Stanford University BPSM Industrial Affiliates Program Field Trip to Black Diamond Mines Regional Preserve
November 13, 2014

Schedule:

7:30-7:45am	Meet at Lot 39 behind Tresidder Memorial Union at Stanford
8am	Depart Stanford University
9:30am	Arrive Black Diamond Mines Regional Preserve. Park in upper parking lot (not at park office). Restroom and snack break. Unload lunches in mine vehicle and transport to Greathouse portal.
10am-2pm	Tour Black Diamond Mines (see details below)
2:15pm	Depart Black Diamond Mines
4pm	Arrive Stanford University

Group Itinerary: 16 people per group

Group 1	Group 2
10-10:45am: Meet naturalist at parking lot gate. Walking tour & slide show with naturalist.	9:45am Walk from parking lot to Hazel Atlas Portal for mine tour with Steve Graham. Tour starts at 10am. End at 11:30am at Greathouse visitor center.
10:45-11:30am Sacramento Basin petroleum systems talk in Greathouse visitor center, followed by exploring the museum.	
11:30am-12:15pm Both groups have lunch in Greathouse visitor center or outside, weather permitting.	
12:15-1:45pm Walk to Hazel Atlas portal for mine tour with Steve Graham. End at Greathouse visitor center.	12:15-1pm Sacramento Basin petroleum systems talk in Greathouse visitor center and explore museum.
	1-1:45pm Slide show & walking tour with naturalist from Hazel Atlas portal to parking lot.
2pm Both groups meet at parking lot for final restroom and snack break.	

The petroleum systems of the Sacramento Basin and adjacent area, California

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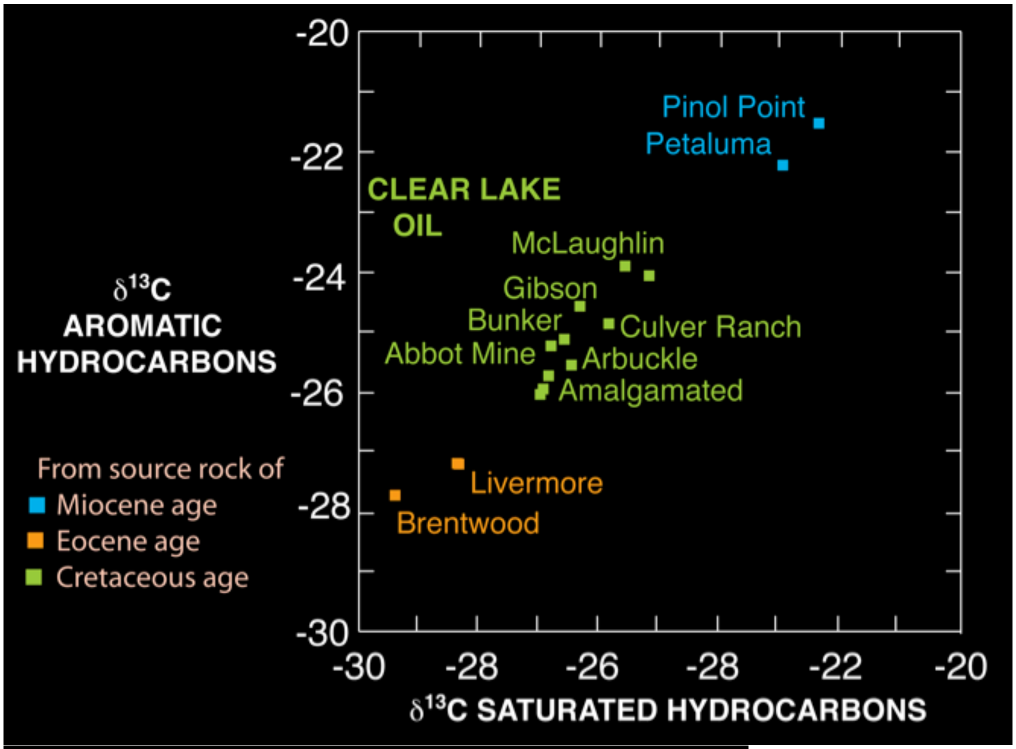
[1] Stanford University, [2] U.S. Geological Survey

There are three oil and two gas petroleum systems in and around the Sacramento Basin. The Black Diamond Mines Regional Preserve, located on the present-day west flank of the basin, is dug into the Eocene Domengine sandstone of such high purity that it was used to make glass; it also contains a low rank coal. This non-marine to shallow marine deposit extends over much of the San Joaquin and Sacramento basins. It underlies an Eocene organic-rich source rock known as the Kreyenhagen Formation in the San Joaquin Basin and the equivalent, suspected source rock, the Nortonville Formation, in the Sacramento Basin. The Domengine sandstone is the major gas reservoir rock in the youngest petroleum system in the Sacramento Basin, containing 55% of the total gas.

A minimum of three oil systems are defined from three oil types using carbon isotopic composition of saturated and aromatic hydrocarbons, but are poorly understood because only one system contains commercial oil and the other two include only seeps and recovered oil from wells. The commercial oil fields include the Brentwood and Livermore fields and contain an oil type from an Eocene source rock, presumably the Nortonville because this oil type is like Kreyenhagen oil in the San Joaquin Basin. The reservoir rock for the Brentwood field in the Sacramento Basin is 4,000 feet deep and is Upper Cretaceous and Paleocene in age with the seal rock being the overlying thin shale. The reservoir rock for the Livermore field in the nearby Livermore Basin is 1,500 feet deep and is Upper Miocene in age and is sealed by thick shale. The pod of active source rock is expected to be between these fields. A complex timing and migration history for this oil charge is suspected since these fields are in different basins with different aged reservoir rocks.

The other two oil types originated from a Cretaceous and a Miocene source rock, respectively. The Cretaceous oil shows and seep samples are located in the fold and thrust belt of the Coast Ranges and in a few wells on the west flank of the Sacramento Basin. The oil charge supposedly originates from an unidentified source rock of Cretaceous age because the isotopic values are the same as the Moreno oil from the San Joaquin Basin. The Miocene oil samples found adjacent to San Pablo Bay have the same heavy isotopic composition as the oil from the Monterey source rock in the San Joaquin Basin.

The two gas petroleum systems are differentiated using the carbon isotope of methane. The impermeable Sacramento Shale separates the gas systems from each other. The deeper system has a carbon isotopic value of -28 per mil plus or minus 5 per mil whereas the shallower, larger gas system has a normal thermogenic gas signature of -40 per mil with a range of 5 per mil. The shallower system contains condensate that decreases in concentration relative to total gas from the Rio Vista gas field to the periphery of the petroleum system. The condensate contains only saturated hydrocarbons with a carbon isotopic value of about -26 per mil. Gas wetness decreases in a similar pattern to the condensate such that the gas is pure methane at the extremity of the system. Nitrogen content also increases, showing that this gas moved faster and farther to fill the distal traps with high concentrations of this inert gas. Based on presumed source rock and the higher proportion of petroleum in a given reservoir rock, the older deeper gas system is named the Dobbins-Forbes(?) and the larger, younger system is the Winters-Domengine(?).


-20
-22
-24
-26
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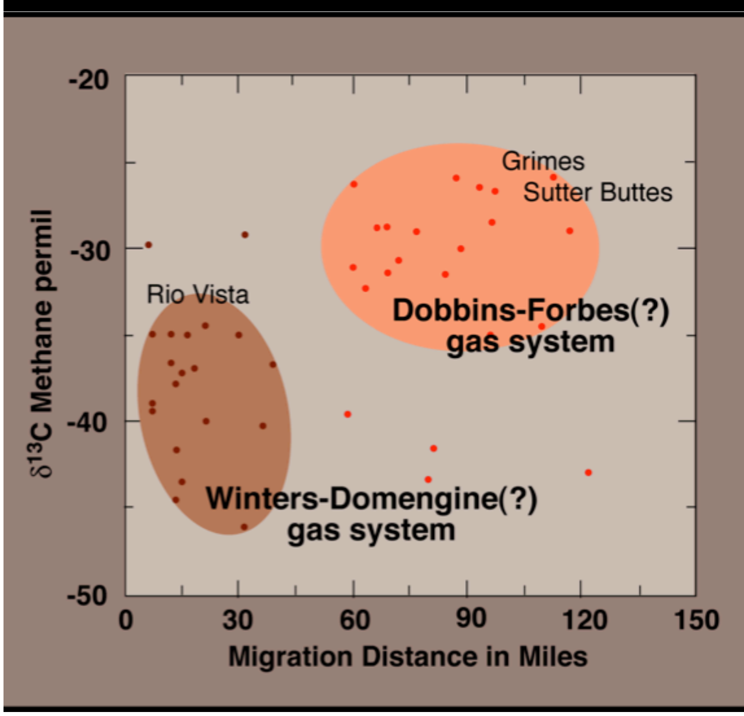
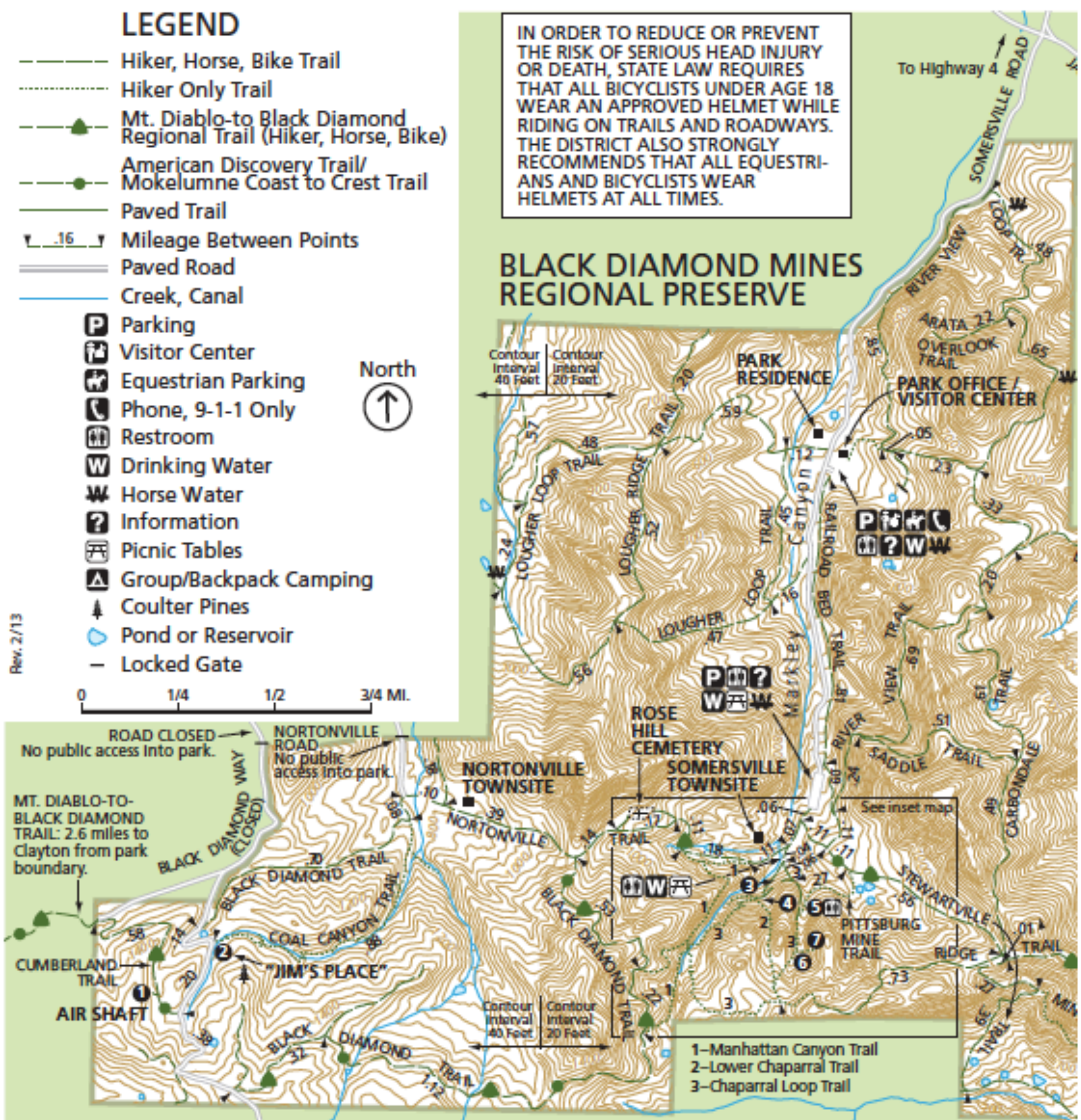
-30
δ13C
AROMATIC
HYDROCARBONS
From source rock of
Miocene age
Eocene age
Cretaceous age
Pinol Point
Petaluma
CLEAR LAKE
OIL
McLaughlin
Gibson
Bunker
Culver Ranch
Abbot Mine
Arbuckle
Amalgamated
Livermore
Brentwood
-30
-28
-26
-28
-22
-20
δ13C SATURATED HYDROCARBONS


-20
-30
-40
-50
δ13C Methane permil
Grimes
Sutter Buttes
Rio Vista
Dobbins-Forbes(?)
gas system
Winters-Domengine(?)
gas system
0
30
60
90
120
150
Migration Distance in Miles

East Bay Regional Park District
2950 Peralta Oaks Court,
P.O. Box 5381
Oakland, CA 94605-0381
1-888-EBPARKS www.ebparks.org
Rev. 2/13



MINING FEATURES as numbered on map:

❶ AIR SHAFT: This air shaft (once 150 feet deep and reached here by a short tunnel) was used to keep a coal mine ventilated and free from dangerous gases. The marks left by miners' picks are still evident on the excavation sides.

❷ "JIM'S PLACE": This little underground dwelling is of unknown origin. Notice the square skylight, round stovepipe hole, and shelf opening.

❸ GREATHOUSE VISITOR CENTER: This portal was the original opening into the sand mine.

❹ EUREKA SLOPE: This inclined shaft was the entrance to the Eureka Coal Mine. Between 1860 and 1895, more than 150,000 tons of coal were hoisted to the surface. The slope is 290 feet long and descends at a pitch of 32 degrees.

❺ HAZEL ATLAS PORTAL: This mine supplied sand used for glass making in the 1920s through the 1940s.

❻ POWDER MAGAZINE: This small excavation was used to store explosives during the sand mining era.

❼ STOPE: This huge chamber was blasted out of sandstone by miners extracting rock for glass making.

❽ PROSPECT TUNNEL: This tunnel was driven in the 1860s by miners in search of commercial-quality coal. Two hundred feet of the 400-foot tunnel are open for exploration. Bring a light.

❾ STAR MINE: This barred tunnel once served as the entrance to the Star Mine, one of the last active coal mines in the area.

Discover Black Diamond

INDIANS have lived in the greater Bay Area for thousands of years. Black Diamond was located in the backcountry between three tribes: Chupcan (Concord), Volvon (Clayton), and Ompin (Pittsburg). All spoke the Bay Miwok language. With the arrival of Spanish, Mexican, and American settlers after 1772, the Bay Miwok way of life was rapidly transformed. However, in spite of pressure to the contrary, many California Indians still practice the traditions of their ancestors.

COAL MINING From the 1850s to the early 1900s, the coal mining towns of Nortonville, Somersville, Stewartville, West Hartley, and Judsonville thrived in the Black Diamond area. As California's largest coal mining operation, nearly four million tons of coal ("black diamonds") were mined. People from all over the world were drawn to the area, and their lives were characterized by hard work and long hours. As many as 900 miners, some as young as eight years old, labored in hundreds of miles of underground workings. At the peak of operations the coalfield was reported to have been the population center of Contra Costa County.

The coal mines had a significant impact on California's economy. By the time operations ceased due to rising production costs and the exploitation of new energy sources, much of California's economy had been transformed from a rural to an industrial base.

SAND MINING In the 1920s underground sand mining began near the deserted Nortonville and Somersville townsites. The Somersville mine supplied sand used in glass production by the Hazel-Atlas Glass Company in Oakland, while the Nortonville mine supplied the Columbia Steel Works in Pittsburg with foundry (casting) sand. Competition from Belgian glass sand and the closing of the steel foundry ended the sand mining by the late 1940s. Altogether, more than 1.8 million tons of sand had been mined.

RANCHING Until the discovery of coal, cattle ranching was the major industry in this area. After the mines closed, some miners found a new career in ranching. Abandoned buildings became barns, railroad ties were used as fence posts, and boilers were converted into water troughs. Descendants of original mining families still graze cattle in the Preserve.

POLICE, FIRE, MEDICAL EMERGENCY	**9-1-1**
EBRPD HEADQUARTERS	**1-888-EBPARKS**
PARK OFFICE	**1-888-EBPARKS, option 3, ext. 4506**
VISITOR CENTER	**(510) 544-2750**
CAMPING	**1-888-EBPARKS, option 2**
TDD	**(510) 633-0460**

A REGIONAL PRESERVE The East Bay Regional Park District began acquiring land for the Preserve in the early 1970s. Today, most of the mining district is within the Preserve's nearly 6,096 acres. The area is an ideal location for hiking and picnicking. Naturalists conduct a variety of programs related to the Preserve's natural and historic resources. For more information, call the Visitor Center at (510) 544-2750.

VEGETATION The Preserve's 60+ miles of trails traverse areas of grassland, foothill woodland, mixed evergreen forest, chaparral, stream vegetation, and exotic plantings. Notable among the latter are several tree species introduced by the coal miners, including black locust, pepper tree, almond, eucalyptus, and tree of heaven.

Black Diamond is noted as the northernmost location of Coulter pine, black sage, desert olive, and dudleya. In addition, several species that are restricted to the Mount Diablo area occur here, including the Mt. Diablo globe lily, Mt. Diablo helianthella, and Mt. Diablo manzanita. The hills are covered with remarkable springtime wildflower displays.

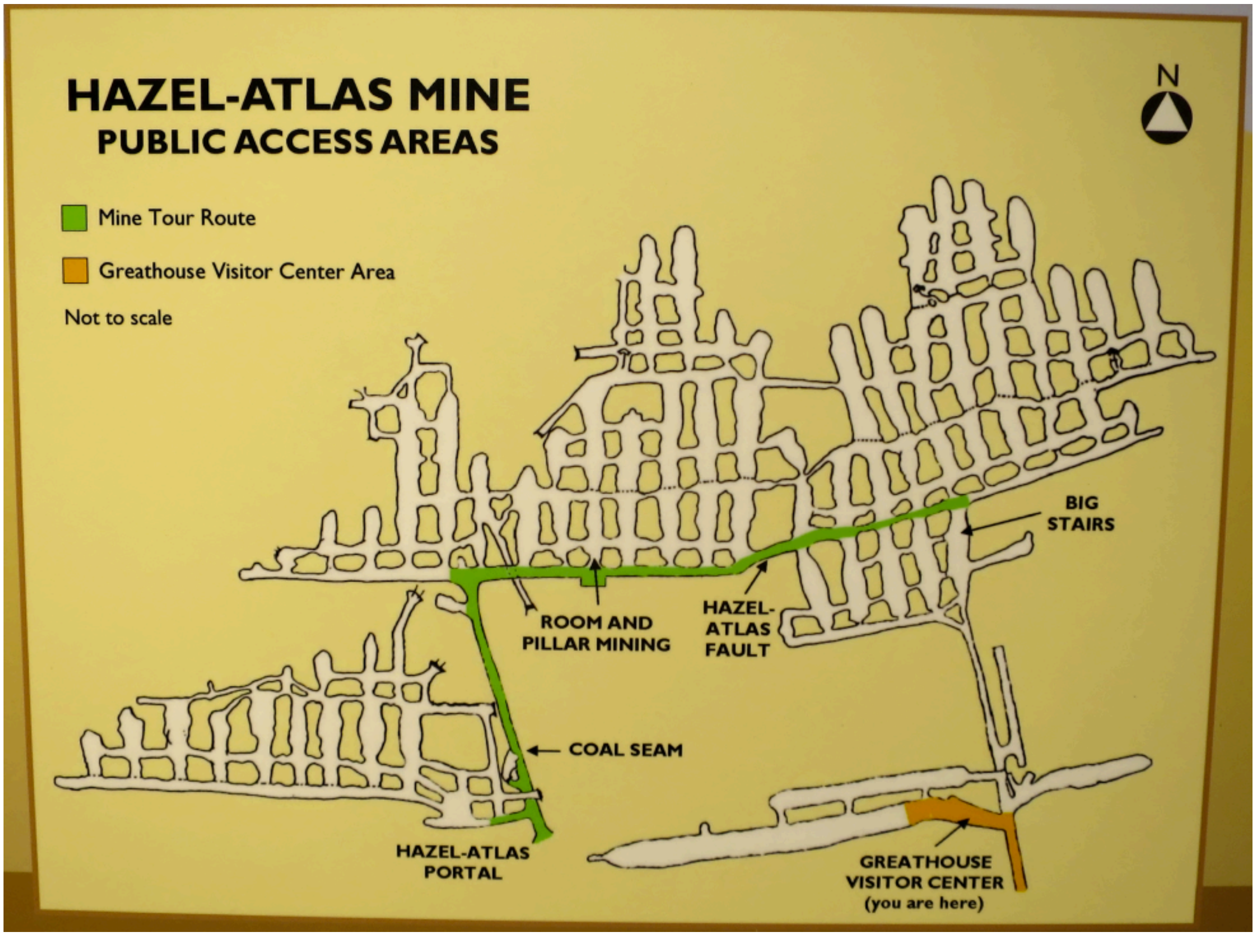
WILDLIFE The Preserve supports a healthy wildlife population, and it is not uncommon for the observant hiker to see the tracks of raccoons, skunks, opossums, rabbits, and deer. Mountain lions, bobcats, foxes, and coyotes are occasionally spotted, while birds of prey soar overhead. Over 100 species of birds have been seen, from the rare golden eagle to the ever-present meadowlark.

The side-blotched lizard has its northern limit in the Preserve, and several rare animal species have been found here, including the white-tailed kite, the Alameda striped racer, the red-legged frog, and the California tiger salamander.

ROSE HILL CEMETERY Although little remains of the coal mining communities themselves, a historic cemetery serves as a monument to the lives of the former residents. Buried here are children who died in epidemics, women who died in childbirth, and men who died in mining disasters. Although more than 10 nationalities resided in the mining area, Rose Hill was a Protestant cemetery that served as the burial ground for many of the Welsh residents.

WON'T YOU HELP US? Over the years, vandalism has taken its toll on the cemetery, which the Park District is attempting to restore. If you have information concerning people buried here, or the locations of missing gravestones, please call the Black Diamond office at 1-888-EBPARKS, option 3, ext. 4506.

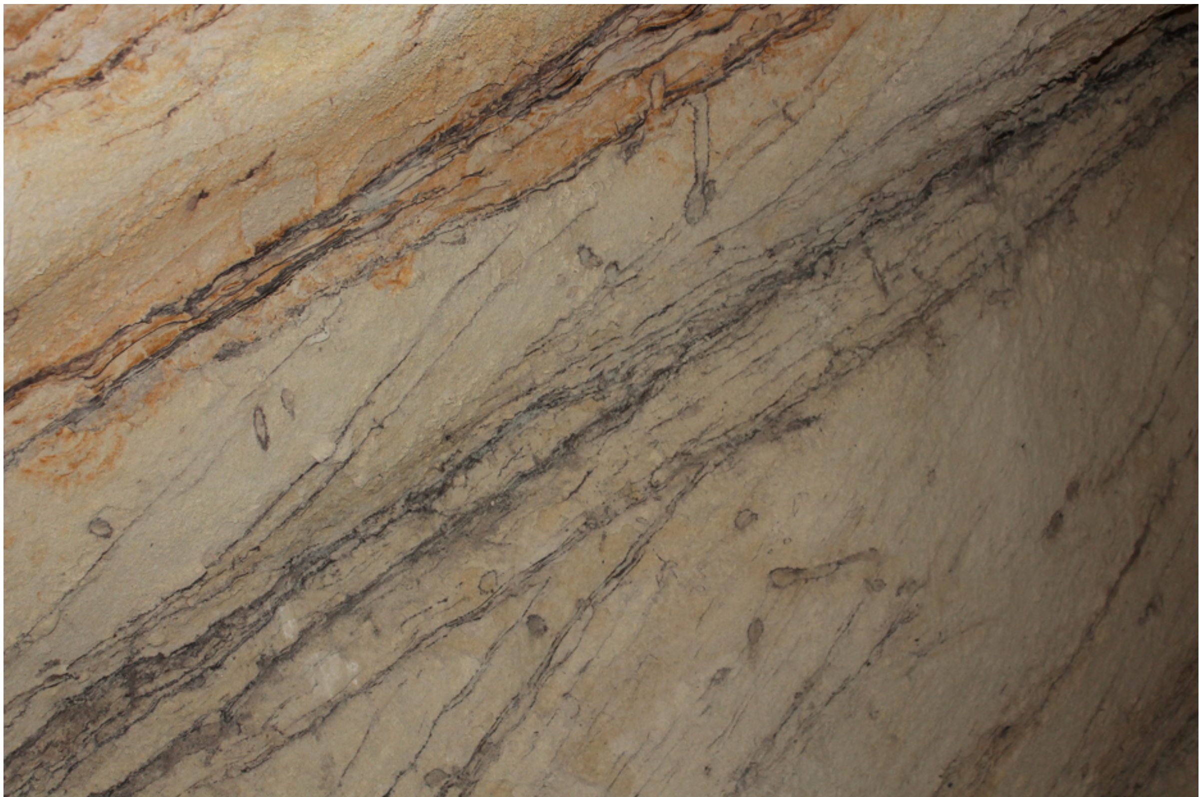
Sheriff: 651 Pine St, 7th Floor, Martinez, CA 94553; David O. Livingston: (925) 335-1500
Highway Patrol: 4999 Gleason Dr, Dublin, CA 94568; (925) 828-0466
Level 1 Trauma Center: San Francisco General Hospital, 1001 Potrero Ave, San Francisco, CA 94110; (415) 206-8000

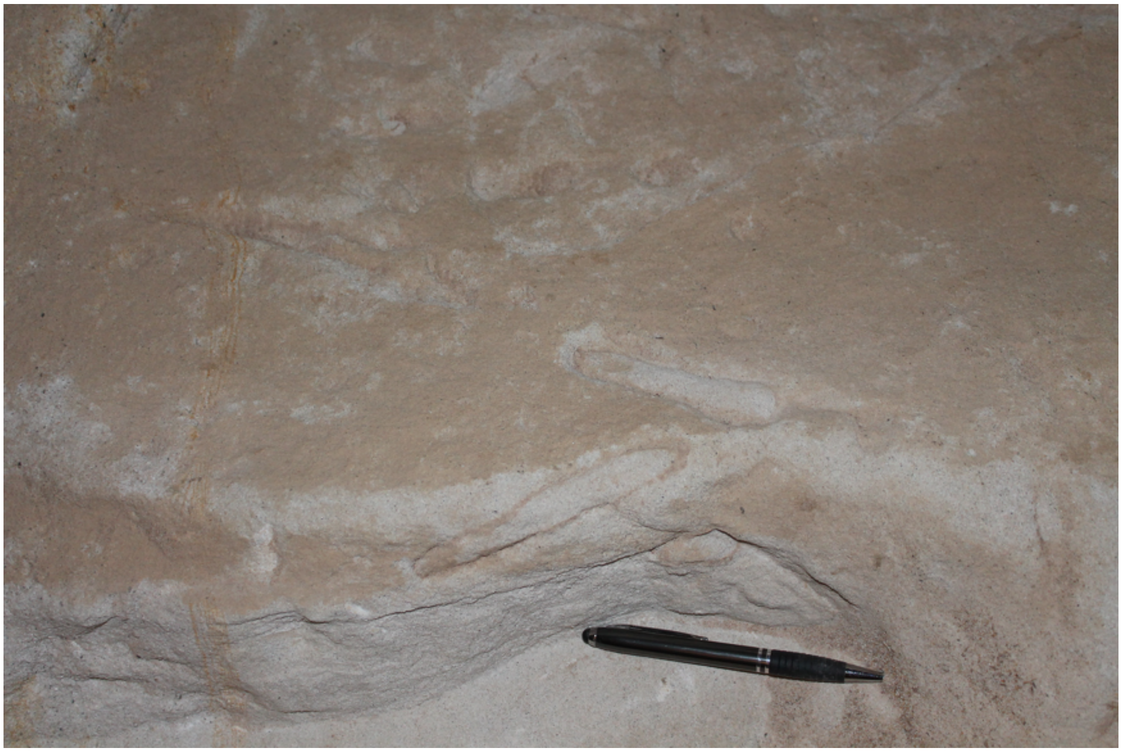


Mine Glossary

Portal	The surface entrance to a tunnel or adit.
Adit	A passageway or opening driven horizontally into the side of a hill generally for the purpose of exploring or otherwise opening a mineral deposit. An adit is open to the atmosphere at one end.
Stope	An excavation in a mine from which ore is being or has been extracted.
Drift	A horizontal passage underground that follows along the length of a vein or rock formation.
Room and Pillar (from Wikipedia)	Also called pillar and stall. A mining system in which the mined material is extracted across a horizontal plane, creating horizontal arrays of rooms and pillars. The ore is extracted in two phases. In the first, "pillars" of untouched material are left to support the roof overburden, and open areas or "rooms" are extracted underground. The technique is usually used for relatively flat-lying deposits, such as those that follow a particular stratum.

Hazel-Atlas portal and adit.





Trace fossils. Top photo shows cross beds in the upper part of the White Sandstone Member of the Domengine Formation. Organic rich mud drapes are common. Numerous *Ophiomorpha nodosa* burrows are seen in the sandstone beds. These represent the dwelling burrows of decapod crustaceans, including species of shrimp. [Explanation from field trip guidebook of Northern California Geological Society by Ray Sullivan et al.]

An example of a stope illustrating room and pillar mining.

Fault with shale smear.

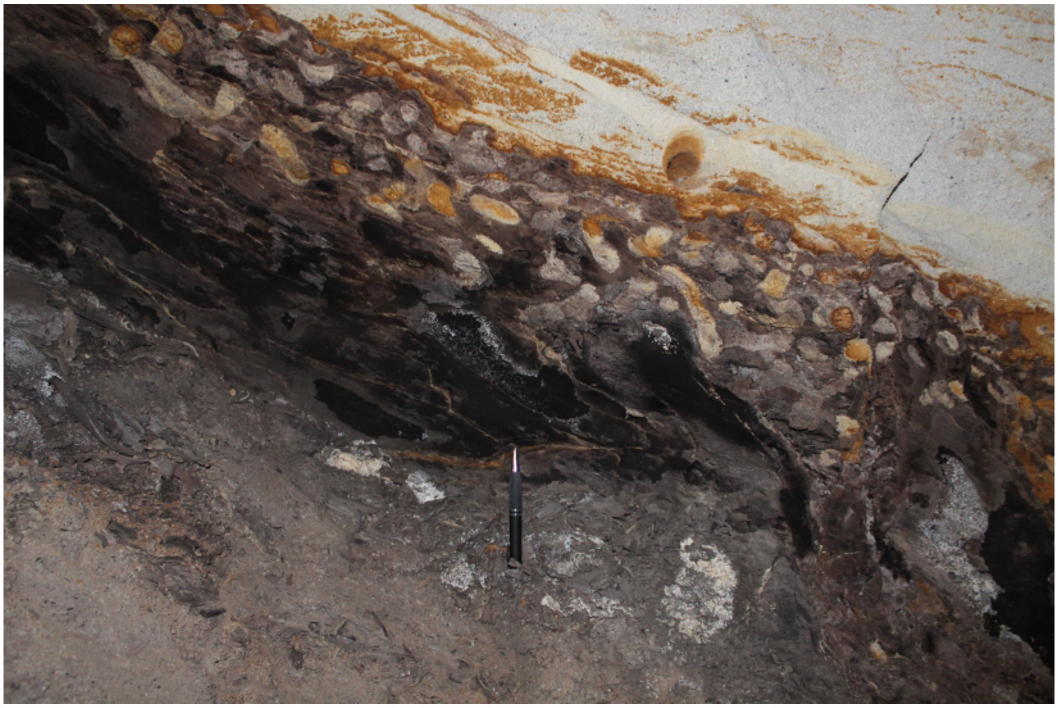
Stair leads down to Greathouse visitor center.

From http://seismo.berkeley.edu/annual_report/ar98_99/node5.html

The Berkeley Digital Seismic Network (BDSN) is a regional network of very broadband and strong motion seismic stations spanning northern California and linked to UC Berkeley through continuous telemetry. During the summer of 1998, a new broadband station was added at the Black Diamond Mines, East Bay Regional Park, south of Antioch. Under permit from the Park District, the addition of the seismographic equipment in an area of the mine not open to public tours is in keeping with the educational and research goals of the Park. The instruments are located approximately 150 meters from the daylight entrance to the mine. Approximately 100 meters of sandstone, shale, and coal overburden cover all the instruments. The overburden is sufficient to limit thermal variations. Additionally, the seismometers are covered with 7 centimeters of foil-faced, closed-cell foam. Differential GPS was used to precisely locate a reference outside the mine, and traditional surveying methods then located the instrument offset from the GPS determined coordinates. Station BDM features a Q4120 data logger, STS-2 broadband seismometers, FBA-ES-T accelerometers and 56 Kbit/s continuous telemetry to Berkeley. A GPS clock provides reference timing. Low loss co-axial cable (<2 dB per 100 feet) was used to minimize the attenuation of the signal and corresponding loss of external clock source.


Immediately below the low-grade coal seam are black, filamentous, sometimes downward-bifurcating features. These are root casts, that is, roots penetrating downward into a soil. These are common features beneath coal seams, but seldom seen so clearly.


Mine-collapse horizon. After coal seams were mined out and the pillar pulled, the mines sometimes collapsed. Later, when they cut new tunnel for sand mining, they intersected some of the old collapsed coal adits.


The black layer is a low-grade coal that was flooded by marine waters in which the overlying white sand dunes were deposited. The burrows at the interface belong to the trace fossil assemblage *teredolites*, which reflect burrowing by certain marine organisms into woody/peaty substrates

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Research Article
DOI: 10.2110/jsr.2012.66

SEQUENCE STRATIGRAPHY AND INCISED VALLEY ARCHITECTURE OF THE DOMENGINE FORMATION, BLACK DIAMOND MINES REGIONAL PRESERVE AND THE SOUTHERN SACRAMENTO BASIN, CALIFORNIA, U.S.A.

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ABSTRACT: **The middle Eocene Domengine Formation crops out in the Coast Ranges along the structurally complex western margin of the basin and forms an economically important gas reservoir in the Sacramento basin, California. Previous studies had interpreted the Domengine Formation as a conformable succession of barrier-island sandstone with tidal channels and coastal-plain deposits or a delta, tidal shelf, marsh complex located along a north–south-trending shoreline bordering the shelf. Integration of outcrop and subsurface data, however, indicate that the Domengine Formation can be regionally subdivided into two sequences. The bases of each sequence consist of fluvial and estuarine sandstones that were deposited in northeast–southwest-trending incised-valley systems that are interpreted to have been formed by fluvial incision. Shelfal shales and shoreline sandstones overlie the incised-valley fills and reflect flooding of the shelf. This cyclicity is interpreted to have been produced by the interplay of tectonism and eustasy. Tectonism is interpreted to have controlled the location of the incised submarine canyons and the fluvial estuarine systems throughout the early Tertiary as they stack vertically and trend southwest toward the structurally controlled depocenter. Eustasy appeared to have controlled the timing of the transgressive–regressive depositional cyclicity present in the lower Tertiary succession due to the strong correlation of available biostratigraphic data constraining the timing of these major periods of incision to the global coastal-onlap curves. Thickness trends observed in the Domengine Formation are interpreted as a product of variable incision, and not the result of depositional thinning in a northwesterly direction suggested by the previous models. The importance of this reinterpretation of the Domengine Formation, within a sequence stratigraphic framework, is that it provides a predictive model for both understanding the thickness trends and facies distributions of the Domengine Formation. It also potentially provides a more accurate depositional model for exploration and development of this important hydrocarbon reservoir.**

INTRODUCTION

The lower Tertiary strata deposited in the Sacramento basin, northern California, U.S.A., display a distinct stratigraphic cyclicity of unconformity-bounded packages. The cycles are transgressive–regressive units composed of bathyal shales filling canyons or shallow marine and fluvial sandstones filling incised valleys at their bases that are capped by neritic mudstones. Three depositional cycles were defined by Almgren (1978), while Sullivan and Sullivan (2007) recognized at least seven of these unconformity-bounded sequences in the Eocene (Fig. 1). The focus of this study is the unconformity-bounded estuarine and fluvial sandstones of middle Eocene Domengine Formation which comprises two of these distinct cycles. The formation has been extensively studied because of its economic importance as a gas reservoir in the Sacramento basin (Clark 1928; Soper 1943; Stewart 1949; Colburn 1961; Todd and Monroe 1968; Bodden 1981; 1983; Cherven 1983a; Graymer et al. 1994; and Sullivan et al. 1994, 1999, 2003). The origin and controls of this cyclic deposition have long been debated, as have the depositional setting of the gas reservoirs in the basin. The original interpretation of this stratigraphic cyclicity (Almgren 1978) suggested it was solely due to tectonism. More recent interpretations suggest that this cyclicity was produced by the interplay of tectonism and eustasy (Fischer and Cherven 1988; Sullivan et al. 2003; Sullivan and Sullivan 2007).

Throughout the late Mesozoic and early Tertiary an active subduction zone existed along the western margin of the North American plate. A shelved forearc basin was situated between the subduction zone and the Sierra Nevada magmatic arc at the site of the present-day Great Valley of California (Dickinson et al. 1979; Ingersoll 1979; Graham et al. 1984; Moxon 1988, 1990; Bartow 1991). The Sierra Nevada and the Great Valley are located on the Sierra Nevada microplate, an element of the broad Pacific–North American plate boundary (Wakabayashi and Sawyer 2001; Moores et al. 2006). The Sierran magmatic arc was the provenance for most of the detritus into the forearc basin (Todd and Monroe 1968; Wakabayashi and Sawyer 2001; Moores et al. 2006). The basin was filled predominantly with Cretaceous and lower Tertiary marine and upper Tertiary terrestrial sediments (Fig. 2). The lower Tertiary succession is over 7500 feet (2265 meters) thick; it unconformably overlies the Mesozoic strata throughout the basin, and lacks the volcaniclastics-rich sediment present in the latter (Dickinson 1981). A change in plate motion at the end of Mesozoic times resulted in a lower angle of plate subduction, which in turn suppressed volcanic activity in the Sierran magmatic arc (Graham et al. 1984; Moxon 1988, 1990). In the

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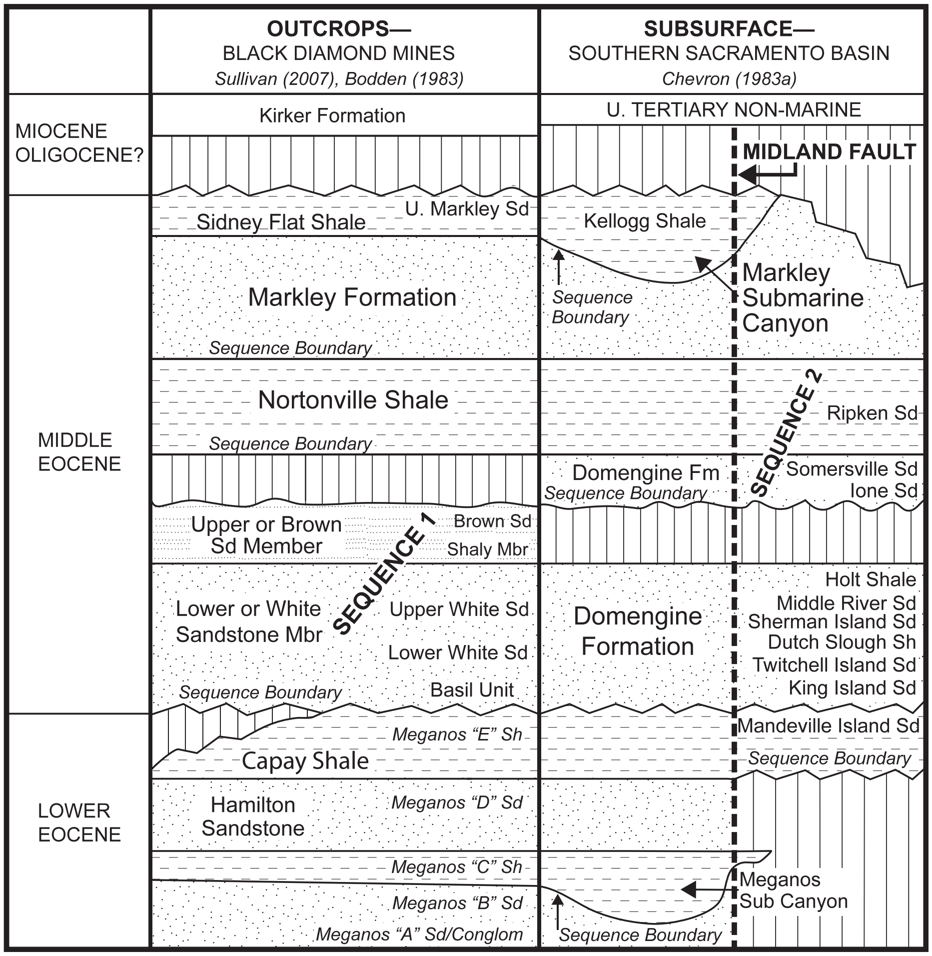


FIG. 1.—Lower Tertiary sequences in the outcrops at Black Diamond Mines Preserve and in the subsurface of the Sacramento basin. At least seven Eocene sequences were recognized by Sullivan and Sullivan (2007). Stratigraphic terminology for the Eocene is after Clark (1918), Fulmer (1956), Bodden (1981), Bodden and Cherven (1983), Cherven (1983a), and Sullivan et al. (2003). The division of the Domengine Formation used in the present account is listed on the left side of the figure, while Bodden's terms are shown in the center, and Cherven's division of the formation into numerous members is listed on the right.

late Tertiary, plate subduction was replaced by transform associated with the development of the San Andreas fault system (Atwater 1970; Graham et al. 1984), and volcanic activity was once more active, associated with the northward migration of the triple junction along the transform boundary (Fox et al. 1985). The upper Tertiary succession consists predominantly of terrestrial sediments in the basin and mixed marine and terrestrial deposits along the western Coast Ranges (Graham et al. 1984; Harwood and Helley 1987).

The east–west Stockton arch uplift is an early Tertiary structural high; it is bounded on the north side by a high-angle reverse fault (Fig. 3). The Stockton arch divided the forearc basin into a northern Sacramento basin and a southern San Joaquin basin (Dickinson et al. 1979; Moxon 1988, 1990; Bartow 1991). The Sacramento basin is approximately 270 miles (435 km) long and 60 miles (96 km) wide. The floor of the basin slopes southwestward away from the Sierra Nevada and the Klamath Mountains (Fig. 2). Tectonic activity in the basin was centered along the southern and western margins. In the basin, north–south growth faults, including the Midland and Kirby Hills fault systems, were frequently active in early Tertiary times due to oblique extension within the subducting plate, and formed a graben that served as the depocenter for the Sacramento basin (Figs. 2, 3; Almgren 1978; Moxon 1988, 1990; Bartow 1991; Krug et al. 1992). A marked change occurs as the lower Tertiary succession is traced eastward from the depocenter since the Paleocene sequences are absent due to intermittent activity on the Midland fault that culminated during the early Eocene in uplift and erosion on the eastern side of the basin. As a result, the lower Tertiary succession is thickest and most complete in the depocentral graben and thins eastward and northward (Fig. 2). The lower Tertiary deposition also extended westward beyond the depocentral graben, but subsequent uplift and erosion associated with the formation of the Coast Ranges together with major transform faulting has removed or displaced most of the evidence. The lower Tertiary succession is intermittently exposed in the Coast Ranges; it is present on the west side from the English Hills southward to Mount Diablo area. On the eastern margin lower Tertiary rocks were also uplifted to the surface in the foothills of the Sierra Nevada (Fig. 3). Late Tertiary uplift of the east–west Stockton arch resulted in the lower Tertiary being eroded across the structure, and the upper Tertiary rocks rest directly on Cretaceous rocks over this structure.

The middle Eocene in northern California was a time of warm and moist climate (Todd and Monroe 1968; Lucas-Clark and Lampley 1988; Kimyai 1993). Large rivers flowed westward from the Sierran magmatic arc depositing vast quantities of quartz and feldspar rich sands into the basin during the deposition of the Domengine Formation (Todd and Monroe 1968; Moores et al. 2006). It is possible that the Coast Ranges on the west side, and the Klamath Mountains in the north, may have also provided a source of sediment (Dickinson et al. 1979). The depositional environment of the Domengine Formation at Potrero Hills and the Rio Vista gas field north of the study area (Fig. 3) was interpreted by Todd and Monroe (1968) as deltaic, tidal shelf, and marsh deposits. In the Black Diamond Mines Regional Preserve, however, Bodden (1981, 1983) and Cherven (1983a) interpreted the equivalent rocks as a sequence of barrier-island, tidal-channel, and marsh deposits located along a north–south-trending shoreline bordering the shelf. Our

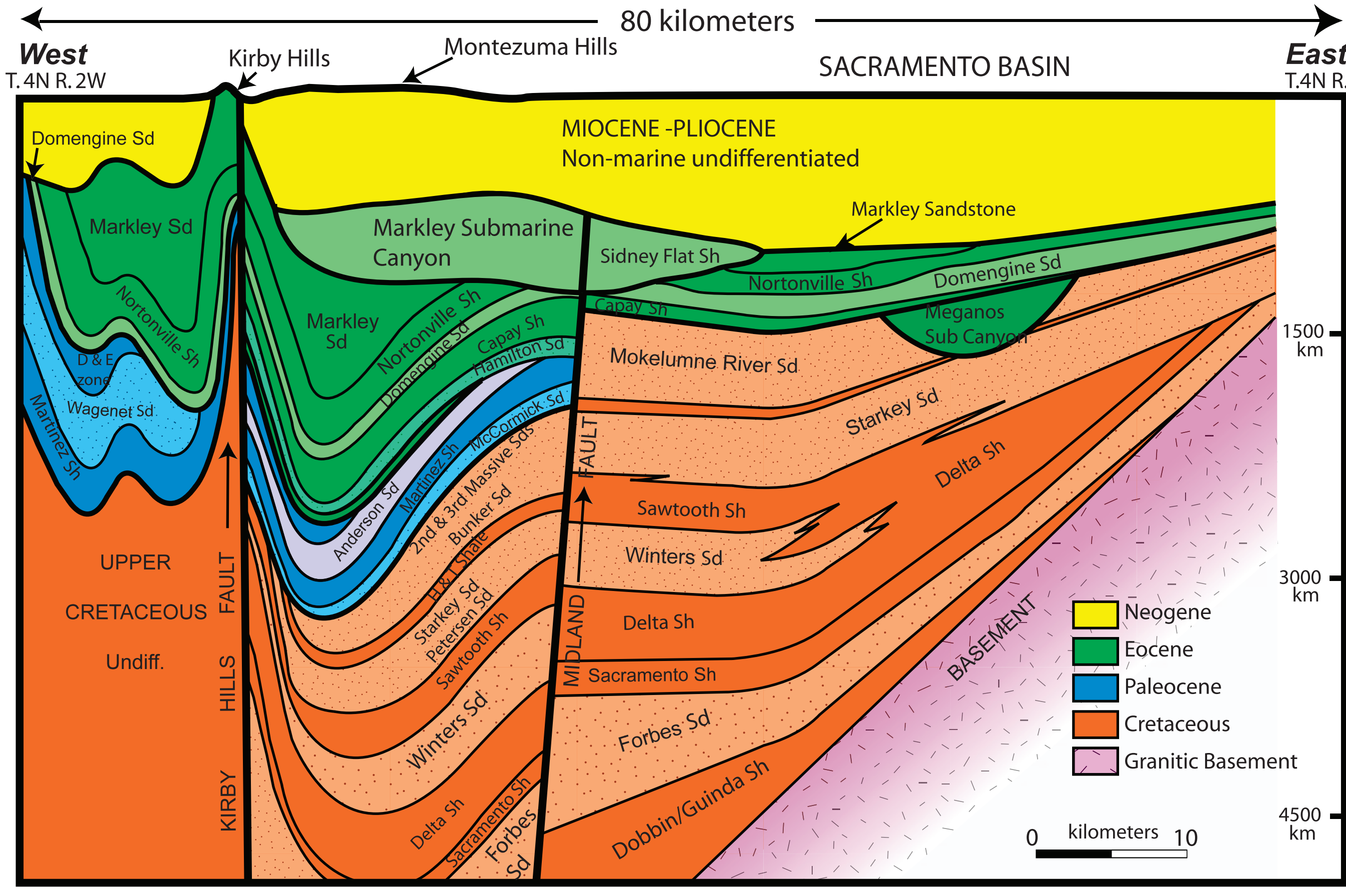


FIG. 2.—West-to-east cross section through T4N in the Sacramento basin (after Edmondson et al. 1967; Krug et al. 1992). See Figure 3 for location of cross section. Shown is the location of the depocenter graben bounded by the Midland and Kirby Hills faults. The Cenozoic succession unconformably overlies the Cretaceous. The Paleocene and early Eocene succession (pre–Capay Shale) is mainly confined to the graben depocenter due to early Eocene uplift and erosion of the section east of the Midland fault.

present study using the integration of outcrop and subsurface data, indicate that the Domengine Formation can be regionally subdivided into two unconformity-bounded sequences. The bases of each sequence are composed of fluvial–estuarine sandstones that were deposited in northeast–southwest-trending incised-valley systems that are interpreted to have formed by fluvial incision during relative lowstands in sea level. Shelfal shales and shoreline sandstones overlie the interpreted incised-valley fills and reflect flooding of the shelf and represent the transgressive and highstand systems tracts of each sequence. The importance of this reinterpretation of the Domengine Formation, within a sequence stratigraphic framework, is that it provides a predictive model for understanding both the thickness trends and the facies distributions of the Domengine Formation. It also potentially provides a more accurate depositional model for exploration and development of this important hydrocarbon reservoir.

MIDDLE EOCENE SUCCESSION

The middle Eocene succession reaches a maximum thickness of approximately 5000 feet (1525 meters) in Black Diamond Mines Regional Preserve on the northeast side of Mount Diablo (Fulmer 1956; Colburn 1961; Sullivan et al. 1994). The succession is divided into the Domengine, Nortonville Shale, Markley Sandstone, and Sidney Flat Shale formations (Fig. 1). The focus of this study is on the Domengine Formation, which has been dated from nannofossils and Foraminifera as middle Eocene, CP 12b or B1 age (Cherven 1983a; Almgren et al., 1988; Sullivan et al. 1994). The Domengine Formation has been further subdivided into both formal and informal lithological units (Fig. 1) by many workers, including Clark (1928), Soper (1943), Stewart (1949), Colburn (1961), Todd and Monroe (1968), Bodden (1981, 1983), Cherven (1983a), Graymer et al. (1994), and Sullivan et al. (1999, 2003).

The Domengine Formation at Black Diamond Mines Regional Preserve is 700 to 800 feet (210 to 240 meters) thick. It is dominated by thick-bedded, medium- to coarse-grained, massive to cross-bedded sandstones with subordinate conglomerate, and interbedded siltstone, shale, and coal interpreted to have been deposited in a shallow marine to coastal-plain setting. To the west, across the Concord fault (Fig. 3), a marked change occurs, and the Domengine Formation is composed of approximately 1500 feet (460 meters) of extremely amalgamated, massive-bedded sandstones with thinly interbedded mudstones interpreted as deepwater turbidites deposited on the upper slope.

The overlying Nortonville Shale is about 405 feet (135 meters) thick in the outcrops at the Black Diamond Mines Regional Preserve. It is composed of interbedded shales, mudstones, and lithic sandstones. Fulmer (1956) reported rich assemblages of foraminifers, radiolarians, diatoms, and thin-shelled clams from the Nortonville Shale. The Nortonville Shale is of middle Eocene age (CP 13 or A-2, Cherven 1983a; Almgren et al. 1988; Bukry et al. 1998), and was interpreted to have been deposited at bathyal depths on a west-sloping shelf (Cherven and Bodden 1983; Cherven 1983b). The regional flooding surface (Fig. 1) that separates the Domengine Formation and the Nortonville Shale is readily traceable in the outcrops and into the subsurface of the Sacramento basin.

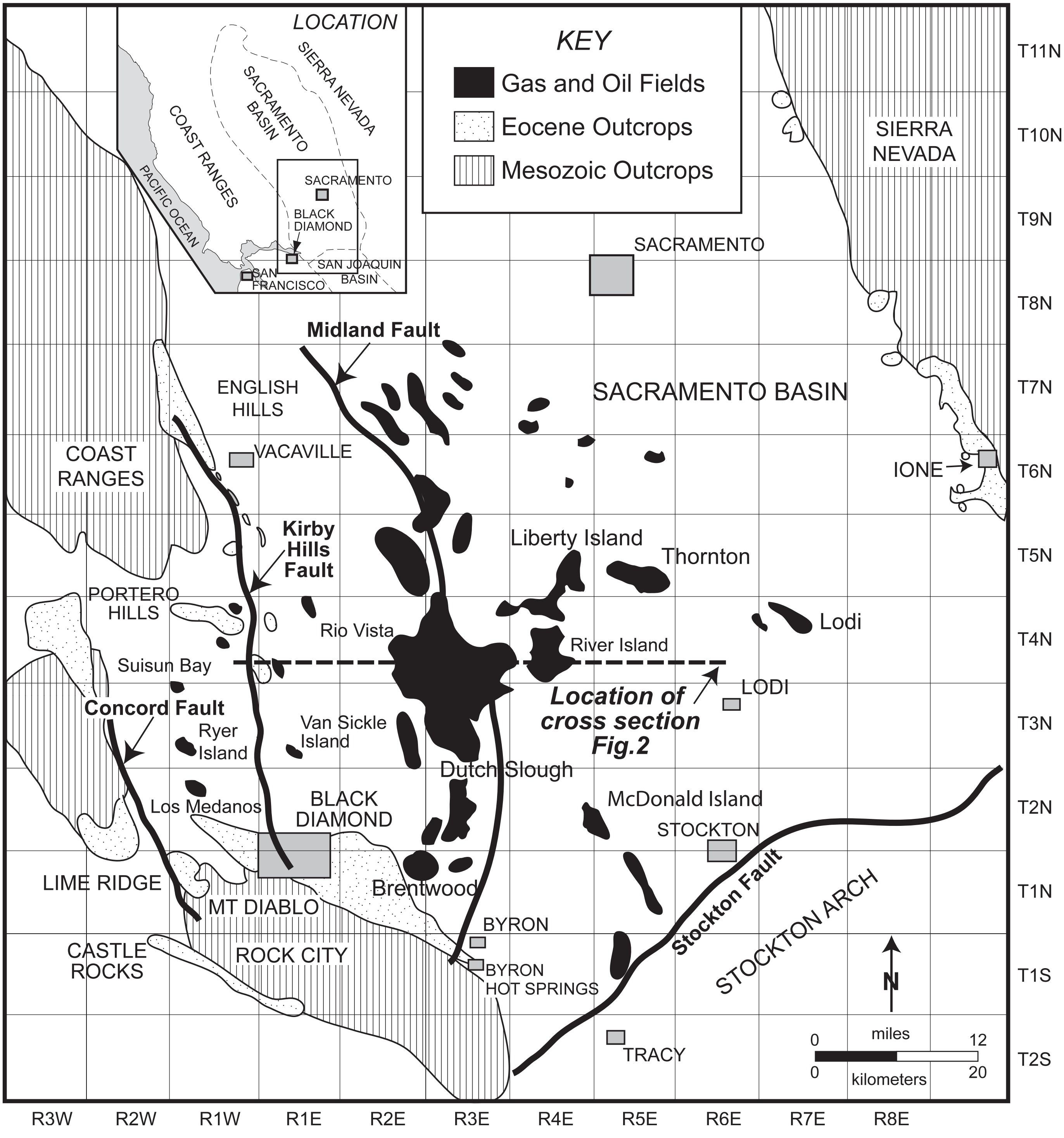


FIG. 3.—Location map of major gas fields in the southern Sacramento basin, California. Many of the largest fields are located in the graben depocenter in the southwest portion of the basin, which is bounded by the north–south Midland and Kirby Hills faults, which were active during the early Tertiary. The location of west–east section in Figure 2 is shown on the map.

DETAILED CHARACTERIZATION OF THE DOMENGINE FORMATION

The detailed characterization of the Domengine Formation is based on the integration of outcrop observations from 12 detailed measured sections, field mapping, and over 2250 wells from the Sacramento basin. The wells are concentrated in the central part of the basin, and limited subsurface information on the western and eastern margins makes detailed correlation difficult in these areas. The focus of the study was the exceptionally well-exposed outcrops of the Domengine Formation at the Black Diamond Mines Regional Preserve on the northeast flanks of

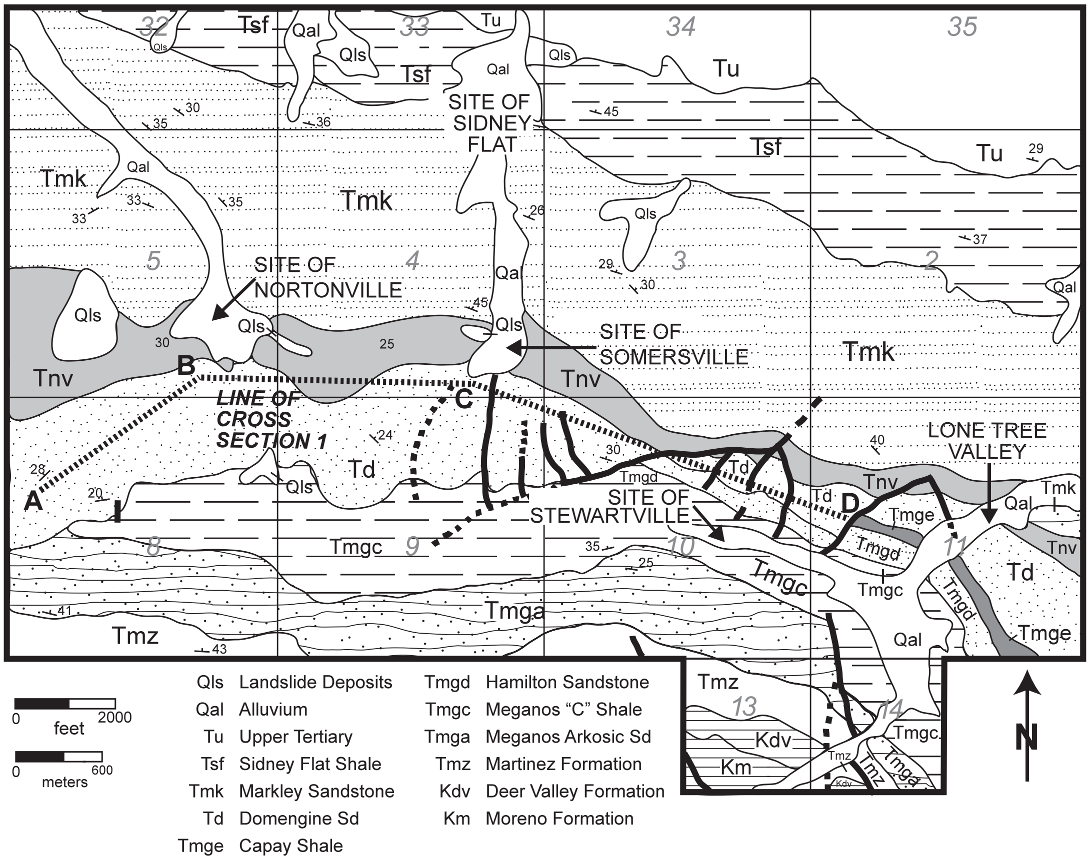


FIG. 4.—Geological map of Black Diamond Mines Preserve (after Dibblee 1980a, 1980b; Graymer et al. 1994). The base of the Domengine Formation is an erosional unconformity, and in the Black Diamond Mines Regional Preserve it overlies strata ranging from early Eocene to Cretaceous as the contact is traced westward on the northeastern flanks of Mount Diablo. The thinning of the Domengine Formation eastward to Stewartville is in part due to absence of the basal conglomeratic unit. In addition, variation in structural dip and topography in the eastern outcrops is another contributing factor.

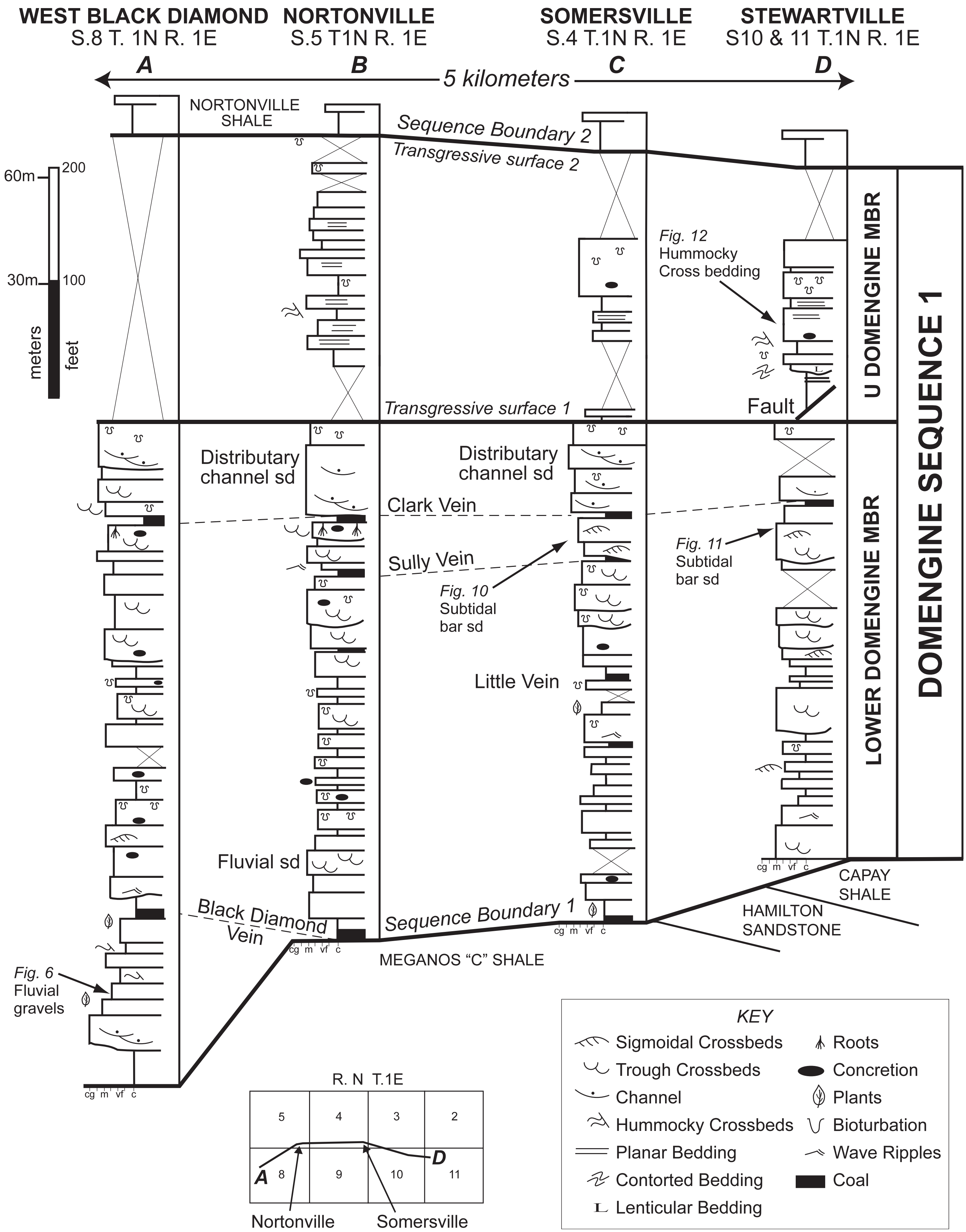
Mount Diablo. These strata crop out in a series of east–west-oriented strike ridges south of the town sites of Nortonville and Somersville, but are best exposed in the underground mines of the Black Diamond Mines Regional Preserve (Fig. 4). The lower Tertiary strata present in the Preserve are within the depocenter of the Sacramento basin and, therefore, represent the most complete stratigraphic section (Figs. 1, 3). The Domengine Formation in outcrop can be further subdivided into two members, a lower white sandstone member and an upper brown sandstone member (Figs. 1, 5). The lower member is made up predominantly of quartz-rich sandstones with thin interbedded siltstones, mudstones, and coal, and the upper member is composed of lithic sandstones and interbedded siltstones and shales.

Lower Member of the Domengine Formation

The lower member is about 600 feet (185 meters) thick. The stratigraphic details of this member have been described by Bodden (1981, 1983), Cherven (1983a), and Sullivan et al. (1994, 2003). The Domengine Formation is separated from the underlying strata by a regional unconformity which, when traced westward, progressively truncates older units until the Domengine rests on Cretaceous rocks west of the Black Diamond Mines Regional Preserve (Fig. 5). Locally at the base of the lower member is a poorly sorted conglomerate unit with minor interbedded sandstones and siltstones, which reaches a maximum thickness of 110 feet (35 meters) in the western exposures. The basal unit at this location rests directly on Meganos C Shale, a bathyal shale (Fig. 6) containing rich assemblages of Foraminifera that have been dated as early Eocene (P6 age, Keller 1988 personal communication and CP 10–11, Almgren et al. 1988). The conglomerate is clast-supported, indicating deposition as bedload, and is composed of well-rounded cobble- and pebble-size clasts of black chert, quartzite, sandstone, and volcanic rocks with a Sierran provenance (Walker 2004). Occasional red chert pebbles suggest a minor local Franciscan source in the Coast Range (Dickinson et al. 1979). The conglomeratic packages occur as lenticular units that fine upwards into lithic sandstone and siltstone; the latter contains abundant plant fragments and poorly preserved fossil leaves. These upward-fining successions are 10 to 30 feet (3 to 10 meters) thick.

Sharply overlying the basal conglomerate and sandstone unit is the regionally extensive Black Diamond coal vein, measuring approximately 3 feet (1 meter) thick and which can be traced throughout the Preserve and beyond (Fig. 5, MacKevett 1992). This sub-bituminous coal was widely mined during the 19th century (Jennings 1957; Sullivan and Waters 1980). Petrified wood is common in this bed. Above the Black Diamond coal is a regionally extensive white sandstone unit, which is the source of the informal name for the lower member. It is predominantly composed of 400 to 500 feet (130 to 165 meters) of thick-bedded, quartz-rich sandstones (Figs. 5, 7). Interbedded mudstones and siltstones are common in the middle of the member and form a more recessive unit within the resistant cliff forming massive white sandstone units (Fig. 8).

Based on vertical and lateral organization and continuity, grain size, and sedimentary structures, the lower member can be further subdivided into five distinct lithofacies associations, which are similar to those


WEST BLACK DIAMOND
S.8 T. 1N R. 1E
NORTONVILLE
S.5 T1N R. 1E
SOMERSVILLE
S.4 T.1N R. 1E
STEWARTVILLE
S10 & 11 T.1N R. 1E
A
B
C
D
5 kilometers
NORTONVILLE SHALE
Sequence Boundary 2
Transgressive surface 2
60m
200
30m
100
meters
feet
Fig. 12
Hummocky
Cross bedding
U DOMENGINE MBR
DOMENGINE SEQUENCE 1
Transgressive surface 1
Fault
Distributary channel sd
Distributary channel sd
Clark Vein
Sully Vein
Fig. 10
Subtidal
bar sd
Fig. 11
Subtidal
bar sd
LOWER DOMENGINE MBR
Little Vein
Fluvial sd
Black Diamond Vein
Sequence Boundary 1
cg m vf c
CAPAY SHALE
HAMILTON SANDSTONE
MEGANOS "C" SHALE
Fig. 6
Fluvial
gravels
R. N T.1E
5 4 3 2
8 9 10 11
A
D
Nortonville
Somersville
KEY
Sigmoidal Crossbeds
Trough Crossbeds
Channel
Hummocky Crossbeds
Planar Bedding
Contorted Bedding
Lenticular Bedding
Roots
Concretion
Plants
Bioturbation
Wave Ripples
Coal

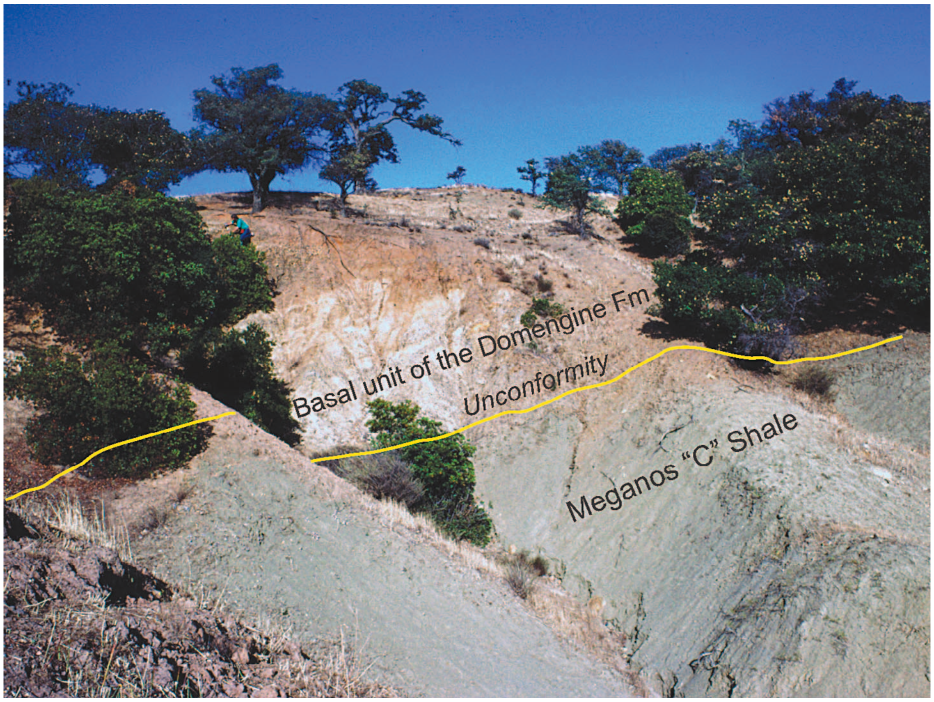


FIG. 6.—Basal conglomerate of the lower member of the Domengine Formation is shown resting unconformably on Meganos C Shale at location A in Figure 4 (S8, T1N R1E) in the western border of the Preserve. The section is also stratigraphically located in Figure 5. The basal unit is about 110 feet (35 meters) thick. It is a fluvial gravel lag deposit that occupies a local valley incision that thins laterally to the east and west.

described by Bodden (1981 and 1983) and Cherven (1983a): (1) lenticular, upward-fining, cross-bedded sandstones; (2) lenticular, upward-fining, bioturbated sandstones; (3) lateral continuous, upward-fining, bioturbated sandstones; (4) upward-coarsening, cross-bedded sandstones, and (5) coal and carbonaceous mudstones.

The stacked upward-fining, cross-bedded, coarse-grained sandstones comprise packages typically five to ten feet (1.5 to 3 meters) thick. Pebbles and shale rip-up clasts frequently occur at the bases of these lenticular sandbodies, which grade upward into fine- to medium-grained sandstones, siltstones, carbonaceous mudstones, and thin coals. Individual sedimentation units in this fining-upward lithofacies are characterized by internally structureless, sharp-based beds 0.5 to 5 feet (15 cm to 1.5 meters) thick. Bedding surfaces are commonly marked by 0.1 to 2.7 feet (3 cm to 0.8 meters) thick basal lags of mud intraclasts. The intraclasts range from less than half an inch to several inches in length (several millimeters to tens of centimeters), and are typically elongated and extremely angular in shape. The angularity and delicate nature of these clasts suggest that they were still ductile and unlithified at the time they were ripped up and incorporated into the sediments. Plant fragments are abundant in the mudstones. Bioturbation is rare or absent in these deposits, and the only trace fossils found are *Teredolites* burrows in carbonaceous lenses. These lenticular packages are commonly found in the lower and upper parts of the white sandstone unit. They are particularly well developed in the upper most 80 feet (25 meters) of this member in the underground tunnels and cliff exposures at Somersville and in the outcrops at Nortonville (Fig. 7), where the lenticular packages are stacked upon each other without the interbedded siltstones and mudstones.

The second lenticular, upward-fining sandstones lithofacies association differs from the first by the presence of sandstones that are distinctly finer in grain size and show poorly developed cross-stratification. These structureless to faintly cross-bedded, fine grained sandstones form 5 to 10 feet (1.5 to 3 meters) thick, fining upward, erosionally based packages that are typically only hundreds of feet (tens of meters) in lateral extent. Marine trace fossils are also common in this lithofacies and include *Ophiomorpha* and abundant *Teredolites*.

Also common in the succession are upward-fining, fine- to medium-grained sandstones that are sheet-like rather than lenticular in lateral distribution. These sharp- based sandstones exhibit less erosion and scouring at their bases and typically grade upward into siltstones and carbonaceous mudstones (Fig. 9). They are often mottled and appear structureless due either to secondary modification or to rapid deposition so that the sediments lack sedimentary structures (Sullivan et al. 2003). Bodden (1981, 1983) has proposed that the weathering of feldspar grains to kaolinite may have obscured the sedimentary structures in these sandstones. Thin-section analysis of these sandstones, however, reveals that the beds also have a high degree of cryptic bioturbation (Henck personal communication) which is not readily apparent in outcrop and is the most likely reason for the massive appearance. Interstratified siltstones often exhibit wave ripples and mudstones containing fossil plants. These fining-upward beds are common throughout the section but are particularly well developed in the lower and middle part of the member.

Distinct upward-coarsening packages of cross-bedded, bioturbated sandstones are particularly well developed in the upper part of the white

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FIG. 5.—Cross Section 1. West-to-east stratigraphic cross section of the Domengine Formation in the Black Diamond Mines Regional Preserve (see Fig. 4 for location). At the base of the Domengine Formation is an unconformity (sequence boundary 1), and the Domengine Formation progressively onlaps the Capay Shale, the Hamilton Sandstone, and the Meganos C Shale westward across the area. The lower member of the Domengine Formation is made up of fluvial and estuarine sandstones of the lowstand systems tract of Sequence 1. It is separated from the upper member by a regionally extensive surface of transgression (transgressive surface 1) and change in depositional style. The shales and sandstones of the upper member make up the transgressive and highstand deposits of Sequence 1. The Nortonville Shale above is separated from the Domengine Formation by a widespread surface of transgression (transgressive surface 2) of Sequence 2.

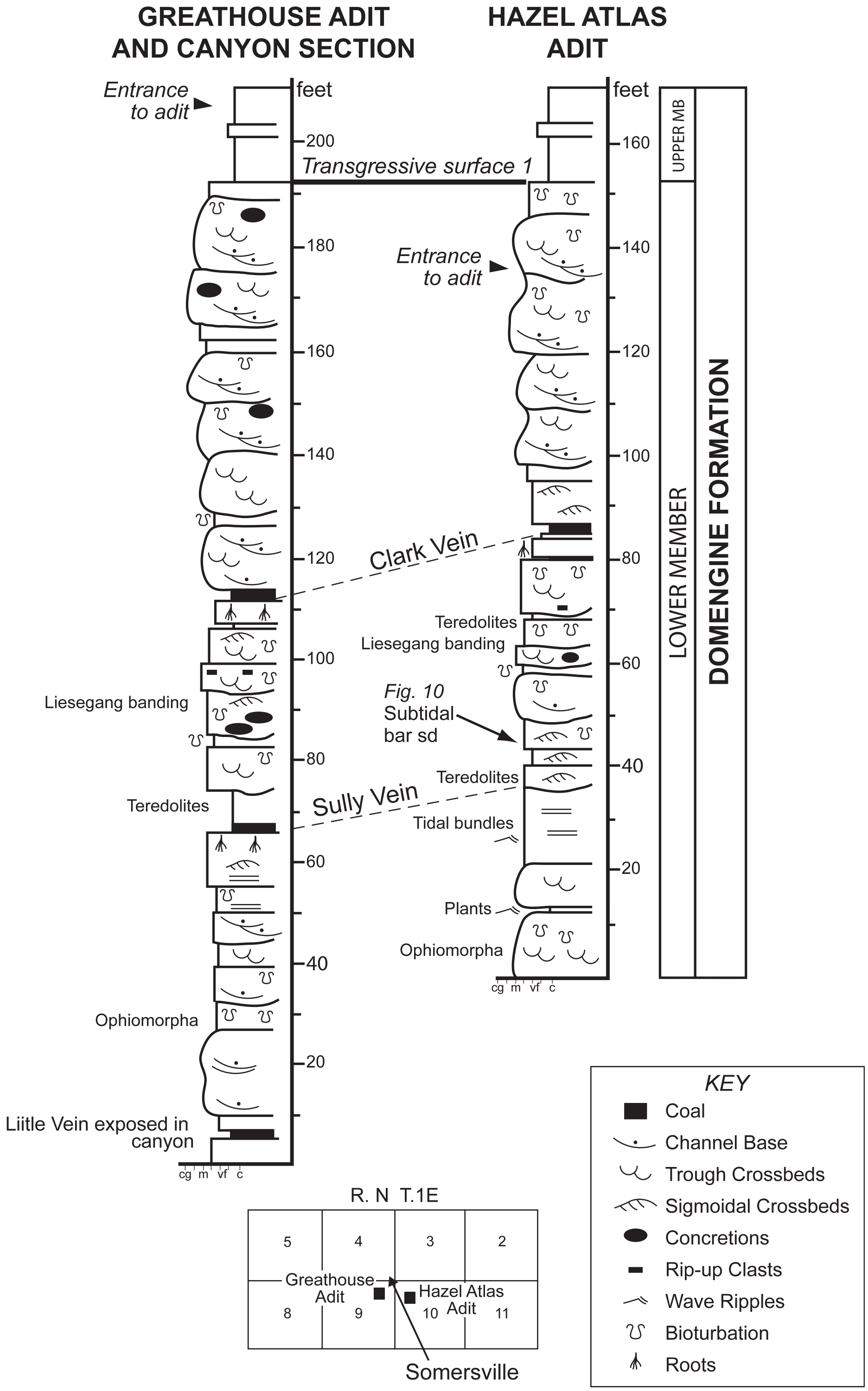

FIG. 7.—West–east correlation of lower member of the Domengine Formation in the Greathouse and Hazel Atlas adits at Somersville (see Fig. 4 for location). Only the upper 200 feet (60 meters) of the member was mined for glass sand in these two adits. The sections can be correlated using the Clark and Sully veins as marker beds. The units above the Clark vein are thick-bedded fining-upward channelized sandstones with the occasional *Teredolites* and *Ophiomorpha* that were deposited in distributary channels. The lower section below the Clark vein is composed of coarsening-upward subtidal-bar sandstones containing mud-draped sigmoidally cross-bedded units with abundant mud-lined *Ophiomorpha* burrows (photo of this unit is in Fig. 10).

sandstone unit, between the Clark and Sully veins, in the underground mines at Somersville (Fig. 7). Individual cross-bed sets form upward-coarsening bars 1 to 6 feet (0.3 to 2 meters) thick with flaser-bedded sandstones containing thick mud drapes at their base. These grade upwards into low-angle, cross-stratified sandstones with thin mud drapes that are capped by clean, sigmoidally cross-bedded sandstones (Fig. 10). Numerous scour and reactivation surfaces are also observed that suggest bidirectional flow of the currents (Van Wagoner 1999; Boyd et al. 2006). The trace-fossil suite is dominated by *Ophiomorpha* burrows but also includes other trace fossils such as *Macaronichnus*, *Palaeophycus*, and *Anconichnus.* In the surface exposures, the mud drapes and mud-lined burrows have been weathered and are outlined by brown limonitic staining (Fig. 11).

Thin coals and carbonaceous mudstones are present at several horizons throughout the section. Thin coals do not have great lateral extent, but thicker coals are more extensive and serve as marker beds. These include

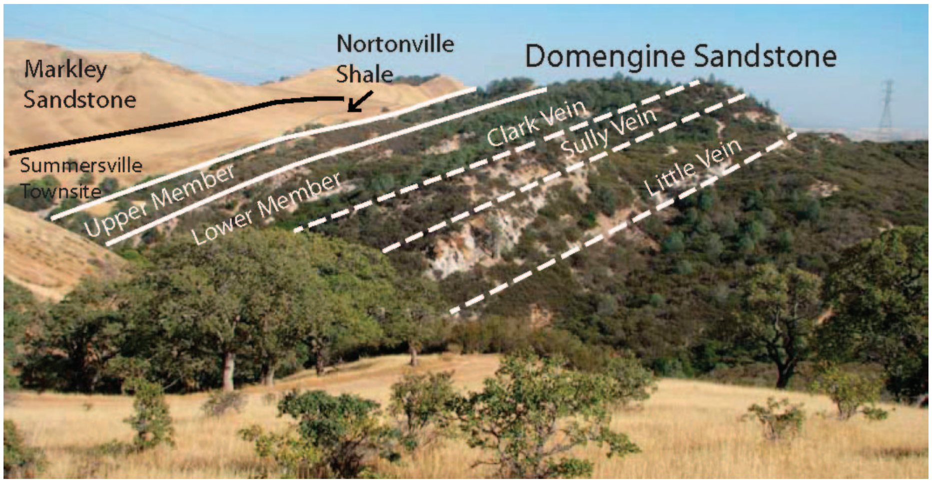

FIG. 8.—View looking east from the Manhattan trail, located south of the town site of Somersville (section C Figs. 4, 5) in S4, T1N R1E. The formations dip approximately 30 degrees north. The approximate trend of the underground Greathouse adit is located within the hill in the foreground. The lower member of the Domengine Formation forms the chaparral-covered hill; the upper unit of this member is composed of about 200 feet (60 meters) of thick beds of quartz-rich sandstones with interbedded coals. The coals serve as local stratigraphic markers in the section. The overlying upper member of the Domengine Formation produces a ridge with a grassy oak-covered dip slope. The overlying Nortonville Shale forms an east–west strike valley bounded above by the ridge formed in the Markley Sandstone.

the Black Diamond vein at the base of the white sandstone unit, the Little or Belshaw veins in the middle, and the Sully and Clark veins in the upper part (Figs. 5, 7, 8, and Goodyear 1877). Siltstones with root structures underlie the coals and clearly indicate that they were formed *in situ*.

Macrofossils are extremely rare in the lower member, but sandstones have yielded shallow marine dinocysts (Sullivan et al. 1994). Coals have produced a fairly rich assemblage of spores and pollens from subtropical plants (Lucas-Clark and Lampley 1988; Kimyai 1993). Fossil leaves and petrified wood are also locally found in the carbonaceous mudstones and siltstones at several horizons in the section. Occasional clam casts are found in the mudstones.

Todd and Monroe (1968) described the petrology of the equivalent sandstones in the Potrero Hills, north of the study area (Fig. 3). The main sediment source for these quartz- and feldspar-rich sandstones was from the pre-Tertiary granitic and metamorphic rocks of the Sierra Nevada and Klamath Mountains (Dickinson et al. 1979). Todd and Monroe (1968) showed that the sediments were eroded and deposited during a period of warm and humid climate that extended over this latitude in Eocene times. Under these intense weathering conditions, the feldspars in the soils and detritus were altered to kaolinitic clay. The result is a quartz-rich sandstone set in a kaolinitic clay matrix. The sandstones are the source for the glass and foundry sand in the area. The composition of the sand is 85–92% quartz and 10–15% sodium plagioclase (Davis and Goldman 1958). Accessory minerals include hypersthene, zircon, ilmenite, tourmaline, kyanite, garnet, rutile, beryl, marcasite, andalusite, and pyrite. Moreover, near-surface oxidation of organic-rich mudstones and sulfide minerals is a common occurrence, and results in brown ferruginous staining of the rocks above the oxidation contact zone. Other diagenetic structures include liesegang bands, which are marked by concentric iron-stained laminations (Fig. 7). Limonite nodules and pellets are also common in the sandstones.

Upper Member of the Domengine Formation

There is an abrupt conformable contact between the lower member and the overlying upper member of the Domengine Formation that can be easily correlated in outcrop and in the subsurface (Fig. 5). This sharp planar contact was exposed in the tunnel wall of the Greathouse adit at Somersville until it was covered to safeguard the entrance to the mine (Sullivan et al. 1999; Sullivan et al. 2002; Sullivan et al. 2003). At the surface, the upper member forms a ridge with an oak grassland dip slope

FIG. 9.—Fining-upward units in the lower part of the lower member along the Black Diamond Trail measured in northwest corner of S9, T1N R1E (see Fig. 4 for location). The fine-grained sandstones are overlain by siltstones and carbonaceous mudstone deposited in intertidal sand and mud flats of the Domengine estuary.

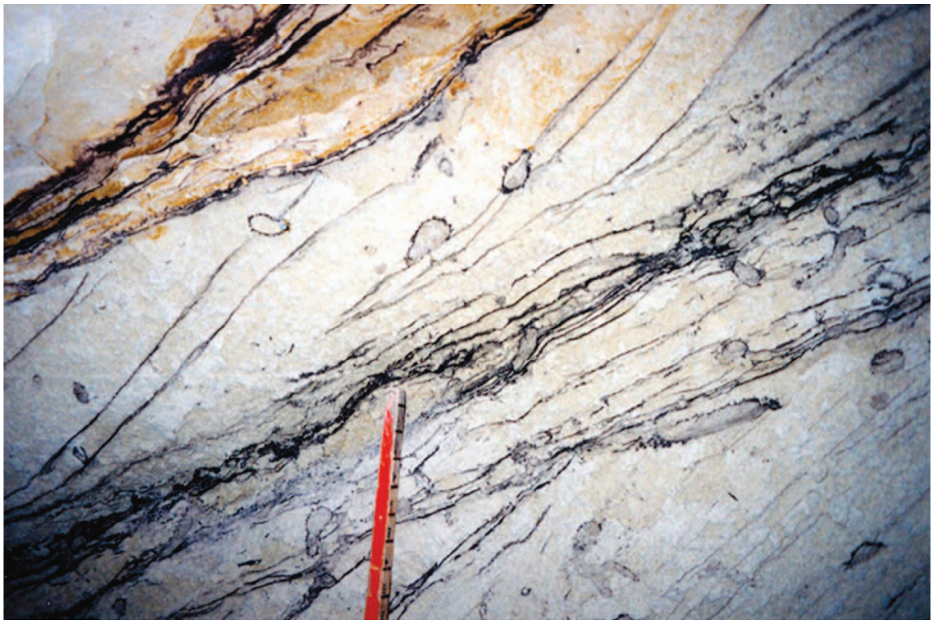

FIG. 10.—Tidal bar sandstones of lower member of the Domengine Formation displayed in the underground workings of the Hazel Atlas adit, Somersville (Fig. 7). Sandstones are sigmoidally cross-bedded with mud drapes on the foresets. This association is typical of tidal deposits; the mud draping formed during the slack water, and the cross-bedded sands were deposited during the high-energy flood and/or ebb water stage of the tidal cycle. *Ophiomorpha* burrows formed by shrimp-like creatures are extremely common in these deposits.

which is in marked contrast to the rugged chaparral covered ridges developed in the underlying more massive sandstones of the lower member (Fig. 8). The upper member is generally poorly exposed but does crop out in the canyon and ridges south of the former town sites of Nortonville and Somersville. It is best exposed, however, in the Prospect and Star Mine adits, which are two underground coal entries located south of Stewartville (Fig. 5, and Bodden 1981, 1983).

The upper member is between 150 to 250 feet (50 to 80 meters) thick. The lower 50 feet (15 meters) of the member is typically shale-rich and is composed of stacked thickening-upward interbedded packages of laminated shale, siltstone, and rare sandstone. The shale and siltstone beds display wave ripples, load casts, flame structures, and convolute laminations (Bodden 1981, 1983). They commonly grade upward into thin, wave-rippled to hummocky cross-stratified, lithic sandstones. The shales directly above the contact with the underlying white sandstone contain abundant arenaceous Foraminifera. Numerous specimens of the trace-fossil *Bergaueria,* which was formed by an actinian anemone, as well as horizontal grazing trails typical of the *Cruziana* trace fossil assemblage, can be found in the siltstones at Somersville and Nortonville.

The upper portion of the member is more sandstone-rich and is dominated by brown-weathering lithic sandstones and siltstones composed of quartz, feldspar, biotite, and glauconite grains with a calcareous-cement. The more calcareous cemented beds stand out as resistant beds in the hillsides. On the whole the sandstones are much finer grained and more poorly sorted than the quartz-rich sandstones in the underlying lower member. Some sandstones and siltstones are planar bedded. Other

FIG. 11.—Tidal bar sandstones of the lower member Domengine Formation in outcrop south of the site of the mining town of Stewartville (S11, T1N R1E, location D in Fig. 4 and stratigraphic position in section in Fig. 5). The beds display bidirectional cross bedding typical of that found in tidal sand bars. The foresets were mud draped, but the organic-rich muds have been oxidized at the surface to limonite-stained laminations.

FIG. 12.—Hummocky cross-bedded lithic sandstones in the upper member of the Domengine Formation observed in the outcrops above Stewartville in S10, T1N R1E (Fig. 5 for stratigraphic location). They were deposited in the lower-shoreface setting, in marked contrast to the fluvial–tidal lowstand deposits of the lower member.

resistant sandstones contain hummocky cross-bedding as well as wave ripples (Fig. 12). Calcareous sandstones in the upper part of the section are locally rich in a diverse coral–molluscan fauna reflecting marine conditions.

DEPOSITIONAL SETTING OF THE DOMENGINE FORMATION

Previous studies by Todd and Monroe (1968), Bodden (1981, 1983), and Cherven (1983a) interpreted the lower member of Domengine Formation as a delta or barrier island, tidal channel, marsh, and fluvial system along a north-to-south-trending shoreline near a shelf margin. There is little evidence in the sandstone architecture, sedimentary structures, and stratigraphic relationships to support a delta or barrier-island model. Instead there is abundant evidence for a system dominated by tidal and fluvial processes. Todd and Monroe (1968) suggested that the tidal sandstones of the Domengine Formation were deposited on a tide-dominated shelf, while Cherven (1983a) thought that they were deposited in a subsidence trough formed by compaction of the underlying mud-filled Meganos submarine canyon. Westward of the tidal channel was a proposed barrier island or possibly a delta-front and shoreline sand-rich complex that interfingered seaward with shelfal shales. We propose, however, that the lower member of the Domengine Formation was deposited in a strongly tide-dominated estuarine system with little to no wave influence. In contrast, the upper member reflects deposition in a wave-dominated setting with little to no tidal influence.

The estuarine setting for the lower member can be broadly divided into those areas at the head of the system that are fluvially dominated, an intermediate area of intertidal flats and distributary channels that are often areas of mixed fluvial and tidal processes, and the seaward part of the estuary where subtidal channels and bars are strongly influenced by tidal deposition (Fig. 13).

The thick, lenticular conglomeratic package at the base of the lower member, which lacks any marine indicators such as trace fossils or wave- or tide-generated sedimentary structures, and exhibits a distinct upward-fining organization, is interpreted as channelized fluvial deposits (Fig. 6). They are thought to represent braided-stream deposits, based on the extremely coarse-grained nature of this lithofacies association, the lack of lateral accretion, and strong evidence for channelization as seen in its lenticular lateral distribution. The channelized, basal conglomeratic unit thins rapidly in both directions along the outcrop (Fig. 5), and the incised nature of the contact indicates that hundreds of feet of erosional incision must have occurred locally. These fluvial deposits are, therefore, further interpreted to be filling an incised valley. The lenticular, coarse-grained, upward-fining sandstones with local rip-up clasts at the base are also interpreted to be fluvial channel fills. This is supported by the erosional bases of individual lenticular bodies, the dominance of unidirectional cross-beds, and the lack of any marine indicators. The deposits also display a distinct upward-fining character with decreasing evidence for erosion upwards. Siltstones in the unit contain abundant fossil leaves and plant fragments. The sandstones are distinctly finer grained than the conglomeratic packages at the base of the member and reflects either a change in the available grain size or a change in fluvial style. The interpretation is that a change in fluvial style occurs in the upper beds and these deposits are point bars, or low-energy fluvial channel fills, associated with meandering rivers at the proximal river dominated portion of the estuary (A in Fig. 13).

The transition from the fully river-dominated portion of the system to mixed portion of the estuary is represented by lenticular, upward-fining sandstone lithofacies with the common occurrence of marine trace fossils. The distinct lenticularity and upward-fining nature of these sandstones also suggests a channelized origin. Cross-bedding is poorly developed in this lithofacies, but when present it does reflect tractional deposition consistent with a fluvial setting. The *Ophiomorpha* and abundant *Teredolites* trace fossils present throughout this lithofacies association, however, indicate that there was a marine influence. These marine-influenced, channelized deposits are interpreted as distributary-channel deposits, and probably the distal end of the rivers that extended into the intertidal sand and mud flats of the estuary (B in Fig. 13).

The bioturbated, sheet-like deposits are interpreted to represent the transition from a river-dominated to a tidal dominated system. The bases of these sandstones exhibit little to no erosion or scouring. Diagnostic physical sedimentary structures indicative of the depositional setting are rare due to the interpreted intense bioturbation of these deposits. The association of this lithofacies association with other tidally influenced deposits, their sheet geometry, and the local presence of wave ripples and plant fragments, are all consistent with deposition on intertidal sand flats (Van Wagoner 1999; Boyd et al. 2006; C in Fig. 13).

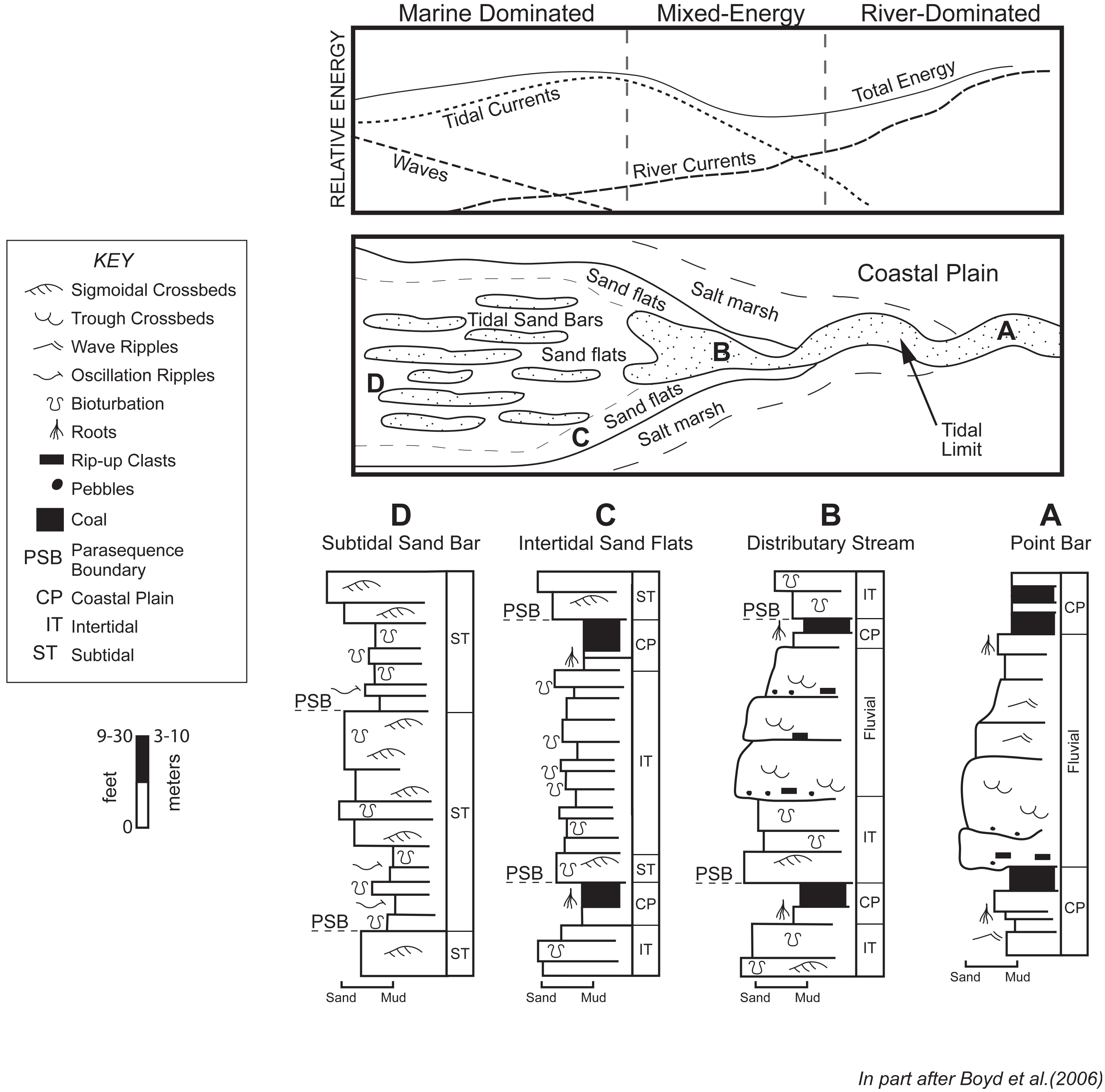

FIG. 13.—Schematic fluvial–tidal depositional model of a river dominated estuarine system as represented in the Domengine Formation (in part after Boyd et al. 2006). The most proximal deposits of the Domengine incised-valley fill are fluvial channel fills (A) which pass seaward into distributary-channel sandstones (B), highly burrowed sandstones and mudstone representing intertidal-flat deposits (C), and tidal bar sandstones with mud draped cross beds and abundant burrows (D). Coastal swamp and plain deposits are also present and are represented by thin interbedded carbonaceous mudstones and coals. These lithofacies are stacked vertically in the lower member as the depositional system fluctuated through time.

The most distal deposits interpreted in the lower member are the coarsening-upward, bioturbated, cross-stratified units. These deposits are again similar to the tidal deposits described by Van Wagoner (1999) and Boyd et al. (2006), and many others, and the presence of a restricted assemblage of trace fossils, and a very characteristic development of sedimentary structures, clearly support an estuarine origin in a tidal setting (D in Fig. 13). These features include sigmoidal cross-beds, unidirectional and bidirectional reactivation surfaces, mud drapes, and mud couplets. The mud drapes, as individual cross-bed sets, form upward-coarsening bars 1 to 6 feet (0.3 to 2 meter) thick with flaser-bedded sandstones exhibiting thick mud drapes at their bases. These grade upwards into low-angle cross-stratified sandstones containing thin mud drapes that are capped by clean, sigmoidally cross-bedded sandstones (Figs. 7, 10). The flaser-bedded and cross-bedded sandstones are interpreted to have been deposited by migrating bars during the dominant tidal cycle. The mud drapes were formed during the slack-water

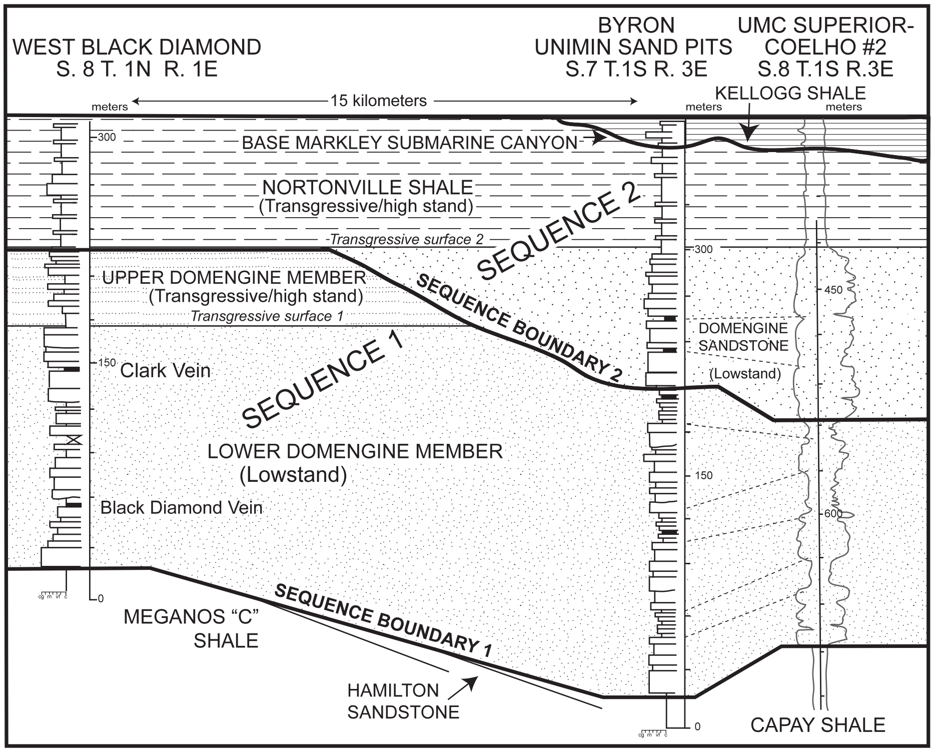

FIG. 14.—Stratigraphic cross section 2 (see Figs. 17, 18 for location) for the Domengine Formation between Black Diamond Mines and Byron. This more regional view of the distribution of the Domengine Formation shows that it can be traced in outcrop southeastward from Black Diamond Preserve to Byron and into the subsurface of the Sacramento basin. The upper member of Sequence 1 is absent at Byron due to erosion and incision at the base of a younger lowstand deposit (Sequence 2). The Markley Sandstone is absent due to erosion at the base of the overlying Markley submarine canyon.

period of the tidal cycle. The trace-fossil suite, while dominated by *Ophiomorpha* burrows, also includes other trace fossils such as *Macaronichnus*, *Palaeophycus*, and *Anconichnus*. Although burrowing is common in this facies association, the assemblage of trace fossils is relatively restricted and reflects environmental stresses common in tidal (brackish-water) settings (Pemberton et al. 1992). In the outcrop exposures, the mud-drapes and mud-lined burrows have been weathered and are outlined by brown limonitic staining (Fig. 11).

The upper member, in contrast, represents a distinct change from an incised tide-dominated setting to a wave-dominated setting with little to no influence of tides (Sullivan et al. 1994; Sullivan et al. 2003). The lower shale rich-portion of this member includes planar-bedded siltstones with the trace-fossils typical of the *Cruziana* trace-fossil assemblage. Arenaceous, benthic foraminiferal assemblages recovered from the member are listed in Sullivan et al. (1994). The microfaunal assemblage points to deposition occurring at bathyal depths. However, the work by Lagoe (1988) in the Tejon Formation of central California favored an outer-shelf or shelf-edge environment for this benthic foraminiferal biofacies. The sandstone-rich upper portion of the member contains sedimentary structures indicative of deposition in a wave-dominated setting. These sandstones with their rich molluscan fauna and hummocky cross-bedded units are interpreted as offshore to lower-shoreface deposits in a wave-dominated system.

SEQUENCE STRATIGRAPHIC ANALYSIS OF THE DOMENGINE FORMATION

From a detailed facies analysis and correlation of regional stratal surfaces, the Domengine Formation can be subdivided into two unconformity-bounded sequences (Sequences 1 and 2, Figs. 1, 5). This subdivision is based on the observed truncation, onlap, and angular discordance, interpreted basinward shift in facies, and changes in parasequence stacking patterns. Mainly the lower sandstone-prone interval of the lower Sequence 1 is well exposed in the outcrops at Black Diamond Mines Regional Preserve, while both Sequences 1 and 2 are present in the subsurface of the southern Sacramento Valley and in the sand mines near Byron, approximately 10 miles (16 kilometers) to the southwest.

The base of the Domengine Formation is a sequence boundary marked by a major angular unconformity with the underlying strata. In the Black Diamond Mines Regional Preserve, the Domengine Formation rests on the lower Eocene strata and truncates progressively older units to the west until it ultimately overlies Cretaceous strata. The boundary is also marked by an abrupt change in facies with conglomeratic fluvial channel fills at its base. This basal conglomerate unit thins rapidly in both directions along the outcrop (Fig. 5), and the incised nature of the contact indicates that hundreds of feet of erosional incision must have occurred locally. These channelized fluvial deposits are, therefore, further interpreted to be filling an incised valley which was cut by fluvial incision during a relative lowstand in sea level. Overlying the fluvial conglomerates are fluvial and estuarine deposits, also interpreted to be filling incised valleys, that were deposited during the late lowstand systems tract. Sharply overlying the predominantly fluvial and estuarine sandstones, mudstones, and coals of the lower member of the Domengine Formation, which are aggradationally to progradationally stacked, are the retrogradationally stacked shoreface deposits of the upper member. This change in stacking patterns, and the observed significant landward shift in deposition at this contact (transgressive surface 1 in Fig. 5), indicate that the surface marks a widespread flooding event at the base of the overlying transgressive systems tract.

In the subsurface west of Black Diamond, the twofold member division of the Domengine Formation (Sequence 1) observed in the Black Diamond Preserve produces a distinctive well-log signature. The massive sandstone units in the lower member, and the overlying upper member that coarsens upward from shale prone at the base into sandstone above, can be recognized in the logs. These two members of Sequence 1 can be correlated northwestward from the Preserve into the Los Medanos (T2N R1W) and nearby gas fields (Fig. 3) where the upper member is referred to as the "Domengine silt" (Pittman 1976). The correlation can be extended into the Ryer Island and Suisun gas fields in T3N R1W (Fig. 3 and Edmondson et al. 1967).

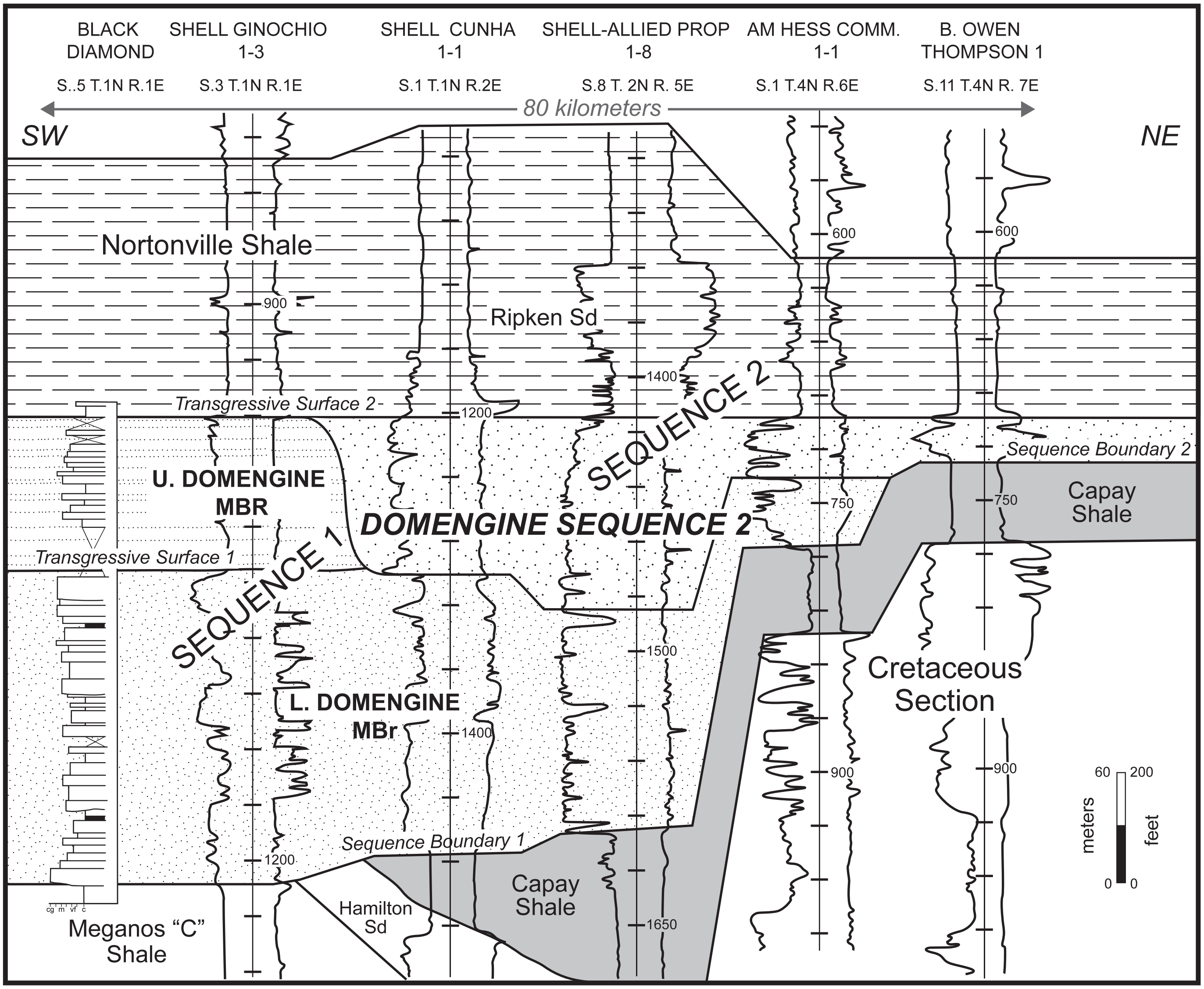

FIG. 15.—Stratigraphic cross section 3 (see Figs. 17, 18 for location) of the Domengine Formation between Black Diamond Mines Preserve and the subsurface of the Sacramento basin. The section is oriented NE–SW along the depositional strike of the fluvial–estuarine system. The same stratigraphic relationships illustrated in Figure 14 are shown in this cross section, and a younger valley system (Sequence 2) of the Domengine Formation is incised into the underlying Sequence 1 eastward in the subsurface of the basin. Structural control on the Domengine incised-valley systems is indicated by the "sagging" due to differential subsidence of the Capay Shale beneath the Domengine Formation.

The Domengine Formation can be traced in outcrop for 10 miles (16 kilometers) southeastwards from the Black Diamond Mines Regional Preserve to the hills immediately west of Byron and then into the subsurface in nearby wells (Fig. 14). In this southern area, the Unimin Company, and more recently a subsidiary of Gallo Wine Company, is mining the Domengine Formation for glass sand utilizing a series of large open-cast pits. These sandstone deposits are very similar in lithology to the sand-rich lowstand section at Black Diamond. They are predominantly fine- to medium-grained, light-colored, thick-bedded, quartz-rich sandstones with thin interbeds of claystone, mudstone, siltstone, and lignite (Fig. 14). Bed sets typically are composed of stacked sandstone beds, many of which are lenticular and channelized, with stringers of conglomerate and mud rip-ups at the channel base. Primary sedimentary structures are rarely observed in the steep cuts of the sand pits, although well-preserved mud-lined *Ophiomorpha* burrows are particularly common at several horizons. At the top of the Domengine section the sandstone grades upward into siltstones and mudstones, which are in turn overlain by Nortonville Shale.

There are important stratigraphic differences in the middle Eocene succession between the two areas. First, the section of shale and brown lithic sandstone that composes the upper member of the Domengine Formation at Black Diamond is absent from the section at Byron (Fig. 14). The Nortonville Shale directly overlies quartz-rich, white sandstones of the Domengine Formation with a gradational contact. Second, the Domengine Formation section has markedly increased in thickness from 600 feet (180 meters) at Black Diamond to about 1000 feet (305 meters) in the Byron area. The thickening of the sand-rich succession is interpreted to be due to the presence in the Domengine section of an additional lowstand sandstone sequence (Sequence 2), which is very similar in lithology and depositional setting to the underlying one. The lower 700 feet (210 m) of the sandstone-rich succession at Byron is equated to lower member (Sequence 1), whereas the upper 300 feet

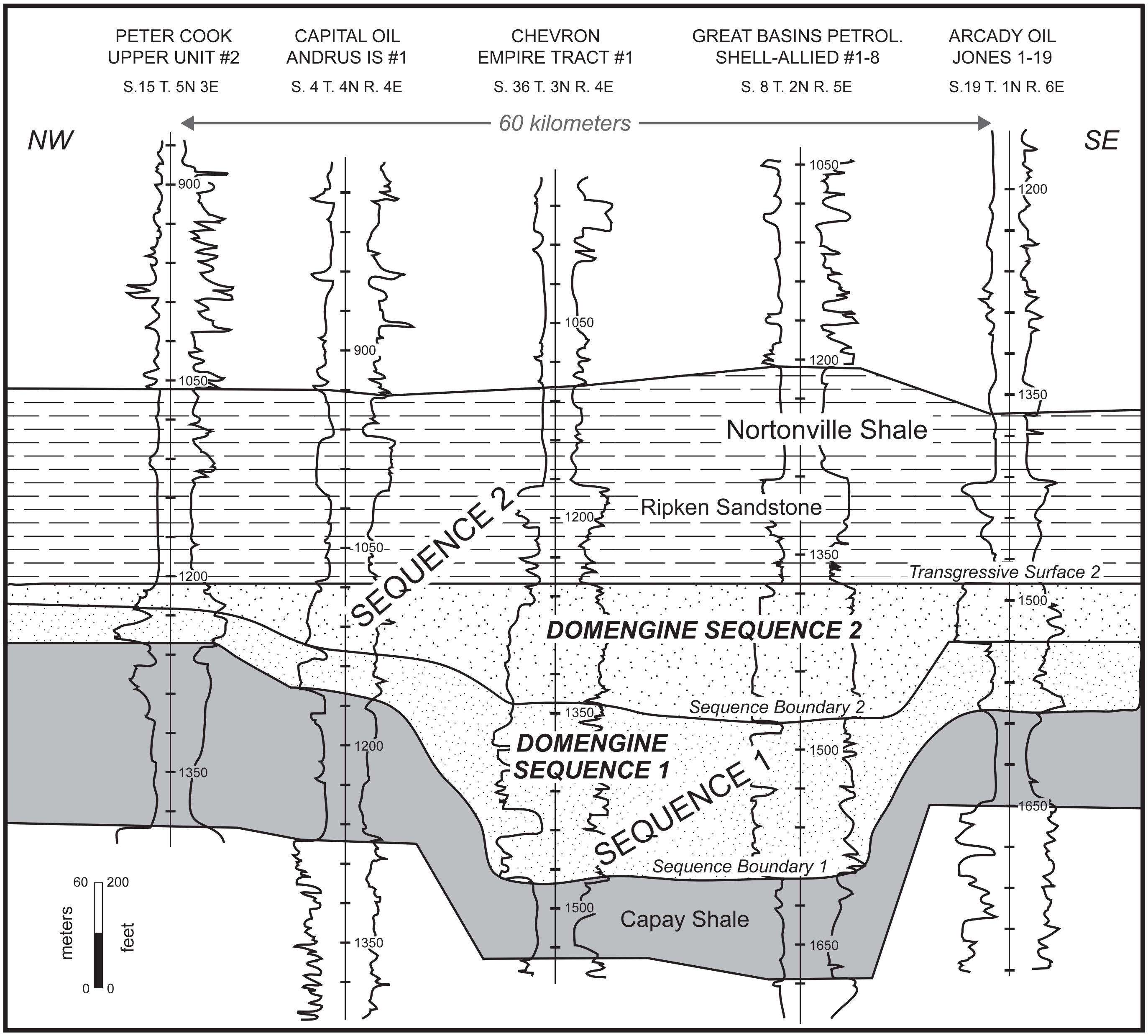

FIG. 16.—Stratigraphic cross section 4 (see Figs. 17, 18 for location) of the Domengine Formation in the Sacramento basin. The section is oriented NW–SE across the depositional strike of the northeast–southwest fluvial–estuarine system. The Domengine Formation is shown thinning along the margins of the lowstand incisement. Cherven (1983a), on the other hand, interpreted that the formation was deposited along the N–S shoreline of a barrier-island system and sandstones thinned and intertongued northwestward into shelfal shales.

(90 meters) is assigned to the new lowstand sequence (Sequence 2). An unconformity (sequence boundary 2 in Fig. 14) separates the two lowstand sequences. The upper Sequence 2 lowstand is incised into Sequence 1 as the section is traced southeast from Black Diamond and, as a result of this incision, the transgressive and high stand deposits of Sequence 1 are eroded at the base of the overlying second lowstand sequence.

A similar stratigraphic relationship emerges when the Domengine Formation is traced eastwards from Black Diamond to the Brentwood oil field, and then into the main part of the southern Sacramento basin (Fig. 15). The upper part of the section shows an abrupt facies change a few miles east of Black Diamond in T1N R2E. The shale-prone upper member of Sequence 1 is once more replaced in the section by a sandstone-rich unit which at its base incises and erodes into the upper part of the Domengine Formation. On the basis of regional truncation and interpreted basinward shift in facies, a second sequence boundary is again defined (sequence boundary 2, Fig. 15) at the base of a younger Domengine sequence (Sequence 2). The stratigraphic relationship between the two sequences is, therefore, the same one that was observed in the Domengine Formation between Black Diamond and Byron. At the top of Sequence 2 there is a regionally correlative flooding surface (transgressive surface 2) that marks the transition back to primarily shale-prone deposition of the overlying transgressive and highstand systems tract. This transgressive surface is correlative with the contact between the Domengine Sandstone and the Nortonville Shale, although the absence of the Sequence 2 lowstand sandstones in Black Diamond

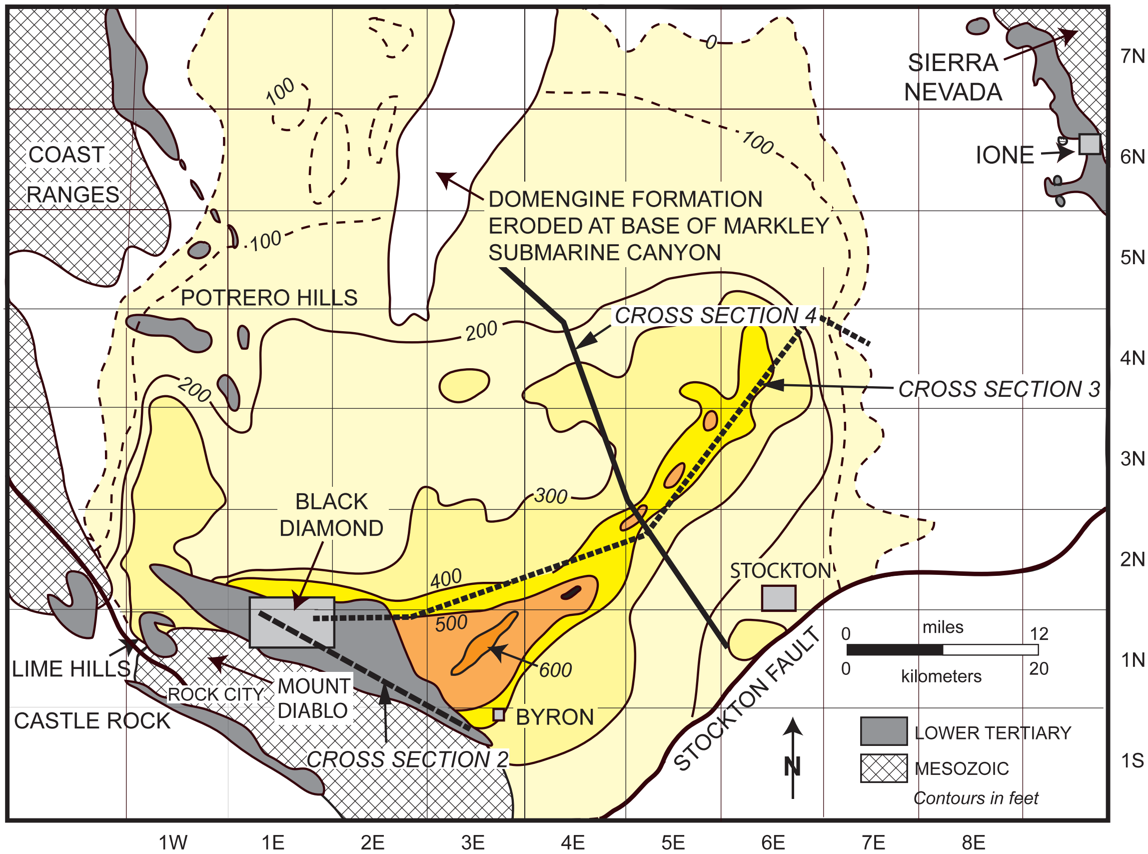

FIG. 17.—Isopach map of Sequence 1 lowstand deposits of the lower member of the Domengine Formation in the southern Sacramento basin (contours in feet). The thickness trend of the lower member supports the interpretation of it being deposited in a northeast–southwest trending incised-valley system into the depocenter of the basin. Wells are sparse on the western and eastern margins of the basin, and the interpretation is tentative in these areas.

results in this contact being both a flooding surface and sequence boundary (Figs. 1, 15).

Sequence 2 is typically about 250 to 400 feet (75 to 120 meters) thick in the basin and is capped by 50 to 75 feet (15 to 23 meters) of green glauconitic sandstone and siltstone (Figs 15, 16). It is recognized over wide areas of the basin by its fining-upward log signature; Cherven (1983a) correlated it with the Ione Formation and termed the overlying glauconitic sandstone unit the Somersville Member (Fig. 1). However, Bartow (1991) showed that the Ione Formation on the eastern side of the basin is most likely younger than the Domengine Formation.

Isopach maps of Sequences 1 and 2 reveal that the sequences were deposited in northeast–southwest-trending incised systems (Figs. 17, 18) that closely follow the trend of the Meganos submarine canyon, an older erosional structure cut into the shelf and slope during late Paleocene and early Eocene times (Bodden 1981, 1983; Sullivan et al. 1999). This middle Eocene incised system was bounded to the east by the Sierra Nevada and to the west by the Coast Range.

TECTONIC AND EUSTATIC CONTROLS ON DEPOSITION IN THE SACRAMENTO BASIN

There has been a difference of opinion on the importance of tectonism versus eustasy in the formation of the lower Tertiary cyclic succession of bathyal and neritic shales and shallow marine sandstones in the Sacramento basin (Almgren 1978; Fischer and Cherven 1988; Sullivan and Sullivan 2007).

Tectonic subsidence of the basement occurred primarily due to thermal contraction and/or flexuring of the lithosphere (Moxon 1988, 1990), and it played a major role in the formation of the forearc basin located between the western subduction zone and the Sierran magmatic arc. Tectonic subsidence of the basement, beneath the thick sedimentary fill, resulted in a deepening of the southern portion of the Sacramento basin toward the Stockton arch and the southwestern margin.

Three important lines of evidence strongly support that the distribution of the Domengine incised systems was controlled by tectonic and differential subsidence within the basin. First, the correlation of the stratal surfaces beneath the Domengine Formation, such as the base of the Capay Shale, which is a major regional flooding surface (Figs. 15, 16), are typically subparallel to the thickness trends of the overlying sandstones, suggesting that subsidence was concurrent with the deposition. It is also observed that there is less erosion and truncation at the base of each the Domengine incised valleys than the thickness of the valley fills (Figs. 15, 16). This also suggests that subsidence was concurrent with Domengine deposition. Third, the Domengine incised valleys for both Sequences 1 and 2 are stacked vertically, and these incised systems are vertically stacked upon older Eocene and Paleocene incised-canyon deposits (Fig. 19). In summary, the conformance of stratal markers below the Domengine Formation to isopach thickness in the Domengine Formation, the limited erosion at the base of the formation relative to the thickness of the incised valleys, and the strong vertical stacking of these incised systems throughout the early Tertiary strongly support that tectonic influences were the focus for Domengine deposition. The north–south growth-fault system was intermittently active during Paleocene and early Eocene times and added to the regional subsidence. A broad uplift east of the Midland fault, occurring after the deposition of the lower Eocene Hamilton Sandstone, uplifted and eroded the Paleocene and pre-Capay Shale section over this region (Figs. 1, 2; Pepper and Johnson 1992).

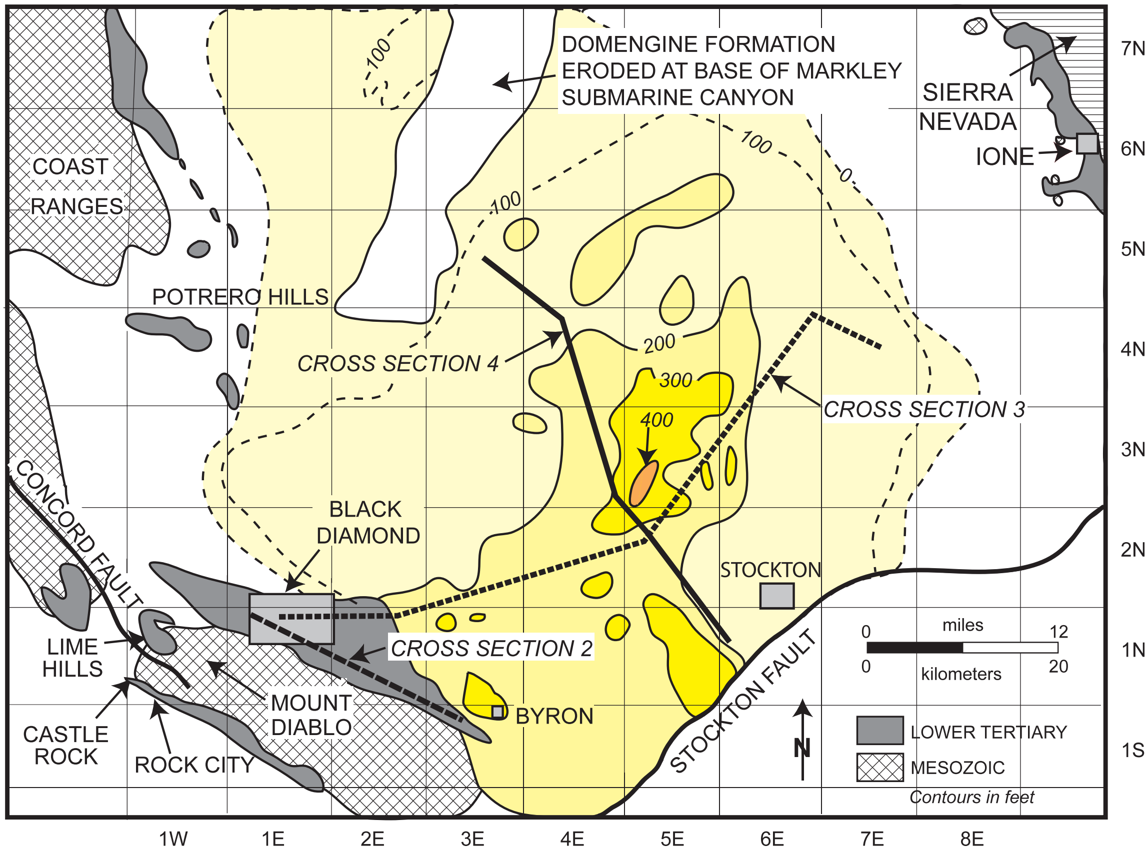

FIG. 18.—Isopach map of Sequence 2 of the Domengine Formation lowstand (contours in feet). The thickness trend of this second lowstand sandstone supports the interpretation of it being deposited in a northeast–southwest-trending incised-valley system in the depocenter of the basin. Wells are sparse on the western and eastern margins of the basin, and the interpretation is tentative in these areas.

Although tectonics impacted the location of the Domengine incised valleys, it appears that the timing and frequency of incision in the lower Tertiary of the Sacramento basin was strongly controlled by eustasy (Fig. 20). The impact of eustatic variations on sediment distribution has been documented in numerous basins around the world and dates back to the original work by Vail et al. (1977), Vail and Harbenbol (1979), and Haq et al. (1988). The impact of eustasy in tectonically active basins, such as the Sacramento basin, has been documented in others basins in California (May et al. 1984; Lohmar et al. 1991; Campion et al. 1994; Campion et al. 1996). Within the available biostratigraphic data for the lower Tertiary in the Sacramento basin, each of the proposed unconformity-bounded sequences can be correlated to the third-order regressive–transgressive cycles observed on the global coastal-onlap curve (Fig. 20).

Based on this reinterpretation of the middle Eocene stratigraphy, the Domengine–Nortonville stratigraphic interval is composed of two distinct sequences, and each of these unconformity-bounded units are correlated to the third-order transgressive–regressive units observed on the global coastal-onlap curve (Fig. 20). The global coastal-onlap curve, which has been produced by studying coastal-onlap geometries at shelf margins around the world, has been interpreted to be the product of world-wide eustatic changes in sea level (Vail et al. 1977). The relationship between the timing of the transgressive–regressive units in the Sacramento basin and the global coastal-onlap curve suggests a strong eustatic control on the timing of the development of these depositional cycles in the basin (Fig. 20). The cutting of submarine canyons on the slope and development of incised valleys on the shelf, which is observed for each of the unconformity-bounded sequences, are therefore interpreted to have occurred at lowstands of sea level. Each of the Domengine sequences was deposited in fluvial–estuarine incised valleys associated with the middle Eocene lowstands in sea level. The overlying offshore shales and sandstones of the upper member of the Domengine Formation and Nortonville Shale represent transgressive to highstand deposition for Sequences 1 and 2.

The interplay of tectonism and relative sea-level change, on the other hand, combined to determine which type of depositional sequence formed. If subsidence rates exceeded the rate of sea-level fall then relative sea level remained high and less of the shelf was subaerially exposed as part of the coastal plain. The coastal plain, therefore, would have short fluvial systems but more extensive submarine canyon systems on the shelf and slope. Conversely, when the rate of sea-level fall exceeded subsidence rates then large tracts of the shelf would be subaerially exposed during lowstand times. Widespread fluvial systems would be incised on a broader coastal plain at the basin margin.

CONCLUSIONS

This study shows the application and importance of sequence stratigraphy in reinterpreting the Domengine Formation of middle Eocene age in the outcrops at the Black Diamond Mines Regional Preserve and in the subsurface of the southern Sacramento basin. A reinterpretation of the stratigraphic relationships shows that the Domengine Formation can be regionally subdivided into two sequences. Both sequences are composed of lowstand fluvial and estuarine sandstones overlain by neritic to bathyal shales of the transgressive and high stand systems tract. The two sequences of the Domengine Formation

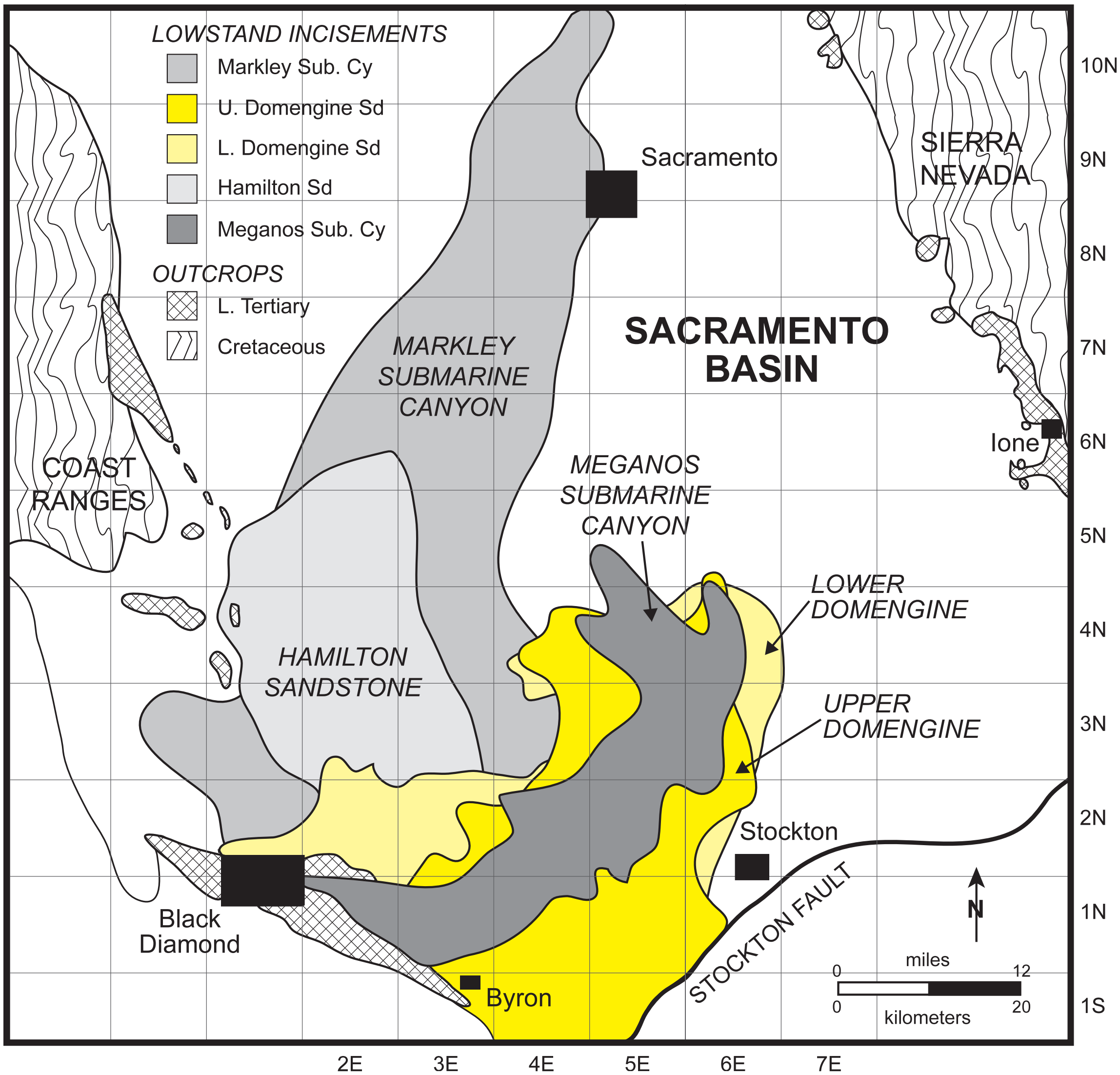

FIG. 19.—Locations of the Eocene lowstand sequences which stack vertically upon each other in the depocentral area of the basin. The sequences are not in their correct stratigraphic order but are arranged to best show their location. The stratigraphic order of the sequences is shown in the accompanying key. The strong vertical stacking of the erosionally confined portions of each sequence strongly suggests that tectonic subsidence, which was greatest in the depocentral area, controlled their location in the basin.

are part of a series of fluvial and estuarine-based depositional sequences that alternate with submarine-canyon depositional cycles in the lower Tertiary succession in the Sacramento basin. The timing of these sequences in the lower Tertiary can be correlated with global coastal-onlap curves of Vail et al. (1977). The interplay of eustasy and tectonism played an important role in the kind of depositional sequences that formed in the basins. Tectonism in the basin controlled the location of the sequences.

The lowstand sandstones of Domengine Formation had been interpreted previously as a succession of delta or barrier-island, tidal-channel or tidal-shelf, marsh and fluvial sediments deposited along a north–south-trending shoreline bordering the shelf (Todd and Monroe 1968; Bodden 1981, 1983; Cherven 1983a). In the barrier-island and tidal channel models, the estuary was thought to be located in a subsidence trough located above the mud-filled Meganos submarine canyon of early Eocene age (Figs. 1, 19). Seaward of the trough was a barrier-island system, and beyond was the shelf covered with fine mud deposits. There is, however, no evidence in succession for a barrier island, beach or delta complex, but there is abundant evidence for a fluvial and tidal dominated system. The new interpretation demonstrates that the rocks of the Domengine Formation were deposited in two northeast–southwest-trending incised-valley systems which were cut by fluvial incision during relative lowstands in sea level, and back-filled primarily with fluvial and estuarine sandstones and mudstones. Thickness trends observed in the Domengine Formation are interpreted as the product of variable incision associated with the incised-valley systems and not the result of deposition in a subsidence trough coupled with depositional thinning in a basinward (northwestward) direction as suggested by the previous models. The sandstones of this age seen on the southside of Mount Diablo, deposited by high-density turbidity currents, are further interpreted to be the slope or basin equivalents of the Domengine incised-valley deposits on the shelf.

The Domengine incised valleys were filled with sediment derived predominantly from rivers flowing out of the Sierra Nevada. These rivers were the same ones that deeply eroded valleys in the mountains, and deposited the rich placer gold deposits of this age in the Sierran foothills

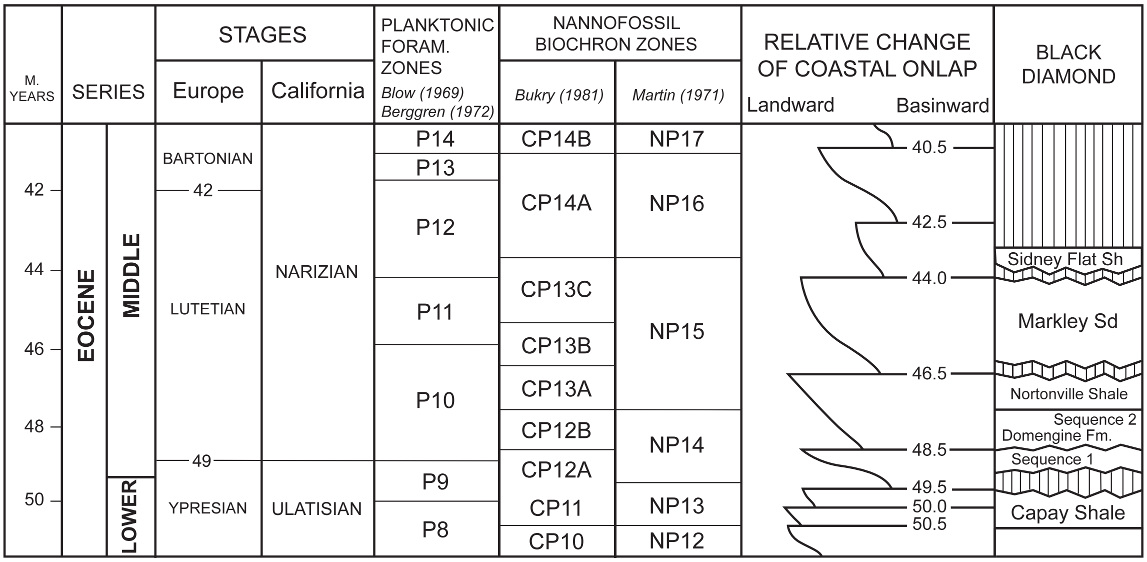

FIG. 20.—Chronostratigraphic interpretation of the Eocene succession in the Black Diamond Mines Regional Preserve (after Almgren 1978; Cherven 1983a; Barron et al. 1984; Almgren et al. 1988; Fischer and Cherven 1988; Haq et al. 1988; Campion et al. 1994; Bukry et al. 1998). There is a strong relationship between the relative lowstand in sea level, indicated by the abrupt basinward shift in coastal onlap, and the development of unconformities in the Eocene stratigraphy, suggesting a critical control by eustasy on the timing of the formation of incise valleys and submarine canyons.

(Lindgren 1911; Peterson et al. 1968). The widespread occurrence of auriferous gravels in the Sierran foothills, and the abundance of sand in the Domengine estuaries, would suggest that the drainage systems were large and vigorous. They developed during a period of wet subtropical climate. The western side of the basin was also bounded by low coastal hills, and there is evidence in the succession that smaller fluvial systems locally supplied sediment into the estuary from this side of the basin. Although Domengine sandstones are frequently coarse grained and channelized, particularly in the upper part of the lower member, sediments deposited directly by streams, without a tidal influence, are rare. The abundance of fluvial and estuarine sandstones and the general sparsity of intertidal mudstones would also support a river dominated estuarine system.

The importance of the reinterpretation of the Domengine Formation, within a sequence stratigraphic framework, is that it produces a predictive model for understanding the architecture, thickness trends, and facies distribution of the Domengine Formation. Such studies potentially provide a model for other similar lowstand deposits in the geological record, and they provide a more accurate depositional model for hydrocarbon exploration.

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