron seismic lines that cross the southeastern part of the field image a 2-km-wide southwest-vergent anticline that exhibits a minimum of about 800 m (2612 ft) of structural relief on the Domegine sandstone between the State 3896.1, #51-1 well, and the Ryer #2 (redrill) well. The crest of this fold, herein called the Ryer Island anticline, was penetrated by the Ryer #2, #3, and #5 wells (Figure 3). Although the axis of the Ryer Island anticline is approximately coincident with the axis of the pop-up block to the northwest (Figure 4), the two structures have different geometries, and based on the difference in structural relief along the northwest-southeast axis of the Ryer Island gas field, the structures have accommodated different amounts of total shortening.

As shown on the structure contour map (Figure 3), we interpret that the Roe Island anticline is separated from the northwest end of the Ryer Island anticline by a northeast striking, high-angle tear fault or lateral ramp. The presence of a tear fault also is consistent with structural trends imaged by a series of northeast-southwest Chevron seismic lines shot at 1-2 km intervals across Roe Island and Ryer Island. To the southeast, seismic reflection data image a syncline southwest of the anticline that forms the southeastern end of the Ryer Island gas field. The axis of this syncline is not imaged by the next reflection profile to the northwest; rather, seismic data indicate that the syncline axis projects into the northeast-dipping limb of the Roe anticline (Figure 3), which strongly suggests either that the Roe anticline plunges radically to the southeast, or that a fault or other structural discontinuity is present that truncates the Roe anticline on the north and the syncline axis on the south (Figure 5). We have adopted the latter interpretation in preparing the structure contour map (Figure 3) because Hoffman (1992) has interpreted the presence of such faults in the Los Medanos Hills anticlinorium to the south (see Section 3.2). We acknowledge a large measure of uncertainty in this interpretation, however, given the spacing of the seismic data and paucity of the well data.

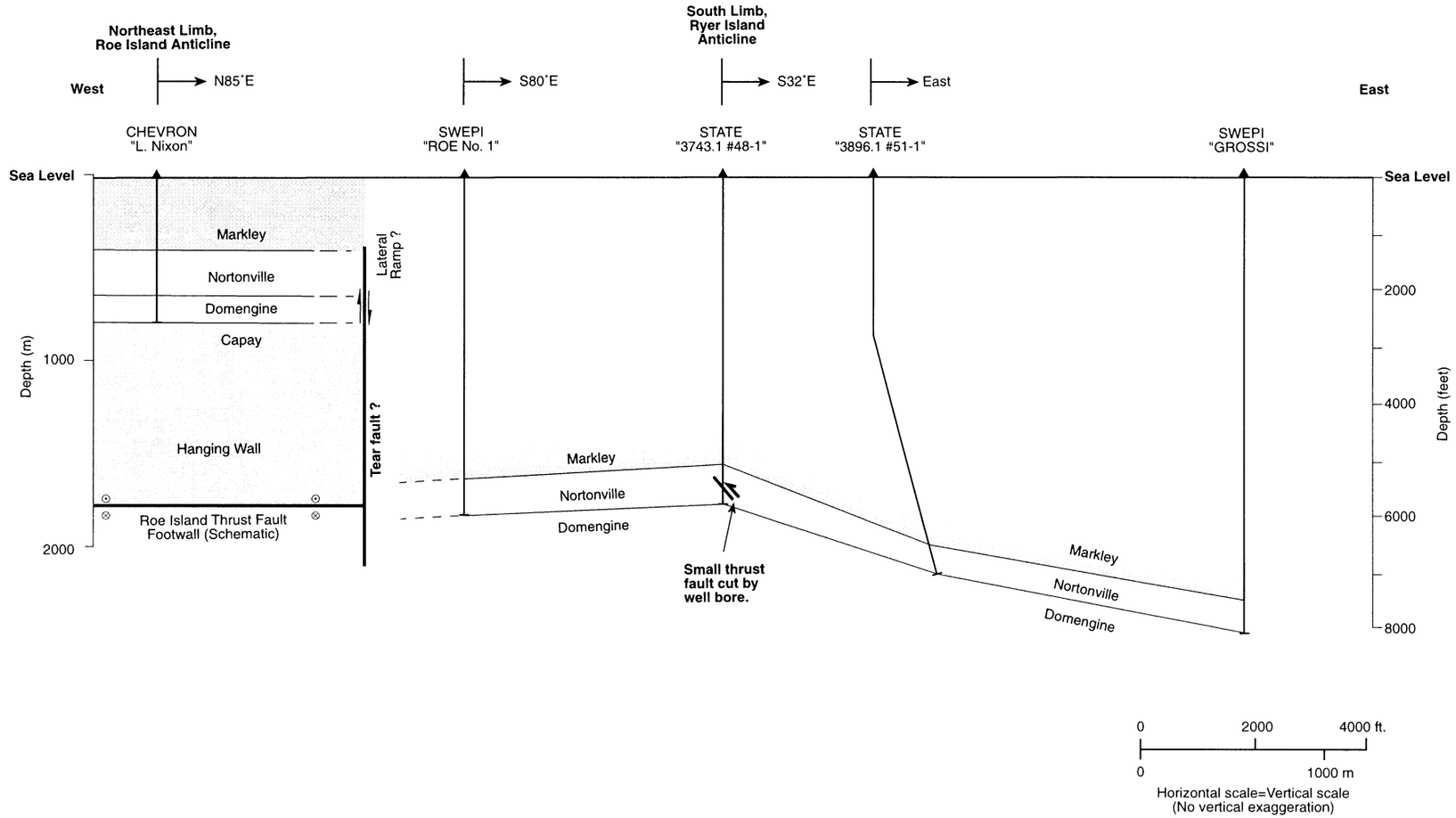

Figure 5. Generalized east-west cross section through gas wells in the Roe Island and Ryer Island fields showing a large change in average depth on the top Domengine across a tear fault or lateral ramp that we interpret to form the eastern structural boundary of the Roe Island anticline (see Figure 3 for location of section line).

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3.4 Grizzly Island Anticlinorium

The Suisun Bay-Grizzly Island gas field is associated with a faulted, northwest-trending anticlinorium or anticlinal fold trend (Division of Oil and Gas, 1982). The axis of the structure lies along the southern end of Grizzly Island (Figure 2). For simplicity, we refer to the structure as the Grizzly Island anticlinorium. Based on analysis and mapping of well data, minimum length of the anticlinorium is about 10 km and the minimum width is about 4 km (Figure 6). Maximum structural relief on the Eocene Domengine sandstone across the anticline is about 580 m (1900 ft), significantly less than the structural relief across the Los Medanos Hills and Roe Island anticlines to the southwest (Figure 2).

Based on the patterns of reflectors imaged by a proprietary north-south-trending Chevron seismic reflection profile across the Grizzly Island structure, the anticlinorium is asymmetric and vergent to the north-northeast. Changes in the dip of reflectors at depth suggest the presence of a south- or southeast-dipping thrust fault, but the quality of the data is poor and multiple interpretations of the reflector pattern are possible. Based on construction of a correlated cross-section through several wells across the eastern end of the structure, however, we believe that a south- or southeast-dipping thrust fault is present beneath the fold (Figure 7). The correlated well data in the cross-section support the asymmetric geometry of the fold visible in the seismic data, and dipmeter data from two wells ("Suisun Community #16", "Fontana Farms #7") reveal abrupt changes in bedding dip at depth similar to those imaged by the seismic data, consistent with the presence of a thrust fault beneath the fold (Figure 7). In our interpretation of the Fontana Farms #7 well, the thrust fault displaces the Domengine sandstone about 200 m. Total slip on the thrust fault at depth probably is greater than 200 m because much of the displacement appears to have been accommodated by fault-propagation folding and growth of the Grizzly Island anticlinorium.

Although the subsurface data are sparse and we did not have access to multiple seismic reflection profiles across the structure to verify continuity of fold geometry along the trend of the axis, the available well data suggest that the anticlinorium is divided or segmented by a series of faults that are oblique to the northwest trend of the structure (Figure 6). The Division of Oil and Gas (1982) also adopted this interpretation in their structure contour map of the field. The primary evidence for these faults is a series of abrupt changes in the depth of the Domengine sandstone between closely spaced wells that are difficult to depict by drawing smooth, unfaulted structure contours through the well data. We interpret that the axis of the anticlinorium is offset by a series of high-angle faults that consistently displace the Domengine sandstone down to the east (Figure 6). In our interpretation, we show these faults as splaying into a northwest-striking thrust fault or faults that underlie the Grizzly Island anticlinorium, but the well data are too sparse to demonstrate this compellingly. An alternative interpretation that would satisfy the well data is that there are a series of older, approximately north-south-striking normal faults that consistently offset the Domengine sandstone down to the east, and which were subsequently folded during growth of the Grizzly Island anticlinorium.

3.5 Honker Bay and Van Sickle Island Structures

The Honker Bay and Van Sickle Island gas fields are located north of the Sacramento River directly north of the city of Pittsburgh (Figure 2). Although the antiformal hydrocarbon traps associated with the fields are treated as discrete structures by the Division of Oil and Gas (1982), we evaluate them together because of their close proximity.

The Van Sickle Island gas field is formed by an anticline or dome that is cut by the Pittsburg-Kirby Hills fault (Figure 8), which is an approximately north-south-striking fault that coincides with an alignment of seismicity north of the town of Pittsburgh. High resolution seismic reflection profiles

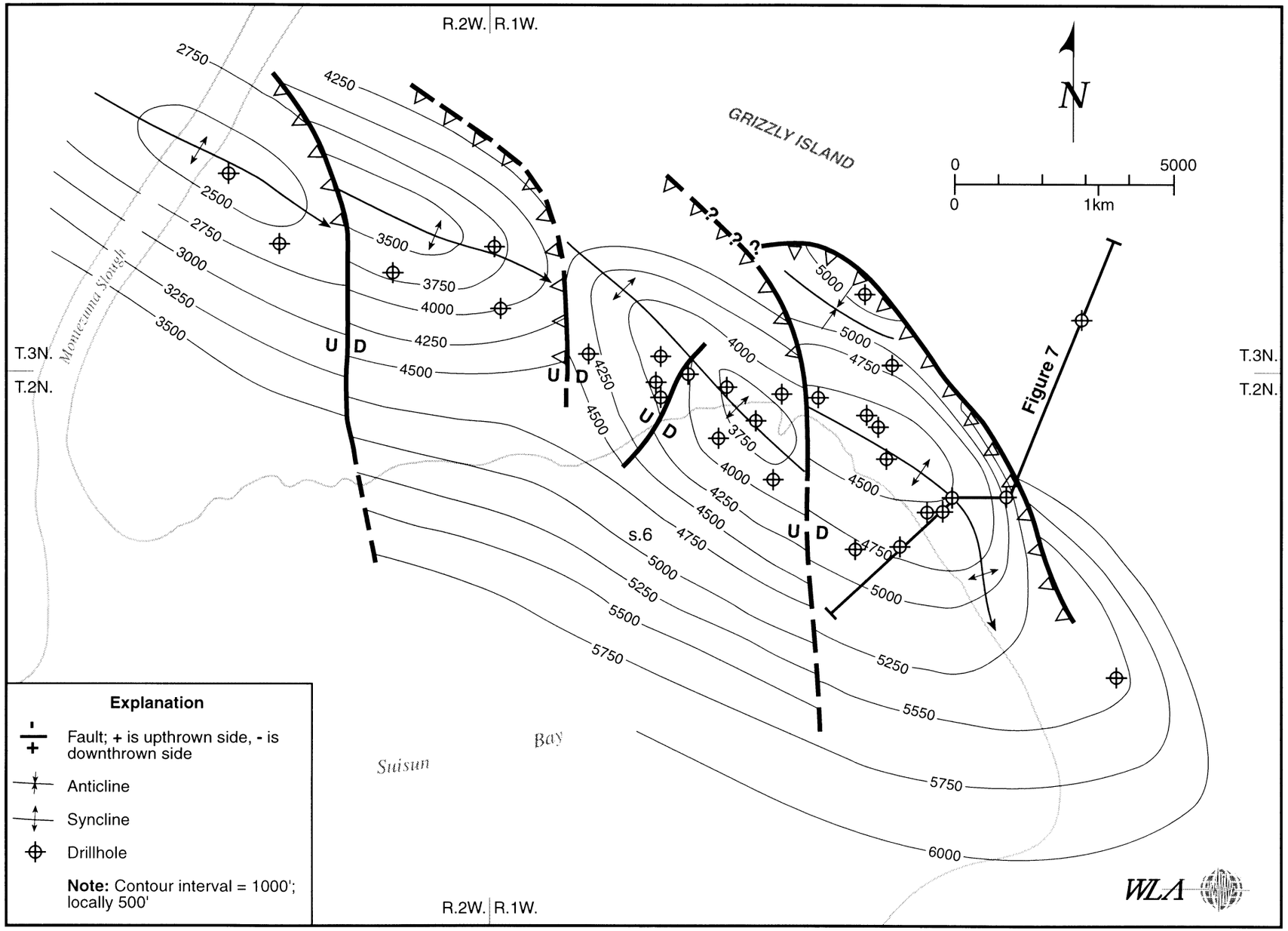

Figure 6. Structure contour map on the top of the Eocene Domengine sandstone, Suisun Bay and Grizzly Island gas fields, showing interpreted structure of the Grizzly Island anticlinorium (see Figure 2 for location in the western Delta study region).

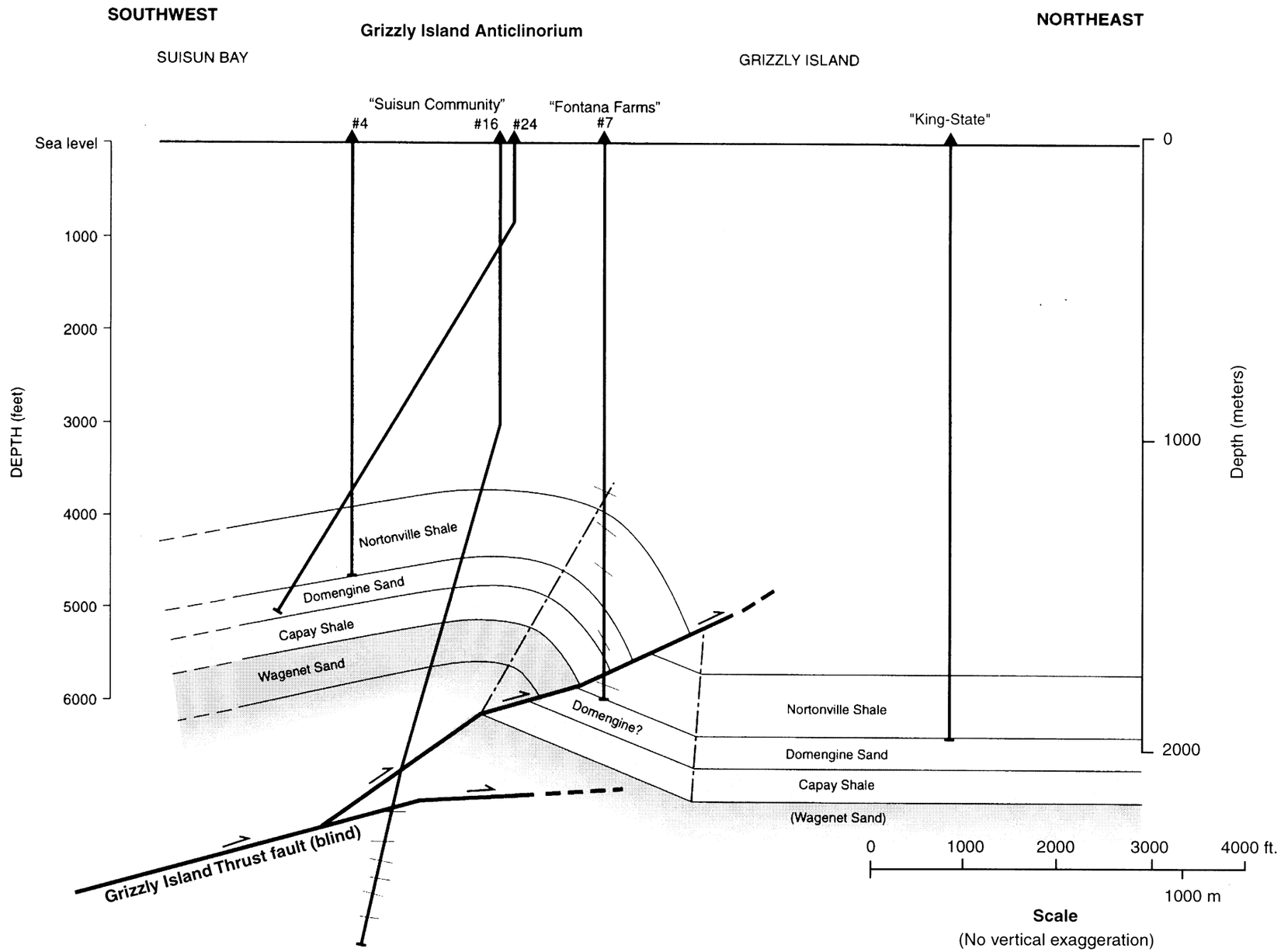

Figure 7. Northeast-southwest cross-section across the Suisun Bay and Grizzly Island gas fields showing the north-vergent Grizzly Island anticlinorim and underlying south-dipping Grizzly Island thrust fault (see Figure 6 for location of section line).

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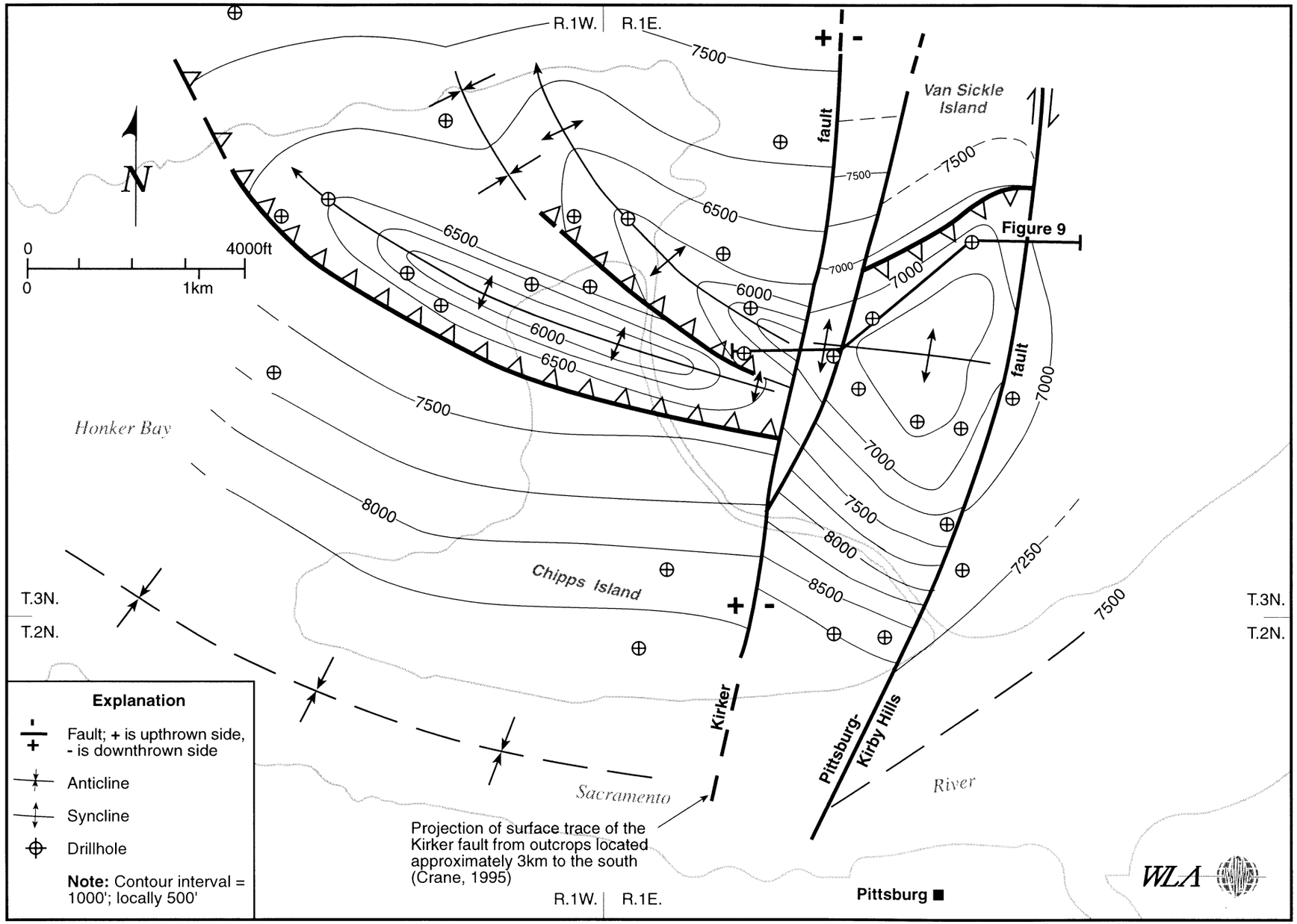

Figure 8. Structure contour map on the top of the Eocene Domengine sandstone, Honker Bay and Van Sickle Island gas fields (see Figure 2 for location in the western Delta study region).

acquired as part of the BASIX program indicate that the fault is steeply dipping to subvertical, at least where imaged beneath the Sacramento River (McCarthy et al., 1994), and that shallow sediments in the Sacramento River channel are deformed by the fault (P. Williams, oral communication, 1997; also, Williams and Gabet, 1997). Although poorly constrained by the available well data, the anticline or dome appears to be broader and has less structural relief on the east side of the fault than on the west. Based on an abrupt steepening in the bedding on the northwest side of the closure indicated by dipmeter logs, we interpret that the fold west of the Pittsburg-Kirby Hills fault is asymmetric, vergent toward the north, and may be underlain by a southeast-dipping thrust fault (Figure 8). If this interpretation is correct, then the fault geometry suggests that the south-dipping thrust merges with the Pittsburg-Kirby Hills fault at depth.

The Honker Bay and Van Sickle Island gas fields are separated by an approximately north-south-striking fault zone that displaces the Domegine sandstone a total of about 360 m (about 1200 ft) down to the east (Figure 8). We infer that the fault zone consists of at least two splays. The location of the westernmost splay is constrained by data from the Honker Farms #4 and Van Sickle Gas Unit #6 wells to the west, and the Sesnon #4-30 well to the east (Figure 9). These three wells document about 280 m of relief (east-side down) on the Domengine sandstone across the fault zone over a distance of about 500 m. We infer the presence of the eastern splay from about 80 m (250 ft) of east-side down relief on the Domengine sandstone between the Sesnon #4-30 well on the west, and the Abel #1 (redrill) and Honker Farms #2 wells located about to the east (Figure 9). Also, the dipmeter log for the deviated Sesnon #4-30 well shows an interval of scattered, incoherent dips that may indicate the presence on an east-dipping fault zone in the area where the Domengine sandstone steps abruptly down to the east (Figure 9).

We interpret that the east-side-down fault zone between the Van Sickle Island and Honker Bay fields is related to other structures in the greater Delta region mapped as early Tertiary normal faults. Previous workers have recognized a series of faults that primarily displace Eocene and older strata on the northeastern flank of Mt. Diablo (Mackevett, 1992; Crane, 1995b). The faults can be traced northward in the subsurface of the Sacramento-San Joaquin Delta region, where drill hole and seismic reflection data indicate that the structures are associated with a series of approximately north-trending, late Cretaceous to early Tertiary half-graben (Krug et al., 1992). Specifically, we correlate the east-side-down fault zone between the Van Sickle Island and Honker Bay fields (Figure 9) with the Kirker fault of Graymer et al., 1994 (also shown as the "Kirker Pass fault" on compilation maps by Crane, 1995a,b), which is mapped southwest of Pittsburgh within the uplifted and northeast-tilted section of Cretaceous and Tertiary strata on the backlimb of the Mt. Diablo anticline (Figure 1).

The late Cenozoic growth of the Mt. Diablo anticline has produced a unique opportunity to assess the cross-sectional geometry of the Kirker fault. Uplift and tilting of the backlimb of the fold has exposed a homoclinally east-dipping section of Mesozoic and Tertiary marine strata that accumulated in the ancestral Great Valley forearc basin. Because the backlimb of the Mt. Diablo anticline is over 20 km long, measured from the crest of the fold northeastward into the western Central Valley, the homoclinal exposure of strata affords a distorted cross-sectional view of fault structures and depositional relationships in the upper 7-10 km of the crust. When this homoclinally tilted section is viewed downdip on a geologic map (Figure 10), the Kirker fault appears to cut steeply downsection through Eocene strata and flatten in the Marsh Creek fault system. The Eocene Markley Formation (i.e., unit Te_2 in Figure 10) is thicker on the east side of the Kirker fault than on the west side, and the Markley section generally thickens westward toward the fault. Geologic map patterns show that bedding dips of Eocene strata rotate into the plane of the Kirker fault, and fault imbricates on the north side of the Marsh Creek fault also show consistent rotation of stratigraphic contacts between Cretaceous units into the plane of the fault. These stratigraphic and structural relations are consistent with syndepositional east-side-down

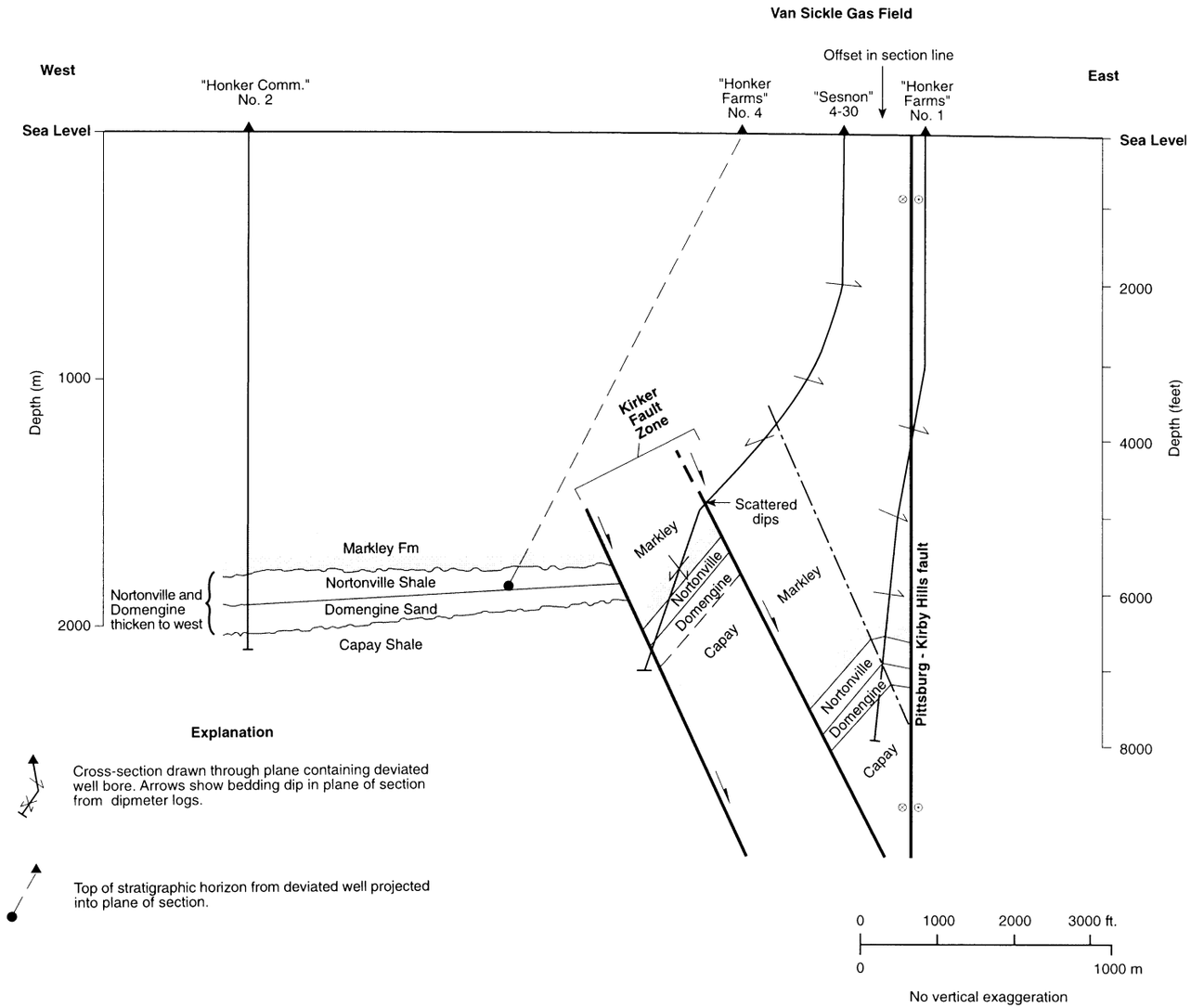

Figure 9. Generalized east-west cross section through gas wells in the Honker Bay and Van Sickle Island fields showing interpreted normal offset (east side down) of the Domengine sandstone across two splays of the Kirker fault (see Figure 8 for location of section line).

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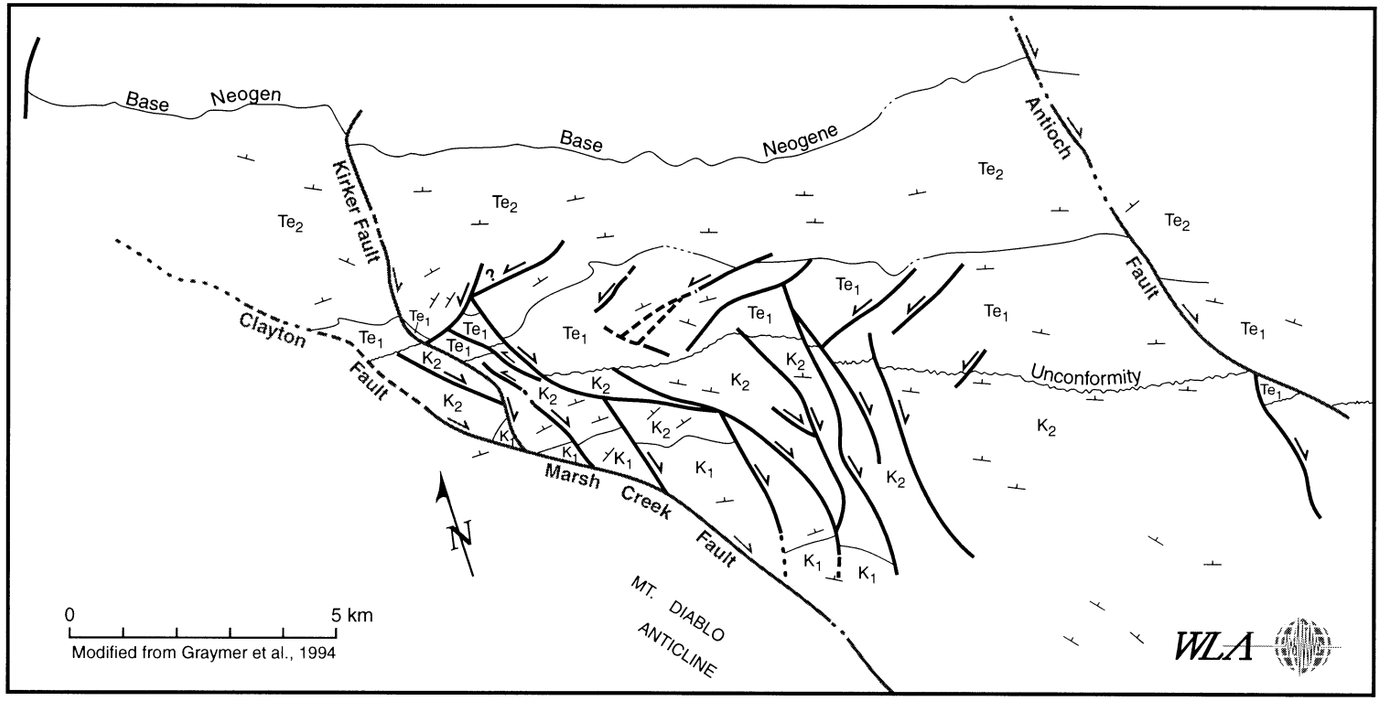

Explanation

Te_2 – Eocene Markley Formation
Te_1 – Paleocene-Eocene, undivided
K_2 – Upper Cretaceous (Santonian and younger)
K_1 – Upper Cretaceous (Turonian and older)

Dip direction of bedding

Fault showing sense of stratigraphic offset

Figure 10. Cross-sectional exposure of structural relationships on northeast flank of Mt. Diablo anticline, corrected to approximate a down-dip view.

growth faulting in a half-graben as inferred by Krug et al. (1992) for correlative structures in the Delta region north of Mt. Diablo. We interpret that the Kirker and Marsh Creek faults are part of the regional system of early Tertiary extensional structures, and together exhibit a listric geometry (Figure 10).

Following the Division of Oil and Gas (1982) and MacKevett (1992), we interpret the Honker Bay structure west of the Kirker fault to be a faulted anticline or anticlinorium (Figure 8). A seismic reflection profile from the western end of the Honker Bay gas field published by MacKevett (1992) shows that the structure is an asymmetric, north- to northeast-vergent anticline similar to the Suisun-Grizzly anticlinorium. MacKevett (1992) interpreted that the anticline is bounded on the northeast and southwest by inwardly-dipping thrust faults. Based on the vergence of the fold, the southwest-dipping fault identified by MacKevett (1992) probably has accommodated the greatest amount of slip at the northwest end of the anticline. The well data available to us for mapping the structure do not constrain the location of this southwest-dipping thrust fault along strike to the east. Based on the seismic reflection data published by MacKevett (1992), we suggest that it may cut upsection to the stratigraphic level of the Domengine sandstone north of the area covered by well data (i.e., north of the detailed map area in Figure 9). Moving eastward, slip on the southwest-dipping thrust fault beneath the Honker Bay anticline may be transferred to one or more north-dipping backthrusts, which are primarily responsible for growth of the two small anticlines shown in the structure contour map (Figure 8).

The structure contour map (Figure 8) provides a basis for assessing the sense of slip on the Pittsburg-Kirby Hills fault at the Van Sickle Island gas field. The vertical separation on the top of the Domengine sandstone across the fault changes along strike; i.e., to the south, the Domengine sandstone is higher on the east side, and to the north the Domengine sandstone is higher on the west side (Figure 8). Although this pattern of alternating separation could be generated by east-side-down faulting of the eastern flank of an originally continuous domal structure by the Pittsburg-Kirby Hills fault, the late Quaternary separation on the fault in the vicinity of Pittsburgh south of the river is east-side-up (P. Williams, oral communication, 1997), opposite the required sense of vertical slip to generate the observed deformation in the Van Sickle gas field to the north. Alternatively, the variation in separation could reflect a strike-slip component of movement on the fault. Varying separation is a characteristic feature of strike-slip faults, and focal mechanisms from small earthquakes located along the fault trace near Pittsburgh exhibit right-lateral strike-slip displacement on north-striking nodal planes (Ellsworth et al., 1982; Weber-Band, 1998). As discussed in a subsequent section (Section 4.0), we favor a right-lateral strike-slip interpretation for the Pittsburg-Kirby Hills fault, with the caveat that the fault may have a local component of east-side-up reverse displacement in the vicinity of Pittsburgh (P. Williams, personal communication, 1997). The patterns of folding and faulting in the Van Sickle gas field that we infer from analysis of drill hole data (Figure 8) may be associated with development of a positive flower structure along the Pittsburg-Kirby Hills fault, consistent with structures imaged across the fault in the Sacramento River to the south by the BASIX experiment (McCarthy et al., 1994).

3.6 Kirby Hills

The "Kirby Hills" collectively refer to a range of low hills located north of Van Sickle Island, west of the Montezuma Hills, and southeast of the Potrero Hills (Figure 11). The Kirby Hills gas field is divided into a "main area" south of Nurse Slough and a "north area" north of Nurse Slough. As discussed below, we interpret that the gas-producing structures in both areas are associated with splays of the Pittsburgh-Kirby Hills fault zone.

The "Main Area" of the Kirby Hill gas field is developed in several distinct anticlinal structures that are cut by strands of the Pittsburg-Kirby Hills fault zone (Figure 12). Near the southern end of the

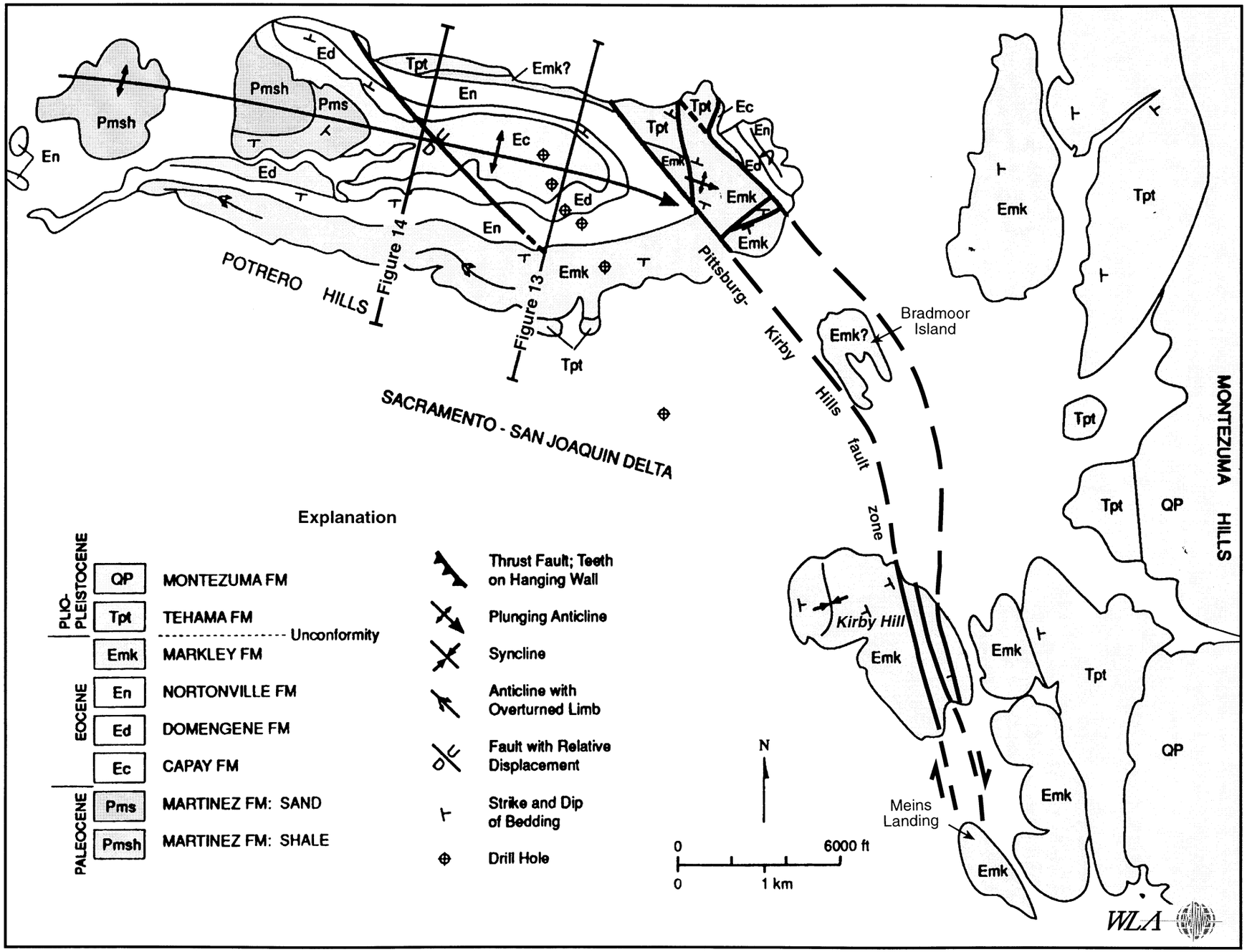

Figure 11. Generalized geologic map of the Potrero Hills- Kirby Hills region, California.

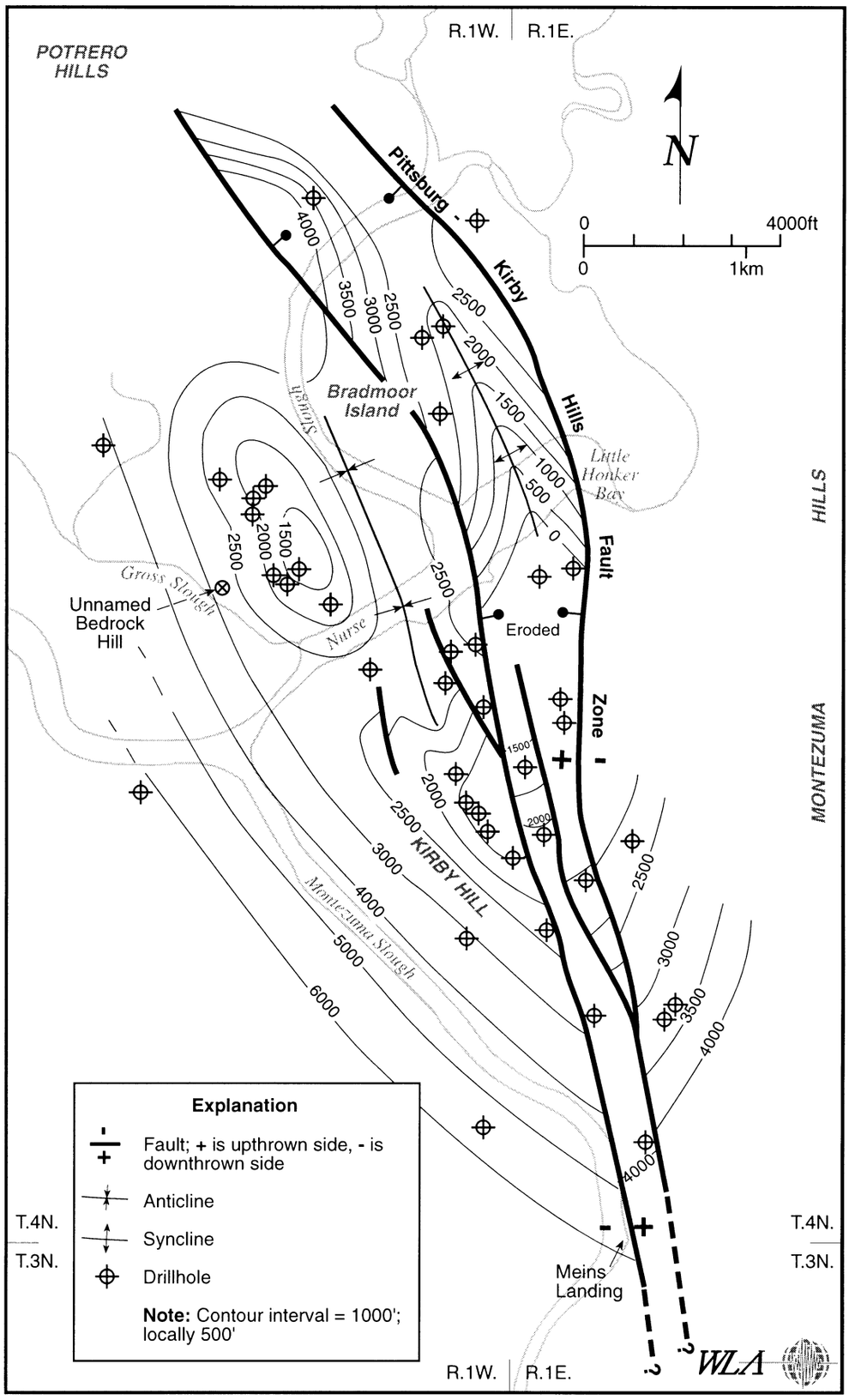

Figure 12. Structure contour map on the top of the Eocene Domengine sandstone, Kirby Hill gas fields (see Figure 2 for location in the western Delta study region).

detailed map area, the Pittsburg-Kirby Hills fault zone passes through or along a small unnamed bedrock hill that lies east of Meins Landing and rises about 40 m above the marshy areas adjacent to Montezuma slough. Well data are sparse in this region, but we interpret that the Domengine sandstone in the vicinity of the unnamed hill is elevated a few hundred feet relative to surrounding areas by two splays of the Pittsburg-Kirby Hills fault.

We trace splays of the Pittsburg-Kirby Hills fault about 1.0 km north to Kirby Hill (Figure 12), which rises about 80 m above the surrounding marshlands and is associated with a local structural high in the Domengine sandstone. Analysis of aerial photos and topographic maps reveals several pronounced north-northwest-trending bedrock lineaments in eastern Kirby Hill that control local drainage patterns and probably are coincident with major splays of the Pittsburg-Kirby Hills fault zone. Our interpretation of the fault splays in Figure 12 is based in part on the location of the prominent topographic lineaments at Kirby Hill. A distinct anticlinal closure in the Domengine sandstone about 1.0 km northwest of Kirby Hill is associated with a very small, unnamed 30-m-high bedrock hill. The anticlinal closure is irregular in shape, represents about 460 m (1500 ft) of local relief on the Domengine sandstone, and appears to be abruptly truncated to the east by a splay of the fault zone (Figure 12).

We trace two major splays of the Pittsburg-Kirby Hills fault zone north of Kirby Hill. The splays appear to diverge slightly and encompass Bradmoor Island, a 30-m-high bedrock hill that is bounded by Nurse Slough on the northwest and Little Honker Bay on the southeast. Based on the structure contour mapping (Figure 9), Bradmoor Island appears to be associated with a northwest-plunging anticline or closure between the two major strands of the Pittsburg-Kirby Hills fault zone. Because the well coverage in this region is sparse, the detailed structure between the two fault splays is uncertain. A separate dome or anticline with about 450 m of closure is located southwest of the major fault zone between Gross Slough and Nurse Slough.

North of Bradmoor Island, the Pittsburg-Kirby Hills fault zone turns westward and projects toward a fault zone mapped along the eastern margin of the Potrero Hills anticline (Figure 11; see discussion in Section 3.7, below; also, Weber-Band 1998). As mapped by Sims et al. (1973), the fault zone is bounded by two northwest-southeast-striking faults, contains slivers of Eocene and Pliocene strata, and cuts obliquely across the east-west trend of the Potrero Hills anticline axis (Figure 11).

3.7 Potrero Hills Anticline

The Potrero Hills is an east-west-trending range of low hills along the northern boundary of the study area (Figures 1 and 11) that coincides with an east-west-trending anticline. Based on the extent of the Potrero Hills and the mapped exposures of folded early Tertiary strata, minimum length of the anticline is about 9 km. The north-south width of the Potrero Hills is about 3 km, but drill hole data (discussed below) indicate that the width of the associated anticline probably is greater than 3 km. Based on map patterns of folded Capay shale, Domengine sandstone and Nortonville shale in the Potrero Hills, the anticline plunges east and is truncated on its eastern margin by the northern extension of the Pittsburg-Kirby Hills fault zone (Figure 11). Sims et al. (1973) show that Pliocene-Pleistocene strata of the Tehama Formation are deformed along the limbs of the fold; if this mapping is correct, then at least some growth of the fold has occurred during late Cenozoic time.

We constructed two north-south cross-sections across the Potrero Hills anticline to evaluate the subsurface structure. Our interpretations follow previous unpublished cross-sections by D. Diamond developed for gas exploration at the Potrero Hills field. The anticline shown in the eastern cross-section (Figure 13) is constrained by surface mapping and data from 6 wells drilled

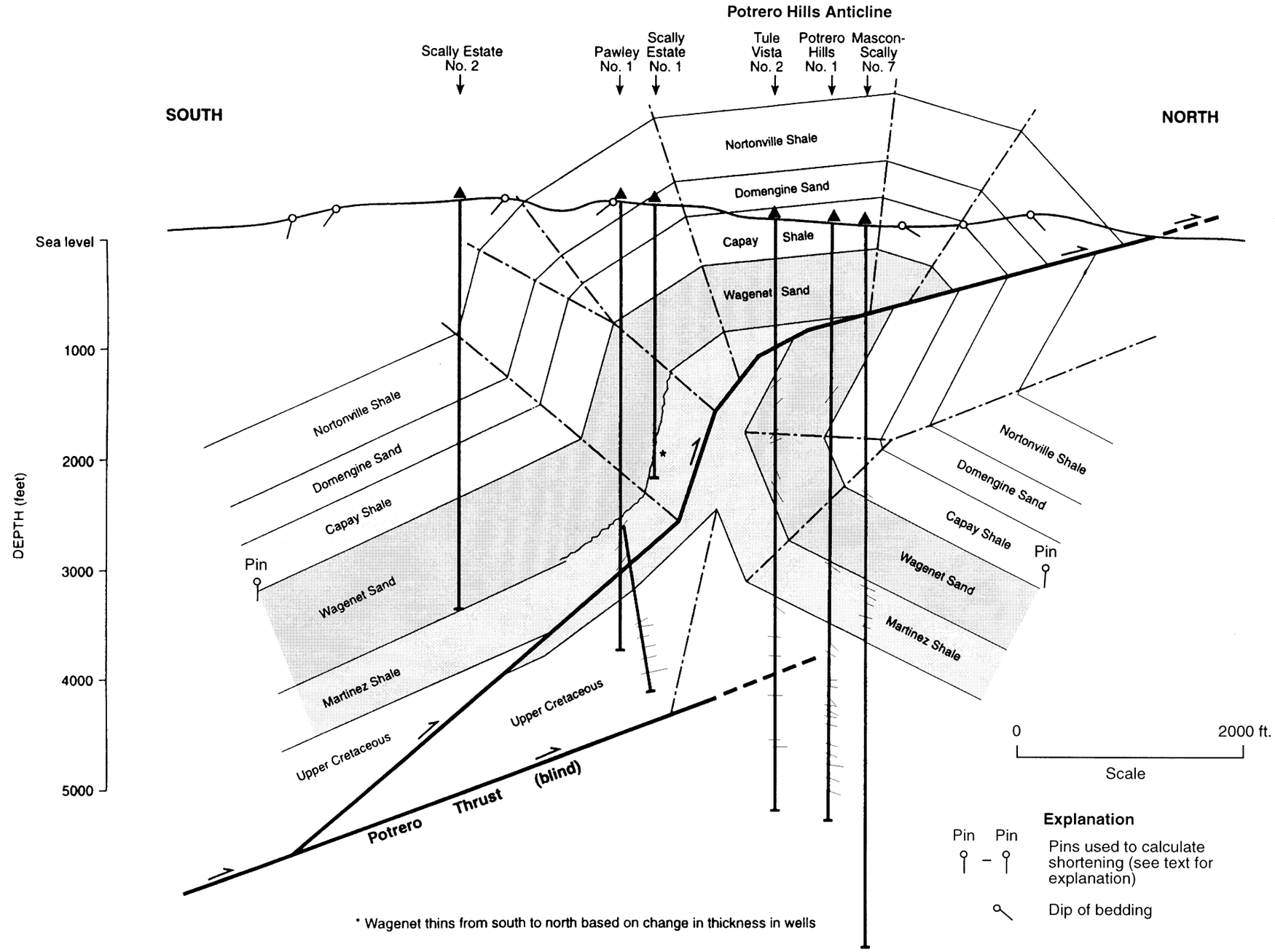

Figure 13. North-south cross section through the Potrero Hills anticline (see Figure 11 for location of section line).

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in the now-abandoned Potrero Hills gas field. Dipmeter logs for three of these wells, and paleontological analysis of the deformed Eocene and Cretaceous strata at depth, were incorporated in the cross-section (Figure 13) and provide good constraints on the internal structure of the anticline. Because only one well was drilled in the vicinity of the western cross section (Figure 14), the subsurface relations are based primarily on projecting surface geology to depth, and by assuming lateral continuity of some of the structures interpreted in the eastern cross-section (Figure 13).

The eastern cross-section (Figure 13) depicts the Potrero Hills as an asymmetric, north-vergent anticline. The asymmetry of the fold is best defined by dipmeter data, which indicate that the Eocene strata exposed in the core of the fold at the surface are overturned beneath the northern limb at depth and dip southwest (Figure 13). We interpret that the anticline formed primarily by fault-propagation folding above the tip of a blind, north-vergent thrust fault. A thrust or reverse fault with about 150 m to 200 m of displacement is inferred to cut upsection through the tightly folded Eocene Martinez shale in the core of the fold and flatten in the upper 300 to 500 m. This fault probably roots in a deeper, less steeply south-dipping thrust fault at depth that has accommodated most of the slip during development of the Potrero Hills anticline (Figure 13).

The interpretation of subsurface structure in the cross-section to the west (Figure 14; see Figure 11 for location) similarly depicts the Potrero Hills anticline as a north-vergent fault-propagation fold deformed by complex faulting at depth. We infer that the reverse fault that cuts the core of the anticline in the cross-section to the east also is present to the west, and that it splits into two splays. Based on dipmeter and paleontology data from the Potrero No. 3 well (Figure 14), the lower splay displaces the Eocene Martinez sand approximately 250 m to the north over the Capay shale. The upper splay is less well constrained by the data; if present, it probably has accommodated 60 m or less of total dip-slip displacement. We interpret that a small, south-vergent anticline on the southern limb of the Potrero Hills anticline indicated by overturned Eocene strata dipping steeply to the north is related to the presence of a small, antithetic north-dipping thrust fault that splays upward from the reverse faults in the core of the fold. An antithetic thrust fault mapped at the surface north of the fold axis similarly is shown as a shallowly-rooted feature with a maximum displacement of several tens of meters (Figure 13). We infer that the faults in the western cross-section (Figure 14) splay upward from a deeper, south-dipping thrust fault that is primarily responsible for growth of the Potrero Hills fault-propagation fold.

We estimate local shortening across the Potrero Hills anticline by measuring bed lengths in the cross-sections between two arbitrary points or "pins". We use the contact between Capay shale and Waganet sand for the shortening estimates because this contact was picked in all wells shown on both cross-sections and thus is contact best constrained by subsurface data. Total deformed length of this contact between the pins on the eastern cross-section (Figure 13) is about 3250 m (10,652 ft), and the horizontal distance between the pins is 2015 m (6600 ft). If it is assumed that the Capay-Waganet contact was originally horizontal prior to folding, shortening between the pins on Figure 13 is 1235 m, or 38% of the predeformed length. Performing a similar analysis on the western cross-section, total length of the Capay-Waganet contact between the pins shown on Figure 14 is 2210 m (7250 ft) and the horizontal distance between the pins is 981 m (3219 ft), indicating a local shortening of 1229 m or 56% of the predeformed length. The ratio of the present horizontal length of this contact to the predeformed length for the eastern and western cross sections is 62% and 44%, respectively. We emphasize that these are minimum shortening estimates for the Potrero Hills anticline because the "pins" we have chosen are not placed far enough apart to fully encompass the limbs of the structure.

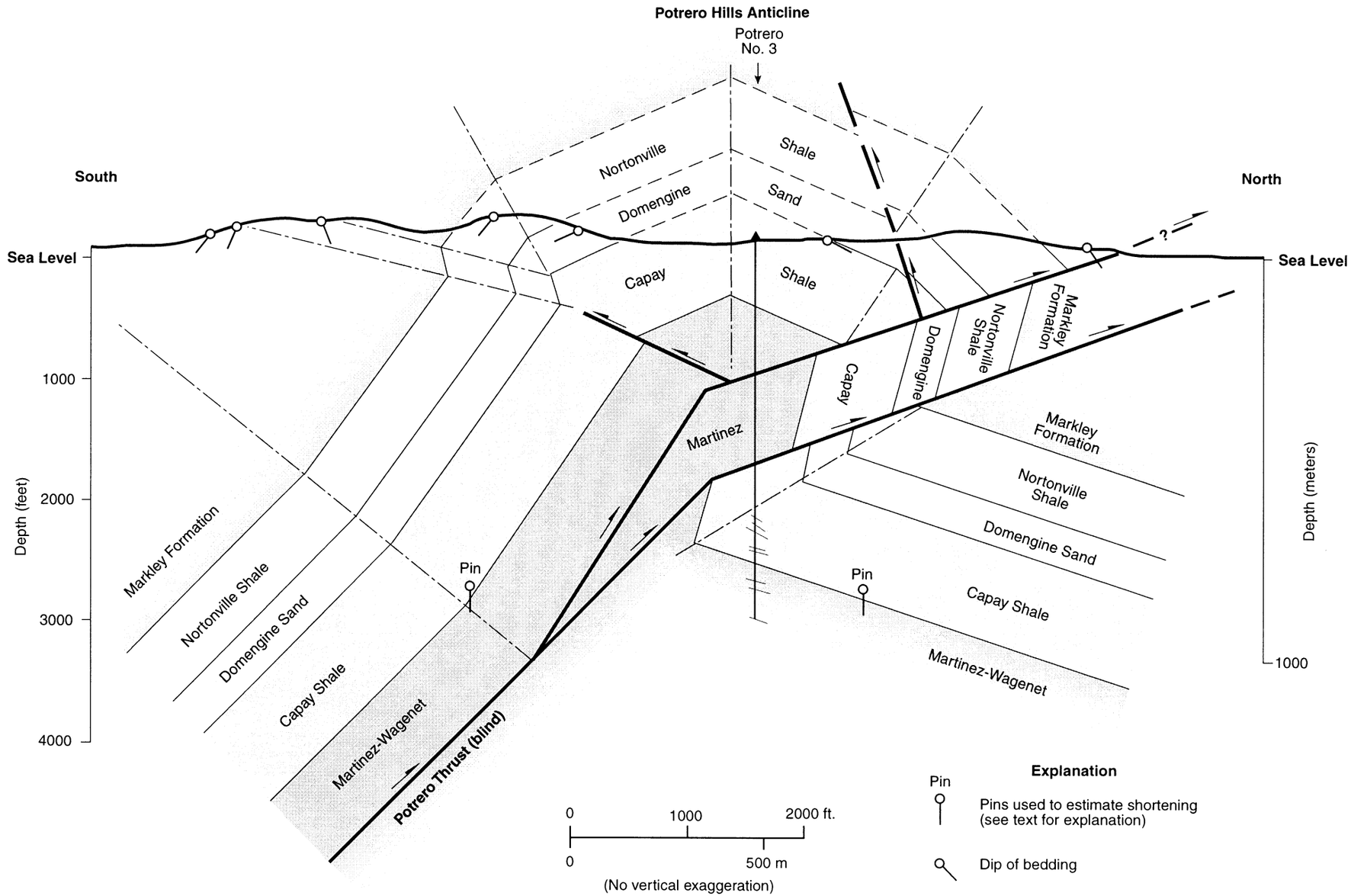

Figure 14. North-south cross section through the Potrero Hills anticline (see Figure 11 for location of section line).

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4.0 KINEMATICS OF SEISMOGENIC DEFORMATION IN THE WESTERN DELTA REGION

The western Delta area in general, and the Kirby Hills area in particular, is a region of high background seismicity relative to surrounding areas. Previous workers (Ellsworth et al., 1982; Hector and Unruh, 1992; McCarthy et al., 1994; Weber-Band, 1998) have recognized a north-south-trending alignment of epicenters that can be traced from the Pittsburgh area northward across the Sacramento River to eastern Chipps Island, then northward through the Van Sickle gas field to the Kirby Hills. The seismicity terminates as a well-defined north-trending alignment near the latitude of the Potrero Hills. The alignment of epicenters generally coincides with the trace of the Pittsburg-Kirby Hills fault zone as mapped through the Van Sickle and Kirby Hills gas fields (Sections 3.5 and 3.6). Hypocenters of these events are located at depths ranging from 18-22 km or greater, which represents some of the deepest seismicity recorded in northwestern California (Ellsworth et al., 1982).

We evaluated the kinematics of seismogenic deformation in the western Delta study region by inverting focal mechanisms from small and moderate magnitude earthquakes for components of a reduced incremental strain tensor using the method of Twiss et al. (1993). Focal mechanisms were obtained via the Internet from the Northern California Earthquake Data Center at UC Berkeley. We separated the focal mechanisms into groups associated with specific structures using the program SELECT by D. Oppenheimer (USGS), then calculated seismic P and T axes for the mechanisms using the program PTFROMDAT (UC Davis). We used an automated grid-searching algorithm called FLTSLP (R. Twiss and L. Guenther, UC Davis) to find an incremental deformation tensor that minimizes the misfit between the observed seismic P and T axes, and the P and T axes associated with the final best-fit model parameters. The inversions provide the orientations of the maximum extensional principal incremental strain (d_1); the maximum contractional principal incremental strain (d_3); a scalar parameter (D) that characterizes the relative magnitudes of the principal strains; and a scalar parameter (W) that characterizes the contribution of independent block rotations to patterns of seismogenic slip. A detailed description of the analytical approach and the inversion parameters are given in Unruh et al. (1997b); examples of the application of this method to analysis of seismogenic deformation can be found in Unruh et al. (1996; 1997b) and Unruh and Lettis (1998).

Focal mechanisms for events located in the north-northeast-trending reach of the alignment of seismicity between Pittsburgh and Kirby Hill predominantly reflect strike-slip faulting (Figure 15). A lower hemisphere Kamb plot indicates that the majority of seismic P and T axes are subhorizontal, consistent with right-lateral shear on north-northwest-striking nodal planes (Figure 16). These events directly underlie the mapped trace of the Pittsburg-Kirby Hills fault (Figure 15). The kinematic inversion of these data show that the deformation is an approximately horizontal plane strain (Figure 16). The maximum contractional principal strain (d_3) is subhorizontal and oriented northeast-southwest, and the maximum extensional principal strain (d_1) is subhorizontal and oriented northwest-southeast. This strain geometry is consistent with the predominance of strike-slip focal mechanisms along this reach.

Between the Kirby Hills gas field and the Potrero Hills, many focal mechanisms are thrust events (Figure 17). A lower hemisphere Kamb plot indicates that the majority of seismic P axes in this region are subhorizontal and trend northeast-southwest, similar to the orientation of P axes along the seismicity trend to the south. The majority of T axes are steeply dipping to subvertical, however, indicating that the deformation is dominated by reverse slip on east-west-striking nodal planes (Figure 17). Inversion of these focal mechanisms reveals that the maximum contractional

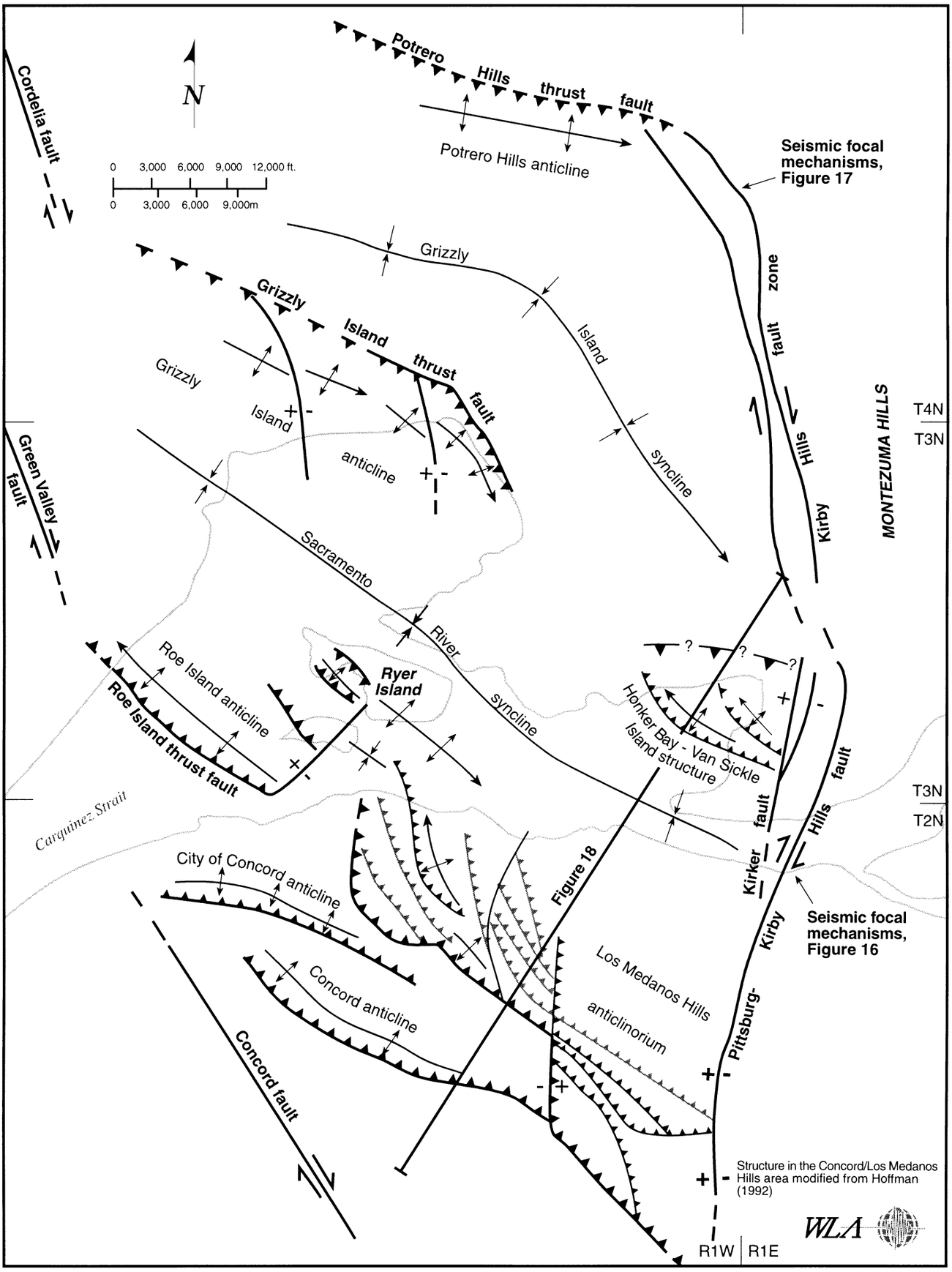
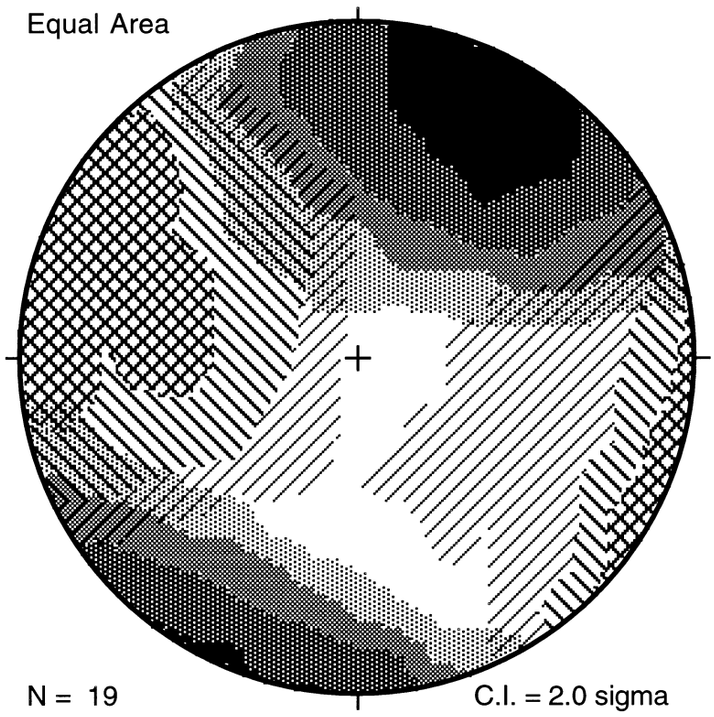


Figure 15. Map of major structures in the western Delta study region.



Pittsburg-Kirby Hills Fault Zone
(PKHF; NCEDC dataset; P shaded, T striped)

Inversion Results:

d1 (maximum extension) = **115°, -22°** (trend, plunge)

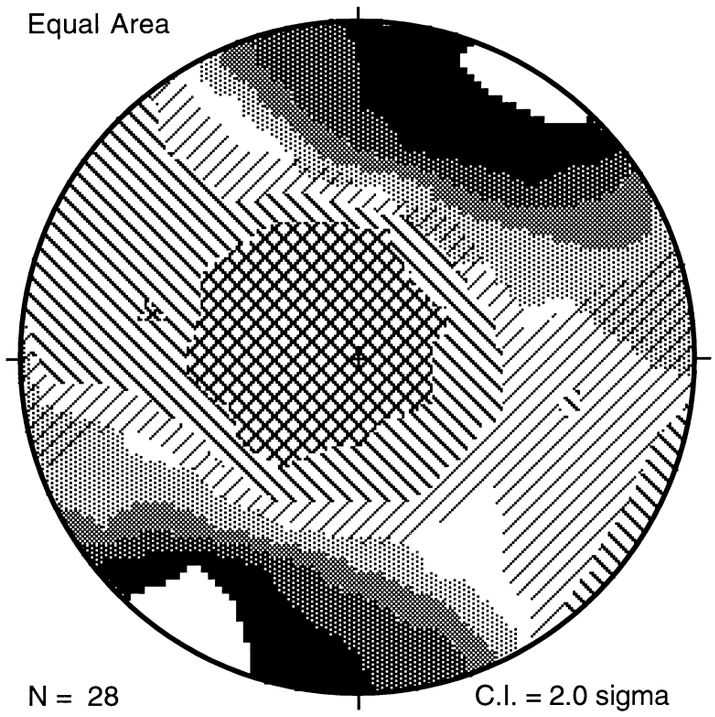
d3 (maximum shortening) = **26°, 4°**

D (deformation parameter) = **0.4**

W (net voriticity) = **0.1**

Inverse Mean Cosine Error = 4.8972

Figure 16: Kamb contour plot of seismic P axes (shaded) and T axes (striped) from focal mechanisms for events along the southern reach of the Pittsburg-Kirby Hills fault.



Seismicity in the Kirby Hills-Potrero Hills area (KHPT; NCEDC dataset; P shaded, T striped)

Inversion Results:

d1 (maximum extension) = **120°, 29°** (trend, plunge)

d3 (maximum shortening) = **24°, 11°**

D (deformation parameter) = **0.3**

W (net voriticity) = **0.25**

Inverse Mean Cosine Error = 5.9842

Figure 17: Kamb contour plot of seismic P axes (shaded) and T axes (striped) from focal mechanisms for events along the northern reach of the Pittsburg-Kirby Hills fault.

principal strain (d_3) is subhorizontal and oriented northeast-southwest, and the maximum extensional principal strain (d_1) is moderately plunging to the southeast, indicating that the seismogenic deformation accommodates components of both horizontal shearing and vertical thickening of the crust. The "transpressional" deformation indicated by the focal mechanisms generally is consistent with the presence of small folds in the Kirby Hills region, and the general east-west strike of the nodal planes is similar to the orientation of the Potrero Hills anticline.

The simplest interpretation of the subsurface and seismicity data is that the Pittsburg-Kirby Hills fault is a steeply-dipping to subvertical right-lateral strike-slip fault in the reach between Pittsburgh and the Kirby Hills gas field. This interpretation is consistent with seismic reflection profiles across the Pittsburg-Kirby Hills fault in the Sacramento River, which appear to show a subvertical structure at depth (McCarthy et al., 1994). We interpret the predominance of reverse and thrust focal mechanisms in the vicinity of the Potrero Hills to reflect localized contraction driven by a restraining bend geometry at the northern end of the Pittsburg-Kirby Hills fault. Specifically, we interpret that the Pittsburg-Kirby Hills fault primarily is a high angle, right-lateral strike-slip fault that bends west in the vicinity of the Kirby Hills and intersects the south-dipping thrust fault beneath the Potrero Hills anticline (Figure 15). The similarity in the patterns of strain accommodated by small earthquakes along the trend of aligned seismicity indicates that the deformation geometry is relatively uniform along the Pittsburg-Kirby Hills fault, and is consistent with large-scale macroscopic dextral shear oriented north-northwest. The Pittsburg-Kirby Hills fault also can be viewed as a tear fault or lateral ramp that forms the eastern structural boundary of the western Delta region and accommodates differential northeast-southwest shortening between the eastern and western Delta areas.

5.0 TECTONIC MODEL FOR THE WESTERN DELTA REGION

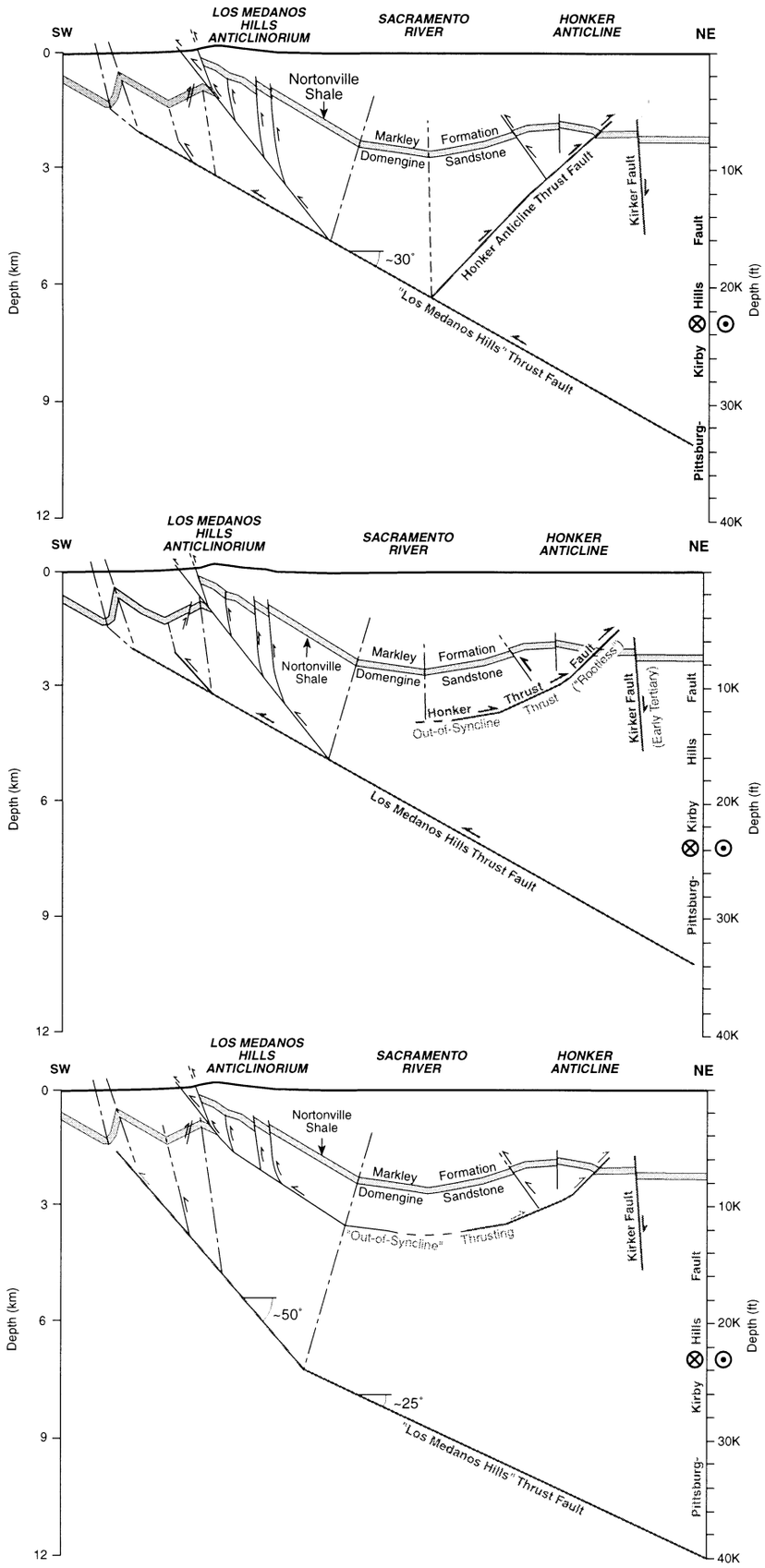
As discussed in Section 2.0, contractional structures in the western Delta region represent the northern continuation of the late Cenozoic Mt. Diablo fold-and-thrust belt. Based on surface geologic mapping and structural geologic analysis, Unruh and Sawyer (1997) concluded that asymmetric folds of the Mt. Diablo fold-thrust belt are underlain by blind, northeast-dipping thrust faults. In the following section, we present a model for the geometry of blind thrust faults beneath the folds in the western Delta study region, and evaluate the kinematics of contractional deformation.

The Roe Island anticline has the same trend and vergence as the Los Medanos Hills anticlinorium to the south-southeast (Figures 1 and 15). Both structures are interpreted to be underlain by northeast-dipping thrust faults, and have accommodated similar amounts of post-Domengine horizontal shortening (i.e., about 2.4 km). Although it is possible that the Roe Island anticline is simply the northwestern continuation of the Los Medanos Hills anticlinorium, the axes of the two folds are not continuous across the northeast-striking tear fault along the eastern margin of the Roe Island anticline (Figure 1; see discussion in Section 3.3). Also, the tip lines of the northeast-dipping thrust faults beneath the two structures may be offset in a right-lateral sense across the tear fault. Note that the axis of the Concord anticline is interpreted to lie near or above the tip of the blind thrust fault that dips beneath the Los Medanos Hills anticlinorium (Figure 18). Projected to the northwest along strike, across the northeast-striking tear fault, the tip of the blind Los Medanos thrust fault appears to be located about 3 km southeast of the tip of the Roe Island thrust fault. If this apparent offset between the structures continues to depth, then the thrust faults do not share a common, continuous surface. We therefore conclude that although the two folds accommodate similar styles and amounts of deformation, they should be treated as independent structures.

North of the Roe Island and Los Medanos Hills structures, the vergence of the contractional structures changes from southwest to northeast, as evidenced by the asymmetry of the Grizzly Island, Honker Bay and Potrero Hills anticlines. The change in structural vergence occurs across the axis of a broad syncline that coincides with the Sacramento River north of Pittsburgh, and trends west through Suisun Bay north of Ryer Island (Figure 15). We refer to this structure informally as the Sacramento River syncline. The north-vergent anticlines north of the syncline axis have significantly lower structural relief and have accommodated less shortening than the southwest-vergent Los Medanos Hills and Roe Island anticlines (Figure 2). Also, it is interesting to note that both the Sacramento River syncline axis, as well as the axes of the Grizzly Island anticlinorium and the Honker Bay anticline, appear to be slightly offset or deflected in a right-lateral sense across the northeastward projection of the tear fault that we interpret to separate the Los Medanos Hills and Roe Island anticlines.

As discussed in sections 3.2 and 3.3, the Los Medanos Hills and Roe Island anticlines are fault-propagation folds developed above blind, northeast-dipping thrust faults. The Suisun-Grizzly and Honker Bay anticlines to the north are contained within the hanging walls of these structures, and are underlain by south-dipping thrust faults. Because the southwest-vergent folds are significantly larger and have accommodated greater shortening, we infer that the northeast-dipping thrust faults probably extend as discrete, continuous structures to the base of the seismogenic crust. We thus propose several models to account for the interaction of the north- and south-dipping thrust faults at depth (Figure 18):

(1) The south-dipping thrust faults extend into the subsurface at moderate angles and root into the northeast-dipping thrust faults at depth (Figure 18a); or



"Rooted Fault" Scenario:

1. Master Thrust dips ~30° northeast beneath Los Medanos Hills and western delta
2. Synthetic faults in the Los Medanos Hills anticlinorium and antithetic fault beneath Honker anticline are rooted in Master Fault (the "Los Medanos Hills Thrust fault")
3. Master Fault intercepts the Pittsburg - Kirby Hills Fault at approximately 10km depth.

"Partially Rooted" Fault Scenario:

1. Master Fault dips 30° beneath the Los Medanos Hills and western delta
2. Synthetic thrust faults in the Los Medanos Hills are rooted in the Master Fault
3. Honker Thrust is a "Rootless" out of syncline thrust.

"Deep Fault" Scenario:

1. Master Fault beneath Los Medanos Hills anticlinorium dips more steeply than 30°.
2. Los Medanos Hills anticline is a fault propagation fold above a hinge in the Master Fault.
3. Master Fault intersects the Pittsburg-Kirby Hill and beneath Honker Anticline are out-of-syncline faults, and not rooted in the Master Fault.
4. Master Fault intersects the Pittsburg-Kirby Hills Fault at approximately 12km depth.

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Figure 18. Models for the structural and kinematic relationship between the northeast-dipping Los Medanos thrust fault and the south-dipping thrust fault or faults beneath the Honker Bay-Van Sickle Island structure.

(2) The south-dipping faults have formed primarily as flexural slip "out-of-syncline" thrust faults and sole into bedding at shallow depths. The master northeast-dipping thrust fault beneath the Los Medanos Hills may extend to depths of 10 km or greater, depending on its down-dip geometry (Figures 18b, 18c).

In all of these cases, we believe that the southwest-dipping thrust faults beneath the Grizzly Island anticline and the Honker-Van Sickle structure are shallowly rooted, do not extend to depths at which moderate to large magnitude earthquakes typically nucleate (i.e., 10-15 km; Sibson, 1982), and thus probably are not independent seismic sources. We suggest that the faults may move sympathetically during large events on the northeast-dipping faults, or that they may accommodate post-seismic deformation of the hanging-wall blocks of the northeast-dipping thrust faults (see discussion and examples in Hitchcock and Kelson, in press). As such, the faults may be sources of aftershock seismicity.

The subsurface extent of the south-dipping thrust fault that we infer to underlie the Potrero Hills anticline (Figure 15) is difficult to evaluate because the geometry of the fold is incompletely constrained by the data available for this study. We cannot ascertain the full width, structural relief and asymmetry of the fold to determine whether the thrust faults in the core of the fold extend to significant depths. An indirect way of estimating total wavelength or width of the fold is to assume that the back limb extends from the crest of the Potrero Hills anticline south to the axis of the Grizzly Island syncline. If the structure map in Figure 15 is accurate, then the width of the Potrero Hills anticline is similar to that of the Roe Island anticline. We emphasize that this approach produces highly uncertain results because there are no data to accurately locate the axis of the Grizzly Island syncline (Figure 15). In lieu of additional well data or north-south seismic reflection profiles across the Potrero Hills anticline to verify the geometry shown in Figure 2, we assume that a south-dipping thrust fault probably is present at significant depth beneath the fold.

To summarize, we interpret that northeast-southwest contraction across the western Delta region is associated with transpressional development of the Mt. Diablo fold and thrust belt. The folds exhibit a well-defined right-stepping en echelon geometry, and they accommodate distributed right-lateral shear between the Concord-Green Valley fault on the west and the Pittsburg-Kirby Hills fault on the east. Northeast-dipping thrust faults beneath the Roe Island and Los Medanos Hills anticlinoriums accommodate the majority of shortening in this region and probably extend to seismogenic depths. Southwest-dipping thrust faults beneath Grizzly Island and Honker Bay anticlines are shallowly rooted and unlikely to be significant seismic sources. Based on available data, we conclude that a southwest-dipping thrust fault is present beneath the Potrero Hills anticline and probably extends to seismogenic depths.

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