Structural Geology and Oil Field Traps of the Western and Southern Margins of the San Joaquin Basin, California September 30 and October 1, 2016.

Field trip leaders: Thom Davis, Yannick Wirtz, and Greg Gordon

Departure time and place: 7:00 am from the AERA Energy parking lot off Old River Road (to the west of the office building; building address is 10,000 Ming Ave., Bakersfield, CA 93311).

Return time and place: The trip will return at 6:00 pm each day to the meeting point.

Hanging wall deformation near the Pleito thrust fault with Courtney Marshall for scale, Pleitito Creek, San Emigdio Mountains.

Guidebook and field trip themes: This guidebook is largely graphical with numerous maps, cross sections, stratigraphic columns, and field photos of the western and southern margins of the San Joaquin basin. Each stop has a short text providing key presentation points and questions for discussion. The goal of the field trip is to show and discuss the geometry, kinematic development, and timing of many of the map-scale structures in the field and some of the major hydrocarbon traps. Most of the cross sections shown are based on well data and surface geology, and of course, are very interpretive at depth and away from the control. Portions of a few of the cross sections are supported by 2D reflection seismic lines but unfortunately these data cannot be reproduced here. Portions of several seismic lines are shown in Davis' (2015) paper Structural wedge with a hydrocarbon prospective triangle zone, west-side of the San Joaquin Basin (WS), California: implications for untested large traps included at the end of the guidebook.

This field trip has several structural themes that will be developed during its course. The first theme will focus on key field relationships that can be explained in the terms of structural models; specifically fault-ramp folds, wedge structures and back thrusting, and their importance to subsurface interpretation and oil and gas exploration. The second portion will emphasize fault detachments and shallow-level fold belts in the Monterey and Tulare Formations, and their role in oil field trapping and reservoir characterization. Thirdly the trip will emphasize the influence of pre-convergent structures on the fold and thrust belt structural style and oil field trapping along the western and southern margins of the San Joaquin basin. A recurring theme will be the importance of geologic surface mapping, its commonly interpretive nature, and specifically knowing the stratigraphic-up direction in steeply-dipping strata.

Transpression along the San Andreas plate boundary: Fault-related fold models that illustrate the geometry and kinematic development of petroleum traps and structures (Figures 2 & 3) are frequently used to assist basin exploration and development of structurally complex oil fields. World-wide, several petroleum-rich provinces are situated in convergent strike-slip settings with adjacent convergent structures that are commonly petroleum traps. Strain studies and modelling of these settings are dominated by the wrench fault model, and examples from the San Andreas fault plate boundary and its its influence on the formation of structural traps in adjacent large oil fields abound (Wilcox, et al., 1973). Use of this model in petroleum exploration in California is problematic and can lead to wasted drilling dollars. As discussed and shown on this field trip the wrench model and its associated flower structures (Harding, 1976) and palm tree structures (Sylvester, 1988) fail to explain the oil trapping style and structure of the uppermost crust along the western and southern margins of the San Joaquin basin.

The San Andreas transform fault through much of southern and central California is oblique to the direction of motion between North America and the Pacific plates, and

two models have been used to explain the strain response to the stress field: 1) the wrench model that results from a high shear strength on the San Andreas fault and 2) strain-partitioning along a weak San Andreas fault that is characterized by pure strike-slip, and an adjacent belt of convergent structures that are parallel to subparallel to the San Andreas fault (Mount and Suppe, 1987; Zoback, et al., 1987, Townend and Zoback, 2004). During the field trip we present data and interpretations that support the strain-partitioned model that is characterized by a strike-slip San Andreas fault with no vertical offset, and development of an adjacent and coeval fold and thrust belt with little or no strike-slip component along the western and southern margins of the San Joaquin basin (Namson and Davis, 1988a, b). Further we show that application of geometric and kinematic models commonly used in fold and thrust belts, for example fault-bend and fault-propagation folds (Figures 2 & 3)(Suppe, 1983; Suppe and Medwedeff,1990), provide a realistic, testable, and economically successful methodology for basin exploration and oil field development in the convergent petroleum traps of southern and central California. A more optimistic view of this area's oil and gas exploration potential is provided by the fold and thrust model as the larger thrust sheets conceal footwalls with untested sub-basins and structures with known oil source and reservoir rocks (Davis, et al., 1988; Davis, 2015).

Earthquake hazards and structural geology: Following the 1983 Coalinga earthquake Namson and Davis showed that the deformed western margin of the San Joaquin basin is best interpreted as a northeast-directed structural wedge that is being driven into the undeformed basin (Figure 5), and balanced cross sections and fault-fold models could be used for seismic risk evaluation of blind thrust faults (Namson and Davis, 1988a). At that time the Coalinga earthquake perplexed much of the earthquake community due to its lack of surface rupture from an earthquake with a M>6.0 and its main shock slip solution of pure convergence on a low angle fault plane located near and dipping towards the San Andreas fault. With the exception of Bob Yeats and his students working in the Ventura basin the geologists and seismologists involved in seismic risk evaluations at that time relied on surface geology, observations in very shallow trenches across faults, shallow borings, and much deeper seismological data, but the structural geology from a hypocenter to just below the earth's surface was poorly appreciated or understood. This community did not use publically available subsurface data from oil and gas wells, or appreciate the relationship between folding and thrust faulting, and the possibility of "blind" thrust faults being the source for significant and damaging earthquake.

Hikes and safety: Several of the field stops are located along roads and the greatest safety risk is being struck by other vehicles so please use caution when walking along the sides of the roads and crossing the roads. Several of the stops will involve hikes of about one mile, and participants should wear long pants due to the dry weeds and brush. Rattlesnakes are commonly encountered in the excursion area so please look before you step, reach, and sit down. Rattlesnakes are not aggressive, bites are uncommon, and fatalities rare.

Emergency contact information:
In case of emergency call 911 available 24 hours/day and 365 days/year.
Mercy Southwest Hospital (nearest full hospital with an ER), 400 Old River Rd., Bakersfield, 93311, Phone: 661-663-6000.

Thom Davis, Yannick Wirtz, and Greg Gordon welcome you to our field trip.

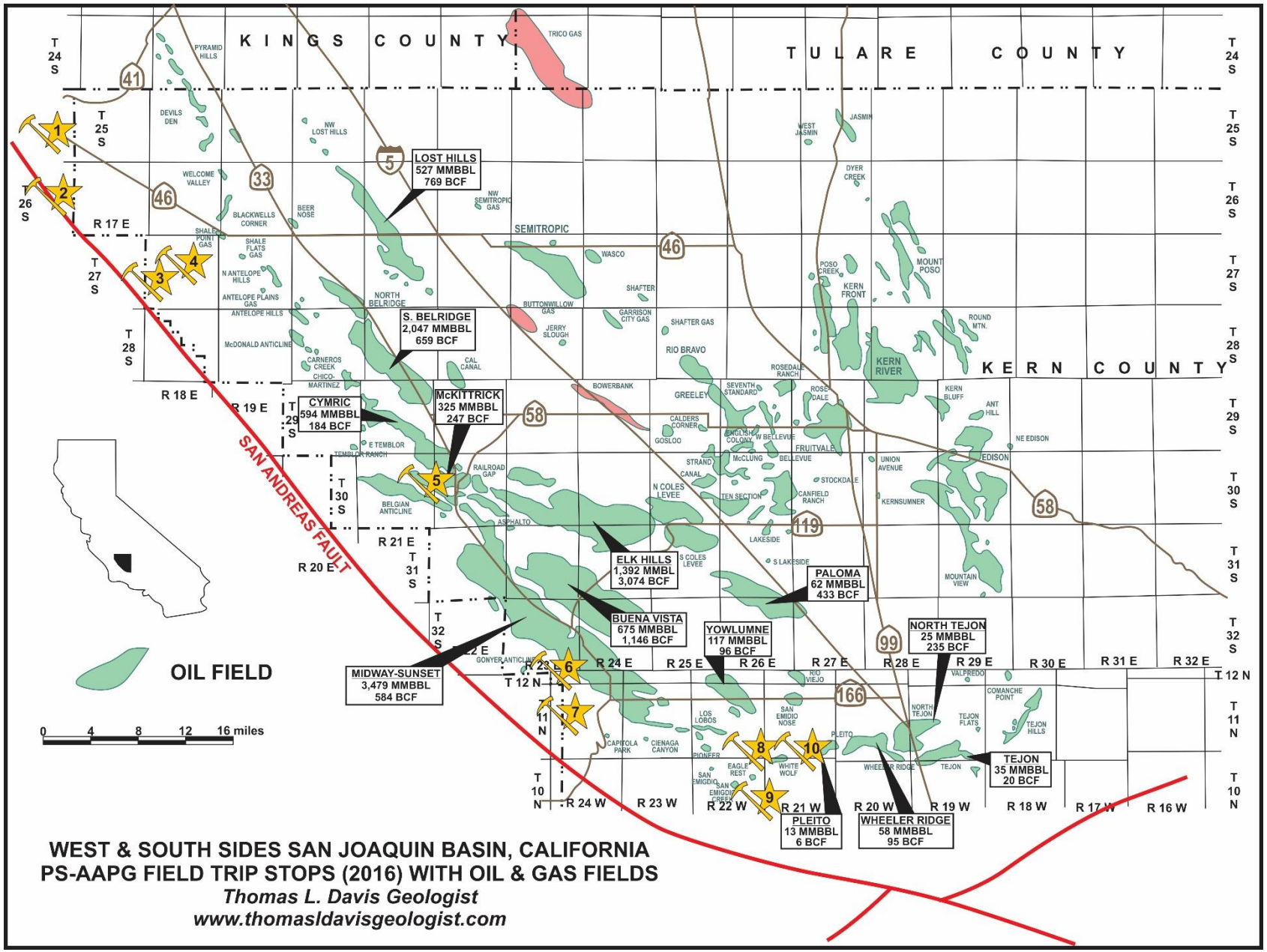
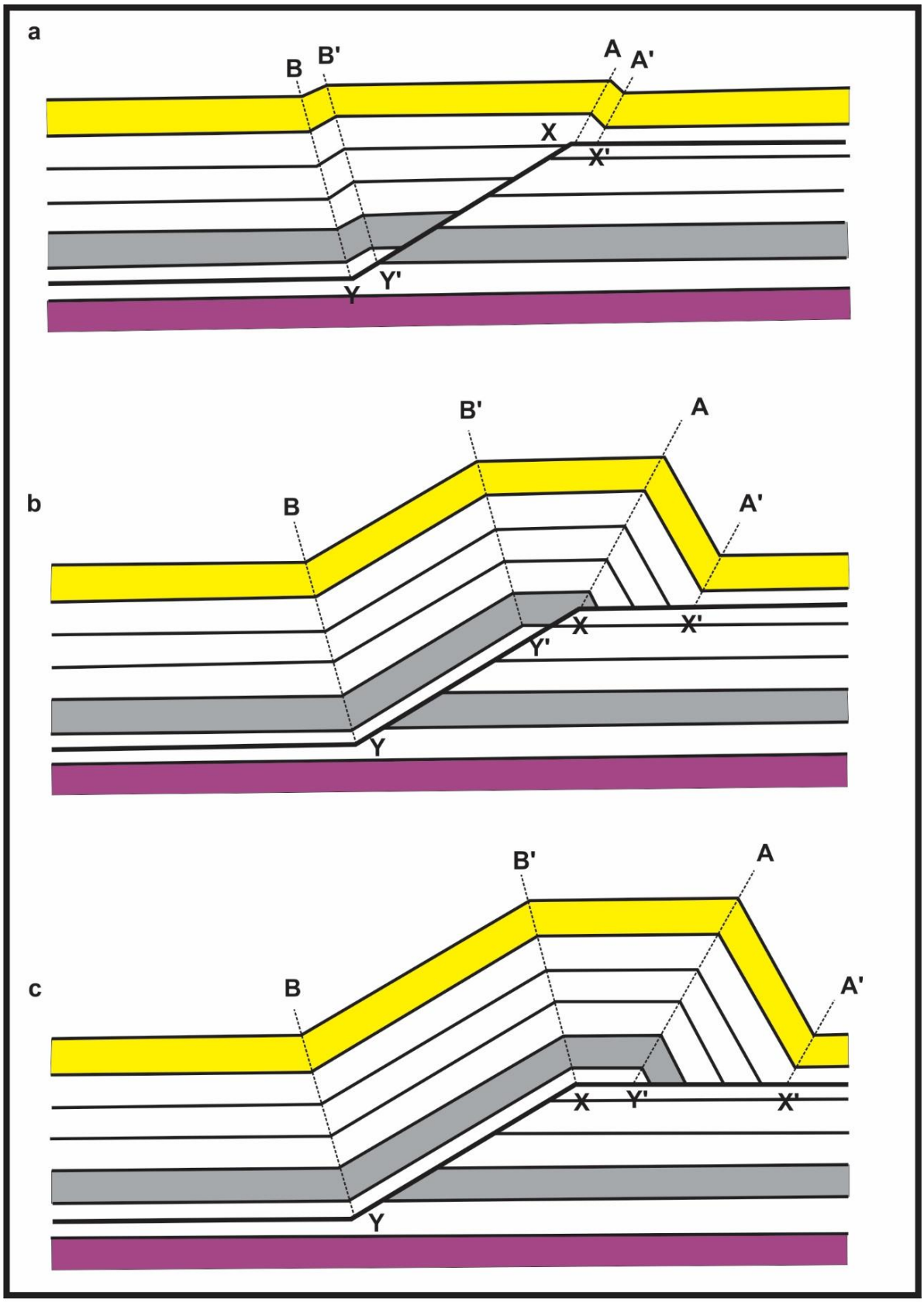


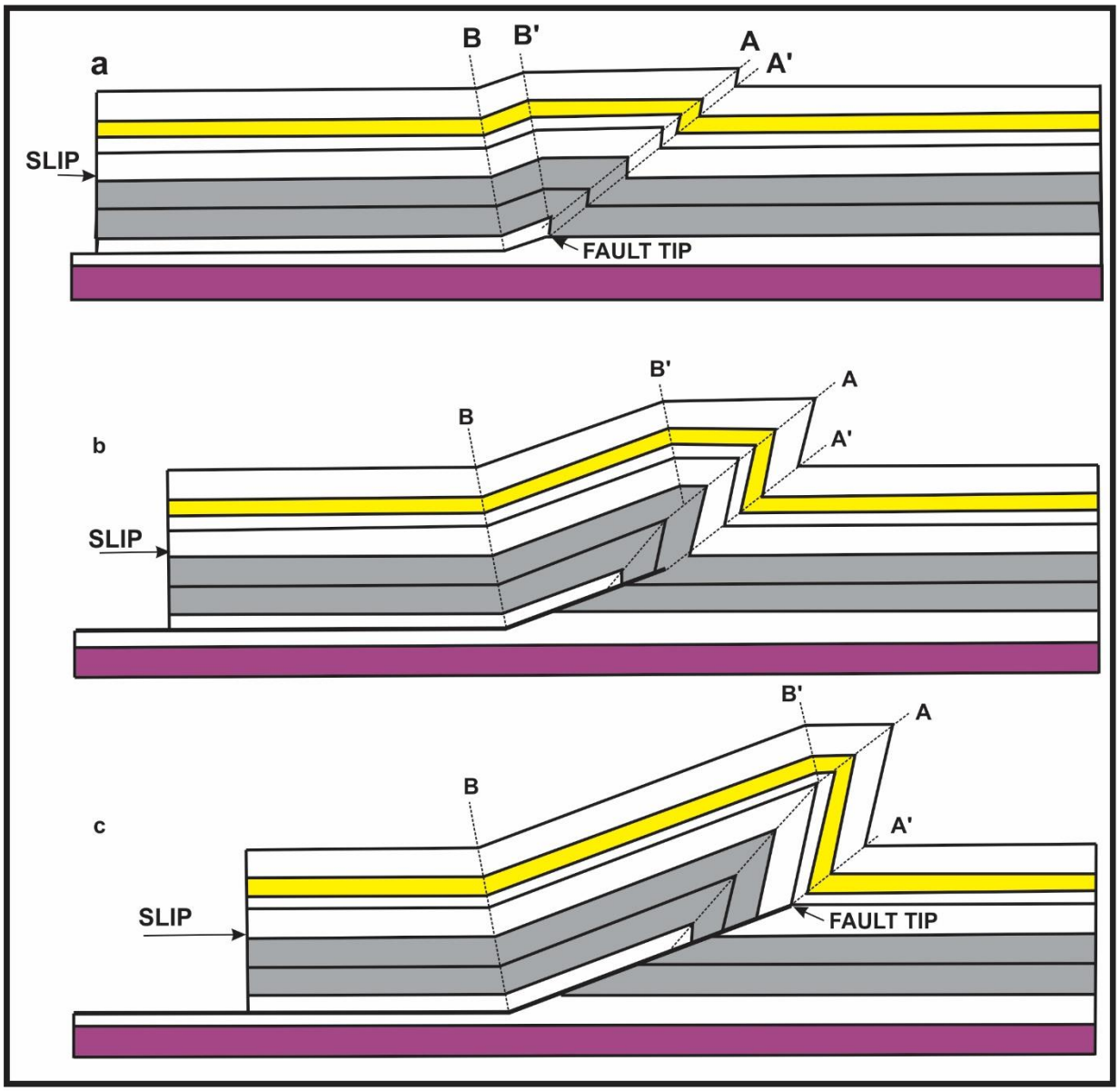
Figure 1, field trip stops and oil & gas fields of the southern San Joaquin basin.

Figure 2, fault-bend fold.



Schematic progressive development of fault-bend folds as a thrust sheet rides over a step in decollement (Suppe, 1983, 1985)

Figure 3, fault-propagation fold.



Schematic progressive development of a fault-propagation fold at the tip of a thrust fault. (Suppe, 1985)

1st Day (Friday, September 30, 2016)

Stop 1, Structure of the Antelope Valley (35.720277°,-120.162772°).

This stop combines a lot of structural geology into a small area and provides surface clues about the structural style along the west side of the San Joaquin basin. In addition many of the major rock packages of the central Coast Ranges are exposed along the margins of the Antelope Valley.

Present and discuss:

- Antelope Valley thrust (Sawtooth fault of Dibblee) and other nearby convergent structures.

- Structural modeling concepts including fold models, backthrusting, triangle zones, cross section construction and retrodeformation of sections (Figures 2, 3 & 5).

- Complex hanging wall structure of the Antelope Valley thrust at Orchard Peak. Is there a low angle detachment structure exposed along the Badger fault?

- Footwall of the Antelope Valley thrust.

- Structure of the southwest side of Antelope Valley.

- Regional cross sections shown in Figures 9 & 10.

- A few comments about the local stratigraphic record, paleogeography, tectonic history (Figures 7 & 8).

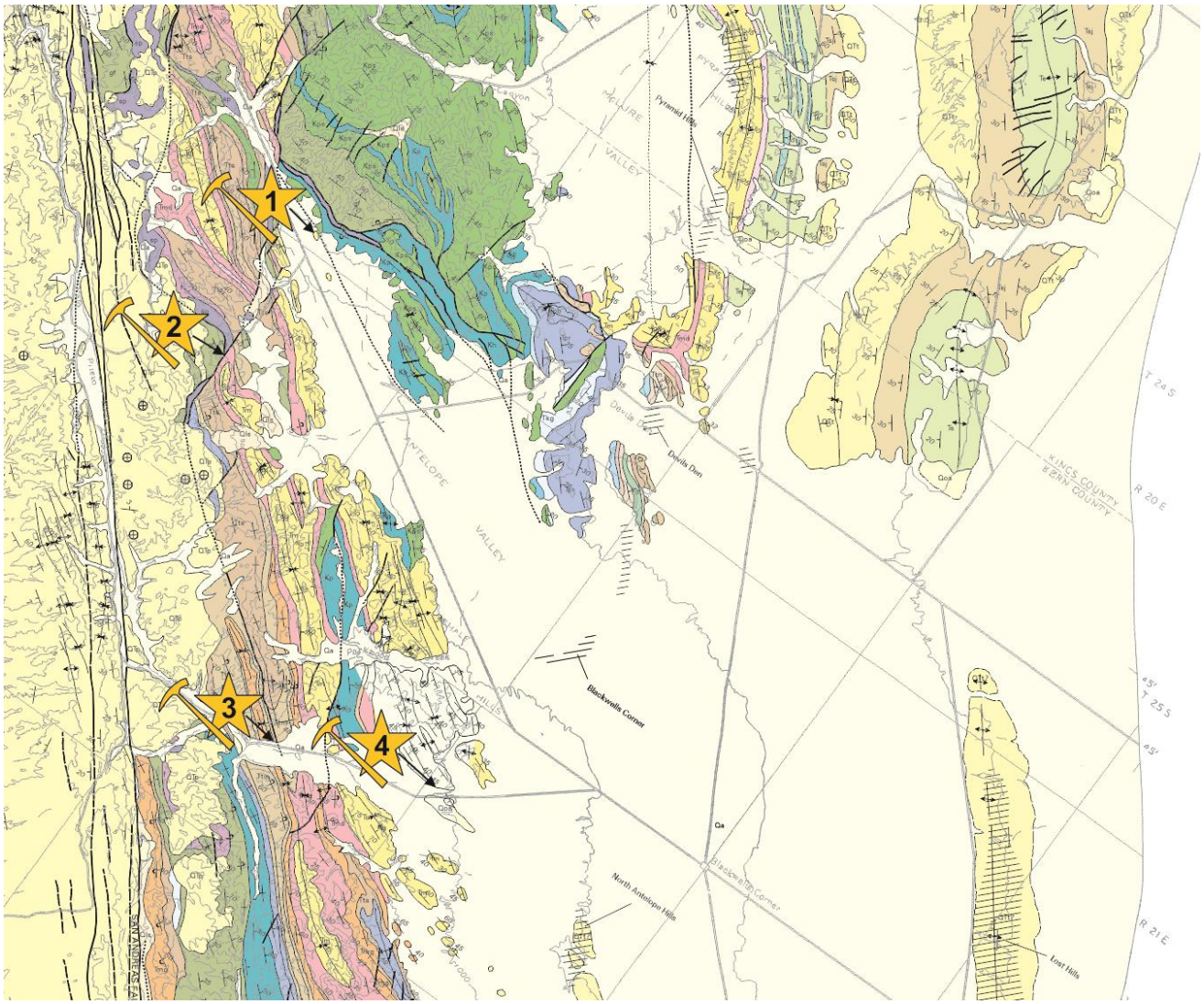


Figure 4, portion of USGS map I-757, Dibblee (1973) showing the northern Temblor Range and field trip stops.

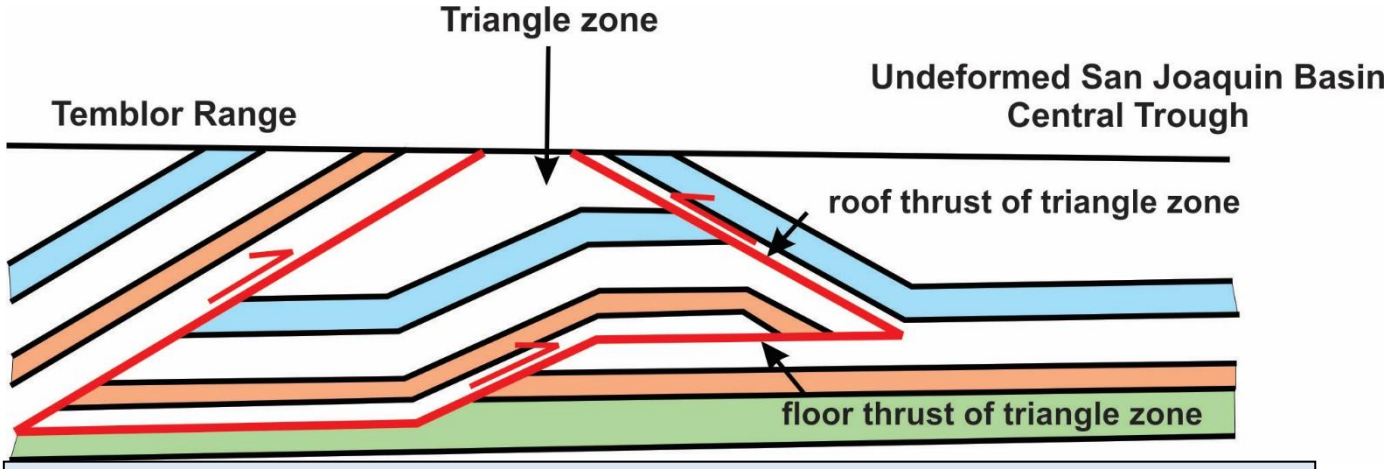


Figure 5, generalized triangle zone model for the northern Temblor Range.

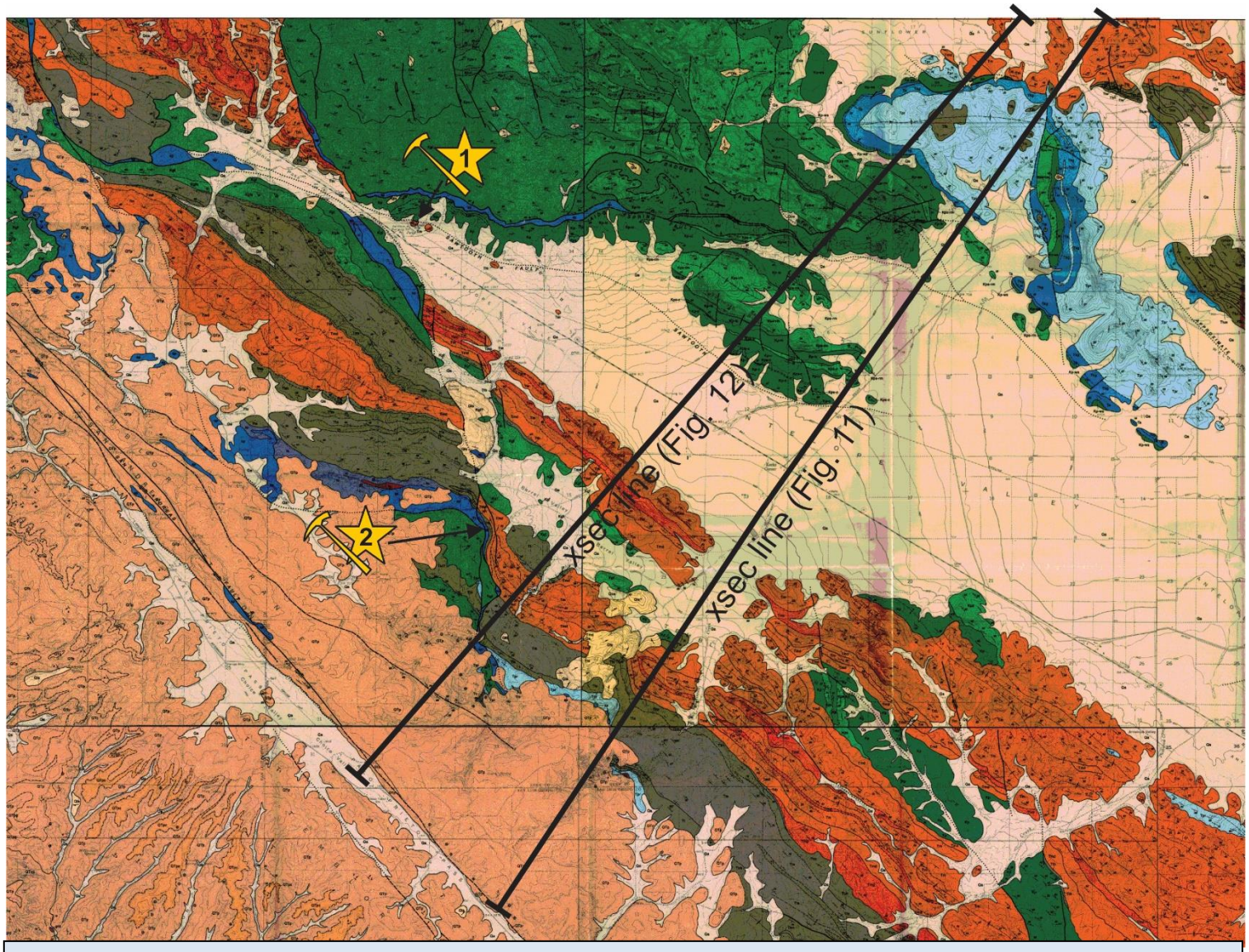


Figure 6, portions of Dibblee maps of Orchard Peak (Dibbee, 2005a), Sawtooth Ridge and Emigrant Hill (2006a), and Holland Canyon and Packwood Creek (2006b). Cross sections shown in Figures 11 & 12.

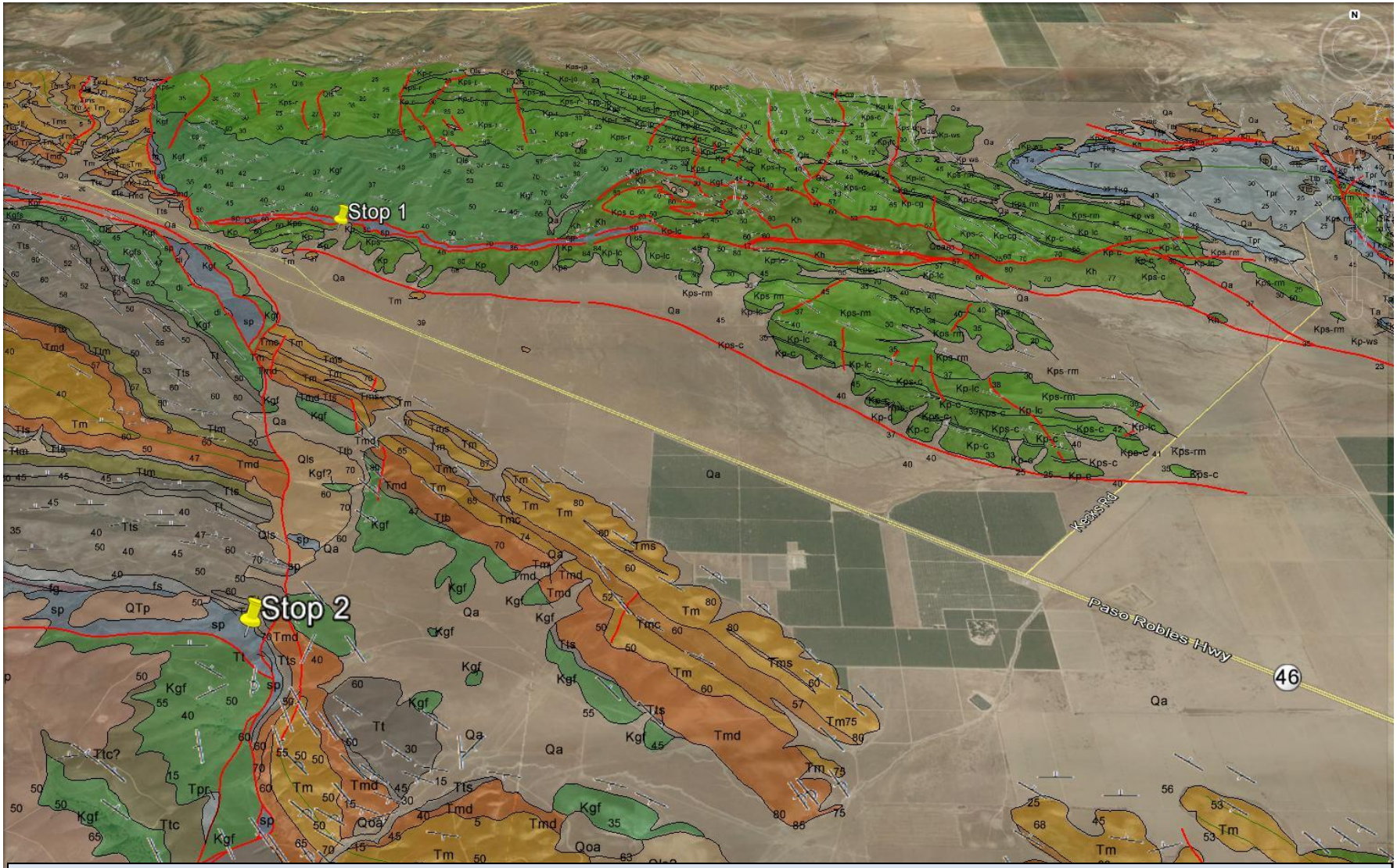


Figure 7, Google earth image of the Antelope Valley showing Stops 1 & 2 and Dibblee's mapping superimposed. Such overlays can be made with GIS geologic maps.

Figure 8, Google Earth image of the south flank of Orchard Peak showing the blue band of serpentinite along the Aido Spring fault. Most of the south flank consists of Cretaceous strata, but near Hwy 46 are two outcrops of Monterey Formation in the footwall of the Antelope Valley thrust (lower left of image).

Figure 9, Dibblee map explanations.

SAWTOOTH RIDGE AND EMIGRANT HILL MAP (DF-266)

LEGEND

Qs

SURFICIAL SEDIMENTS

Qs *Alluvial gravel, sand and clay, mostly clay in valley areas, unconsolidated, undissected, covered by sand; age, at or near surface, Holocene, may include older alluvium and Tulare Formation, Pleistocene in subsurface of valley areas to depths of 800 ft.*

Qls

LANDSLIDE RUBBLE

Qls *Rubble, shale and sandstone slid downslope from local bedrock*

Qoa

OLDER SURFICIAL SEDIMENTS

Qoa *Alluvial fan gravel of sandstone detritus near north border of quadrangle*

UNCONFORMITY

QTp | QTt

PASO ROBLES & TULARE FORMATIONS

Valley alluvial sediments, weakly indurated; age, Pleistocene and possibly latest Pliocene

QTp *Paso Robles Formation, of Cantizo Plain, alluvial pebble gravel, sand and clay, gray, crudely bedded; pebbles mostly of siliceous shale derived from Monterey Shale of Temblor Range*

QTt *Tulare Formation of San Joaquin Valley, exposed only in northeast area, alluvial sediments similar to those of QTp*

UNCONFORMITY

Tm, Tmc, Tmd, Tms, Tml

MONTEREY SHALE

Marine biogenic and clastic age, Miocene

Tm *McLure Shale Member, siliceous shale, white weathered, thin bedded, platy, porcelaneous; , brittle, much fractured; includes Tml, silty shale, light gray, splintery fractured; includes "Antelope Shale" (above Tm) and "McDonald Shale" Member*

Tmc *Claystone, gray, soft, crumbly; locally includes thin fine grained sandstone layers; age, middle to early Miocene (Relizian-Saucesian Stages)*

Tms *Sandstone, tan, arkosic, coherent; facies of Tm*

Tmd *Devilwater Shale Member, (Alferitz Formation of Van Couvering and Allen, 1943), clay shale, gray, locally silty, crumbly; age, Luisian Stage, middle Miocene*

UNCONFORMITY WHERE ON CRETACEOUS UNITS

Ttb, Ttm, Ttc, Ttn, Tts, Tt, Ttw, Ttu, Ttul, Ttus

TEMBLOR FORMATION

(Hennah Formation of Van Couvering and Allen, 1943) Marine clastic, lithified; age, lower Miocene

Ttb *Button Bed Sandstone Member, (Escuda Formation of Van Couvering and Allen, 1943), sandstone, light gray to tan, locally calcareous, with shell fragments; unconformity at base in northwest area; age, Relizian Stage, early middle Miocene*

Ttm *Media Shale Member, clay shale, gray, micaceous, crumbly with spheroidal fracture; age, Saucesian Stage, lower Miocene*

Ttc *Cameros Sandstone Member, light gray to tan, thick bedded, arkosic; age, Saucesian Stage*

Ttn *Santos Shale Member, clay shale, similar to Ttm; age, Saucesian Stage*

Tts *Sandstone, unnamed, similar to Tts, but includes some interbedded clay shale in upper part; age, lower Saucesian Stage*

Tt *Clay shale, unnamed, similar to Ttm, Ttn; age, Zamorrian?*

Ttw *Wygal Sandstone Member, similar to Tts, Tts; age, Saucesian-Zamorrian Stage*

Ttu *Clay shale (Wagonwheel Formation of Van Couvering and Allen, 1943, Turney Formation of subsurface (Atwill, 1935) clay shale similar to Ttm and Ttn, but includes (Ttul), white weathered semi-siliceous shale; age, Zamorrian Stage*

Ttus *Sandstone (Oceanic Sandstone of subsurface, similar to Tts, Tts; age, Zamorrian Stage*

Holocene | Pleistocene | Pliocene | Miocene | QUATERNARY | TERTIARY | CENOZOIC

ORCHARD PEAK MAP (DF-143)

LEGEND

Qs

SURFICIAL SEDIMENTS

Qs *Alluvial gravel, sand and clay of valley areas, mostly gravel near mountain and hill source areas to mostly clay and sand in Antelope Valley area; includes gravel and sand of stream channels*

Qls

LANDSLIDE RUBBLE

Qls *Rubble of shale and sandstone slid down slope from local bedrock*

Qoa

OLDER SURFICIAL SEDIMENTS

Qoa *Alluvial fan gravel of shale and sandstone detritus, dissected, in northwest area; in northwest area may be same unit as QTp, but thin, undeformed*

— UNCONFORMITY —

QTp | QTc

PASO ROBLES FORMATION

Valley sediments, weakly indurated; age, Pleistocene, possibly in part latest Pliocene

QTp *Northeast of San Andreas fault, brown alluvial pebble gravel of shale and sandstone detritus derived from Temblor Range within map area; southwest of San Andreas fault, gray alluvial fan gravel and sand of mostly siliceous shale detritus derived from central and southeast Temblor Range, but includes some granitic detritus*

QTc *Alluvial clay, soft, gray, locally gypsiferous, southwest of San Andreas fault*

— UNCONFORMITY —

Tm, Tms, Tmc, Tmd

MONTEREY SHALE

Marine biogenic and clastic, lithified; age, Miocene

Tm *McLure Shale Member, siliceous shale, white weathered, thin bedded, hard, platy, porcelaneous, brittle, much fractured; age, Mohnian Stage*

Tms *Sandstone, light gray, fine-grained to silty, siliceous; includes some siltstone sandy facies within Tm*

Tmc *Clay shale to siltstone, gray, crumbly with splintery to ellipsoidal fracture, clayey facies within Tm*

Tmd *Devilwater Shale Member, clay shale, gray, silty, crumbly, poorly exposed; age, Luisian Stage, unconformity at base where on Kgf*

Ttb, Ttm, Ttc, Tts, Tt

TEMBLOR FORMATION

Marine clastic, lithified; age, lower Miocene

Ttb *Button Bed Sandstone Member, similar to Tts, in east central area forms basal sandstone unit of Monterey Shale; age, Relizian Stage, early middle Miocene*

Ttm *Media Shale Member, clay shale similar to Tt; age, Saucesian Stage, lower Miocene*

Ttc *Cameros Sandstone Member, similar to Tts; age, Saucesian Stage*

Tts *Sandstone, some clay shale, undivided, includes Cameros Sandstone, Santos Shale and Wygal Sandstone equivalents of adjacent quadrangles*

Tt *Clay shale, gray, micaceous, crumbley with ellipsoidal fracture*

— UNCONFORMITY —

Tpr

POINT OF ROCKS FORMATION

Marine clastic, lithified, exposed only over southeast corner

Tpr *Sandstone, light gray to tan, thick-bedded, arkosic*

— UNCONFORMITY (?) —

Holocene | Pleistocene | Pliocene | Miocene | Eocene | QUATERNARY | TERTIARY | CENOZOIC

Figure 10, Dibblee map explanations continued.

EOCENE SEQUENCE

Marine clastic, lithified

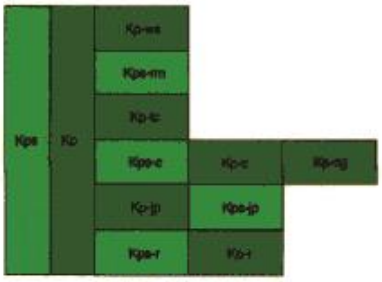
Tku *Kreyenhagen Shale, upper unit clay shale, gray, micaceous, crumbly, rarely sub-siliceous, contains concretions locally; age, Narizian Stage, upper Eocene*

Tpr *Point of Rocks Sandstone (of Van Couvering and Allen, 1943), The type area at Devils Den area, (this quadrangle) is light gray to tan, in massive beds about 1 to 4 ft (1/3 to 1m) thick, arkosic; age, Narizian and Ulatisian Stages, middle Eocene*

Tkg *Kreyenhagen Shale, lower unit, or Gredal shale Member, similar to Tku (Gredal Formation of Van Couvering and Allen, 1943), clay shale; age, Ulatisian Stage*

Ta *Avenal Sandstone (equivalent to Domengine Sandstone of Coalinga area), tan, massive, arkosic; includes pebble conglomerate of quartzite and metavolcanic rocks; age, Penutian Stage, lower Eocene*

Eocene



PANOCHE FORMATION

(of Anderson and Pack, 1915, Dibblee, 1973a,b, 1974); Panoche Group of Hall and Loomis, 1992, named units in north area are of Hall and Loomis, 1992, designated as formations, of Panoche Group; age of units by Tennis,1966, in Hall and Loomis, 1992; Panoche unit designated herein as a formation of marine sandstone and shale as originally defined, named units within as member; not everywhere distinguished; in south area units unnamed; ages unknown

Kpa *Sandstone, unnamed, light brown, bedded, arkosic, contains large brown concretions 1 to 2 ft. in diameter; includes interbedded clay shale in varying amounts*

Kp *Clay shale, unnamed, gray-dark gray, micaceous, crumbly with ellipsoidal fracture*

Kp-ws *Willow Spring Shale, clay shale like Kp; age, early Maastrictian-late Campanian, may be in part equivalent to Moreno Shale in Coalinga area*

Kpa-rm *Red Man Sandstone, similar to Kpa; includes very little shale; age, Campanian*

Kp-tc *Lowell Canyon Shale, similar to Kp; age, Campanian-Santonian*

Kpa-c *Catskin Sandstone, similar to Kpa; includes minor interbedded clay shale; also a conglomerate layer (Kp-og) in upper part*

Kp-c *Catskin clay shale facies, similar to Kp; includes minor interbedded sandstone; age of Catskin Member Santonian*

Kp-jp *Johnson Peak Shale, clay shale similar to Kp; includes minor sandstone; age of Johnson Peak unit Cenomanian*

Kpa-jp *Johnson Peak Sandstone similar to Kpa; includes interbedded shale*

Kpa-r *Risco Sandstone, similar to Kpa; includes interbedded clay shale; age, late Albian*

Kp-r *Risco Shale, clay shale similar to Kp; includes minor sandstone; age, late Albian*

GRAVELLY FLAT FORMATION

(of Rose and Colburn, 1963, Badger Shale of Marsh, 1960) marine clastic, lithified; age, range Hauterivian-Valenginian (lower Cretaceous to Tithonian, latest Jurassic)

Kgf *Clay shale, similar to Kp but darker olive gray, thinner bedded*

HEX SHALE

(of Marsh, 1960, Dibblee, 1973a, 1974, Hall and Loomis, 1992) marine clastic. lithified; age, lower and upper Cretaceous

Kh *Clay shale, gray, micaceous, crumbly, devoid of bedding; includes several bluish-gray, shear zones; derived from unit Kgf and possibly Kp shale units (Hall and Loomis, 1992)*

CRETACEOUS

MESOZOIC

SERPENTINITE

Serpentinized peridotite, probably part of Coast Range Ophiolite Complex?; age, late Jurassic

sp *Serpentinite, blue-green-gray, amorphous antigorite (hydrous magnesium silicate) sheared, slickensided*

JURASSIC

PANOCHE FORMATION

(of Anderson and Pack, 1915; Dibblee, 1973a, 1974; Panoche Group of Hall and Loomis, 1992; named units below are of Hall and Loomis, 1992, as formations of Panoche Group, but here designated as members of Panoche Formation; ages of units by Tennis, 1966, in Hall and Loomis,. 1992, marine clastic, lithified; age, upper Cretaceous

Kpa *Sandstone, unnamed, light brown, hardly-bedded, arkosic, contains large dark brown hard concretions 1-2 ft in diameter, includes interbedded micaceous clay shale in varying amounts*

Kp *Clay shale, gray-dark gray, micaceous, crumbly with spheroidal fracture*

Kpa-jp *Johnson Peak Sandstone, similar to Kpa; age of Johnson Peak unit, Santonian*

Kp-jp *Johnson Peak Shale, clay shale, similar to Kp, includes few sandstones*

Kpa-r *Risco Sandstone, similar to Kpa, includes interbedded clay shale*

Kp-r *Risco Shale facies, clay shale similar to Kp, includes a few sandstone layers; age of Risco units, late Albian*

GRAVELLY FLAT FORMATION

(of Rose and Colburn, 1963, Dibblee, 1973a, 1974, Badger Shale of Marsh, 1960) marine clastic, lithified; age, range Cretaceous (Hauterivian and Valenginian (lower Cretaceous) to Tithonian (latest Jurassic) in fossil evidence

Kgf *Clay shale, similar to Kp, but darker gray, thinner bedded, locally includes thin interbeds of olive brown fine-grained graywacke sandstone; in Barrel Valley area may be Kp poorly exposed*

Kgfs *Clay shale and sandstone, south of Palonio Pass, clay shale includes thin interbeds of olive brown fine-grained sandstone (may be Kp?)*

CRETACEOUS

MESOZOIC

SERPENTINITE AND DIABASE

Coast Range Ophiolite Complex?; age, late Jurassic?

sp *Serpentinite, blue-gray-green, amorphous antigorite (hydrous magnesium silicate) with specks of magnetite, sheared, slickensided*

di *Diabase, gray-black weathered brown, massive, fine-grained*

FRANCISCAN ASSEMBLAGE

Submetamorphosed mostly clastic sedimentary rocks; age, late Mesozoic

fs *Graywacke sandstone, greenish-gray, weathered brown, hard, massive, fine-grained, severely fractured, brecciated, includes melange, sheared gougy black claystone*

fg *Greenstone (metabasalt) greenish-black, weathered brown, aphanitic, massive, contains calcite veinlets, shattered*

JURASSIC(?)

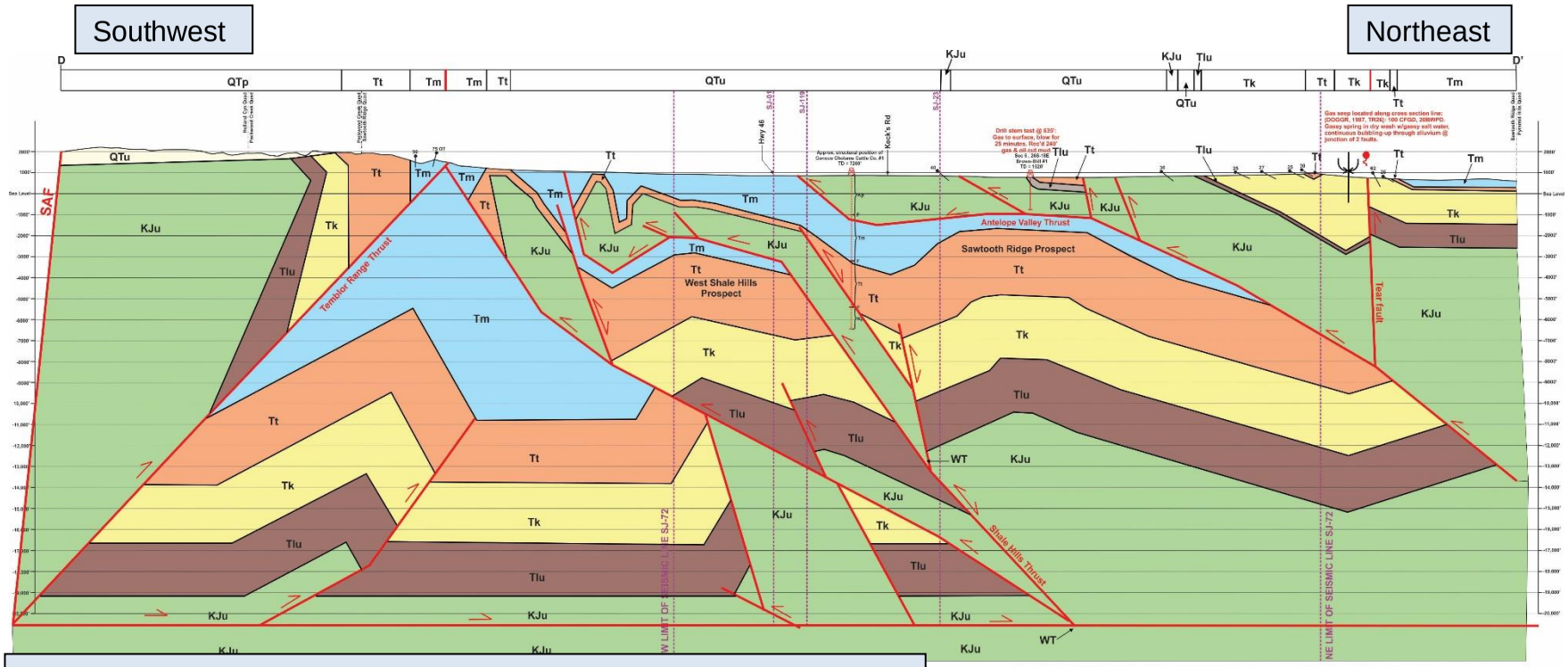
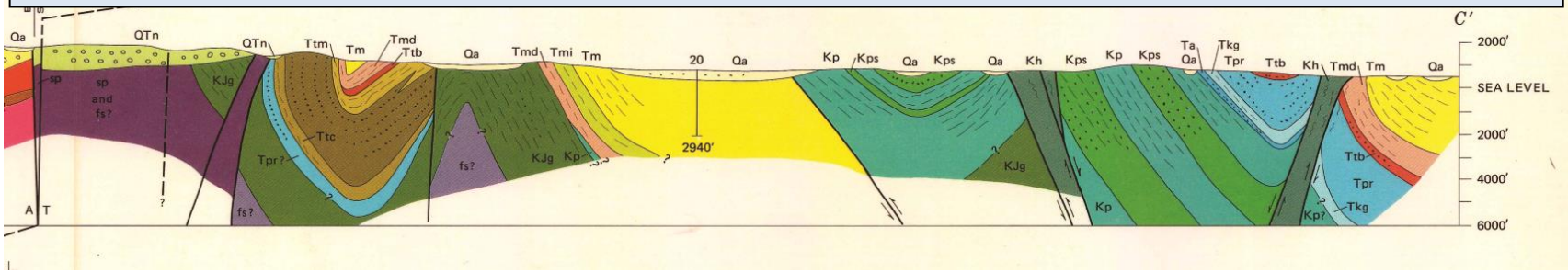


Figure 11, cross section across the Antelope Valley with a fold and thrust belt interpretation and a large amount of shortening. Restoration of the section would show a broader extent of the earlier Antelope Valley Peninsula. Location of section shown in Figure 6.

Explanation

QTu=Various Quaternary and uppermost Tertiary nonmarine units, mostly Tulare and Paso Robles Fms.
Tm=Undifferentiated Monterey Shale.
Tt=Undifferentiated Temblor Fm,, includes key reservoir target such as Carneros and Phacoides sand units.
Tk=Kreyenhagen Fm, mostly Welcome Valley shale and Point of Rocks sandstone.
Tlu=Undifferentiated lower Tertiary units including Canoas shale (Gredal shale equiv), Mabury sandstone (Gatchell sd equiv), Lodo shale, and undifferentiated lower Eocene & Paleoence units.
KJu=Undifferentiated Cretaceous and upper Jurassic units including Moreno Shale Redman sandstone of Marsh (1957), Panoche Fm,Hex claystone & Gravelly Flat Fm, and Franciscan Fm w/ isolated serpentinite bodies

Figure 12, portion of cross section C-C' from USGS map I-788, Dibblee (1974).



Stop 2, Antelope Ranch transect (35.663198°,-120.150345°).

The transect will go up Franciscan Creek to Barrel Valley crossing a map-scale anticline cored with lower Cretaceous Gravelly Flat Formation and flanked by Temblor and Monterey Formations (Figure 6). As the transect climbs out of Barrel Valley it will cross a north-northeast trending fault, possibly a tear fault, with serpentinite outcrops along the fault's trace. Upon reaching the crest of the northern Temblor Range the transect will cross over a large patch of Paso Robles Formation before reaching the San Andreas fault. The transects provide exposures of many of the key rock units along the west side of the San Joaquin basin and southern and central Coast Ranges and offers locations with panoramic view locations to discuss the mapping.

Present and discuss:

- Redman sandstone of the upper Cretaceous Panoche Formation that belongs to the Great Valley sequence-a forearc deposit. We will pass near Redman sandstone outcrops at Sawtooth Ridge that is just north of Hwy 46 (Figures 13 & 14).

Transect across the southwest margin of the Antelope Valley:

- Monterey shale (Devilwater member) outcrops with vertical dips along northeast limb of the Barrel Valley anticline (Figure 16). Note the underlying Temblor Formation is missing from the crest of the anticline and the Monterey shale rests unconformably on lower Cretaceous Gravelly Flat Formation.

- Temblor Formation, mostly Carneros sandstone, outcrops in Woods Canyon can be observed from a distance (Figure 15).

- Antelope Valley Peninsula: Note the great variation in Temblor Formation stratigraphic thickness, and even its presence, along the limbs of the folds that are documented in the map shown in Figure 6 and the cross section in Figure 12. Pence (1985) states that the variation is the result for growth of the Antelope Valley Peninsula-a large northwest trending uplift of early Miocene age. Pence's work and Dibblee's surface mapping show the Temblor Formation was deposited in two parallel basins that were separated by the Antelope Valley Peninsula.

Transect across the southwest margin of the Antelope Valley (cont.):

- Serpentinite outcrops along a possible tear fault (Figure 17 & 18). Serpentinite outcrops are common along many of the large faults of the Antelope Valley and their emplacement is open to several interpretations.

- San Andreas fault (SAF) and deformed Paso Robles Formation. Drainage offsets, pressure ridges, and other tectonic landforms along the San Andreas fault; no evidence along the SAF for vertical offset (Figure 19).

Figure 13, Sawtooth Ridge and Orchard Peak in the background to the right. The ridge is along the south limb of a large syncline within the hanging wall of the Antelope Valley thrust and the footwall of the Aido Spring fault.

Figure 14, Upper Cretaceous Redman sandstone at Sawtooth Ridge. Sandstone is poorly sorted and conglomeratic.

Figure 15, lower Miocene Carneros sandstone that is absent from the Barrel Valley anticline to the southeast; Jack Canyon.

Figure 16, vertical dipping Monterey shale (Devilwater member) along north limb of the Barrel Valley anticline.

Figure 17, serpentinite outcrop along a possible tear fault at Annette Road with Yannick Wirtz for scale.

Figure 18, close-up of serpentinite outcrop along Annette Road.

Figure 19, San Andreas fault (SAF) at Palo Prieto Valley. The narrow ridge in the center of the photo is a composite pressure ridge with the most recent trace of the SAF to its left and along the base of the ridge. SAF is characterized by large horizontal displacements and no evidence for vertical displacements.

Stop 3, Bitterwater Road (35.559117°, -120.045949°).

Trip will descend Bitterwater Canyon from the San Andreas fault to the Bitterwater Valley crossing an extensive section of overturned Cretaceous, Eocene, Oligocene, and Miocene strata. Stop 3 is near the mouth of Cedar Canyon (Figures 20 and 22).

Present and discuss:

- Temblor Formation outcrops (Media shale and Carneros sandstone). As in much of the northern Temblor Range there is great variation in Temblor Formation stratigraphic thickness, and even presence, along the limbs of the folds due to growth of the Antelope Valley Peninsula during the early Miocene (Figures 20 and 21).

- Dibblee (1974, 2006b) has mapped the Bitterwater Creek area with tight folds with vertical and overturned limbs in Cretaceous through Miocene strata (Figures 20 & 22), and Dibblee's mapping closely follows the mapping of Heikkila and MacLeod (1951). Are all of these units really overturned, and if not, what are the alternative structural interpretations to the mapping and cross sections? On the second day of this trip, at another Bitterwater Creek in the southern Temblor Range, we will visit a thick Temblor Formation section mapped by Dibblee as overturned, but the field evidence suggests the section is right-side-up.

- East of Cedar Canyon and high on the ridge Dibblee (1974) has mapped a large, regional syncline with Monterey Formation in its trough (Figure 20). The trough is complicated structurally: cut by faulting that is subparallel to the axis of the syncline and with limbs that are commonly overturned. What are the alternative structural interpretations to the mapping and cross sections?

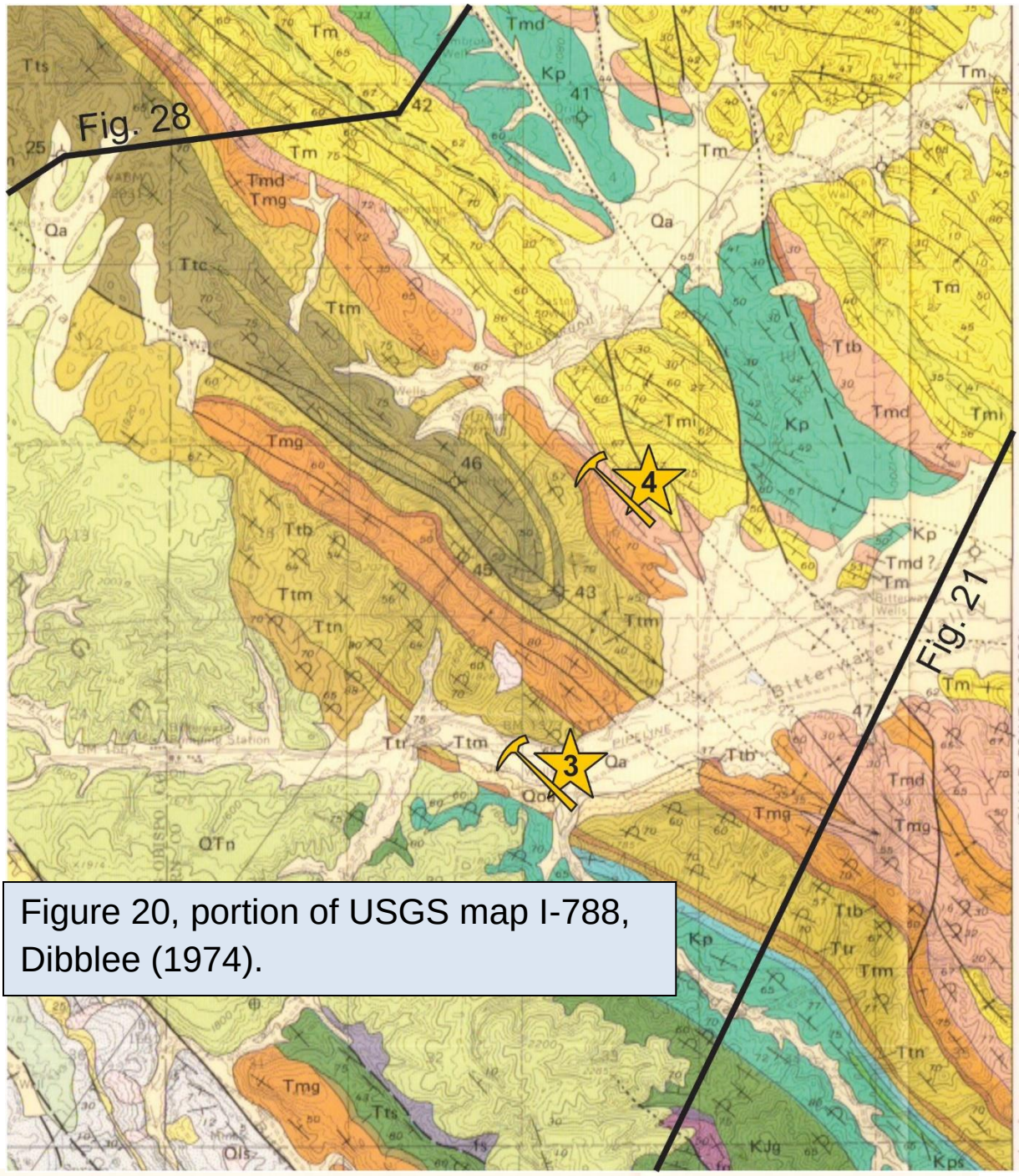


Figure 20, portion of USGS map I-788, Dibblee (1974).

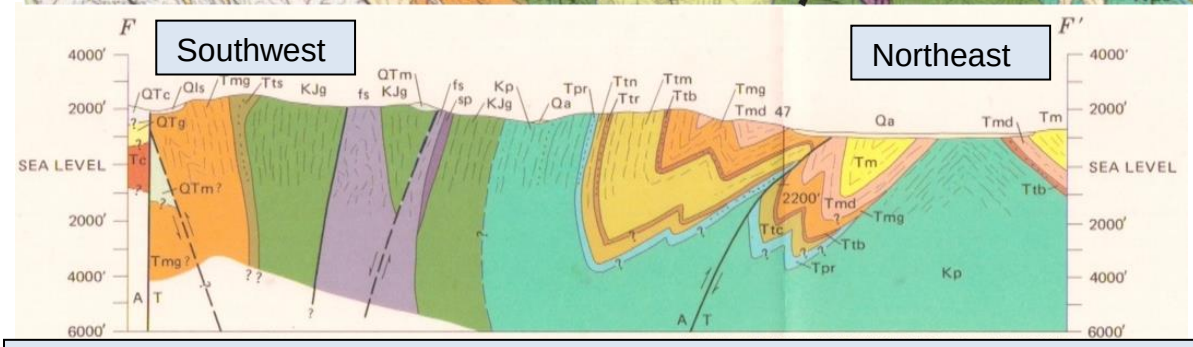


Figure 21, cross section F-F' from USGS map I-788, Dibblee (1974).

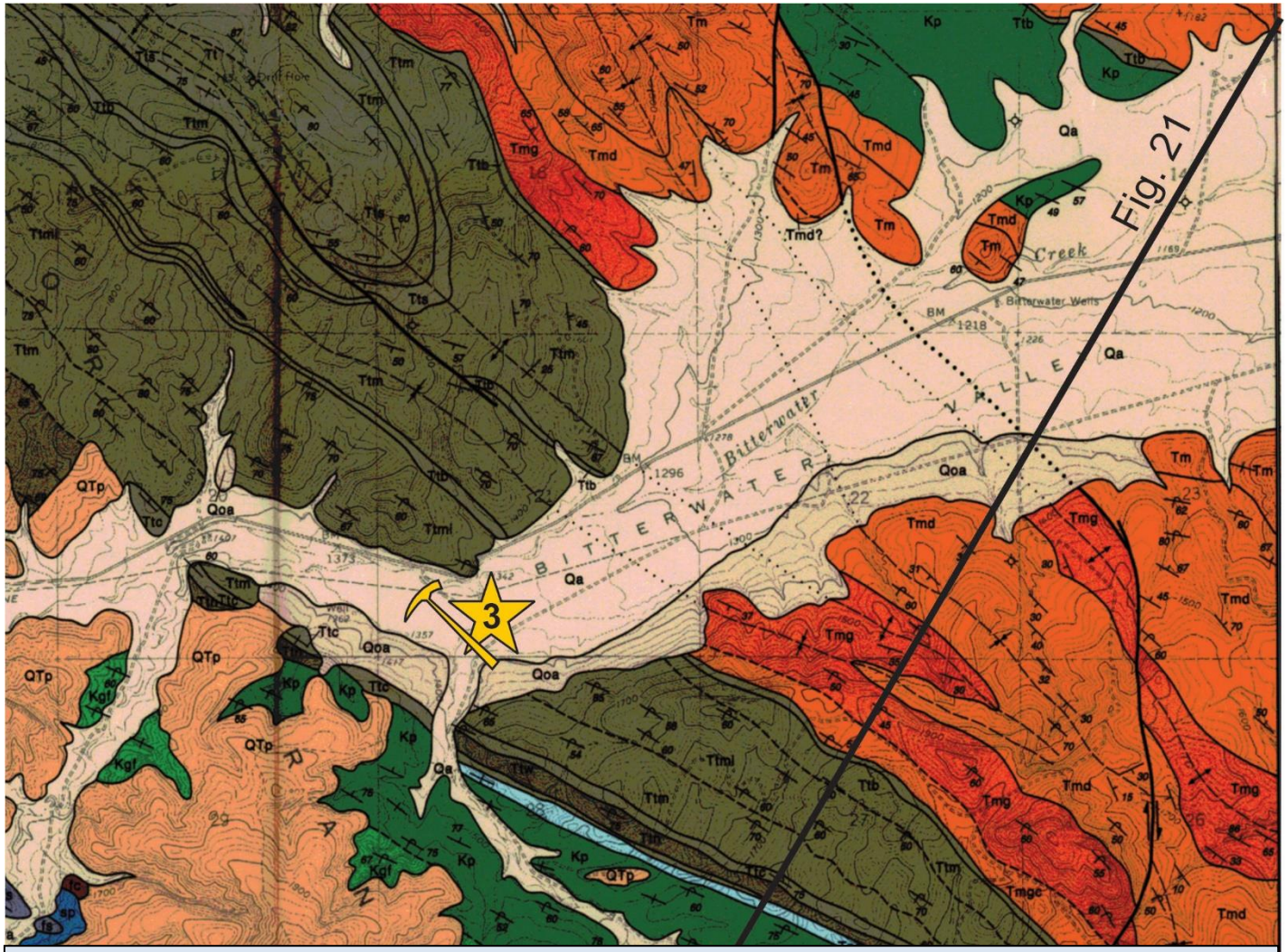


Figure 22, portion of Dibblee map of Holland Canyon and Packwood Creek (2006b). The color fill in the trough of the syncline just north of Stop 3 should be orange indicating Monterey Formation-compare with Figure 20.

Figure 23, Carneros sandstone at the mouth of Cedar Canyon. Sedimentary features here show the beds are overturned and younger to the left (east)(Pence, 1985).

Figure 24, highly fractured Media shale outcrop along the Bitterwater Road with Yannick for scale.

4) Shale Point fold belt (35.582270°, -120.037960°).

The trip will make a short detour off the Bitterwater Road to view the fold belt from the hills to the north (Figures 26 & 27).

Present and discuss:

- Structural style of folding in the Monterey Formation and influence of Monterey lithology and influence on folding.

- Character of folding in pre-Monterey Formation strata (Figure 28) and various structural interpretations of the Shale Point fold belt.

- Structural interpretation of the Antelope Uplift. See the Davis (2015) article at the end of this guidebook.

- Local stratigraphy recorded in exploration wells (Figures 29 & 30).

Figure 25, Shale Point fold belt with Orchard Peak in the background.

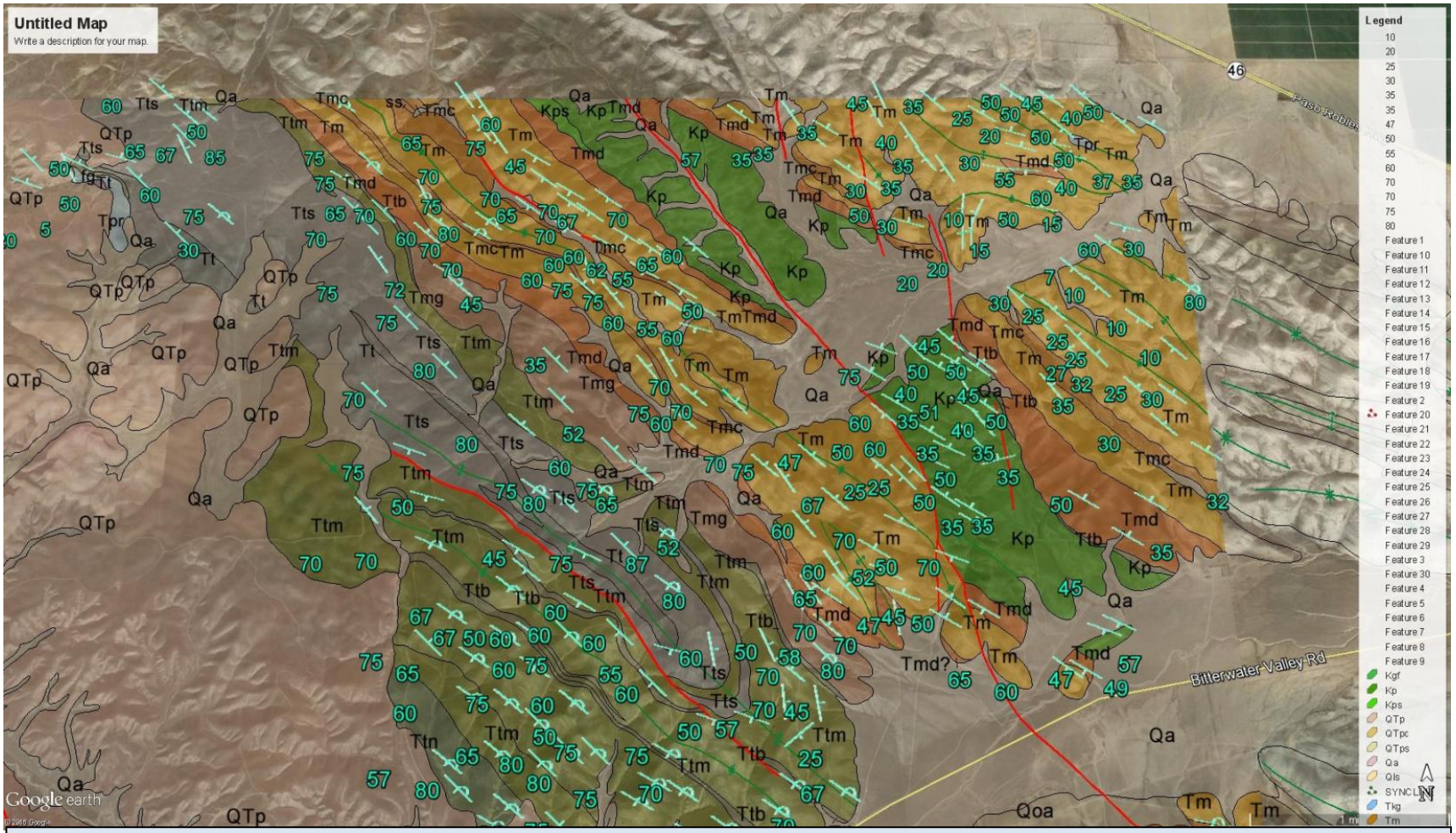


Figure 26, Google earth image with Dibblee mapping superimposed. Such overlays can be made with GIS geologic maps.

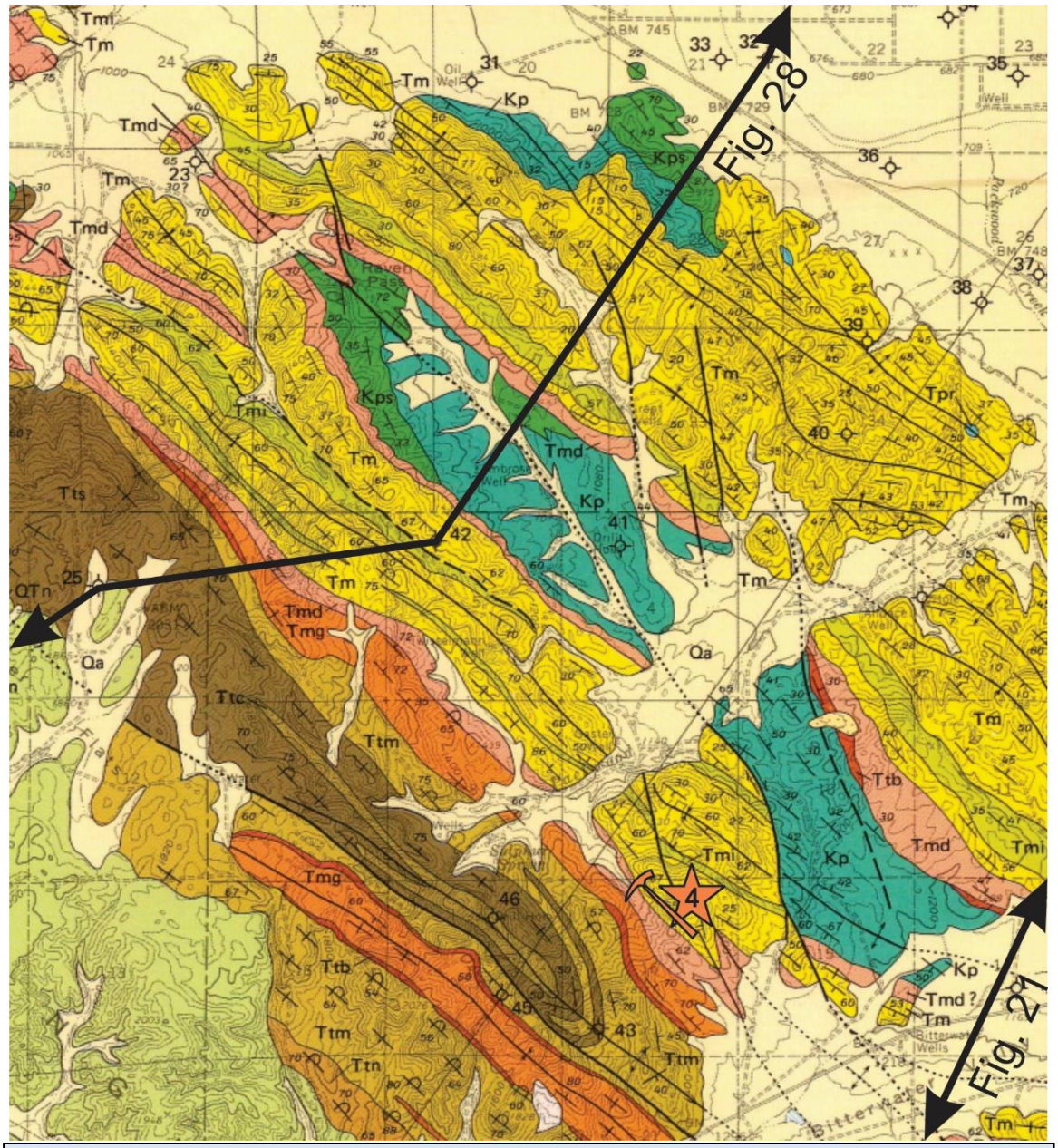


Figure 27, portion of USGS I-788 map (Dibblee,1974) showing the Shale Point fold belt and Stop 4.

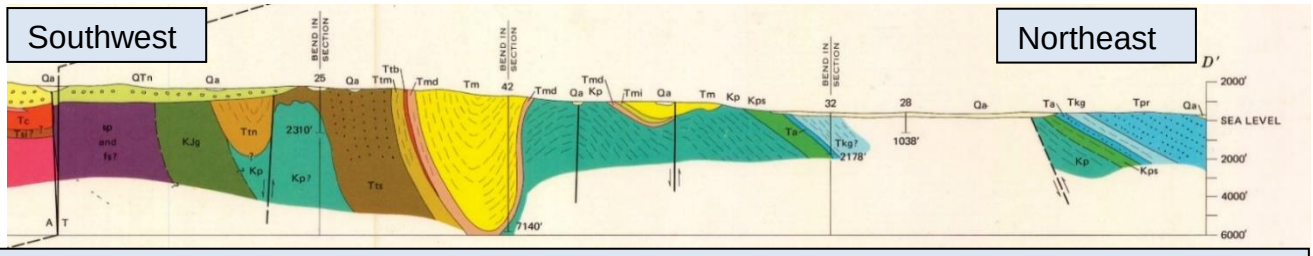


Figure 28, portion of cross section D-D' from USGS map I-788.

TYPE LOG
TWISSELMAN RANCH AREA
GENERALIZED STRATIGRAPHY

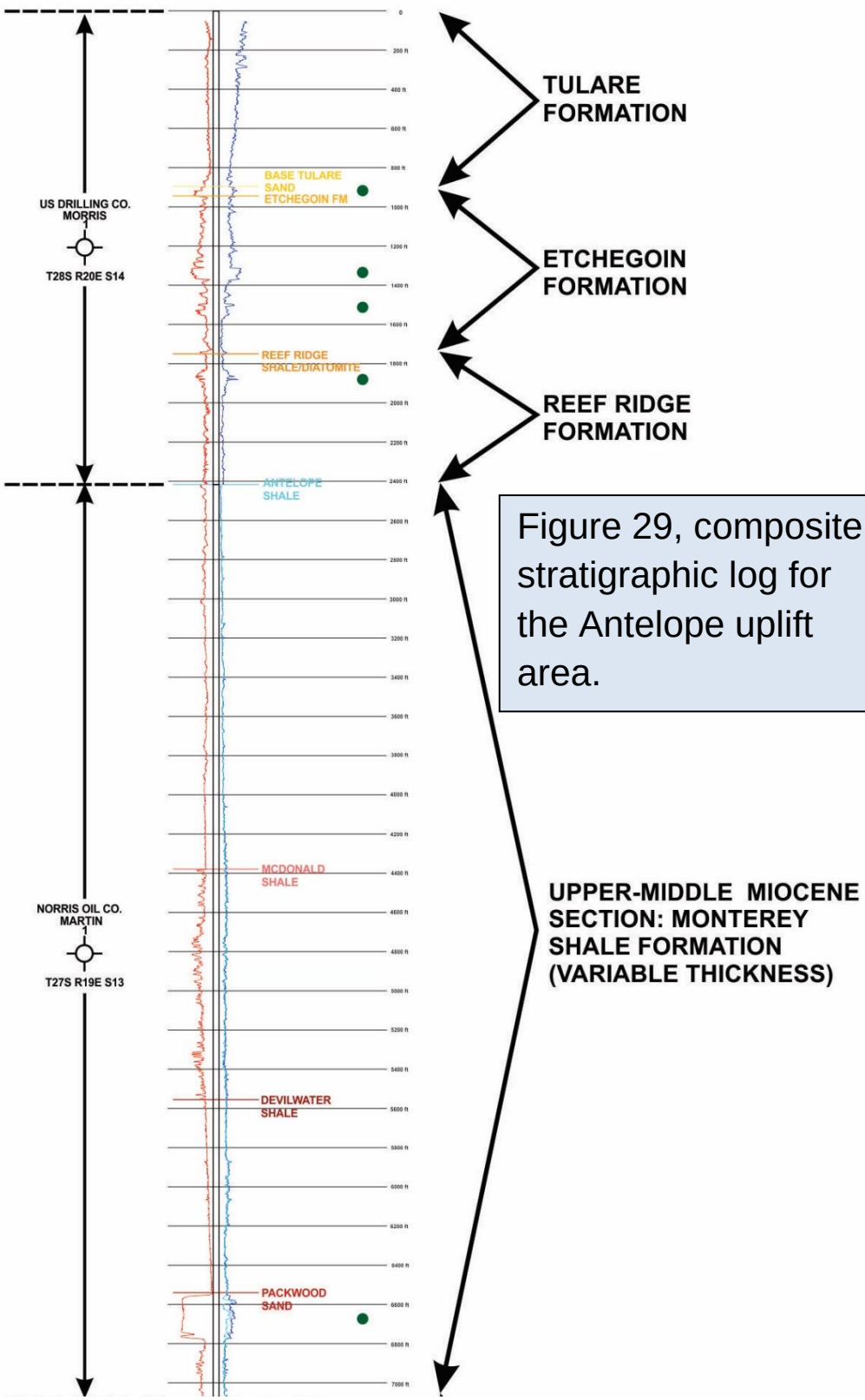


Figure 29, composite stratigraphic log for the Antelope uplift area.

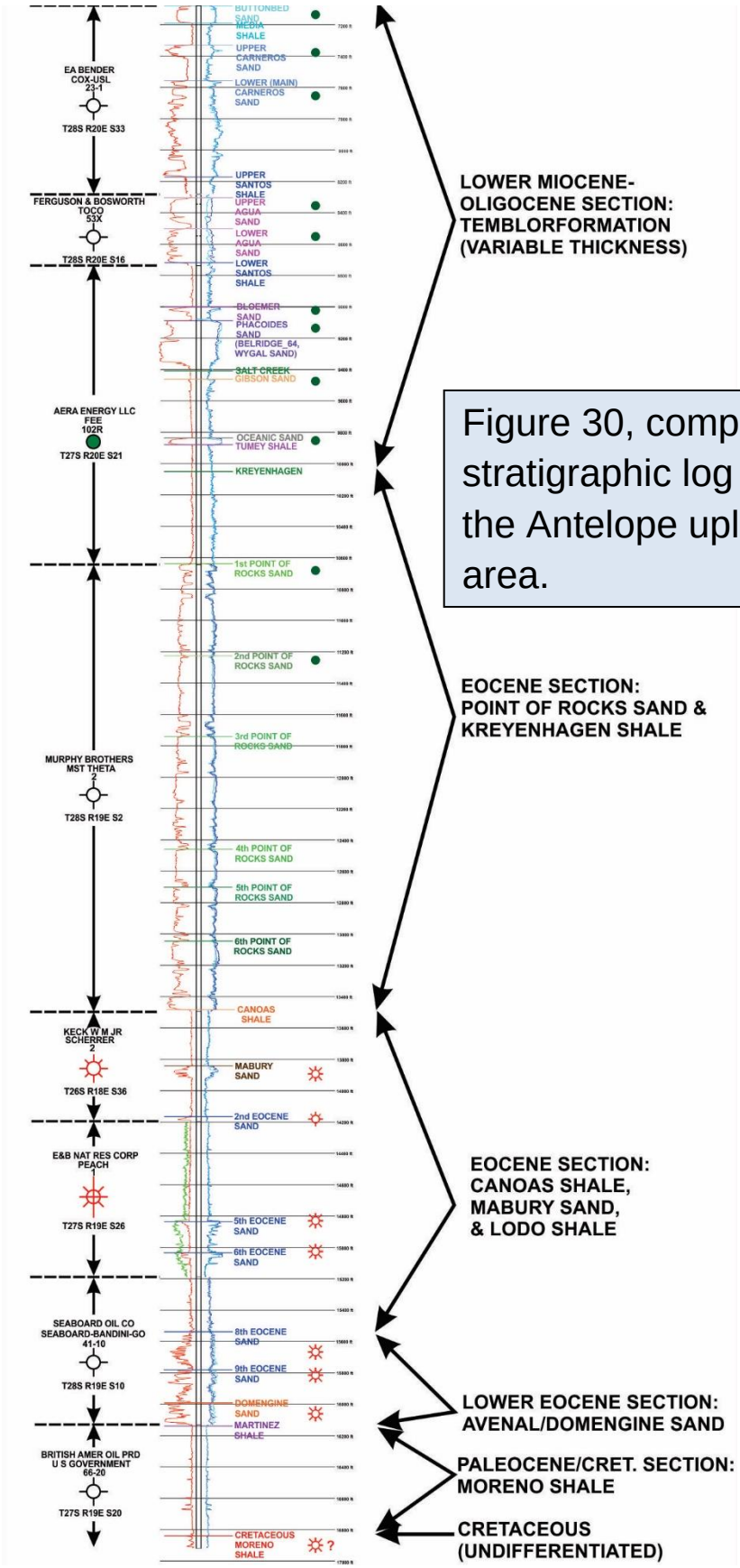


Figure 30, composite stratigraphic log for the Antelope uplift area.

Stop 5, Structure of the central Temblor Range, and structure of the McKittrick and Cymric oil fields and (35.323080, -119.671510).

Trip will stop along the Reward Road northwest of the town of McKittrick and at the north end of the Main Area of the McKittrick oil field (Figure 31). We have included in the guidebook several figures and concepts from Farley's (1990) paper on the Tulare fold belt.

Present and discuss:

- Surface structure of the central Temblor Range and the northwest trending Temblor Ranch synclinorium (Figure 31) and deeper backthusting.

- Late Miocene breccia deposits on the crest of the range.

- McKittrick thrust (Figures 32 & 37): its geometry and movement history.

- Structure of the McKittrick oil field (Figures 34 & 35). Main area's updip seal formed by a high-angle fault that pre-dates convergence on the McKittrick thrust. Northeast pool is trapped by a late Miocene fold capped by an angular unconformity.

- Structure of the Willow Springs area, McKittrick thrust, and Temblor Ranch synclinorium (Figure 39).

- Structure of the Cymric oil field: Welport pool is trapped by a late Miocene fold capped by angular unconformity. (Figure 40).

- The Tulare fold belt is series of northeast vergent folds developed in the Tulare Formation. Below are key points from Farley's (1990) interpretation of the fold belt (Figure 41). Farley shows that fault-related fold models can be very useful to reservoir developments projects.
    - Anticlines are fault-propagation folds (Figure 42).
    - Anticlines developed above a detachment at the top of the Amnicola sand (Figure 42).

- Detachment is northeast continuation of the McKittrick thrust.

- Detachment is folded by deeper folding off of a detachment at the base of the San Joaquin Formation.

- Heavy oil reservoirs in Tulare Formation were undergoing thermal recovery and understanding of the fold and fault geometry and positions of fluid levels were important to the design and monitoring of the thermal recovery projects.

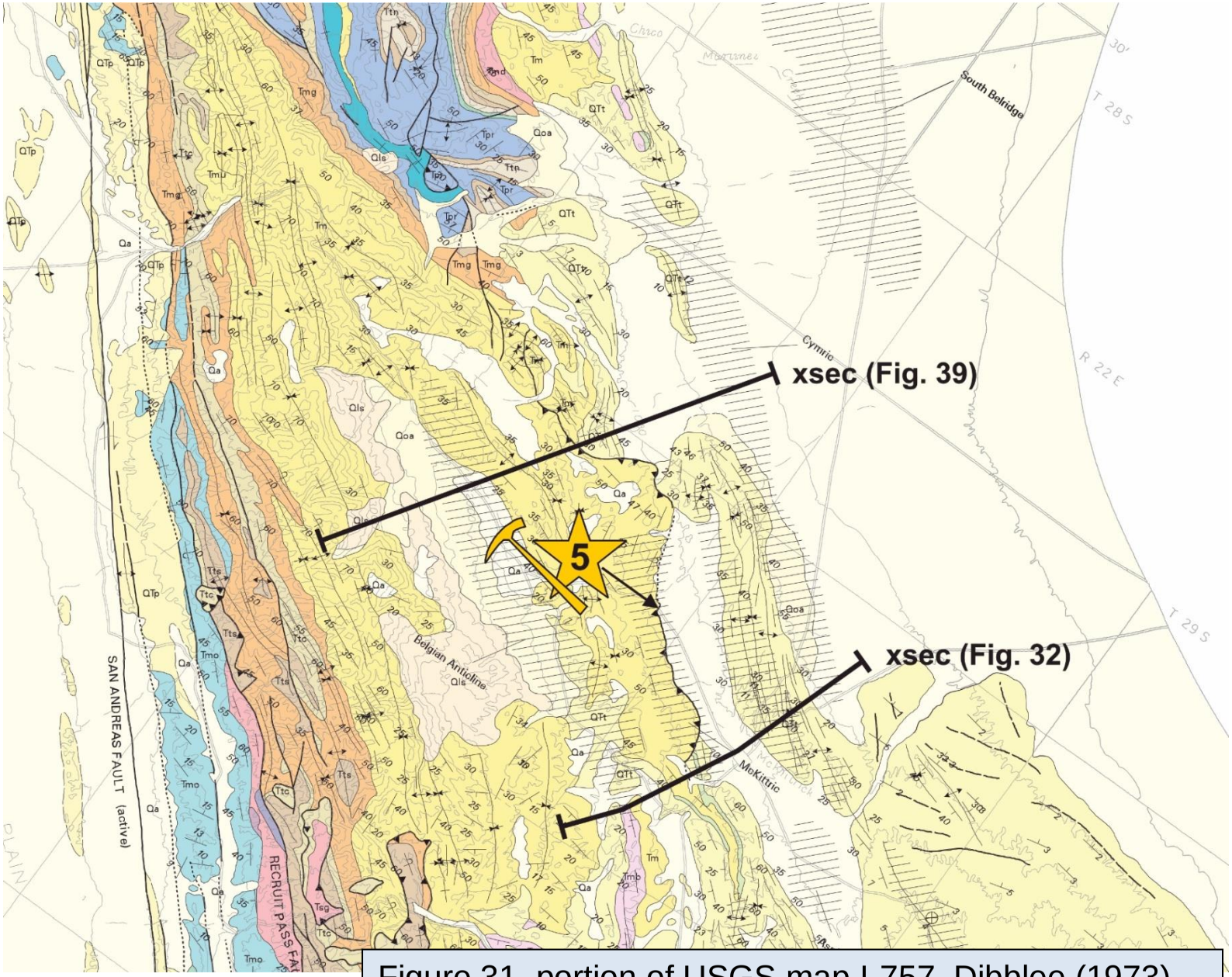


Figure 31, portion of USGS map I-757, Dibblee (1973).

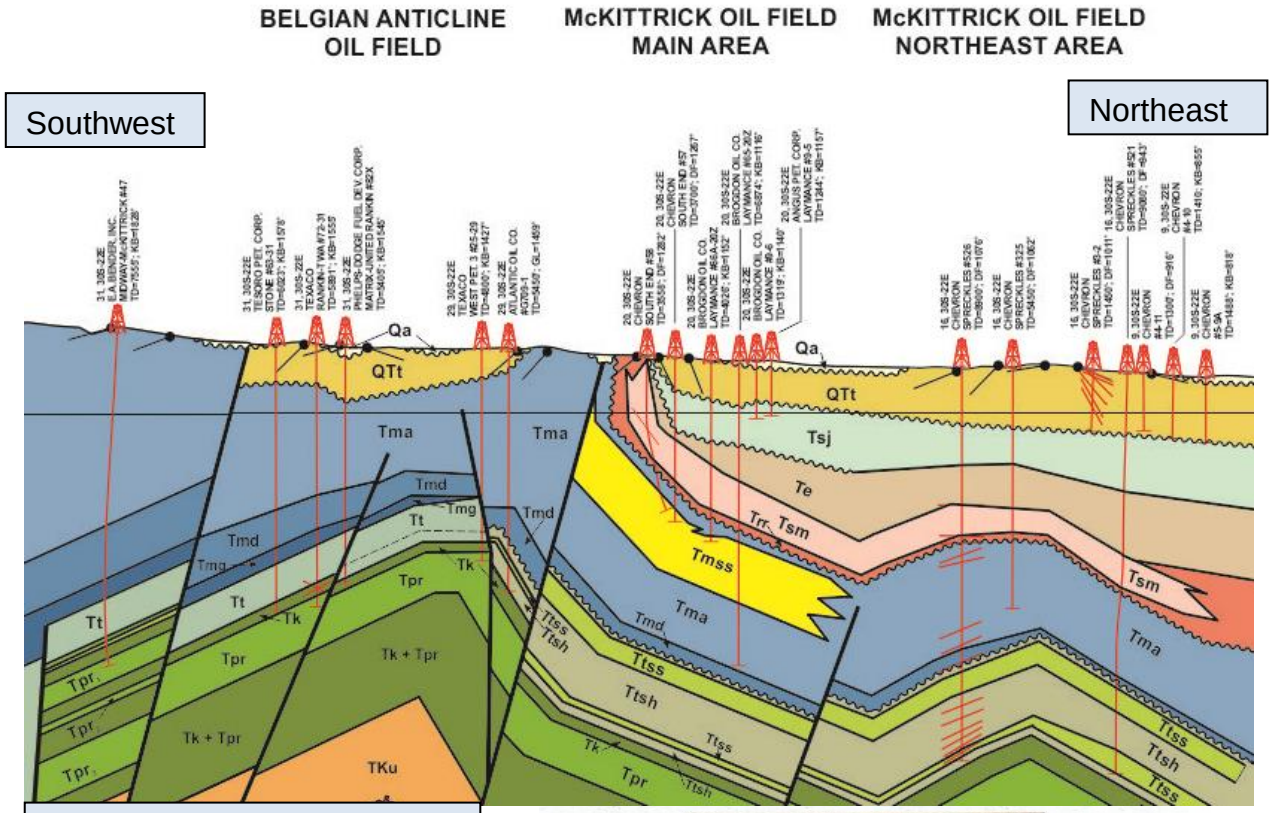


Figure 32, cross section showing faulted limb trap at the Main Area pool of Mc Kittrick oil field. Location of line in Figure 31.

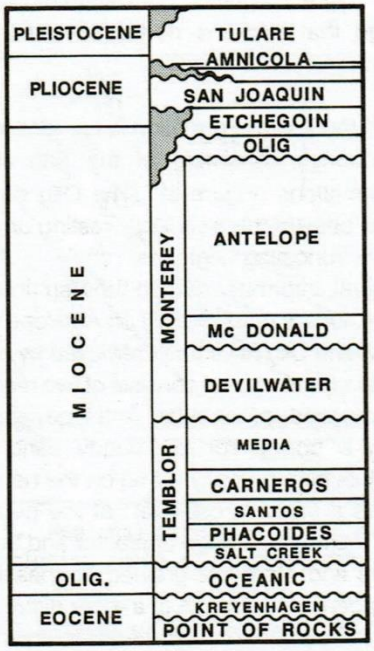


Figure 3. Generalized stratigraphic column for the Cymric-McKittrick area. Missing section in late Miocene and younger units is indicated by shading. Rock units in larger type size are oil-productive.

Figure 33, from Farley (1990).

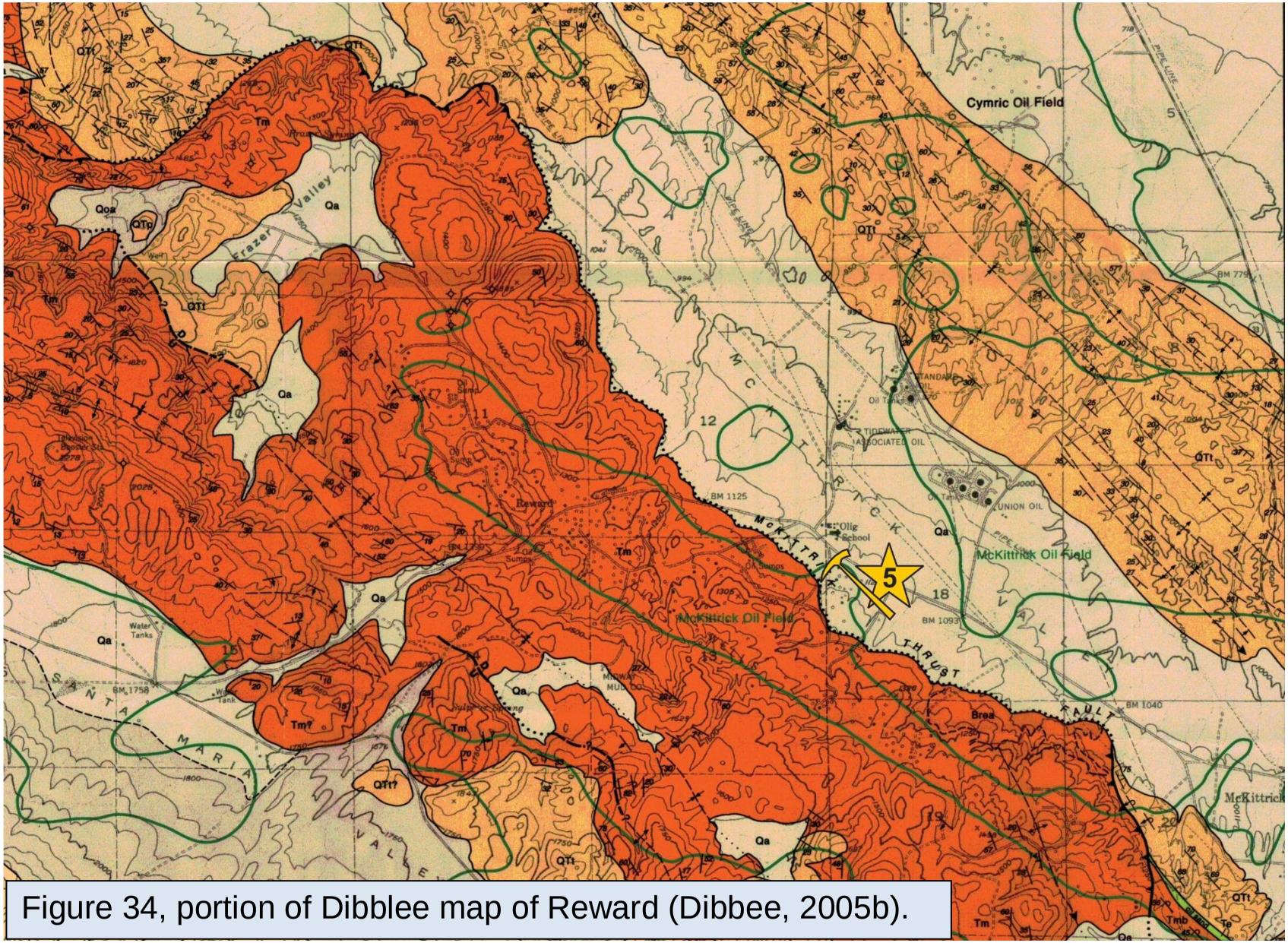


Figure 34, portion of Dibblee map of Reward (Dibbee, 2005b).

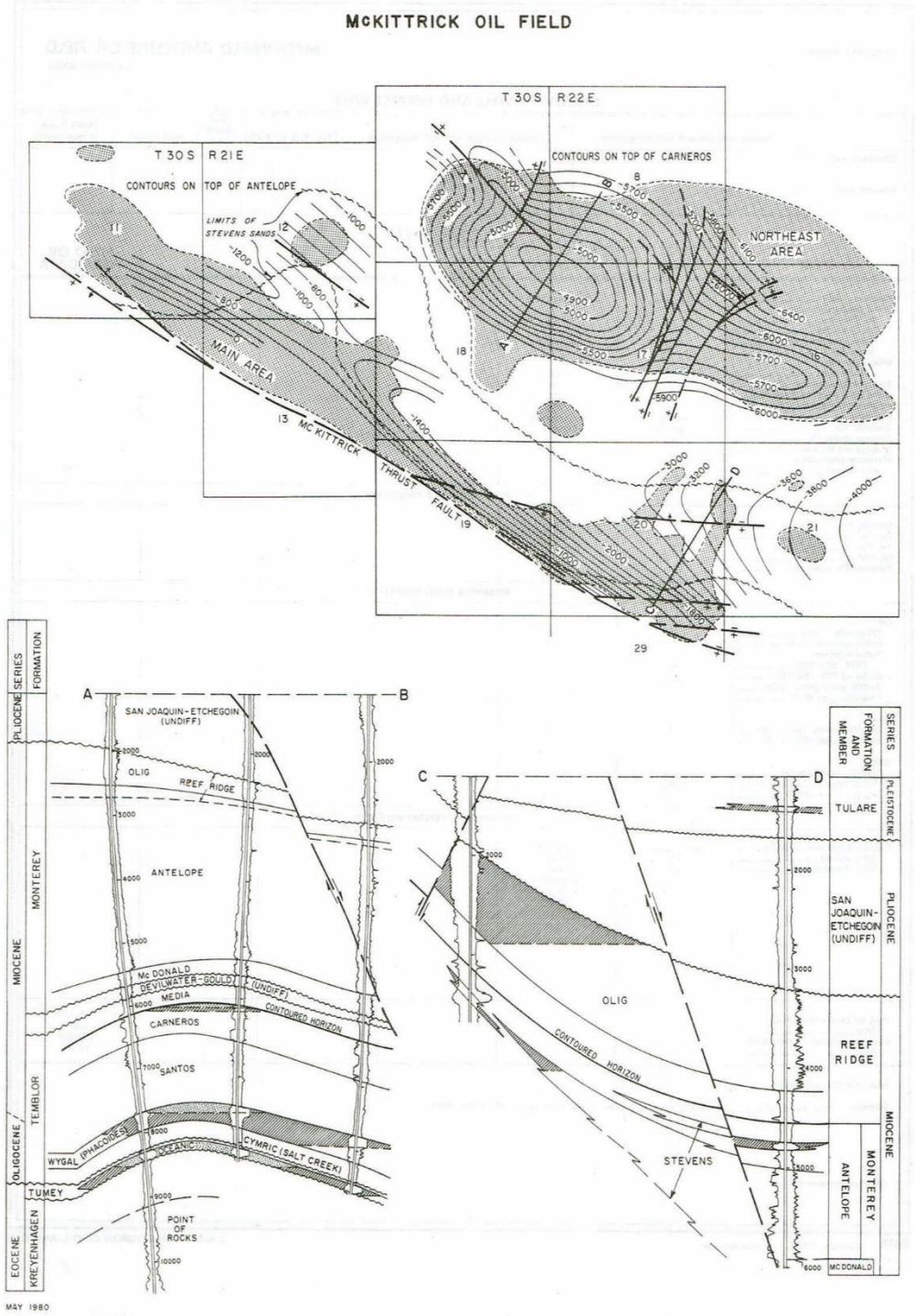


Figure 35, from DOGGR (1998).

Figure 36, Mc Kittrick oil field, Main area.

Figure 37, exposure of the Mc Kittrick fault, Mc Kittrick oil field.

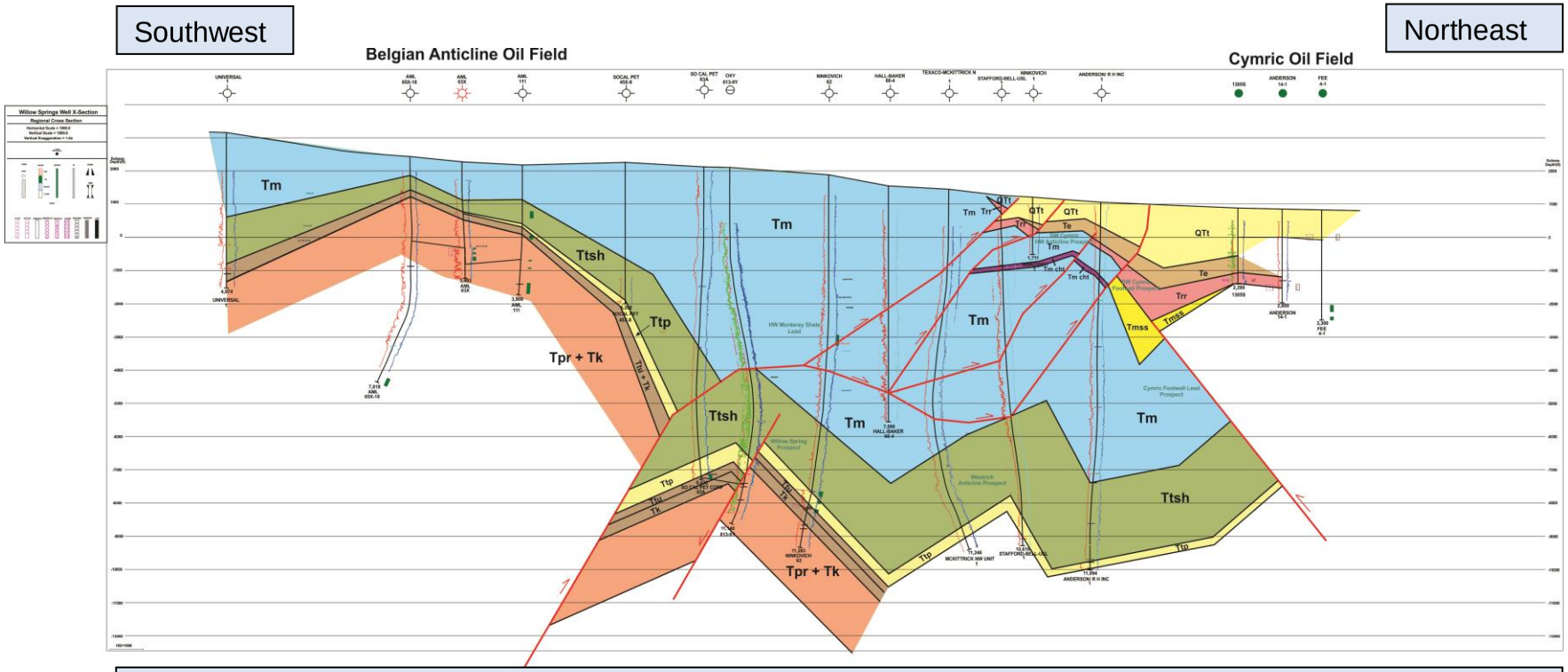


Figure 39, cross section from the Belgian Anticline oil field to the Cymric oil field. Location of section shown in Figure 31.

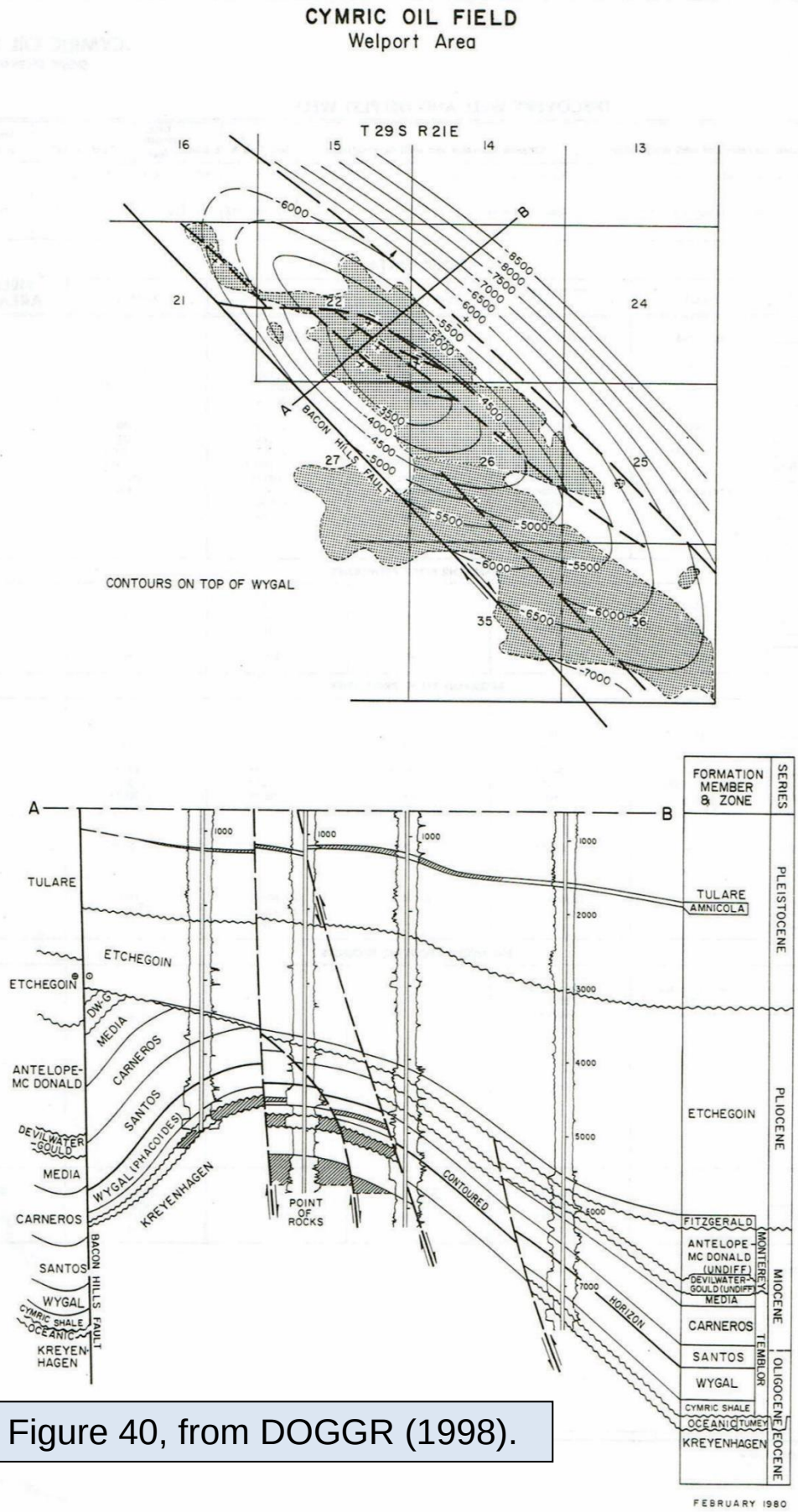


Figure 40, from DOGGR (1998).

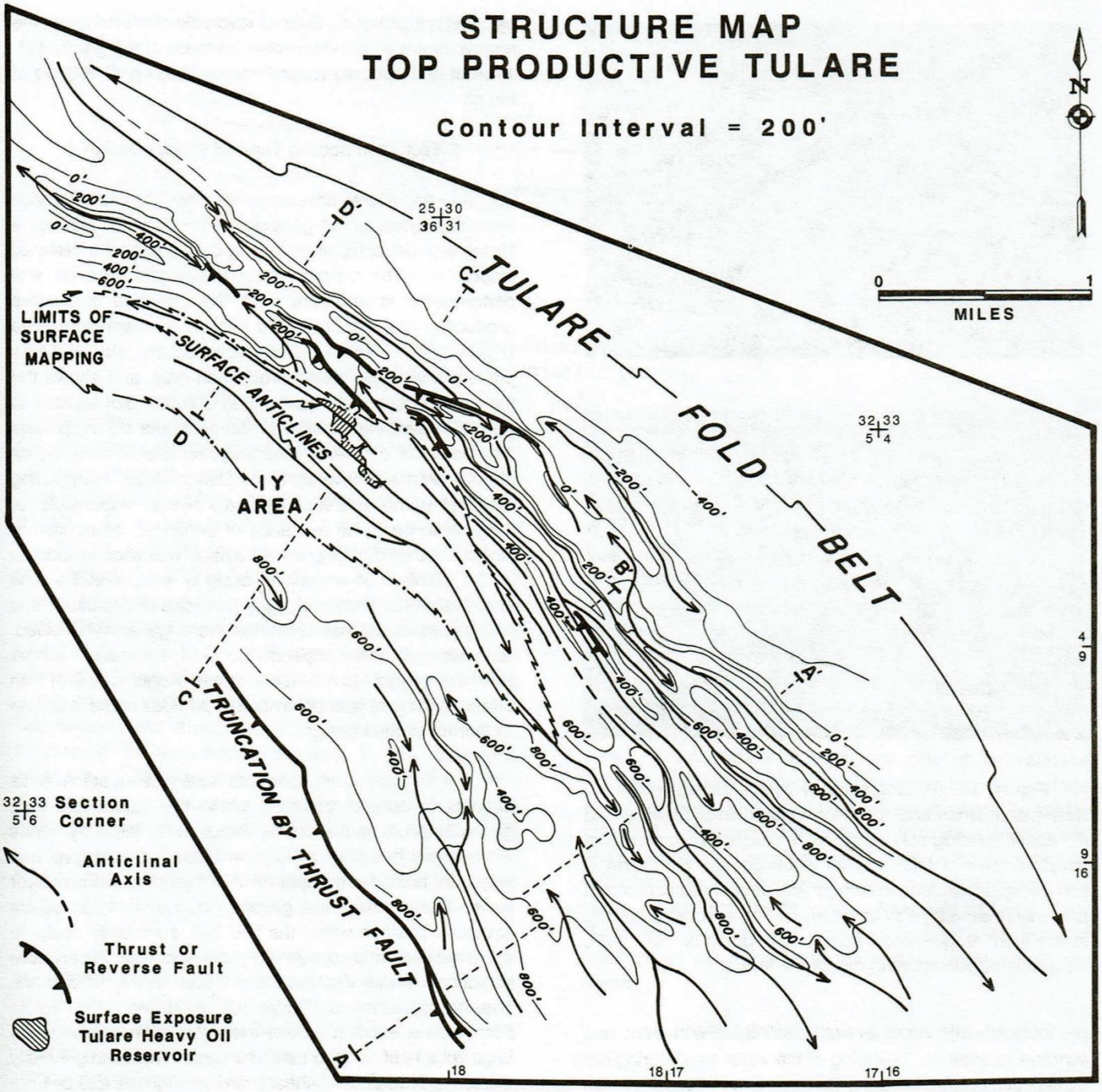


Figure 13. Structure map on Top Productive Tulare horizon.

Figure 41, from Farley (1990).

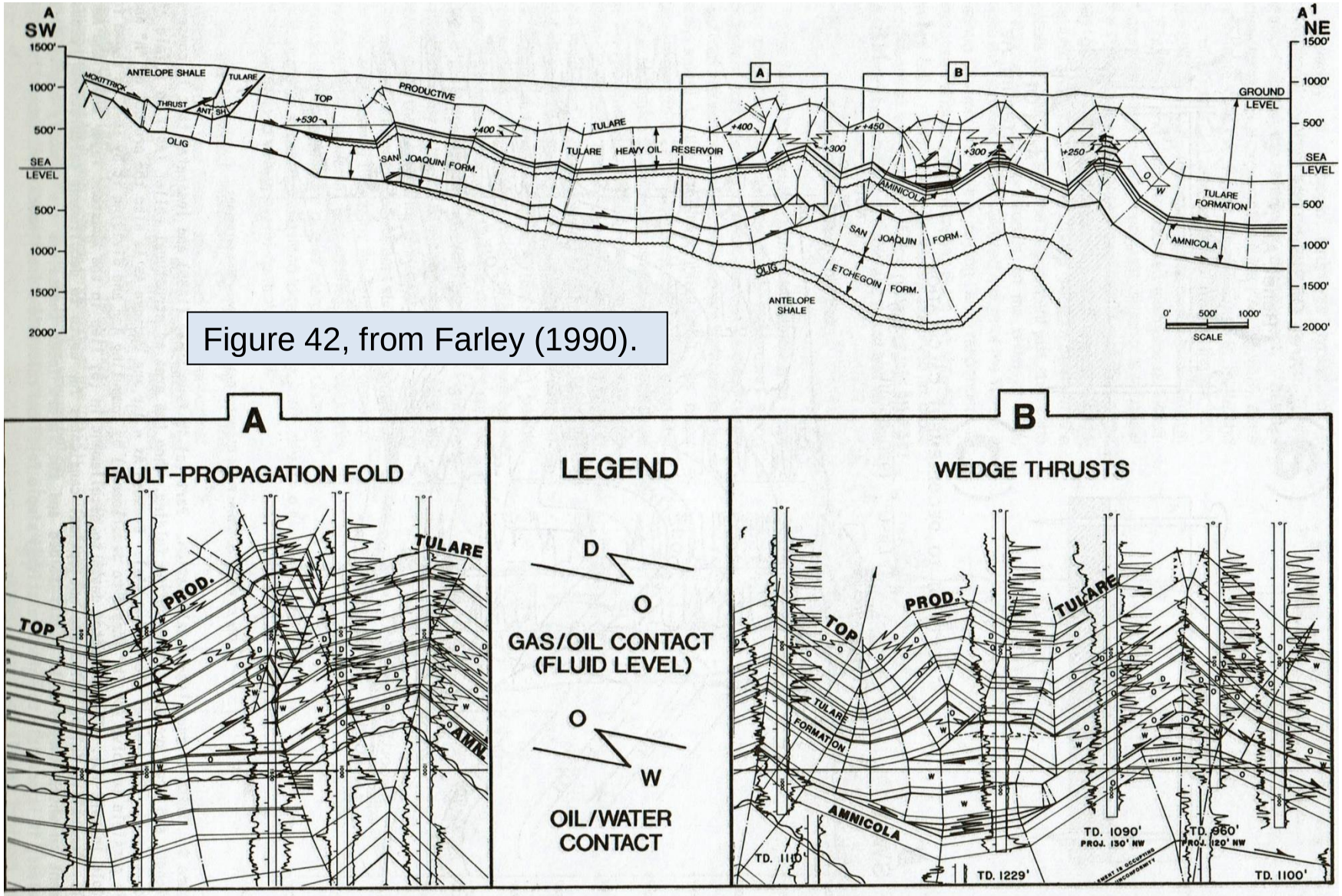


Figure 8. (Top) Cross section A-A′, through Tulare fold belt. Elevations (+530, +400, etc.) indicate position of fluid level traps relative to sea level. Cross-section segments in boxes "A" and "B" are shown in expanded scale at bottom of figure and correspond to specific features cited in the text. The cross section represents the Tulare reservoir at field discovery; fluid levels have been simplified because of scale.

2d Day (Saturday, October 1, 2016)

Stop 6, Midway-Sunset oil field and structure of the southwest San Joaquin basin (35.11477, -119.46829).

This stop provides a panoramic view of the major oil fields of the southwestern San Joaquin basin, the southern Temblor Range, and the San Emigdio Mountains to the southeast.

Present and discuss:

- Surface structure of the southern Temblor Range (Figures 43 & 44).
- Nature and origin of the Santa Margarita Formation outcrops along crest of range.
- Cross section of the southwestern San Joaquin basin showing deep structural interpretation (Figure 45) and restoration (Figure 46).
- Stratigraphy and tectonic record of the southern Temblor Range (Figure 47).

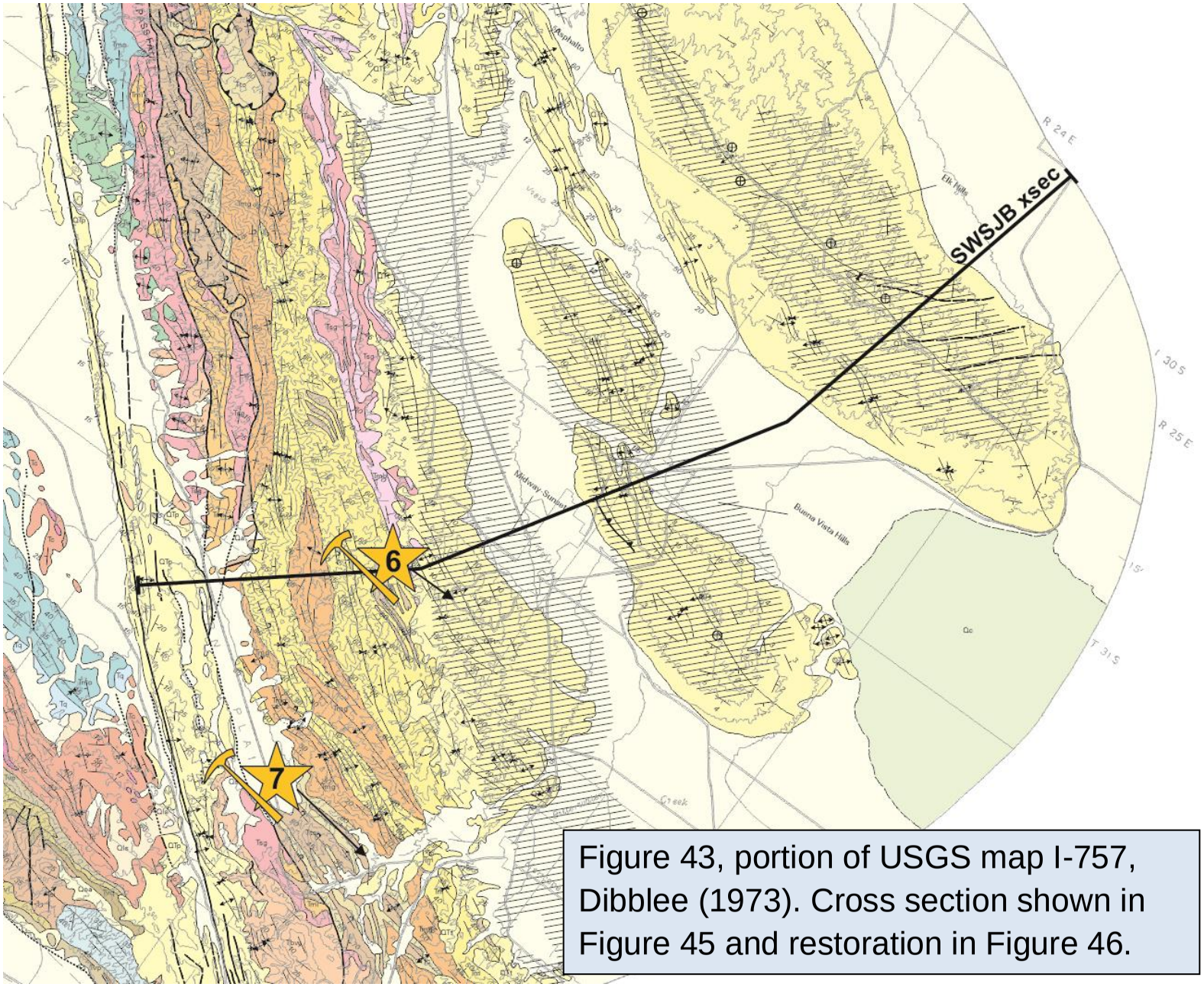


Figure 43, portion of USGS map I-757, Dibblee (1973). Cross section shown in Figure 45 and restoration in Figure 46.

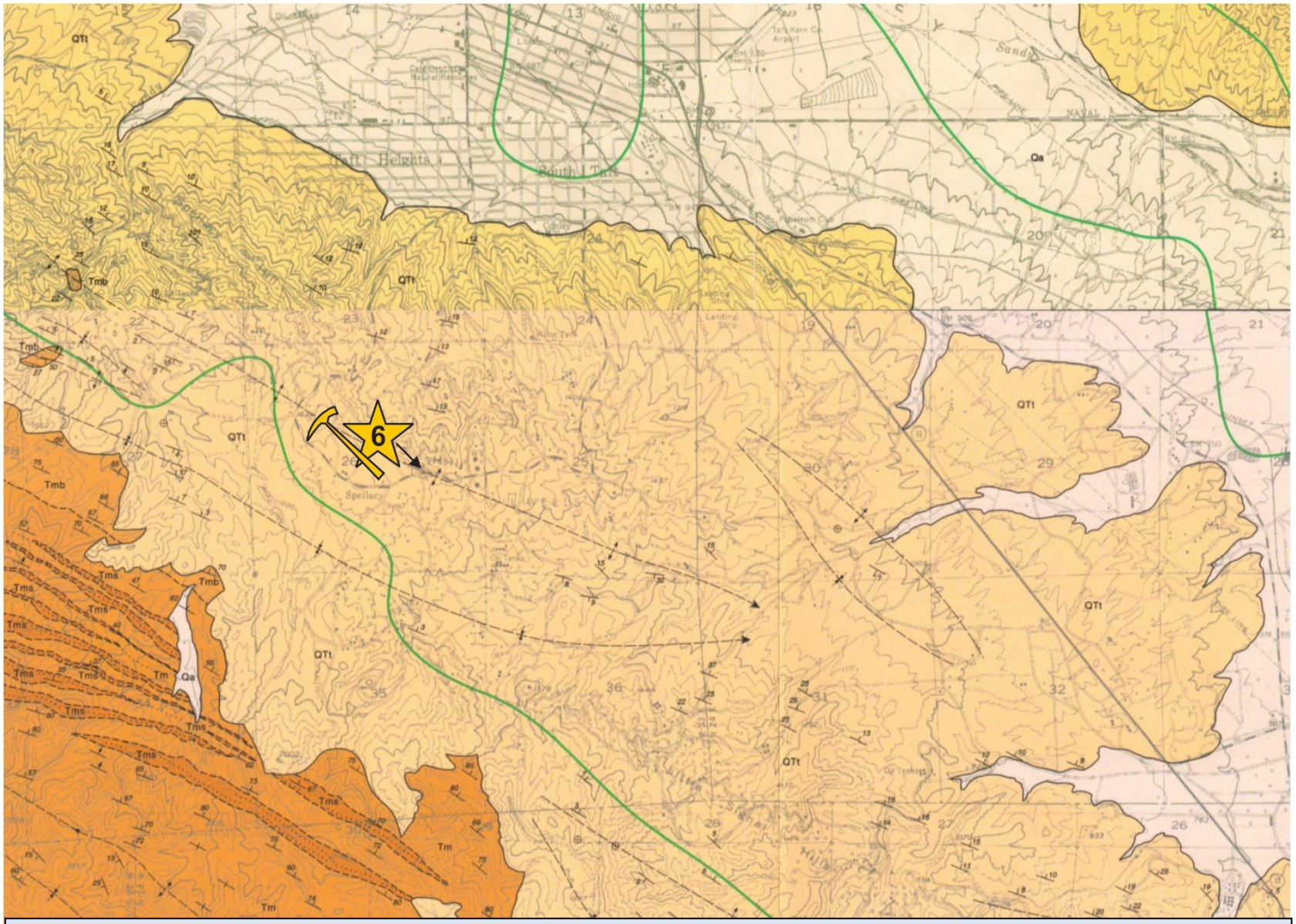


Figure 44, portion of Dibblee maps of Taft and Mouth of Kern (Dibblee, 2005c), and Maricopa and Pentland (Dibbee, 2005d).

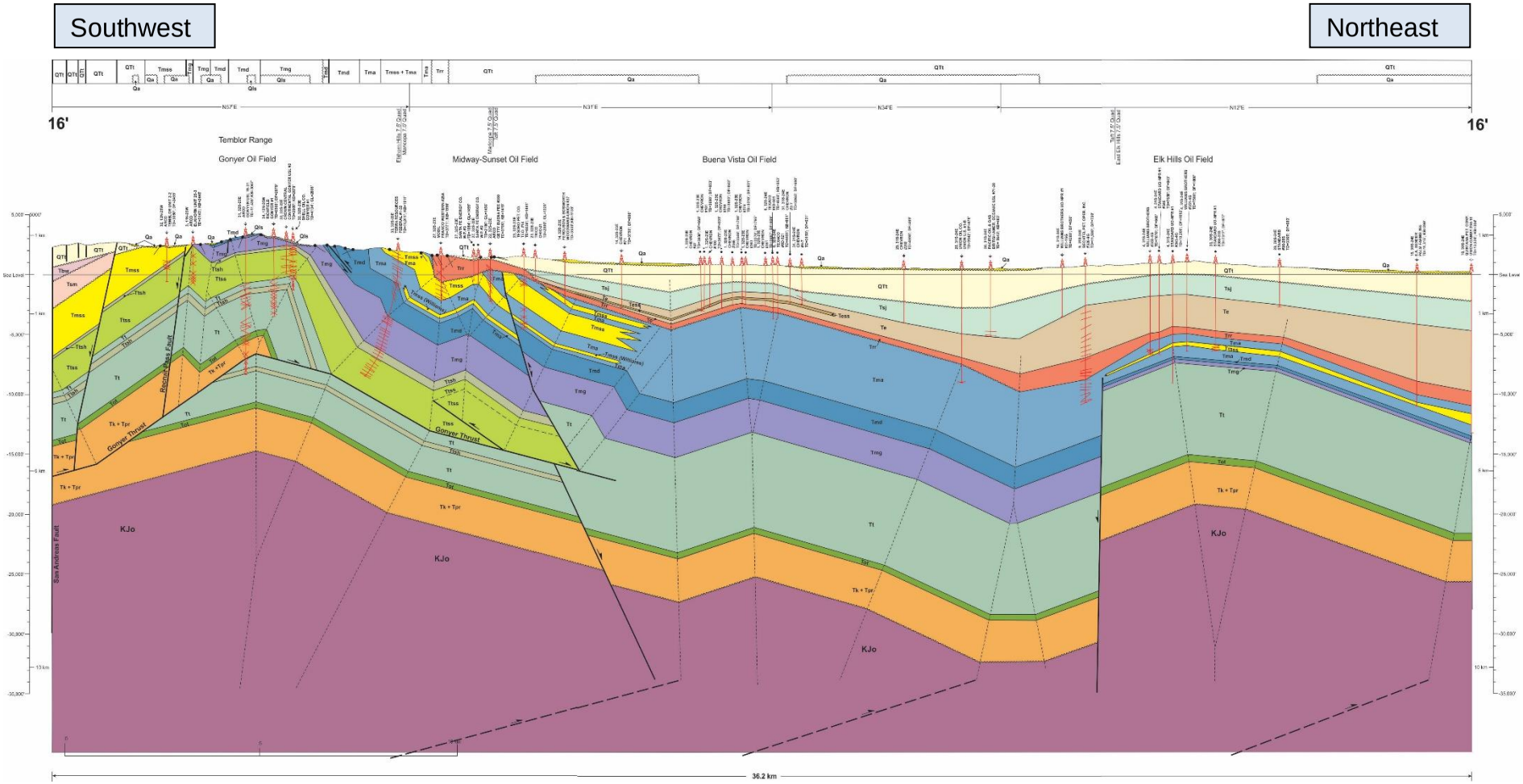


Figure 45, cross section of the southern Temblor Range and southwestern San Joaquin basin. Location of section line shown in Figure 43.

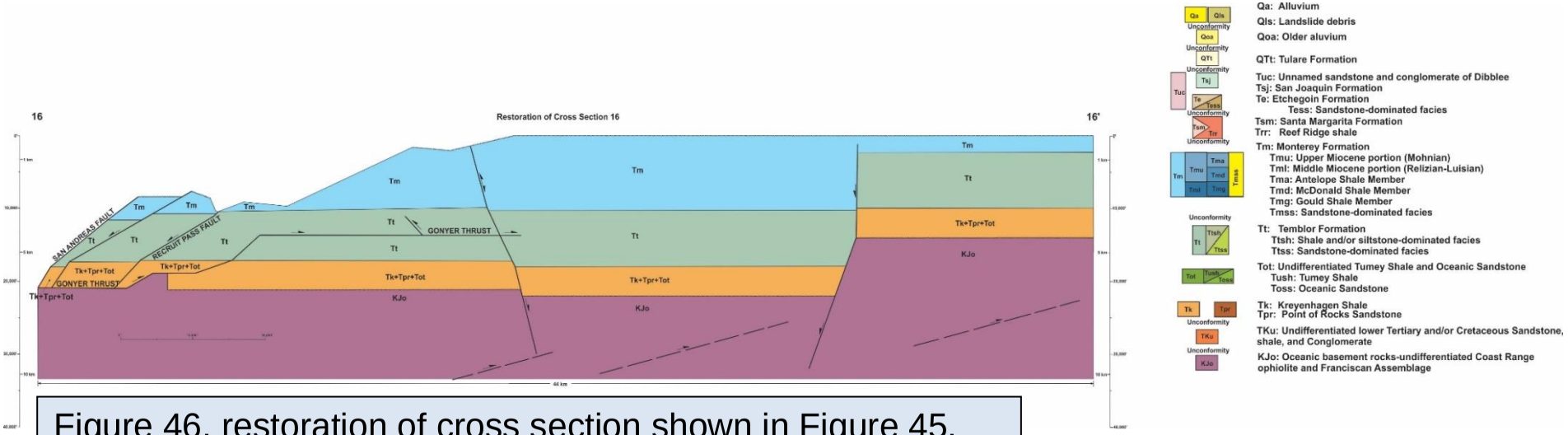


Figure 46, restoration of cross section shown in Figure 45.

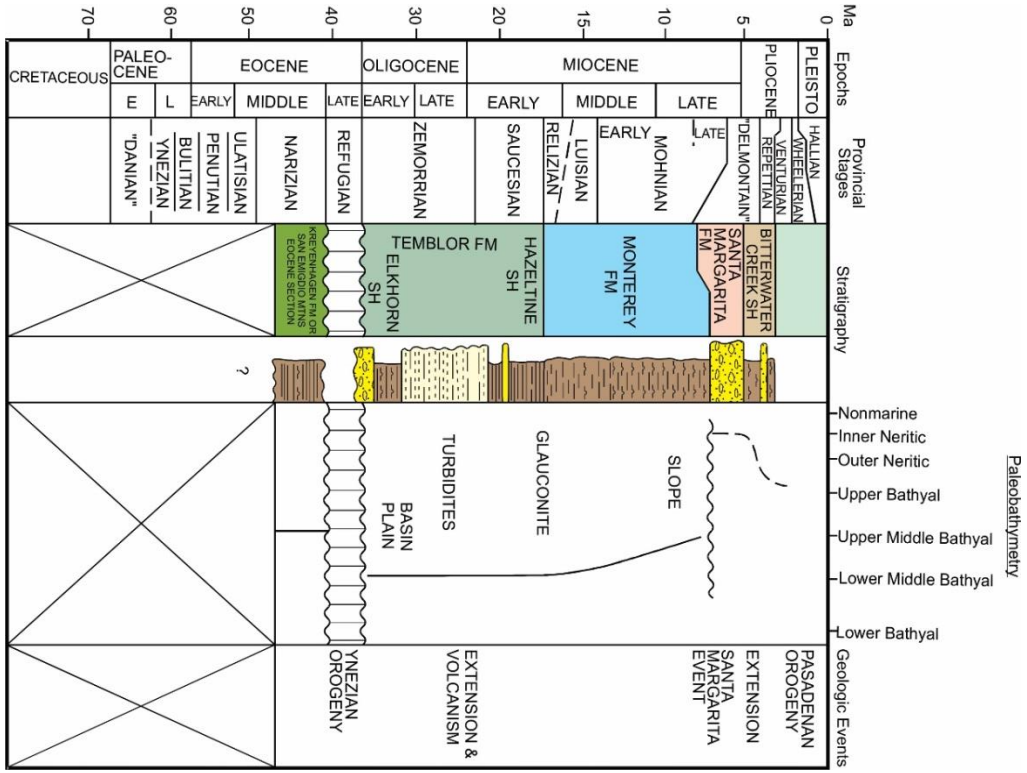


Figure 47, generalized stratigraphic column of the southern Temblor Range. Note the various tectonic events.

Stop 7, Southern Temblor Range section along Bitterwater Creek (35.027583°, -119.441983°).

Stop 7 is in the second Bitterwater Creek for this trip. The road up Bitterwater Creek provides good views of a thick section of folded Monterey Formation. Further up the canyon is a thick section of Temblor Formation that Dibblee mapped as overturned.

Present and discuss:

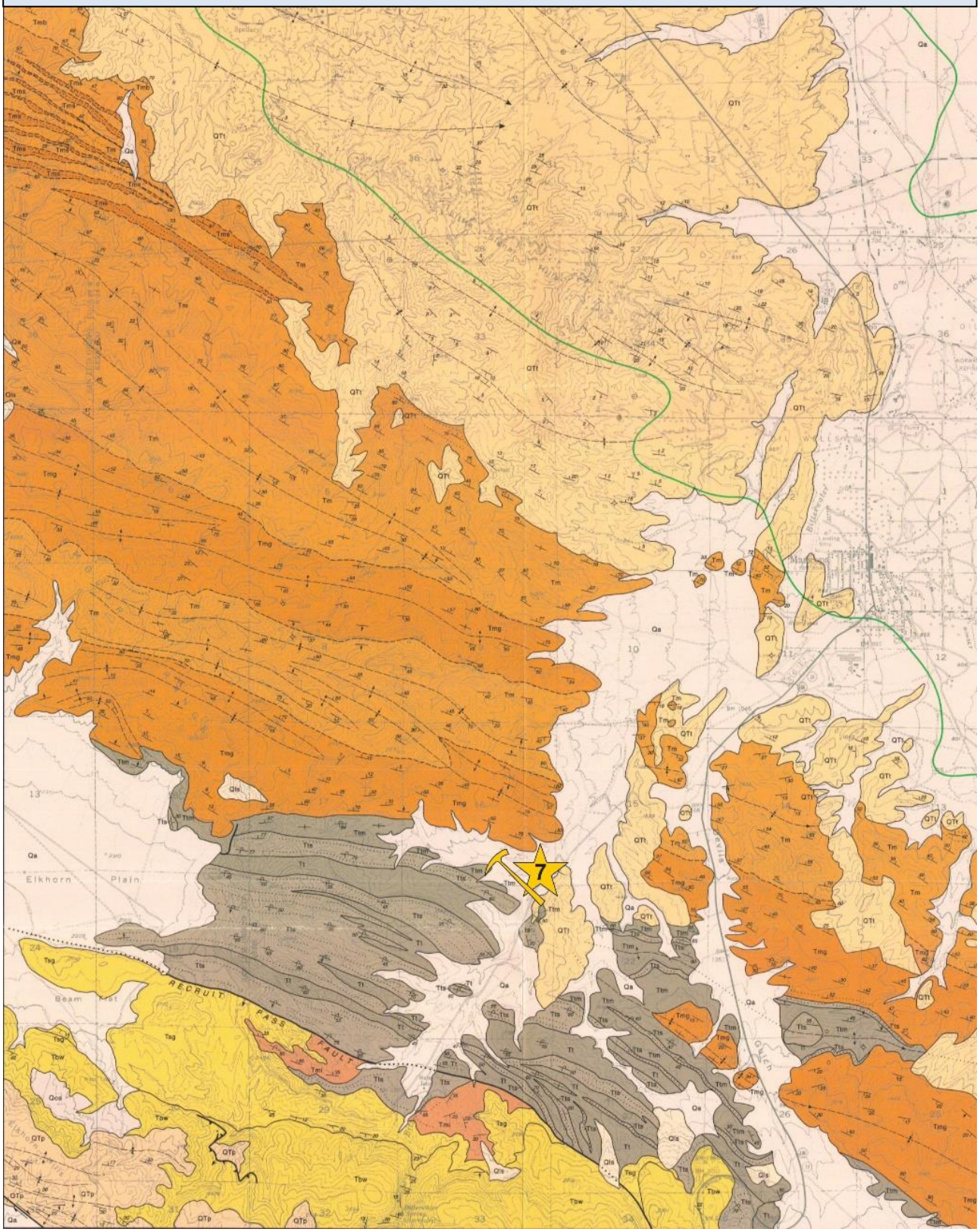
- Surface structure of the southern Temblor Range (Figure 48).

- Overturned section of Temblor Formation: is it overturned? What do the stratigraphic-up indicators show and detailed mapping of marker beds in the Temblor Formation (Figure 49)?

- If the Temblor Formation is not overturned and stratigraphic-up is to the southwest how does this alter the surface mapping (Bitterwater thrust), and what are the possible structural interpretations at depth (Figures 50 & 51)?

- The Recruit Pass fault and structure of the west flank of the Temblor Range (Figures 48 & 49).

Figure 48, Dibblee map of Maricopa and Pentland (Dibbee, 2005d).



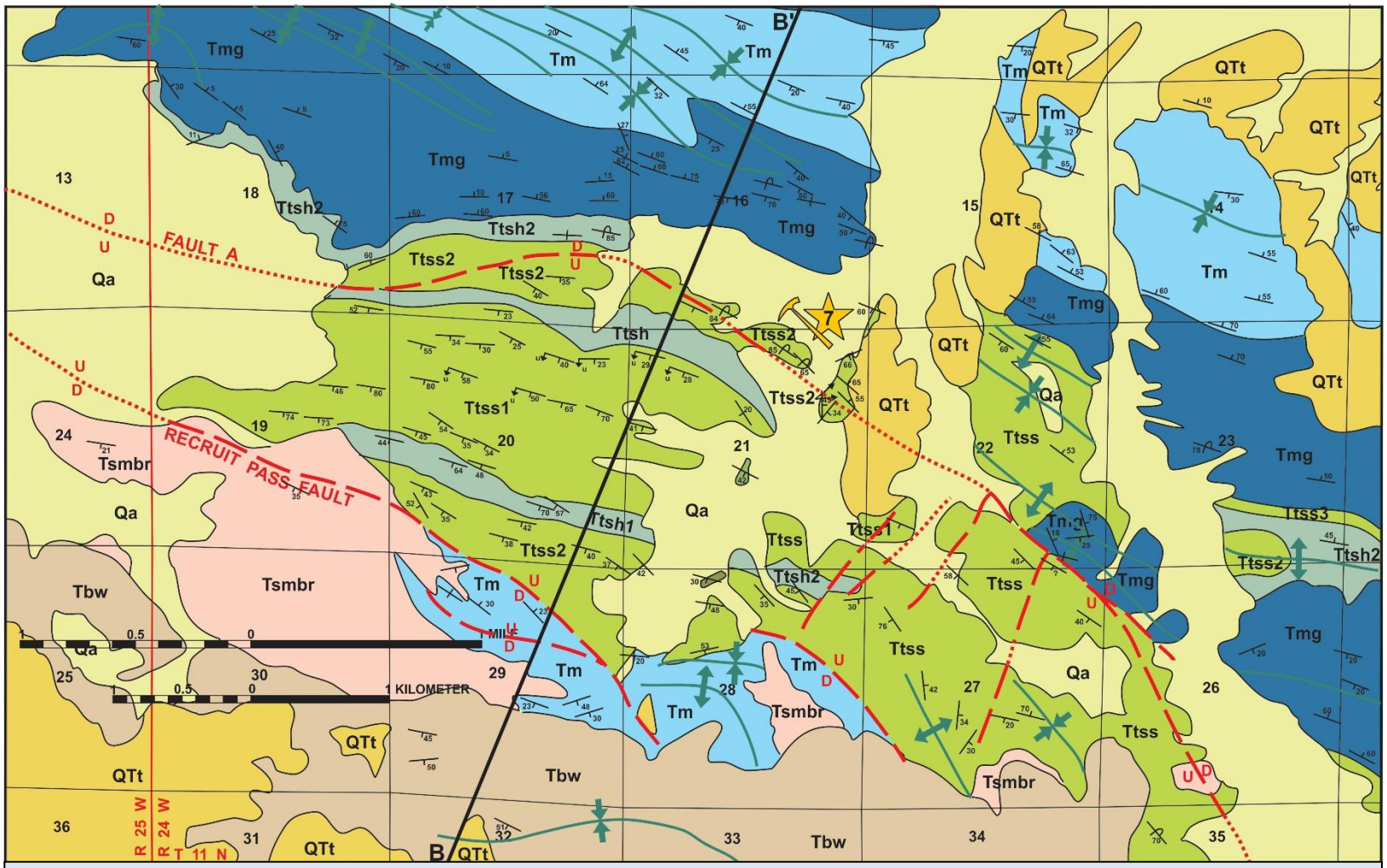


Figure 49, Surface mapping by Thom Davis along Bitterwater Creek (S/2 Maricopa 7.5' quad). Sedimentary features such as flame structures and graded bedding show the thick Temblor Formation section is right-side-up which requires a significant fault at the base of the section. Compare to Dibblee's mapping shown in Figure 48.

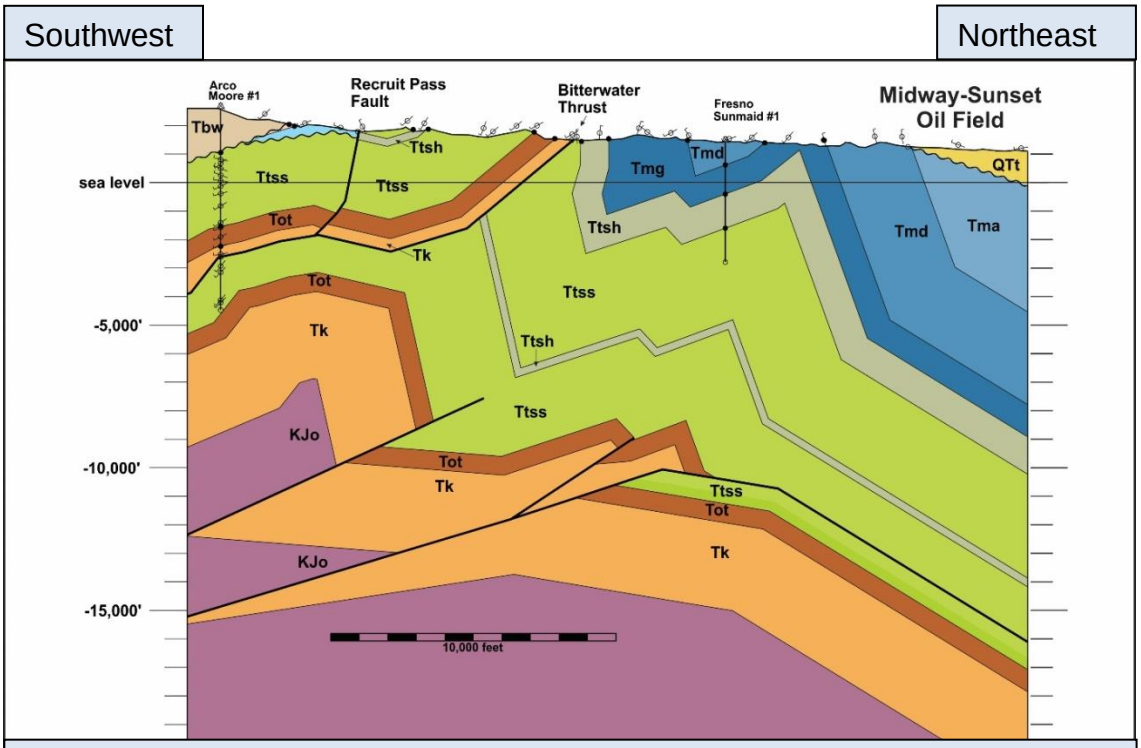


Figure 50, possible cross section interpretation along line B-B'. The Temblor Formation section to the left of the Bitterwater thrust is shown as right-side up.

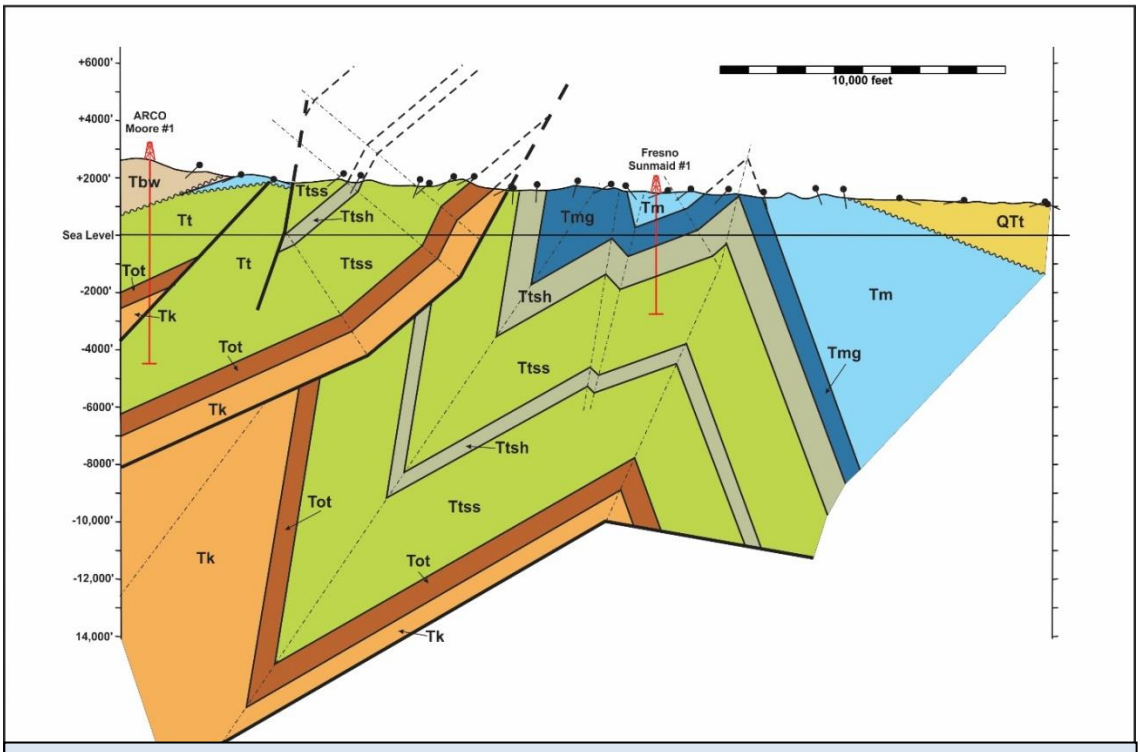


Figure 51, another possible cross section interpretation along line B-B'.

Stop 8, Lower San Emigdio Canyon (Figure 52), the Wind Wolves Preserve, and deformed southern margin of the San Joaquin basin-optional (34.994669°, -119.184650°).

The San Emigdio Mountains consist of a series of east-west trending folds and south-dipping thrust faults belonging to the Pleito thrust system (PTS), and folding and thrusting during the Pliocene and Quaternary has deformed a thick sequence of Eocene through Quaternary strata and the underlying crystalline basement. Recent uplift of the east-west trending San Emigdio Mountains across the northwest trending depositional strike of the San Joaquin basin provide a unique, natural cross section of a basin from nonmarine deposits in the east to deep marine deposits in the west. Abundant surface exposures and well data provide mapping control of the stratigraphic trends and reveal fault piercing points in the hanging wall and footwall of the Pleito thrust ("sensu stricto") that indicate little or no lateral displacement despite the nearby San Andreas fault.

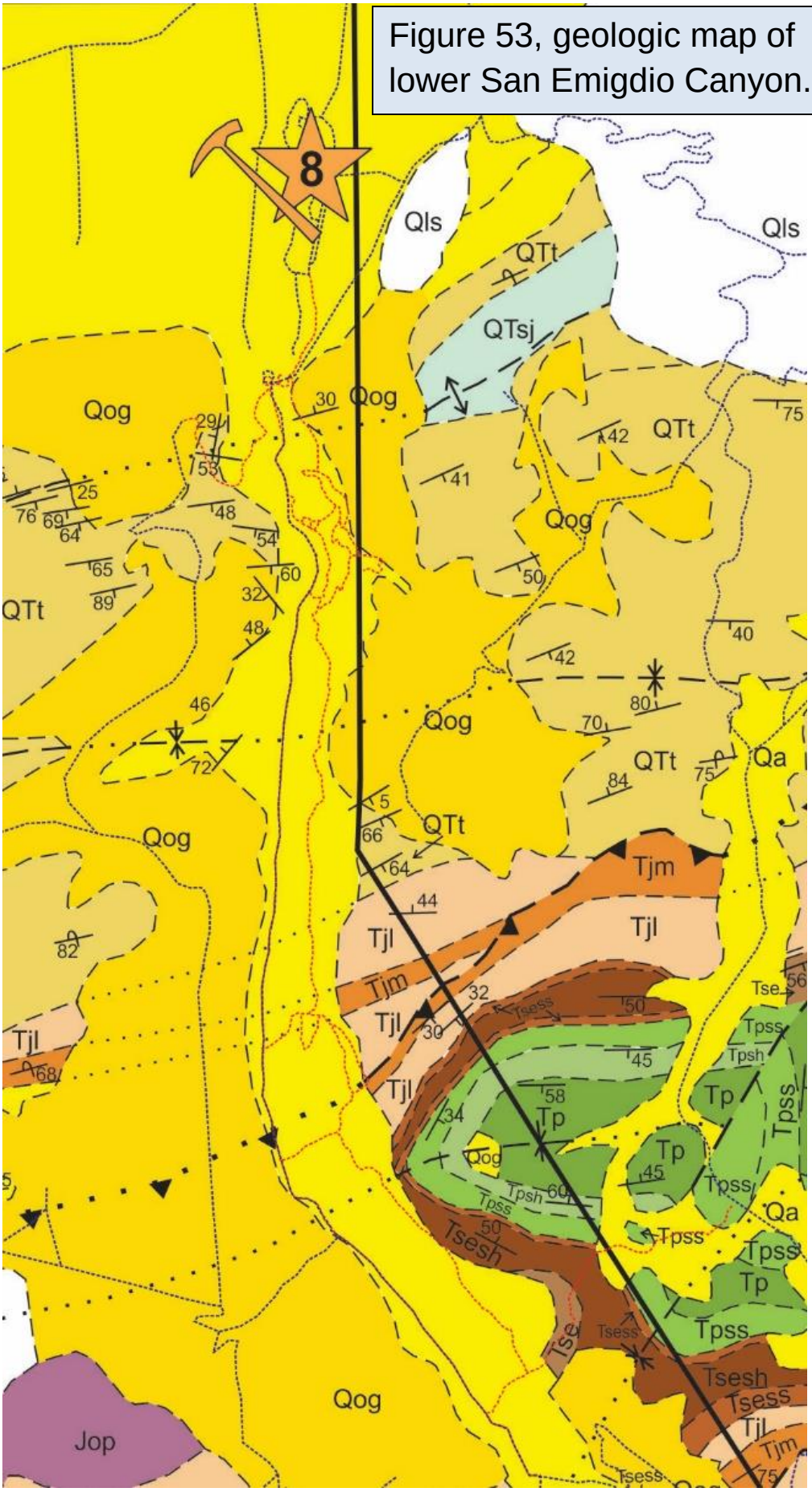
The rocks of the San Emigdio Mountains can be grouped into four packages: 1) In the high country are Mesozoic granitic rocks that are the southwestern extension of the southern Sierra Nevada that include older metamorphic pods of gneiss, schist, and marble. Within the granitic mass is a narrow tectonic window of Rand Schist (Pelona Schist equivalent) situated below a mylonitic fault zone. To the northwest of the granitic rocks are an ultramafic igneous body related to the Coast Range ophiolite sequence. 2) Eocene and lower Oligocene marine shale, siltstone, and sandstone of the Tejon, San Emgidio, and Pleito Formations. 3) Upper Oligocene and Miocene marine shale, siltstone, and sandstone of the Temblor, Monterey (including Reef Ridge), and Santa Margarita Formations. 4) Uppermost Miocene, Pliocene, and Quaternary shallow marine, brackish-water, and nonmarine shale, siltstone, sandstone and conglomerate of the Etchegoin, San Joaquin, and Tulare Formations (the name Chanac is not generally used in surface mapping here). These rock packages are separated by unconformities that resulted from tectonic events (Figures 54 & 57).

Present and discuss:

- Wind Wolves Preserve.
- Geology of lower San Emigdio Canyon (Figures 53 & 54).
- Deformed probable Riverbank age terrace deposits (Qog)(Figure 55).
- Transect along San Emigdio Canyon (cross section C-C'): Qog/QTt unconformity, San Emigdio anticline and syncline, Pleito thrust system (PTS) and Salt Creek-Harris Ranch splay.

Figure 52, lower San Emigdio Canyon with extensive late Pleistocene terrace deposits (probable Riverbank Formation). View southward towards San Emigdio Mountains, and in the far background the snow-covered east ridge of Mount Pinos.

Figure 53, geologic map of lower San Emigdio Canyon.



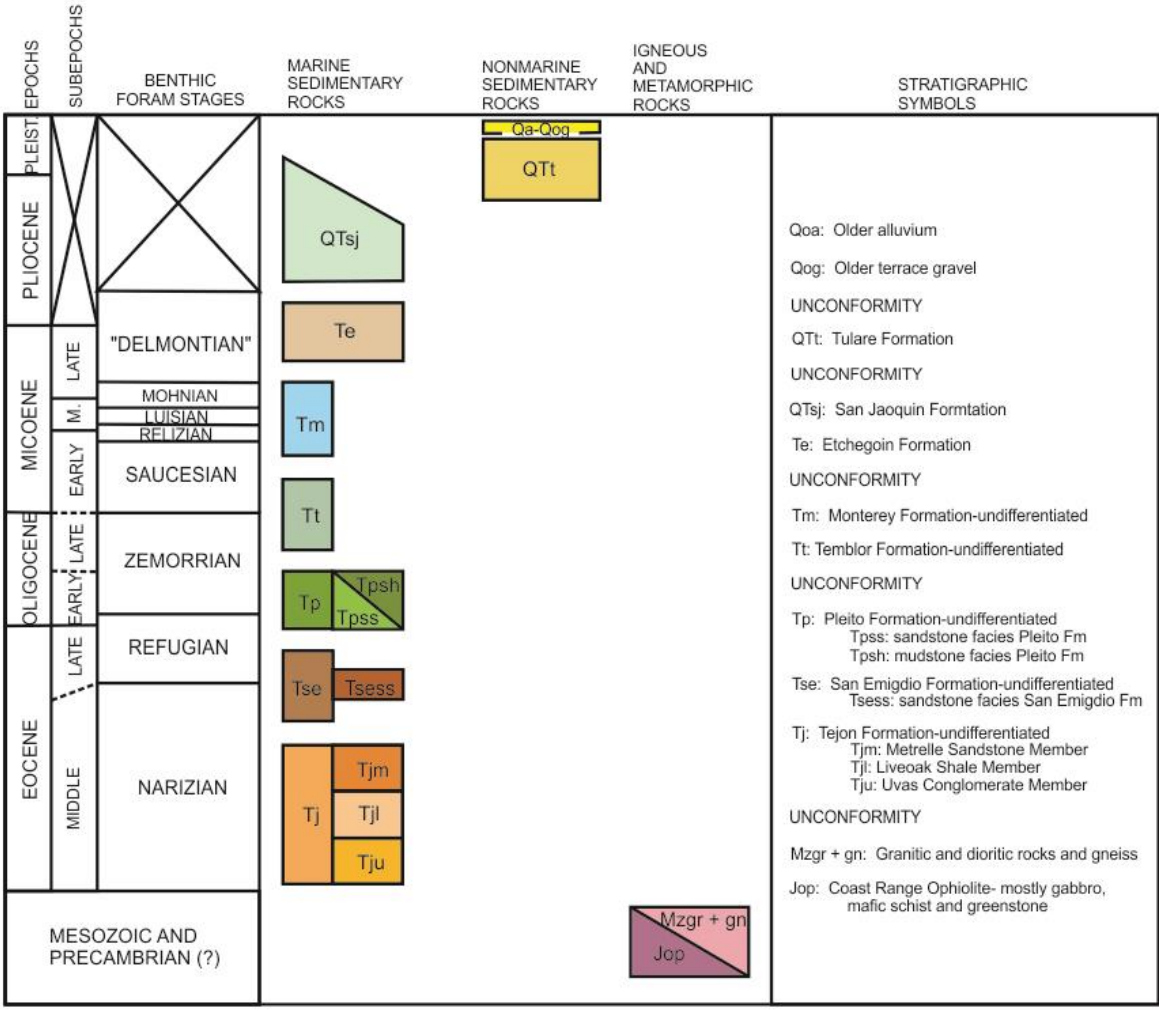


Figure 54, map explanation for Figure 53; note unconformities separating rock packages.

Figure 55, tilted terrace deposits (Riverbank? age) at the San Emigdio Mountain front, lower San Emigdio Canyon.

Figure 56, unconformity separating terrace deposits and Tulare Formation.

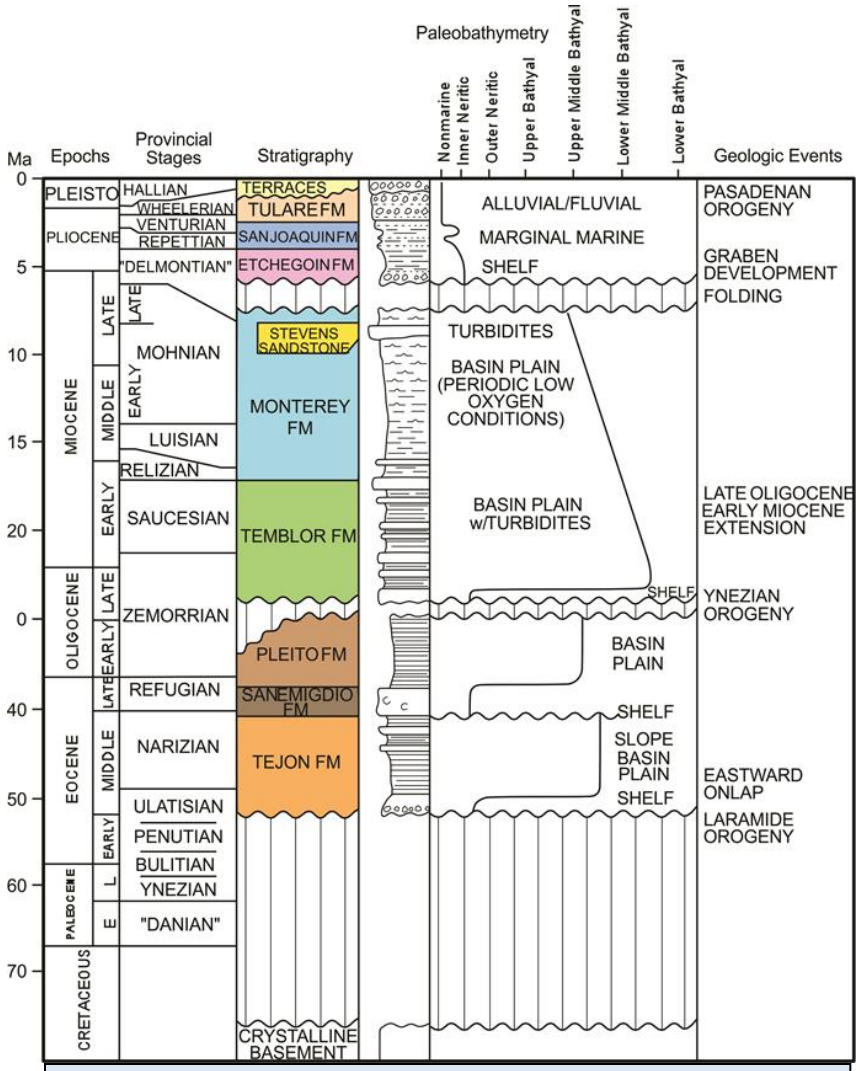
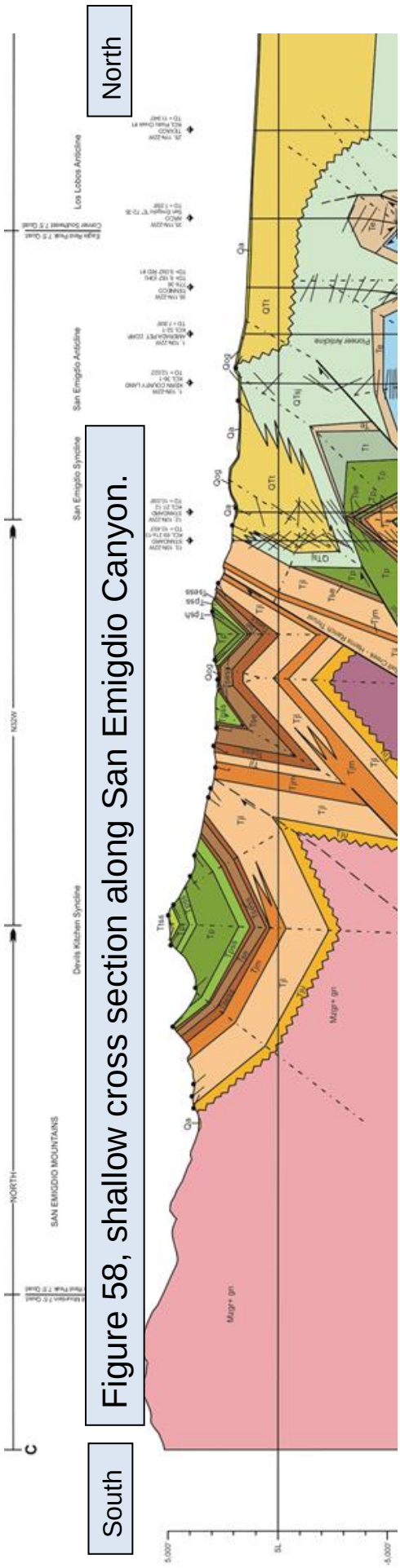


Figure 57, Generalized column for the southern San Joaquin basin and the San Emigdio Mountains near San Emigdio Canyon showing ages, stratigraphic nomenclature, rock column, water depth, and tectonic events (Martin Lagoe, unpublished). Faults, unconformities, syn-orogenic deposits, and igneous flows and intrusions in the San Emigdio Mountains document a number of tectonic events found throughout southern and central coastal California: Cretaceous emplacement of oceanic crust against granitic rocks of the southern Sierra Nevada belt, Cretaceous to early Cenozoic emplacement of the granitic rocks over the Rand schist, Cretaceous to early Eocene uplift and exposure of the crystalline basement, late Eocene uplift and shoaling, middle Oligocene folding and uplift (Ynezian orogeny of Dibblee), late Oligocene to early Miocene extension and volcanism, late Miocene folding coeval with late Miocene to early Pliocene normal faulting and very deep basin development north of the White Wolf fault, and development of a late Pliocene and Quaternary fold and thrust belt that is seismically active (Pasadenan orogeny).



Stop 9, Upper San Emigdio Canyon and Devils Kitchen Syncline (Wind Wolves preserve) and deformed southern margin of the San Joaquin basin (34.911765, -119.159975).

We will take a short hike for a better view of the syncline and the Oligocene and Eocene marine strata exposed along the canyon wall (Tejon, San Emigdio, and Pleito Formations).

Present and discuss:

- Hanging wall of Salt Creek-Harris Ranch splay of the PTS, Devil's Kitchen syncline, and close proximity of the San Andreas fault.

- Tejon Formation: The middle Eocene Tejon Formation is in depositional contact with crystalline basement, up to 4600 ft interbedded marine mudstone, sandstone, and conglomerate. Fossils indicate the unconformable base becomes younger to the east (transgressive onlap). The Metrella sandstone member is neritic, thickens rapidly westward, and thins abruptly into turbidite sandstone near San Emigdio Creek. These relationships occur across the Pleito thrust fault and show there has been little, or no, lateral displacement across the fault.

- San Emigdio Formation: The upper Eocene San Emigdio Formation, possibly as thick as 4300 ft, lies conformably above the Tejon Formation west of San Emigdio Canyon, but to the east appears to onlap the upper Tejon contact before grading into the nonmarine Tecuya Fm. The middle San Emigdio Formation consists of deltaic sandstones which prograded westward over the Tejon Formation. Higher in the San Emigdio Formation are bathyal turbidites and mudstones which reflect a rise in relative sea-level and transgression to the east. The upper San Emigdio consists of shallow marine sandstones which show renewed westward progradation of the shelf environments.

- Pleito Formation: The uppermost Eocene to lower Oligocene Pleito Formation is up to 3000 ft thick, and overlies the San Emigdio Formation and grades eastward into the lower Tecuya Formation. In the type area near San Emigdio Canyon the formation consists mainly of marine sandstone with sub-ordinate conglomerate and sandy mudstone. Facies within the Pleito reflect additional transgression and regression of the San Joaquin basin margin. The lower Pleito consists primarily of shallow marine sandstones in the San Emigdio Canyon area, but is overlain by a succession of facies possibly indicative of a clastic ramp (DeCelles, 1986). The middle Pleito grades from shallow marine and strandline deposits in the east to bathyal? mudstones and muddy sandstones in the area of San Emigdio Canyon. West of San Emigdio Canyon and north into the subsurface the Pleito Formation consists primarily of bathyal mudstone. The uppermost Pleito

Formation reflects renewed eastward progradation of shelf environments. DeCelles (1986) documents evidence for major seismic events in the upper part of the lower Pleito Formation. These prominent mass-flow, rock fall, and soft-sediment-deformed units, termed "seismites" DeCelles seem to reflect a major tectonic event that produced major changes in stratigraphic packaging between the middle Pleito Formation and other units.

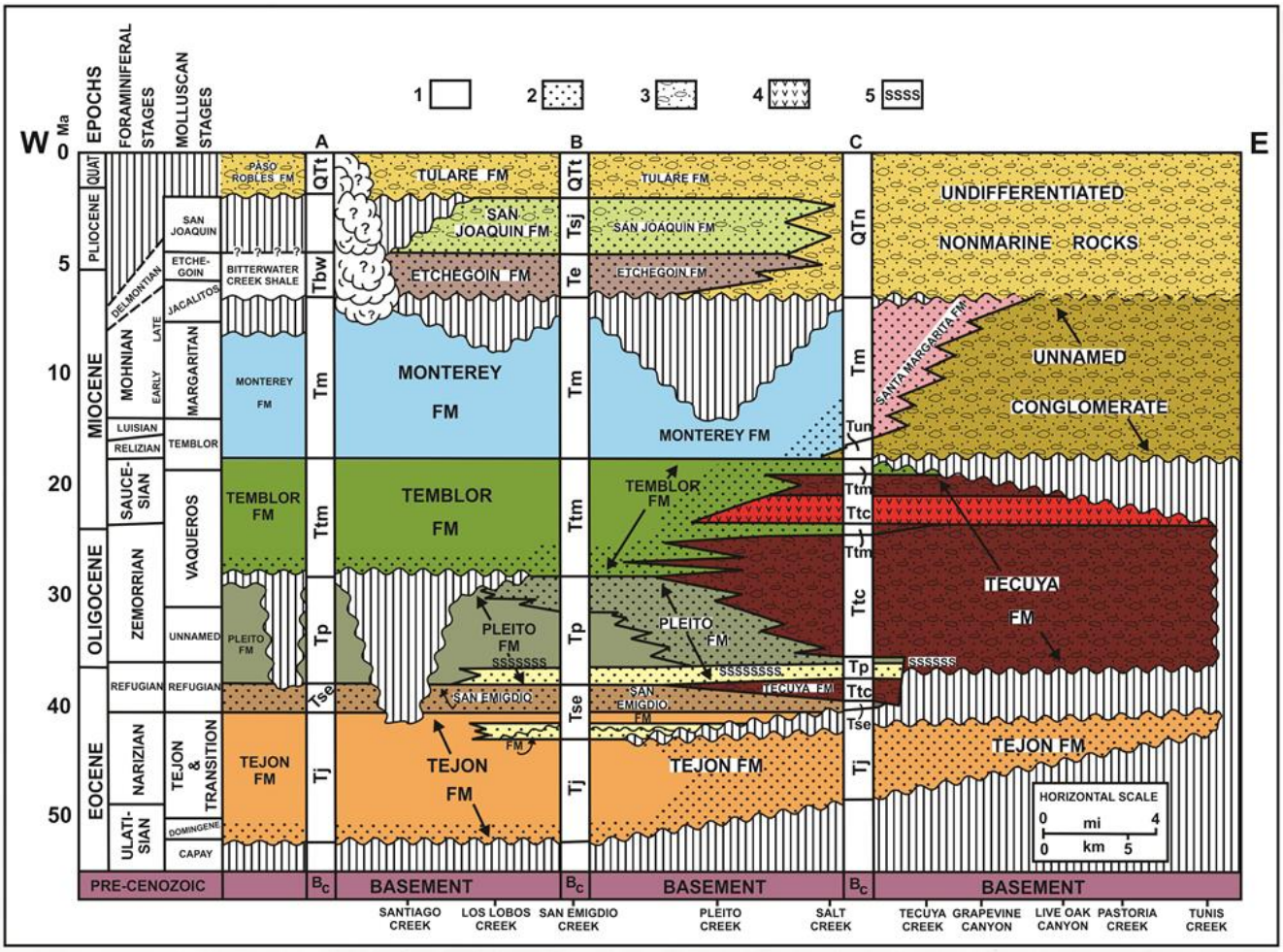
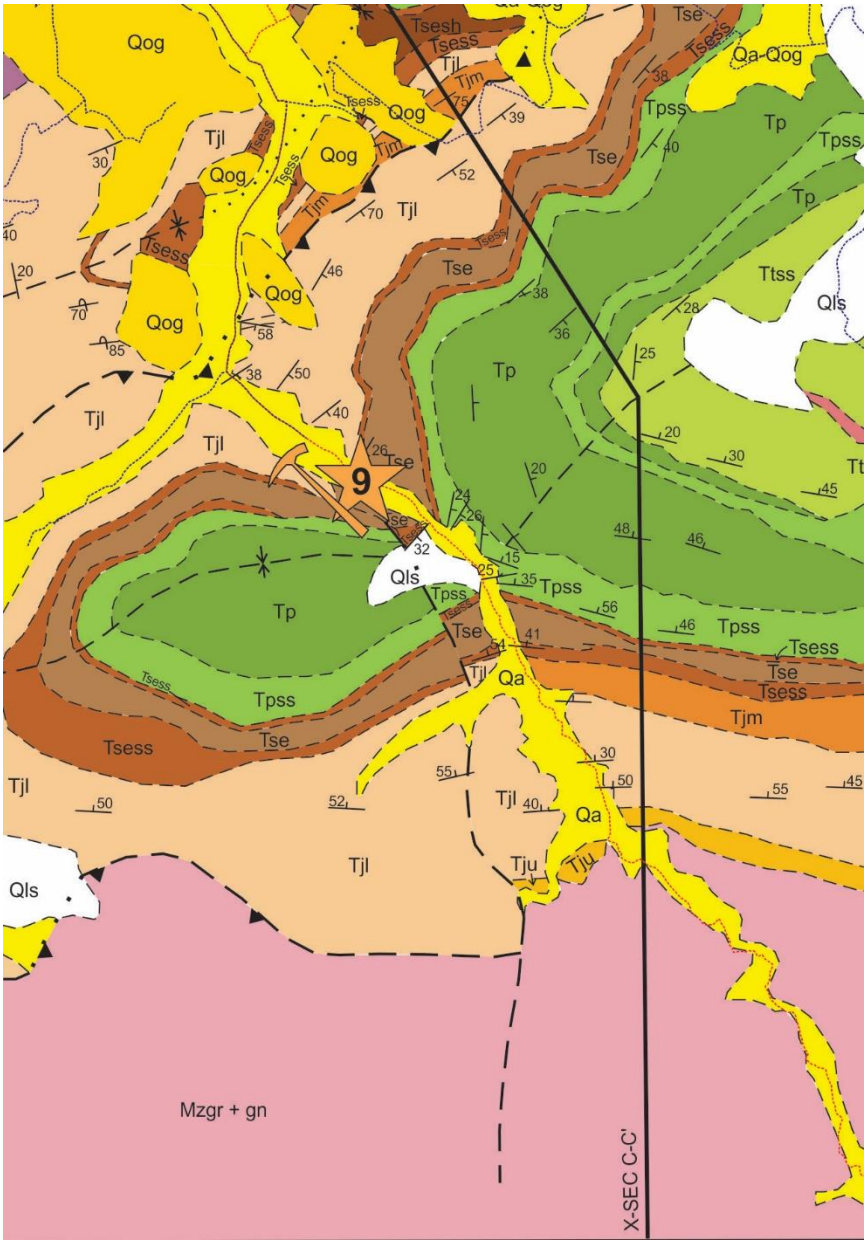


Figure 59, An east-west stratigraphic profile of Cenozoic rocks of the San Emigdio Mountains (Lagoe, 1987). The orientation of the San Emigdio Mountains offer a unique stratigraphic cross section of the southern San Joaquin basin from nonmarine deposits on the east to deep marine deposits on the west. Relationships shown in profile are generalized from several east-west oriented transects. Lithologic symbols shown at top of profile: 1-bathyal sandstone and mudstone, 2-neritic sandstone and mudstone, 3-nonmarine rocks, 4-volcanic rocks, 5-“seismites” of DeCelles (1986), and locations of stratigraphic sections shown in Lagoe (1987).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Stop 10, Pleito Creek oil field and Pleito thrust (34.993424°, -119.093305°).

Stop 10 is between Pleito Creek and the Pleito Creek oil field, and is a good location to observe and discuss the structure along the front of the San Emigdio Range and the uplifted southern end of the San Joaquin basin. The area is being actively deformed by the south-dipping Pleito thrust system (PTS) that includes the Wheeler Ridge, Pleito, Salt Creek, and Harris Ranch thrusts. Deep cross sections show the complex trapping style of the oil field and the influence of the pre-convergent White Wolf fault.

Present and discuss:

- Pleito Creek oil field (Figures 62, 63, & 64).
- Pleito thrust system (PTS) (Figures 65 & 66).
- San Emigdio Mountains fold and thrust belt and the PTS: map (Figure 65), isopach map across PTS (Figure 66), cross section and restoration (Figure 67).
- White Wolf fault

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Figure 62, Pleito Creek oil field.

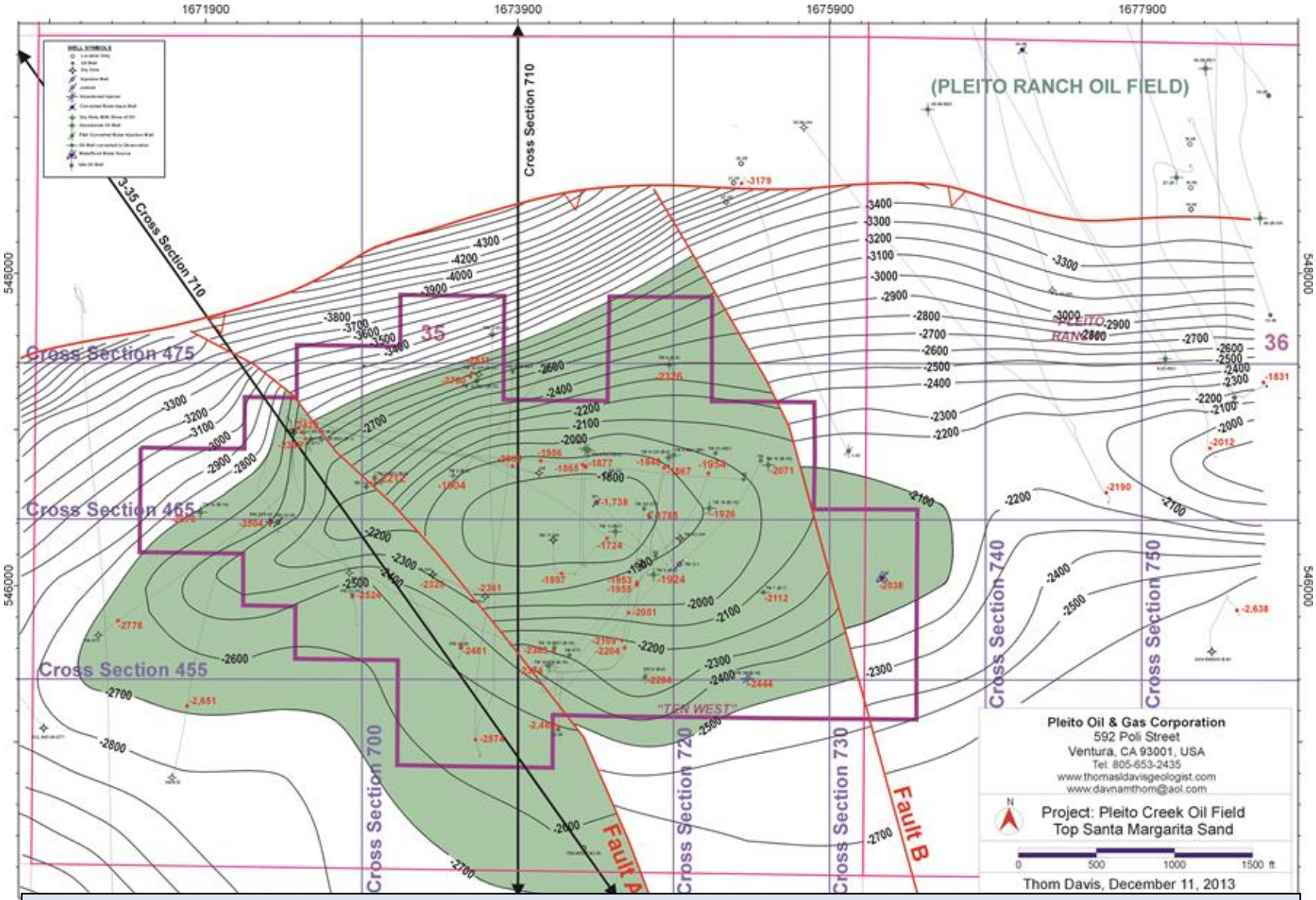

Figure 63, Structure contour map Pleito Creek oil field. Contours on top of Santa Margarita sandstone reservoir. Cross section 710 is shown in Figure 64.

South

North

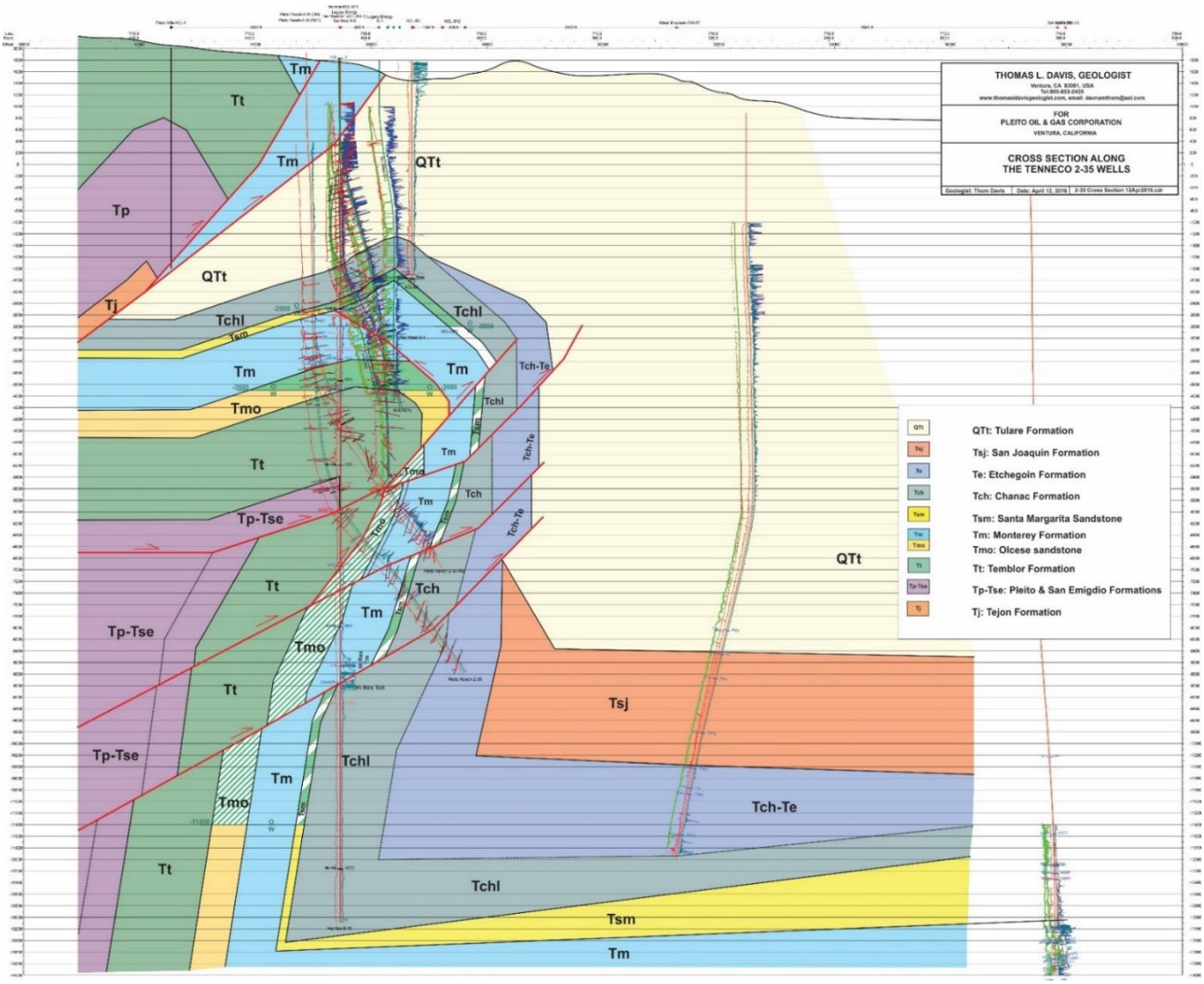

Figure 64, cross section 710 through the Pleito Creek oil field. Note the rotated White Wolf fault, dramatic thinning of the post-Santa Margarita sandstone section on to the growing structure, and the great depth of the Monterey oil source rock. Location of section shown in Figure 63.

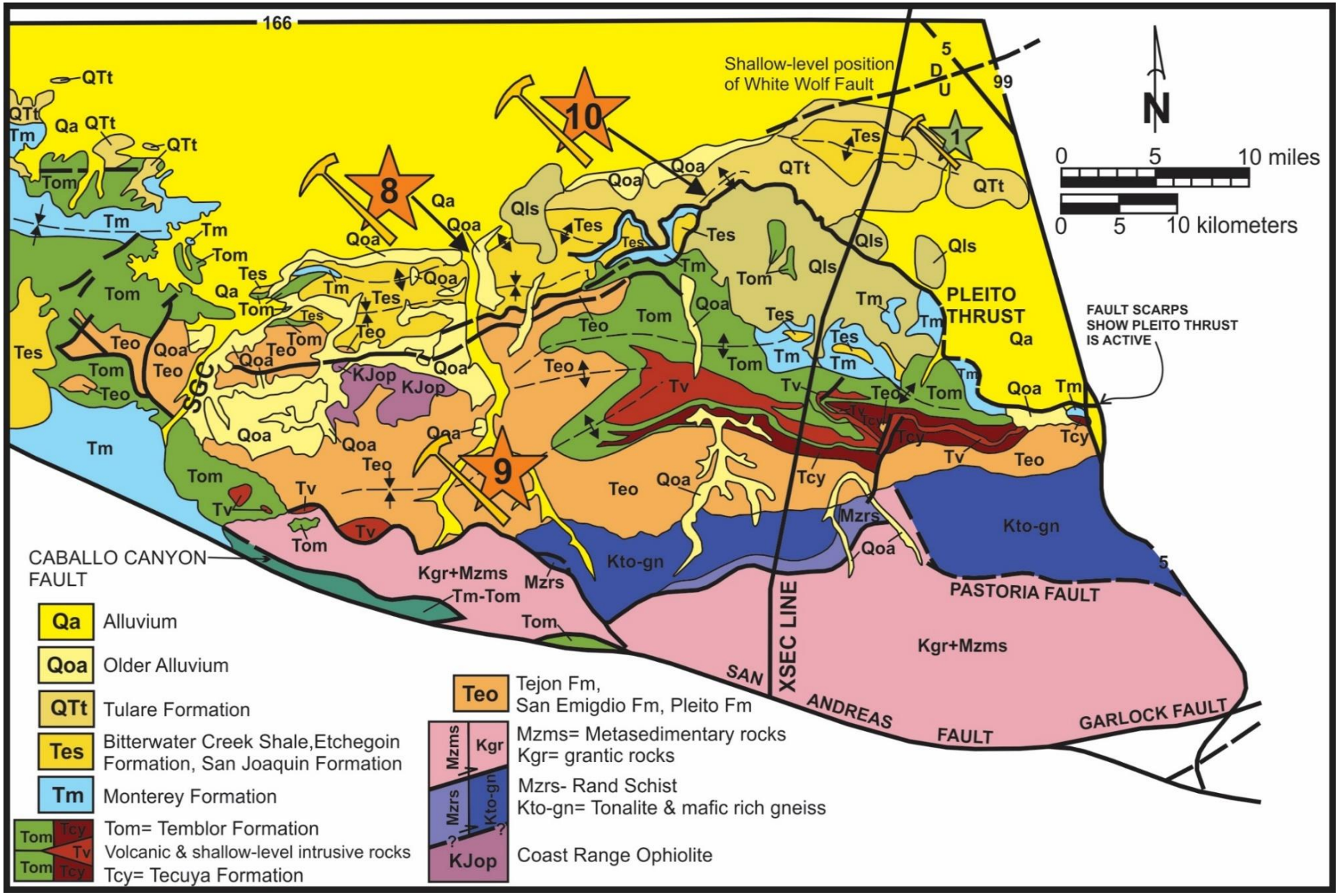

Figure 65, caption on next page.

Figure 65, Geologic map of the San Emigdio Mountains that comprise a fold and thrust belt located at the juncture of the southern San Joaquin basin and the western Transverse Ranges and adjacent to the western big bend of the San Andreas fault. East-west trending folds and faults of the south-dipping Pleito thrust system deform Eocene to Quaternary strata and Mesozoic age crystalline rocks. Mapping modified from Dibblee, 2005e,f; Dibblee and Nilsen, 1973; and unpublished mapping by T.Davis.

Temblor Formation: The Oligocene to lower Miocene Temblor Formation, up to 5500 ft thick, contains interbedded marine sandstone and mudstone which grades eastward into the upper part of the Tecuya Formation. The formation contains predominantly shallow marine sandstone in its easternmost exposures but consists of progressively more bathyal sandstone and mudstone west of San Emigdio Canyon. In many places the Temblor Formation contains a basal unit of shallow marine sandstone and/or conglomerate which rests unconformably on underlying units. Near Brush Mountain the Temblor has truncated the Pleito, San Emigdio, and Tejon Formations to rest directly on the crystalline basement.

San Emigdio Mountains fold and thrust belt: The lack of lateral offset along PTS shows the positive flower structure model with oblique-slip convergent faults cannot account for the folding and thrusting, and uplift of the San Emigdio Mountains (Davis, 1986). Similar isopach mapping that integrates surface and subsurface sections over the eastern portion of the Pleito thrust shows no evidence for lateral displacement (Nilsen, 1973). Lack of strike-slip on the PTS is consistent with the surface strands of the fault system terminating to the west and east of the San Emigdio Mountains (Dibblee and Nilsen, 1973). This evidence plus the east-west trend of the fold axes and thrust fault indicate north-south directed contraction, allows for north-south cross sections to be retrodeformed in their 2D plane, and dismisses the criticism that cross sections adjacent to the San Andreas fault cannot be retrodeformed due to strike-slip in and out of the cross section plane. Focal mechanisms of recent earthquakes show the present day compressive stress is also north-south directed and near horizontal (Davis, 1986). Dibblee (1986) provides a good summary of the geology of the San Emigdio Mountains.

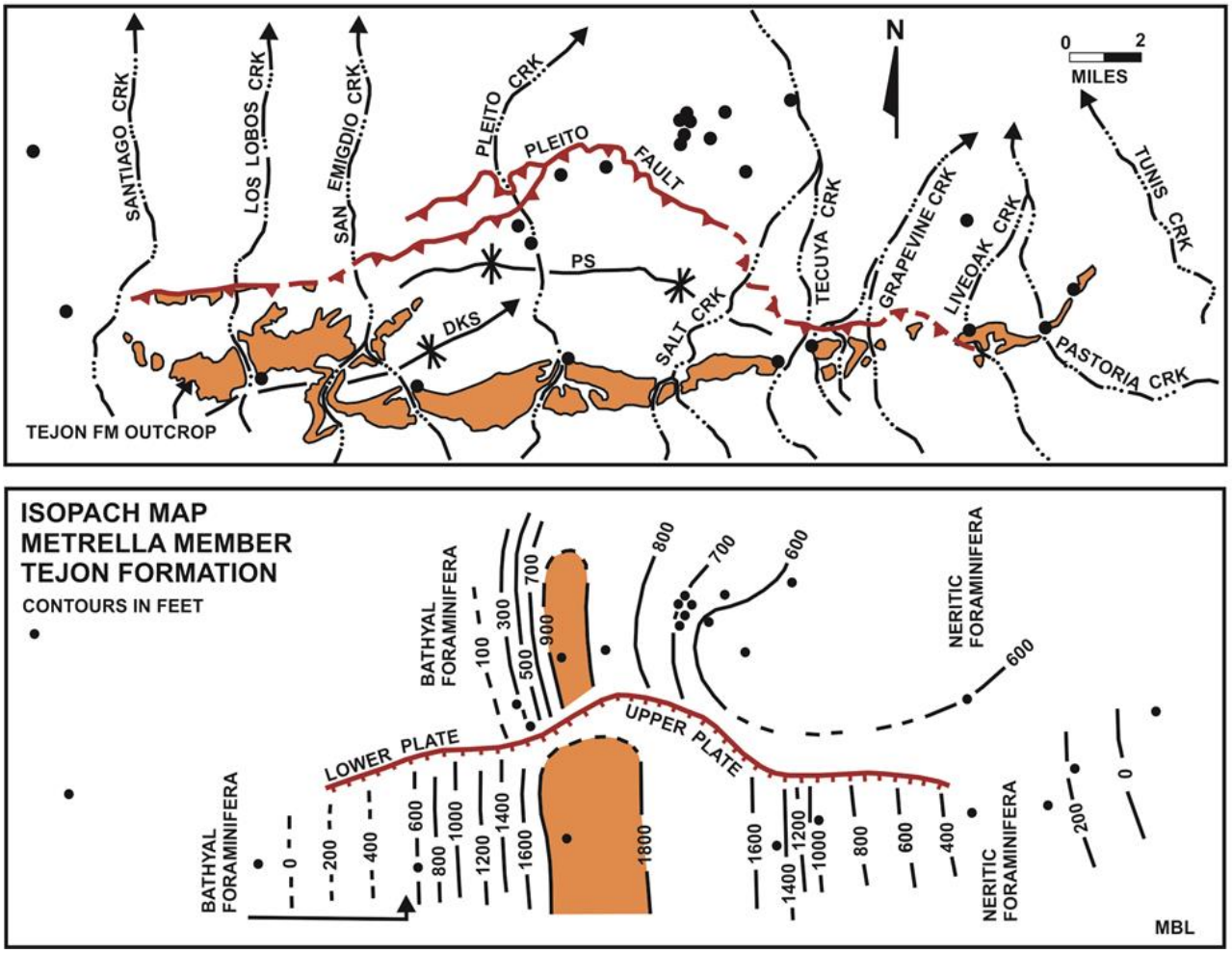

Figure 66, isopach map of the Metrella Sandstone Member of the Tejon Formation showing depositional trends and biofacies in the upper and lower plate of the principal strand of the Pleito thrust (Lagoe, 1987); contours are in feet. The alignment across the thrust fault of the trend of thickness variations and a small depocenter (orange-colored fill), plus deep and shallow marine biofacies indicate little or no strike-slip movement, despite the close proximity of the San Andreas fault.

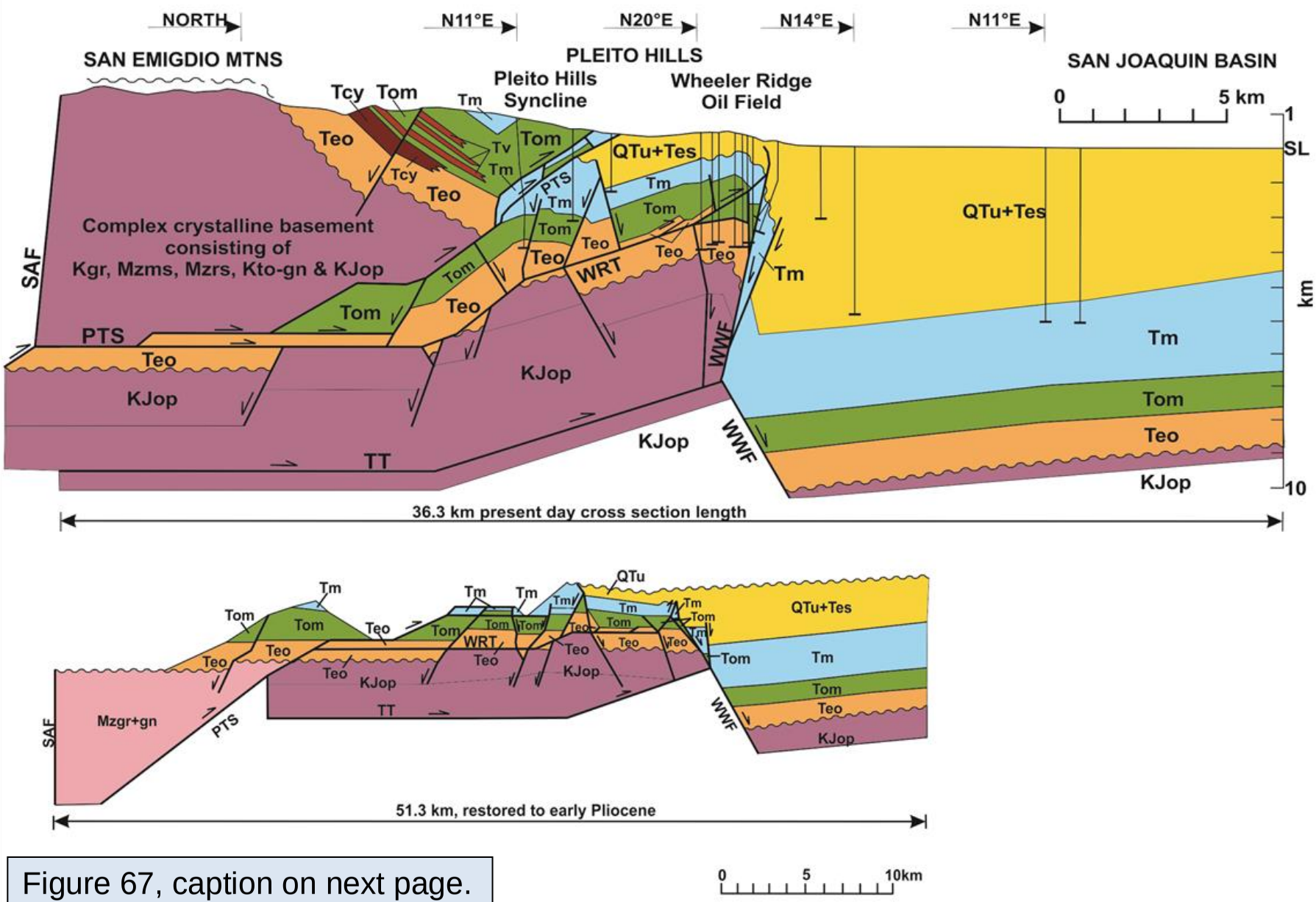

Figure 67, caption on next page.

Top figure: Cross section across the San Emigdio Mountains and southern San Joaquin basin showing fold and thrust interpretation of late Pliocene and Quaternary age north directed convergence. The cross section integrates surface geology and well data and shows the thrust faults of the Pleito thrust system (PTS) flatten with depth, and ramps in their thrust surfaces make fault-bend and fault-propagation folds. The long, hanging-wall thrust flats at the base of the Temblor Fm (Tom) and within the Eocene formations (Teo) indicate the PTS intersects the San Andreas fault at a high angle, and show the San Andreas and PTS merge into a south-dipping strike-slip fault also shown in Namson and Davis (1988) and Fuis, et al. (2013). The White Wolf fault is interpreted to be an older normal fault that formed the edge of the Tejon depocenter during the Miocene and Pliocene. A normal fault interpretation is preferred as both side of White Wolf fault were subsiding with respect to sea-level, with the north side subsiding at faster rate as shown by the growth strata. The shallow portion of the White Wolf fault was subsequently folded into a reverse fault geometry by growth of a fault-propagation fold associated with late Pliocene and Quaternary movement on the deeper Tejon thrust (Tt).

Bottom figure: Line-length restoration of late Pliocene through Quaternary compressive structures along the cross section. Comparison between deformed and restored sections yields 19.2 km of convergence since late Pliocene time (3 Ma) or 6.4 mm/yr. Restoration shows the thrust belt has deformed several small horsts and grabens and the White Wolf normal fault.

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Structural wedge with a hydrocarbon prospective triangle zone,

west-side of the San Joaquin Basin (WS), California: implications for untested large traps

August 6, 2015, Thom Davis, Geologist, Ventura, CA

This article presents a structural model and conventional play concept for a portion of the west-side of the San Joaquin basin (WS) that, if valid, adds significantly to its hydrocarbon potential by providing additional area containing untested large traps with known reservoir and source rock units. The WS of the San Joaquin basin, California is a folded and faulted belt that has produced and proven reserves totaling 11.7 BBO as of 2005.[1] The WS is located between the San Andreas fault and the relatively undeformed central trough of the San Joaquin basin and includes the Temblor Range and the southern Diablo Range (Fig. 1). Despite the great number of exploration wells along the WS the potential for additional conventional oil discoveries is likely due to the rich source rock units such as the Monterey, Tumey, and Kreyenhagen shale units, and the structural and stratigraphic complexity of the area that offer a variety of trapping situations assisted by an active and very prolific petroleum system.[2] Structural complexity and other seismic acquisition issues prevent a clear image of much of the WS, but ironically the poor imaging can be appreciated as an exploratory positive that has allowed traps, even large ones, to remain untested. The conventional structural play in the San Joaquin, despite its years of success, has had less recent interest due to the geologic perception that little prospective "running room" remains to hold moderate to large traps, and the difficulty of mapping such prospects, both dependent on using a realistic structural model to overcome the poor seismic imaging. Structural studies show a fold and thrust belt structural style involving a northeast-directed wedge model best explains the late Cenozoic structural geometry and kinematic evolution of the WS than previous models.[3 4 5]

Much of the recent exploration and renewed interest in the San Joaquin basin, and in other oil basins of California, has focused on the unconventional shale plays especially in the Monterey Formation and the results to date have been disappointing; and recent drilling in the deeper portions of the San Joaquin basin where the source units are thermally mature has not overcome the disappointing results.[6 7 8] It is fair to say that significant questions remain about the commercial viability of the Monterey Formation as a resource play, and probably the other shale units as well. The unconventional shale play's lack of success does not diminish the importance of these rich source rocks units and their prolific petroleum systems for other play types, and shows that traps containing migrated hydrocarbons (the conventional play) have been the most successful play for the basin, and for now provide the lowest-risk and least expensive untested prospects. One such newer conventional play is the result of overthrusting associated with the late Cenozoic age fold and thrust structural style common to many of California's oil basins. Overthrusting increases the prospective "running room" by repeating proven reservoir and source rock units, increases source rock burial and hydrocarbon maturity, and increases the number of untested subthrust anticlines and other concealed structural traps available to capture the migrated hydrocarbons.[9 10]

Wedge model interpretation of the WS of the San Joaquin basin

Geologists exploring in highly deformed areas such as the WS of the San Joaquin basin commonly rely on structural models to map, assist poor seismic reflection imaging, and develop prospects. The convergent wrench fault model has been the dominate structural model for the WS for the last half century to explain the large oil trapping folds and their

relationship to the nearby San Andreas transform fault. [11 12] Convergent wrench faulting is characterized by distinctive structural elements such as oblique-slip, reverse-faults that steepen with depth into a master strike-slip fault, positive flower structures, and the footwall area available for exploration is limited (Fig. 2A). A more realistic and data-based model of the structural style of the WS, and other areas of southern and central California with late Cenozoic convergent deformation, is a strain-partitioned transpressional belt characterized by pure strike-slip along the San Andreas fault, and small fold and thrust belts subject to pure shear to either side of the San Andreas fault.[3 13 14 15] In addition, the fold and thrust belt interpretation provide a more optimistic view of California's future petroleum potential as the larger thrust sheets do not steepen with depth, but flatten with depth, and consequently conceal extensive footwall area with untested subbasins and structures.

Most fold and thrust belts have a wedge-shaped, cross-sectional profile with a taper thinning towards the undeformed basin as the does the WS of the San Joaquin basin (Fig. 2B). The wedge grows basinward by internal thrust faulting and folding, and deformational progression is akin to the material being moved by a bulldozer or snowplow.[16] Thrust faults within the wedge need not have the same direction of movement (vergence), and the resulting geometry is commonly characterized by a master backthrust (roof thrust) and a sole thrust with opposing vergence that creates a distinctive triangle zone (Fig. 2B). At the south end of the Diablo Range the northeast-dipping Antelope Valley thrust presents an excellent surface exposure of a backthrust (Fig. 3) located along the top of the basinward-directed wedge making the WS. Mapping by the author shows that other large back thrusts are present along other portions of the WS; for instance, the Temblor Creek thrust in the Temblor Range (Fig. 1), and the Waltham Canyon fault west of Coalinga anticline in the Diablo Range.[3]

The wedge model was first proposed by in 1988 to explain the structural development of the northern portion of the WS, and the 1983 Coalinga earthquake (Mw=6.5) and its relationship to the Coalinga anticline (Fig. 1).[3 4] In the Coalinga area the wedge creates a triangle-zone geometry with a subthrust anticline(s) that involve mostly Cretaceous- and Jurassic-age rocks with little oil potential. In this study the wedge model is applied to the Antelope uplift portion of the WS that is present between the northern Temblor Range and North Belridge oil field (Fig. 4). At the Antelope uplift the wedge involves Tertiary rocks that are known source and reservoir units making the Antelope uplift more prospective than the Coalinga area.

Structure of the Antelope uplift

The Antelope uplift is an area of lower Tertiary strata exposed at the surface or present in the shallow subsurface as shown by numerous shallow oil and gas wells and seismic reflection surveys (Fig. 4). To the author's knowledge the structural geometry and origin of the uplift has never been questioned despite its great size, structural relief, and dissimilarity to the nearby large oil-trapping anticlines. This article presents a regional cross section (Fig. 5A) that utilizes fault-ramp folding such as fault-bend and fault-propagation folds, and cross section balancing constraints to make an interpretation of the Antelope uplift and the WS.[17 18 19 20] The cross section interpretation, while not unique and untested by drilling is valid as it can be retrodeformed (Fig. 5B), and shows the possible structural geometry beneath the uplift and its untested hydrocarbon potential. There is no evidence of strike-slip faults intersecting the cross section line that lies east of the San Andreas fault, and that allows 2D restoration of the strata to their undeformed geometry in the direction of convergent strain (along the cross section line) as shown by fold axes and thrust faults. Restoration of the cross section and matching the hanging wall and footwall ramps and flats provide a test of the validity of the interpretation. The cross

section integrates several reprocessed 2D seismic lines, well data, and surface geology (Fig. 4). The broad crest of the uplift and its northern, eastern and southern limbs are shown by contouring the top of the Temblor Formation, and the west limb of the uplift is a regional syncline, cored with Monterey Formation, that lies along the foothills of the northern Temblor Range. Upper Tertiary and Quaternary strata are absent or thin across the Antelope uplift as a result of late Cenozoic folding and erosion, and the uplift lies within an earlier and broader uplifted block, i.e., the "Antelope Valley peninsula" whose Oligocene to early Miocene age history is recorded by non-deposition, erosion, and stratal onlap.[21]

Seismic Line B shows detail of the northeast-dipping limb of the Antelope uplift and its large amount of structural relief. Regional mapping of the limb show it is a part of a large structure that involves much of the upper crust, and is more important to the development of the WS than the small faults that cross the uplift's crest and toe. Line B also show that the folding and uplift involves strata as young as late Miocene, and folding and uplift occurred during latest Miocene and Pliocene time and before deposition of the relatively unfolded Quaternary age Tulare Formation. The northeast-dipping limb formed a deformational front that developed before the Quaternary age anticlines at Lost Hills, and North and South Belridge that have a different geometry and smaller size than the older Antelope uplift (Fig. 4 & 5A). The leading edge of the pre-Quaternary deformational front, which lies along the base of the limb, is interpreted to lie above the wedge tip (WT) as shown in the generalized model shown in Fig. 2B. The absence of significant pre-Quaternary deformation to the northeast of the uplift limits the possible fault-ramp fold and fault-slip configurations that could make the uplift, and in the cross section is interpreted to be the back-side of fault-bend fold developed in the hanging wall of a roof thrust that the here is called the Shale Hill thrust (SHT).

Line C crosses the northern Temblor Range where the surface geology is dominated by a northeast-dipping panel of strata of Cretaceous through Miocene age (Fig. 4). Seismic Line C reveals a large panel of southwest-dipping strata directly below the northeast surface dip (Fig. 7), and this abrupt change in dip is interpreted to be a large southwest-dipping convergent fault referred to as the Temblor Range thrust (TRT). The surface and shallow subsurface geology restrict the TRT to reaching the surface along the trough of the regional syncline that occur along the foothills of the Temblor Range. Similarly the northeast dipping SHT is restricted to reaching the surface along the synclinal trough, and the opposing thrusts form an untested triangle zone capped by Monterey Formation. Field examination of the "syncline" show its trough is complexly faulted with no bedding continuity between opposing limbs, and the trough is a likely a zone for TRT and SHT to "daylight" and juxtapose Monterey Formation originally deposited miles apart.

The western portion of Line E (Fig. 8) also shows the northeast-dipping panel of strata that dominates the northern Temblor Range, and southwest-dipping reflectors at depth are separated by the TRT. The line lies south of the portion of the Antelope uplift dominated by shallow depth, lower Tertiary strata (Fig. 4). Along the eastern portion of line E the surface and shallow subsurface geology consist of a thick section of folded and faulted Monterey Formation. The line reveals the triangle zone formed beneath the TRT and SHT and the opposing dips of large subthrust anticline. A nearby exploration well drilled in 1946 to nearly 11,000 ft and projected into the line reached the very top of Temblor Formation and had numerous oil shows. Well core dips are consistent with the well drilling into the northeast limb of the anticline.

The stratigraphy of the triangle zone below the SHT and TRT can be postulated by two methods that indicate the zone should involve known reservoirs and source rock of late Cretaceous through Miocene age: 1) Geologic units within the footwall block have approximately the same structural relief as the undeformed units to the east in the central trough once slip is removed along the Quaternary age Lost Hills thrust as shown in Fig. 5B. 2) The stratigraphy, including the

producing oil reservoirs, of the Cymric oil field can be mapped northward using deep well data and strike seismic lines (Fig. 9). These geologic units plunge northward and beneath the lateral ramps forming the southern edge of the Antelope uplift and into the triangle zone.

The better imaged seismic lines plus a few exploration wells as shown in Fig. 8 show the triangle zone and subthrust area beneath the Antelope uplift are folded into anticlines and synclines as would be expected in this area of significant convergence. Untested anticlines subthrust could range from 1,000 to 10,000 AC of closure based on structural modeling of the numerous reprocessed 2D seismic lines (most not shown here). For comparison, Elk Hills oil field-an anticlinal trap, has a maximum productive area of about 21,170 AC with produced and reserves totaling 1,392 MMBO. The subthrust area as presented here adds about 18% to the WS capable of holding large traps (the footwall area of the uplift is approximately 80,000 AC while the WS trend of large oil fields is about 440,000 AC). The exploration potential of the footwall block is further enhanced by deep thrust burial of known source rock units that should provide sufficient hydrocarbon maturity from below the uplift and short distance migration pathway from kitchen to traps. It is possible to apply the wedge model concept to other portions of the WS given the presence of back thrusting in the Temblor Range and other areas of the west side, and such an approach should provide even more prospective “running room” for large untested traps along the WS.

Acknowledgements

The author would like to recognize and thank the following companies for granting permission to show data and interpretations: Seismic Exchange Incorporated, Pacific Seismic Incorporated, and Badlands Energy, Inc. Reprocessing of the 2D seismic was done by Tricon Geophysical, Inc.

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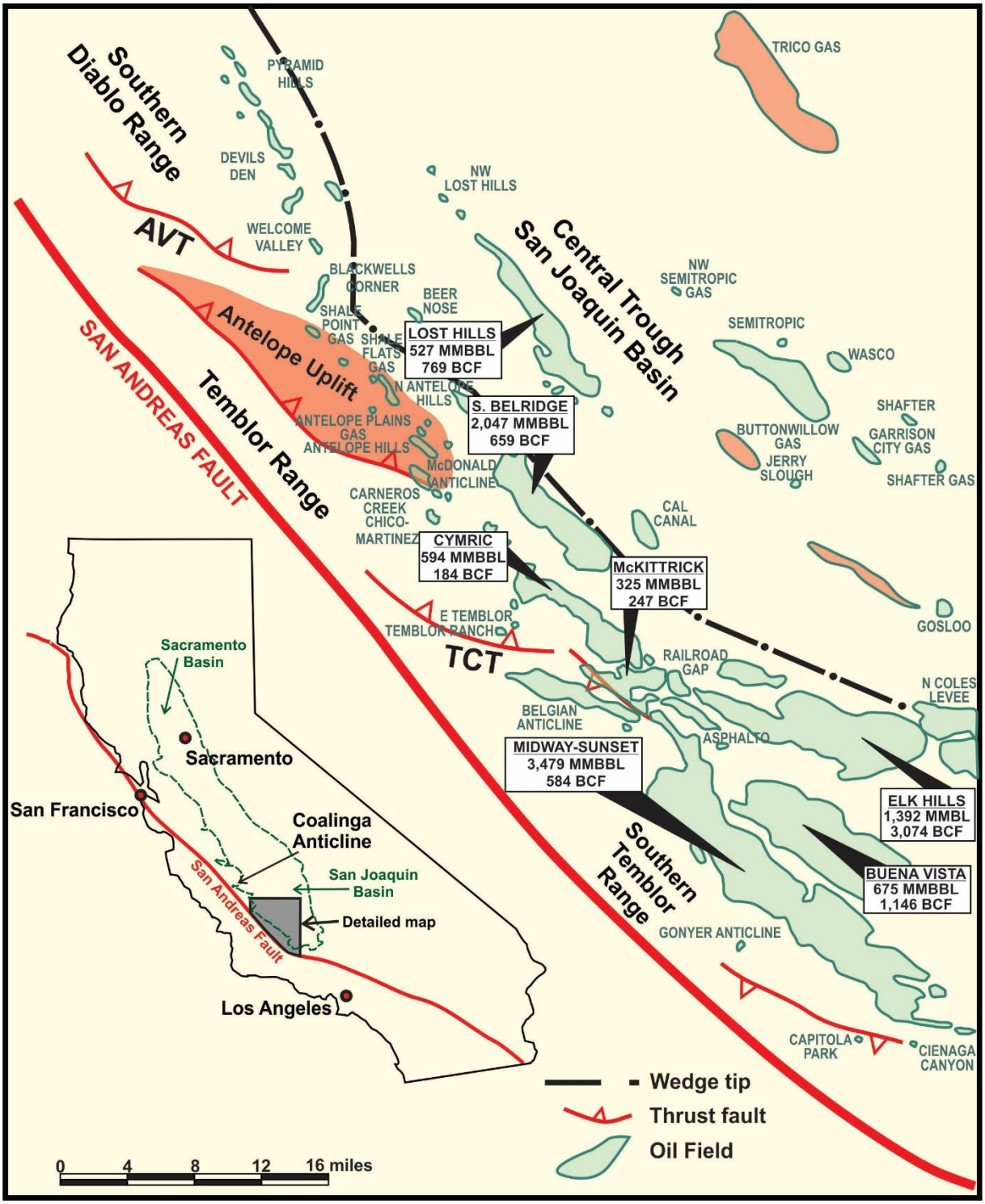


Fig. 1. On the left is a map of the State of California showing the most prolific oil producing area along the west-side of the San Joaquin basin (WS). Detailed map on the right shows this area with cumulative and proven reserves for the larger fields (but not including Coalinga anticline) as of 2009[1], location of the Antelope uplift, northeastern edge of deformed wedge (wedge tip), and some of the major backthrusts within the wedge. The exploration play presented here adds an additional 18% to the area of the WS capable of having large traps.

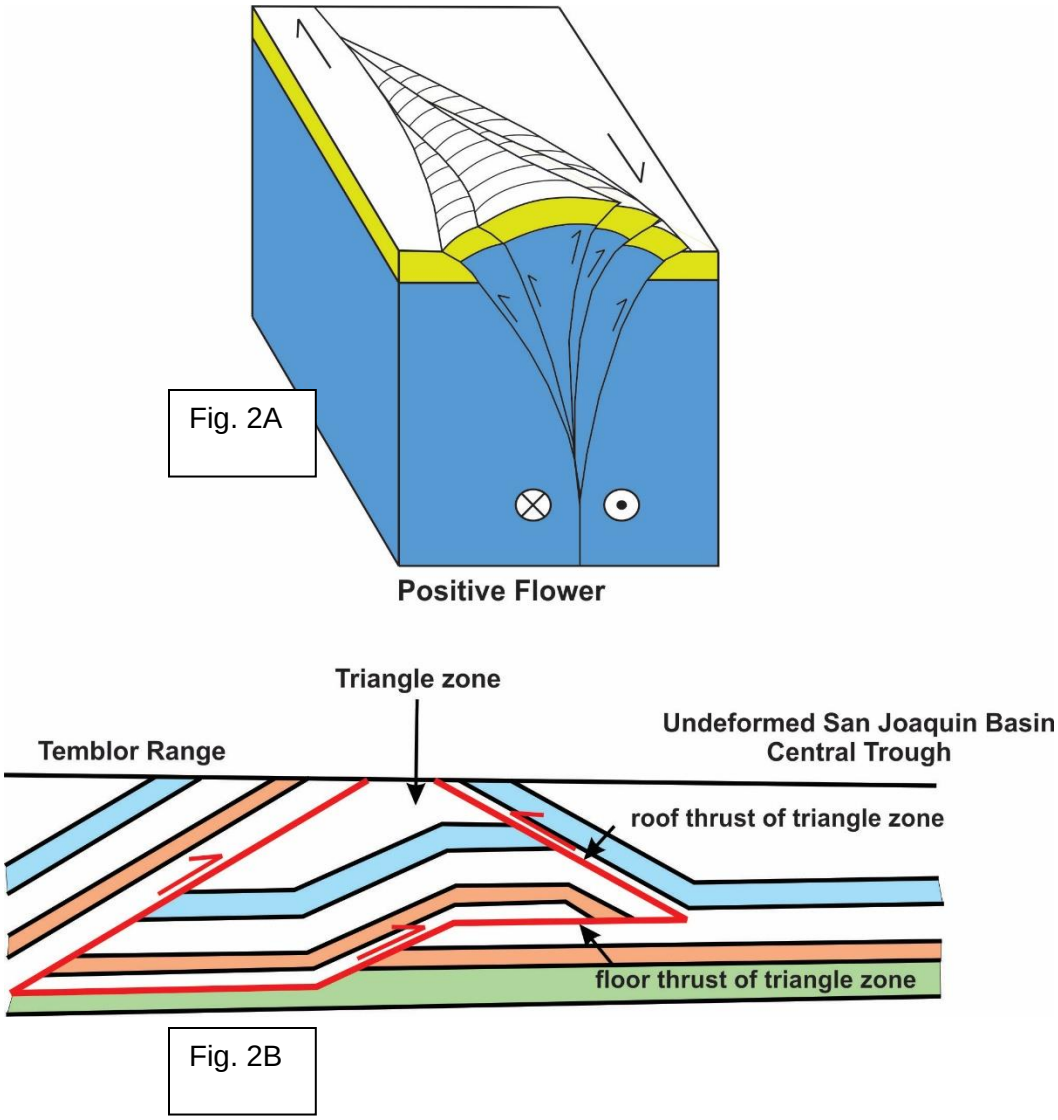
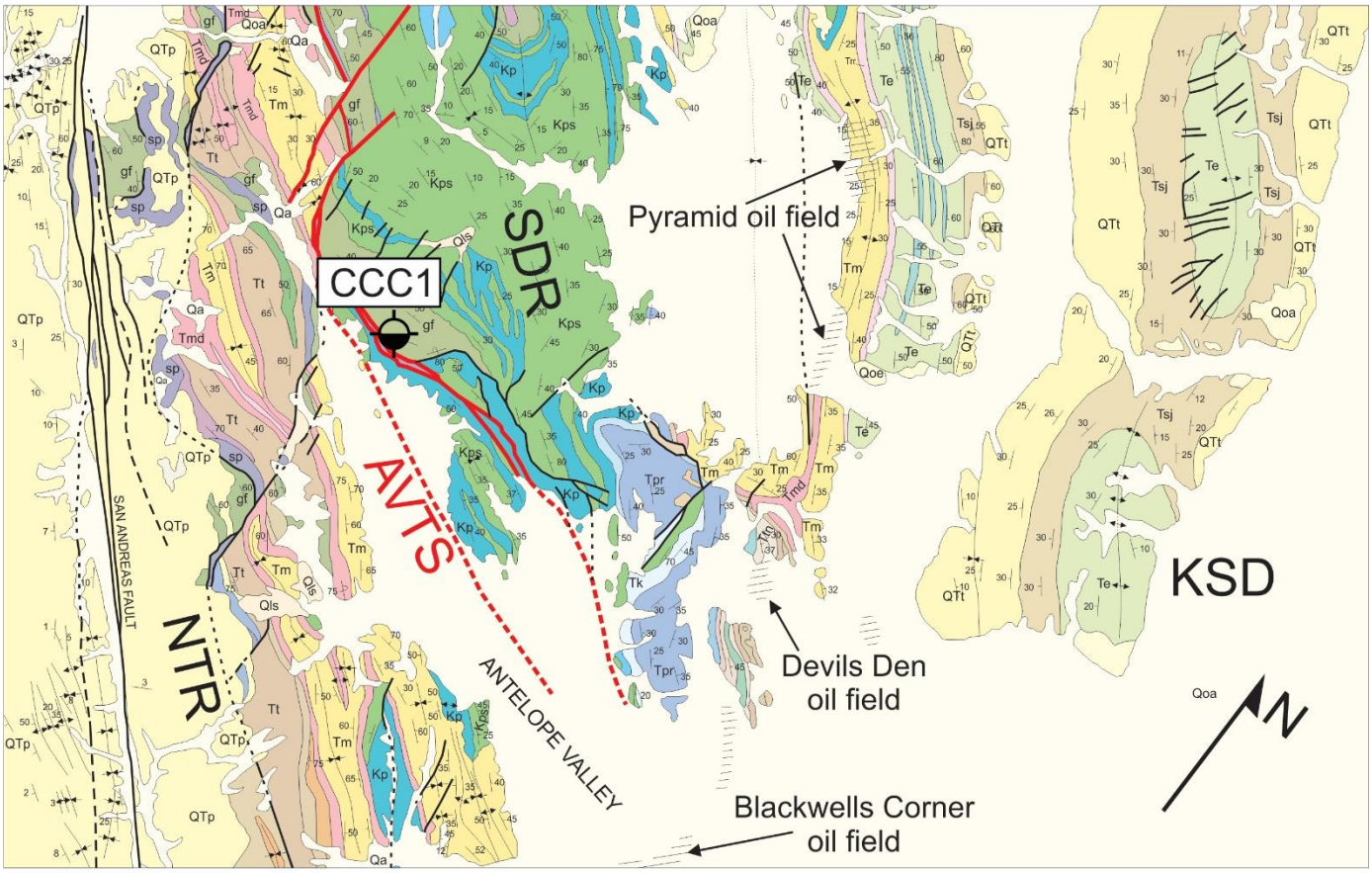


Fig. 2A. Model of a convergent wrench fault making a positive flower structure. A flower structure is characterized by distinctive structural elements such as oblique-slip reverse-faults that steepen with depth into a master strike-slip fault. In general the exploration area below a reverse fault in a flower structure setting is more limited in size relative to the area below a thrust fault that flattens with depth.

Fig. 2B. Model of a convergent wedge forming a triangle zone [22] within a fold and thrust belt. Model has been modified for the WS. Repetition of source and reservoir rocks and the presence of concealed subthrust traps in a fold and thrust setting offers more exploration potential compared to flower structure



Geologic Units
QTt=Tulare Fm; QTp= Paso Robles Fm
Tsj=San Joaquin Fm
Te=Etchegoin Fm
Trr=Reef Ridge shale
Tm=Monterey Fm; Tmd= Devilwater Shale Mbr

Geologic Units
Tt=Temblor Fm
Tk= Kreyenhagen Fm; Tpr= Point of Rocks Sandstone Mbr
Kp= Panoche Fm; Kps= Sand dominated member
gf= Gravelly Flat Fm
sp= Serpentinite

Key faults
SAF=San Andreas fault
AVTS= Antelope Valley thrust system

Fig. 3. Surface geologic map of the Antelope Valley portion of the WS [23] showing a set of northeast-dipping backthrusts (AVTS=Antelope Valley thrust system). The structurally lowest member of the system places Cretaceous and Jurassic rocks over the Miocene Monterey Formation. The Conoco Cholame Cattle Company #1 well (CCC1) spudded in the hanging wall of the AVTS, cut the thrust(s), encountered Monterey Formation directly below the lowest thrust, and showed the lowest member of the AVTS has a dip of 20 to 30 degrees to northeast and under the southern Diablo Range. Other abbreviations: KSD=Kettleman South Dome, NTR=Northern Temblor Range, and SDR=Southern Diablo Range.

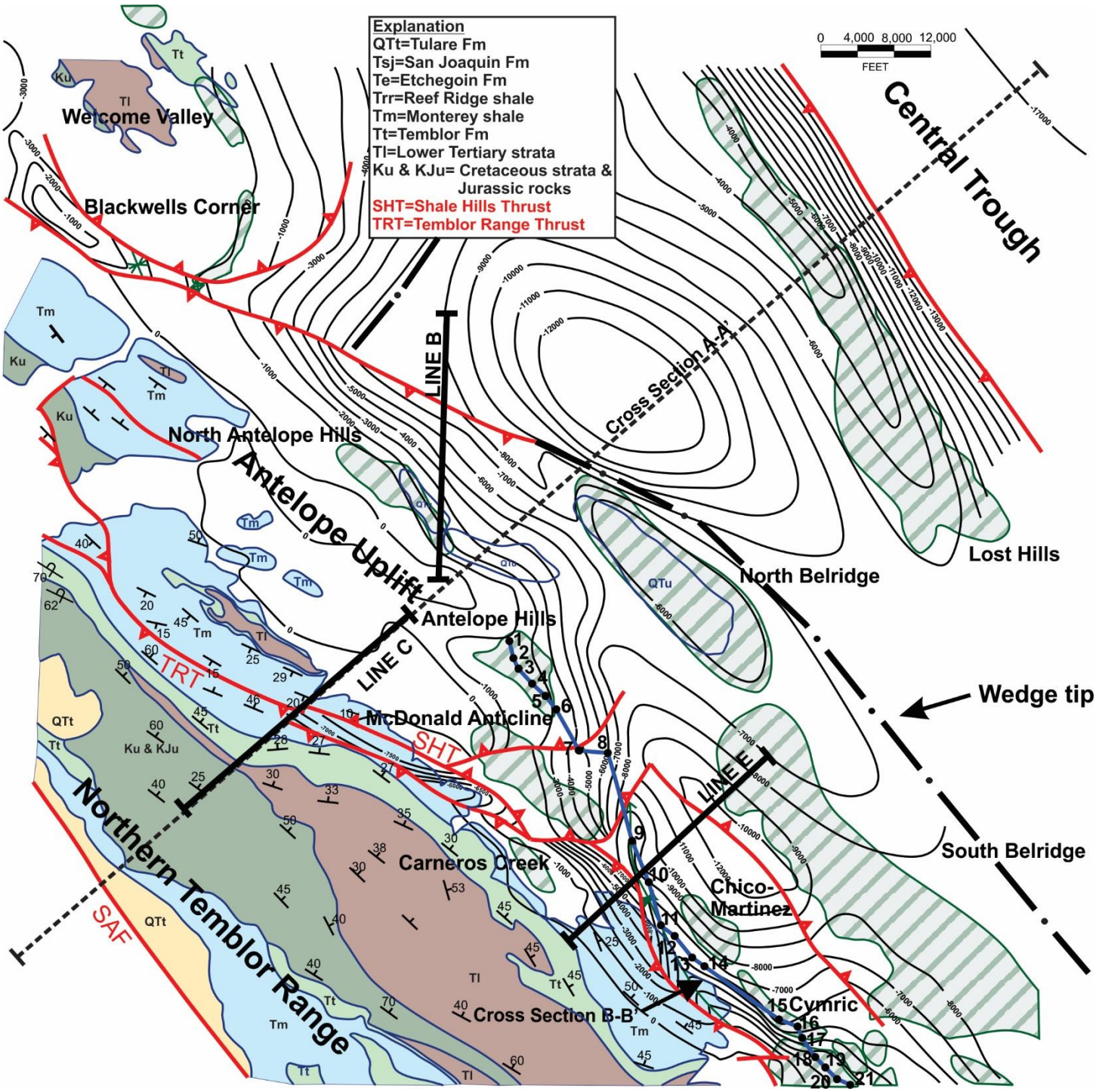


Fig. 4. Map showing the surface geology of the northern Temblor Range, the shape of the Antelope uplift, local oil fields (green cross-hatch) and the location of the wedge tip (dash-dot line). Abbreviations: key surface units=black lines, key faults=red lines, subsurface contours on top of Temblor Fm=black lines with depth values. 2D seismic Line B (Fig. 6), Line C (Fig. 7), and Line E (Fig. 8). Geologic cross sections: A-A' (Fig. 5) and B-B' (Fig. 9).

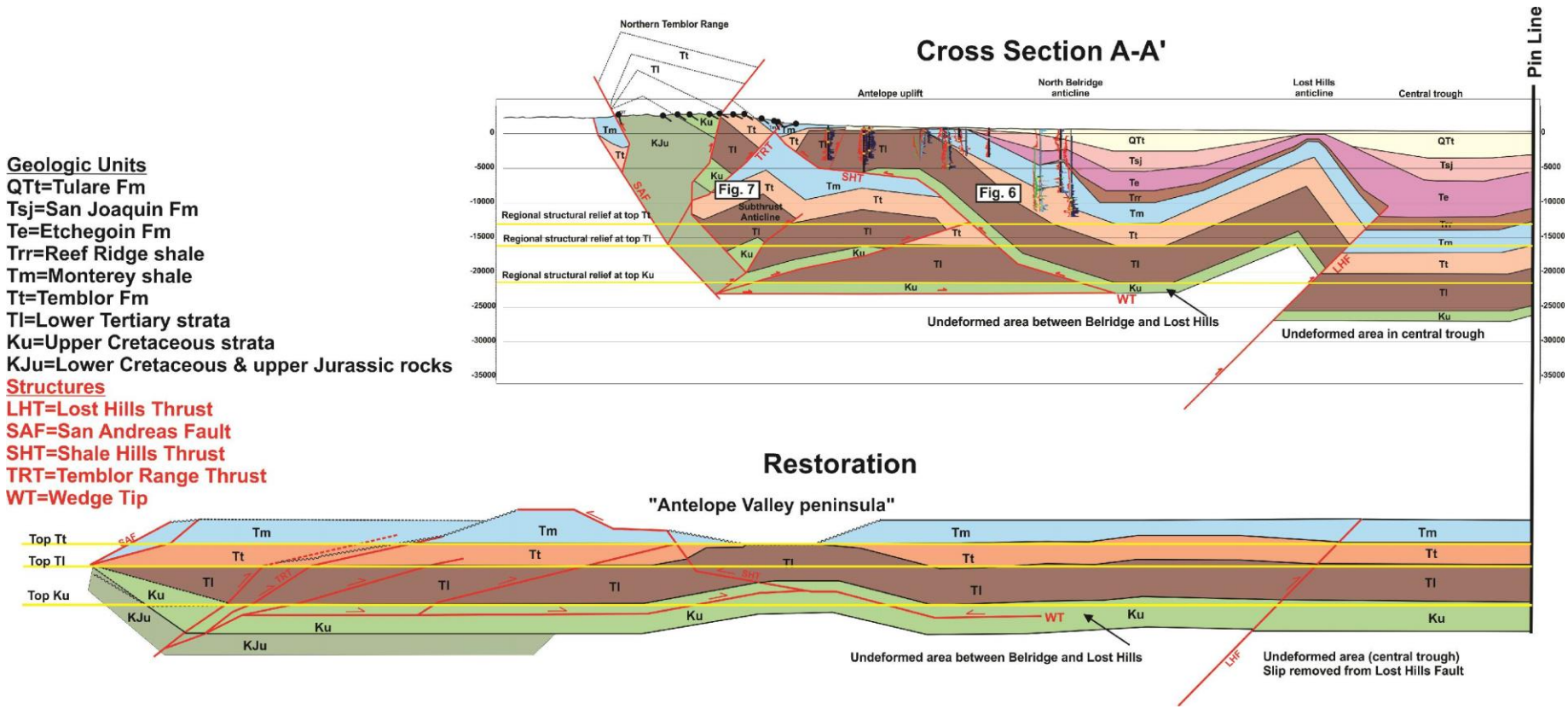


Fig. 5A. Regional cross section A-A' across the Antelope uplift portion of the WS. The interpretation shows the uplift to be a southwest-vergent fault-bend fold above a northeast-directed structural wedge. The uplift is the result of a large ramp in SHT surface and the SHT is roof thrust to the wedge. The portions of the cross section constrained by nearby 2D seismic lines are labeled as Figs 6 & 7. Note the extensive and untested triangle zone between the TRT and SHT. The triangle zone has known source and reservoir rocks based on the undeformed structural relief of formation tops (restoration), well to well correlation (Fig. 9), and strike seismic lines extending southward to the northern portion of Cymric oil field. See text for further details of interpretation.

Figure 5B. Line-length restoration of cross section A-A' that shows WS strata in their relatively undeformed state (late Miocene). Restoration shows the "Antelope Valley peninsula[21]" that separated this portion of the WS into two subbasins that existed during the

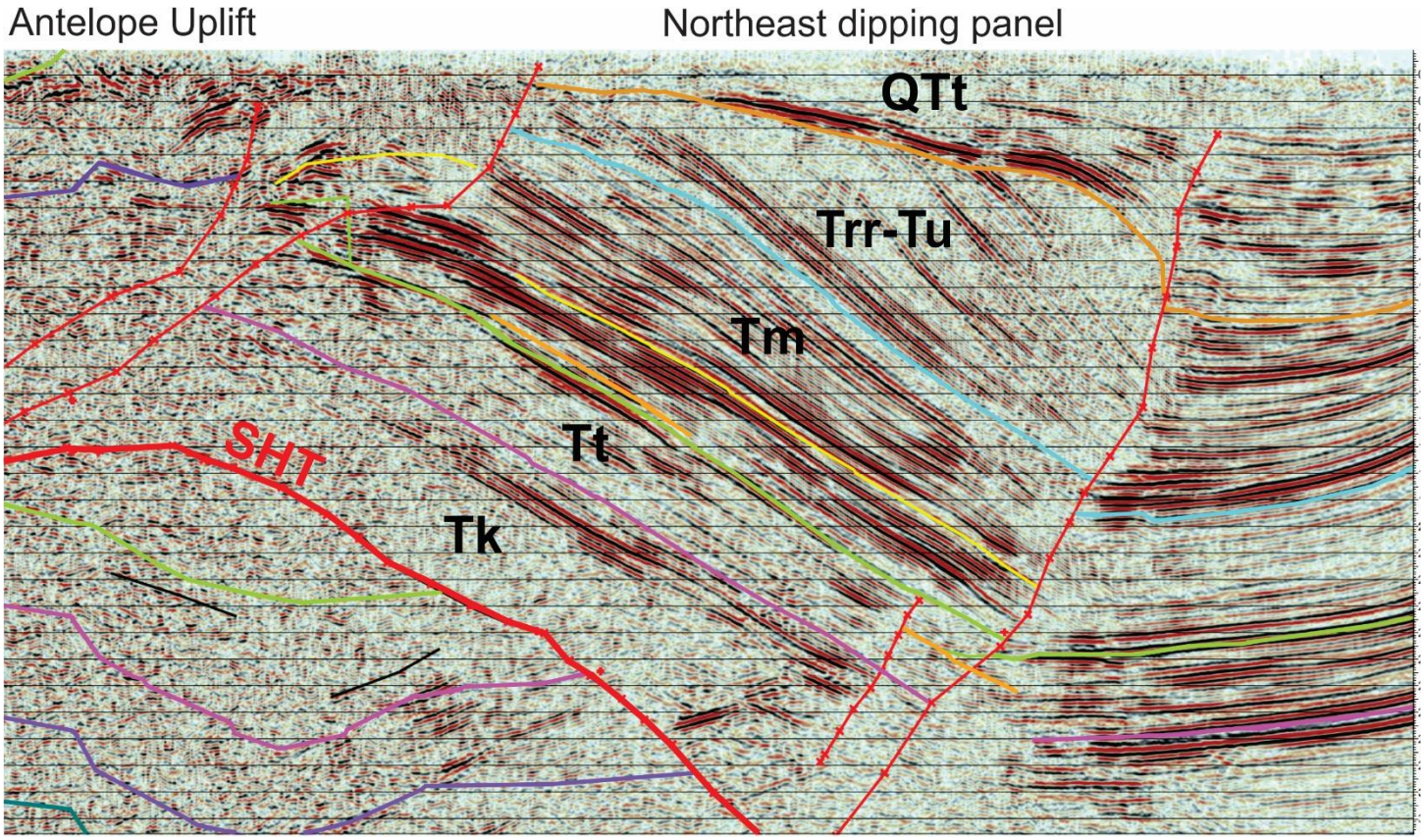


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Fig. 6. 2D seismic line B. Line shows geometry and detail of the northeast limb of the Antelope uplift. Limb dip is interpreted to be caused by strata being translated up a ramp in

the Shale Hills thrust (SHT) making a fault-bend fold above the thrust (this portion of line is only maging back-limb of fold. See text for details of interpretation. Geologic unit abbreviations: Tk=Kreyenhagen Formation, Tt=Temblor Formation, Tm=Monterey Formation, Trr-Tu=undifferentiated Reef Ridge, Etchegoin and San Joaquin Formations, and QTt=Tulare Formation.

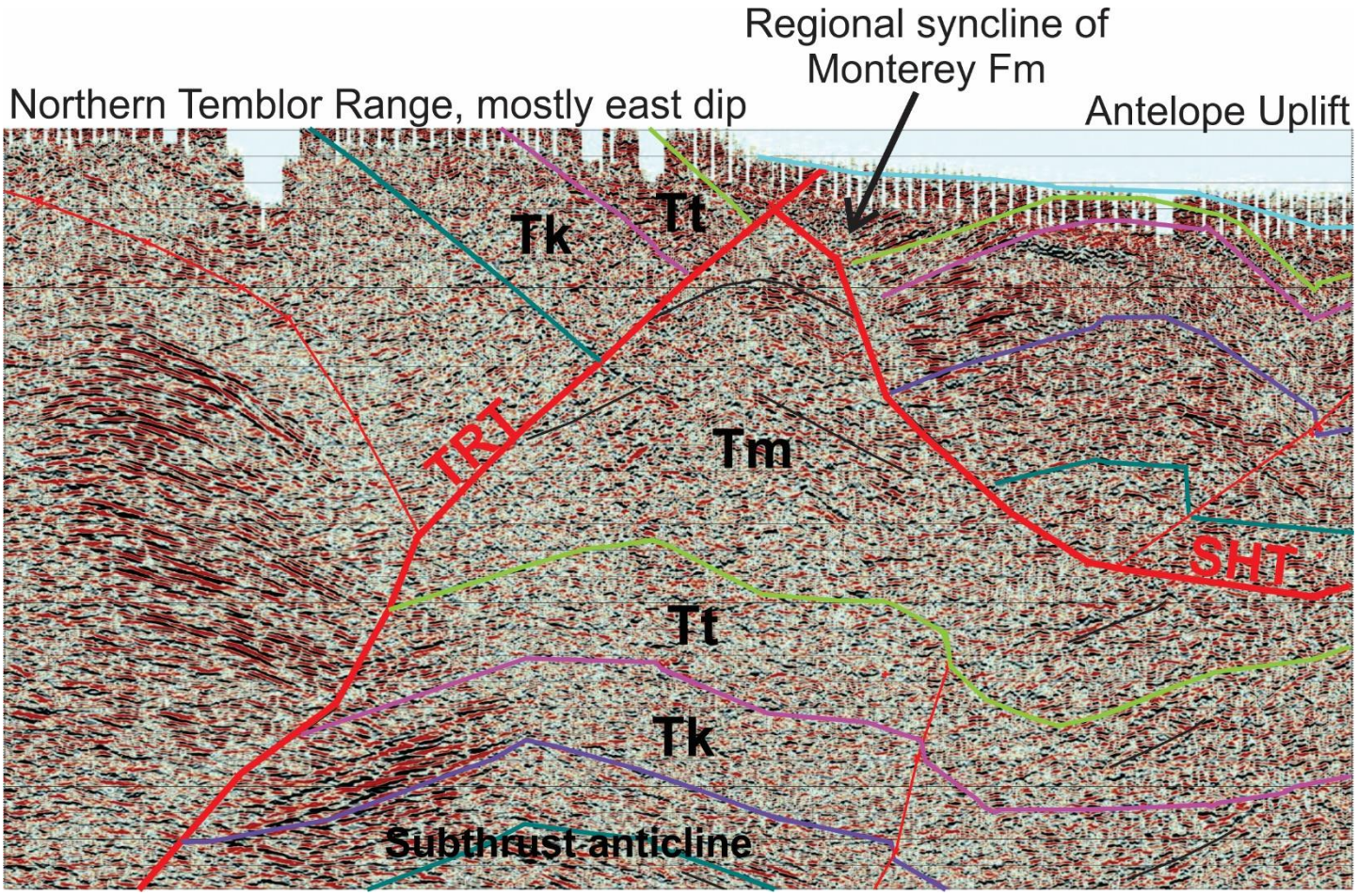

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Fig. 7 (2D seismic line C). The surface structure of the northern Temblor Range is dominated by northeast-dipping strata, but line C and other similarly oriented 2D lines, show a large west-dipping panel beneath the range, and abrupt change in dip is caused by offset along the Temblor Range thrust (TRT). The opposing dips of the TRT and the Shale Hills thrust (SHT) form a triangle zone along the foothills of the northern Temblor Range and beneath the Antelope upift. See text for details of interpretation. Geologic units explained in Figure 6 caption

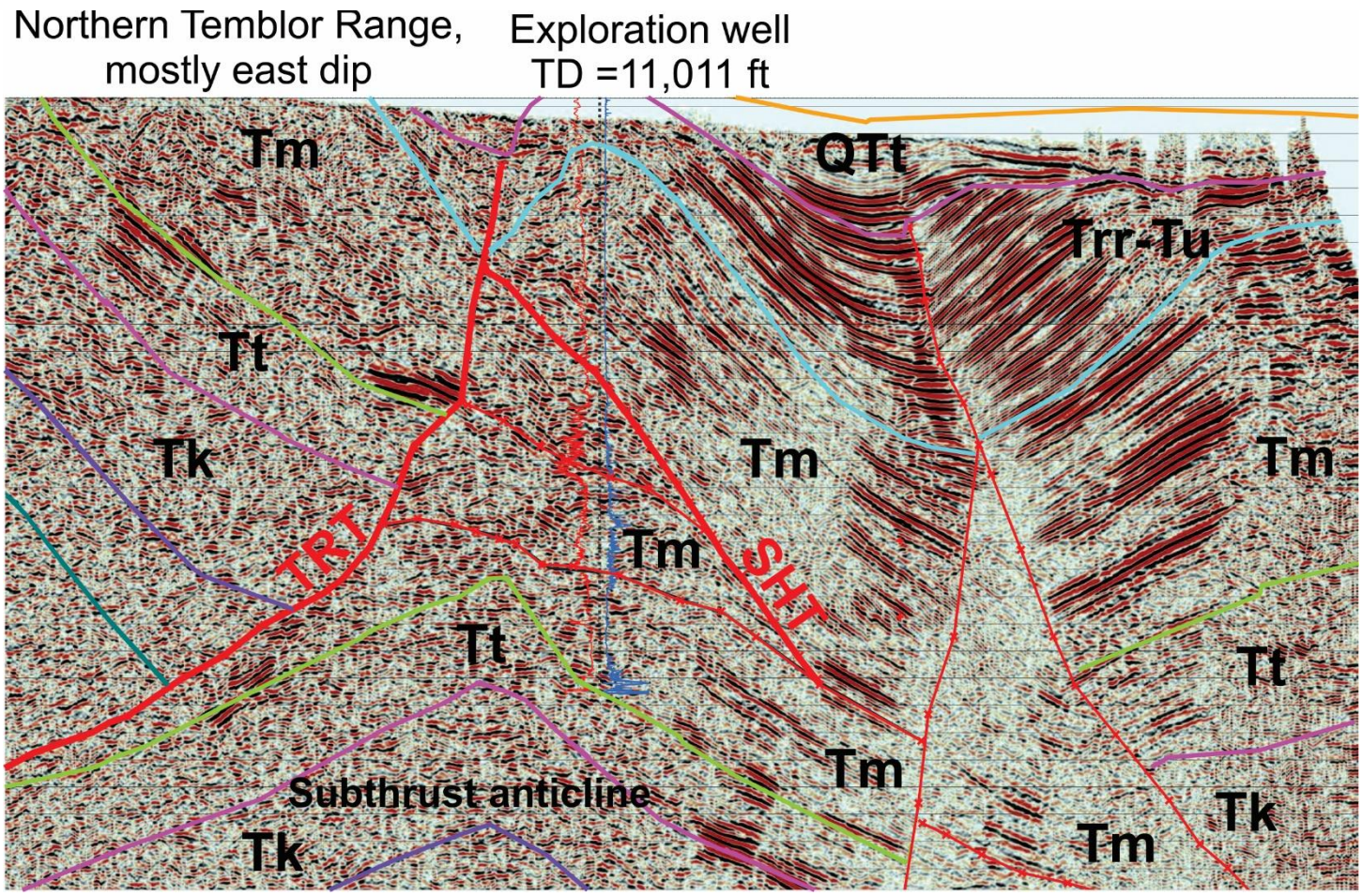

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Fig. 8 (2D seismic line E). Line E images triangle zone between the Temblor Range thrust (TRT) and Shale Hills thrust (SHT). A nearby exploration well spudded in 1946 is projected into the seismic line and shows that the usually thick section of Monterey Fm (Tm) is due repetition by the SHT. Well reached the top of Temblor Formation near the bottom of hole, and a formation test across a 440 ft interval abreast of the Monterey and Temblor contact recovered gassy oil and salt-water. Hole was eventually abandoned due to drilling problems. See text for details of interpretation. Geologic units explained in Figure 6 caption.

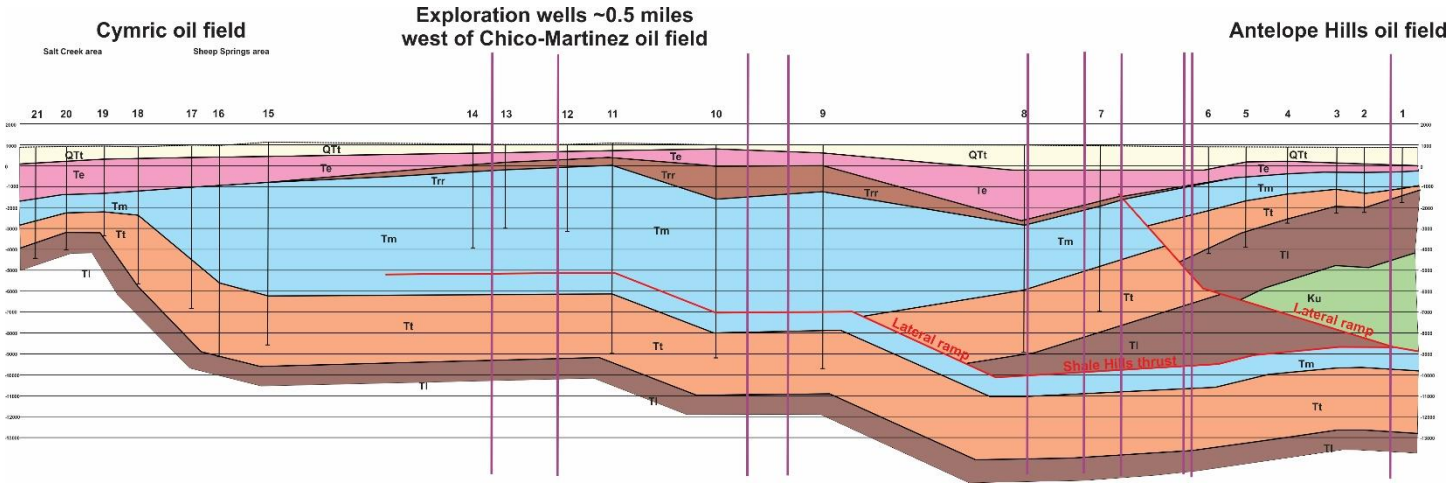

Fig. 9 (well to well cross section B-B', view is to the southwest). Footwall strata below the Antelope uplift is postulated by well to well correlation from the northern portion of Cymric oil field to beneath the uplift area. Wells are numbered and vertical purple lines are intersections of reprocessed 2D seismic lines that were used in mapping. Southern edge of Antelope uplift ends along lateral thrust ramps in the Shale Hills thrust system. See text for details of interpretation.

1=Shell, Hopkins A 48X

Sec 31,27S-20E

TD= 2,600

2=E&B Nat Res Corp, Voight 784-6

Sec6,28S-20E

TD=3,100

3=E&B Nat Res Corp, Voight 781

S6,28S-20E

TD=3,117

4=Shell, Williams 87-6

S6,28S-20E

TD=3,600

8=Ferguson&Bosworth, Toco 53X

S16,28S-20E

TD=9,769

9=Exxon Corp, T P Bacon 1

S27,28S-20E

TD=10,674

10=Laymac Corp, Bacon Hills 1-27

S27,28S-20E

TD=10,130

11=Atlantic Richfield Co, Shaw A 1

S34,28S-20E

15=Transco Oil, Richardson 46

S7,29S-21E

TD=9,643

16=Los Nietos Co, Richardson 77X

S7,29S-21E

TD=10,129

17=Los Nietos Co, Richardson 81

S18,29S-21E

TD=7,810

18=Chevron USA Inc, CWOD 633

S17,29S-21E

TD=6,540