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Detailed Mapping and Analysis of Fold Deformation Above the West Tracy Fault, Southern San Joaquin-Sacramento Delta, Northern California: Collaborative Research with Lettis Consultants International and InfraTerra

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Abstract

Reprocessed oil industry seismic reflection data from the northwestern San Joaquin Valley image structural and stratigraphic relations bearing on the activity, and geometry of the West Tracy and Midland faults. Interpretation of available LiDAR datasets and geotechnical borings in the area of Clifton Court Forebay provide additional information on the activity of the West Tracy fault based on apparent deformation and offset of surficial and near-surface deposits.

The West Tracy fault is a west- to southwest-dipping blind reverse fault or reverse-oblique fault along the western valley margin approximately between the towns of Tracy and Byron. The fault passes beneath the southwestern part of Clifton Court Forebay, a reservoir that facilitates transfer of water from the Sacramento-San Joaquin Delta into the California Aqueduct and Delta-Mendota Canal. Seismic reflection data analyzed for this study reveal that the West Tracy fault has produced uplift of strata in the hanging wall and northeast tilting above the blind fault tip; the updip surface projection of the fault is coincident with a synformal fold hinge across which the tilted strata flatten eastward into the San Joaquin Valley. Stratigraphic and structural relationships imaged by the reflection data, as well as regional map relationships, indicate that the West Tracy fault probably was active between Eocene and Miocene and has been reactivated to accommodate late Cenozoic transpression.

Stratigraphic relations visible in the seismic data indicate that tilting associated with activity of the fault involves Pliocene-Pleistocene strata. Limitations of the seismic data prevent unequivocal determination of whether the fault tip has ruptured to the surface beneath Clifton Court Forebay, but photo lineaments, springs and topographic anomalies associated with the updip projection of the fault near Byron suggest that local Quaternary surface rupture may have occurred. A well-expressed, 2-km-long linear scarp located northwest of Clifton Court Forebay likely

records down-to-the-east offset of a late Quaternary fan surface and coincides with apparent left-lateral deflection of the tidal margin of Holocene marshlands. A transect of geotechnical borings across the updip projection of the fault at Clifton Court Forebay records apparent down-to-the-east offset of basal Holocene peat deposits.

The Midland fault is a west-dipping structure that accommodated west-down normal displacement during deposition of Cretaceous and early Tertiary marine strata in this region. Stratigraphic and structural relations imaged by the seismic data indicate that Midland fault has been locally reactivated in a reverse sense since late Miocene time. Evidence for late Cenozoic activity includes uplift, eastward-tilting, and minor antiformal folding of the Miocene Neroly Formation in the hanging wall of the Midland fault. An angular unconformity separating the Neroly Formation from overlying Plio-Pleistocene gravels also is deformed, indicating progressive tilting during Quaternary time.

Structural relief measured on a variety of stratigraphic and geomorphic datum implies that the long-term average separation rate on the West Tracy fault since late Neogene time ranges between about 0.23-0.34 mm/yr. Separation rates determined from latest Pleistocene and Holocene features are similar to rates determined from offset of late Miocene and Plio-Pleistocene stratigraphic markers, implying relatively a uniform late Cenozoic activity rate. Based on the height and morphology of the scarp in latest Pleistocene-early Holocene fan deposits northwest of Clifton Court Forebay, the West Tracy fault may have produced two surface-deforming earthquakes in the past approximately 11,000 years, each generating about 1.5 m of relief. In this interpretation, the most recent event post-dates and deforms the base of 4,300 year-old peat deposits beneath Clifton Court Forebay. For 1.5 m average surface displacements, empirical relations in Wells and Coppersmith (1994) suggest earthquake magnitudes ranging from **M**6.7 to **M**7.1.

1.0 Introduction

This final technical report for National Earthquake Hazard Reduction Program (NEHRP) award no. G14AP00069 presents an analysis of late Cenozoic deformation along the southwestern margin of the Sacramento-San Joaquin Delta associated with the West Tracy and Midland faults (Figure 1). Both faults originally were identified and mapped in the subsurface during exploration for oil and gas in this region (e.g., Division of Oil and Gas, 1983; Sterling, 1992; see Unruh, 2012, for further discussion). The Midland fault in particular has been well studied and was active in late Cretaceous and early Tertiary time during extensional opening of the ancestral Rio Vista basin, which underlies the central and western Delta region (Unruh et al., 2007; also, Unruh et al. in press). Although there is evidence for late Cenozoic activity of the West Tracy and Midland faults (Weber-Band, 1998; Sterling, 1992; Unruh and Hitchcock, 2009), there is no documented evidence to date for surface rupture, and the interpreted mode of coseismic deformation is uplift, tilting and folding (Unruh and Hitchcock, 2011). The Midland and West Tracy faults were included as potential seismic sources in the Delta Risk Management Strategy (DRMS) analysis of ground shaking hazards to the levee system (URS Corporation/Jack Benjamin & Associates, Inc., 2008), but their subsurface geometry, activity and potential for surface deformation are poorly understood and have large uncertainties.

This present study builds on a previous analysis for the California Department of Water Resources (Unruh and Hitchcock, 2011), in which the Principal Investigators interpreted reprocessed petroleum industry seismic reflection lines to evaluate the location and geometry of the West Tracy fault beneath Clifton Court Forebay between the towns of Byron and Tracy. The new work performed for this NEHRP grant included a re-analysis of the proprietary reflection data using state-of-art seismic interpretation software; interpretation of vintage aerial photography and topographic maps that pre-date construction of Clifton Court Forebay to assess

potential surface expression of the West Tracy fault; and correlation of stratigraphy to develop new data on the timing and rate of activity of the structure.

2.0 Geologic Setting

The western Central Valley is interpreted to be underlain by a system of hidden or "blind" west-dipping thrust and reverse faults similar to the fault that produced the 1983 Coalinga earthquake (Wong et al., 1988; Wakabayashi and Smith, 1994). Collectively, these structures are informally referred to as the "Great Valley fault system" (Working Group on Northern California Earthquake Probabilities, 1999; Working Group on California Earthquake Probabilities (UCERF2), 2008). Although blind thrust faults are assumed to be present along most of the western valley margin and responsible for uplift and folding of the eastern Coast Ranges, they have only been studied in detail locally. At the latitude of present study area (approximately between the towns of Tracy and Byron; Figure 1), the structure that likely represents the local reach of the Great Valley fault system is the West Tracy fault, a northwest- striking, southwest-dipping reverse fault that has been active since late Miocene time (Sterling, 1992). In the central Sacramento-San Joaquin Delta region to the north, the major Quaternary-active structure along the western margin of the Central Valley is the Midland fault, a late Cretaceous-early Tertiary normal fault that has been reactivated to accommodate reverse or reverse-oblique slip in the modern tectonic setting (Working Group, 1999; Unruh and Hitchcock, 2009). The intersection and interaction of the West Tracy fault and Midland fault, if any, is not well understood (e.g., compare mapping of Brabb et al., 1971, with that of Sterling, 1992).

3.0 Interpretation of Seismic Reflection Data

Five seismic reflection profiles originally acquired in the 1980's by ConocoPhillips were licensed by the California Department of Water Resources (DWR) and re-processed using state-of-practice methods to obtain time- and depth-migrated

seismic sections. See Figure 1 for locations of the seismic profiles. Excel Geophysical Services, Inc (Excel) in Denver, Colorado reprocessed the data using ProMax and Green Mountain Geophysical (GMG) software to convert the seismic arrival-time data to seismic reflection cross sections in both time and depth. A detailed description of the processing sequence is provided in Unruh and Hitchcock (2011). For this NEHRP study, depth sections were used to develop the geologic interpretations.

We interpreted the reprocessed reflection data using Kingdom Suite software, a standard platform used for seismic data analysis in the oil and gas industry. Faults were identified and interpreted primarily based on consistent and traceable offsets of layered reflectors in the seismic data. An initial assessment of the seismic lines was made to determine if subsurface faulting or deformation could be observed where previous workers (e.g., Brabb et al., 1971; Crane, 1988; Weber-band, 1998; Sterling, 1992) mapped the traces of the buried faults. In the case of the Midland and West Tracy faults, clear subsurface offset and folding of reflectors were observed in association with the map traces (Figure 1). We utilized both 1:1 and vertically exaggerated versions of the seismic lines to interpret the extent and geometry of the faults in the subsurface. In particular, we found the vertically exaggerated sections useful for tracing faults through complex patterns of folded and offset strata. Final interpretations were made on 1:1 scale sections (no vertical exaggeration) so that the dips of faults could be estimated as accurately as possible.

The seismic data that we analyzed and interpreted for this study are proprietary and cannot be publicly released under DWR's lease agreement with the data owner. To illustrate and document the first-order subsurface relationships that form the basis for our interpretation, we prepared line tracings of the seismic lines and overlaid our stratigraphic and structural interpretations (Figures 2 through 6). The tracings display the general reflector geometries without providing precise information about locations, polarities and amplitudes of specific reflectors.

3.1 Seismic Stratigraphy

We identified several key unconformities imaged by the seismic data in the upper 4000 ft depth range (approximately 1,200 m), and where possible we traced them updip to the surface and correlated them with stratigraphic contacts exposed and mapped along the western valley margin. These unconformities include:

1) Angular Unconformity Between Upper Cretaceous and Eocene Marine Strata: Seismic line 4 (Figure 2) images a distinct angular unconformity in the 4,000 ft to 6,500 ft depth range (about 1,200 m to 1,981 m) beneath the western San Joaquin Valley that separates gently east-dipping layered strata above from a slightly more steeply dipping layered section below. The top Cretaceous unconformity clearly cuts down-section westward through the older strata, and the reflectors overlying the unconformity are more laterally continuous and traceable than the underlying reflectors. We used the depth of the top Cretaceous unconformity and contrast in reflector character across it in line 4 to identify the unconformity in lines 3, 2 and 9 to the north (see Figure 1 for line locations). On line 2 (Figure 3), the unconformity projects updip toward the exposed unconformable contact between Cretaceous and Eocene strata mapped in the Byron Hot Springs quadrangle by Brabb et al. (1971) and Crane (1988). The unconformity appears to be displaced down several hundred feet to the west across west-dipping normal faults in line 2, and it projects toward the base of the Eocene section exposed just west of the end of the seismic line. The depth range of the top Cretaceous unconformity as imaged on line 4 in the San Joaquin Valley (Figure 2) is comparable to the Eocene-Cretaceous contact encountered by exploration and production wells in nearly gas fields. For example, the basal Eocene unconformity was reported at a depth of about 5,500 ft (1,676 m) in the Union Island gas field east of the seismic array,

and at about 6,700 ft (2,042 m) in the East Brentwood gas field to the north (DOG, 1983).

2) Angular Unconformity at the Base of the Neroly Formation: The western end of seismic line 2 crosses the contact between the non-marine Neroly Formation and underlying Eocene strata mapped in outcrop (Figure 1; Brabb et al., 1971). On the north flank of Mt. Diablo, the Neroly Formation is bounded by the 11 Ma Kirker Tuff below and the 4.8 Ma Lawlor Tuff above (Graymer et al., 1994), placing it within the middle to late Miocene. The basal Neroly contact is an unconformity that can be traced to depth eastward in line 2 (Figure 3) and correlated with the same contact on line 9 (Figure 4) at the intersection of the two lines. Traced northward on line 9, the basal Neroly contact with the underlying Eocene strata locally is an angular unconformity (Figure 4), indicating that some deformation occurred in this region between Eocene and Miocene time. The depth to the basal Neroly unconformity in the San Joaquin Valley at the eastern end of lines 2 and 9 ranges between about 4,000 ft to 4,500 ft (about 1,200 m to 1,370 m). By comparing reflector patterns in the same depth interval in lines 3 and 4, we tentatively identify the basal Neroly unconformity at a depth of about 4,500 ft to 4,750 ft (1,370 m to 1,448 m) in the San Joaquin Valley south of line 9. This is comparable to the depth of the base of undifferentiated non-marine strata resting unconformably on Eocene marine strata at about 4,200 ft in the Union Island gas field to the east-southeast (DOG, 1983).

3) Angular Unconformity at the Base of Plio-Pleistocene Deposits: The western end of seismic line 2 crosses an unconformable contact between the Miocene Neroly Formation and overlying Pliocene-Pleistocene deposits variously mapped as “Wolfskill Formation” (Brabb et al., 1971), “Plio-Pleistocene gravel” (Crane, 1988), and “Tulare Formation” (Graymer et al., 1994). Although the nomenclature for the post-Neroly deposits varies

among these authors, the location and geometry of the contact is very similar on their respective maps. North of the present study area, Graymer et al. (1994) map the Tulare Formation as overlying the 4.8 Ma Lawlor Tuff in the foothills of Mt. Diablo. If this regional correlation is correct, then the base of the Tulare Formation, and presumably that of the local Plio-Pleistocene gravel unit in the study area mapped by Brabb et al. (Figure 1), is early Pliocene in age or younger.

The base of the Plio-Pleistocene deposits can be traced from outcrop to depth eastward in line 2 as a distinct angular unconformity with the underlying Neroly Formation in the depth range of about 2200 ft to 2500 ft (i.e., about 670 m to 762 m; Figure 3). The base of the Plio-Pleistocene unit dips less steeply east than bedding in the Neroly Formation (i.e., the contact cuts down-section to the west), and the deposits are characterized by less well-expressed and laterally continuous layered reflectivity than the underlying Neroly Formation. The angular unconformity at the base of the Plio-Pleistocene unit is clearly recognizable on line 9 (Figure 4) where it crosses line 2 (Figure 1), and can be traced to the northern and southern ends of the line. The angular discordance associated with the contact also is recognizable in line 4 (Figure 2) in the 2,200 ft to 2,500 ft (671 m to 762 m) depth range. We tentatively interpret the unconformity at the base of the Plio-Pleistocene unit in the same depth range on line 3 based on the contrast in reflector character with the underlying Neroly Formation, with the caveat that an angular discordance between the two units is not discernable on this line.

4) In addition to the relatively shallow Tertiary and late Cenozoic stratigraphic markers described above, we recognize an angular (?) and/or disconformable (?) contact between the Mesozoic Great Valley Group marine forearc strata and the acoustic basement at depths ranging from about 23,000 ft to 25,000 ft (7,010 m to 7,620 m). This contact is best

imaged in the east part of seismic line 4 (Figure 2) as a boundary between sub-horizontal reflectors above and moderately west-dipping reflectors below that are higher amplitude and more coarsely spaced. We pick the contact to coincide with the dip discordance. Similar relations are imaged below about 23,000 ft (7,010 m) depth in the central and east parts of seismic line 3 (Figure 5), and at the southeast end of seismic line 9 (Figure 4).

Although there are numerous seismic markers within the Great Valley Group below about 5,000 ft depth (1,524 m), we did not focus on identifying and correlating individual unconformities as they likely record multiple episodes of Mesozoic and early Tertiary deformation. We did, however, assess layered reflectors below 5,000 ft depth for lateral continuity in interpreting the down-dip geometry of faults.

3.2 Fault Geometry from Interpretation of Seismic Reflection Data

a) West Tracy Fault

Sterling's (1992) trace of the West Tracy fault is crossed at a relatively high angle by seismic lines 3 and 4 (Figure 1). Both seismic lines image uplift and eastward tilting of layered strata in the hanging wall of the fault.

Seismic line 4 is 7.4 miles long and was acquired southeast of Clifton Court Forebay (Figure 1). The first-order structure imaged by the data is a panel of homoclinally northeast-dipping reflectors associated with the Great Valley Group and younger rocks that flatten eastward across a synformal hinge (Figure 2). We interpret the West Tracy fault to coincide with a narrow, steeply west-dipping zone of mismatches and discontinuities in individual reflectors (Figure 2). The zone also separates dipping strata to the west (in the hanging wall) from sub-horizontal strata to the east (in the footwall), although possible aliasing of the seismic data in the western part of line 4 likely obscures the true bedding dip at depth. The resolution

and continuity of reflectors below about 20,000 ft (about 6,100 m) are fair, and we trace the West Tracy fault downdip via reflector discontinuities and abrupt changes from essentially sub-horizontal reflectors in the footwall to tilted or dipping reflectors in the hanging wall. Thus interpreted, the West Tracy fault dips 75° or more toward the west in line 4 (Figure 2).

The precise up-dip termination of the West Tracy fault is difficult to assess on line 4 because the seismic data were not acquired to maximize resolution at shallow depths, and because there is large data gap directly updip of the fault (i.e., the V-shaped gap in reflectors at the top of the seismic section). With the caveat that the amplitude and resolution of the reflectors decreases west of the synformal hinge, reflectors in the upper 2,000 ft (610 m) above the fault appear to be continuous across the fold (Figure 2). Consequently, we infer that the fault tip is located at a maximum depth of about 7,000 ft (about 2,133 m; the shallowest depth that reflector offset is confidently interpreted across the fault), and a minimum depth of about 2,000 ft (610 m) at the latitude of line 4 (Figure 1).

Seismic line 3 is 4.5 miles long, trends NE-SW, and passes along the northwestern border of Clifton Court Forebay (Figure 1). Similar to line 4, the first-order structure imaged on line 3 is a panel of homoclinally northeast-dipping reflectors associated with the Great Valley Group and younger strata, which flattens eastward across a synformal hinge in the central part of the line (Figure 5). We infer the location of the West Tracy fault in the upper part of the seismic line to coincide with a steeply west-dipping zone of reduced reflector amplitude, across which individual reflectors are discontinuous or mismatched. Although there are some east-dipping reflectors in the eastern part of the seismic line similar to those imaged in the hanging wall of the fault in line 4, resolution is generally poor in the eastern part of seismic line 3. Detailed geologic mapping of the excavation for the Intake Channel, which links Clifton Court Forebay to Bethany Reservoir about 2 km south of line 3, documented bedding dips in the Cretaceous rocks of 55° or greater, and dips of 30° to 50° in the overlying Neroly Formation (DWR Project Geology, 1970). The

seismic acquisition geometry for line 3 probably was not configured to image these relatively steep dips.

In our interpretation of line 3, the fault dip shallows below about 11,000 ft (3,353 m) depth. The data resolution decreases below about 15,000 ft (4,572 m) depth in the southeastern part of the seismic line, so our interpretation of the fault at depth is uncertain. The updip termination of the West Tracy fault is poorly imaged in line 3, primarily due to the fact that reflectors cannot be traced through or correlated across the axis of the synformal hinge above the fault tip. Based on terminations and offsets of reflectors, we tentatively trace the West Tracy fault upward to a minimum depth of about 1,000 ft (305 m; Figure 5), above which we cannot confidently discern whether or not reflectors are displaced.

Seismic line 1, which is 15.7 miles long and is crossed by both lines 3 and 4 (Figure 1), provides oblique imaging of the West Tracy fault and additional information on its extent and 3-D geometry. Based on the interpretations of lines 3 and 4, the west-dipping West Tracy fault plane intersects seismic line 1 at about 25,500 ft (7,772 m) depth at the crossing with line 4, and likewise intersects line 1 at about 9,300 ft (2,835 m) depth at its crossing with line 3. In the plane of seismic line 1, we interpret that the West Tracy fault shallows to the northwest at the latitude of Clifton Court Forebay and thus has a component of dip toward the south (Figure 6). We interpret that the fault projects updip north of line 3 toward the axis of a syncline in the base of the Neroly Formation, approximately coincident with a salient in bedrock exposures along the valley margin between Clifton Court Forebay and the town of Byron.

South of Clifton Court Forebay, the strike of the West Tracy fault rotates clockwise to a more northerly orientation and the fault obliquely crosses seismic line 1 just north of the intersection of Byron Road and Interstate 205 near the northern Tracy city limits (Figure 1). This interpretation of the location and geometry of the West Tracy fault differs from that of Sterling (1992), who mapped the fault as striking

sub-parallel to and not crossing line 1 (Figure 1). We recognize the West Tracy fault in the southern part of line 1 as a blind, steeply dipping to sub-vertical structure via reflector terminations that can be traced to a minimum depth of about 20,000 ft (6,096 m), below which reflector amplitude and resolution decrease (Figure 6). The fault terminates upward at the base of the base of the Neroly Formation. The Neroly and overlying Pliocene-Pleistocene gravel flatten southward across a monoclonal flexure in the hanging wall of the steeply dipping fault, indicating late Cenozoic reverse slip accommodated at shallow depth by fault-propagation folding.

Given this interpretation, the West Tracy fault forms the southern structural boundary of a broad, long-wavelength antiformal fold in underlying Cretaceous strata imaged in the central-south part of line 1 (Figure 6). This fold also is expressed in map-scale stratigraphic and structural relationships of Cretaceous and late Cenozoic strata in the Altamont Hills west of seismic line 1 (Graymer et al., 1996) (Figure 7). The dip direction in the Cretaceous strata progressively rotates counter-clockwise from south to north, defining a broad east-trending antiformal closure, and the base of the Neroly Formation cuts progressively downsection through the Cretaceous strata across the northern limb of the antiform, consistent with the distinct angular unconformity at the base of the Neroly Formation visible in line 1 (Figure 6). Maximum structural relief of Cretaceous reflectors across the axis of the fold as imaged in line 1 is about 2,500 ft (762 m), whereas structural relief on the Neroly Formation across the fold is about 800 ft (244 m), indicating that the majority of structural growth associated with the fold occurred prior to Neroly time. The fact that the Neroly Formation sits directly on Cretaceous strata with no intervening Eocene rocks in the Altamont Hills to the west (Graymer et al., 1996), as well as in the northern part of seismic line 1 near Clifton Court Forebay (Figure 6), indicates that uplift, growth of the fold, and erosion of the crest occurred between Eocene and Miocene time. Map relations in Figure 7 further show the base of the Neroly Formation locally cutting out the Miocene Cierbo Formation on the south limb of the anticline, indicating that at least

some deformation and/or fold growth likely occurred between Cierbo and Neroly time (i.e., in the mid to late Miocene). Given that the fold is bounded by and in the hanging wall of the West Tracy fault, these relations imply that the West Tracy fault is a structure with an older Tertiary history that has been reactivated to accommodate shortening in the late Cenozoic transpressional setting.

In a previous study, Unruh and Hitchcock (2011) interpreted the high-angle fault at the southern end of seismic line 1 to be the southern termination of the West Tracy fault, effectively serving as a structural or geometric southern segment boundary and forming the basis for their assessment of a 15 km maximum rupture length. In our revised interpretation for this report, the strike of the West Tracy fault rotates clockwise and the dip of the fault steepens south of Clifton Court Forebay, such that it intersects the south end of seismic line 1 obliquely and continues for an unknown distance to the southeast. Thus, the 15 km length of the fault imaged in seismic line 1 should be considered a minimum potential rupture length for estimating maximum magnitude.

ii) Midland Fault

Seismic lines 2 and 9 cross the Midland fault just north of the town of Byron (Figure 1). At this latitude workers have mapped several different locations for the buried trace of the Midland fault: (1) the trace shown by Brabb et al. (1971; Figure 1); (2) a trace shown by Crane (1988); and (3) a trace shown by Jennings (1994) that terminates in the San Joaquin Valley northwest of Byron.

Seismic line 2 is 3.7 miles long, trends east-west, and images several dominantly west-dipping faults that displace reflectors corresponding to Cretaceous and Eocene strata down to the west, but do not offset the Neroly Formation or younger strata (Figure 3). These structures are likely late Cretaceous-early Tertiary in age and associated with extensional deformation that formed the Rio Vista basin (Krug et al., 1992). The fault trace in the approximate center of the profile is most closely

associated with Crane's buried trace of the Midland fault. This structure dips west and distinctly offsets the top Cretaceous and top Eocene markers in the depth range of about 4,000 ft to 6,500 ft (1,219 m to 1,981 m). As imaged in line 2, displacement on the fault dies out in the Eocene section, and does not offset the basal Neroly Formation ("top Eocene") unconformity (Figure 3). Similar relationships are exposed in the likely outcrop exposure of the Midland fault southwest of seismic line 2 (Figure 1), indicating that normal displacement on the fault died out prior to deposition of the Neroly Formation.

Although the Midland fault does not displace the base of the Neroly Formation in a west-down normal sense similar to the underlying Eocene strata, seismic line 2 images a synformal hinge in layered Neroly Formation strata updip of the fault tip, west of which the Neroly has a distinctly steeper dip than to the east (Figure 3). These relationships are consistent with post-Neroly fault-propagation folding associated with reverse reactivation of the Midland fault at depth.

Below about 6,500 ft (1,981 m) depth, the trajectory of the Midland fault through layered Cretaceous strata is uncertain. Two alternative interpretations for the Midland fault, which we informally refer to as the "preferred" and "alternate" models, are shown on Figure 3. In the preferred model (orange line), the Midland fault dip shallows slightly below about 6,500 ft (1,981 m) depth, then steepens again below about 9,500 ft (2,896 m) depth, exhibiting a convex morphology. This model fault dips about 50° west below 10,000 ft (3,048 m) and follows a well-defined series of truncations and lateral discontinuities in reflectors within the Upper Cretaceous section, intersecting the eastern edge of seismic line 2 at about 17,500 ft (5,334 m) depth. In contrast, the alternate model (colored yellow) for the Midland fault maintains a steep west dip (about 75°) to about 14,000 ft (4,267 m) depth, below which the fault plane shallows and exhibits a concave morphology to about 22,500 ft (6,858 m) depth where it intersects the eastern edge of the seismic line (Figure 3). The downdip trajectory of the alternate model is less well expressed on line 2 by consistent truncations of seismic reflectors than the more

shallowly dipping, convex model, but the reflectors in the hanging wall of the alternate model dip more steeply than those in the footwall, consistent with syndepositional growth faulting, and/or uplift and tilting associated with late Cenozoic reverse reactivation of the Midland fault.

Seismic line 9 (Figure 4) is 8.2 miles long and has the most crooked geometry of all five lines in the seismic array (Figure 1). The Midland fault is imaged at shallow in the central part of line 9 as a steeply west-dipping structure that clearly offsets reflectors in the depth range of about 5,000 ft to 6,000 ft (1,524 m to 1,823 m; Figure 4). Similar to relationships imaged in line 2 (Figure 3), the Midland fault terminates within the Eocene section and does not displace the basal contact of the Miocene Neroly Formation (i.e., the top Eocene marker). The preferred and alternate geometries for the down-dip trajectory of the Midland fault through the Cretaceous strata are shown by respective orange and yellow lines in Figure 4. The two interpretations are generally equivalent above about 17,000 ft (5,182 m) depth, and diverge slightly below As interpreted in lines 2 and 9, both fault models define a generally north-striking, west-dipping fault surface, consistent with the regional geometry of the Midland fault as inferred from regional subsurface mapping in the Delta (Krug et al., 1992). Whereas the preferred fault model is better expressed by consistent reflector truncations in line 2, the downdip geometry of the alternate model in line 9 is better expressed as both reflector truncations and abrupt changes in reflector dip.

Line 9 reveals that late Cretaceous and Eocene strata in the hanging wall of the Midland fault (for both the preferred and alternate models) are folded into a broad anticline (Figure 4). The base of the Neroly Formation is a distinct angular unconformity with the Eocene strata and does not exhibit similar antiformal closure, indicating that some reverse reactivation of the fault occurred between Eocene and Miocene time, possibly coeval with development of the broad fold imaged in the central-south part of line 1, and mapped in outcrop to the west in the Altamont Hills (Grayer et al. 1996). In detail, stratigraphic relations above the basal Neroly

unconformity imaged by line 9 record progressive late Cenozoic uplift and eastward or northeastward tilting along the western valley margin (Figure 4): the post-Neroly stratigraphic section thins westward, and the angular unconformity between the Neroly Formation and Plio-Pleistocene deposits imaged on line 2 (the "top Neroly" marker) also is well expressed on line 9 (Figure 4).

Given that the Midland fault extends downdip to the eastern end of seismic line 2, it is potentially imaged in the northern part of seismic line 1 that intersects line 2. Figure 6 shows two possible interpretations for the Midland fault on line 1 consistent with the strike and dip of the preferred and alternate models interpreted in lines 2 and 9, and with geologic mapping by Brabb et al. (1971) that traces the Midland fault south of Byron and into the bedrock foothills along the valley margin. Both geometries in line 1 (Figure 6) show the fault offsetting Eocene reflectors down to the west, but not displacing the basal Neroly Formation unconconformity, consistent with stratigraphic and structural relationships mapped by Brabb et al. (1971). Although both fault trajectories are locally associated with reflector discontinuities and abrupt changes in reflector dip, in some places the faults pass through apparently unbroken reflectors. This could be due to serendipitous juxtaposition of offset reflectors by faulting, but it also suggests that the Midland fault may die out south of Byron, as suggested by Crane's (1988) and Jenning's (1994) mapping, and thus is not distinctly imaged in seismic line 1.

4.0 Geomorphic Setting

Following the last glacial maximum about 15,000 years ago, sea level rise flooded much of the broad inland valley presently occupied by the modern Sacramento-San Joaquin Delta (Atwater et al., 1977; Atwater 1980). Rising waters reached the western edge of the Delta approximately 7,000 years ago (Shlemon and Begg,

1975; Wells, 1995). Water levels rose another 8 m during the past 6,000 years (Wells, 1995).

Tectonic controls on the distribution of tidal marshlands formed as a result of sea-level rise can be clearly seen in the vicinity of Clifton Court Forebay. Figure 8 shows the limits of the marshlands as represented by the 1850 tide line, which closely parallels the buried traces of the Midland and West Tracy faults. The updip projections of these faults, as shown on the figure, locally coincide with the inland extent of marshlands, suggesting the presence of geomorphic relief associated with deformation of the ground surface. A southern extension of the marshlands located along the updip projection of the West Tracy fault southeast of Clifton Court ends at, and appears deflected eastward by, the buried Vernalis fault.

Rise in sea level was accompanied by development of tidal marshes and deposition of peat through the Late Holocene (Atwater et al., 1979). Intertidal peat began to accumulate in the Delta about 6,000 to 7,000 years ago (Shlemon and Begg, 1973; Drexler et al., 2006). Estuary marshlands expanded into the southern Delta in response to the higher sea levels. Radiocarbon dates indicate that peat deposition associated with expansion of tidal areas into the area of Clifton Court Forebay began between 4,000 and 5,000 years ago (Atwater, 1982). Three radiocarbon dates from a depth profile collected in peat within the northeastern corner of Clifton Court Forebay by West (1977) provide dates for the base of peat that range from about 4,000 to 4,400 years (± 150 years) before present (Table 1).

Table 1. Radiocarbon dates for peat sampled in Clifton Court Forebay (from West, 1977).

Sample Location*	Depth Below Sea Level (cm)	Material	Laboratory Number	Age in ^{14}C Years before 1950
37°51'15" -121°34'15"	172-177	Peaty muck	GX 4221	2,950 ±150
37°51'15" -121°34'15"	340-347	Peaty muck	GX 4222	3,940 ±140
37°51'15" -121°34'15"	368-373	Peaty muck	GX 4223	4,340 ±150

* See Figure 12 for locations from Atwater (1982).

5.0 Quaternary Deposits and Landforms

The late Pleistocene landscape in the southern Delta formed on well-consolidated sandy deposits during low stands of sea level. The older land surfaces, where preserved, are often associated with well-developed buried soils (paleosols) that represent prolonged periods of land stability. Geoarchaeological investigations conducted in the Kellogg Creek Valley watershed northwest of Clifton Court Forebay near Byron, revealed at least three episodes of deposition within a 15,000-year-old alluvial sequence (Meyer and Rosenthal 1997). Each of these depositional episodes was followed by a separate period of landform stability and soil formation during the Early, Middle, and Late Holocene (Meyer 1996).

Buried soils identified in older alluvial fans, terraces, and floodplains along Kellogg and Marsh Creeks northwest of Clifton Court have been dated by radiocarbon methods to about 11,000 cal B.P. (Meyer and Rosenthal, 1997). The geomorphic surfaces associated with these soils project out to, and are correlative with, the older alluvial fan deposits preserved along the eastern Diablo Range range between Clifton Court Forebay and the town of Byron. The soils associated with the alluvial fan remnants located northwest of Clifton Court Forebay are mapped as Solano and Rincon loam (Welch et al., 1966). Solano and Rincon series soils

are characterized by well-developed subsurface horizons of accumulated clay (Bt) and/or calcium carbonate (Bk). In the surrounding region, these soils are generally associated with alluvial fans that are Latest Pleistocene to Early Holocene (Meyer and Rosenthal, 1997; Knudsen et al. 2000).

6.0 Evidence for Late Quaternary Deformation

As noted above, and illustrated in Figure 8, the mapped southern tip of the West Tracy fault roughly coincides with an elongate extension of historic tidal marshes, constrained by the 1850 tide line. The presence of young deposits overlying the projection of the fault from the subsurface and modification of the landscape for agriculture and water conveyance has obscured evidence of potential faulting or fold deformation southeast of Clifton Court Forebay.

Topographic and slope maps derived from LiDAR data for the Sacramento-San Joaquin Delta area of California from the California Department of Water Resources were used to image and profile late Quaternary surfaces north of Clifton Court Forebay (Figures 9 and 10). Collected in 2007 and published in 2010, these data consist of two-meter-cell grids, down-sampled from an original resolution of 1 meter (Wang et al., 2012).

We identified two key localities in the vicinity of Clifton Court Forebay with sufficient data to evaluate possible fault-related deformation. These locations include:

1. Topographic Scarp North of Clifton Court Forebay: A northwest-trending (N50°W), northeast-facing topographic scarp is located approximately 1.8 km northwest of Clifton Court Forebay (Figures 9 and 10). The scarp is within older alluvial fan deposits and appears to separate two distinct, similar surfaces in a northeast-down sense. The approximately 200-m-wide scarp has a beveled steep front edge that is roughly 1.5 m high (Figure 11). Total height of the scarp, including the bevel, is roughly 3 m. The scarp

extends 2 km northwest from the 1850 tide line to where it appears to be covered by younger alluvial fan deposits, located 1.4 km southeast of the intersection of Byron Highway and Camino Diablo.

2. Geotechnical Profile along the Northern Margin of Clifton Court Forebay: Over 120 geotechnical borings have been drilled within the immediate vicinity of Clifton Court Forebay by the California Department of Water Resources and their consultants (Figure 12). Field logs of these borings identify sediment packages based on the Unified Soil Classification System and soil properties including plasticity, dilatancy, toughness, dry strength, color, and grain-size distribution.

A geologic profile of these borings along the northern margin of Clifton Court Forebay (Figure 13) shows a down-to-the-east step in the elevation of peat deposits of approximately 1.5 meters.

7.0 Discussion

7.1 Mid-Tertiary Activity of the Midland and West Tracy Faults

Stratigraphic and structural relations imaged in the reflection data indicate that both the West Tracy fault and Midland fault were active in early to middle Tertiary time to accommodate crustal shortening. These observations are consistent with map-scale relationships in the Altamont Hills to the west indicating that net uplift and erosion of Eocene strata occurred there prior to deposition of the Neroly Formation (Figure 6). This mid Tertiary deformation may have been more regional in extent and included south-side-up reverse reactivation of the east-west-striking Stockton fault buried beneath the San Joaquin Valley to the east: correlated well data from the Union Island gas field (DOG, 1983) show about 1,100 ft (335 m) of south-up

separation on basal Eocene strata across the Stockton fault, which occurred prior to deposition of the unconformably overlying late Miocene Neroly Formation. The timing of this event on the Stockton fault may be the same as the mid (?) Tertiary deformation in the Altamont Hills represented by the angular unconformity at the base of the Neroly Formation (Figure 7). As discussed by Bartow (1991) and Imperato (1992), the Stockton fault has a long and complex tectonic history, including an early phase of extension in the late Mesozoic and early Tertiary similar to the Midland fault.

7.2 Structural Cross Section of the West Tracy Fault

A NE-SW-trending cross section at the latitude of Clifton Court Forebay (section A-A', Figure 1) that synthesizes stratigraphic and structural relations interpreted from geologic maps and the seismic reflection data (especially seismic lines 1, 3 and 4) is presented in Figure 14. The cross section also incorporates geologic relations that were exposed and mapped in detail by DWR during excavation of the Intake Channel that links Clifton Court Forebay to Bethany Reservoir (Project Geology, 1970). As shown in the cross section, the West Tracy fault is interpreted to be a steeply southwest-dipping fault along the southwestern margin of the Delta. Cretaceous strata in the hanging wall of the fault have been uplifted and tilted to the northeast, and are unconformably overlain by the Neogene Neroly Formation and Plio-Pleistocene deposits. Eocene deposits are missing in the hanging wall of the fault but present in the subsurface of the San Joaquin Valley to the east in the footwall, consistent with the evidence summarized in Section 7.1 above for a mid-Tertiary episode of activity on the fault that produced regional uplift, tilting and erosion of the Eocene section prior to deposition of the Neroly Formation in late Miocene time. Late Cenozoic activity on the fault began after deposition of the basal Neroly strata and before deposition of the Plio-Pleistocene deposits, which cut downsection to the west through tilted and eroded Neroly strata. Activity of the West Tracy fault continued during deposition of the Plio-Pleistocene deposits, resulting in stratigraphic thickening of this unit in the footwall of the structure relative to the hanging wall.

Cross section A-A' extends southwest to cross the Midway fault, a late Quaternary-active fault in the eastern Altamont Hills (Jennings, 1994). The Midway fault is depicted as a sub-vertical strike-slip fault (Figure 14) based on the linear map trace and observations of sub-horizontal slickenside lineations in a trench excavated across the fault (R. Barry, personal communication, 2015). If this inference is correct, and if the steep southwest dip of the West Tracy fault observed in reflection data is projected to depth, then the West Tracy and Midway faults meet or intersect at a depth of about 15 km, which is at or near the base of the seismogenic crust in this region. The geometry of the two faults as depicted in the cross section recalls that of a positive flower structure, suggesting that activity of the two faults may be kinematically related in the modern transpressional tectonic setting.

7.3 Separation Rates for the West Tracy Fault

Long-term average late Cenozoic separation rates for the West Tracy fault can be estimated from structural relief on the base of the Neroly Formation and the base of the unconformably overlying Plio-Pleistocene deposits.

From the cross section in Figure 14, the elevation difference of the base of the Neroly Formation between the footwall and hanging wall is measured to be about 4,700 ft (1,400 m). This value probably represents a minimum because the Neroly Formation is missing in the western part of the Intake Channel exposure, and thus total relief on the now-eroded base of the section likely is greater than the maximum relief depicted in the cross section. Given that the 4.8 Ma Lawlor Tuff overlies the Neroly Formation (see previous discussion in Section 3.1), it is possible that the tuff is conformable with the Neroly Formation, implying that it pre-dates the onset of movement on the West Tracy fault and related folding of the hanging wall, or it post-dates the onset of deformation and is separated from the Neroly Formation by an angular unconformity. The Lawlor Tuff underlies the Plio-Pleistocene deposits, so it must have been deposited relatively close in time to the onset of late Cenozoic deformation. For the purposes of this discussion, we

assume that 1,400 m of relief on the Neroly Formation at the latitude of Clifton Court Forebay has accumulated in the past 4.8 Ma, implying a long-term average separation rate of about 0.29 mm/yr on the West Tracy fault since late Miocene time.

Similarly, the cross section in Figure 14 shows the elevation difference of the base of the Plio-Pleistocene deposits to be about 2,600 ft (800 m) across the West Tracy fault. This estimate is also probably a minimum given that the base of the deposits locally is missing and likely eroded in the hanging wall. If it is assumed that the base of these deposits is about 3.5 Ma in age, then the long-term separation rate is about 0.23 mm/yr.

These long-term (Neogene-early Quaternary) separation rates are comparable to latest Quaternary and Holocene rates inferred from geomorphic and subsurface relations between Clifton Court Forebay and the town of Byron. The well-expressed, 2-km-long linear scarp located northwest of Clifton Court Forebay (Figures 10 and 11; Section 6.0) likely records down-to-the-east offset of a late Quaternary fan surface and coincides with apparent left-lateral deflection of the tidal margin of Holocene marshlands. Assuming a minimum age of 11,000 years, we estimate a latest Quaternary-early Holocene separation rate of 0.13 to 0.27 mm/yr based on the observed 1.5 m to 3 m scarp height in the fan surface. The transect of geotechnical borings across the updip projection of the fault at Clifton Court Forebay (Figure 12) similarly records apparent down-to-the-east fault offset or folding of basal peat deposits. Offset of 1.5 meters of the base of peat estimated to be 4,300 years old (Table 1) suggests a Holocene vertical separation rate of approximately 0.34 mm/yr. These relations suggest that the late Quaternary separation rate across the West Tracy fault is approximately 0.3 ± 0.1 mm/yr, similar to the late Neogene rates discussed above. The full range in separation rates from late Neogene to Holocene is 0.23 mm/yr to 0.34 mm/yr.

7.4 Earthquake Recurrence and Magnitude for the West Tracy Fault

The bevel in the scarp captured in the topographic profile in Figure 11 may represent at least two discrete episodes of surface deformation that post-date the late Pleistocene fan deposits. One event may have created the scarp and produced about 1.5 m of relief across the fan surface. The scarp subsequently may have been eroded and laid back to produce the bevel. A second event may have occurred after the bevel formed to produce the relatively steep northeast-facing scarp (Figure 11). Based on the height of the steepest part of the scarp, the second event also may have been accompanied by about 1.5 m of uplift for the observed 3 m cumulative separation of the fan surface. The second event in this scenario may also be recorded by the approximately 1.5 m of relief on the base of the 4,300 year-old base of peat deposits at Clifton Court Forebay on trend to the south.

If it is assumed that the separation rate is about 0.3 mm/yr, and if each event produces about 1.5 m of relief, then the average return period for earthquakes on the West Tracy fault that produce this pattern of surface deformation is about 5,000 years, consistent with evidence for at least two events within the past 11,000 years as inferred from the faulted fan surface located north of Clifton Court Forebay. Based on empirical relations between average surface displacement and earthquake magnitude in Wells and Coppersmith (1994), a 1.5 m scarp implies a **M**6.7 reverse-faulting earthquake. The Wells and Coppersmith (1994) regression on average displacement and magnitude for all styles of faulting suggests a **M**7.1 earthquake.

8.0 Conclusions

Based on analysis of seismic reflection data, the West Tracy fault is a structure with a mid-Tertiary history of activity that has been reactivated in the late Cenozoic time to accommodate transpressional deformation. Structural relief measured on

a variety of stratigraphic and geomorphic datum suggests that the long-term average separation rate for the West Tracy fault since late Neogene time ranges from 0.23 mm/yr to 0.34 mm/yr. Separation rates determined from latest Pleistocene and Holocene features are similar to rates determined from offset of late Miocene and Plio-Pleistocene stratigraphic markers, implying a relatively uniform activity rate in the past approximately 4.8 million years. Based on the height and morphology of a scarp in latest Pleistocene-early Holocene fan deposits northwest of Clifton Court Forebay, the West Tracy fault may have produced two surface-deforming earthquakes in the past approximately 11,000 years, with each event generating about 1.5 m of relief. In this scenario, the most recent event post-dates and deforms the base of 4,300 year-old peat deposits beneath Clifton Court Forebay. If the West Tracy fault typically produces 1.5 m average surface displacements, then empirical relations in Wells and Coppersmith (1994) suggest that surface-deforming earthquakes on the structure could range from **M**6.7 to **M**7.1.

References

Bartow, A.J., 1991, The Cenozoic Evolution of the San Joaquin Valley: United States Geological Survey Professional Paper 1501, 40 p. plus maps.

Brabb, E.E, Sonneman, H.S., and Switzer, J.R., Jr., 1971, Preliminary geologic map of the Mt. Diablo-Byron area, Contra Costa, Alameda and San Joaquin Counties, California: United States Geological Survey Open-File Map 71-53.

California Department of Water Resources, 2010, LiDAR data for the Delta Area of California: https://catalog.data.gov/dataset/lidar-data-for-the-delta-area-of-california2946e. Accessed 14 September 2015.

California Wetlands Monitoring Workgroup (CWMW). EcoAtlas. Accessed 14 September 2015. http://www.ecoatlas.org. (http:www.sfei.org).

Crane, R., 1988, Geologic maps of the Byron Hot Springs, Bethany and Brentwood 7.5-minute quadrangles: unpublished maps available from H&L Hendry, Concord, CA; scale 1:24,000.

Crane, R.C., 1995, Geology of the Mt. Diablo region and East Bay hills, in Sangines, E.M., Andersen, D.W., and Buising, A.V., eds., Recent Geologic Studies in the San Francisco Bay Area: Society of Economic Paleontologists and Mineralogists, Pacific Section Volume 76, p.
87-114.

Division of Oil and Gas, 1983, East Brentwood Gas Field, in California Oil and Gas Fields, Northern California: California Department of Conservation Publication TR 10, v. 3, supplement to 1982 edition.

Division of Oil and Gas, 1983, Tracy Gas Field, in California Oil and Gas Fields, Northern California: California Department of Conservation Publication TR 10, v. 3, supplement to 1982 edition.

Division of Oil and Gas, 1983, Union Island Gas Field, in California Oil and Gas Fields, Northern California: California Department of Conservation Publication TR 10, v. 3, supplement to 1982 edition.

Drexler, J Z, Verosub, K L, Delusina, I, de Fontaine, C S, Lunning, N, Wong, S, 2006, Project REPEAT: Rates and Evolution of Peat Accretion through Time in the Sacramento- San Joaquin Delta, California: Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract PP51A-1125.

Graymer, R.W., Jones, D.L., and Brabb, E.E., 1994, Preliminary geologic map emphasizing bedrock formations in Contra Costa County, California: United States Geological Survey, Open-File Report 94-622.

Graymer, R.W., Jones, D.L., and Brabb, E.E., 1996, Preliminary geologic map emphasizing bedrock formations in Alameda County, California: United States Geological Survey, map derived from digital database Open-File Report 96-252.

Imperato, D., 1992, Structure and tectonics of the Stockton fault zone (abstract), *in* Structural Geology of the Sacramento Basin: Association of American Petroleum Geologists (Annual Meeting, Pacific Section, Sacramento, California, April 27, 1992-May 2,1992), Miscellaneous Publication 41, p. 157.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

Knudsen, K.L., Sowers, J.M., Witter, R.C., Wentworth, C.M., and E.J. Helley, 2000, Description of Mapping of Quaternary Deposits and Liquefaction Susceptibility,

Nine-County San Francisco Bay Region, California: U.S. Geological Survey, Part 3 of Open-File Report 00-444, Version 1.0. http://geopubs.wr.usgs.gov/open-file/of00-444/

Krug, E.H., Cherven, V.B., Hatten, C.W., and Roth, J.C., 1992, Subsurface structure in the Montezuma Hills, southwestern Sacramento basin, in Cherven, V.B., and Edmondson, W.F., eds., Structural Geology of the Sacramento Basin: Volume MP-41, Annual Meeting, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 41-60.

Meyer, Jack, and Jeffrey S. Rosenthal, 1997, Archaeological and Geoarchaeological Investigations at Eight Prehistoric Sites in the Los Vaqueros Reservoir Area, Contra Costa County. Los Vaqueros Final Report #7. Anthropological Studies Center, Sonoma State University, Rohnert Park, California. Report prepared for Contra Costa Water District, Concord, California.

Project Geology, 1970, Final geologic report, Delta pumping plant, intake channel, and fish facility: California Department of Water Resources, Project Geology Report C-54, 38 p. plus plates.

Rogers, J. David, 1988, Pleistocene to Holocene Transition in Central Contra Costa County, California. In Field Trip Guide to the Geology of the San Ramon Valley and Environs, pp. 29-51. Northern California Geological Society, San Ramon, California.

Schlemon, R. J., and E. L. Begg, 1973, Late Quaternary evolution of the Sacramento-San Joaquin Delta, California: Proc. Ninth Congress of the International Union for Quaternary Research 1973:259-266.

Sterling, R.H. Jr., 1992, Intersection of the Stockton and Vernalis Faults, Southern Sacramento Valley, California. In Cheveron, V.B., and Edmondson, W.F., eds.,

Structural Geology of the Sacramento Basin: Miscellaneous publication, Pacific Section, AAPG, p. 143-151.

Unruh, J.R., 2012, Chapter 3: Seismic Sources and Ground Rupture, in Delta Seismic Design: report to the California Department of Water Resources by GEI Consultants, Inc., June 2012, p. 23-36.

Unruh, J.R., Dumitru, T.A., and Sawyer, T.L., 2007, Coupling of early Tertiary extension in the Great Valley forearc basin with blueschist exhumation in the underlying Franciscan accretionary wedge at Mt. Diablo, California: Geological Society of America Bulletin, v. 119, no., 11/12, p. 1347-1367; doi: 10.1130/B26057

Unruh, J.R., and Hitchcock, C.S., 2009, Characterization of Potential Seismic Sources in the Sacramento-San Joaquin Delta, California: Final Technical Report submitted to the U.S. Geological Survey National Earthquake Hazard Reduction Program, Award Number 08HQGR0055, 45 p.

Unruh, J.R., and Hitchcock, C.S., 2011 Final Letter Report summarizing results of reprocessing and interpreting seismic reflection data across the West Tracy fault near Clifton Court Forebay: prepared for Project Geology Branch, Department of Water Resources.

Unruh, J., Hitchcock, C., Blake, K., and Hector, S., in press, Characterization of the Southern Midland Fault in the Sacramento-San Joaquin Delta: to be published by the Association of Engineering Geologists.

URS Corporation/Jack Benjamin & Associates, Inc., 2008, Delta Risk Management Strategy (DRMS) Phase 1: report prepared for the California Department of Water Resources.

Wang, R. & Ateljevich, E., 2012, A Continuous Surface Elevation Map for Modeling (Chapter 6): In Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Mars, 23rd Annual Progress Report to the State Water Resources Control Board. California Department of Water Resources, Bay-Delta Office, Delta Modeling Section.

Weber-Band, J., 1998, Neotectonics of the Sacramento-San Joaquin Delta area, east-central Coast Ranges, California: Ph.D. dissertation, University of California, Berkeley, 216 p.

Wells, L.E., 1995, Radiocarbon dating of Holocene tidal marshdeposits: Applications to reconstructing relative sea level changes in the San Francisco estuary. In Quaternary geochronology and paleoseismology, ed. J.S. Noller, W.R. Lettis, and J.M. Sowers, 3.95–3.102. Washington DC: Nuclear Regulatory Commission.

Wells, D. L., and Coppersmith, K. J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Seismological Society of America Bulletin, v. 84, no. 4, p. 974-1002.

West, G. J., 1977, Late Holocene Vegetation History of the Sacramento-San Joaquin Delta, California. Cultural Heritage Section, California Department of Parks and Recreation, Sacramento California. Prepared for California Department of Water Resources, Sacramento, California.

Wong, I. G., Ely, R. W., and Kollmann, A. C., 1988, Contemporary seismicity and tectonics of the northern and central Coast Ranges - Sierran block boundary zone, California: Journal of Geophysical Research, v. 93, p. 7813-7833.

Working Group on Northern California Earthquake Probabilities, 1999, Earthquake probabilities in the San Francisco Bay region: 2000 to 2030 - A summary of findings: U.S. Geological Survey Open-File Report 99-517.

Working Group on California Earthquake Probabilities, 2008, The Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2): United States Geological Survey Open-File Report 2007-1437.

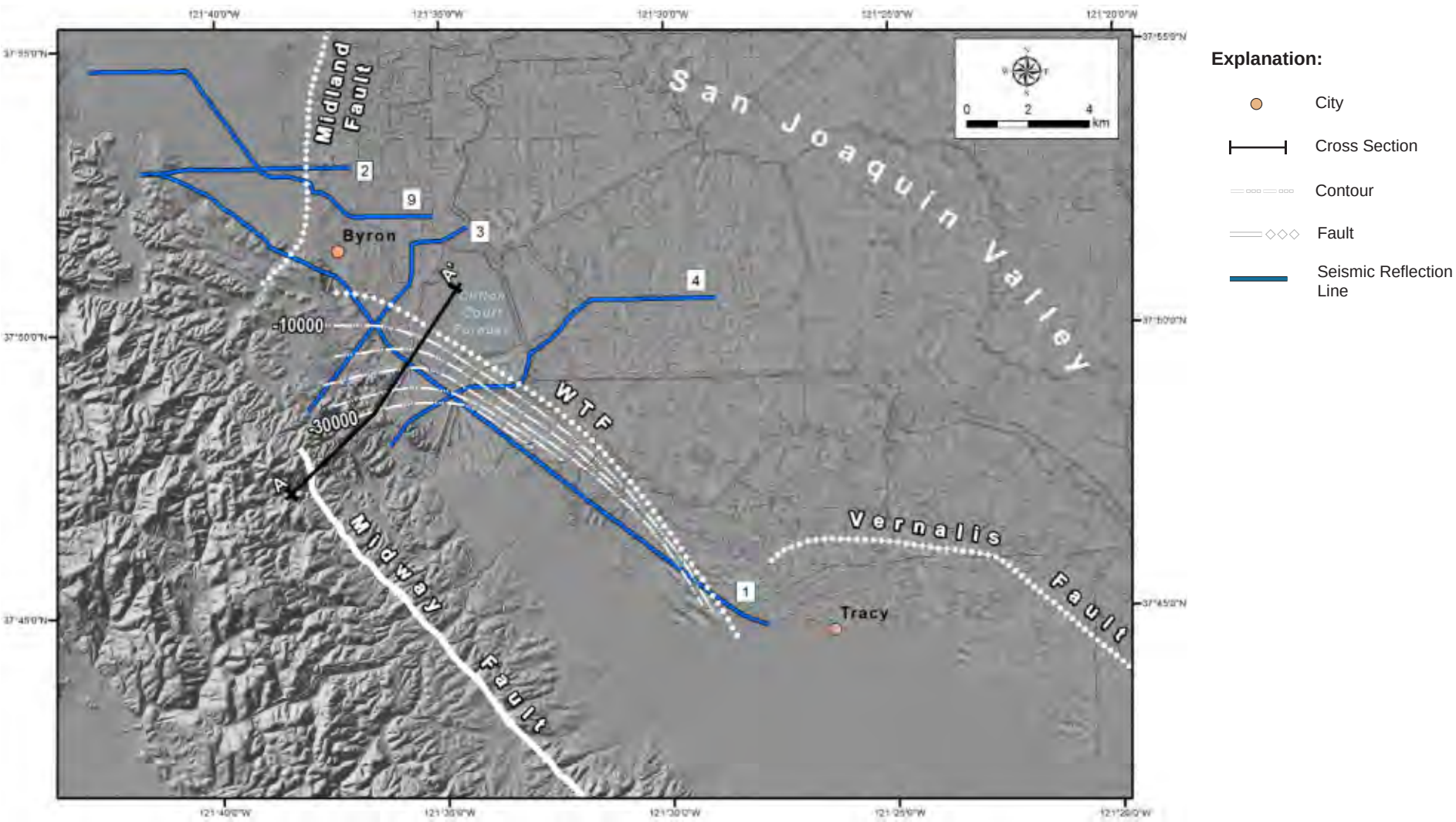

Figure 1: Map showing location of the study area in the northwestern San Joaquin Valley. The traces of the buried Midland fault, Vernalis fault and West Tracy fault (WTF) are shown with dotted white lines. The Midway fault has a distinct surface trace and is shown with a solid white line. The solid blue lines show the locations of seismic reflection profiles analyzed for this study (see Figures 2 through 6 for interpreted line tracings of the seismic profiles). The dashed white lines directly adjacent to the West Tracy fault are structure contours on the southwest-dipping fault plane based on interpretation of the fault geometry in seismic lines 1, 3, and 4. Structure contours are labeled for -10,000 ft and -30,000 ft elevations. See text for discussion.

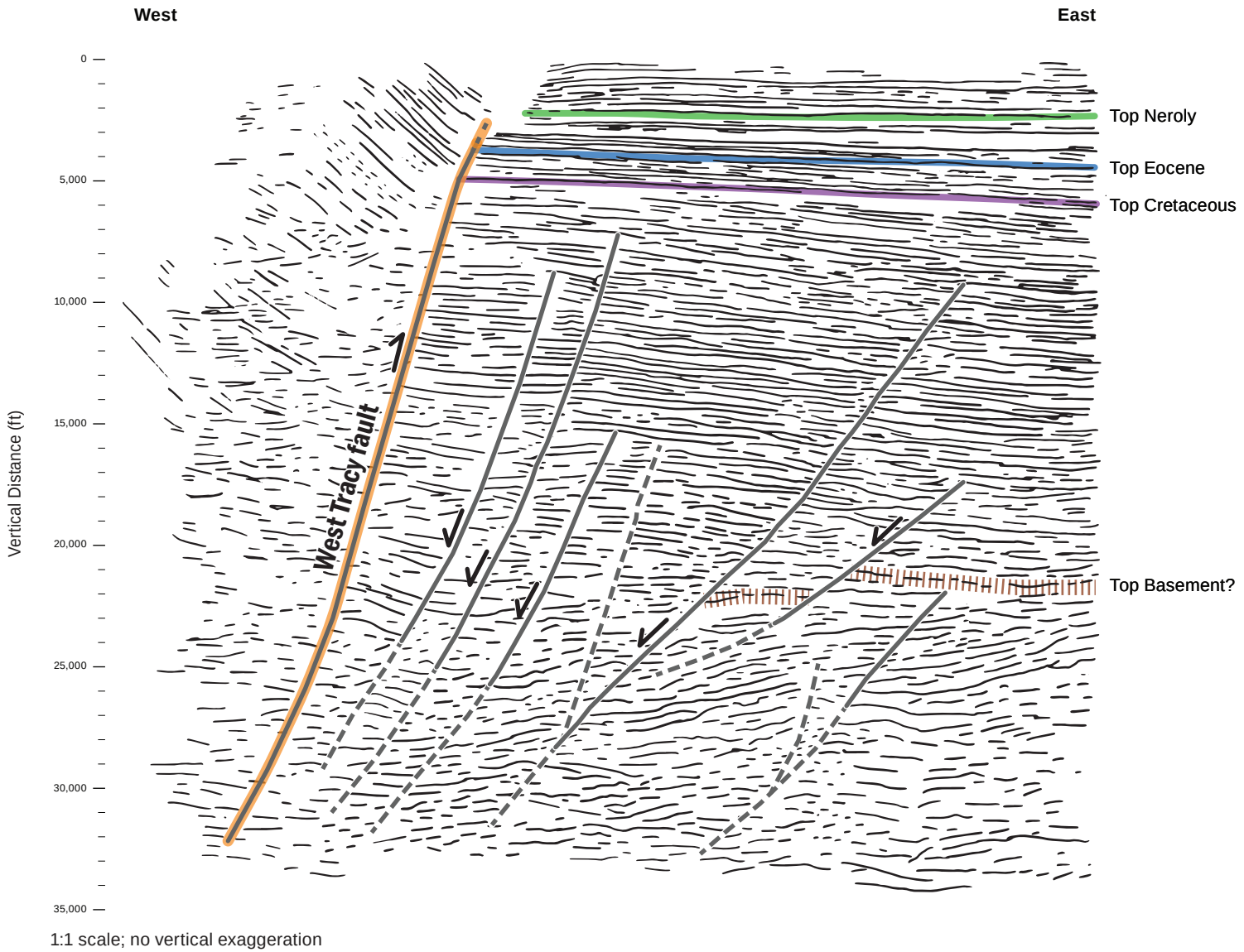

Figure 2: Interpreted line tracing of seismic line 4. See Figure 1 for location.

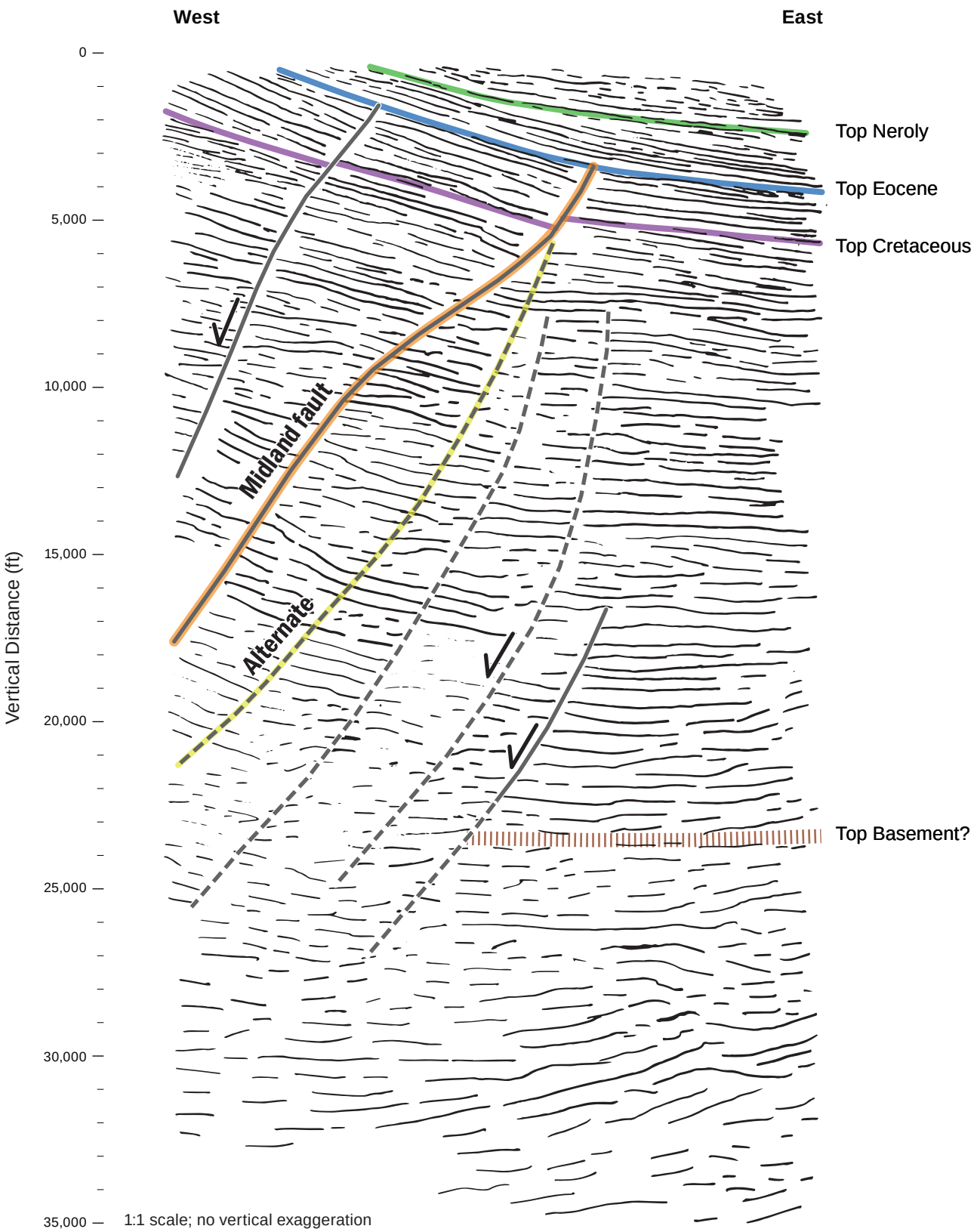

Figure 3: Interpreted line tracing of seismic line 2. Preferred interpretation of Midland fault indicated by orange line; alternative interpretation highlighted in yellow. See Figure 1 for location.

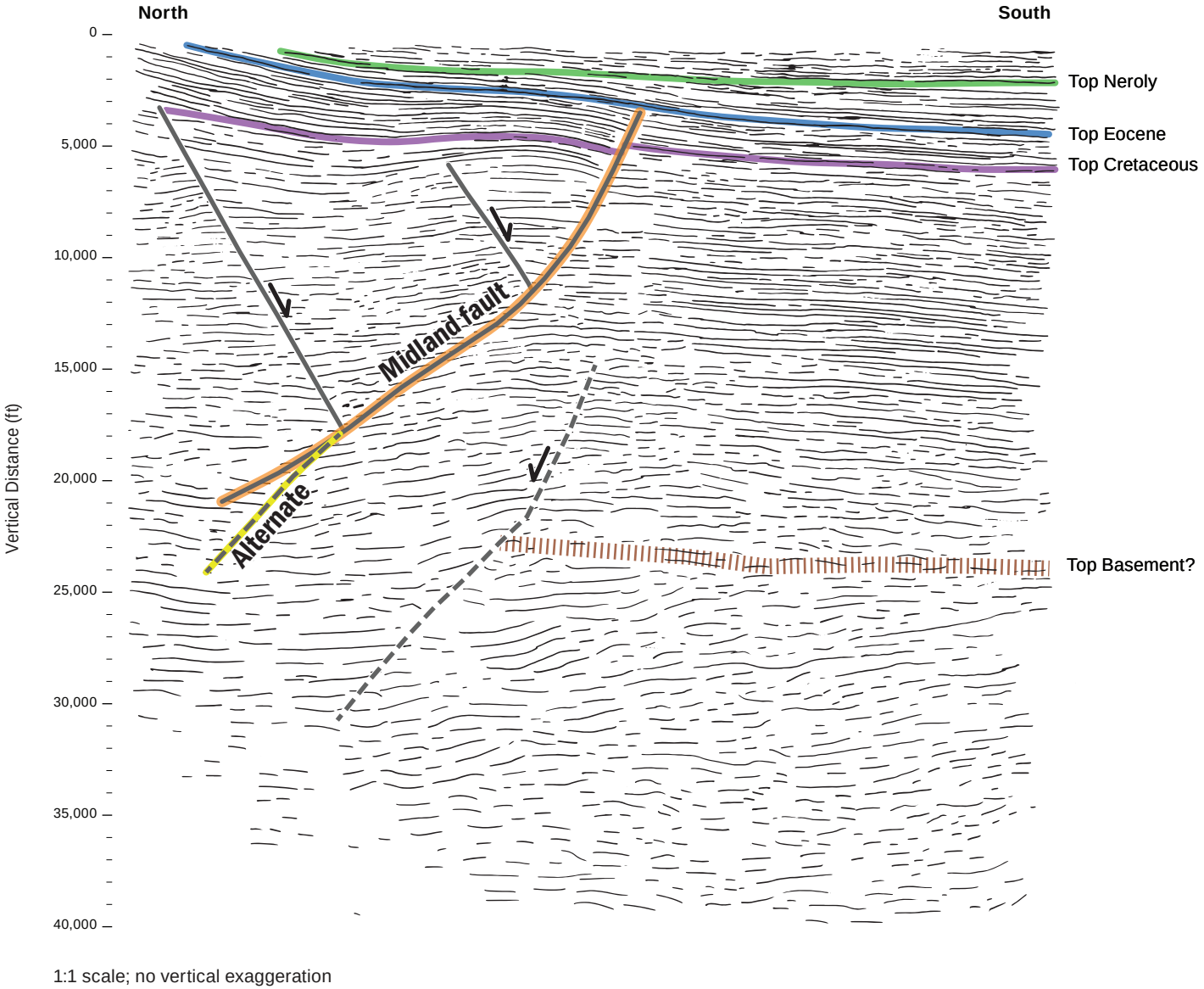

Figure 4: Interpreted line tracing of seismic line 4. Preferred interpretation of Midland fault indicated by orange line; alternative interpretation highlighted in yellow. See Figure 1 for location.

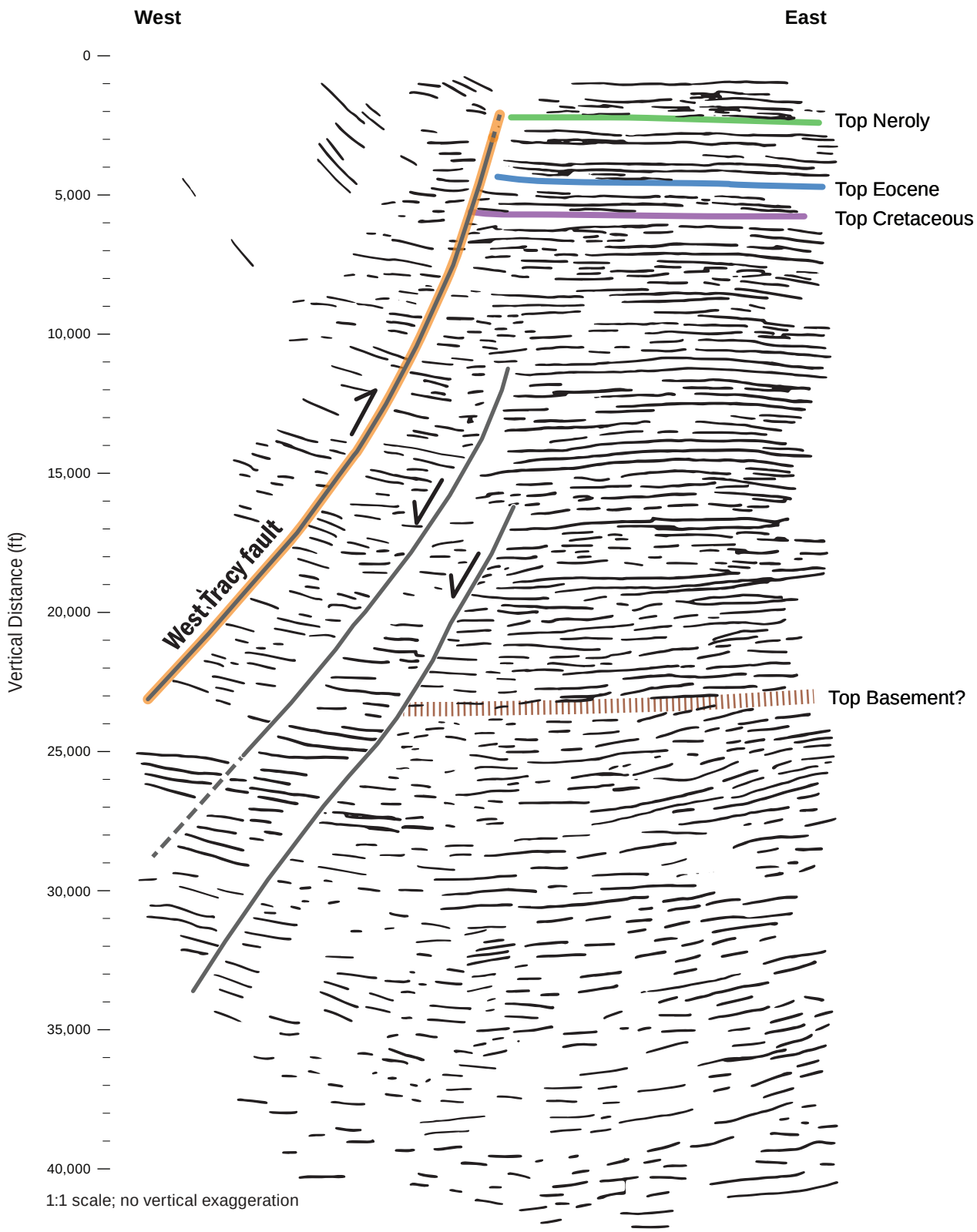

Figure 5: Interpreted line tracing of seismic line 3. See Figure 1 for location.

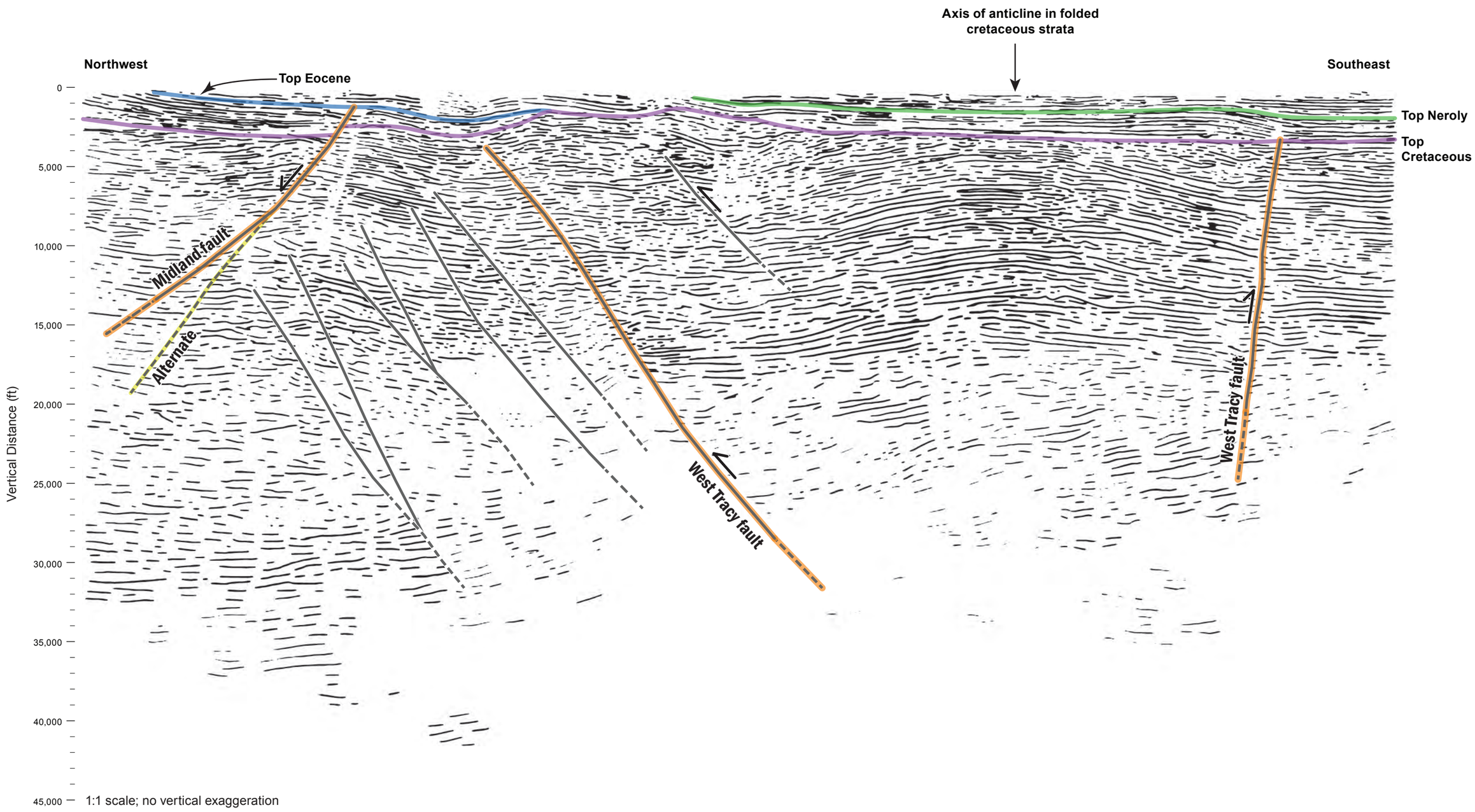

Figure 6: Interpreted line tracing of seismic line 1. Preferred interpretation of Midland fault indicated by orange line; alternative interpretation highlighted in yellow. See Figure 1 for location.

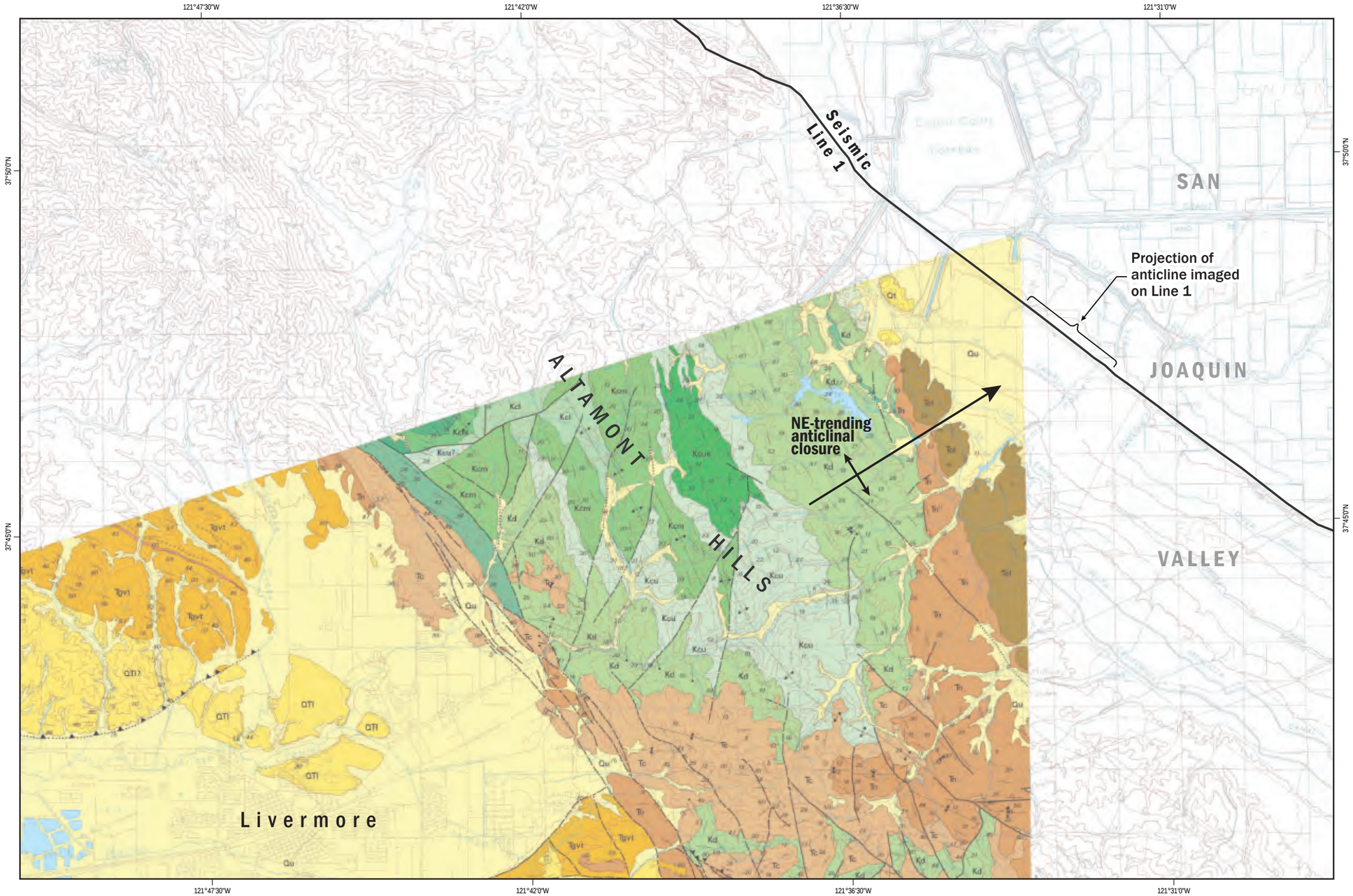

Figure 7. Part of the Alameda County geologic map compiled by Graymer et al. (1996), and location of seismic line 1 in the western San Joaquin Valley. Examination of bedding dips in Cretaceous strata (map unit Kd, in green) in the southern Altamont Hills reveals a broad, northeast-trending anticlinal closure that projects toward the anticline imaged in the south-central part of seismic line 1 to the east (see Figure 6). The base of the Miocene Neroly Formation (map unit Tn, reddish brown) cuts downsection to the south across the axis of the anticline in the Altamont Hills, indicating that folding of the Cretaceous rocks predates deposition of the Neroly Formation.

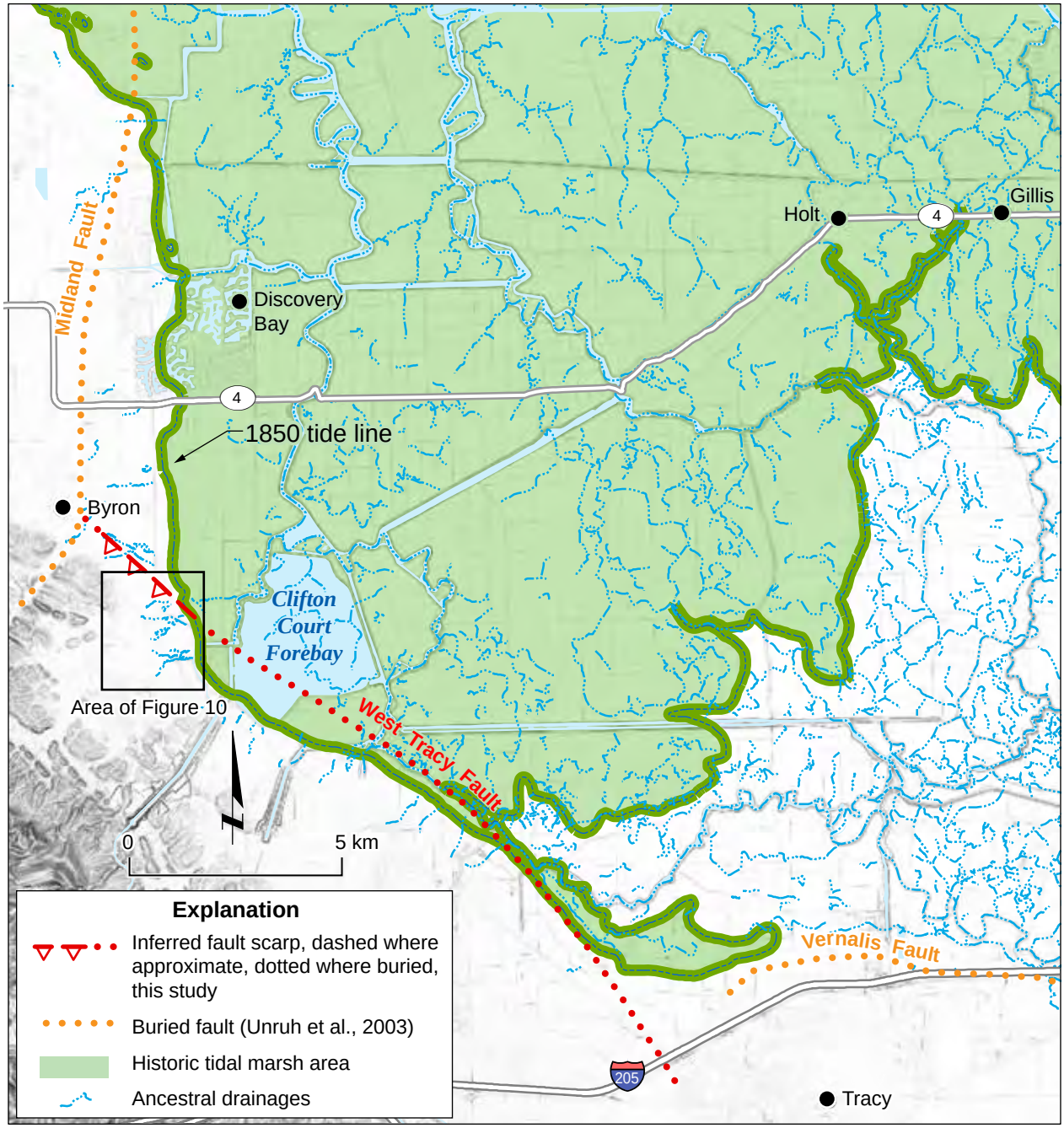

Figure 8. Fault map showing inferred trace of the West Tracy fault (this study) and historic extent of tidal areas.

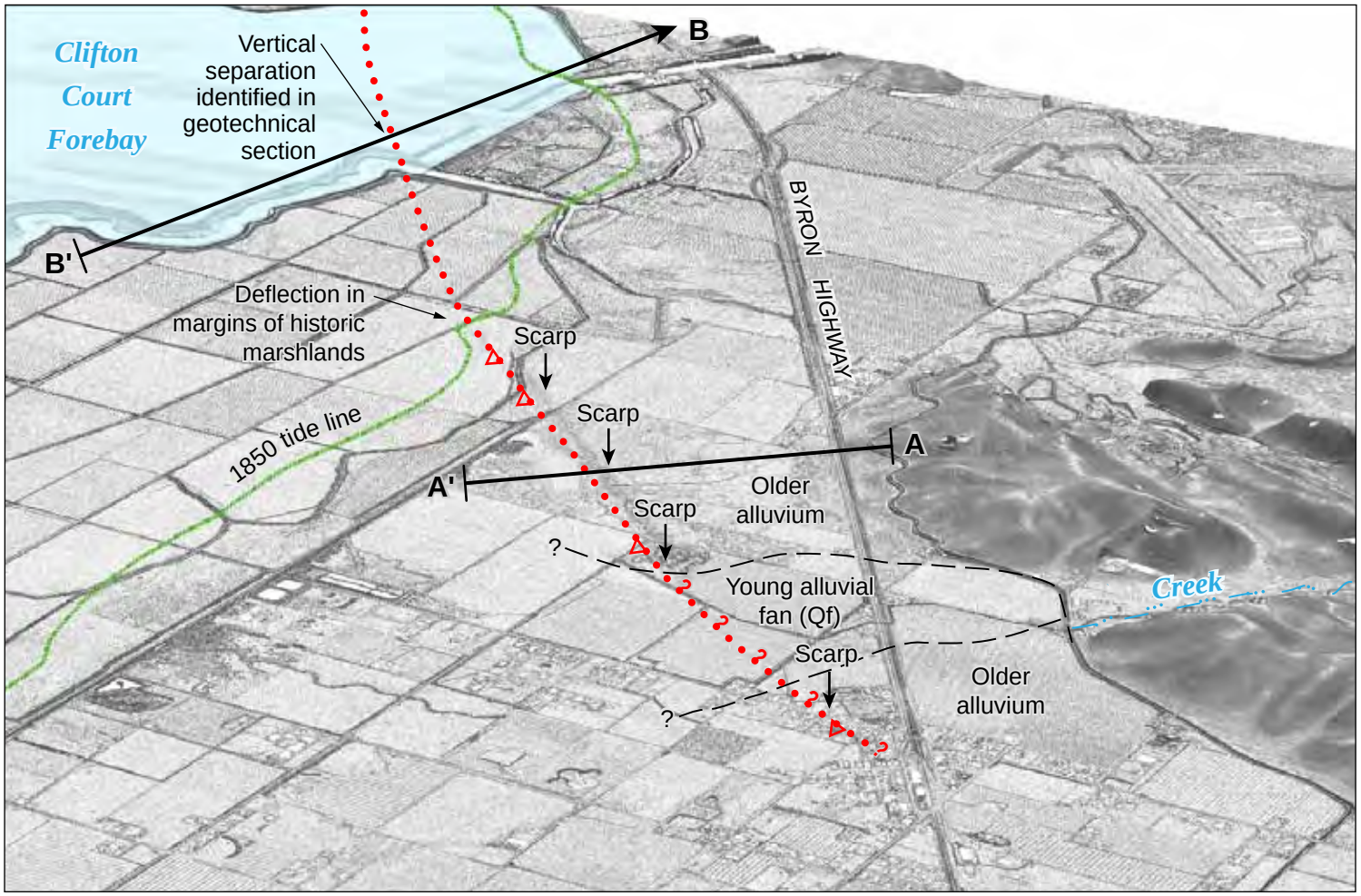

Figure 9. Perspective view to south of LiDAR data (slope) showing location of inferred fault scarps and other fault-related features.

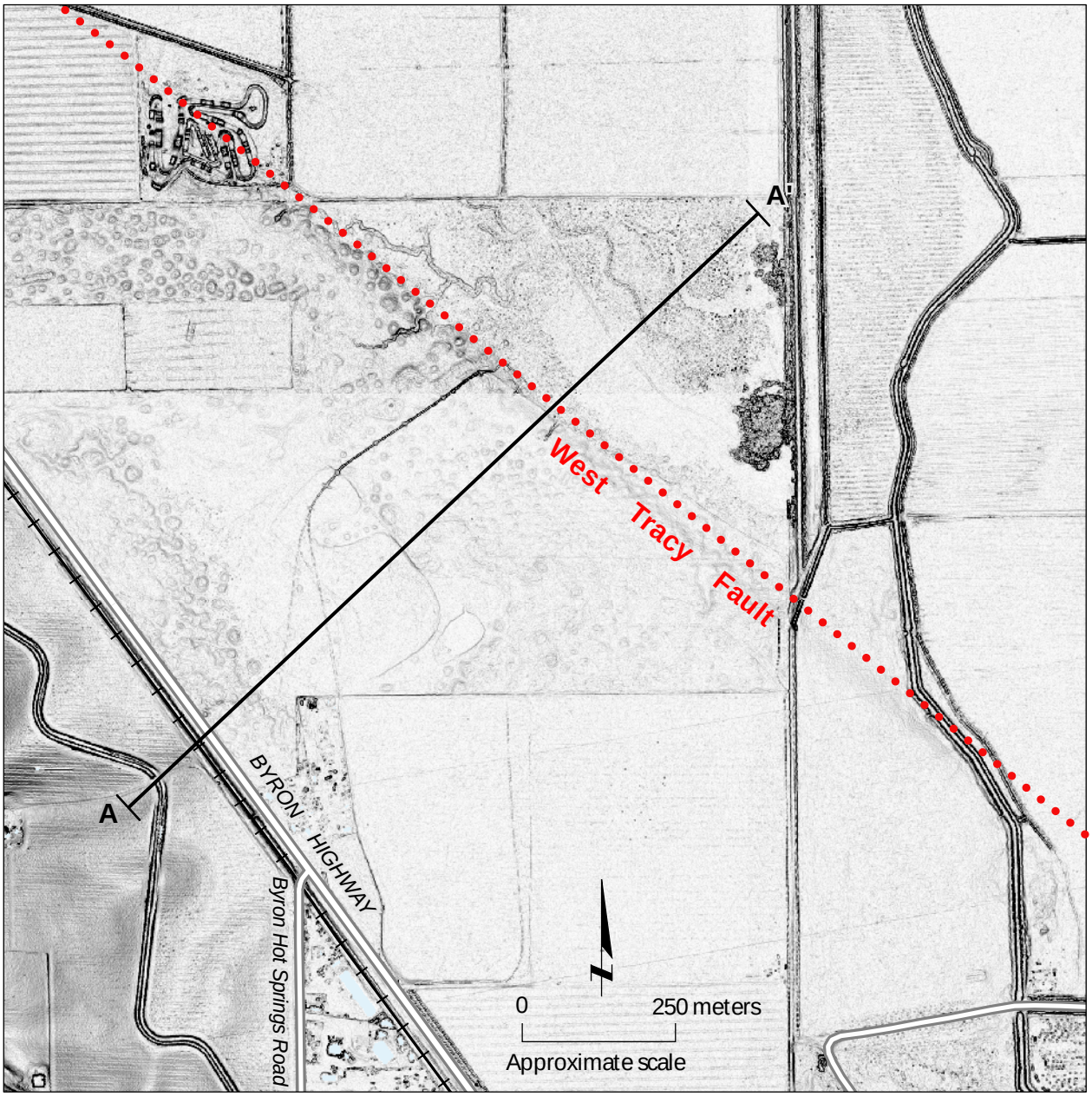

Figure 10. LiDAR relief map showing inferred scarp of West Tracy fault and cross section location (see Figure 11).

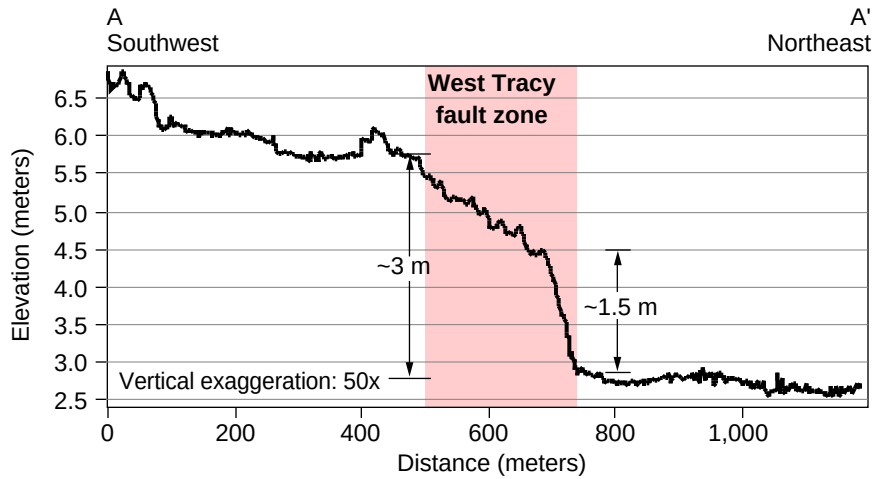

Figure 11. Topographic profile A - A'.

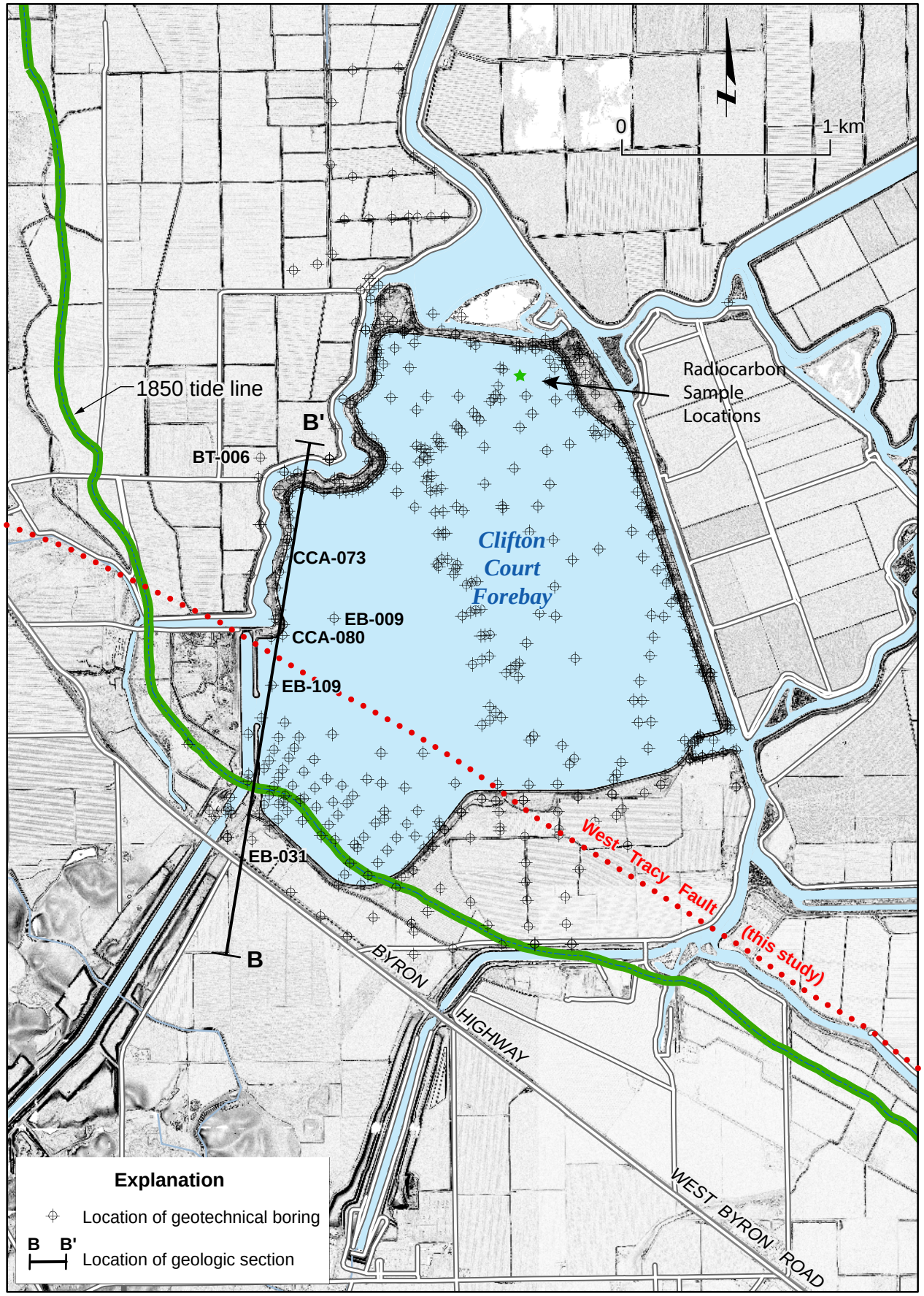

Figure 12. Map of geotechnical borings at Clifton Court Forebay.

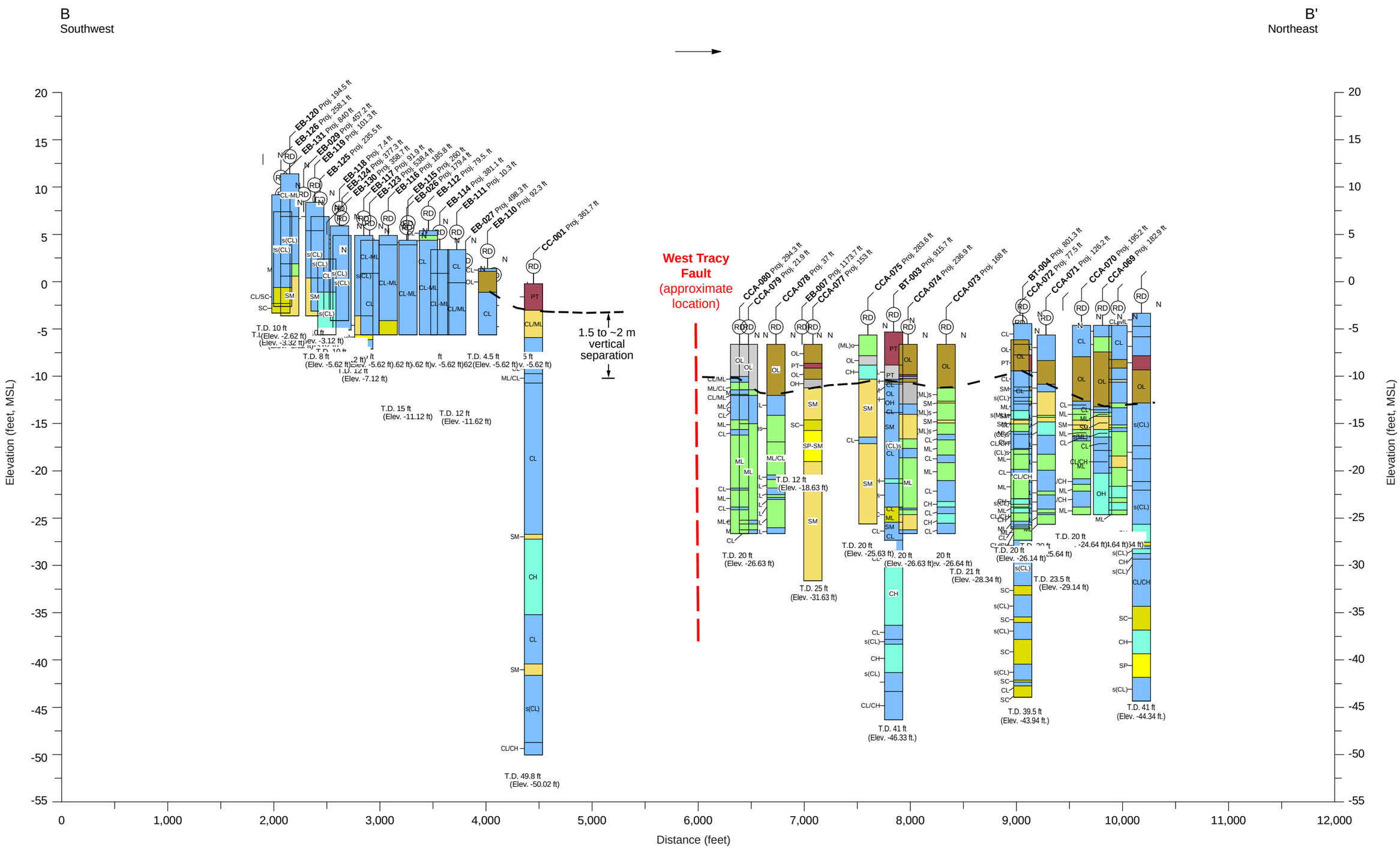

Figure 13. Cross section of geotechnical borings within Clifton Court Forebay

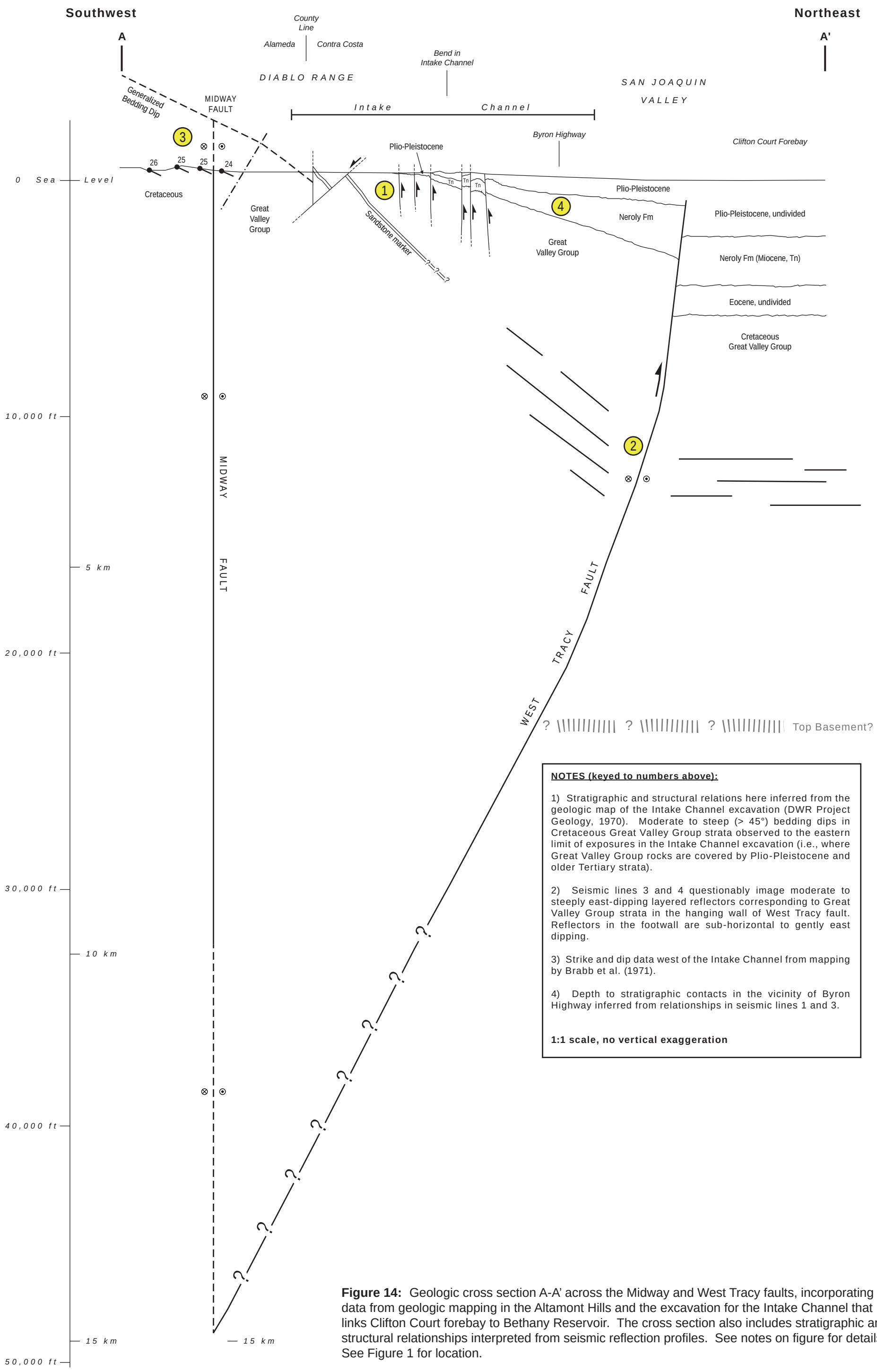

Figure 14: Geologic cross section A-A' across the Midway and West Tracy faults, incorporating data from geologic mapping in the Altamont Hills and the excavation for the Intake Channel that links Clifton Court forebay to Bethany Reservoir. The cross section also includes stratigraphic and structural relationships interpreted from seismic reflection profiles. See notes on figure for details. See Figure 1 for location.