The Petroleum System of the Salinas Basin (California) and Its Outcrop Expression

Basin and Petroleum System Modeling Group
Fieldtrip for 3rd Annual Industrial Affiliates Meeting
November 6, 2010

Stanford University
Department of Geological and Environmental Sciences

Compiled by T.A. Menotti and S.A. Graham
2010

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Fieldtrip Participants

Name	**Affiliation**
Bonnie Bloeser	Aera Energy
Changrui Gong	BP
Brad Cey	Chevron
Noelle Schoellkopf	Chevron
Zehui (Tim) Huang	Marathon Oil
Tony Reid	Occidental, Elk Hills
Vaugh Thompson	Oxy CA Exploration
Wanger Bastos	Petrobras
Marco Moraes	Petrobras
Luiz Trindade	Petrobras
Ken Peters	Schlumberger
Carolyn Lampe	Ucon Geoconsulting
Stephan Graham (professor)	Stanford University, BPSM
Meng He (student)	Stanford University, BPSM
Tess Menotti (student)	Stanford University, BPSM
Allegra Scheirer (researcher)	Stanford University, BPSM

Safety Information

Local hospital contact information
George L. Mee Memorial Hospital
300 Canal St.
King City, CA 93930
831-385-6000

Twin Cities Community Hospital
1100 Las Tablas Rd.
Templeton, CA 93465
805-434-3500

Potential safety hazards on this trip

1) Slipping/tripping on narrow path along Arroyo Seco (STOP 1).
2) Traffic – outcrops along roads (STOPS 2, 3b – 3d).
3) Environmental:
    a. Dehydration
    b. Sunburn
    c. Poison oak

Fieldtrip Itinerary

Summary

DEPART	**From Stanford University, “Bambi Parking Lot” at Panama St. and Via Ortega.**
(7:30 am)	*Bambi Parking lot:* 37.427509918,-122.176467453
STOP 1	**Arroyo Seco Day Use Area – United State Forest Service.**
(10:00 – 11:00 am)	*Parking in Day Use Area:* 36.2366820828,-121.480142165
STOP 2	**Elm Ave, near bridge over Arroyo Seco.**
(11:20 – 11:40 am)	*Parking:* 36.2795330222,-121.319992056
LUNCH	**San Lorenzo Regional Park, King City.**
(12:00 – 1:00 pm)	*Park kiosk:* 36.2038681314,-121.141271902
STOP 3a	**Private driveway just south of 90 degree turn over bridge on Co. Rd. G19.**
(1:40 – 2:00 pm)	*Parking:* 35.8070510593,-120.855751306
STOP 3b	**Tar sand outcrop on Co. Rd. G19.**
(2:05 – 2:30 pm)	*Outcrop:* 35.7933177901,-120.866360681
STOP 3c	**Co. Rd. G19, just before San Antonio Reservoir Dam.**
(2:35 – 2:45 pm)	*Parking and view of outcrop:* 35.7933177901,-120.866360681
STOP 3d	**Co. Rd. G19, just before Nacimiento Lake Dam.**
(2:55 – 3:45 pm)	*Parking:* 35.7630918448,-120.884772782
STOP 4	**Alvarado Rd. Exit off US-101 N.**
(4:10 – 4:30 pm)	*Parking and view of San Ardo field:* 35.9477556376,-120.877445516
RETURN	**To Stanford University.**
(7:00 pm)	*Bambi Parking lot:* 37.427509918,-122.176467453

Detailed Itinerary

The fieldtrip will begin at Stanford University, at the “Bambi Parking Lot” on **Saturday November 6, 2010**. Departure is at **7:30 am**. The “Bambi Parking Lot” is located on the Stanford campus, at the intersection of Panama St. and Via Ortega, across from a parking garage.

DIRECTIONS: Stanford to STOP 1 – *128 miles, ~ 2 hours, 30 minutes*

STOP 1

Park kiosk: 36.2354121255,-121.476653647

Parking in Day Use Area: 36.2366820828,-121.480142165

Outcrop: 36.2366445025,-121.481037225

- Leave from the “Bambi Parking Lot”, at the intersection of Panama St. and Via Ortega on Stanford University campus.
- Turn left out of parking lot onto Panama St.
- Left on Campus Dr.
- Right at Junipero Serra Blvd.
- Left at Alpine Rd. Follow to **I-280 S** on ramp.
- Take **I-280 S** – ***9.8 mi***.
- Exit onto **CA-85 S**, toward **Gilroy** – ***19 mi***.
- Merge onto **US-101 S** – ***75.2 mi***.
  Drive past the town of Salinas, and head southeast down through the Salinas Valley.

  Just south of the small town of Soledad,
- **Exit 301**, **Arroyo Seco Rd**. – ***1.3 mi***.
- Keep left at fork to continue on Arroyo Seco Rd. – ***14.9 mi***.
  Drive west toward the Santa Lucia Range, following the Arroyo Seco.
- Bear left to continue on Arroyo Seco Rd – ***4.5 mi***.
  (Carmel Valley Road branches to the right, but do not take this.)
- Arrive at entrance to **Los Padres National Forest**, Arroyo Seco Recreation Area kiosk.
  Cross bridge, and take an immediate **right** into the **Day Use Area**.
  Drive to far (west) end of parking lot, and park.

STOP 1 *(10:00 – 11:00 am)*

Arroyo Seco Day Use Area – United State Forest Service.

$$ - Park entrance fee: $7/vehicle.

Source rock facies of lowermost Monterey Formation.

DIRECTIONS: STOP 1 to STOP 2 – *11.5 miles, ~20 minutes*

STOP 2

Parking: 36.2795330222,-121.319992056

Outcrop: 36.2811314985,-121.322871577

Retrace the route east on Arroyo Seco Rd. and CR G16:

- Turn left out of Day Use parking area, cross back over the bridge to the kiosk.
- Continue east on **Arroyo Seco Rd.** – ***11 mi***.
- Slight right at **Co. Rd. G16, Elm Ave**.
- Right at **Co. Rd. G16**, Elm Ave and cross the bridge.
  Reliz fault outcrop will be on your left just before turning right onto the bridge.
- Carefully park on shoulder on ***left*** side of the road, **0.15 mi** after crossing the bridge.
  Use caution walking along the road here due to the narrow shoulder. Wearing orange vests is recommended at this stop.

STOP 2 *(11:20 – 11:40 am)*

Elm Ave, near bridge over Arroyo Seco.

Basin tectonics: strike-slip on the Reliz fault (20 min)

DIRECTIONS: STOP 2 to LUNCH – *17 miles, ~20 minutes*

LUNCH

Park kiosk: 36.2038681314,-121.141271902

- Head east on Co. Rd. G16/Elm Ave. (Pass Reliz Canyon on right.) – ***5.3 mi***.
- Right on **S. El Camino Real** (in Greenfield).
- Continue on **US-101 S** – ***10.6 mi***.

  Immediately **after bridge** over Salinas River:
- **Exit 282B, Broadway St.**, toward King City; loop around to the right and cross under the overpass.
- Left at **Broadway St.**
- Continue on **San Antonio Dr.** to the **San Lorenzo Regional Park** entrance kiosk.

LUNCH *(12:00 – 1:00 pm)*

San Lorenzo Regional Park, King City.

$$ - Park entrance fee: $8/vehicle.

DIRECTIONS: LUNCH to STOP 3a – *36 miles, ~40 minutes*

STOP 3a

Parking: 35.8070510593,-120.855751306

Outcrop: 35.8091308827,-120.857901595

- Head east on San Antonio Dr.
- Right on Broadway St.
- Left merge onto **US-101 S** – ***30 mi***.
  Pass the San Ardo oil field on your left as you drive south on US-101.
- **Exit 252, Jolon Rd**, toward Fort Hunter Liggett.

- Right at **Co. Rd. G18**/Jolon Rd.
- Left on **Co. Rd. G19**/Nacimiento Lake Dr. – ***5.2 mi***.
    - The road makes a 90° turn to the left, and crosses a small river. Just after the bridge, turn right into a private driveway.

<u>STOP 3a</u> <u>*(1:40 – 2:00 pm)*</u>

Private driveway just south of 90 degree turn over bridge on Co. Rd. G19.

Diatomite exposure overlain unconformably by Pliocene sediment. Porcelanite exposure underneath diatomite, along the riverbank.

DIRECTIONS: STOP 3a to STOP 3b – *1.4 miles, ~2 minutes*

<u>*STOP 3b*</u>

Outcrop: 35.7933177901,-120.866360681

- Continue south on **Co. Rd. G19** – ***1.4 mi***.
- Park on broad shoulder on right side of road.
  <u>Use caution</u> crossing the road to view the outcrop. Wearing <u>orange vests</u> is recommended at this stop.

<u>STOP 3b</u> <u>*(2:05 – 2:30 pm)*</u>

Tar sand outcrop on Co. Rd. G19.

Migration and trapping of oil in the Salinas basin. Plio-Pleistocene nonmarine tar sand unconformably atop fractured siliceous upper Monterey Formation. The Monterey Formation here is an example of an exhumed fractured Monterey reservoir.

DIRECTIONS: STOP 3b to STOP 3c – *0.7 mile, ~ 2 minutes*

<u>*STOP 3c*</u>

Parking and view of outcrop: 35.7933177901,-120.866360681

- Continue west on **Co. Rd. G19**, towards the Nacimiento Lake Dam – ***0.7 mi***.
- Park on right side of road, beside gate with stone gate posts.

<u>STOP 3c</u> <u>*(2:35 – 2:45 pm)*</u>

Co. Rd. G19, just before San Antonio Reservoir Dam.

Sedimentary fill thickness of Salinas basin. Exposures of thick upper Monterey Formation.

DIRECTIONS: STOP 3c to STOP 3d – *3.9 miles, ~ 9 minutes*

<u>*STOP 3d*</u>

Turn-around: 35.7614492228,-120.885122444
Parking: 35.7630918448,-120.884772782
Outcrop: 35.764314216,-120.885986721

- Turn around, and head east on **Co. Rd. G19** – ***0.4 mi***.
- Turn right on **Co. Rd. G19**, **Nacimiento Lake Dr.** – **2.7 mi**.
- **Pass parking area on shoulder** on the left, and continue down hairpin turn, passing folded Monterey on the right, until reaching an under-construction park entrance just before the dam – ***0.4 mi***.
- Turn around, and head back past the folded Monterey outcrop (this time on the left), and park on the wide shoulder on the right up the hill just beyond the outcrop – ***0.4 mi***. Use caution walking along the road here due to the blind curves in the road. Wearing orange vests is recommended at this stop.

STOP 3d *(2:55 – 3:45 pm)*

Co. Rd. G19, just before Nacimiento Lake Dam.

Basin tectonics: Late stage shortening and basin inversion. Severely folded upper Monterey Formation.

DIRECTIONS: STOP 3d to STOP 4 – *16.3 miles, ~ 25 minutes*
STOP 4
Parking and view of San Ardo field: 35.9477556376,-120.877445516

Retrace the route north to San Ardo field, off US-101 N:

- Head northeast on **Nacimiento Lake Dr.** – ***2.7 mi***.
- Turn right on **Co. Rd. G19**, **Nacimiento Lake Dr.** – **6. 9 mi**.
- Right on **Co. Rd. G18**, **Jolon Rd.** – ***0.4 mi***.
- Take **US-101 N** – ***5.9 mi***.
- **Exit 258**, **Alvarado Rd.** (San Ardo field).
- Left at Alvarado Rd., and cross over the highway.
- Right up the hill to a gated lease road. Park here.

STOP 4 *(4:10 – 4:30 pm)*

Alvarado Rd. Exit off US-101 N.

Migration and trapping of oil in the Salinas basin. Overview of San Ardo oil field.

END of guided fieldtrip. If returning to Stanford, proceed on Highway 101 northbound. Expect to arrive back at Stanford around 7:00 pm.

Overview map of Salinas Valley with stop locations. See Detailed Itinerary for directions and latitude/longitude coordinates.

Map with directions from US-101 S to **Stop 1** – Arroyo Seco Day Use Area.

Map with directions from US-101 S to **Stop 3d** – Folded Monterey by Nacimiento Dam.

The Petroleum System of the Salinas Basin (California) and Its Outcrop Expression

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Introduction

The Salinas basin is a petroliferous intermontane basin within the Coast Ranges of central California (Fig. 1). The basin has an unusual field-size distribution: it houses the giant San Ardo field, which produces relatively heavy oil from shallow reservoirs (<1 km), as well as a half dozen very small, largely depleted fields (all < 5mmbl and most <<1 mmbl). The basin is nearly encircled by outcrops of uplifted basin fill (Fig. 1), and from these it is possible to (1) identify all of the critical elements of the basin's petroleum system, (2) predict the likelihood of commercial petroleum accumulations in the basin, (3) identify the probable limits on distribution of accumulations and (4) anticipate where undiscovered accumulations, if any, may reside. In addition, as the petroliferous basin closest to adjacent offshore region of central California, it may offer insights to the petroleum potential of that area, where relatively few data exist.

Basin Context

The Salinas basin is a composite sedimentary basin: Upper Cretaceous (Campanian-Maestrichtian) and Paleocene nonmarine to deep-marine strata deposited atop arc basement in a forearc basin setting (Grove, 1993) are overlain by Eocene to Recent nonmarine to deep-marine units deposited in restricted marine borderland and intermontane basin settings (Graham, 1978). All known petroleum accumulations in the Salinas basin occur in Neogene strata, so Paleogene and older strata generally are considered to be economic basement. The distribution of petroleum reserves directly reflects the stratigraphic distribution of petroleum-source rock units and their burial history, which in turn reflects the tectonic evolution of the basin.

The granitic/metamorphic basement of the Salinas basin is part of a larger block of arc basement termed the Salinian block. Although somewhat controversial, the dominant current view holds that this basement block originally was a continuation of the southern Sierra Nevada arc terrane which has been translated to its present position by episodes of strike-slip faulting (Dickinson and Butler, 1998). In this view, the Cretaceous-Paleocene version of the Salinas forearc basin was modified into a marine borderland as a consequence of late Paleocene faulting, which likely was related to strike-slip emplacement of the Salinian block into central California (Fig. 2; Nilsen and Clark, 1975; Graham, 1978; Dickinson et al., 1979). The borderland structural and topographic configurations set up by the Paleogene deformational event persisted into the Neogene, when after collision of the East Pacific Rise spreading center with North America, the Salinian block was again put into motion by strike-slip along the San Andreas transform fault. Rapid foundering of basins in central California in the late Oligocene and early Miocene (Fig. 3) was associated with initiation of the San Andreas fault. Late Cenozoic transpression across the Coast Ranges, associated with a change in pole-of-rotation of the Pacific-North American plate pair, produced deformation and inversion of the fill of the Salinas basin (Graham, 1978; Page et al., 1999). This temporally varying deformation associated with San Andreas transform evolution was essential to the development of the petroleum system of the Salinas basin, as outlined below.

Key Elements of the Salinas Basin Petroleum System

Significant total basin fill. Rapid subsidence associated with the onset of San Andreas tectonism in the early Miocene (Fig. 3) created a deep-marine depocenter along and west of the modern Salinas River. Paleo-water depths of 500 m – 1500 m characterized this basin for the entire Miocene, and accommodation space created by initial and continued subsidence permitted at least 3 km of Neogene sediment to accumulate prior to late Cenozoic basin inversion. This depocenter area of the Neogene Salinas basin, although offset by right-slip on the Reliz-Rinconada fault, is well defined by the map of the structure of the top of the basement (Fig. 4). Significantly, the deepest part of the basin lies in the subsurface just west of the San Ardo field (Figs. 4, 5a and 5b), and a good sense of the thickness of the basin fill is provided by outcrops only 10 km west of San Ardo field. Although the section accumulated mainly during the latter half of the Neogene, the 3+ km of sedimentary burial in the depocenter (in concert with favorable kerogen attributes) was sufficient to generate the oil of San Ardo field (Fig. 6). Pyrolysis (Tmax) data from well Texaco Shell NCT-1 in the deepest part of the basin confirms that the source rock has been in the oil window (Marion, 1986).

Abundant oil-prone organic matter. Source rock is the key to oil occurrence in the Salinas basin. The San Joaquin basin lies between the Salinas basin and the dominant mountain range of California, the Sierra Nevada, and as a result, the deep-marine Salinas basin was shielded from input of voluminous terrigenous detritus in the late Miocene. Bathed in episodically low-oxygen marine water characterized by upwelling-driven plankton, the basin filled with oil-prone biogenic sediment now assigned to the Monterey Formation. The most deeply buried lower and middle Miocene Monterey Formation strata of the Salinas basin are especially organic-rich. Laminated, phosphatic, foraminifer-nannoplankton mudstone of the lower Monterey Formation (Fig. 7, 8) contains up to 7% TOC and average over 4% (Fig. 9). This organic matter is oil-prone type-II kerogen (Fig. 10) and more specifically is the sulfur-rich variety (type IIS) that often typifies anoxic marine settings. This is significant because type IIS kerogen yields liquid hydrocarbons at lower temperatures that other organic matter, thereby offsetting the relative recent burial.

Attractive reservoir stratigraphy. Although isolation from the North American mainland in the Neogene yielded an attractive source-rock section in the Salinas basin, limited terrigenous input hampered development of sandstone reservoirs. For instance, both the San Joaquin and Los Angeles basins, located adjacent to the mainland, contain abundant turbidite reservoirs interleaved with source rock sections, but comparable turbidites are nearly absent in the Salinas basin. In the Salinas basin, the San Ardo field is developed in stacked upper Miocene shelf sands which accumulated on the shelf adjacent to bathyal parts of the Salinas basin where oil-prone biogeneous muddy sediment accrued (Fig. 5a). No sequence stratigrapic study of the San Ardo field reservoirs has been published, but mudstone units interbedded with major sandstone reservoir in the field suggest transgressive/regressive cycles. This stratigraphic alternation and interfingering with basinal mudsone to the west (Fig. 5) forms effective reservoir stratigraphy. In addition, the biosiliceous upper Miocene portion the basinal Monterey Formation is altered from its original diatomaceous character by burial diagenesis to porcelanite and chert where buried more than about a kilometer. The attendant embrittlement associated with this diagenetic change allows for the possibility of fractured reservoirs in the Monterey Formation in depocenter areas of the Salinas basin (Fig. 4).

Reservoir quality. San Ardo field sandstone is feldspathic quartz arenite. Shelf current and wave action texturally matured San Ardo sands, and granitic provenance (Graham, 1987) and shallow burial acted to minimize diagenetic degradation of the reservoirs.

Reservoir structure. Basin- and local-scale structures play critical roles in determining the occurrence of petroleum accumulations in the Salinas basin. At the basin scale, the only places where substantial burial of the Monterey Formation has been achieved are the basement depressions west of San Ardo field, and beneath the Arroyo Seco (Figs. 1, 4, 5). These two depocenters appear to be opposite halves of an originally contiguous depocenter that has been right-laterally offset across the Reliz-Rinconada fault (Fig. 11) (Dibblee, 1976; Graham, 1978). This relationship, discernible from thickness of outcrop sections, as well as subsurface data, constrains the location of mature portions of Monterey Formation source rocks and therefore prospective areas of the basin. Furthermore, because the prospectivity of the Arroyo Seco depression has been degraded by inversion during late Cenozoic transpression, exploration interests have been focused on the area around the depression west of San Ardo field.

Specific structural relations around San Ardo field account for the major occurrence of petroleum in the field. First, the faulted and/or flexed step-down of basement west from San Ardo field (Figs. 4, 5, 12) is a feature that first controlled paleogeography/palebathymetry in the Miocene (Fig. 13), then updip migration pathways for petroleum which matured from the bottom of the thick section of Monterey Formation west of the oil field (Fig. 5). Late Cenozoic transpression thrusted part of the basinal Monterey Formation section to the east over the basement slope and western part of the San Ardo shelf (Fig. 5). This deformational episode also enhanced a faulted basement structure beneath the field and created or enhanced an elongate doming of the upper Miocene shelf sequence which became the trapping structure for San Ardo field (Fig. 12). Unfortunately, the relatively simple structure of basement in the subsurface elsewhere east of the Salinas River (Fig. 4), and extensive basin inversion in the Santa Lucia Range west of the river (Fig. 14), limit the opportunities for analogous trapping situations in the basin.

Timing. The giant San Ardo field exists because favorable elements of the petroleum system contribute in an effective temporal sequence: (1) fundamental basin structure was set by Mesozoic tectonism, and overprinted by late Cenozoic deformation associated with the San Andreas fault; (2) the late Cenozoic deformation first triggered enhanced subsidence that established a Miocene deep-marine basin in which an anoxic water column developed and oil-prone sediments were deposited; (3) basin configuration permitted simultaneous deposition of high-quality oil-source sediments in the basinal realm immediately adjacent to a shallow-marine shelf on which good quality sand units accumulated, (4) this configuration persisted throughout the Miocene, permitting deposition of sediment thicknesses sufficient for petroleum, maturation, and (5) transpressional structuring of the Salinas basin associated with a late Cenozoic phase of plate margin tectonics created or enhanced the structural trapping configuration at San Ardo field, which was charged with oil that migrated up from its point of origin beneath the adjacent depocenter to the west.

Stop Descriptions

STOP 1. Arroyo Seco section of Sandholdt Member of the lower Monterey Formation source rocks. Walk a short distance west past the end of the picnic area parking lot to exposures of brown calcareous mudstone exposed along the south bank of the Arroyo Seco. **Beware of abundant poison oak plants in the area!** The section here is laminated, phosphatic, foraminiferal and organic-rich. Even in the weathered outcrops, assays yield 4% TOC of oil-prone kerogen (Fig. 7-10).

STOP 2. Reliz fault. Stop at the south side of the bridge across Arroyo Seco to observe an excellent exposure of the Reliz fault in the terrace cliff across the road from the bridge. This fault apparently has accrued several tens of kilometers of right-slip, as well as 2-3 km of dip-slip at this locality, in the late Cenozoic (Figs. 4, 11).

STOP 3a. Diatomite facies of upper Monterey Formation. The diatomite facies of the upper Monterey Formation (Buttle Member) has been preserved in this location. The biostratigraphic age of the diatomite in this exposure is 9.2-8.9 Ma (Barron, 2010, oral comm.), distinguishing this as the youngest dated section of Monterey diatomite in the Salinas basin. Beneath the diatomite, exposed in the river bank, is the porcelanite phase of the Monterey. The diatomite here is overlain unconformably by the Pliocene shelfal sand facies of the Pancho Rico.

STOP 3b. Unconformable contact between white upper Miocene biosiliceous strata of the Monterey Formation and overlying black tar-filled Plio-Pleistocene fluvial sandstone and conglomerate of the Paso Robles Formation. This roadcut provides excellent insights into key aspects of the petroleum system of the Salinas basin:

1) The unconformity reflects late Cenozoic inversion of the Salinas basin from a deep-marine depocenter to its current state as a subaerial intermontane basin.
2) The unconformity helps date the contractile deformation which created or enhanced structural trapping in the basin.
3) The Monterey Formation exposed here is the top of the thickest section of the formation in the basin (Figs. 4, 5), and the oil demonstrates that the underlying formation has matured sufficiently to yield oil.

4) Tar-lined fractures in the Monterey Formation demonstrate that they likely served as migration pathways, and suggest the possibility of a fractured shale exploration play.
5) Communication of oil from the Monterey Formation to overlying siliciclastic strata in the roadcut essentially reproduces at a local scale the migration pathway which charged nearby San Ardo oil field.

STOP 3c. Depocenter section of the Monterey Formation. The view north from the road shoulder affords the opportunity to see the upper portion of the very thick section of biogenous, fine-grained Monterey Formation that fills the basin depression west of San Ardo field (Figs. 4, 5), and to gain some sense of the thickness of the potential source-rock section (fieldguide cover photo). Here, the outcropping Monterey Formation is upper Miocene and consists of chert, porcelanite and siliceous shale which are leached white by weathering. Note that the dam is built on top of the Reliz-Rinconada fault, just like the bridge at STOP 2!

STOP 3d. Evidence of late Cenzoic transpression. The deep roadcut on the north side of the curve in the road exposes striking recumbent folds developed in thin-bedded, fine-grained biosiliceous strata of the Monterey Formation (Fig. 14). This deformation is part of the post-Miocene transpression that affected the Salinas basin.

STOP 4. San Ardo oil field overlook. This locality provides a good perspective view of the giant San Ardo field. At this point, we are standing on the upper plate of the Los Lobos thrust (Fig. 5), which crops out at the level of the highway. The oil field represents the successful combination of all of the elements of the petroleum system discussed above. Although a giant accumulation, unfortunately, San Ardo reservoirs are sufficiently shallow that the oil is degraded to 10°-13° API gravity and is best recovered with steam assist.

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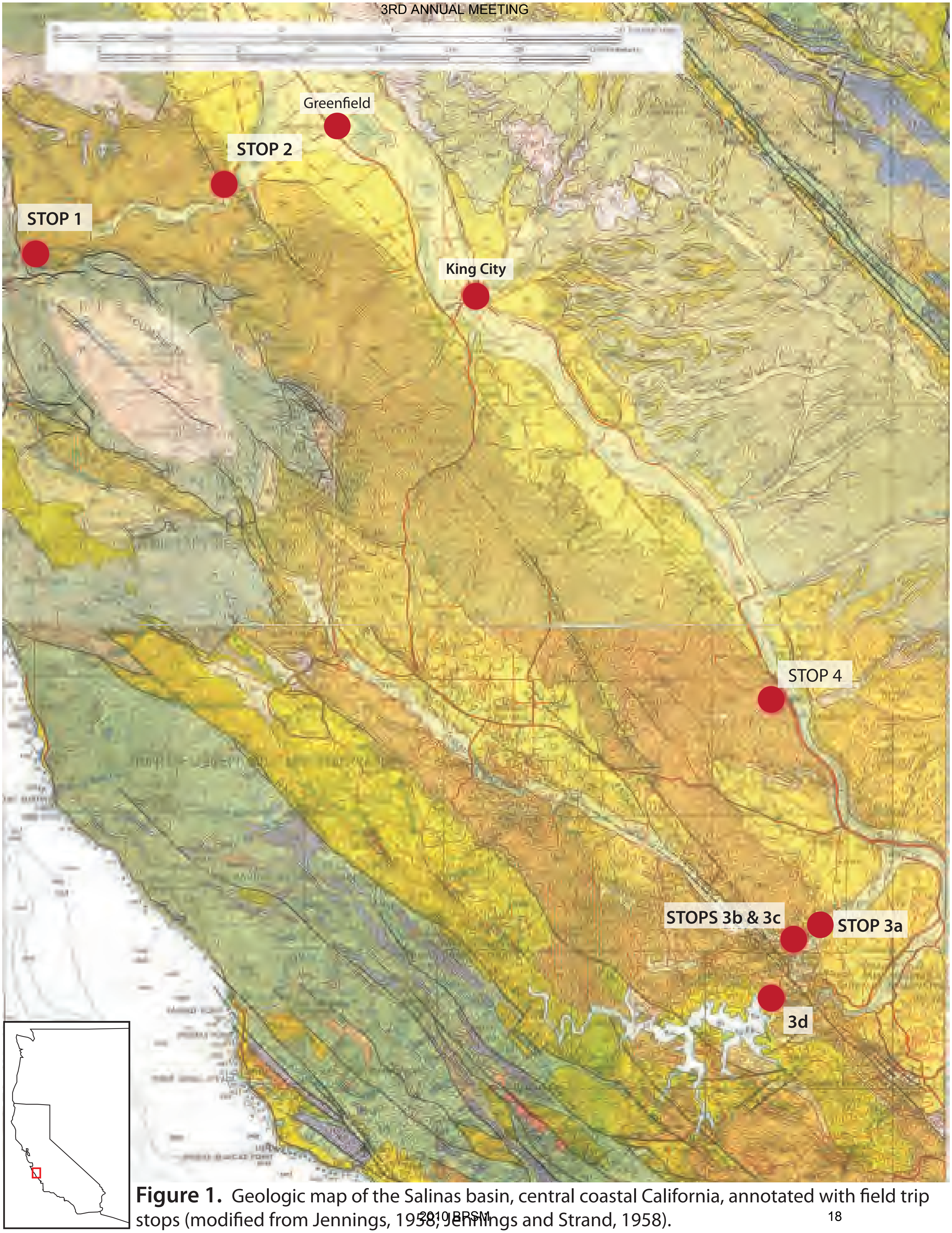


Figure 1. Geologic map of the Salinas basin, central coastal California, annotated with field trip stops (modified from Jennings, 1958; Jennings and Strand, 1958).

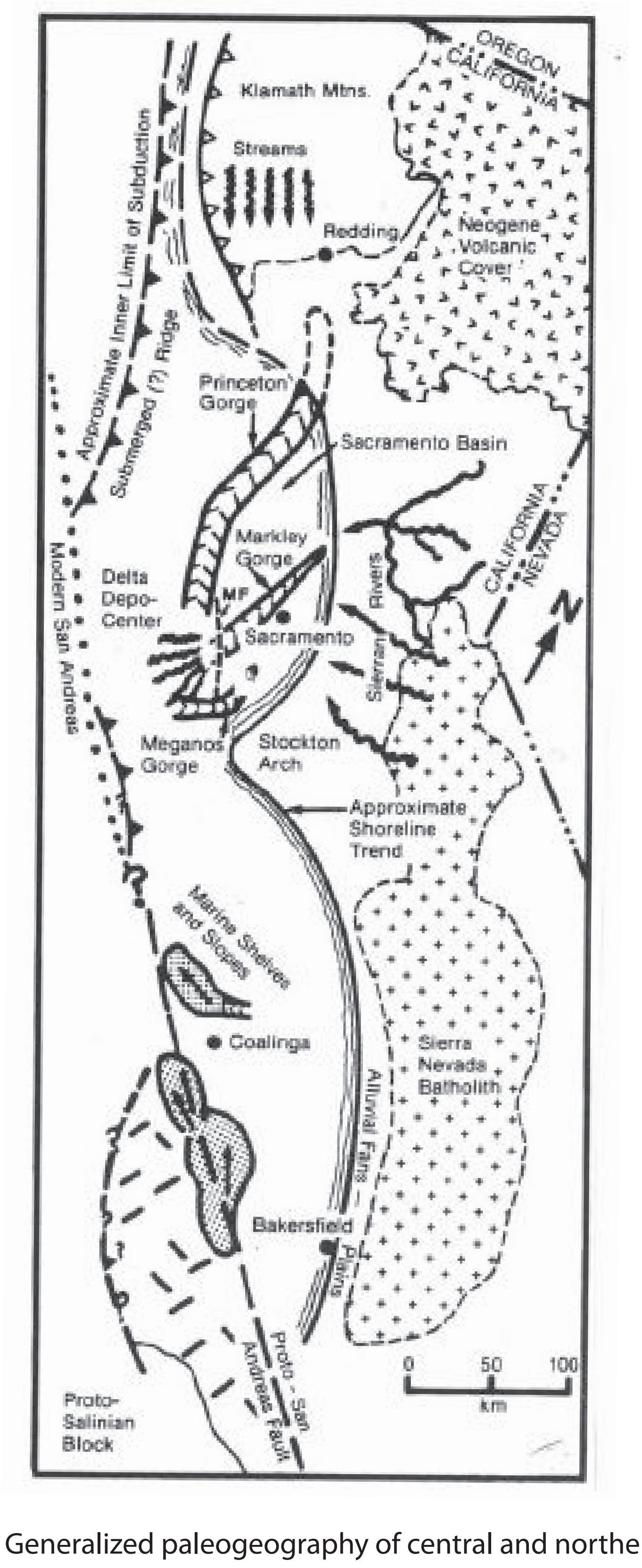


Figure 2. Generalized paleogeography of central and northern California during the Paleogene. Note the position of the granitic Salinian block outboard of the marine forearc San Joaquin basin (Coalinga-Bakersfield area). After Graham (1981).

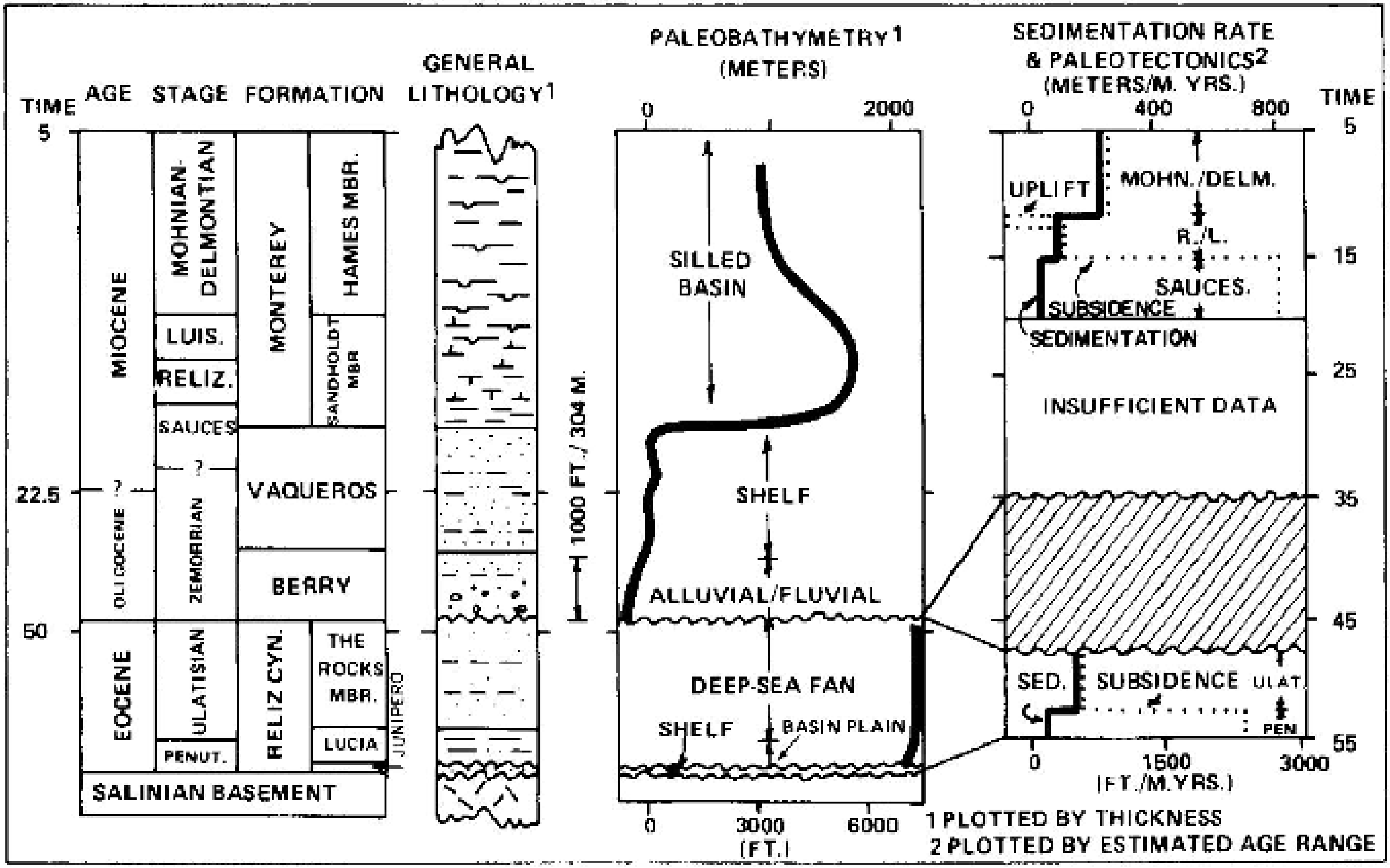


Figure 3. Eocene-Miocene section of the Arroyo Seco depocenter of the Salinas basin, as exposed in Reliz Canyon. Note rapid and profound subsidence which marked the onset of Monterey Formation deposition (after Graham, 1976).

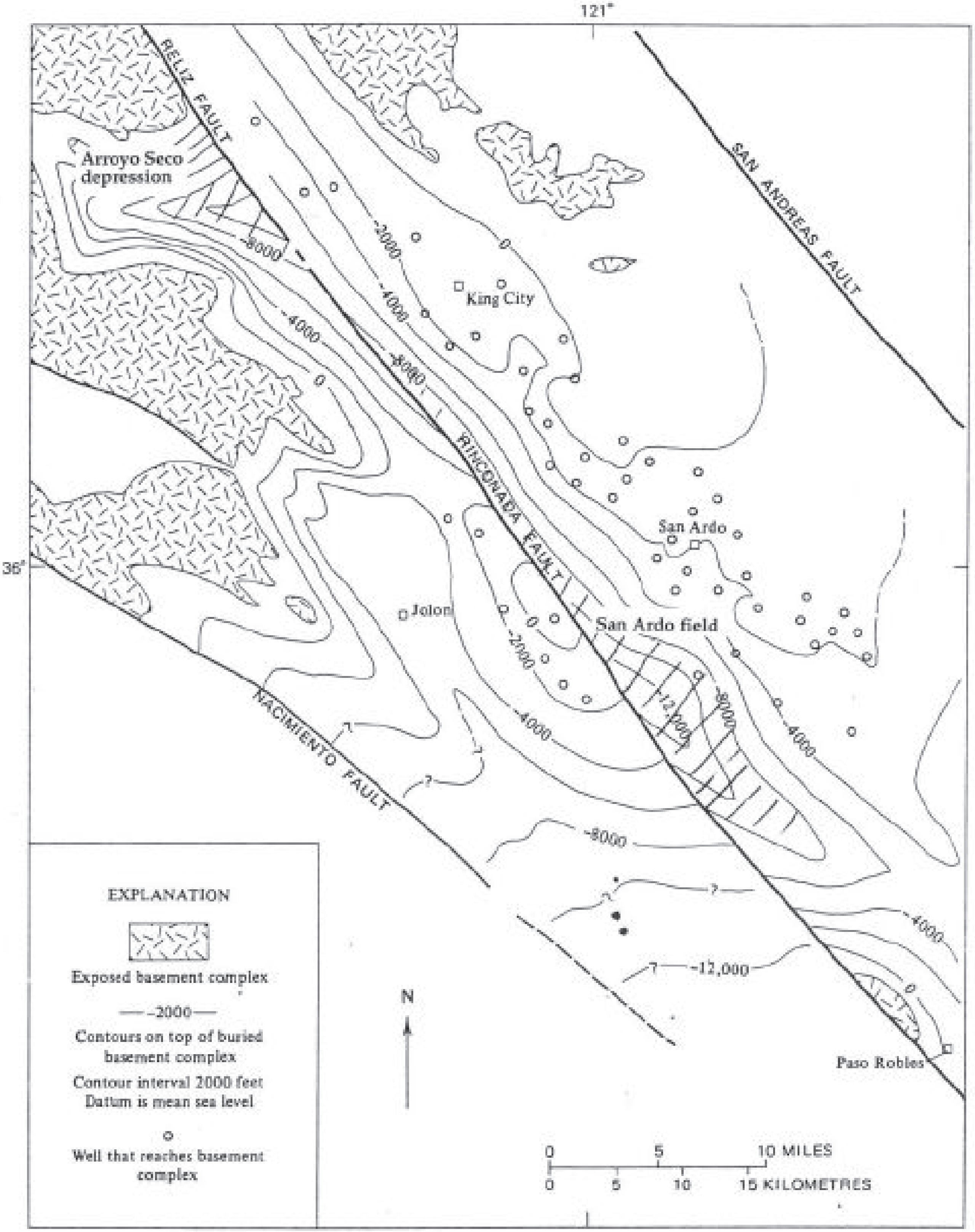
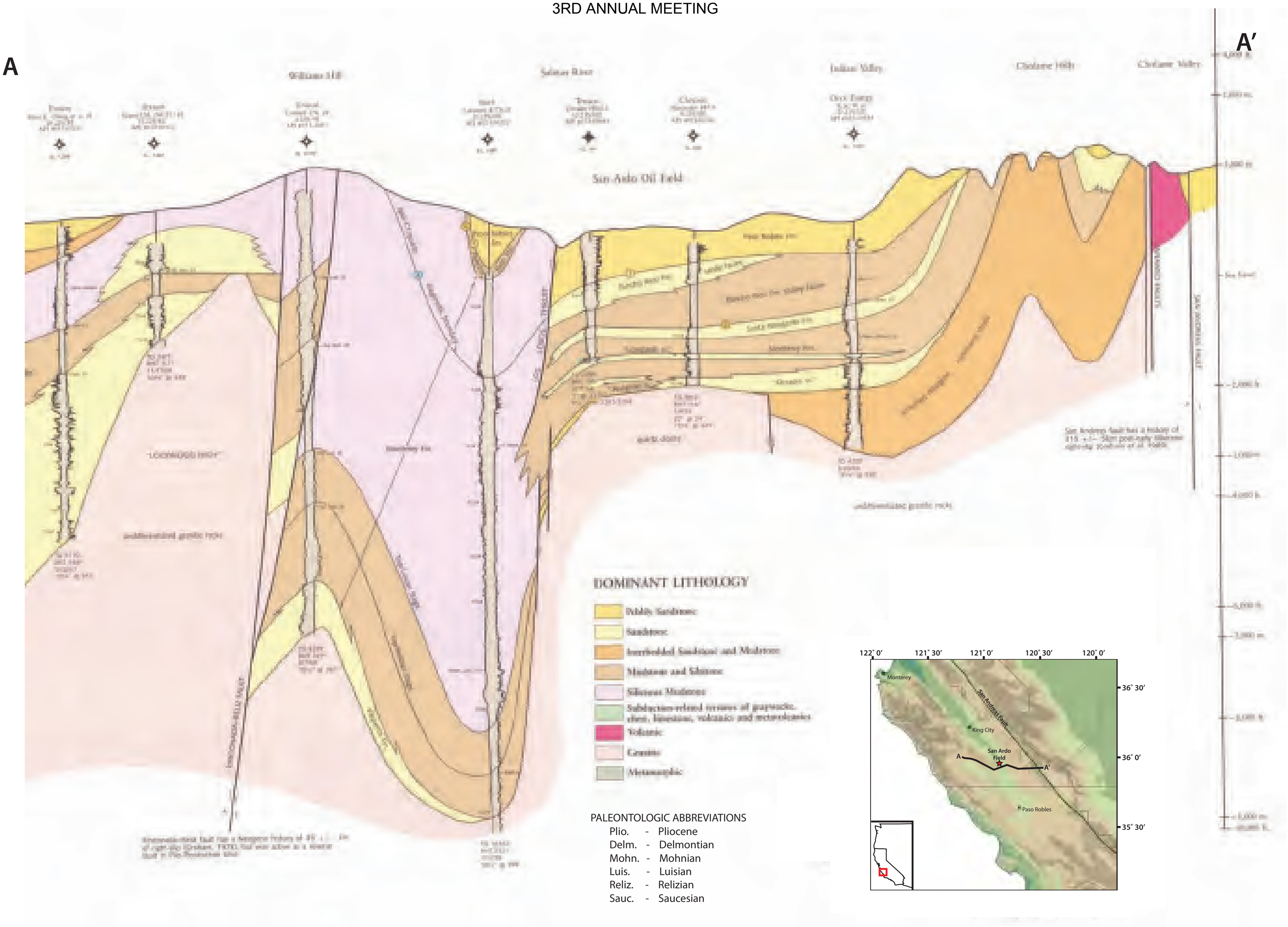


Figure 4. Map of the structure of the basement surface beneath the Salinas basin (modified after Dibblee, 1976). Contours in feet below sea level. Note the two deep depressions of the basin, beneath the Arroyo Seco and southwest of San Ardo oil field. These two likely were once contiguous and have been offset by right-slip along the Reliz-Rinconada fault. Cross-ruled portions of the two depocenters indicate areas where the lower Monterey Formation has been sufficiently buried to generate oil.



PALEONTOLOGIC ABBREVIATIONS
Plio. - Pliocene
Delm. - Delmontian
Mohn. - Mohnian
Luis. - Luisian
Reliz. - Relizian
Sauc. - Saucesian

Figure 5a. East-west cross section through San Ardo oil field and depocenter area immediately to the west (after Graham et al., 1991). The section captures structural and stratigraphic relations which gave rise to the petroleum accumulation at San Ardo. (See **Figure 5b** for map showing location of cross-section transect.)

Figure 5b. Geologic map showing east-west cross section through San Ardo oil field and depocenter area immediately to the west (after Graham et al., 1991). The section captures structural and stratigraphic relations which gave rise to the petroleum accumulation at San Ardo. (See **Figure 5a** for cross-section from A to A′.)

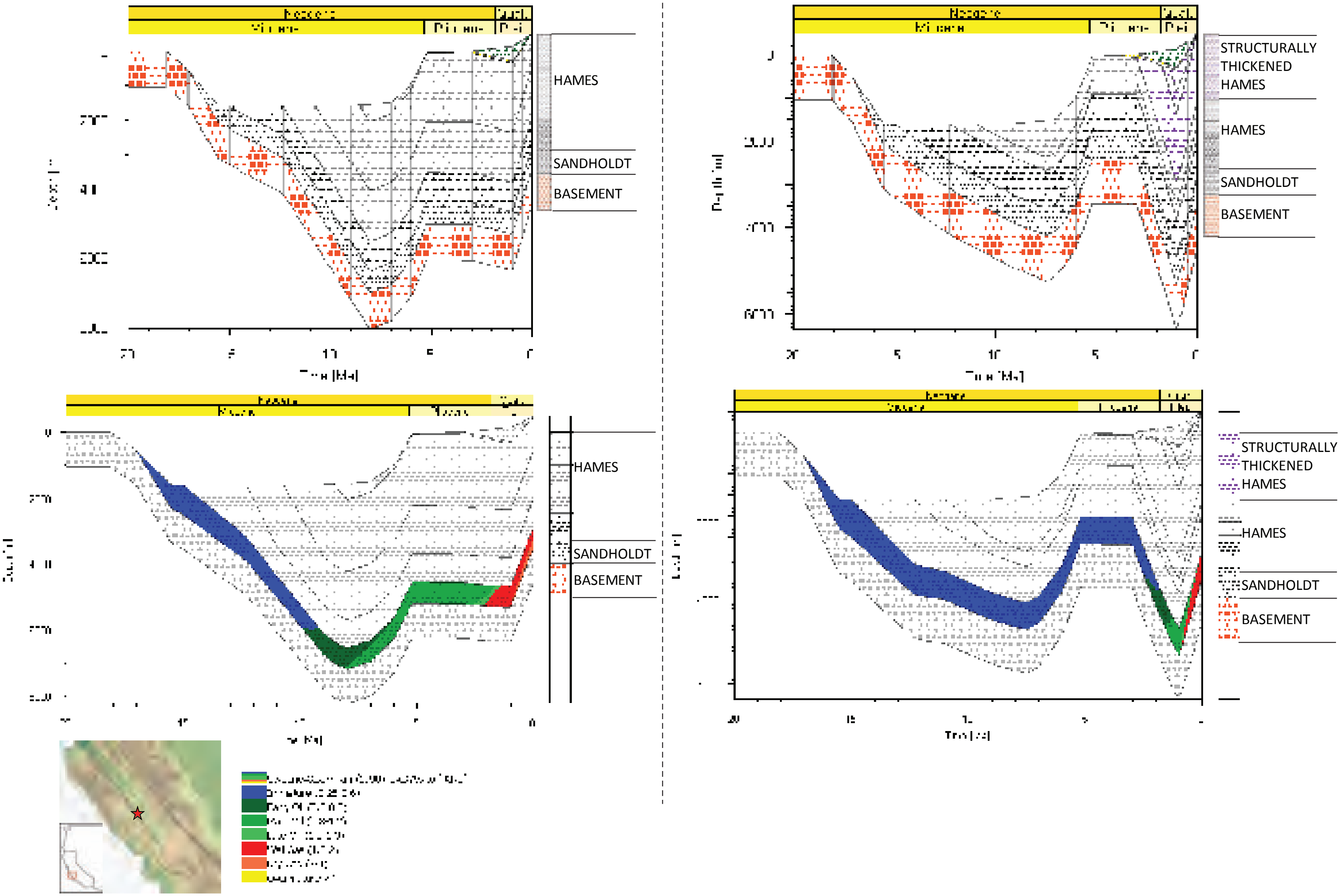


Figure 6. Burial history diagrams with thermal maturity of source rocks (Sandholdt and lower Hames Members of Monterey Formation) highlighted. Burial histories on the left assume thickness of Monterey is entirely stratigraphic. Burial histories on the right assume late-stage structural thickening of the Monterey, resulting in delayed maturation of the source rock (Menotti, 2010).

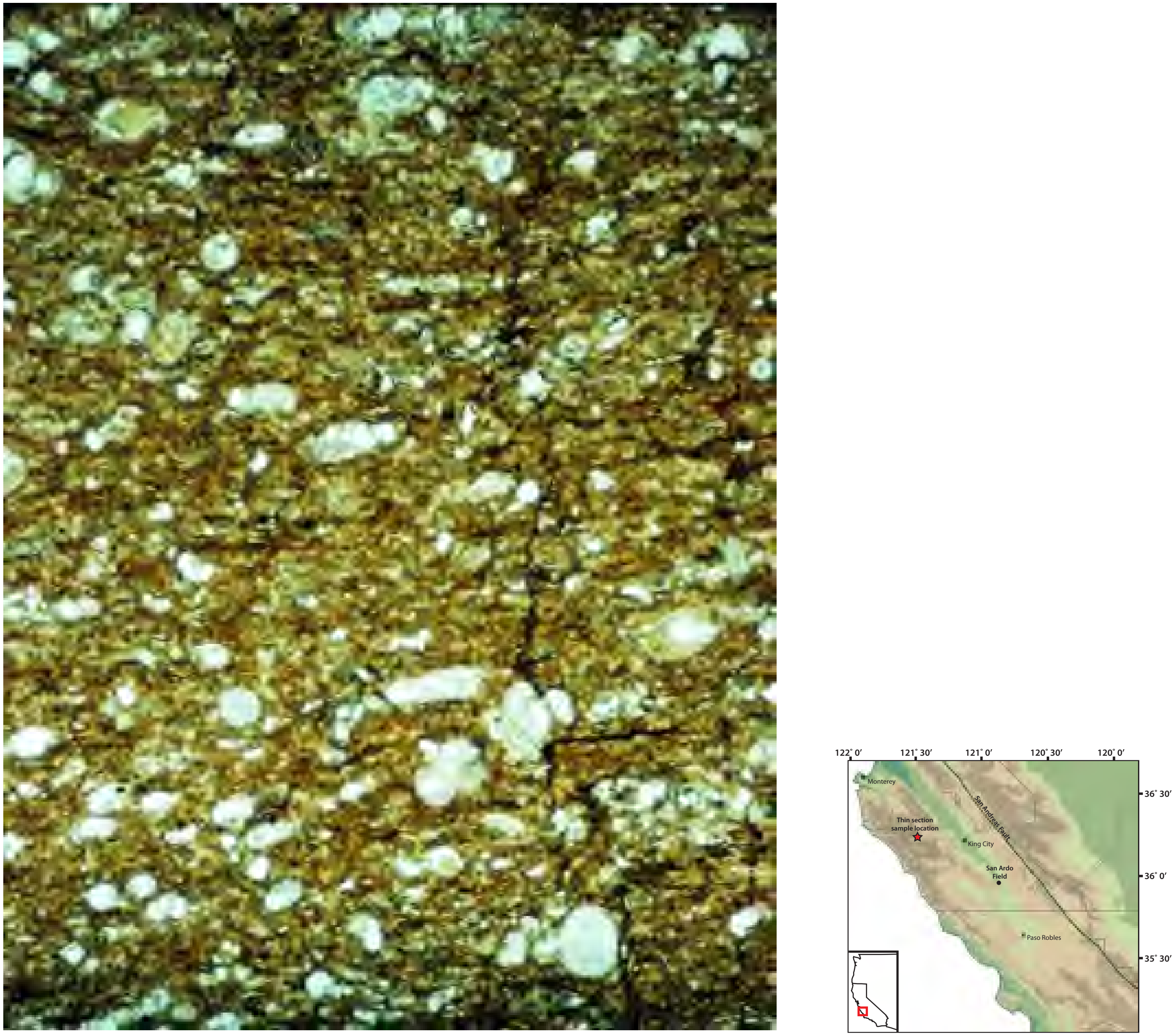


Figure 7. Thin section photomicrograph of lower-middle Miocene oil-prone source rock from the Arroyo Seco (STOP 1). White objects are foraminifer tests. TOC 4%, Tmax 420°.

SCHEMATIC STRATIGRAPHIC SECTION-SANDHOLDT MEMBER
MONTEREY FORMATION, ARROYO SECO AREA.
SANTA LUCIA MOUNTAINS, CALIFORNIA

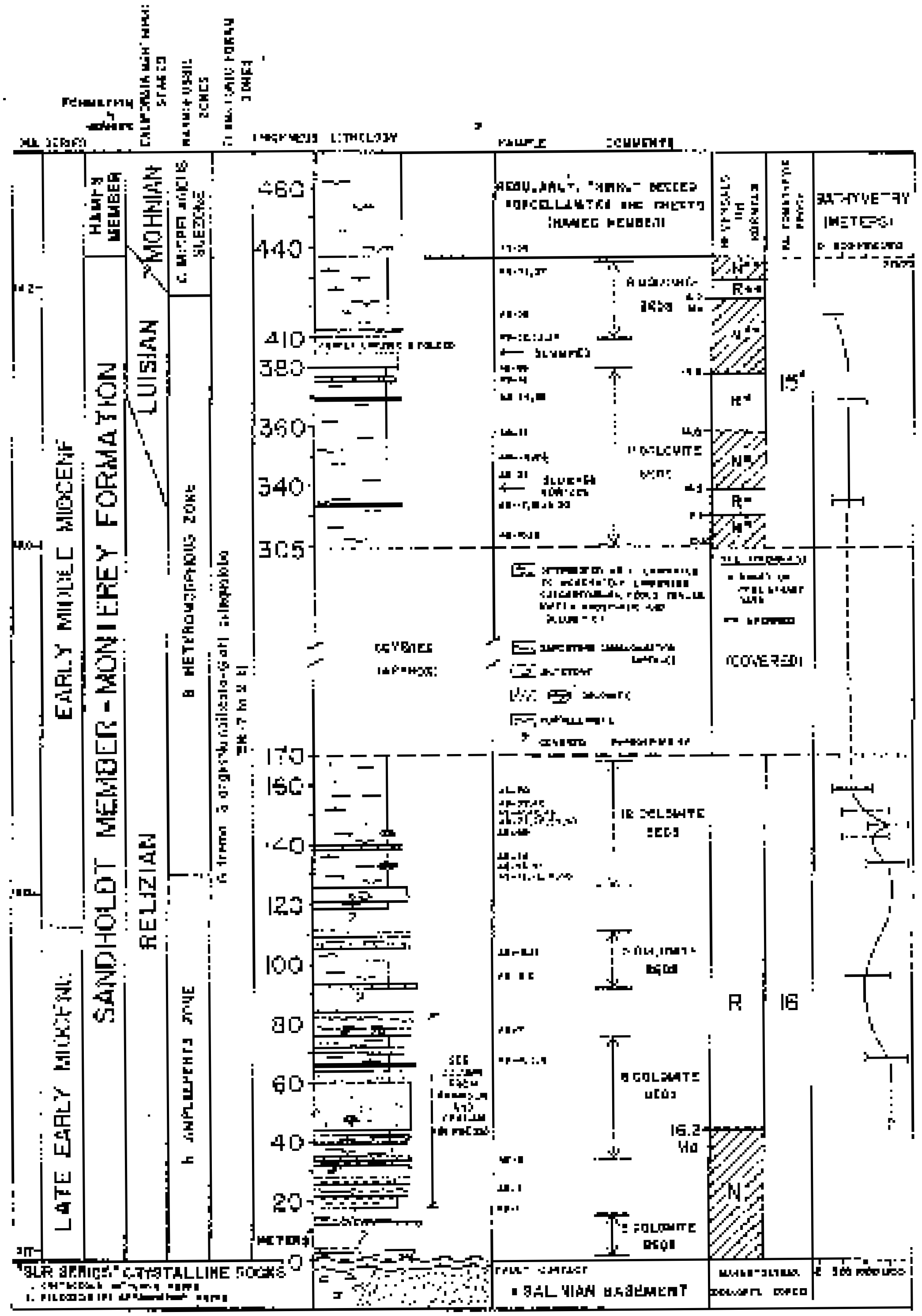
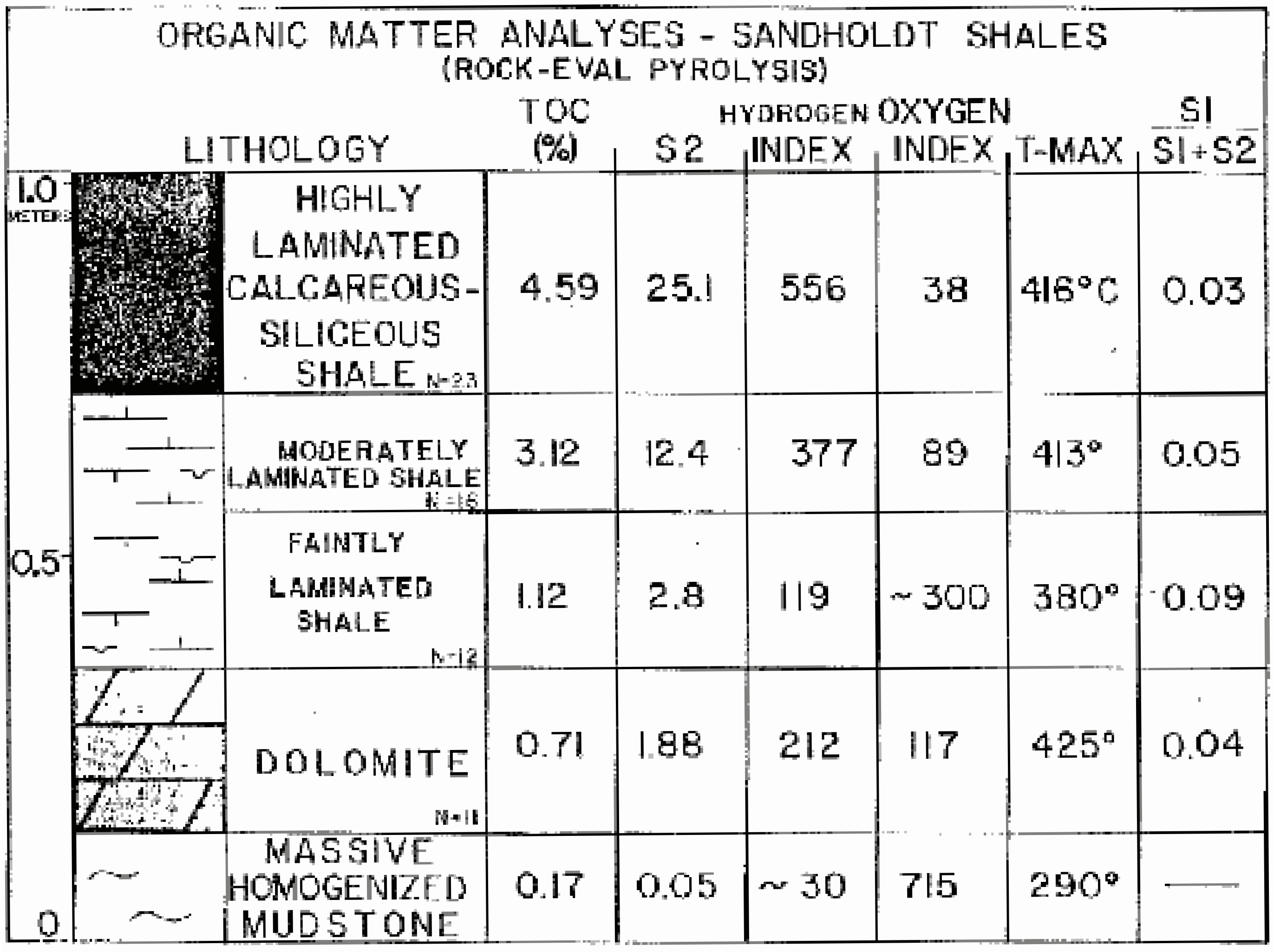


Figure 8. Stratigraphy of the lower Monterey Formation as exposed at Arroyo Seco Picnic Grounds (after Mertz, 1984).



ORGANIC MATTER ANALYSES - SANDHOLDT SHALES
(ROCK-EVAL PYROLYSIS)

	LITHOLOGY	TOC (%)	S2	HYDROGEN INDEX	OXYGEN INDEX	T-MAX	SI / SI+S2
1.0 METERS	HIGHLY LAMINATED CALCAREOUS-SILICEOUS SHALE N=23	4.59	25.1	556	38	416°C	0.03
	MODERATELY LAMINATED SHALE N=16	3.12	12.4	377	89	413°	0.05
0.5	FAINTLY LAMINATED SHALE N=12	1.12	2.8	119	~ 300	380°	0.09
	DOLOMITE N=11	0.71	1.88	212	117	425°	0.04
0	MASSIVE HOMOGENIZED MUDSTONE	0.17	0.05	~ 30	715	290°	——

Figure 9. Summary of organic characteristics of lithofacies of the lower Monterey Formation (Sandholdt Member), Salina basin (after Mertz, 1984).

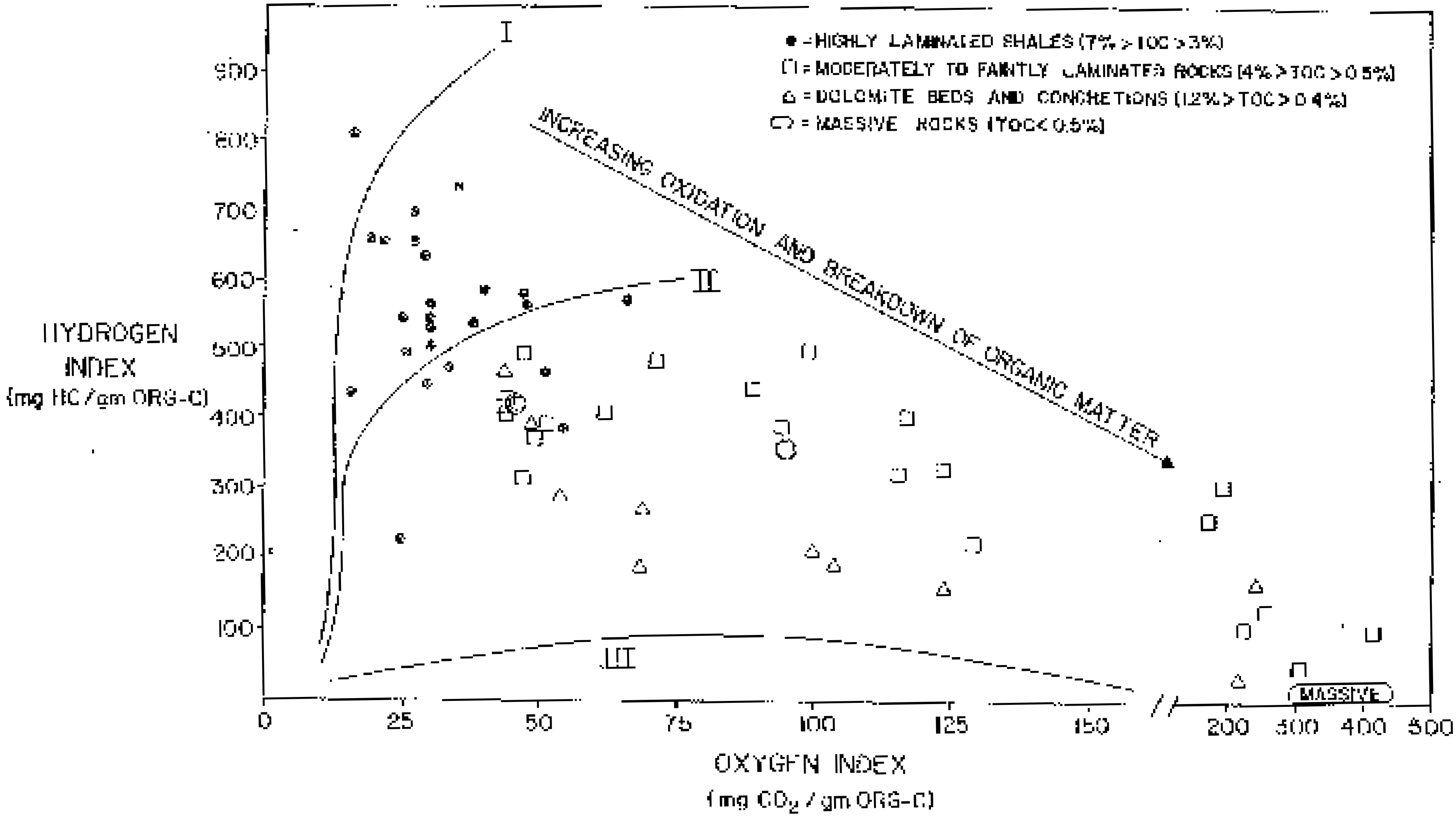


Figure 10. Summary of organic characteristics of lithofacies of the lower Monterey Formation (Sandholdt Member), Salina basin (after Mertz, 1984).

Figure 11. Exposure of the Reliz-Rinconada fault at Arroyo Seco bridge (STOP 2).

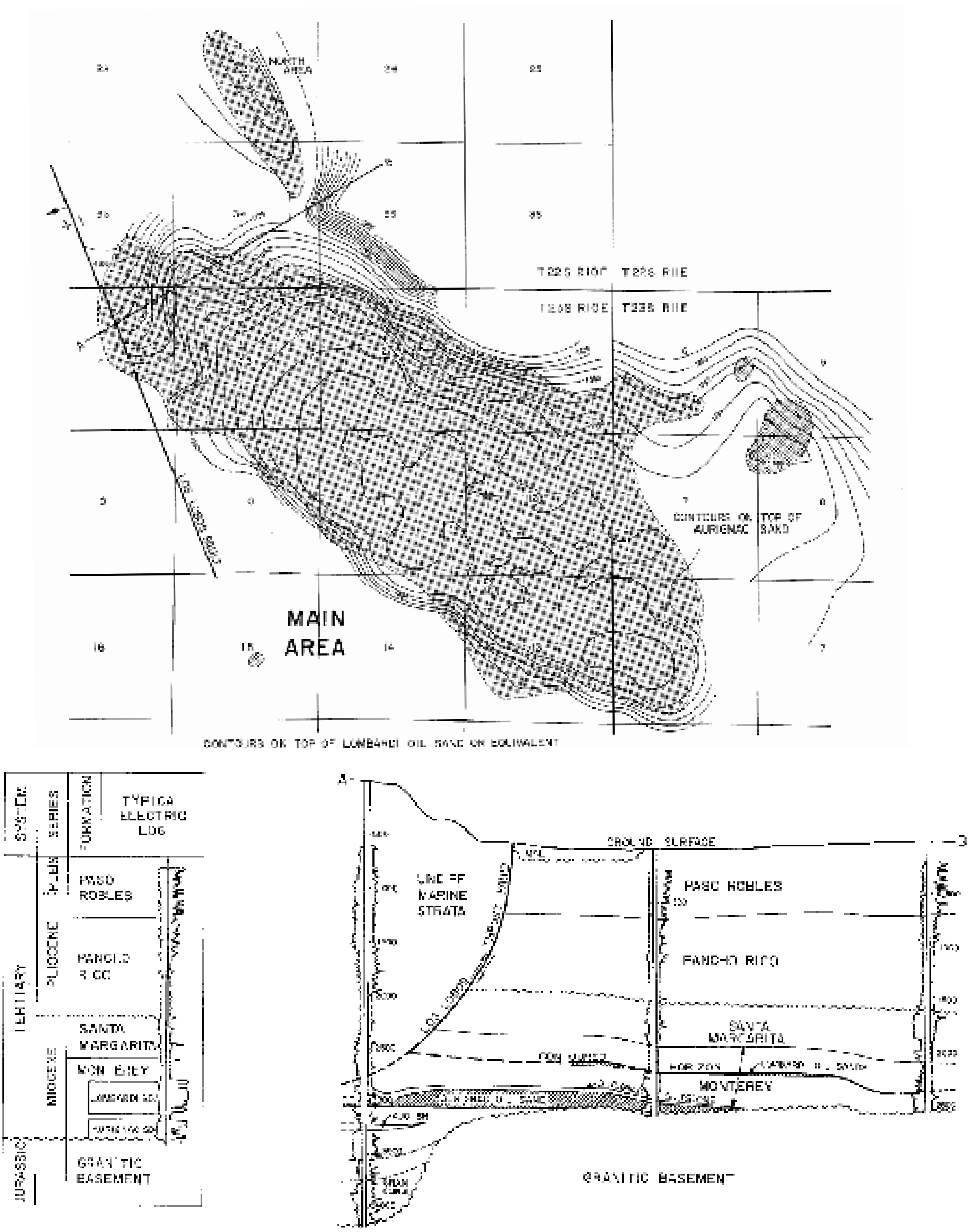


Figure 12. Structure of San Ardo oil field (California Division of Oil and Gas, 1973; STOP 4).

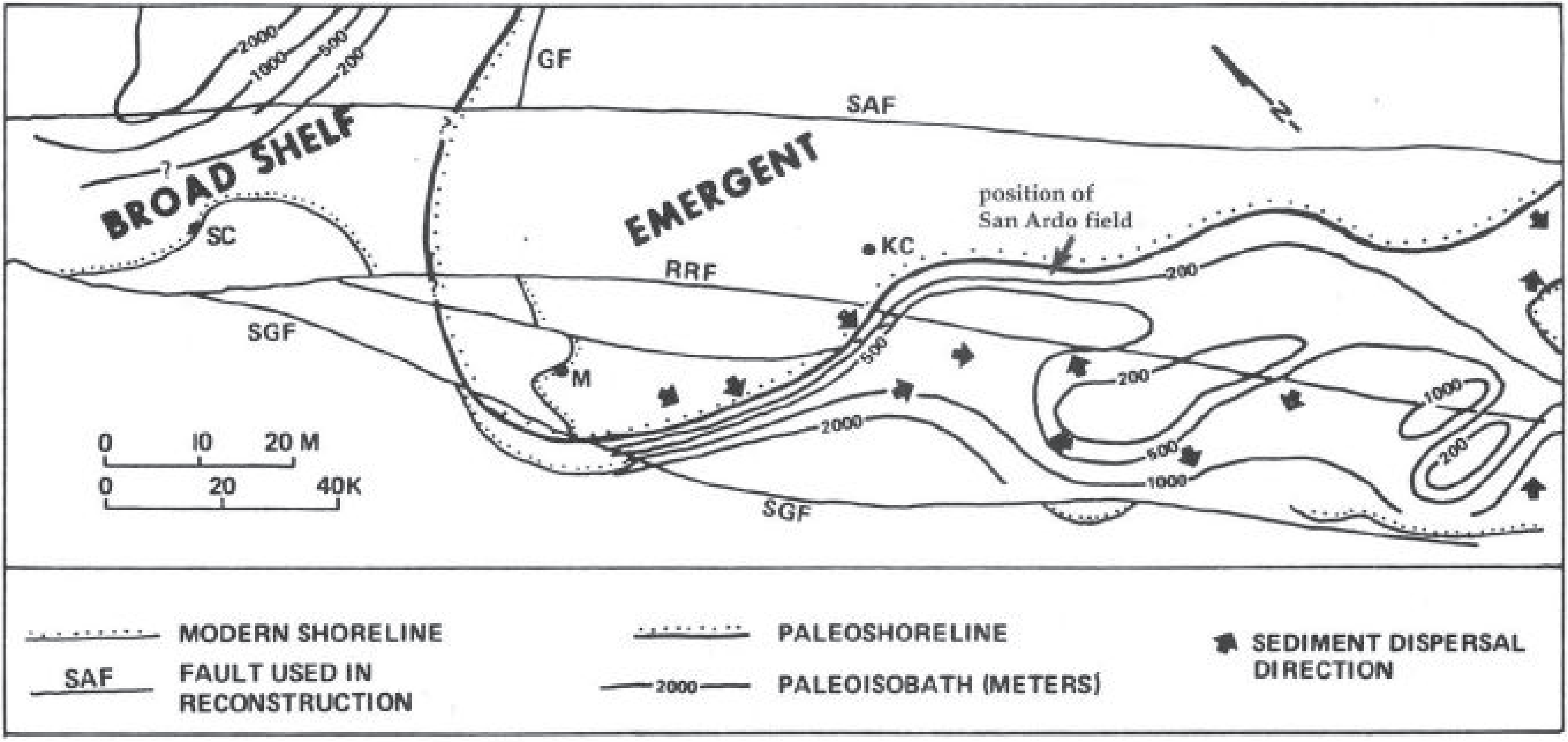


Figure 13. Reconstruction of the paleogeography of central California in the middle Miocene. Right-slip has been restored on the San Andreas (SAF), Reliz-Rinconada (RRF), and San Gregorio-Hosgri (SGF) faults. KC=King City, M-Monterey, SC=Santa Cruz. After Graham (1976).

Figure 14. Intensely folded upper Miocene Monterey Formation exposed just north of Nacimiento Dam (STOP 3d).

Figure 15. Tar-filled Plio-Pleistocene fluvial clastics overlying Monterey Formation along CR G19 near San Antonio Dam (STOP 3b).