THE SALINAS BASIN, CENTRAL CALIFORNIA: A PETROLEUM SYSTEM IN OUTCROP

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Introduction

The Salinas River Valley and adjacent Santa Lucia Mountains of central California, U.S.A., offer a unique opportunity to observe a petroleum system expressed in outcrop. Although the majority of the Salinas Basin remains at depth (~4 km maximum burial; Compton, 1966), a shift in relative motions of the Pacific and North American tectonic plates uplifted portions of sedimentary basins along coastal California during late Neogene time (Atwater and Stock, 1998). This is manifested in the western Salinas Basin as the Santa Lucia Range. As a consequence of this uplift, petroleum system elements, such as the source rocks of the Monterey Formation (Fm), are now accessible as outcrop exposures, while their subsurface equivalents charge the giant San Ardo oil field. This and adjacent fields comprise a proven conventional petroleum play that drives Salinas Basin oil production. San Ardo field, discovered in 1947, has in excess of 500 million barrels of recoverable oil, ranking it as the eighth largest producing oil field in California (DOGGR, 2010). While production of heavy oil (~10-13° API gravity) at the San Ardo field and adjacent fields continues, the prospect of unconventional resource potential led to a recent resurgence of exploration interest in the basin. The economic viability of a fractured reservoir play in the Monterey Fm remains unknown and the play unproven.

We present excursions to the Northern and Southern Salinas Valley, which together provide an overview of petroleum system elements in the context of a strike-slip basin. Outcrops of uplifted and tilted sedimentary cover border the basin's western edge (Figure 2a). Observing these exposures allows one to identify and evaluate petroleum system elements, to characterize known hydrocarbon accumulations, and to assess the probability of undiscovered subsurface accumulations. The Salinas Basin is of particular significance to California petroleum exploration and assessment because this basin offers insights into the petroleum potential of offshore central coastal areas (e.g., Sur Basin, northern Santa Maria Basin), which are underexplored and lack well control. Petroleum system components represented in this field trip include: (1) multiple facies of thermally immature source rock (Stop 1.1), (2) regional and localized structures (Stops 1.2 and 1.4), (3) ~1 km-thick exposures of overburden rock (Stop 1.2), (4) migrated biodegraded oil in fractures and matrix porosity (Stop 1.5), and (5) production operations at the San Ardo oil field (Stop 1.6; see Figure 3 for a location map).

General Access

This guide leads you sequentially through the components of a petroleum system, guiding the participant through three stops at the northern end of the Salinas Basin, then progressing south for the final three stops. The entire trip can be accomplished in one full day, covering a driving distance of ~98 miles. All stop locations are on public property including the Arroyo Seco Day Use Area in the Los Padres National Forest (nominal entry fee) and county roads (Monterey and San Luis Obispo counties). Several stops are located near reservoir dams and an active oil field, however the suggested viewing locations are along public roads (permissions and permits are not required). On the 2015 BPSM Field Trip, we are getting special permission to access safe parking areas located beyond locked gates.

Equipment & Safety

This field excursion requires minimal walking as all locations are accessible by vehicle. Sturdy walking shoes are recommended. Locations are accessible via paved roads, and many stops are roadside. Due to road proximity, fluorescent safety vests and/or traffic cones are recommended to alert traffic to your presence. Additional suggested equipment includes: long pants (protection against thorny plants and poison oak), sun hat, sunglasses, sunscreen, and plenty of drinking water.

Central California is a fairly benign region, but there are a few hazards of which to be aware: poison oak (produces an oil that is irritating to the skin of some people), rattlesnakes, ticks, deer (hazards while driving), and high fire danger given frequent drought conditions. Please refrain from smoking and avoid parking over dry grass. In the event of an emergency, the nearest hospital is located in the town of King City: George L. Mee Memorial Hospital, 300 Canal St., King City, CA 93930.

There are few towns along the field trip route, therefore we recommend starting with a full tank of gas and your food and water provisions for the day. Rest stop locations, restaurants and lodging are in the towns of Greenfield, King City and Paso Robles.

Regional Geology

The Salinas Basin is located in the Coast Ranges province of central California. This elongate basin stretches NNW-SSE and parallel to the transform plate boundary between the North American and Pacific plates. The basin resides on the Salinian tectonic block, which is between two strike-slip faults: the San Andreas fault on the east and the Sur-Nacimiento fault on the west. Beginning in latest Cretaceous time, a strike-slip fault system structurally translated the Salinian block from ~400 km to the southwest of its present-day location (Dickinson and Butler, 1998; Sharman et al., 2013). Strike-slip tectonism dominated the Cenozoic tectonic regime of California, leading to the development of a marine borderland setting and the formation of en echelon pull-apart style basins during late Oligocene-early Miocene time (Nilsen and Clark, 1975). A shift to a transpressional tectonic setting drove uplift and structural deformation of Salinas Basin beginning at end Pliocene time (Page et al., 1998). These tectonic events are recorded by a Neogene succession of predominantly marine facies overlaying pre-Oligocene economic basement. Geologic ages, dominant lithologies and corresponding water depths of the

Neogene-Recent basin fill are noted in Figure 4.

The dynamic tectonic history profoundly impacted the development of the petroleum system by:

1) defining initial basin configuration and depositional setting,
2) rapidly creating abundant accommodation for source rock and overburden sediment accumulation, and
3) structurally deforming the basement and sedimentary cover, resulting in formation of migration pathways, traps and fractured reservoirs.

This field guide leads the participant through explicit examples of these key components of the basin's history.

Overview of the Petroleum System in the Salinas Basin

The petroleum system in the Salinas Basin exists almost entirely within the Miocene Monterey Formation (Figures 1, 5). The Monterey Fm is composed of two main units (the Sandholdt and Hames Members) and blankets nearly the entire basin with bathyal to shelfal facies. This field trip explores variations in lithofacies and related geochemical and rock properties within the Monterey Fm, as well as the role that structural deformation plays on modifying or creating additional petroleum system components (e.g., migration and trapping mechanisms, overburden enhancement).

This trip includes the following petroleum system components:

1. Source Rock: Sandholdt Mbr of the Monterey Fm; oil-prone organic matter in marine shales – Stop 1.1
2. Overburden Rock: Hames Mbr of the Monterey Fm; sedimentary basin fill – Stops 1.3 and 1.4 (we are omitting stop 1.3 on the 2015 BPSM Field Trip)
3. Reservoir & Seal Rocks: Upper Miocene shallow marine facies of the Monterey Fm; interbedded shelfal sandstones and mudstones – Stop 1.6
4. Migration-Accumulation, Trapping: A variety of sedimentary and structural mechanisms – Stops 1.2, 1.5 and 1.6

Approximate Schedule for the day

7:30am	Leave Stanford University Lot L-39
10:00am	Arrive Arroyo Seco parking lot (stop 1.1)
11:00am	Arrive Reliz-Rinconada fault (stop 1.2)
11:45pm	Arrive San Lorenzo Park in King City; leave at 12:30pm
1:15pm	Arrive San Antonio Dam overlook (stop 2.3); leave at 1:45pm
2:15pm	Arrive Nacimiento Dam fold stop (stop 1.4); leave at 2:45pm
3:00pm	Arrive tar sand, fractured chert (stop 1.5); leave at 3:30pm
4:00pm	Arrive overlook San Ardo Field (stop 1.6); leave at 4:30pm

Arroyo Seco

Access: The Arroyo Seco Day Use Area (36° 14' 10.14" N, 121° 28' 44.47" W) is located in the Los Padres National Forest, approximately 17 mi drive west from the town of Greenfield, CA. This is the location of the first stop for this excursion; directions to subsequent stops are described between stop descriptions.

From locations north of Salinas Valley, follow U.S. Route 101 S to Exit 301/Arroyo Seco Rd (~29 mi south of Salinas, just north of Greenfield). Continue on Arroyo Seco Rd (1.3 mi), then keep left to continue on Arroyo Seco Rd (14.9 mi). At the Y-shaped intersection with Carmel Valley Rd, bear left to continue on Arroyo Seco Rd (4.5 mi). Arrive at the entrance kiosk to the Arroyo Seco Recreation Area and Los Padres National Forest. Be prepared to pay a park entrance fee ($5-10). Cross the bridge and turn right into the Day Use Area parking lot.

STOP 1.1 Source Rock: Sandholdt Mbr of the Monterey Fm
36° 14' 10.14" N, 121° 28' 44.47" W

This stop combines outcrop exposures in three different locations, all within walking distance of one another: Stop 1.1a, Stop 1.1b and Stop 1.1c.

Sandholdt Mbr Overview
The presence of source rock is the key to hydrocarbon accumulation in the Salinas Basin. A rim of outcrops along the basin's western edge exposes the source rock: the Sandholdt Mbr of the Monterey Fm (Figures 2a, 4). The combination of high organic richness, favorable kerogen types (I and II), thickness and lateral extent, and subsurface thermal maturity (Mertz, 1984; Marion, 1986) suggest that the Sandholdt Mbr is a viable source rock for oil generation in this basin.

Stratigraphically, the Sandholdt Mbr overlies the Vaqueros Fm, reflecting an abrupt deepening in marine waters from the shallow marine setting during Vaqueros time to upper middle bathyal water depths (500-1500 m) by middle Miocene time. During this period, the continental shoreline was in excess of 200 km east of its current position, and the Salinas Basin was consequently isolated from much of the terrigenous sediment shed from the mountains to the east. Instead, mainland-derived siliciclastic sediments were captured by the deep-marine San Joaquin Basin to the east. The restricted shape of the Salinas Basin minimized the influx of oxygenated ocean currents. Upwelling waters provided nutrients for phytoplankton growth, resulting in production of copious organic matter, which further drove conditions to anoxia (Pisciotto and Garrison, 1981). This, combined with the absence of detrital input, created an ideal setting for accumulation and preservation of organic matter.

Extent of Sandholdt Mbr
The Sandholdt Mbr is mapped north-to-south over the entire length of the basin and onlaps onto granitic basement eastward at the Gabilan shelf edge. The thickness of the Sandholdt Mbr ranges from up to ~900 m in the north to ~240 m in the southern region of the basin (Durham, 1974).

Geochemical Properties
The source rock quality of the Sandholdt Mbr of the Monterey Fm is largely facies-dependent (Mertz, 1984). Generally, facies comprising highly laminated shales contain an abundance of total organic carbon (TOC; 4-7 wt %) having relatively high hydrogen indices (HI; 500-810 mg HC/TOC) and low oxygen indices (OI; 15-30 mg HC/TOC), indicating that this source rock facies contains oil-prone Types I and II kerogen (Figure 6). Tmax values derived from Rock-Eval pyrolysis of outcrop samples range from 308-438 °C, and vitrinite reflectance (Ro) is in the range of 0.31-0.59% (Mertz, 1984). The minimum threshold for thermal maturity (and entry into the "oil window") is Tmax of 435 °C and Ro of 0.6% (Peters and Cassa, 1994). Thus, although the uplifted source rock here is organic-rich and oil-prone, it is thermally

immature. However, well data show that the Sandholdt Mbr of the Monterey Fm is buried 1.7 km below the surface approximately 20 km east of this location. Historical 1950's exploratory wells that penetrate the entire Monterey Fm at this locale have Tmax of up to 442°C, placing the source rock in the early oil window (Marion, 1986). A Tmax of 442 °C requires several kilometers of burial, which is accomplished in part by the very thick accumulation of upper Miocene strata. The base of Monterey Fm contour map in Figure 2b illustrates the impressive degree of burial in the eastern Arroyo Seco area since mid-Miocene time, as well as a deep structural trough in Hames Valley to the south. Thus, the main kitchen (or pod of active source rock, after Magoon and Dow, 1994) is in the Hames Valley trough, and a secondary kitchen underlies the eastern Arroyo Seco area.

Observe at Stop 1.1 – Lithostratigraphy

The Sandholdt Mbr is characterized by well to moderately-laminated, organic-rich hemipelagic and turbiditic shales interbedded with authigenic dolostone lenses and concretions (Figures 7, 8). The dolostone units protrude from the outcrop as well-indurated beds that weather to a distinct orange color. The Sandholdt Mbr contains authigenic phosphate (apatite) nodules and lenses and benthic foraminifera. Forams are easily detectable with a hand lens; the phosphate nodules and lenses are visually apparent. Much less common are re-deposited sediments such as coarse-grained turbidites and muddy debris flow deposits. The Sandholdt section in the Arroyo Seco area is nearly complete, although the basal section is in fault contact with crystalline basement. This suggests that there may be missing section at the base. The section at this locality is ~440 m thick (Figure 7). This guide leads you through 80 m of that section, beginning roughly 90 m above the base of the Sandholdt Mbr. Beds generally dip to the E and SE at ~30°.

STOP 1.1a (36° 14' 11.92" N, 121° 28' 51.73" W)

Access: From the parking lot, walk west on a footpath along the southern bank of the river. You will pass a USGS rain gauge station. A ~5 m tall outcrop of mudstone, shale, and dolostone outcrop is freshly exposed along the riverbank.

Return: To access Stop 1.1b, retrace your steps along the footpath, then cross the parking lot to its opposite (southeastern) end. Walk up to the paved parking lot entrance and cross over Arroyo Seco River on the bridge. Once on the opposite (eastern) shore, proceed to a foot trail on the upstream side of the bridge just beyond the park entrance kiosk. Follow this trail northward and upstream, along a tall bluff of the Sandholdt Mbr beside the riverbank.

STOP 1.1b (36° 14' 9.83" N, 121° 28' 39.17" W)

Access: To view the section in stratigraphic succession, walk as far upstream as the outcrop exposures extend, then turn and retrace your steps to walk upsection.

Return: To access the final location at this stop, retrace your steps back over the bridge to the western shore, and walk down toward the parking lot to the river bank. Continue southward along the river bank in the downstream direction, crossing under *the bridge.*

STOP 1.1c (36° 14' 7.32" N, 121° 28' 40.08" W)
Access: Walk downstream and upsection over banks of freshly cut Sandholdt Mbr bedrock. Proceed downstream no more than ~50 m from the bridge.

Return: This concludes Stop 1.1. To proceed to Stop 1.2, return to the vehicle and depart from the Arroyo Seco Day Use Area, retracing the Arroyo Seco Rd toward Greenfield. From the Arroyo Seco Day Use parking lot, drive 11.2 mi east on Arroyo Seco Rd to the intersection with Elm Ave / County Rd G16 (36° 16' 48.11"N, 121° 19' 35.41" W).

STOP 1.2 Basin Structure & Potential Petroleum Migration Pathway: Reliz Fault
36° 16' 52.07" N, 121° 19' 22.34" W

To access this roadside outcrop, park your vehicle on the broad shoulder of Arroyo Seco Rd just before or after the junction with Elm Ave. Do not park in front of any private road gates or entryways, and avoid "No Parking" areas. Carefully walk down the hill along Elm Ave toward the trellis bridge that crosses the Arroyo Seco. The outcrop is exposed in the river terrace on this shore directly across from the bridge.

Reliz-Rinconada Fault (RRF)
The RRF is a composite of fault segments that bisects the Salinas Basin (Figure 2b). A number of cross-fault ties suggest this fault has accrued ~40 km of dextral strike-slip separation and 2-3 km of dip-slip since late Miocene time (Dibblee, 1976; Graham, 1976). Offset of this magnitude resulted in rearrangement of generative source rock in the basin, placing part of the original kitchen in close proximity to the northern swath of upper Miocene shelf sandstones. The RRF also aligns with the boundary between the basin's significantly uplifted western zone and the central region that remains close to maximum burial depth. The transpressional stresses applied to this region in late Neogene time were partly accommodated through dip-slip along the RRF (Dibblee, 1976).

Fault offset of this magnitude not only profoundly changed the basin geometry, but introduced a possible conduit for secondary hydrocarbon migration. Given the fortuitous placement of the fault through the once whole paleodepocenter and therefore its direct connection to the hydrocarbon source, the RRF is a critical factor for evaluation of the Salinas Basin petroleum system (Menotti et al., 2012). The degree of fault permeability is unclear, as evidence of migrated oil is lacking in the fault zone. However, well-exposed surficial expressions of the RRF are very uncommon (this outcrop being the exception) and undocumented occurrences are possible. Alternatively, impermeable fault properties may be hypothesized. Such uncertainty can be addressed with numerical modeling by testing a range of fault properties (Menotti et al., 2012).

Observe at Stop 1.2
An impressive outcrop of the Reliz segment of the RRF is exposed in the terrace bench on the northern bank of Arroyo Seco River. The fault dips at a high angle (~70°) to the southwest and juxtaposes Monterey Fm on the hanging wall block against Pliocene Pancho Rico Fm in the footwall (Dibblee, 1976). Fault breccias and drag folds are observed in the ~2 m wide fault zone. From the far (southern) side of Arroyo Seco River, the suggestion of a fault trace is identified as a topographic expression to the NNW, at the base of the Sierra de Salinas mountains (Figure 9a).

Return to the vehicle parked on Arroyo Seco Rd. Directions to **San Lorenzo Regional Park, King City** (lunch stop).

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.

STOP 2.3 Lake San Antonio Dam Overlook of Hames Member, Monterey Fm.
35°47'43.08"N, 120°53'18.40"W

*From the park, head east on San Antonio Dr. Turn right on Broadway St and merge onto US-101 S. Continue on US-101 S to Exit 252 / Jolon Rd (30 mi). (Note: this is the second of the two Jolon Rd exits off US 101 S.) After exiting, turn right on Jolon Rd/County Rd G18, followed by a quick left on Nacimiento Lake Dr / County Rd G19. Continue on Nacimiento Lake Dr, crossing over the San Antonio River via a small trellis bridge (at ~5 mi from Jolon Rd intersection). Continue west on Nacimiento Lake Dr., following the river until you reach a gated service road at San Antonio Dam. **Follow lead vehicle up the service road to a parking area requiring special permission.***

From this overlook location, the vast deposited thickness of the Monterey Formation can be appreciated. The view north affords the opportunity to see the upper portion of the very thick section of biosiliceous, fine-grained Monterey Formation that fills the basin depression west of San Ardo field, and to gain some sense of the thickness of the potential source-rock section. 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 1.2!

Hames Mbr Overview
The Hames Mbr of the Monterey Fm is the main contributor of overburden rock in the Salinas Basin: 2-3 km of overburden rock overlies the source rock in the depocenters. This degree of burial in Arroyo Seco/Reliz Canyon and the Hames Valley areas has led to organic matter maturation sufficient for oil generation. Generation potential is confirmed for source rock in both kitchens by Rock-Eval pyrolysis data and 1-D basin models (Figure 10; Marion, 1986; Menotti, 2010; Menotti et al., 2012). However, despite the promising maturity of subsurface source rock, as well as the minor occurrences of migrated oil in outcrops and wellbores in the Arroyo Seco area, there are no commercial accumulations of oil west of the RRF. Because the oil prospectivity west of the RRF has been degraded by late Cenozoic uplift and contractile deformation, recent exploration focuses on the Hames Valley area, west of the San Ardo oil field.

The Hames Mbr marks a transition from deposition dominated by calcareous sediments to dominantly siliceous sediment deposition. The shift in facies, as well as the appreciable thickness of the Hames Mbr, is explained by an explosion of diatom productivity due to global mid-Miocene climatic cooling and increased ocean basin margin upwelling (Pisciotto, 1978; Graham, 1978; Ingle, 1981).

Extent & Surface Expression
The Hames Mbr blankets much of the basin. West of the RRF, cliffs of the unit commonly line the Arroyo Seco and tributary drainages, including Reliz Canyon. A broad spine of the Hames Mbr extends part-way down the center of the basin, with

the RRF at its core (Figure 2a). In the Salinas River Valley, east of this ridge line, nearly all of the Hames Mbr exists in the subsurface and is extensively penetrated by wellbores. Farther east, age-equivalent units drape over the raised basement of the Gabilan shelf. These strata record a transition into shallow marine facies from the basinal facies deposited to the west (Figure 5). The Hames Mbr reaches over 2000 m thickness in the Reliz Canyon and Hames Valley areas, but is generally thinner elsewhere (~300-600 m; Durham, 1974).

Points of interest en route to this stop

1. While driving south on US 101, you will pass the San Ardo oil field to your left (east). You will return to this location for your final stop.
2. The diatomaceous diagenetic facies of the biosiliceous Monterey Fm is exposed in the light buff-colored outcrops in the hills near the bridge over the San Antonio River. This unit is informally referred to as the Buttle Diatomite.

STOP 1.4 Structural Deformation: Folded Monterey Fm.

35° 45' 40.97" N, 120° 53' 7.34" W

Access: Nacimiento Dam is located at the southern end of the Nacimiento Reservoir. From the San Antonio Dam overlook, descend down the hill to the main road and turn right onto Nacimiento Lake Dr. Drive on Nacimiento Lake Dr and turn right into Nacimiento Dam utility access area, just beyond two hairpin turns and before the dam itself (3.1 mi from right turn onto Nacimiento Lake Dr. by San Antonio Dam).

After parking your vehicle, walk back up the hill on the shoulder to the outcrops along the hairpin turns. This exposure highlights the severity of structural deformation in the sedimentary cover in some localities, which formed in response to late Cenozoic transpressional events (Dibblee, 1976). A change in pole-of-rotation of the Pacific and North American plate pair at the end of Miocene time (between ~6 and 8 Ma, and possibly as late as 3.5 Ma; Page et al., 1998) led to extensive folding and uplift of the Salinas Basin. This deformational event contributes to the petroleum system in four primary ways:

1. Tightly folded strata (Figure 9b-d) overlying the source rock increase overburden thickness, adding to the primary overburden from sediment deposition.
2. Tectonism responsible for the folds induced brecciation and fracturing of the brittle strata within the Monterey Fm. These deformation features contribute to oil migration by providing secondary permeability pathways.
3. Transpressional tectonism caused inversion of the basin, removing the sedimentary cover in its entirety in some places. Eroded material must be accounted for when modeling burial history.
4. Folds and faults formed in reservoir sandstones on the Gabilan shelf in response to the late Cenozoic contractile tectonism. These structural features become traps for migrating hydrocarbons.

Observe at Stop 1.4
The north side of the road exposes isoclinal folds developed in thin-bedded, fine-grained biosiliceous Monterey Fm. Although the lithostratigraphy at this location is consistent with the Hames Mbr of Reliz Canyon, these strata are age-equivalent to the Sandholdt Mbr in the Arroyo Seco area.

The tight isoclinal geometry of this unit is accomplished by layer-parallel slip between thin beds of contrasting lithologies where the brittle porcelaneous beds glide past one another along very thin shale partings to accommodate shortening (Figures 9c, 9d). This exposure also demonstrates how more competent dolostone lenses influence fold geometry and position, given its resistance to plastic deformation (Figure 9c). Other notable structural features include bed-scale reverse faults and differential compaction of fine-grained siliceous layers around dolomitized concretions.

*Return to the parked vehicle, turn around, and follow Nacimiento Lake Dr / County Rd G19 back the way you came (3.1 mi). At the T-intersection, turn right to continue on Nacimiento Lake Dr / County Rd G19 (you are passing the San Antonio Dam on your left) and continue to a short (~4 m tall) sloping outcrop of dark brown sandstone on the right side of the road (0.3 mi). Approach this slowly as it is difficult to locate. There is a broad shoulder on the left side of the road. Carefully cross traffic and park here. **Follow lead vehicle into parking area requiring special permission***

STOP 1.5 Exhumed Oil Field & Migrated Oil in Fractures: Paso Robles and Monterey Formations

35° 47' 35.94" N, 120° 51' 58.90" W

Cross the road to the exposure of NE-dipping Pleistocene Paso Robles Fm (to the east) and Monterey Fm (to the west). The unconformity separating these units is slightly obscured by modern weathering and vegetation. Locate a small shrub (~ 1-2 m tall) growing halfway up the outcrop (Figure 11a).

The accumulation of hydrocarbons in the Salinas Basin is hampered by the lack of coarse-grained reservoir beds in the basinal facies of the Monterey Fm. Instead, conventional oil accumulation is mainly restricted to shallow marine sandstone units that occur as a broad swath along the eastern flank of the basin (e.g., San Ardo oil field). The lack of higher permeability coarse-grained units connecting mature source rock to reservoirs also hinders hydrocarbon migration. Oil migration in this basin therefore relies on a combination of fracture networks and faults within the Monterey Fm, in addition to a zone of weathered granite along the basement-Monterey Fm contact.

This location lies near Hames Valley, which overlies the thickest accumulation of Monterey Fm in the basin (Figures 1, 2b, 5, 10b) and the main pod of active source rock. The exposure here provides evidence for oil migration (originating many kilometers below) along fracture planes in porcelanite. This outcrop is a window into plausible processes influencing the petroleum system in the subsurface: (1) the oil-lined fractures overlain with oil-saturated sandstone are small-scale examples of a charge mechanism for San Ardo oil field, less than 15 km to the north and (2) oil saturation of fracture porosity suggests the possibility of an exploration play in fractured shale.

This location also elegantly encapsulates the temporal relationships among petroleum system processes. Episodic uplift and burial produced a chronologic sequence documented in (1) the unconformable contact between the units, (2) the intraformational clasts within the sandstone, (3) the presence of fractures in the porcelanite and chert, and (4) the final surface expression of these strata. The unconformity not only reflects late Cenozoic evolution of the basin from deep-marine to subaerial environments, it also dates contractile deformation that formed an anticlinal structure at the San Ardo oil field location.

Observe at Stop 1.5

The unconformable contact between the upper Miocene Monterey Fm and the Plio-Pleistocene Paso Robles Fm is exposed here. Degraded migrated oil fills fractures in the Monterey Fm (Figures 11b, 11c) and saturates the overlying coarse-grained, conglomeratic fluvial sandstone of the Paso Robles Fm (Figure 11d). Porcelaneous pebbles of recycled Monterey Fm are abundant in the Paso Robles Fm, indicating significant uplift and erosion of upper Miocene strata during late Pliocene and

Pleistocene time. This location is ~1.5 km east of the RRF, which just bypasses the San Antonio Dam to the west. Transpressional motion along this fault and related fault splays is likely responsible for the exhumation of this oil accumulation.

Return to the vehicle and carefully cross traffic to merge back onto Nacimiento Lake Dr / County Rd G19, heading east, back toward US 101 (6.6 mi). Turn right on Jolon Rd / County Rd G18, cross under the highway, and turn right onto the ramp for US 101 N. Drive on US 101 N to Exit 258 / Alvarado Rd (5.9 mi). You will see the San Ardo oil field on your right. Turn left to cross west over the highway, and proceed right and up to a locked gate. Park here for a panoramic view of the oil field.

STOP 1.6 Reservoir Rock, Trap Formation & Accumulation: San Ardo Oil Field

35° 56' 51.92" N, 120° 52' 38.80" W

San Ardo Field Overview

Due to the shallow depth of the San Ardo reservoirs (<1 km), the 10-13 °API gravity oil is moderately biodegraded and requires steam-assist procedures for effective recovery (DOGGR, 2010). From this eastward-facing viewpoint, you are on the hanging-wall block of the Los Lobos thrust fault, which is concealed here but mapped between the highway and the river. Petroleum migration to the San Ardo anticlinal structure relies primarily on the Los Lobos Fault, which connects the basal Monterey Fm units to these shallow reservoirs. Additional migration assistance is provided by the eastward basement-onlapping sub-Monterey Vaqueros Formation, in conjunction with basement normal faults. In addition to the San Ardo oil field, much smaller oil fields (six to eight) produce from age-equivalent shelfal sandstone units to the north, with production volumes of less than two million barrels of recoverable oil each (DOGGR, 2010).

Reservoir Stratigraphy

The reservoir and seal rocks occur within the shallow marine facies of the upper Monterey Fm. Mudstones interbedded with sandstone units (Figure 5) suggest fine-to-coarse, deepening-shallowing depositional cycles. This stratigraphic sequence is conducive to forming prospective reservoirs because it ensures that seal rocks cap all reservoir beds. The stacked arrangement of sandstones also simplifies production planning because multiple reservoir compartments can be accessed with a single vertical wellbore. On the other hand, the alternating stratigraphy complicates steam injection plans and must be considered when designing steam flood operations. The primary reservoirs at the San Ardo oil field are the upper Miocene Lombardi and Aurignac Sandstones. Good reservoir quality has been maintained due to their mature quartzo-feldspathic compositions (Graham, 1987) and shallow burial histories.

Trapping Mechanisms

The deepening-shallowing depositional cycles along the late Miocene shelf produced an eastward "shingling" of sandstone units in the basal section of the upper Monterey Fm. These sandstone pinch-outs form stratigraphic traps in some of the smaller oil fields in the basin. In addition, late Cenozoic transpression flexed and faulted the basement rock underlying the San Ardo field, doming the upper Miocene stratigraphy above. This four-way closure is the trapping structure responsible for containing the San Ardo oil (Graham, 1987). Due to the relatively simple basement structure in the Salinas River Valley, structures of this magnitude are absent elsewhere along the fairway of reservoir rock. The charged domal structure at San Ardo and the smaller-scale traps in upper Monterey Fm sandstone of nearby fields constitute a proven and economically successful petroleum play.

Field Trip Conclusion

The giant San Ardo oil field exists because the petroleum system events followed an effective temporal sequence. Because generation, migration and accumulation of petroleum are controlled by the processes in the basin, key sedimentary and tectonic events must occur in alignment with the petroleum system events (Figure 12).

Developing an understanding of the Salinas Basin petroleum system beyond this field-based assessment requires integration of all the elements into a dynamic and computational framework. An effective approach in comprehensive petroleum system analysis is possible through basin and petroleum system modeling. Assimilation of stratigraphic, structural and geochemical data into three-dimensional (3-D) models allows one to develop explanations for known accumulations (Figure 13), and to evaluate the basin for additional prospectivity.

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Figure Captions

Figure 1. Petroleum system elements and processes, stratigraphy and structure of the Salinas Basin and field trip stop locations.

Figure 2. Geologic and Monterey Fm depth maps. a) Geologic map is simplified from a compilation of 7.5-minute quadrangle maps originally mapped by Thomas W. Dibblee, Jr., and re-published by the Dibblee Foundation and the Santa Barbara Museum of Natural History. b) Contour map of depth to base of Monterey Fm relative to sea level. This highlights the 40 km of separation along Reliz-Rinconada Fault, which offsets the western side of the paleo-depocenter. Depth map is modified from Marion (1986). Legend applies to a) and b). See Figure 3 for location reference map.

Figure 3. Location map of field trip route, stops and key geographic localities.

Figure 4. Generalized stratigraphy of the Salinas Basin. The strata depicted here are the units relevant to the petroleum system; Cretaceous-Eocene strata are also present west of this study area. Generalized rock types and paleo-water depths (PWD) are from Graham (1976). Benthic foraminiferal stage and age framework are based on McDougall (2008). PSE: petroleum system elements.

Figure 5. Cross-section of Salinas Basin stratigraphy. Colors correspond to lithofacies. Formation labels: QPp- Paso Robles Fm; Ppr- Pancho Rico Fm; Mmsm- upper Monterey Fm shallow marine facies, including Santa Margarita sandstone; Mc- undifferentiated upper Miocene nonmarine facies; Mmh- Hames Mbr of Monterey Fm; Mms- Sandholdt Mbr of Monterey Fm; OMvq- Vaqueros Fm; Ob- Berry Fm; Er- Reliz Canyon Fm. Fault labels: RRF- Reliz-Rinconada Fault; LLF- Los Lobos Fault; SAF- San Andreas Fault. Numbers correspond to the following well API (American Petroleum Institute) numbers: 1- 05301219; 2- 05301432; 3- 05320117; 4- 05301352; 5- 05300045; 6- 05301361; 7- 05301388. Spontaneous potential (SP) curves plot on the left; resistivity curves plot on the right. Vertical exaggeration = 3x. See Figure 3 for location of cross-section transect. Modified from Graham et al. (1991).

Figure 6. Pseudo-van Krevelen diagram demonstrating the range of Monterey Fm source rock kerogen types in Salinas Basin. Modified from Mertz (1984).

Figure 7. Stratigraphy of the Sandholdt Mbr of the Monterey Fm based on outcrops in the Arroyo Seco area, including the section at Stop 1.1. Modified from Mertz (1984). Time scale updated following McDougall (2008).

Figure 8. Images of the Sandholdt Mbr of the Monterey Fm lithofacies, seen at Stop 1.1. a) Photomicrograph of organic- and foram-rich shale. White objects are foraminiferal tests. b) Well-laminated, fissile shale. c) Dark, organic-rich shale with white lenses and nodules of phosphate. d) Thin to thick turbiditic sandstone and

conglomerate beds interbedded with mudstone. e) Phosphate nodule with differentially-compacted shale layers, indicating early formation. f) Dolostone layer interbedded with well-laminated shale.

Figure 9. Images of Neogene structural deformation. a) Outcrop expression of the Reliz segment of the Reliz-Rinconada Fault (Stop 1.2). Photo is directed toward the NW. Rocks on the western side of the faulted outcrop comprise the Hames Mbr of the Monterey Fm; the eastern side is made up of Pancho Rico Fm. The fault strikes to the NNW, defining the abrupt change in relief from the valley floor to the western mountains. b) Tight chevron folds in the Hames Mbr at a location ~14 km NNW of Stop 1.4. c) and d) Northeast-verging recumbent isoclinal folds in lower Monterey Fm siliceous strata at Stop 1.4.

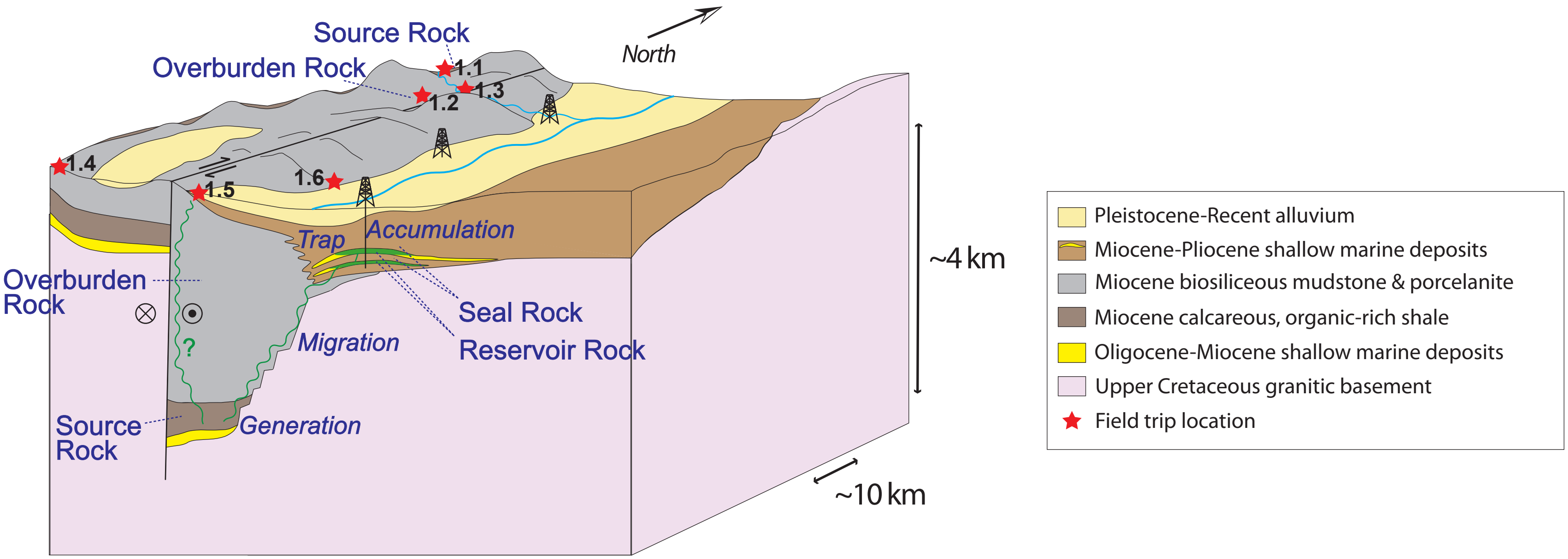
Figure 10. One-dimensional basin models of burial history and source rock maturation in the a) Hames Valley and b) Arroyo Seco depocenters. Source rock is highlighted with colors corresponding to thermal maturity predicted by the models, which are calibrated with Tmax pyrolysis data. Modeling was completed using PetroMod® software, version 2012.2.

Figure 11. Images of biodegraded migrated oil in outcrops at Stop 1.5. a) The unconformity between Monterey and Paso Robles Fms is partially concealed by vegetation. b) Fractures in the porcelaneous rocks are filled with migrated oil that has biodegraded to asphalt. c) Migrated oil stains and streaks fracture surfaces in porcelanite. d) Oil-saturated conglomeratic sandstone of the fluvial Paso Robles Fm.

Figure 12. Petroleum system and tectonic events chart for the Salinas Basin.

Figure 13. Three-dimensional oil migration and accumulation model demonstrates filling of San Ardo field with oil generated from the Hames Valley source rock. Migration assumes flowpath (buoyancy-driven) method only. Modeling was completed using PetroMod® software, version 2012.2.

Figure 1



Source Rock
Overburden Rock
1.1
1.2
1.3
North
1.4
1.5
1.6
Trap
Accumulation
Overburden Rock
?
Migration
Seal Rock
Reservoir Rock
Source Rock
Generation
~4 km
~10 km
Pleistocene-Recent alluvium
Miocene-Pliocene shallow marine deposits
Miocene biosiliceous mudstone & porcelanite
Miocene calcareous, organic-rich shale
Oligocene-Miocene shallow marine deposits
Upper Cretaceous granitic basement
Field trip location

Figure 2

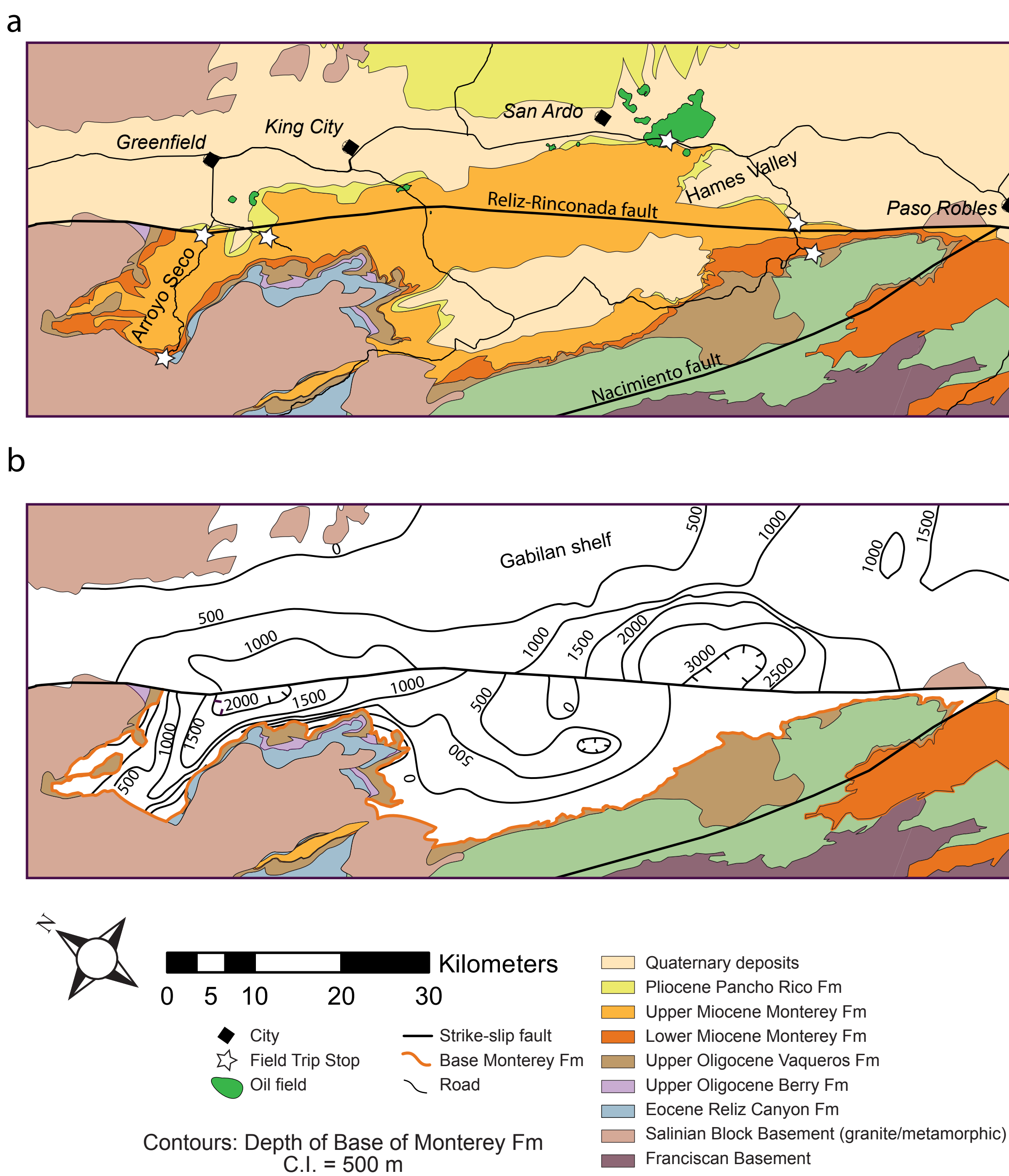
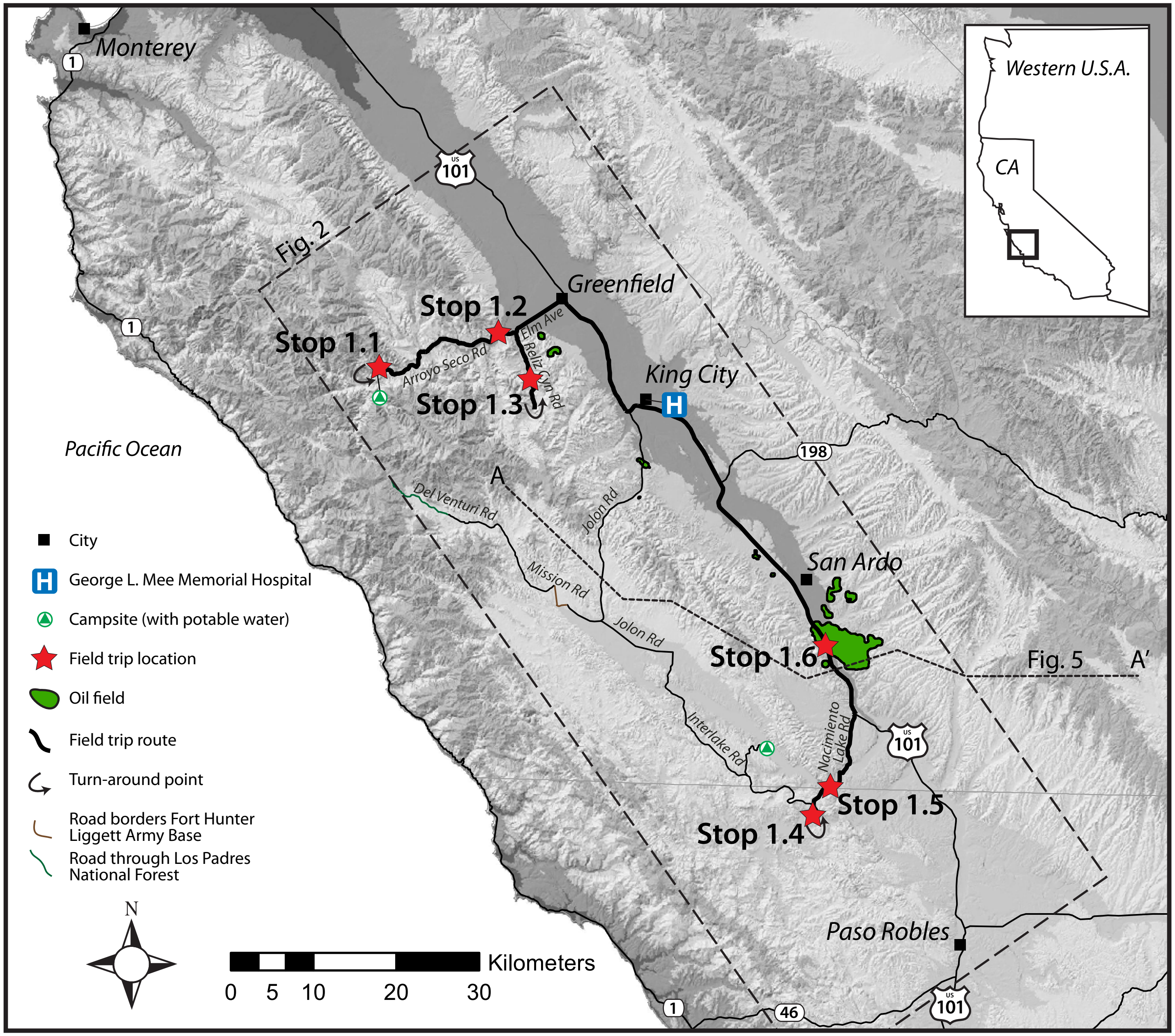
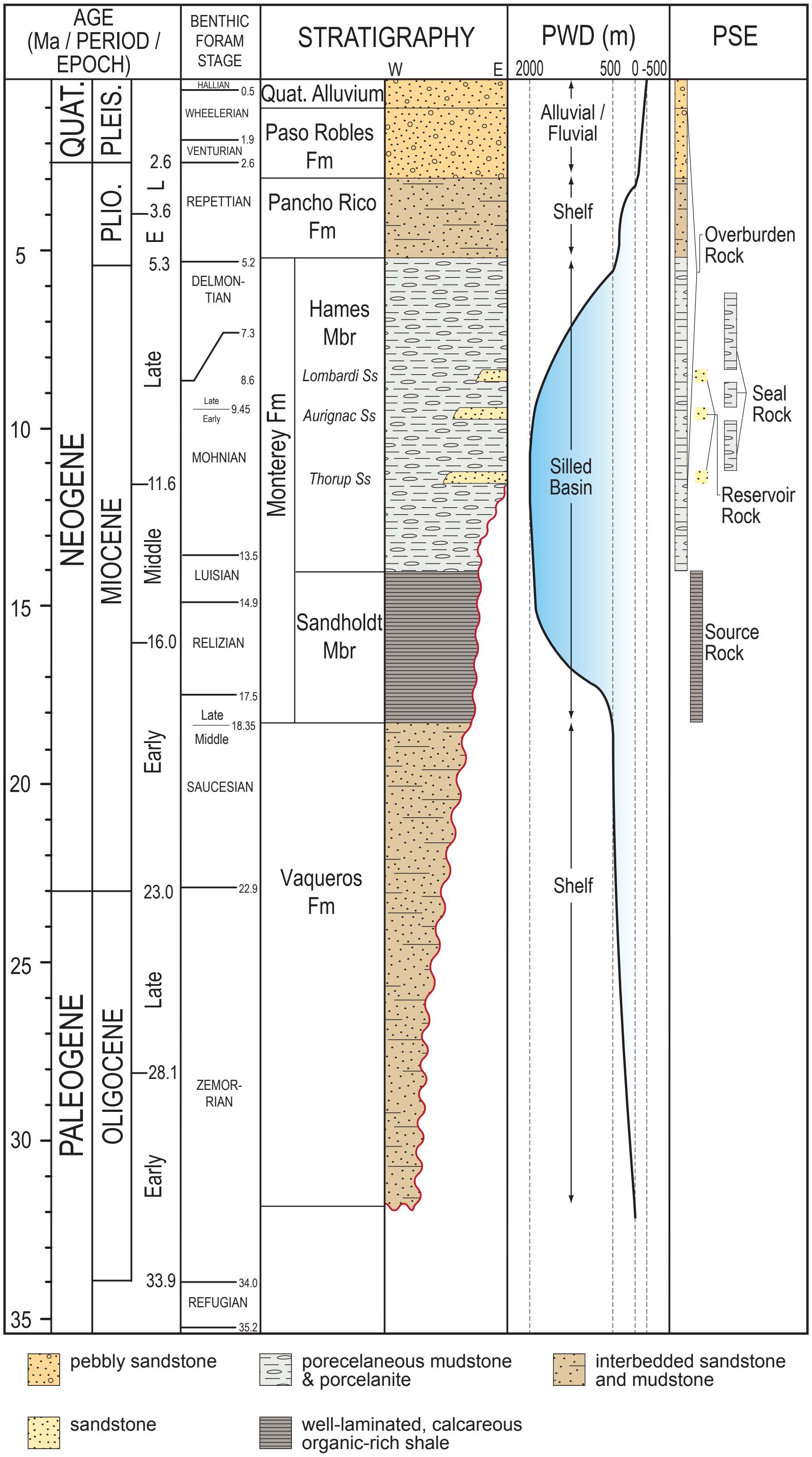

a
Greenfield
King City
San Ardo
Hames Valley
Paso Robles
Reliz-Rinconada fault
Arroyo Seco
Nacimiento fault
b
Gabilan shelf
0
500
1000
1500
2000
2500
3000
Kilometers
0 5 10 20 30
N
City
Field Trip Stop
Oil field
Strike-slip fault
Base Monterey Fm
Road
Quaternary deposits
Pliocene Pancho Rico Fm
Upper Miocene Monterey Fm
Lower Miocene Monterey Fm
Upper Oligocene Vaqueros Fm
Upper Oligocene Berry Fm
Eocene Reliz Canyon Fm
Salinian Block Basement (granite/metamorphic)
Franciscan Basement
Contours: Depth of Base of Monterey Fm
C.I. = 500 m

Figure 3



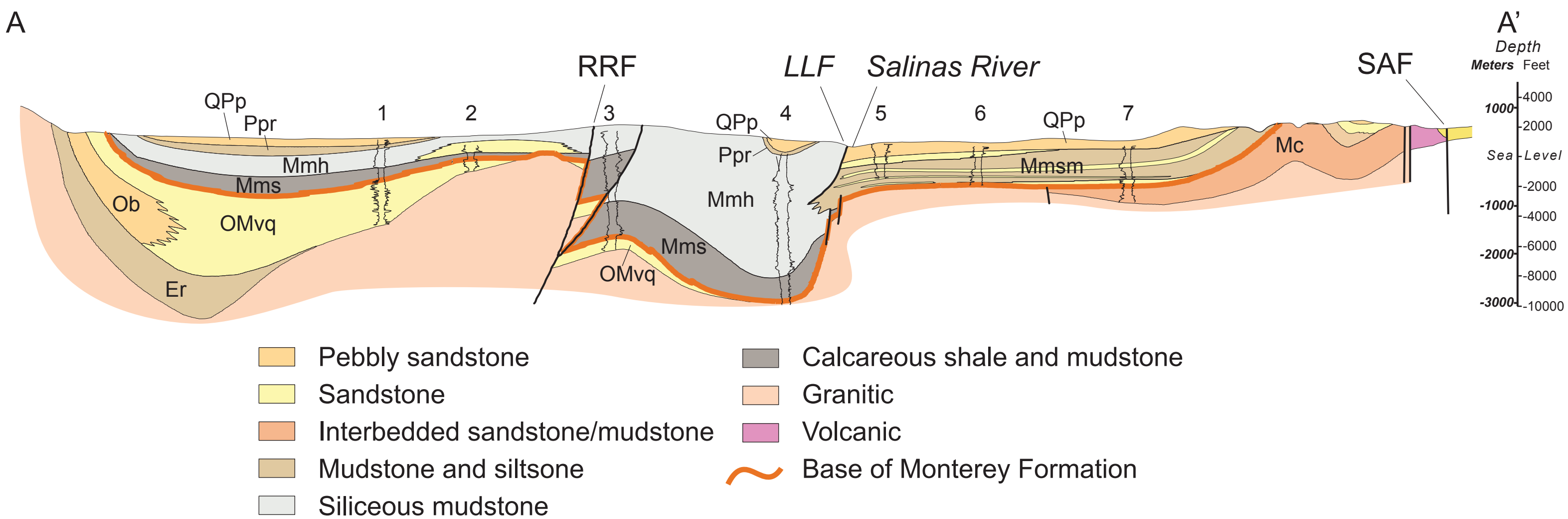
Monterey
Western U.S.A.
CA
101
1
Fig. 2
Greenfield
Stop 1.2
Stop 1.1
Elm Ave
Arroyo Seco Rd
Reliz Cyn Rd
Stop 1.3
King City
Pacific Ocean
198
A
Del Venturi Rd
Jolon Rd
San Ardo
Mission Rd
Jolon Rd
Stop 1.6
Fig. 5
A'
Interlake Rd
Nacimiento Lake Rd
Stop 1.5
Stop 1.4
Paso Robles
46
City
George L. Mee Memorial Hospital
Campsite (with potable water)
Field trip location
Oil field
Field trip route
Turn-around point
Road borders Fort Hunter Liggett Army Base
Road through Los Padres National Forest
N
Kilometers
0 5 10 20 30

Figure 4



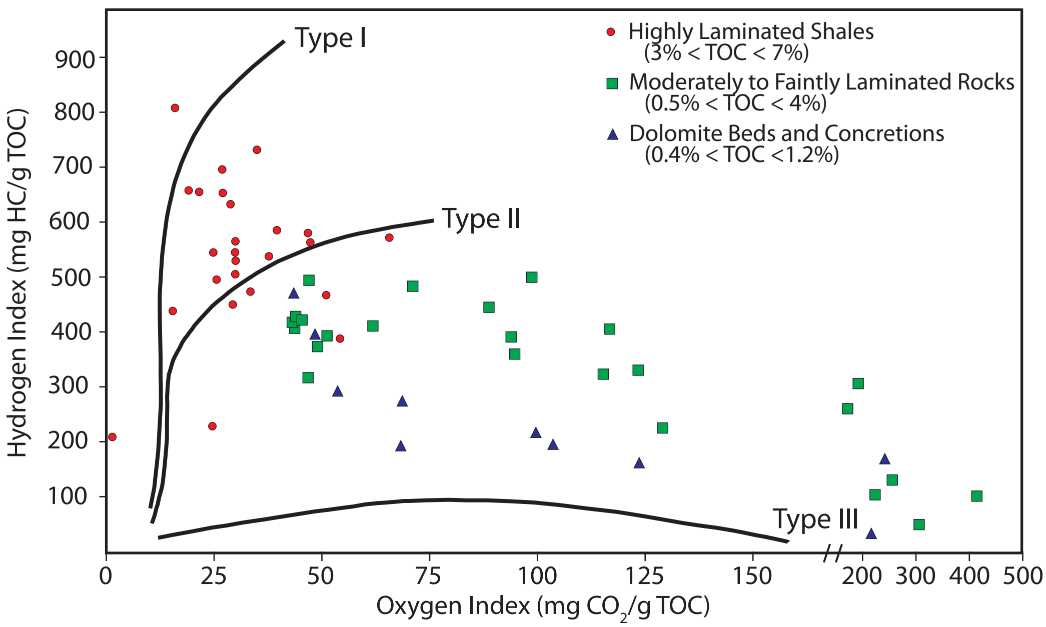
AGE (Ma / PERIOD / EPOCH)
BENTHIC FORAM STAGE
STRATIGRAPHY
PWD (m)
PSE
W
E
2000
500
0
-500
QUAT.
PLEIS.
PLIO.
NEOGENE
MIOCENE
PALEOGENE
OLIGOCENE
L
E
Late
Middle
Early
Late
Early
2.6
3.6
5.3
11.6
16.0
23.0
28.1
33.9
5
10
15
20
25
30
35
HALLIAN
WHEELERIAN
VENTURIAN
REPETTIAN
DELMON-TIAN
MOHNIAN
LUISIAN
RELIZIAN
SAUCESIAN
ZEMOR-RIAN
REFUGIAN
0.5
1.9
2.6
5.2
7.3
8.6
9.45
13.5
14.9
17.5
18.35
22.9
34.0
35.2
Quat. Alluvium
Paso Robles Fm
Pancho Rico Fm
Monterey Fm
Hames Mbr
Lombardi Ss
Aurignac Ss
Thorup Ss
Sandholdt Mbr
Vaqueros Fm
Alluvial / Fluvial
Shelf
Silled Basin
Shelf
Overburden Rock
Seal Rock
Reservoir Rock
Source Rock
pebbly sandstone
porecelaneous mudstone & porcelanite
interbedded sandstone and mudstone
sandstone
well-laminated, calcareous organic-rich shale

Figure 5



A
A'
RRF
LLF
Salinas River
SAF
Depth
Meters
Feet
1000
4000
2000
Sea Level
-2000
-1000
-4000
-2000
-6000
-8000
-3000
-10000
QPp
Ppr
Mmh
Mms
Ob
OMvq
Er
1
2
3
4
5
6
7
QPp
Ppr
Mmh
Mms
OMvq
QPp
Mmsm
Mc
Pebbly sandstone
Sandstone
Interbedded sandstone/mudstone
Mudstone and siltsone
Siliceous mudstone
Calcareous shale and mudstone
Granitic
Volcanic
Base of Monterey Formation

Figure 6



Type I
Type II
Type III
Highly Laminated Shales
(3% < TOC < 7%)
Moderately to Faintly Laminated Rocks
(0.5% < TOC < 4%)
Dolomite Beds and Concretions
(0.4% < TOC <1.2%)
Hydrogen Index (mg HC/g TOC)
900
800
700
600
500
400
300
200
100
0
25
50
75
100
125
150
200
300
400
500
Oxygen Index (mg CO_2/g TOC)

Figure 7

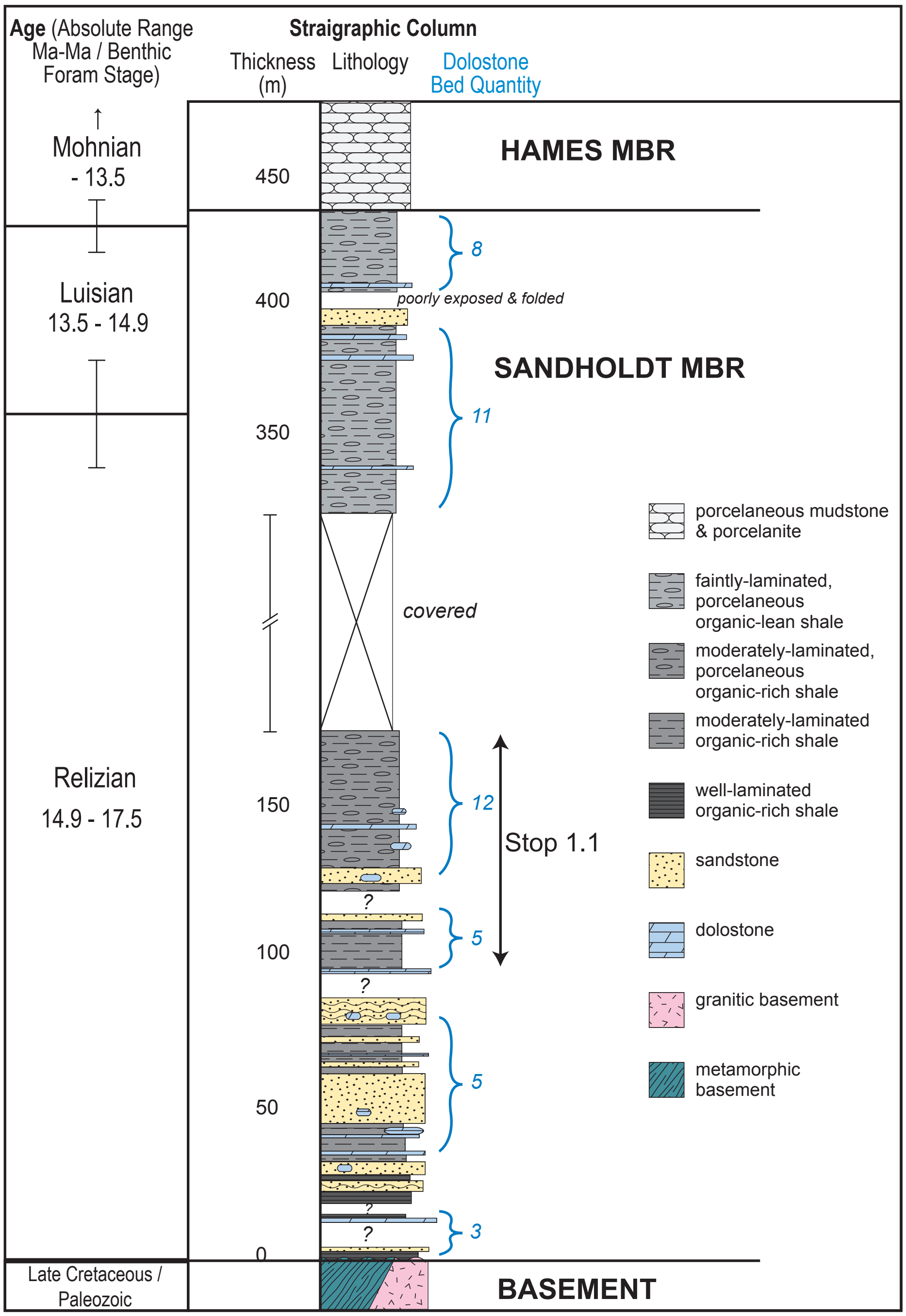

Age (Absolute Range Ma-Ma / Benthic Foram Stage)
Straigraphic Column
Thickness (m)
Lithology
Dolostone Bed Quantity
Mohnian
- 13.5
Luisian
13.5 - 14.9
Relizian
14.9 - 17.5
Late Cretaceous / Paleozoic
450
400
350
150
100
50
0
HAMES MBR
8
poorly exposed & folded
SANDHOLDT MBR
11
covered
12
Stop 1.1
?
5
?
5
?
?
3
BASEMENT
porcelaneous mudstone & porcelanite
faintly-laminated, porcelaneous organic-lean shale
moderately-laminated, porcelaneous organic-rich shale
moderately-laminated organic-rich shale
well-laminated organic-rich shale
sandstone
dolostone
granitic basement
metamorphic basement

Figure 8

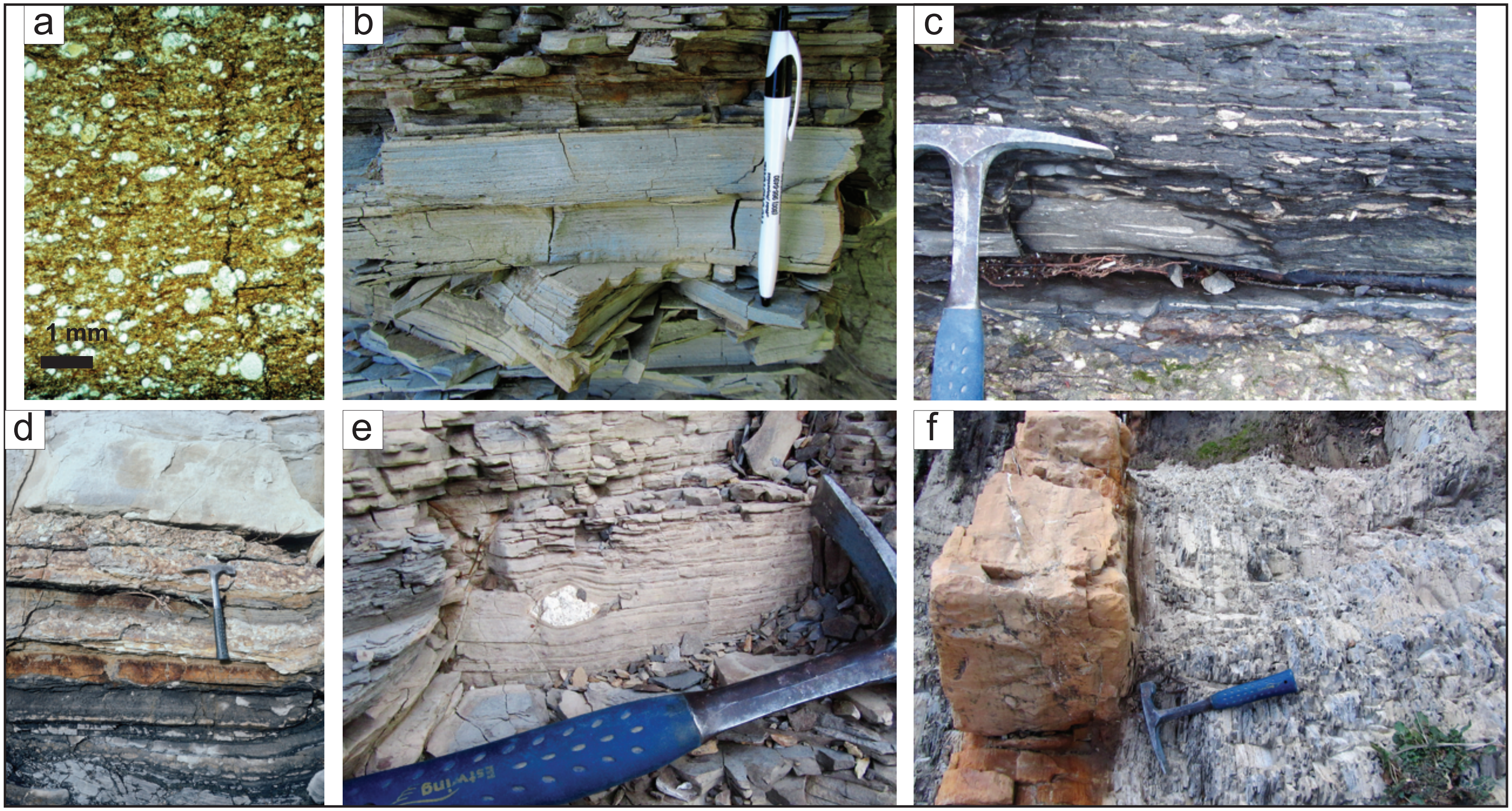


Figure 9

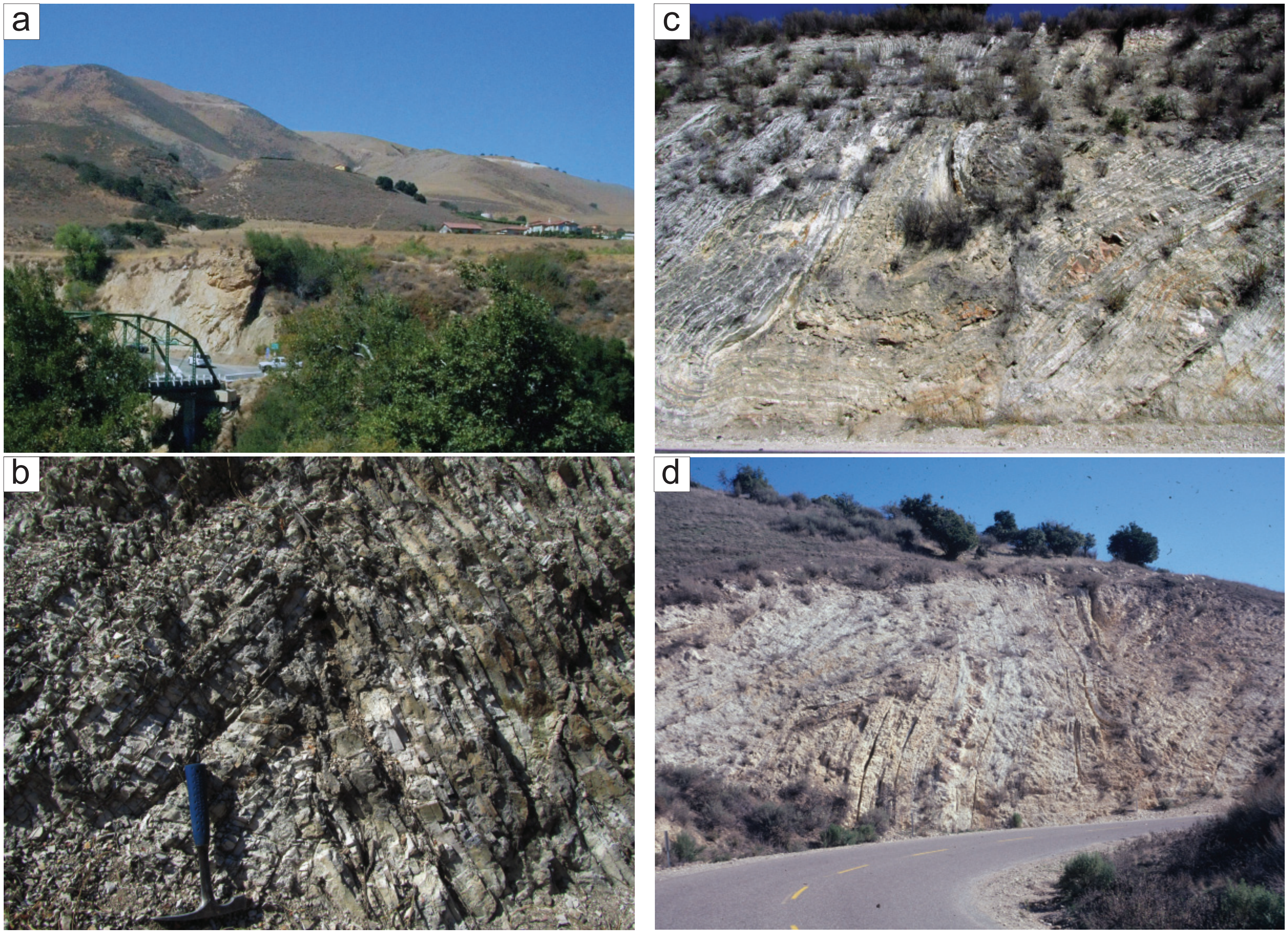


Figure 10

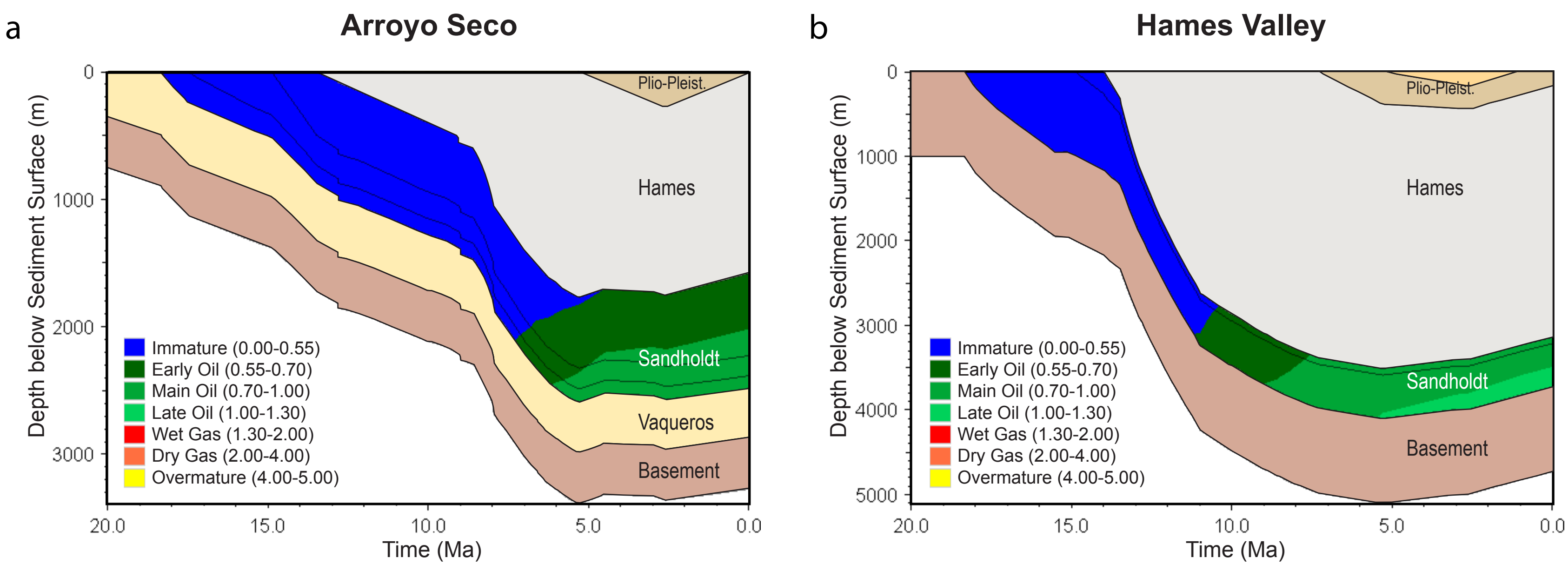

a
Arroyo Seco
0
1000
2000
3000
Depth below Sediment Surface (m)
Plio-Pleist.
Hames
Sandholdt
Vaqueros
Basement
Immature (0.00-0.55)
Early Oil (0.55-0.70)
Main Oil (0.70-1.00)
Late Oil (1.00-1.30)
Wet Gas (1.30-2.00)
Dry Gas (2.00-4.00)
Overmature (4.00-5.00)
20.0
15.0
10.0
5.0
0.0
Time (Ma)
b
Hames Valley
0
1000
2000
3000
4000
5000
Depth below Sediment Surface (m)
Plio-Pleist.
Hames
Sandholdt
Basement
Immature (0.00-0.55)
Early Oil (0.55-0.70)
Main Oil (0.70-1.00)
Late Oil (1.00-1.30)
Wet Gas (1.30-2.00)
Dry Gas (2.00-4.00)
Overmature (4.00-5.00)
20.0
15.0
10.0
5.0
0.0
Time (Ma)

Figure 11

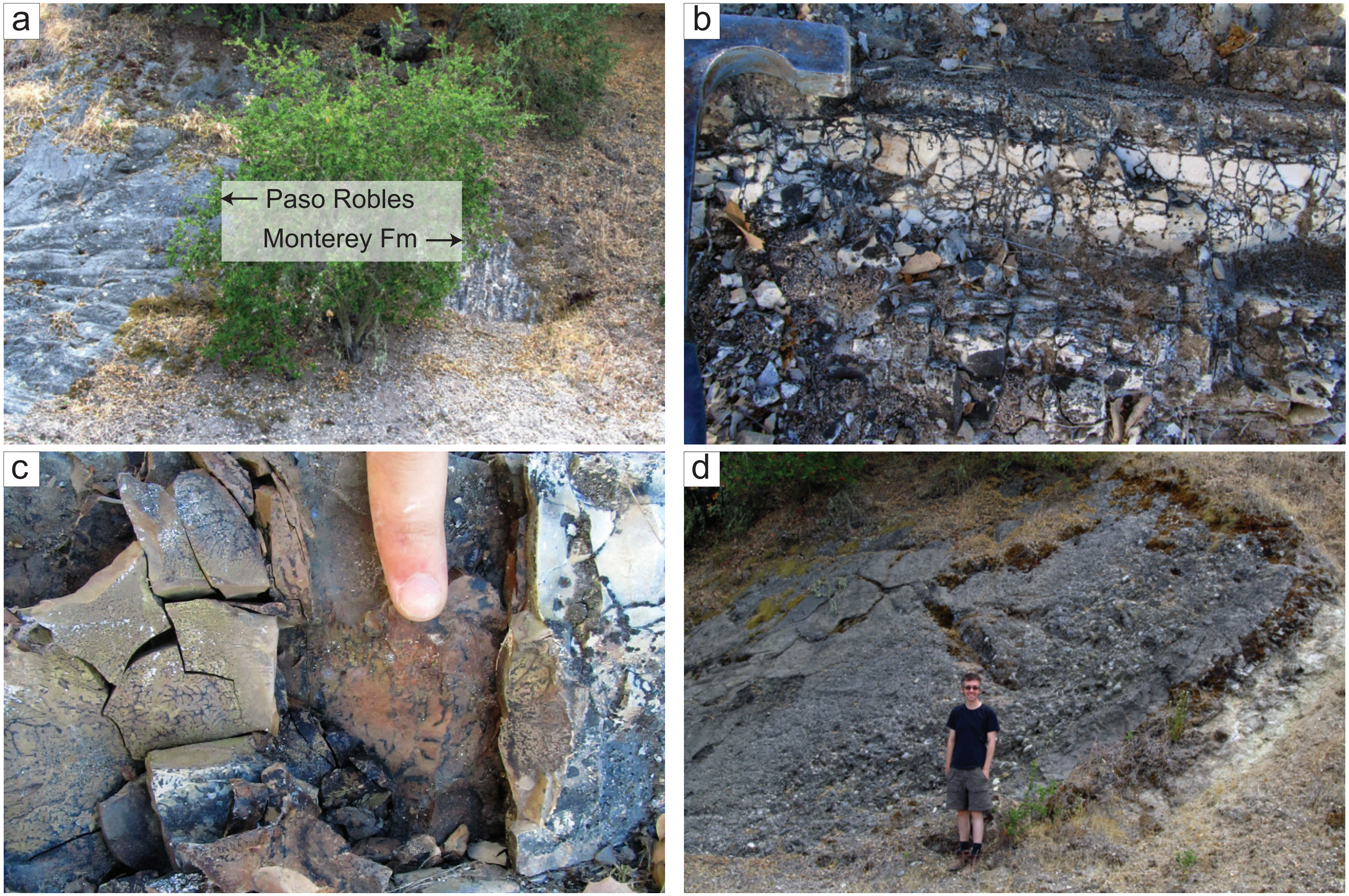
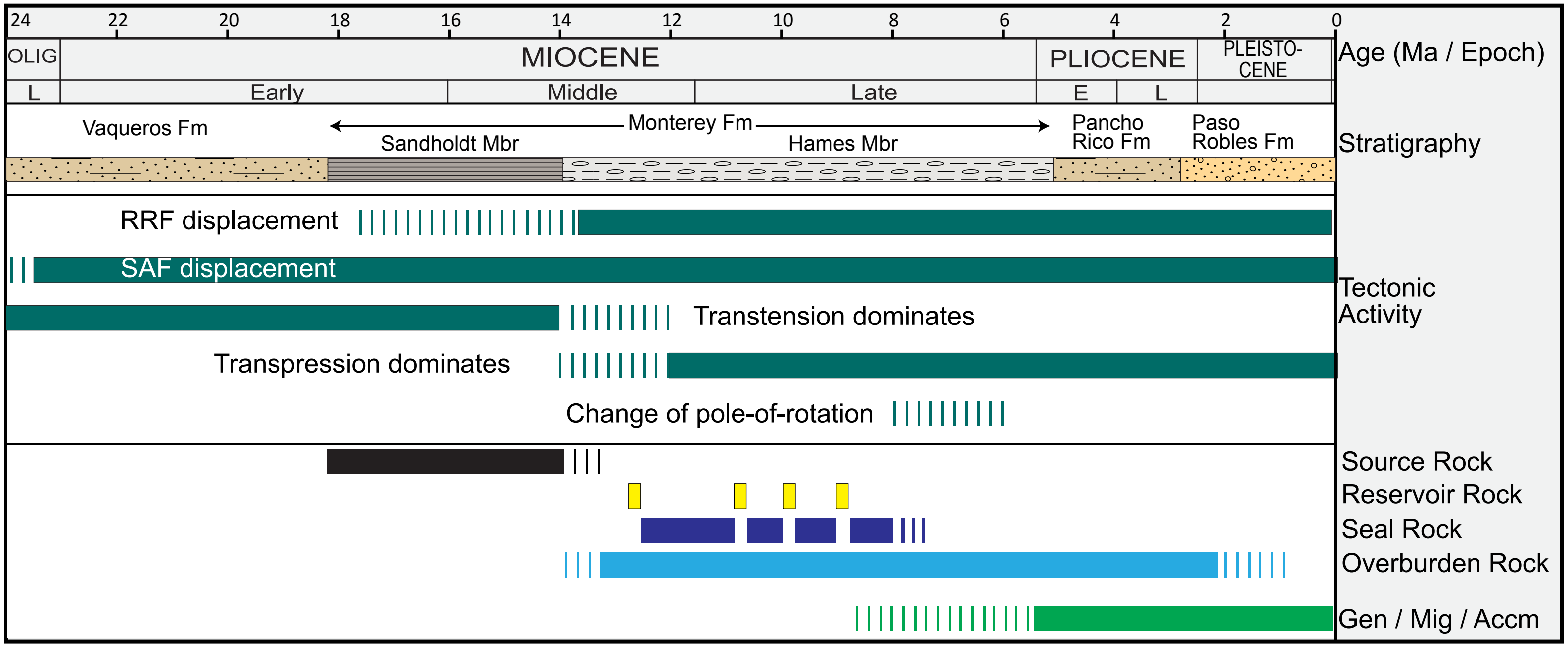
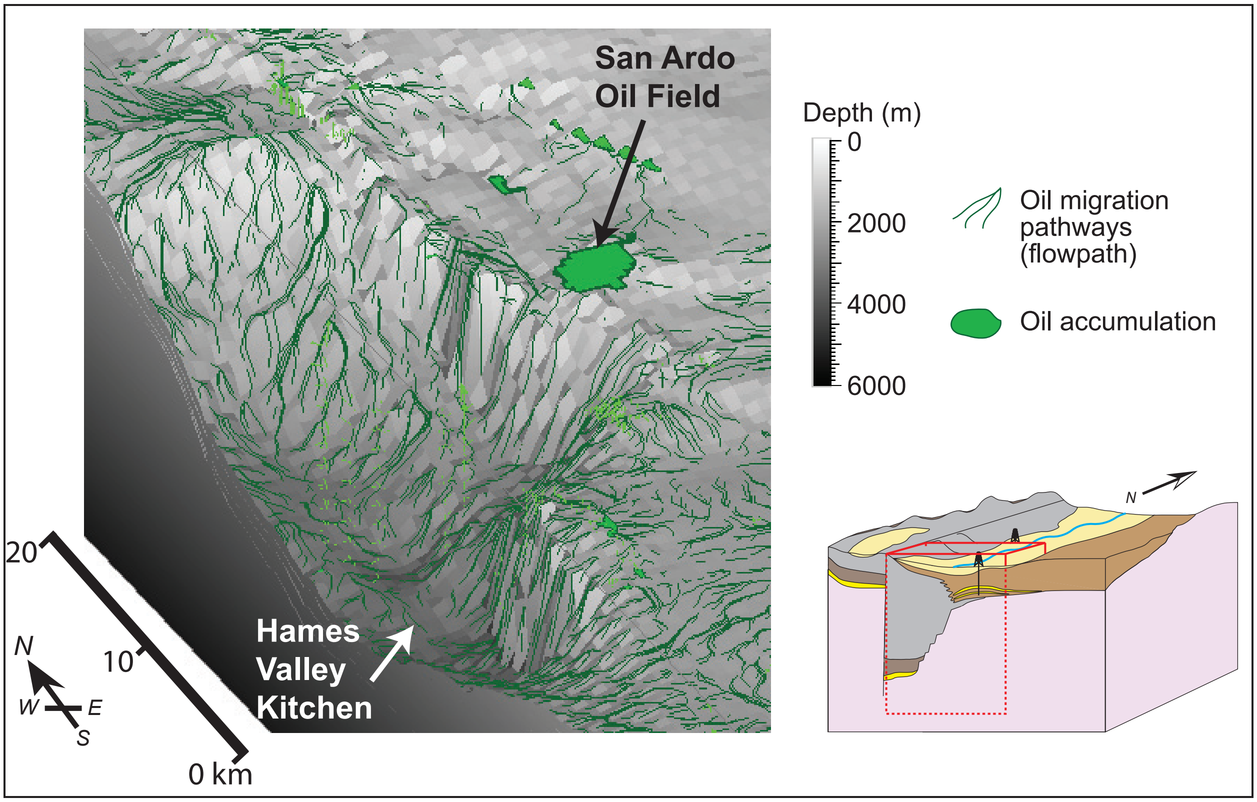


Figure 12



24
22
20
18
16
14
12
10
8
6
4
2
0
OLIG
MIOCENE
PLIOCENE
PLEISTO-CENE
L
Early
Middle
Late
E
L
Age (Ma / Epoch)
Vaqueros Fm
Monterey Fm
Sandholdt Mbr
Hames Mbr
Pancho Rico Fm
Paso Robles Fm
Stratigraphy
RRF displacement
SAF displacement
Transtension dominates
Transpression dominates
Change of pole-of-rotation
Tectonic Activity
Source Rock
Reservoir Rock
Seal Rock
Overburden Rock
Gen / Mig / Accm

Figure 13


San Ardo
Oil Field
Depth (m)
0
2000
4000
6000
Oil migration
pathways
(flowpath)
Oil accumulation
N
20
10
0 km
N
W
E
S
Hames
Valley
Kitchen