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Sedimentation and Thrusting of Late Mesozoic Rocks in the Coast Ranges near Clear Lake, California

ABSTRACT

South and southeast of Clear Lake, California, approximately 35,000 ft of clastic sedimentary strata of the Great Valley sequence ranging in age from Late Jurassic to Late Cretaceous crop out in irregular belts trending from northwest to southeast. Together with overthrust lower Tertiary beds, these rocks form a thrust complex that rests structurally upon the Franciscan assemblage of late Mesozoic age along the Soda Creek thrust and is overlain unconformably by late Cenozoic strata. A number of subsidiary thrusts, that are discordant to bedding, break the Great Valley sequence into at least three and possibly more than four successive thrust plates or slices. In all exposed cases, younger strata overlie older strata along the thrusts. The principal structurally intact stratigraphic components of the thrust complex are:

(1) A conformable Tithonian to Valanginian succession, 6900 ft, dominantly mudstone with 1600 ft of lithic sandstone and conglomerate in the upper part.

(2) Lower Cretaceous strata, 4500 ft, in part Aptian, dominantly thin-bedded quartzose sandstone and interbedded mudstone.

(3) Three structurally isolated "mid"-Cretaceous successions, two of massive sandstone and one of mudstone, total of 5700 ft exposed.

(4) A conformable Upper Cretaceous succession, 17,500 ft, in large part Campanian, composed of five mappable units including massive sandstone (3700 ft), siltstone (3600 ft), massive sandstone (4000 ft), mudstone (1000 ft), and alternating sandstone and mudstone (5200 ft) in ascending order.

(5) A conformable marine Paleocene and Eocene succession (5500 ft).

The lithologic characteristics, petrologic variations, and paleocurrent indicators of the strata in the Great Valley sequence near Clear Lake are comparable to those of correlative parts of the Great Valley sequence along the western side of the Sacramento Valley. Emplacement of the Great Valley sequence and the lower Tertiary beds above the Franciscan assemblage by regional thrusting was probably complete by Oligocene time from evidence elsewhere in the Northern Coast Ranges. The thrusts themselves and the strata of the thrust complex were later folded and cut by younger normal and reverse faults during Cenozoic deformations.

INTRODUCTION

The study area south and southeast of Clear Lake, California, is in the Northern Coast Ranges about 70 miles north of San Francisco (Fig. 1). Most of the area is in the Lower Lake 15-minute quadrangle, but a small part lies in the adjoining Calistoga 15-minute quadrangle on the south. Within the area are late Mesozoic clastic sedimentary strata of the Great Valley sequence exposed in irregular belts that trend from northwest to southeast. Exposures of the late Mesozoic Franciscan assemblage lie between some of the exposed belts of the Great Valley sequence.

The main objectives of the present investigation were: (1) to clarify the relationship between the Great Valley sequence and the Franciscan assemblage within the area, (2) to correlate the Great Valley sequence exposed in the study area with the strata in the main belt of Great Valley sequence exposed along the west side of the Sacramento Valley to the east, and (3) to define the complex structures within the Great Valley sequence of the area.

Regional Geologic Setting

The late Mesozoic rocks of the California Coast Ranges described by Bailey and others (1964) may be grouped into two great assemblages whose lithology and structure are strikingly different. One of these assemblages, commonly known as the Franciscan Series (Lawson, 1895) or the Franciscan Formation, and gen-

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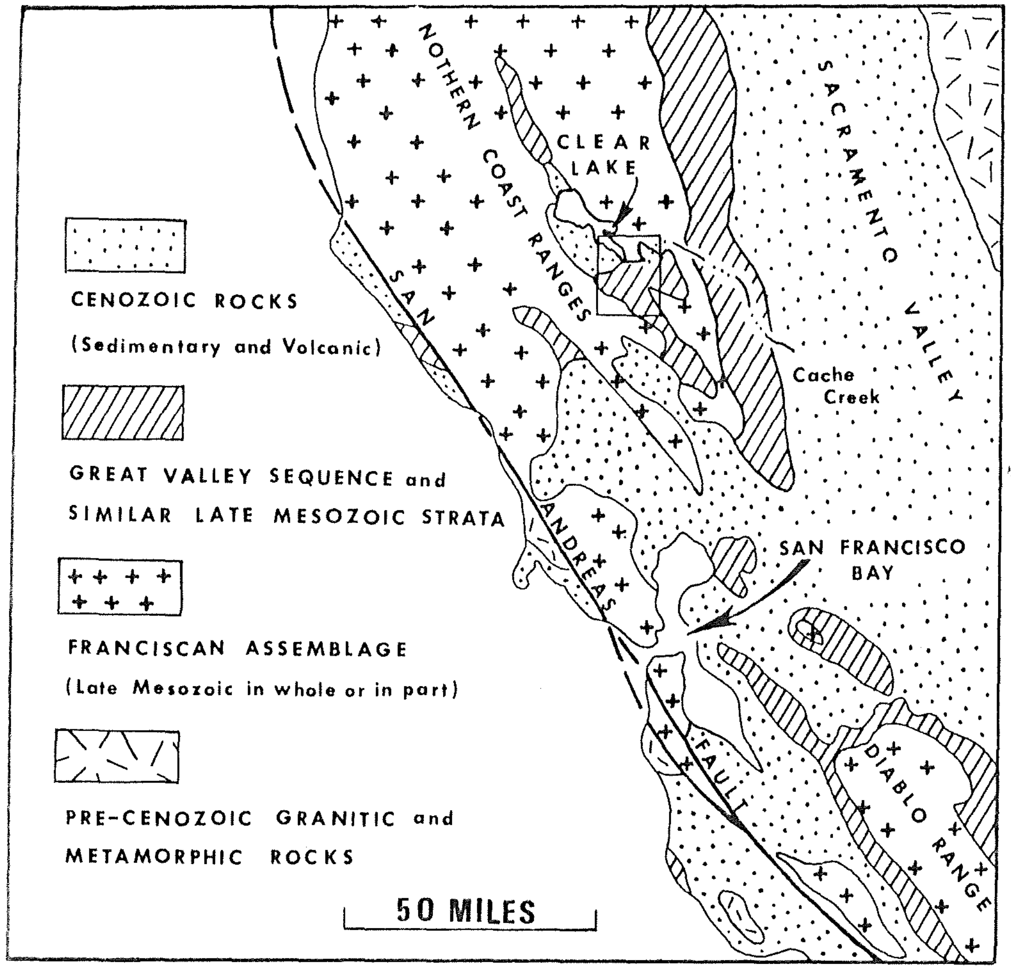


Figure 1. Generalized geologic map of part of California showing the location of the Lower Lake quadrangle *after* California Division of Mines and Geology Bulletin 190.

erally regarded as eugeosynclinal, is composed dominantly of graywacke with minor shale, conglomerate, greenstone, bedded chert, limestone, and some peculiar types of metamorphic rocks. The Franciscan assemblage is a complexly deformed and weakly metamorphosed tectonic mélange (Hsu, 1968) that occupies the core of the northern Coast Ranges east of the San Andreas fault. The other assemblage, the Great Valley sequence of Bailey and others (1964), exhibits simpler lithologic and structural relations. It is an orderly succession of alternating beds or units of mudstone and sandstone with conglomerate lenses at a few horizons. Greenstone and bedded chert, common in the Franciscan assemblage, are present only in the very lowest part of the Great Valley sequence. The Great Valley sequence crops out mainly along the west side of the Great Valley, except for structurally isolated exposures scattered in the Coast Ranges to the west. On the west side of the Sacramento Valley, the Great Valley sequence dips homoclinally away from the complexly deformed Franciscan assemblage, and is about 40,000 ft thick (Page, 1966, Fig. 3). It includes strata ranging in age from Late Jurassic through Late Cretaceous without any appreciable break in the record of sedimentation.

For years no significant fossils were discovered in the Franciscan assemblage, and neither the original top nor base has ever been recognized. Therefore, it was once generally regarded as younger than Paleozoic, but older than the oldest rocks of the orderly late Mesozoic succession now known as the Great Valley sequence. Taliaferro (1942, 1943a, 1943b) argued that the Franciscan assemblage is of Late Jurassic (Tithonian) age, but slightly older than and gradational into the base of the Great Valley sequence. However, fossils of Late Jurassic (Tithonian), Early Cretaceous (Valanginian and Albian) and Late Cretaceous (Cenomanian and Turonian) age were later discovered in the Franciscan assemblage (*see* Irwin, 1957; Bailey and others, 1964). Therefore, the Franciscan assemblage probably also includes rocks that range in age from Late Jurassic to Late Cretaceous even though the continuity of sedimentation cannot be demonstrated directly because of the dislocated mélange style of its internal structure. It may also include some rocks of pre-Tithonian or post-Turonian age. In any event, the Franciscan assemblage is partly equivalent in age to the Great Valley sequence; therefore, the relationship of the two different assemblages to each other poses a difficult problem.

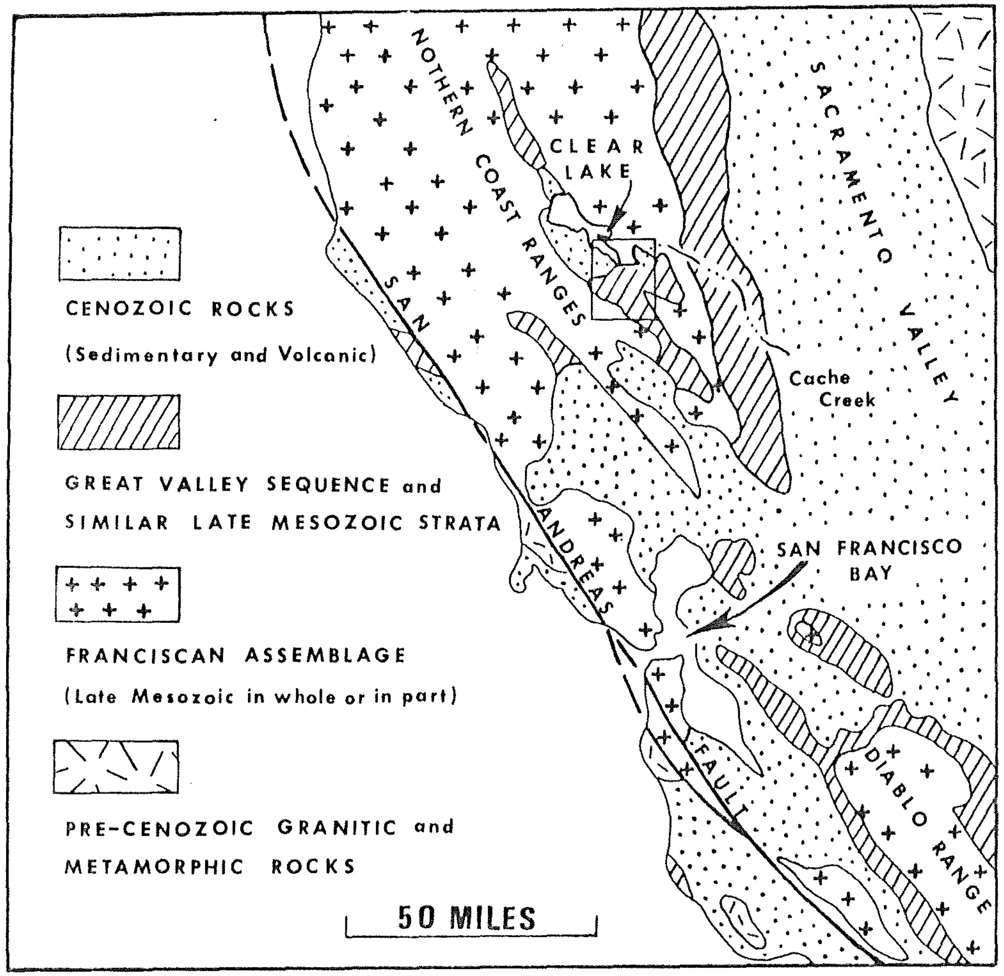
Nowhere in California has a depositional contact between the two assemblages been unquestionably demonstrated. Wherever the Franciscan assemblage and the Great Valley sequence are in contact, a fault or a body of serpentinite intervenes (Bailey and others, 1964). The juxtaposition of the two assemblages with strikingly different structural aspects led Irwin (1964) and Bailey and others (1964) to propose the working hypothesis that the Great Valley sequence has been bodily emplaced above the Franciscan assemblage in the Coast Ranges by thrusting on a regional scale. The intervening serpentinite bodies may possibly have served as a lubricant at the base of the overriding thrust sheet. However, Hsu (1967, 1968) holds that the Franciscan assemblage is pre-Tithonian, although largely unfossiliferous, that it is correlative with the Mesozoic rocks of the Sierra Nevada foothills, from whose site it was thrust westward as a gravitational mélange into the region of the present Coast Ranges during a Late Jurassic orogeny, and that the Franciscan assemblage was later chaotically mixed by Late Cretaceous gravity sliding with parts of the fossiliferous Great Valley sequence, which originally overlay the Franciscan unconformably. However, detailed mapping which supports the concept of regional thrusting has been reported by Dickinson (1965, 1966a, 1966b) in the southern Diablo Range, by Blake (1969) in the northern Diablo Range, by J. Brown (1967) in the Cuyama River gorge, by Page (1969) in the southern Santa Lucia Range, by R. Brown (1964a, 1964b) near Stonyford on the west side of the Sacramento Valley, by Berkland (1969) in the region northwest of Clear Lake, and by Rich (1968) in the region northeast of Clear Lake.

The structures that are described in this report support the hypothesis of regional thrusting for this part of the Coast Ranges, document the presence of related thrusts within the Great Valley sequence of the upper plate, and show that lower Tertiary rocks are involved in the thrusting.

Previous Work

Early references to the late Mesozoic rocks near Lower Lake were made by Whitney (1865) and Gabb (1866). The rocks were described by Becker (1888) and Forstner (1903) in reconnaissance. Dickerson (1914) described the stratigraphy and structure of the rocks around Lower Lake, and differentiated them as Franciscan, Knoxville (Late Jurassic), Chico (Late Cretaceous) and Martinez (Paleocene). However, he did not show the outcrops of Knoxville on his map, even though he described the location and lithology of the Knoxville strata and the occurrence of *Buchia* [=*Aucella*] *piochii* in them.

The Mesozoic rocks in the southern part of the area near Middletown were referred to the Knoxville (Late Jurassic) by Taliaferro (1943b) and were mapped as Knoxville by Yates and Hilpert (1946). The middle part of the area was not described in the literature until Brice (1953) mapped the entire Lower Lake quadrangle. Brice differentiated the late Mesozoic rocks of the Lower Lake quadrangle into Franciscan and Knoxville groups, both of which he regarded as Late Jurassic (Tithonian) in age, and undifferentiated Cretaceous rocks which he correlated with *Buchia crassicollis*-bearing (Lower Cretaceous) strata of the adjoining Morgan Valley quadrangle to the east. Koenig (1963) listed Brice's Knoxville group and undifferentiated Cretaceous rocks as Knoxville (Tithonian) (?) and Lower Cretaceous (?), respectively, on the geologic map of California (Santa Rosa Sheet). In this report, Brice's Knoxville group and undifferentiated Cretaceous rocks are divided into Franciscan assemblage (Upper Jurassic–Upper Cretaceous?) and various parts of the Great Valley sequence (Upper Jurassic–Upper Cretaceous). Extensive exposures of Upper Cretaceous rocks in the area are reported here for the first time.



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Methods

The field work, with emphasis on the Great Valley sequence, was done mainly in the spring and fall of 1966 and the winter of 1967 by Swe. Dickinson later completed field work to resolve the structural relations of the lower Tertiary beds. Aerial photographs at a scale of 1:20,000 and 7.5-minute topographic maps (1:24,000) were used for plotting data. Mapping was mostly executed on the photographs and later transferred to the topographic maps. Geologic cross sections were made from these maps by the methods of Busk (1957), and thicknesses of stratigraphic units were determined from the cross sections. Some sandstone samples were stained for K-feldspar for comparison with the results obtained by Bailey and Irwin (1959). The staining method was particularly successful with well-indurated, coarse-grained sandstones. Point counts of thin sections were made by Swe in consultation with Dickinson. Swe wrote the original manuscript, which was revised and extended by Dickinson to take advantage of valuable suggestions by reviewers.

STRATIGRAPHY

General Statement

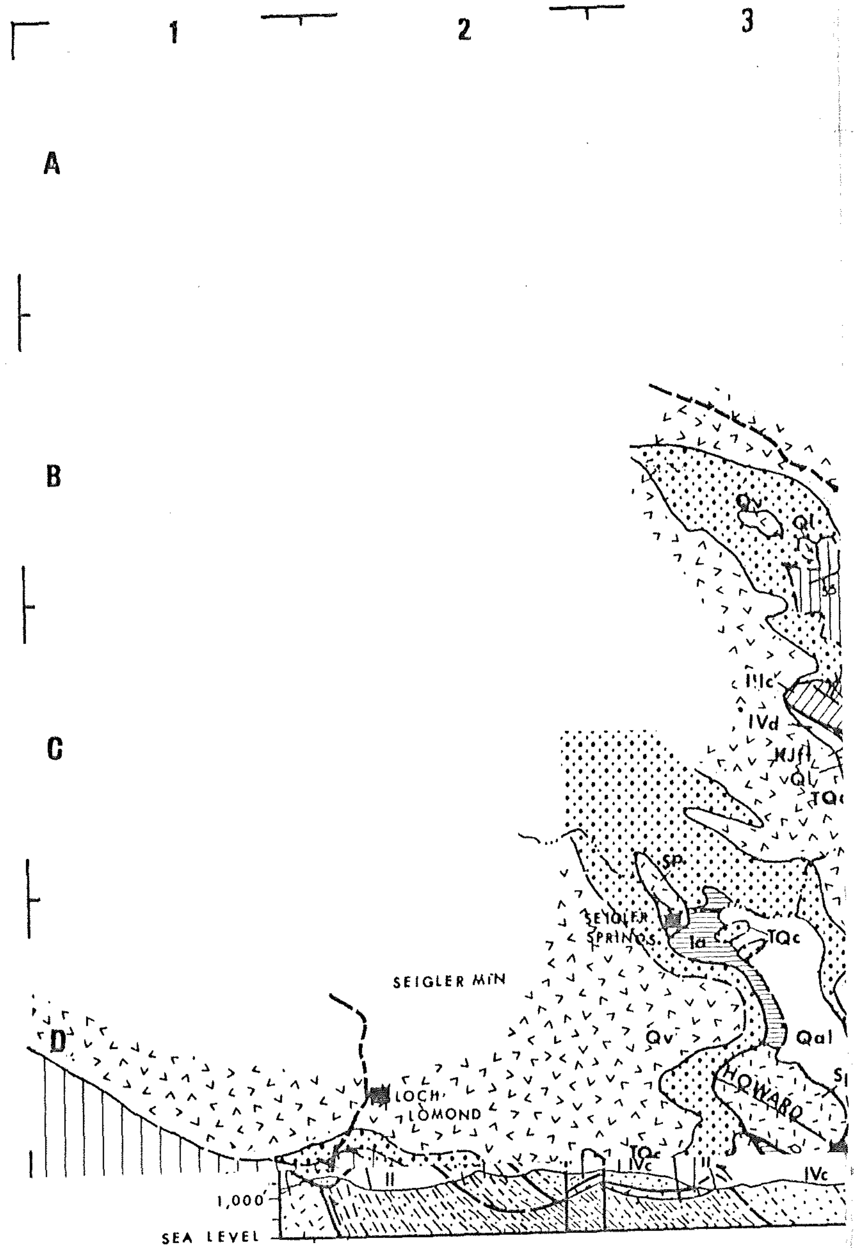
The late Mesozoic rocks in the study area include the eugeosynclinal Franciscan assemblage and the non-eugeosynclinal Great Valley sequence of Bailey and others (1964, p. 123). The Franciscan assemblage forms a complexly dislocated mélange that structurally underlies a less deformed upper plate of Great Valley sequence cut by mappable thrusts. The contact is a fault zone inferred to have been a subhorizontal thrust before Cenozoic folding. This thrust contact is discordant to bedding in the upper plate of Great Valley sequence as well as to lithologic contacts in the Franciscan mélange beneath. Subsidiary thrusts cutting the Great Valley sequence break it into a complex of slices bound discordantly by thrust surfaces. A structurally higher thrust has carried lower Tertiary strata above the Great Valley sequence. Stratigraphic data on these units are presented in this section, but discussion of the structural relations is deferred to a later section. Diverse late Cenozoic strata rest unconformably on the pre-Oligocene rocks, but are not discussed further in this report. These include, *after* Brice (1953): (a) the Pliocene-Pleistocene Cache Formation (Becker, [illegible] tuffs and poorly consolidated sands, silts, and gravels of fresh water origin, together with some interbedded lavas, and (b) younger Quaternary lavas and breccias.

Franciscan Assemblage

A heterogeneous assemblage of complexly deformed graywacke and conglomerate with minor amounts of interbedded shale, bedded chert, greenstone, and some low-grade metamorphic rocks of eugeosynclinal character are assigned to the Franciscan assemblage, which is extensively exposed to the south, west, and north of the map area in the Northern Coast Ranges (*see* Bailey and others, 1964). The Franciscan assemblage underlies approximately 5 sq mi in the middle of the eastern border of the map area (Fig. 2), crops out just west of Brushy Sky High (A9) in the northeast part of the map area, and is also exposed in small windows a few miles southeast of Lower Lake. The Franciscan in the area includes homogeneous low-grade metasedimentary rocks and heterogeneous tectonic breccia, each of which constitutes a discrete structural unit.

The foliate metasedimentary rocks are mainly blueschist and phyllite, and are exposed in the hills just southwest of the Baker Mine (D8) and also northwest of Brushy Sky High (A9). Exotic lithologic types are uncommon in these areas, but are characteristic in the tectonic breccia. Similar foliate metamorphic rocks of coherent structure are regarded as part of the Franciscan assemblage to the north, where they separate the region of typical Franciscan rocks of mélange structure from the Stony Creek fault zone and its associated serpentinites (Brown, 1964a, 1964b; Rich, 1968). Blake and others (1967) have related the development of tectonite fabric and certain progressive metamorphic mineral zones in the Franciscan assemblage to regional thrusting that juxtaposed the Great Valley sequence and other rocks above the Franciscan mélange. The work done in the study area may contribute to a better understanding of these relations by delineating previously undifferentiated exposures of foliate metasedimentary tectonites.

Franciscan tectonic breccia is exposed in an irregular belt in the core of the Soda Creek anticline and in small windows elsewhere. It is composed of massive or jointed blocks of graywacke, bedded chert and greenstone embedded in a finely ground or pervasively sheared mass of mudstone, serpentine, graywacke, bedded chert and greenstone. The tectonic breccia,



however, appears to pass into highly deformed massive graywackes with some pebble conglomerates in the vicinity of the east border of the map area. These conglomerates lie near the projection of the strike line of conglomerates in the Great Valley sequence to the northwest. Brice (1953) believed them to be part of the same conglomeratic belt, even though he noted differences in the clast types and in the degree of induration. The age of the Franciscan rocks in the area could not be ascertained with certainty, but in other parts of the Coast Ranges, the Franciscan assemblage has yielded fossils of Late Jurassic (Tithonian) to Late Cretaceous (Turonian) age.

Great Valley Sequence

The Great Valley sequence in the area includes approximately 35,000 ft of clastic sedimentary strata that range in age from Late Jurassic to Late Cretaceous. It is exposed in three irregular belts that structurally overlie the Franciscan assemblage. Lithologic characteristics, petrologic variations, and paleocurrent indicators within the Great Valley sequence in the study area are closely comparable to those of correlative parts of the main belt of exposure on the west side of the Sacramento Valley which will be referred to simply as the main belt in this report.

Within the study area, the Great Valley sequence can be divided stratigraphically into four main segments. Three are apparently conformable successions of strata, and the fourth includes several isolated, fault-bounded exposures of apparently similar age. Because of faulting, the relative ages of the four segments cannot be demonstrated by physical superposition, but direct evidence from fossils and corroborative evidence from petrology permit satisfactory correlation of most parts of the sequence (*see* Fig. 3). The stratigraphy of the four segments is described first in the following order; their petrology and structural relations are discussed in later sections:

(1) The oldest strata, widely exposed in the study area (*see* Fig. 2), are an apparently conformable succession ranging in age from Late Jurassic (Tithonian) to Early Cretaceous (Berriasian and Valanginian) on the basis of species of *Buchia*.

(2) Younger Lower Cretaceous strata, in an apparently conformable succession of homologous lithology and petrology, are exposed only in the southern part of the study area in fault contact with both older and younger strata.

(3) In the northern part of the study area, poorly dated "mid"-Cretaceous strata crop out in three separate, fault-bounded exposures.

(4) The youngest strata, extensively exposed in the central part of the study area, are an apparently conformable succession of Upper Cretaceous beds that account for about half the thickness of Great Valley sequence exposed in the study area.

Conformable Upper Jurassic and Lower Cretaceous Succession (Unit I)

Unit I is composed dominantly of gray mudstone with subordinate lithic sandstone except for 1600 ft of polymictic conglomerate interbedded with massive sandstone in the upper part of the sequence. The total thickness is about 6900 ft. The strata of unit I were subdivided into two lithostratigraphic units—a lower mudstone unit and an upper conglomerate and sandstone unit, which are informally designated as units Ia and Ib, respectively. As the mudstone unit (Ia) is more widespread and more variable in lithology, the strata in each area of exposure are described separately.

The oldest exposed part of unit Ia is probably that on the Howard Springs structure in the northwestern part of the map area. The Howard Springs structure is an eroded piercement arch; therefore, the strata near the middle of the structure are presumably the oldest in the sequence exposed. These include highly sheared gray mudstone with some thin-bedded white tuffaceous beds and some massive lithic graywacke beds. Pillow lavas associated with thin-bedded red chert occur at Howard Springs. These strata at Howard Springs are included in unit Ia rather than in the Franciscan assemblage because they are interrelated with the less indurated mudstones typical of unit I, and are not associated with foliate metasedimentary rocks or tectonic breccia characteristic of the Franciscan assemblage. Similar greenstone, volcanic breccia, and chert occur within the lower part of the Great Valley sequence in areas to the north where structural relations are not in doubt (Brown, 1964b; Rich, 1968). All the rocks on the Howard Springs structure are extensively sheared and intricately mingled with serpentinite breccia. Palynomorphs of Late Jurassic (Tithonian) age were collected in the core of the structure about 2 miles southeast of Howard Springs.

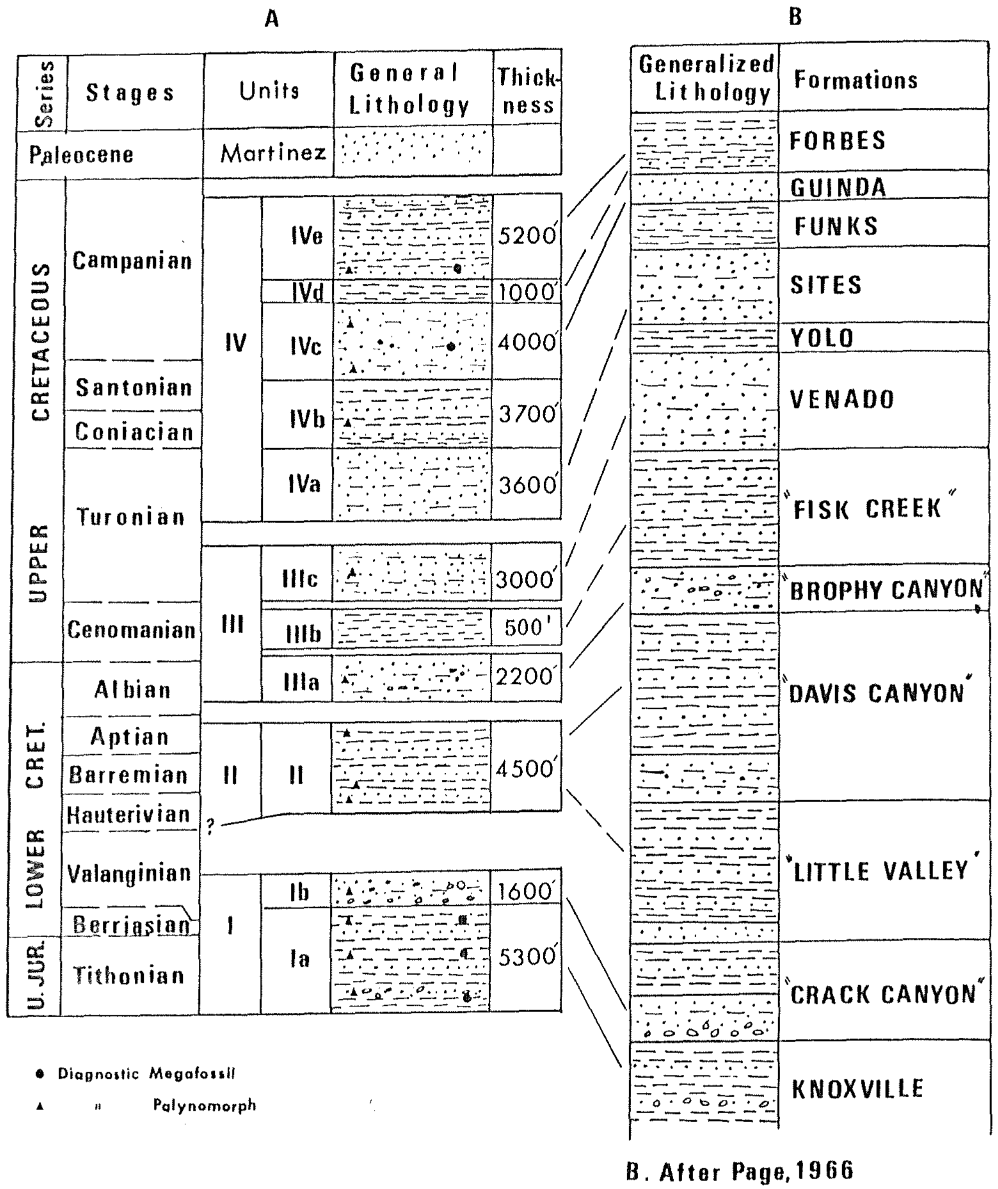


Figure 3. Generalized stratigraphic columns of the Great Valley sequence showing suggested correlations between the sequence near Clear Lake (A) and at Cache Creek (B) on the west side of the Sacramento Valley (*see* Fig. 1). Solid lines between the columns indicate direct paleontologic correlations and broken lines indicate inferred correlations based on gross lithology, petrology, and position in sequence.

B. pacifica of Early Cretaceous (Valanginian) age, are present at several localities near the north border of the piercement arch.

Strata of unit Ia also crop out in two areas near Middletown in the southern part of the map area. In the belt west of Middletown, exposures of well-indurated gray mudstone contain at least five prominent units of white-weathering, thin-bedded siliceous shale or tuffaceous beds in the lower part of the exposed sequence. Sandstone is rare at this locality. Palynomorphs of Late Jurassic (Tithonian) age were collected from the siliceous beds. About a mile north of Middletown, mudstone of unit

Ia contains a few thin-bedded white tuffaceous beds and beds of thin- to medium-bedded volcanic breccia. Irregular bodies of volcanic breccia that were mapped as intrusive gabbro by Brice (1953) and Yates and Hilpert (1946) are also present within the mudstone. Palynomorphs of Late Jurassic (Tithonian) age were also collected from this locality.

The most extensive exposures of unit Ia are in a northwest-trending belt along the axial trace of the Soda Creek anticline south of Lower Lake and in the vicinity of the Baker Mine. Most of the unit is greenish-gray mudstone containing interbeds of thin-bedded to massive lithic sandstone. However, small thrust slices of unit Ia caught up in the underlying Franciscan tectonic breccia are mainly indurated lithic sandstone with scattered mudstone interbeds. *Buchia piochii*, *B. uncitoides*, *B. pacifica* and belemnite fragments were collected from various places on the north limb of the Soda Creek anticline, and *Buchia piochii*, *B. fischeriana* (?) and palynomorphs of Late Jurassic or Early Cretaceous age were collected from the south limb of the anticline. According to Jones and others (1968, p. 104), *Buchia piochii* is Late Jurassic (Tithonian), *B. uncitoides* is Early Cretaceous (late Berriasian), and *B. pacifica* is younger Early Cretaceous (early Valanginian) in age. *Buchia okensis* of early Berriasian age was not found in the area.

The conglomerate and sandstone unit (Ib) conformably overlies the lower mudstone unit (Ia) on the Soda Creek anticline. On the south limb of the anticline, it is composed of thick conglomerate lenses containing interbedded sandstone and mudstone. Conglomerate types range from pebbly mudstone (Crowell, 1957) to cobble conglomerate. Clasts include mainly granitoid rocks, light-colored porphyritic volcanic rocks, and dark aphanitic volcanic rocks. Intrabasinal materials (limestone and sandstone clasts) form only a minor proportion of this conglomerate. Reworked Upper Jurassic species of *Buchia* (*B. piochii*, *B. blanfordiana*) and fragments of belemnites were collected from the middle part of the conglomeratic sequence. Early Cretaceous (Valanginian) fossils, *Buchia pacifica* and *Olcostephanus* (?) sp., were found also in the middle part about 1.25 miles west of and almost along strike from the locality that yielded reworked fossils.

Massive, brown-weathering, gray sandstone (Ib) conformably overlies the lower mudstone unit (Ia) in the north limb of the Soda Creek anticline near Lower Lake. These sandstones occupy about the same stratigraphic position as the conglomerates in the south limb of the fold. However, only a few conglomerate lenses were noted in the north limb.

Massive sandstone of unit Ib that conformably overlies mudstone of unit Ia northeast of Baker Mine is continuous with the sandstone unit of comparable thickness mapped as the basal Blue Ridge Member of the Crack Canyon Formation in the adjacent Morgan Valley quadrangle (Page, 1966, *after* Lawton, 1956).

Lower Cretaceous Strata (Unit II)

Unit II is exposed only in two narrow belts (G3-H5 and H6) in the southern part of the study area. The strata are dominantly thin-bedded sandstone, relatively more quartzose than the sandstone of unit I, with interbedded siltstone and mudstone containing scattered white-weathering limestone concretions. Sandstone beds are mostly graded and are well laminated; some contain worm burrows. Because of discontinuous exposure, the total stratigraphic thickness of unit II in the two exposed belts could not be determined exactly, but is estimated to be about 4500 ft. Palynomorphs of Early Cretaceous age were collected from the western belt of exposure and Early Cretaceous palynomorphs of Aptian age were collected from the eastern belt of exposure. These palynomorphs indicate that Unit II is wholly or partly equivalent in age to some part of the lithologically similar Lower Cretaceous beds referred to the Little Valley and Davis Canyon Formations (Page, 1966, *after* Lawton, 1956) in the main outcrop belt to the east where the two have a total thickness of about 10,000 ft.

"Mid"-Cretaceous Strata (Unit III)

Three structurally isolated successions of upper Lower Cretaceous or lower Upper Cretaceous strata, or both, are exposed in the northern part of the study area. Their stratigraphic relations to one another are not clear from the field mapping, nor from the fossils they contain. As they are distinct from the remainder of the Great Valley sequence in the study area, and are probably all of similar age, they are here described together for convenience.

Near the northern edge of the area (A7), about 2200 ft of a sandstone unit (IIIa) is exposed in a belt across Cache Creek about 2.5 miles northeast of Lower Lake. Unit IIIa is composed dominantly of buff-weathering, massive, quartzo-feldspathic sandstone containing minor conglomerate lenses and mudstone interbeds. Many of the sandstone beds are graded, but current structures are generally not preserved, except for well-developed parting lineations. Palynomorphs of Albian-Cenomanian(?) age and an unidentified ammonite were collected from about the middle part of unit IIIa. Unit IIIa may be correlative with the unit of similar age and lithology called "Salt Creek Conglomerate" (Taliaferro, 1954; Lachenbruch, 1962) or "Brophy Canyon Formation" (Page, 1966, *after* Lawton, 1956) in the main outcrop belt to the east.

Near the western edge of the area (C3), about 500 ft of a mudstone unit (IIIb) is exposed in the trough of a southeast-plunging syncline about 2.5 miles southwest of Lower Lake. Unit IIIb is composed dominantly of mudstone with a few thin- to medium-bedded sandstone intercalations. Palynomorphs of Albian-Cenomanian age were collected from unit IIIb. Unit IIIb may be correlative with the unit of similar age and lithology called "Antelope Shale" (Taliaferro, 1954; Küpper, 1956, p. 40) or "Fisk Creek Formation" (Page, 1966, *after* Lawton, 1956) in the main outcrop belt to the east.

About 3000 ft of another sandstone unit (IIIc) is exposed in the trough of the same plunging syncline as is unit IIIb, but the contact is faulted wherever it can be observed. Unit IIIc is composed dominantly of massive, buff-weathering, litho-feldspathic sandstone with some siltstone interbeds. The sandstones are commonly graded, but other sedimentary structures are not well observed because of poor exposures. Palynomorphs of Late Cretaceous age were collected from unit IIIc. The correlation of unit IIIc with strata of the main outcrop belt is uncertain. However, its thickness and lithology, coupled with its dissimilarity to other strata in the thick Upper Cretaceous section of the study area, suggest a tentative correlation with the Venado Formation (Kirby, 1943), which is the oldest Upper Cretaceous sandstone unit of the main outcrop belt.

Conformable Upper Cretaceous Succession (Unit IV)

The diverse strata of unit IV crop out in two large northwest-trending belts north and northwest of Middletown. The total thickness of about 17,500 ft includes the following five units in ascending order: IVa, lower sandstone unit (3700 ft); IVb, siltstone unit (3600 ft); IVc, upper sandstone unit (4000 ft); IVd, mudstone unit (1000 ft); and IVe, alternating sandstone and mudstone unit (5200 ft). The contacts between the five units are conformable and at least locally gradational.

The lower sandstone unit (IVa) crops out on the crest of Harbin Ridge a few miles northwest of Middletown (G4). Unit IVa is composed mainly of massive, yellowish brown-weathering sandstone with subsidiary interbedded, purple weathering siltstone. In the single small lens of conglomerate observed in the unit, elliptical clasts of white-weathering limestone, possibly of intrabasinal origin, are mixed with subordinate clasts of schist and dark volcanic rocks in a sandstone matrix. Unidentified large pelecypod shells were collected from the conglomerate lens. In the nature of its clasts and in its texture, this conglomerate lens is indistinguishable from others noted higher in the Upper Cretaceous succession.

The siltstone unit (IVb) is exposed in a belt trending northwest-southeast from about 2 miles west of Loch Lomond (D2) to about 2 miles north of Middletown. Unit IVb is composed mainly of thin-bedded, purple-weathering siltstone with some fine-grained, massive, white-weathering sandstone interbeds. A few large, brown- to white-weathering, dark limestone concretions, some of which contain numerous broken pieces of oysters and other pelecypods, occur within the unit. A single lens of fine-grained conglomerate with clasts predominantly of rounded milky quartz set in a sandstone matrix was noted in one place. Glauconitic sandstone is common at some horizons. Fossils collected from the unit include palynomorphs of Late Cretaceous age, *Cucullaea* sp. (identified by A. M. Keen), other unidentifiable pelecypods and cephalopods, and *Bathysiphon perampla* (?).

The upper sandstone unit (IVc) is exposed in two belts on the north and south sides of the Howard Springs structure a few miles northwest of Middletown. Unit IVc is composed dominantly of massive, medium-bedded, yellowish brown-weathering, medium- to coarse-grained sandstone with subordinate siltstone interbeds. The sandstones are mostly graded and laminated, and sedimentary structures are relatively abundant. Some glauconitic sandstones and a single lens of conglomerate containing clasts of probably intrabasinal white-weathering limestone were observed. Palynomorphs of Late Cretaceous age were collected

from the lower and middle part of unit IVc. A poorly preserved impression of an ammonite questionably identified as *Nostoceras* sp. by D. L. Jones was collected from the middle part of the unit on the south side of the Howard Springs structure and suggests an age no older than Campanian (Arkell and others, 1957, p. L224).

The mudstone unit (IVd) was considered as part of the overlying unit (alternating sandstones and mudstones) in a recent abstract by one of us (Swe, 1968). However, as it is persistent and mappable along the entire outcrop belt, it is discussed here as a separate unit. Unit IVd is composed dominantly of mudstone with only a few thin sandstone beds.

The alternating sandstone and mudstone unit (IVe) crops out in a large northwest-southeast belt between Middletown and Lower Lake. Highway 53 runs diagonally across the exposures of the unit. Unit IVe is composed of massive, yellowish brown-weathering, gray sandstone with minor mudstone interbeds alternating with mudstone that contains subordinate thin-bedded, graded sandstone interbeds. Sedimentary structures are relatively common in the unit. Bedding character, sedimentary structures, and rhythmically alternating sequences of sandstone and mudstone strongly suggest turbidite deposition. *Inoceramus schmidti* and palynomorphs of Late Cretaceous age were collected from the lower part of unit IVe. *Desmophyllites diphylloides* and palynomorphs of late Campanian or possibly early Maestrichtian age were collected from near the top of the unit. *Inoceramus schmidti* is of middle to late Campanian age (Matsumoto, 1960, Pl. 1), and *Desmophyllites diphylloides* ranges throughout the Campanian and possibly through the lower Maestrichtian as well (Matsumoto, 1959, p. 11).

The fossil collections indicate that unit IVe is wholly or partly equivalent in age to some part of the Forbes Formation (Kirby, 1943) of the main outcrop belt to the east. The lithology of the Forbes Formation is broadly similar to that of units of IVd and IVe. If the ammonite collected from unit IVc is reliable, this sandstone unit may be correlative with the Guinda Formation (Kirby, 1943) of similar age and lithology beneath the Forbes Formation in the main outcrop belt to the east. Provided the combined units IVe and IVd do correspond to the Forbes Formation, and unit IVc to the Guinda Formation, it is possible to infer correlations of the underlying units IVb and IVa on the more tenuous grounds of lithology comparable to underlying formations of the main outcrop belt and of superposition consistent with the order in the main outcrop belt. If the inference is valid, unit IVb may represent the Funks Formation (Kirby, 1943) and Unit IVa, the Sites Formation (Kirby, 1943).

Lower Tertiary Beds

Brice (1953, p. 27–30) described the exposures of lower Tertiary marine strata within the map area. He reported that the sequence, about 5500 ft thick, includes: (a) Paleocene sandstone and mudstone of the Martinez Formation, and (b) Eocene sandstone of the Tejon Formation. The beds contain fossiliferous horizons with molluscan faunas indicative of deposition in moderately shallow and warm waters. For this report, our attention was confined to definition of the contacts between these strata and the Great Valley sequence.

Paleocene strata near Lower Lake (C8) were assigned by Dickerson (1914) to the Martinez Formation (*see* Popenoe and others, 1960). Along the southern border of the exposures, the Paleocene strata are largely massive sandstone that locally contains a rich megafauna. Along the northern border of the exposures, the Paleocene strata are mainly mudstone. In the syncline trough within the exposures, these Paleocene strata are overlain depositionally by conglomeratic sandstone of Eocene age (Brice, 1953).

A small area (D6) of white, massive, coarse-grained sandstone about 3 miles south of Lower Lake was recognized by Brice (1953) as the Martinez Formation on the basis of lithology, although no fossils were found in it. Below the massive white sandstone is a unit of structureless, massive, fine-grained, light-brown sandstone which Brice (1953) included in the undifferentiated Cretaceous. However, *Turritella pachecoensis*, the Paleocene guide-fossil, was collected by the writers from the upper part of the fine-grained, brown sandstone unit. The brown sandstone unit does not possess sole markings or graded bedding like the Mesozoic strata in the area.

SEDIMENTOLOGY OF GREAT VALLEY SEQUENCE

Sandstone Petrology

A number of sandstone samples were sawed pependicular to bedding and stained for K-feld-spar to check stratigraphic changes in the K-

Table 1. Thin-Section Modal Analyses of Late Mesozoic Sandstones Near Clear Lake, California; Figures Express Percentage of Framework Grains (Ignoring Matrix and Cement)

		Quartz	Plagioclase	K-Feldspar	Volcanic Rock Fragments	Chert	Other Sedimentary Rock Fragments	Quartzite	Other Metamorphic Rock Fragments	Hypabyssal Rock Fragments	Mica	Heavy Minerals and Plant Fragments
Group D (18)	Mean %	37.3	20.3	11.4	15.1	0.8	2.2	2.2	1.6	2.2	6.3	0.6
	Range %	23.8–46.0	12.1–31.2	8.1–19.1	8.4–32.6	0–2.2	0.4–5.0	0–5.3	0.4–3.4	0.3–5.1	2.2–10.4	0–3.0
Group C (6)	Mean %	31.1	19.1	9.8	19.5	1.0	1.9	2.3	2.9	2.9	7.0	0.9
	Range %	26.6–35.8	14.7–24.2	7.4–13.4	13.3–24.5	0–1.9	1.0–2.5	0.7–4.7	1.5–5.6	1.3–4.5	5.4–8.9	0–1.9
Group B₂ (5)	Mean %	43.2	16.9	8.8	15.0	0.2	1.7	2.2	1.6	2.6	3.8	4.1
	Range %	39.3–52.2	13.9–22.1	7.6–11.8	13.3–19.8	0–0.4	0–2.6	0.7–4.4	0.4–3.2	0.4–6.7	1.6–7.0	1.6–6.6
Group B₁ (4)	Mean %	45.6	16.3	4.0	21.0	1.1	2.8	1.4	0.2	1.0	4.4	0.9
	Range %	32.6–56.6	13.2–21.4	3.0–4.6	14.3–29.9	0–2.3	0–8.6	0.4–2.7	0–0.4	0–2.7	2.1–7.8	0.3–1.7
Group A (9)	Mean %	21.7	19.1	2.9	41.3	0.8	5.9	1.6	1.0	2.1	1.9	1.8
	Range %	9.1–43.5	11.6–35.4	Tr.–8.4	23.6–65.8	0–2.3	2.7–12.8	0.3–2.7	0–3.1	0.3–5.5	0–3.2	0.7–4.3
Franciscan (3)	Mean %	13.3	13.3	0	35.8	5.6	12.8	4.2	5.0	1.6	0.5	1.0
	Range %	9.9–19.0	9.8–16.5	0	25.6–50.4	3.7–7.4	9.7–16.7	0–6.3	1.5–8.6	0.7–3.3	0–0.7	0.7–1.1

feldspar content of the Great Valley sequence in the area. Eighty thin sections were also made from these samples, and 45 of them were point-counted with the help of a mechanical stage, as suggested by Chayes (1956) for modal analysis. Noncalcareous samples were deliberately chosen to avoid the problem of detrital grains replaced by carbonate. Four hundred points were counted in each slide; a summary of results is given by Table 1 and a Q-F-L diagram (Fig. 4).

The amount of interstitial matrix, which includes both recrystallized detrital silt and clay and authigenic phyllosilicate cement, is generally high in almost all the sandstone samples examined. In some of the Upper Jurassic samples, the clay-size fraction is authigenic chlorite, much of which grew radially in sheaves from the boundaries of coarse clastic grains. In most samples, the silt and clay includes small micaceous flakes squeezed and aligned with the boundaries of coarser clastic grains, which are in general angular to subangular in outline.

Petrologically, the sandstones of the Great Valley sequence in the study area may be grouped into five broad units (Table 1; Figs. 4 and 5), which are the same as those recognized widely in the main outcrop belt by Rich and others (1968). A few samples plot outside their proper fields on the Q-F-L diagram. This is generally due to abnormally high content of either volcanic or quartz grains, or to selective replacement of detrital grains by carbonate. The occasional samples rich in volcanic rock fragments probably indicate local and temporary volcanism in the source area. Samples rich in quartz suggest winnowing and reworking. Probably source areas and their inferred tectonic relations have been discussed by Ojakangas (1968) and Dickinson (1969). The characteristics of the petrologic units and their respective positions in the stratigraphic column ex-

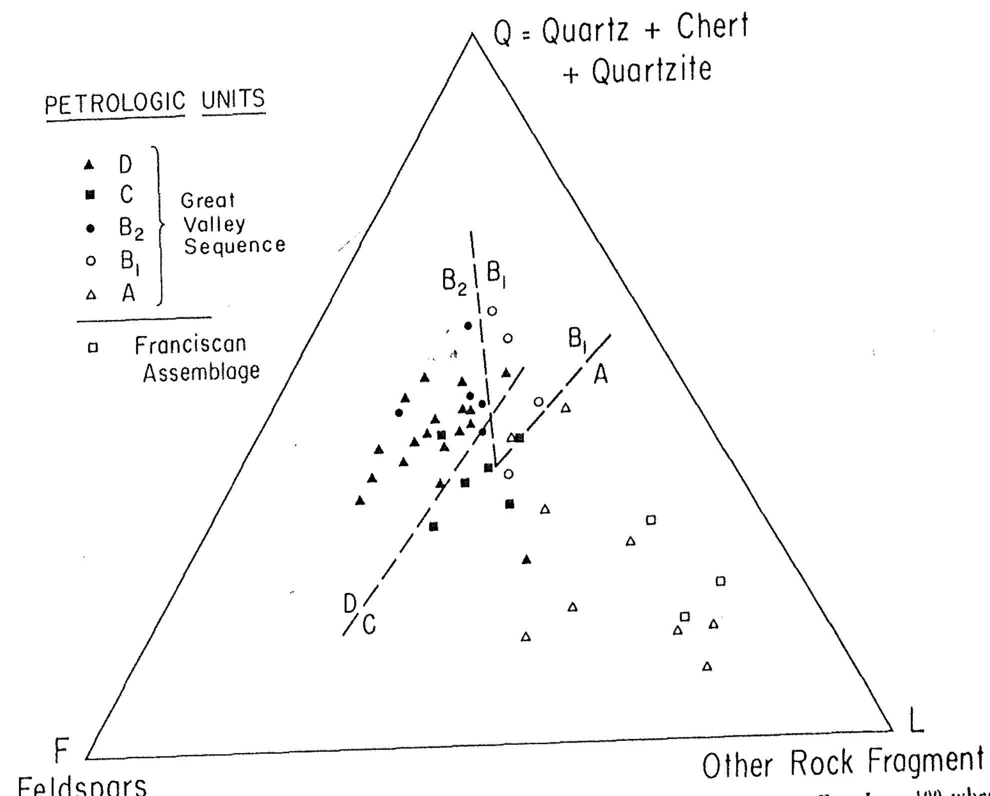


Figure 4. Q-F-L diagram of late Mesozoic sandstones near Clear Lake, California. Q + F + L = 100 where Q is sum of quartz, chert, and quartzite grains; F is total feldspar grains; and L is sum of all other rock fragments. Mica flakes, heavy minerals, and plant fragments do not enter the calculation. Open symbols denote rocks with less than 5 percent K-feldspar and solid symbols denote rocks with more than 5 percent K-feldspar. Dashed lines indicate approximate boundaries of fields between selected petrologic units, ignoring minor overlap.

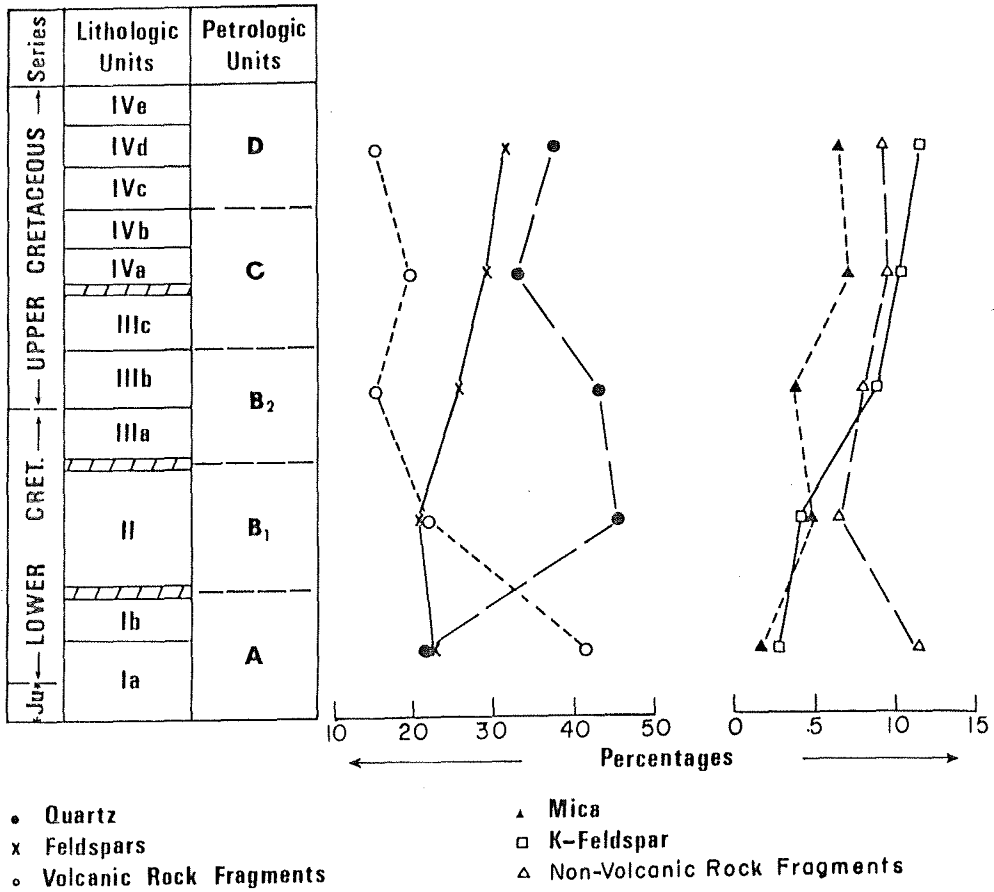


Figure 5. Petrologic variation chart of the Great Valley sequence near Clear Lake, California.

posed along Cache Creek in the main outcrop belt due east of the study area (*see* Fig. 1) are given by Ojakangas (1968). Comparison of the petrologic data with paleontologic data for the study area suggests that the petrologic units can be valuable for gross correlation in the absence of fossils and as a supplement to paleontologic and lithologic data for specific correlations.

Petrologic unit A is represented by stratigraphic unit I and is characterized by quartz-poor sandstones rich in lithic fragments and low in K-feldspar. The apparent overlap of the fields of petrologic units C and D with petrologic unit A on the Q-F-L diagram (Fig. 4) is not a real ambiguity, for the two younger petrologic units contain significantly more K-feldspar (Table 1; Fig. 5). In the main outcrop belt to the east, strata of comparable petrology (petrologic intervals I and II *of* Ojakangas, 1968) are correlative on the basis of paleontology as well.

Petrologic unit B_1 is represented by stratigraphic unit II, and is characterized by relatively quartz-rich sandstones, poor in lithic fragments and low in K-feldspar. The apparent overlap of the fields of petrologic units C and D with petrologic unit B_1 on the Q-F-L diagram (Fig. 4) is not a real ambiguity, for the two younger petrologic units contain significantly more K-feldspar (Table 1, Fig. 5). In the main outcrop belt to the east, some of the strata of comparable petrology (petrologic interval III *of* Ojakangas, 1968) are apparently correlative in age as well (*see* earlier section).

Petrologic unit B_2 is represented by stratigraphic units IIIa and IIIb of mid-Cretaceous (Albian-Cenomanian) age, and is characterized by sandstones about as rich in quartz grains and as poor in lithic fragments as those of petrologic unit B_1, but differing from them in having a relatively high content of K-feldspar. Strata of comparable age (Albian-Cenomanian) in the main outcrop belt to the east are also comparable in petrology (petrologic interval IV *of* Ojakangas, 1968). There is undoubted overlap of the fields of petrologic units B_2 and D on the Q-F-L diagram (Fig. 4) for the study area.

Petrologic unit C is represented by stratigraphic units IIIc and IVa, and is characterized by sandstones containing about equal amounts of quartz grains, feldspar grains, and lithic fragments so that plotted points fall near the middle of the Q-F-L diagram (Fig. 4). Neither of the two stratigraphic units yielded fossils, and the suggested stratigraphic correlations with the Venado and Sites Formations are speculative (*see* earlier section). The petrology of the rocks does not contradict the suggested correlations and lends some support to them, for it is these two formations of the main outcrop belt whose petrology is the most comparable (petrologic interval V *of* Ojakangas, 1968).

Petrologic unit D is represented by most of stratigraphic unit IV, and is characterized by sandstones rich in feldspar and low in lithic fragments. In the main outcrop belt to the east, correlative strata are comparable in petrology (petrologic interval IV *of* Ojakangas, 1968).

Three representative Franciscan sandstone samples were also point-counted for comparison with the rocks of the Great Valley sequence in the area. Petrologically, the Franciscan sandstones in the area are indistinguishable (except for the absence of K-feldspar in the Franciscan sandstones) from those of the lower part (Tithonian through Valanginian, petrologic unit A) of the Great Valley sequence. However, in other parts of the Coast Ranges, Soliman (1958) reported Franciscan sandstones which are petrologically different from those of the present area. These are comparable to sandstones of the upper part (post-Valanginian) of the Great Valley sequence and particularly to late Early Cretaceous (petrologic units B_1 and B_2) rocks. This may indicate that the Franciscan assemblage also possesses trends in petrologic variation that are somewhat comparable to those within the Great Valley sequence. Such would suggest derivation from comparable source areas. The Franciscan rocks in the study area, therefore, probably represent an older part of the Franciscan assemblage, as Bailey and others (1964) have already speculated.

Paleocurrents

One hundred and seventy-two paleocurrent measurements were made from the rocks of the Great Valley sequence in the area. The indicators include various forms of flute casts (Crowell, 1955, p. 1359), groove casts (Shrock, 1948, p. 162), parting lineations (Stoke, 1947, p. 21; Crowell, 1955, p. 1361), bounce casts (Wood and Smith, 1959, p. 182), brush casts (Dzulynski and Slaczka, 1958, p. 231), small-scale cross-stratification (McKee and Weir, 1953, p. 382), flame structures (Walton, 1956), alignment of organic material and imbrication of pebbles (*see* Table 2). Systematic sampling in predetermined localities, as suggested by Krumbein (1960), was not possible because of poor exposures.

Table 2. Stratigraphic Distribution of Various Kinds of Late Mesozoic Current Indicators Observed in the Lower Lake Quadrangle, California

Stratigraphic Units	Flute Cast	Groove Cast	Parting Lineation	Bounce Cast	Brush Cast	Small-scale cross-stratification	Flame Structures	Alignment of Organic Material	Pebble Imbrication	Total Measurement
IVd, IVe	25	35	6	3	3	2				74
IVc	13	18	3	3		4	1	3		45
IVb	6	5	2							13
IIIc	4	3	[illegible]							8
IIIa	1	2	4							7
II		7	6		1	2		1		17
Ia, Ib	4	2					1		1	8
Grand Total										172

Most of the measurements were made from individual beds. However, where more than one paleocurrent direction was observed on the same bed, all the directions were measured and each measurement was given equal consideration in an over-all computation of the general trend. Most of the measurements were made with the help of a protractor and a marking pen in a manner similar to that recently described by Briggs and Cline (1967). Tilt corrections were made for rotations around both horizontal and vertical axes wherever necessary.

Paleocurrents of the Great Valley sequence in the area compare closely to those reported by Ojakangas (1968) from the correlative parts of the Great Valley sequence on the west side of the Sacramento Valley except for the Venado and Funks Formations (*see* Figs. 6, 7). Discrepancies at these levels may be due to strong prevalence of transverse currents from the side of the basin on the east. In general, southerly currents prevail in both areas.

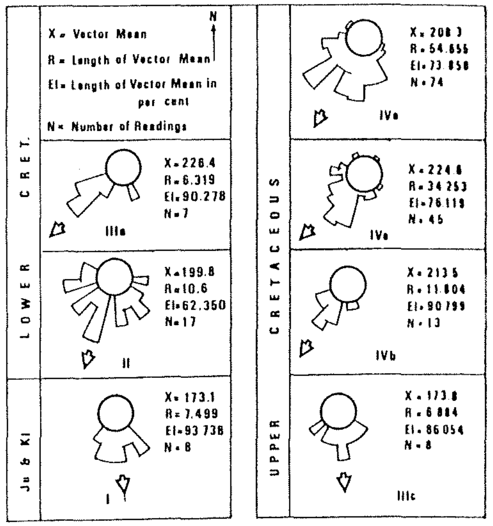


Figure 6. Stratigraphic variation in paleocurrent trends within the Great Valley sequence near Clear Lake, California.

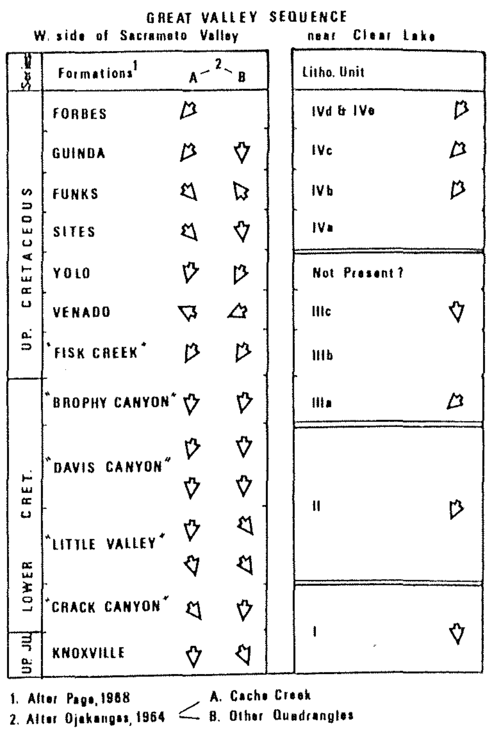


Figure 7. Geographic and stratigraphic variations in paleocurrent trends of the Great Valley sequence.

Environment of Deposition

Repeated graded bedding, sole markings, alternating sequences of thin-bedded mudstone and graded sandstone, and displaced faunas (*see* Dott, 1963; Kuenen, 1957) strongly suggest a turbidite origin for most of the strata, as is the case for the main outcrop belt (Ojakangas, 1968). Absence of large-scale cross stratification and indigenous shallow water organisms also indicate that most of the Great Valley sequence in the area was deposited below wave-base. However, large limestone blocks with numerous broken oysters in the siltstones of unit IVb may indicate a shallower environment. These large blocks do not appear to have been transported appreciably, and oysters thrive only in shallow water with hard bottom conditions. On the other hand, a few sedimentary structures (sole marks) in this unit are very similar to those in the other units which are regarded as typical turbidites. This may indicate that some features apparently indicative of turbidity currents could also form in shallow water environments.

STRUCTURAL RELATIONS OF MESOZOIC ROCKS

Structures described here include mainly those within the Great Valley sequence upon which the present investigation has been focused. The conspicuous structures in the area are the Soda Creek thrust, which marks the discordant base of the Great Valley sequence

above the structurally underlying Franciscan assemblage, and associated imbricate thrusts that sliced the Great Valley sequence. Of the latter, the Harbin Mountain thrust that marks the discordant base of the conformable Upper Cretaceous succession is the most conspicuous. Each of the thrust slices, large and small, were internally deformed, and all of them subsequently folded together and faulted during late Cenozoic deformations. Many of the old thrusts are exposed on the flanks of the younger folds, and many of them dip as steeply as the limbs of the folds in which they are involved. Therefore, it is difficult to separate the steeply dipping old thrusts from younger steep faults whose traces often parallel the Cenozoic fold trends (northwest-southeast). In this report, faults mapped as folded thrusts include those which dip steeply in most areas, but locally have relatively gentle dips (for example, Harbin Mountain thrust), and those which dip locally in opposite directions. However, straight faults which everywhere dip steeply were mapped as younger reverse and normal faults. The thrust faults in the area are mostly recognized by stratal truncations which are also commonly associated with the presence of some unrelated exotic rock types, such as serpentinites and their altered products, or some highly deformed graywackes. Late Cenozoic thrusting is also known in the Coast Ranges (*see* Page, 1966, p. 273), but most of the late Cenozoic thrusts had local roots. Therefore, they should not be confused with the regional thrusts of older age described in this report. Evidence bearing upon the age of the thrusting is discussed in a later section; the following account is confined to the geometry of the thrusts.

Soda Creek Thrust

Even though thrust fault contacts between the Franciscan assemblage and the overlying Great Valley sequence have been reported from other areas by Brown (1964a, 1964b) and Rich (1968) in the Northern Coast Ranges and by Dickinson (1965, 1966a, 1966b) in the Diablo Range, correlation of the faults among the different areas is uncertain. The Great Valley sequence may have been emplaced over the Franciscan assemblage either by a system of giant thrusts or by a single gigantic thrust over the entire Coast Ranges. For convenience in the present discussion, the thrust that separates the overlying Great Valley sequence from the Franciscan assemblage in the study area will be called the Soda Creek thrust after Soda Creek in the east-central part of the area.

The folded trace of the Soda Creek thrust is exposed for about 8 miles in the northern part of the study area on the flanks of the Soda Creek anticline. Limited exposures also ring small windows nearby (C7) between the anticline core and the town of Lower Lake. Large lenses and small pods of serpentinite breccia are widely scattered along the fault, which separates the Franciscan assemblage beneath from mudstone and sandstone of Late Jurassic to Early Cretaceous age in unit I of the Great Valley sequence. The fact that units Ia and Ib are each locally in contact with the Franciscan assemblage indicates that the Soda Creek thrust truncates the bedding of unit I, whose exposed base is a discordant contact.

The Soda Creek thrust also crops out for a short distance just north and northwest of Brushy Sky High (B9) marking the north border of the map area. The thrust here is nearly horizontal as exposed, and carried Upper Jurassic rocks of unit I over Franciscan metasedimentary and minor metavolcanic rocks.

Structurally and stratigraphically, the Soda Creek thrust is the lowest mappable thrust in the area and probably is the main sole thrust beneath the rocks of the Great Valley sequence. A folded thrust delineated by a serpentinite sheet(?) on the Howard Springs structure (E4) is tentatively regarded as a segment of the Soda Creek thrust because it lies at approximately the same stratigraphic and structural level as the Soda Creek thrust in the type locality. However, no Franciscan rocks were recognized below the thrust on the Howard Springs structure. This may be because the serpentinite breccia body along the thrust at that locality is relatively thicker than those along the Soda Creek thrust in the type locality, and erosion may not have been deep enough to expose the Franciscan rocks inferred to underlie the serpentinite on the Howard Springs structure.

Through a somewhat similar line of reasoning, a moderately steep fault near the southwest border of the map area can be interpreted as a segment of the Soda Creek thrust. The fault separates strata of the Great Valley sequence from serpentinite which may overlie the Franciscan to the southwest of the map area. The serpentinite there is also thicker than that along the Soda Creek thrust on the Soda Creek anticline. The serpentinite also may have been remobilized during Cenozoic deformations, for locally the thrust is steeply overturned and serpentinite overrides overturned strata of the Great Valley sequence in this part of the area. However, a small klippe of probable Upper Cretaceous massive sandstones (H4) appears to overlie a small segment of the fault in question, thus suggesting that the steeply dipping fault is a folded thrust of relatively old age.

Imbricate Thrusts Within the Great Valley Sequence

Folded thrusts presumably related to the Soda Creek thrust as imbricate subsidiary structures cut strata of the Great Valley sequence at a number of horizons. Their recognition was based mainly on mapped stratal truncations and the occurrence of serpentinite lenses along them. Outcrops of the fault zones themselves are largely masked by soil and vegetation. Inferences of subsurface extensions and connections of these thrusts present a difficult challenge. The reliability of the interpretations presented here will be seen to vary greatly.

Except for local thin fault slices adjacent to the Soda Creek thrust, no thrusts were mapped within unit I. The only suggestion that thrust surfaces of minor displacement may possibly occur within the exposures are locally unresolved structural complexities within unit Ib in heavy brush on the south flank of the Soda Creek anticline (D9).

Except where it is overlain unconformably by Tertiary strata, all exposed upper contacts of unit I are folded thrusts discordant to bedding. Unit I thus appears to form a folded thrust plate or slice that is internally intact, but is bounded above and below by folded thrusts that are discordant, mostly at low angles, to the bedding within unit I.

About 2 miles north of Middletown, a gently dipping thrust exposed for about a mile placed upper Lower Cretaceous (Aptian) strata of the eastern outcrop belt of unit II over Upper Jurassic (Tithonian) mudstone of unit Ia. Just west of Harbin Springs (H4), a folded thrust that also placed unit II (western outcrop belt) against unit Ia was located in poorly exposed ground with the help of a slender wedge of serpentinite along the thrust surface. The two thrust segments are inferred to represent a single thrust that forms the discordant base of an intact thrust slice composed of unit II. Both thrust segments appear to diverge upward in similar imbricate fashion into the Great Valley sequence from the Soda Creek thrust beneath. The exposed upper contacts of unit II in both its areas of exposure are folded thrust surfaces that are discordant to bedding in unit II and are inferred to be segments of the Harbin Mountain thrust (*see* below). Definite proof of the inferred continuity of the thrust plate or slice of unit II is lacking because exposures of unit IV above the Harbin Mountain thrust separate the exposures of unit II into two belts.

Near the northern edge of the study area, a nearly horizontal thrust placed massive sandstone (unit IIIa) of probable mid-Cretaceous age over Upper Jurassic to Lower Cretaceous mudstone (unit Ia). The thrust surface is slightly discordant to the bedding of the sandstone. The trace of the thrust is sinuous because it is involved in small plunging folds, and it was also cut by younger normal faults. Its location is sharply delineated because of the strong contrast between the lithology of the rocks above and below the thrust. A short segment of probably the same thrust crops out about a mile due north of Cache Creek Dam. This fault has the same relationship to adjacent strata as the one farther east. Just south of Lower Lake, a steeply dipping fault between lower Lower Cretaceous strata (unit Ib) and massive sandstones (unit IIIa ?) that are probably correlative with those near Cache Creek Dam may be a steeply folded segment of the same thrust that became involved in the big syncline whose axial trace lies between Lower Lake and Cache Creek Dam.

The exposed upper contacts of unit IIIa are everywhere unconformities with Cenozoic strata. Any relationships that may have existed with younger Mesozoic rocks prior to Cenozoic erosion are thus unknown. The structural relationships of units IIIb and IIIc are even more enigmatic. The contact between them is a folded thrust (C3) that truncates strata in both units and placed unit IIIc above unit IIIb. The only other exposed contacts of units IIIb and IIIc are unconformities with Cenozoic strata and late Cenozoic faults that offset Cenozoic as well as Mesozoic strata (Brice, 1953). Huge fault slivers of Franciscan(?) greenstone, chert, and serpentinite occur along the fault contact between unit IIIc and unit IV.

Units IIIa, IIIb, and IIIc crop out only in the northern part of the area whereas the thrust-bounded slice or slices of unit II crop out only in the southern part of the area. It is tempting

to speculate that units IIIa, IIIb, and IIIc may represent parts of an internally dislocated but semi-intact thrust plate or slice of mid-Cretaceous strata. Whether or not the three units are really structurally associated with one another as "unit III," there are no grounds to suppose that any one of the three is in depositional contact with any parts of units I, II, or IV, at any place within the study area.

Harbin Mountain Thrust

On the south slope of Harbin Mountain northwest of Middletown, the trace of a thrust that placed rocks of units IVa and IVb over rocks of unit II is here called the Harbin Mountain thrust. Thrust segments at the discordant base of unit IV elsewhere are inferred provisionally to be extensions of the same thrust. However, subsidiary imbricate thrusts that locally diverge upward from the Harbin Mountain thrust introduce ambiguity into several interpretations. The thrust in lower Cockrell Canyon (H5) that locally forms the contact mapped between units IVb and IVc is the most conspicuous example. To the west, displacement and discordance along this thrust, which is subparallel to bedding, gradually decrease, and the contact between units IVb and IVc appears so gradational and conformable that it is difficult to locate in the timber of upper Cockrell Canyon. To the east, this subsidiary branch thrust of Cockrell Canyon appears to merge with the main Harbin Canyon thrust. Around the Big Canyon road about 2.5 miles north of Middletown, a folded segment of the merged thrust surface placed Upper Cretaceous massive sandstone (unit IVc) over upper Lower Cretaceous strata (unit II). A relatively thin sheet of serpentinite breccia lies along the thrust beside the Big Canyon road. It appears superficially to form a conformable wedge within the clastic strata and was previously mapped as detrital serpentine by Brice (1953). However, paleontologic data now indicate the difference in age of strata below (Aptian) and above (probably Campanian) the serpentinite sheet. Local structural mapping has revealed discordance with the strata below and above the serpentinite sheet.

A small klippe (H4) of probable Upper Cretaceous massive sandstone (unit IVa) west of Harbin Ridge is apparently surrounded by an erosionally isolated segment of the Harbin Mountain thrust. On Highway 53 about a mile north of Middletown, a thrust that placed Upper Cretaceous massive sandstone (unit IVc ?) above Upper Jurassic (Tithonian) mudstone (unit Ia) is also inferred to be part of the branching Harbin Mountain thrust system.

Except as it is partly dislocated near the base by branching thrusts, unit IV forms a coherent thrust plate or slice whose erosional remnants extend over much of the study area. The exposed upper contacts of unit IVc at the highest stratigraphic levels exposed in the Mesozoic sequence are unconformities or faults with Cenozoic strata.

Summary of Thrust Geometry

The most likely structural relations of the principal thrust plates and imbricate, lenticular thrust slices can be summarized as follows (*see* Fig. 8):

(1) Resting discordantly upon the Soda Creek thrust and its branches at the lowest structural levels in the Great Valley sequence is an intact plate of variable thickness composed entirely of unit I, the conformable Upper Jurassic and Lower Cretaceous succession, which is bounded above by various discordant thrust surfaces. Remnants of this unit I plate are distributed throughout the study area; where higher structural levels are exposed at the surface, it is probably present at depth.

(2) At the highest structural levels in the Great Valley sequence of the southern and central parts of the study area is an intact plate of unit IV, the conformable Upper Cretaceous succession, which rests discordantly upon the Harbin Mountain thrust and its branches. There is no definite evidence that this unit IV plate was ever present in the northern part of the study area, but it may well have been removed from there by Cenozoic erosion.

(3) In the southern part of the study area, the unit I plate and the unit IV plate are locally separated by a thrust slice or slices of Lower Cretaceous strata (unit II) that are bounded above and below by discordant thrust contacts. There is no evidence that this lenticular and possibly discontinuous unit II plate extends northward at depth much beyond its present outcrop area, nor can it be proved that the plate never extended over the entire study area.

(4) In the northern part of the study area, three structurally isolated packages of mid-Cretaceous strata may conceivably be dismembered parts of an internally dislocated "unit III" thrust plate that occupied some inter-

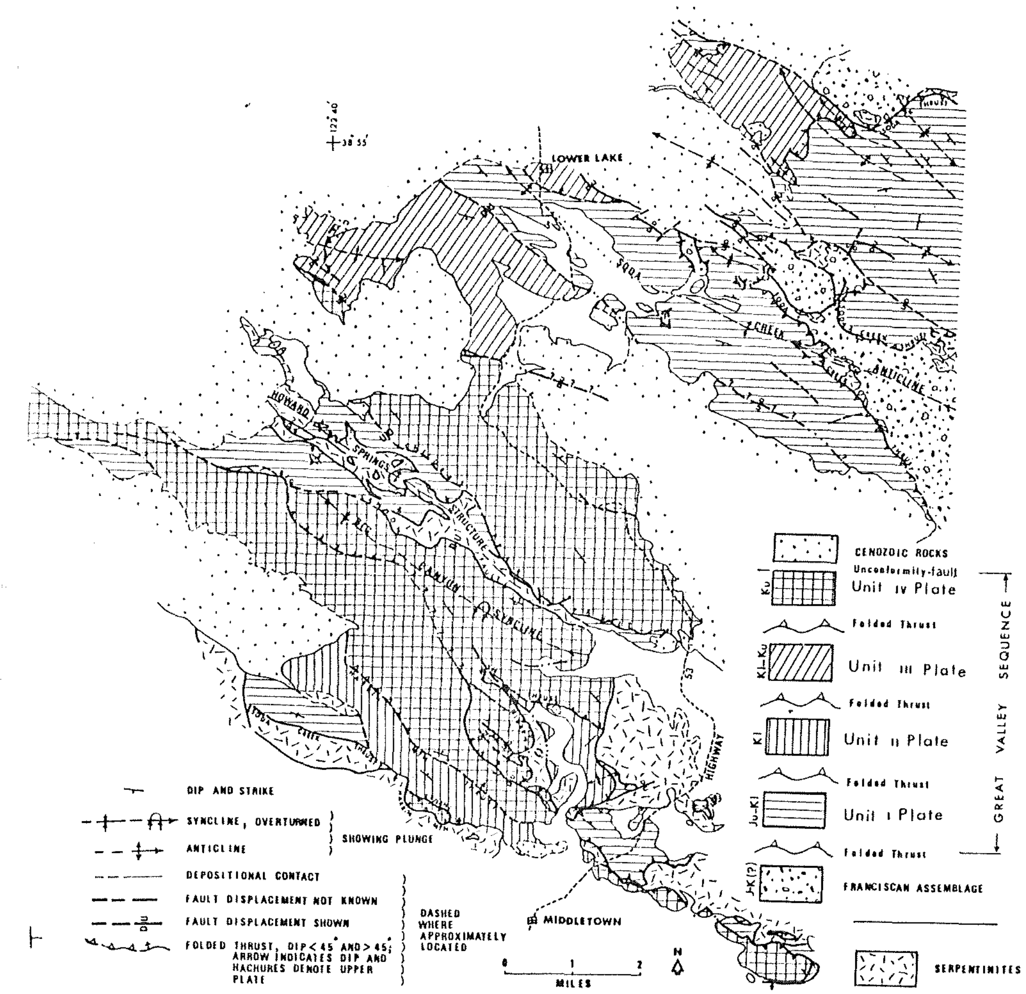


Figure 8. Tectonic map of the area south and southeast of Clear Lake, California, showing preferred interpretation of thrust plate geometry within the Great Valley sequence.

mediate structural level between the unit I and unit IV plates. Alternatively, they may be three unrelated thrust slices, or all three may even be related to some unknown northern extension of the unit II plate.

(5) At each thrust contact mapped, the strata above the thrust are younger than the strata below the thrust; some degree of stratal truncation is evident on both sides of each thrust.

Folds

The folds of the area are neither simple nor well defined because of complicated faulting. It is difficult to follow the axes of even big folds for more than a few miles because minor folds are generally present on their flanks. The two largest folds in the area are the Soda Creek anticline near Lower Lake and the Big Canyon syncline a few miles northwest of Middletown.

The Soda Creek anticline is a complicated fold with an axis plunging northwest. The Franciscan assemblage, the structurally lowest rocks in the area, is exposed along the core in the southeast. Also involved in the Soda Creek anticline is unit I, which overlies the Franciscan along the Soda Creek thrust. Due to erosion on the crest of the anticline, the trace of the Soda Creek thrust is exposed on the flanks of the anticline. In the southeastern part of its axial trace, where the Franciscan rocks are exposed, the Soda Creek anticline appears to be a broad fold. However, in the northwest, near Lower Lake, the fold appears to be tightly appressed; mudstones near the axial trace of the fold are steeply dipping or vertical. On the northwest, just west of Lower Lake, the axial trace of the Soda Creek anticline passes beneath tuffs of the Pliocene-Pleistocene Cache Formation. On the southeast, the axial trace continues beyond the border of the map area, and the Franciscan assemblage is extensively exposed for many miles along the core of the fold (*see* Koenig, 1963).

The Big Canyon syncline is also a complex fold. Along the middle reaches of its axial trace on the Big Canyon road about 3 miles northwest of Middletown, it is isoclinal, and its axial surface dips steeply to the north. However, it is less tightly appressed and loses its isoclinal character to the northwest. The strata involved in this syncline are those of unit IV; most of the north limb of the fold was cut off by the Big Canyon fault.

The Howard Springs piercement structure in the western part of the area is an uplifted structural block bordered by two high-angle reverse faults, the Childers Peak fault of Brice (1953) on the north and the Big Canyon fault on the south. The axis of the structure trends northwest-southeast for about 8 miles. Both ends of the structure are covered by Cenozoic strata and alluvium. The rocks exposed in the uplifted block are unit I and underlying serpentinite. Border faults at the margins of the structure, the serpentinite of low density in the central block, and an over-all archlike shape suggest this structure may be diapiric. As its axis follows fold trends of the Coast Ranges, it may have formed during late Cenozoic orogenesis. Uplift and erosion of the central block may have been very rapid, for the structure is overlapped by tuffs of the Cache Formation which was dated by Becker (1888) as Pliocene-Pleistocene in age in the region east of Clear Lake. The age of the tuffs directly overlying the Howard Springs structure, however, is not definitely known.

TIME AND SETTING OF THRUSTING

The inferred timing of the major tectonic events that affected the area is summarized in Table 3. Because rocks as young as Campanian and Maestrichtian occur within the thrust complex of the Great Valley sequence, the structural relations of the lower Tertiary beds to the Mesozoic rocks provide critical information about the time of thrusting. Unfortunately, exposures of the contact are poor in most places, obscured by surficial materials or vegetation. However, east of Lower Lake (C8), exposures on a grassy hillside are adequate to show that Paleocene strata there are in thrust contact with unit Ia of the Great Valley sequence not far from exposures of the Franciscan assemblage below the Soda Creek thrust. The mudstones and thin sandstone interbeds of unit Ia are dislocated by minor shear surfaces for at least 100 feet beneath the contact with the structurally overlying Paleocene rocks. Along the contact are discontinuous pods of serpentinite, metagabbro, and greenstone forming a sheared sheet, locally 100 ft thick, that delineates the thrust surface, as do similar sheets along structurally lower thrusts within the Great Valley sequence. The massive Paleocene sandstones adjacent to the thrust are shattered and mineralized by pyrite

Table 3. Chronologic Sequence of Depositional and Tectonic Events Affecting Rocks in the Area South and Southeast of Clear Lake, California

1. Separate origin of the Franciscan assemblage and the Great Valley sequence.	Late Jurassic to Late Cretaceous
2. Deposition of the lower Tertiary marine beds above the Great Valley sequence in moderately shallow, warm waters.	Paleocene to Eocene
3. Tectonic emplacement of the Great Valley sequence above the Franciscan assemblage by thrusting, with subsidiary thrusts cutting the Great Valley sequence and the lower Tertiary beds.	Oligocene and earlier (?)
4. Uplift and erosion of the area. No record of Oligocene and Miocene deposition.	Probably late Eocene or Oligocene to probably early Pliocene
5. Late Tertiary-early Quaternary orogeny affecting earlier thrusts and unconformities in the area. Synorogenic deposition of the fresh water Cache Formation. Volcanism in the final stages of Cache deposition.	Pliocene-Pleistocene
6. Uplift and erosion of the region with continuing intermittent volcanism.	Late Pleistocene to Recent

weathered to limonite for a distance of 50 to 100 ft from the contact. Other contacts of lower Tertiary strata with Mesozoic rocks are too poorly exposed to permit observations of similar quality, but are inferred to be folded segments of this thrust. South of Lower Lake (D6), where the thrust contact is questioned on the map, the lower Tertiary strata may be in depositional contact with unit IV, the youngest part of the Great Valley sequence.

As the lower Tertiary succession includes Eocene beds, the last thrust movements were apparently at least as young as Eocene. Northwest of Clear Lake, recent work by Berkland (1969) shows that Paleocene and Eocene strata are also present with strata of the Great Valley sequence in a large klippe in thrust contact with the Franciscan assemblage. There is no evidence either there or southeast of Clear Lake to indicate when the thrusting began or if the movements occupied some span of time. Nor is there evidence in either area to indicate the latest possible date of thrust movements with satisfactory precision. However, field relations near Round Valley along regional tectonic strike, but 75 miles to the northwest, suggest the hypothesis that the youngest regional thrust movements were post-Eocene but pre-Miocene. Reconnaissance of that area suggests that the Cretaceous, Paleocene, and Eocene succession mapped by Clark (1940) is a large klippe resting upon the underlying Franciscan assemblage along a thrust contact. The outcrop pattern of Clark's map shows the contact to be discordant to bedding in the succession above the thrust. In the same area, Miocene strata assigned by Clark (1940, p. 131–138) to the Temblor Formation rest unconformably on the Franciscan assemblage, which by then evidently had been exhumed locally by erosion. Thick conglomerates in the local Miocene section contain abundant pebbles of graywacke, vein quartz, red and green chert, greenstone, and serpentine derived from the underlying Franciscan rocks. The Miocene sandstones contain plentiful chromite, glaucophane, and lawsonite indicative of a Franciscan provenance in the heavy mineral fraction (Clark, 1940, p. 136–137). By contrast, Cretaceous conglomerates of the inferred klippe contain a different pebble assemblage similar to those found elsewhere in the Great Valley sequence. Moreover, the lower Tertiary sandstones within the inferred klippe lack chromite, glaucophane, and lawsonite, but contain garnet, which is absent in the Miocene sandstones. In the area we have mapped near Clear Lake, the lower Tertiary sandstones also contain garnet as well as staurolite, but lack glaucophane (Brice, 1953, p. 28, 30).

The available evidence thus suggests that the close of the period of regional thrusting of the Franciscan assemblage beneath the Great Valley sequence and overlying lower Tertiary strata was no older than Oligocene. This suggested timing may have significant bearing on general concepts of the tectonic evolution of coastal California. Dickinson and Grantz (1968) have argued that the present framework of steep faults reflecting a late Cenozoic regime of regional strike-slip related to the San Andreas system was probably preceded in time by a framework of regional thrust faults. Termination of the earlier regime of deformation by juxtaposition of great crustal slabs along thrusts may have coincided with initiation of the later regime of strike-slip. It is of interest to note that the evidence for cumulative offset of successively older strata in the Southern Coast Ranges suggests that the San Andreas fault may have been active since Oligocene time, but inferences of more ancient strike-slip movements along the fault are questionable (Grantz and Dickinson, 1968). Crowell (1962), working in southern California, and Dott (1965), working in southwestern Oregon, have also implied that strike-slip along major faults with northwesterly trends related to the San Andreas system may have begun at about Oligocene time.

The tectonic setting of the thrusts is open to various interpretations in detail. However, the lithology and petrology of the stratigraphic units of the Great Valley sequence in the study area are generally comparable to those of correlative parts of the Great Valley sequence in the main outcrop belt to the east. This circumstance leaves little doubt that the strata now found within the thrust complex were connected to the rocks of the main outcrop belt before thrusting. The predominance of turbidites with southerly paleocurrent indicators in both areas suggests not only that the units now exposed in the two separate areas were laterally continuous at the time of deposition, but also that the thrust plates and slices were not rotated or disoriented to any marked degree with respect to strata in the main outcrop belt.

On a regional scale, most exposures of the Great Valley sequence lie east of most exposures of the Franciscan assemblage. Therefore, the

juxtaposition of the two masses of rock at the Soda Creek thrust would seem to require either (a) overthrusting of the Great Valley sequence with a westerly component of movement, or (b) underthrusting of the Franciscan assemblage with an easterly component of movement. Overthrusting and underthrusting have only a relative meaning on a local scale, but if relative movement with respect to the external mass of the Sierra Nevada is taken into account, the two terms are not synonymous. Strata of the Great Valley sequence in the subsurface east of the main outcrop belt rest unconformably without decollement on the Sierra Nevada block under the whole length of the Great Valley, and limited exposures of the contact are known in the Sierra Nevada foothills. Therefore, if the thrust complex of the study area was emplaced by gravitational overthrusting, the detachment zone must lie within the main outcrop belt or just west of it. Previous workers have not detected any evidence suggestive of the presence of structures that might be related to detachment in that region. Consequently, the hypothesis that the thrust complex may have been formed by underthrusting of the Franciscan assemblage is attractive. As the Franciscan is commonly thought to have been deposited on oceanic crust, further work may give substance to this hypothesis by relating it to sea-floor spreading (for example, Page, 1969). Either overthrusting or underthrusting of the types discussed might equally well account for the observation that all the subsidiary thrusts above the Soda Creek thrust place younger rocks above older rocks.

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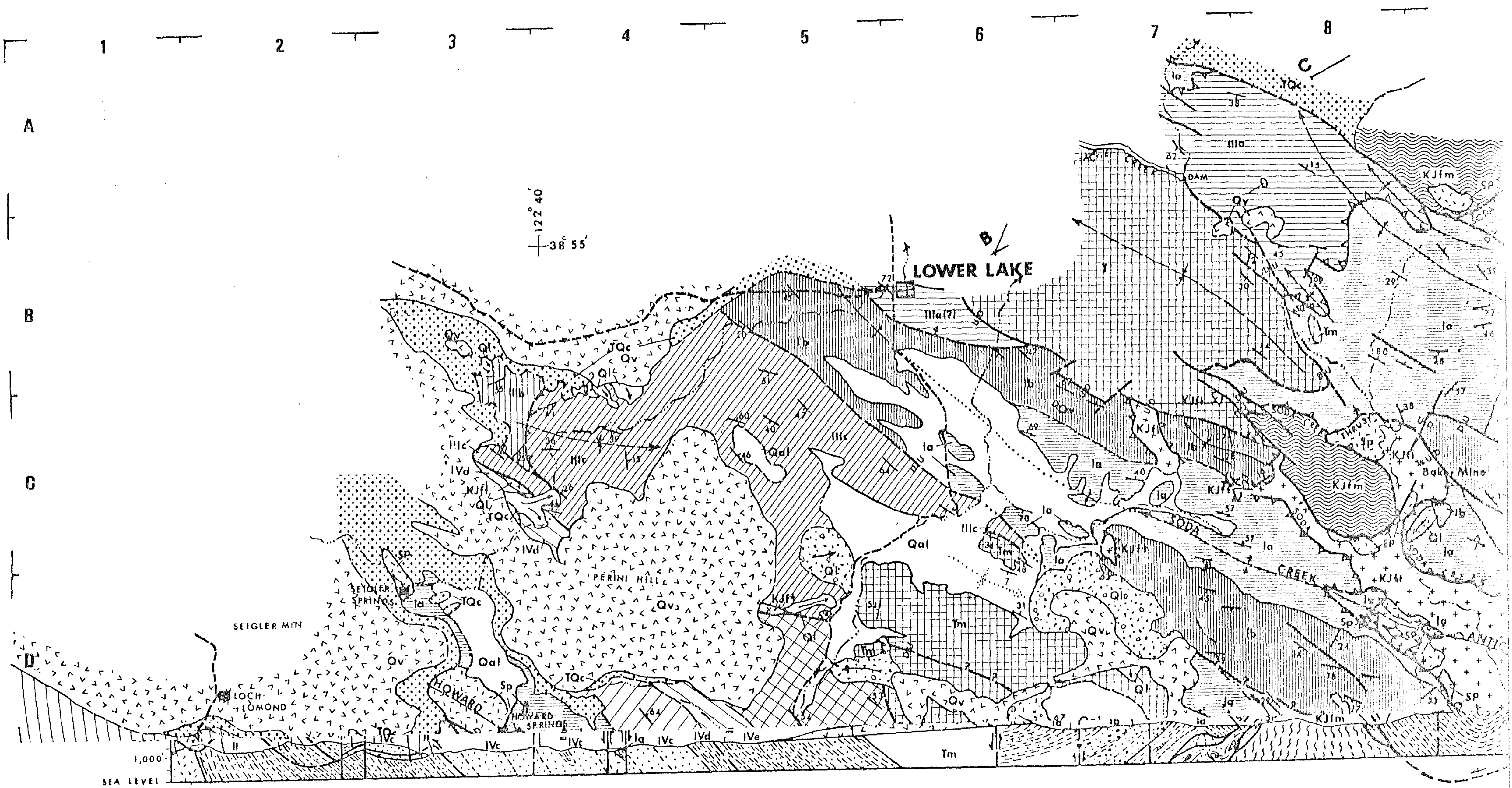
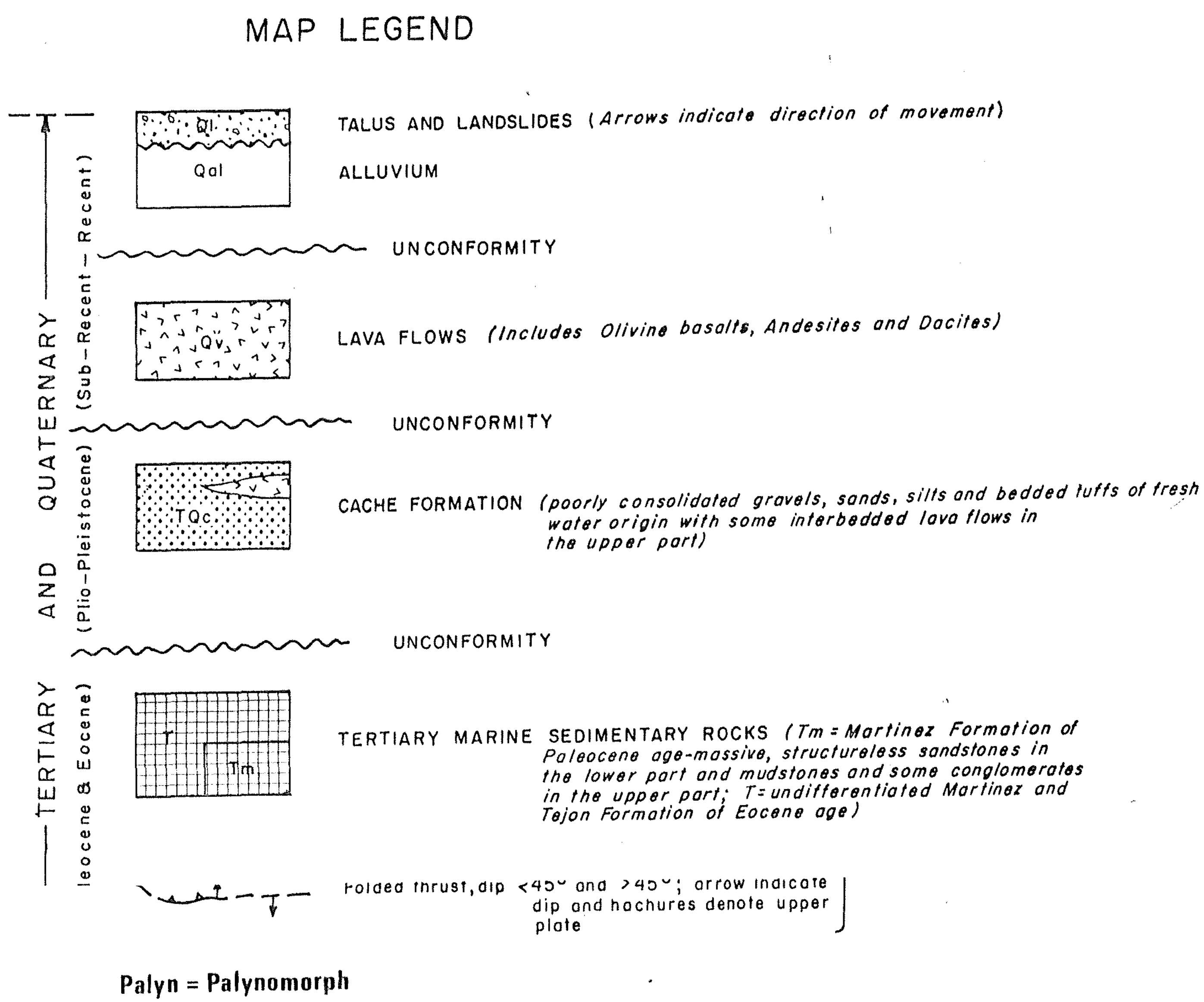


Figure 2. Geologic map and cross sections of late Mesoz



SWE AND DICKINSON. FIGURE 2.

however, appears to pass into highly defo massive graywackes with some pebble glomerates in the vicinity of the east bord the map area. These conglomerates lie nea projection of the strike line of conglomera the Great Valley sequence to the north. Brice (1953) believed them to be part of same conglomeratic belt, even though he n differences in the clast types and in the d of induration. The age of the Franciscan in the area could not be ascertained certainty, but in other parts of the C Ranges, the Franciscan assemblage has yie fossils of Late Jurassic (Tithonian) to Cretaceous (Turonian) age.

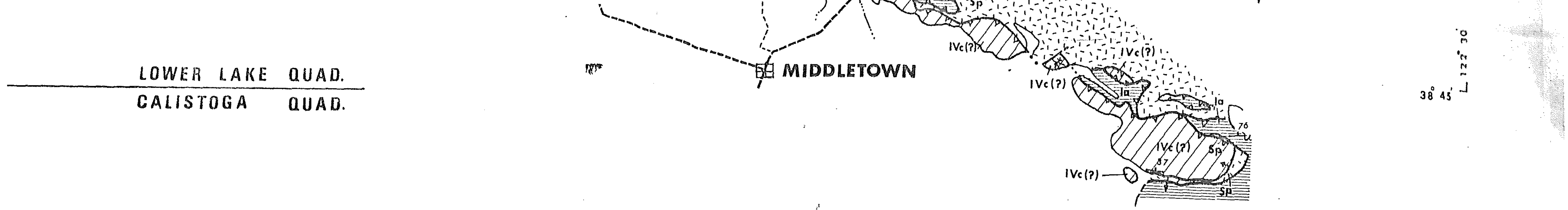
Great Valley Sequence

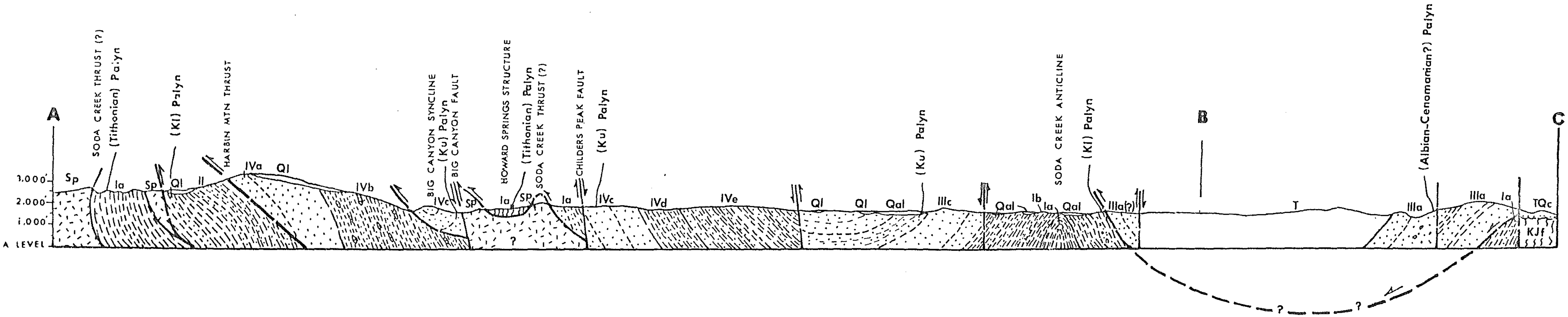
The Great Valley sequence in the area cludes approximately 35,000 ft of cla sedimentary strata that range in age from L Jurassic to Late Cretaceous. It is expose three irregular belts that structurally ov the Franciscan assemblage. Lithologic c acteristics, petrologic variations, and pa current indicators within the Great Va sequence in the study area are closely com rable to those of correlative parts of the m belt of exposure on the west side of the Sac mento Valley which will be referred to sim as the main belt in this report.

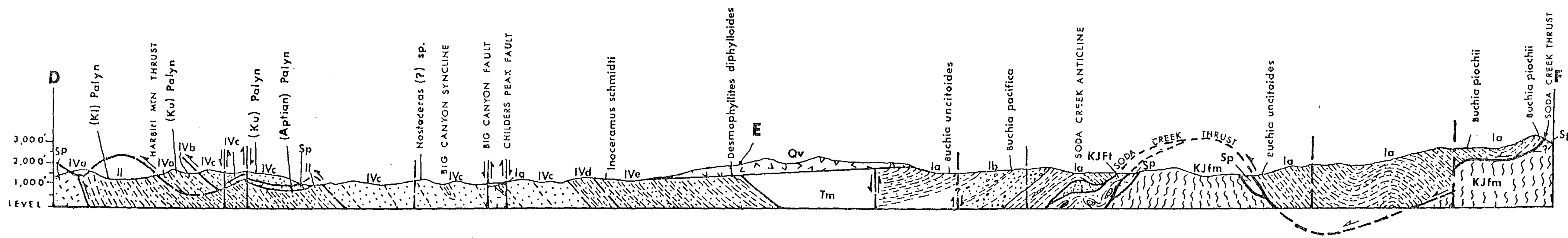
Within the study area, the Great Val sequence can be divided stratigraphically i four main segments. Three are apparently c formable successions of strata, and the four includes several isolated, fault-bounded ex sures of apparently similar age. Because faulting, the relative ages of the four segmen cannot be demonstrated by physical supe position, but direct evidence from fossils a corroborative evidence from petrology perm satisfactory correlation of most parts of t sequence (*see* Fig. 3). The stratigraphy of t four segments is described first in the followi order; their petrology and structural relatio are discussed in later sections:

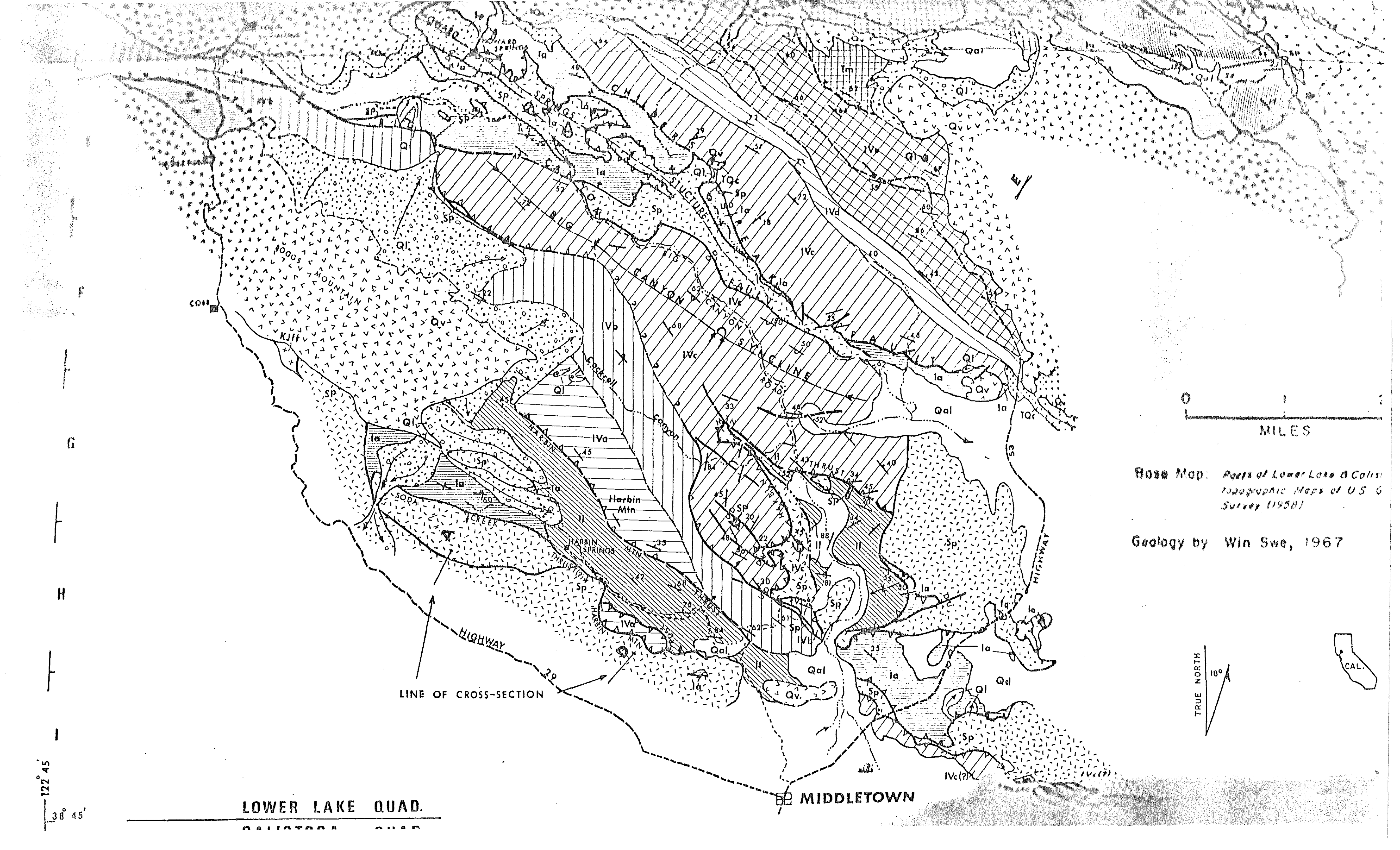
(1) The oldest strata, widely exposed in th study area (*see* Fig. 2), are an apparently con formable succession ranging in age from Lat Jurassic (Tithonian) to Early Cretaceou (Berriasian and Valanginian) on the basis o species of *Buchia*.

(2) Younger Lower Cretaceous strata, in a apparently conformable succession of homo ogous lithology and petrology, are expose only in the southern part of the study ar


LOWER LAKE QUAD.
CALISTOGA QUAD.
MIDDLETOWN
Sp
IVc(?)
Ia
76
37
38° 45'
122° 30'


A
B
C
3,000'
2,000'
1,000'
A LEVEL
SODA CREEK THRUST (?)
(Tithonian) Palyn
(Kl) Palyn
HARBIN MTN THRUST
BIG CANYON SYNCLINE
(Ku) Palyn
BIG CANYON FAULT
HOWARD SPRINGS STRUCTURE
(Tithonian) Palyn
SODA CREEK THRUST (?)
CHILDERS PEAK FAULT
(Ku) Palyn
(Ku) Palyn
SODA CREEK ANTICLINE
(Kl) Palyn
(Albian-Cenomanian?) Palyn
Sp
Ia
Ql
II
IVa
IVb
IVc
IVd
IVe
Qal
IIIc
Ib
IIIa(?)
T
IIIa
TQc
KJf


D
E
F
3,000'
2,000'
1,000'
LEVEL
(Kl) Palyn
HARBIN MTN THRUST
(Ku) Palyn
(Ku) Palyn
(Aptian) Palyn
Nostoceras (?) sp.
BIG CANYON SYNCLINE
BIG CANYON FAULT
CHILDERS PEAK FAULT
Inoceramus schmidti
Desmophyllites diphylloides
Buchia uncitoides
Buchia pacifica
SODA CREEK ANTICLINE
SODA CREEK THRUST
Buchia uncitoides
Buchia piochii
Buchia piochii
SODA CREEK THRUST
Sp
IVa
II
IVb
IVc
IVd
IVe
Qv
Tm
Ia
Ib
KJFt
KJfm



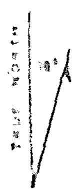
BOGGS MOUNTAIN
BIG CANYON SYNCLINE
BIG CANYON FAULT
Cockrell Canyon
Harbin Mtn
HARBIN SPRINGS THRUST
SODA CREEK
LINE OF CROSS-SECTION
HIGHWAY 29
HIGHWAY 53
MIDDLETOWN
LOWER LAKE QUAD.
122° 45'
38° 45'
0 1 2
MILES
Geology by Win Swe, 1967
TRUE NORTH
18°
CAL.

0 1 2

MILES

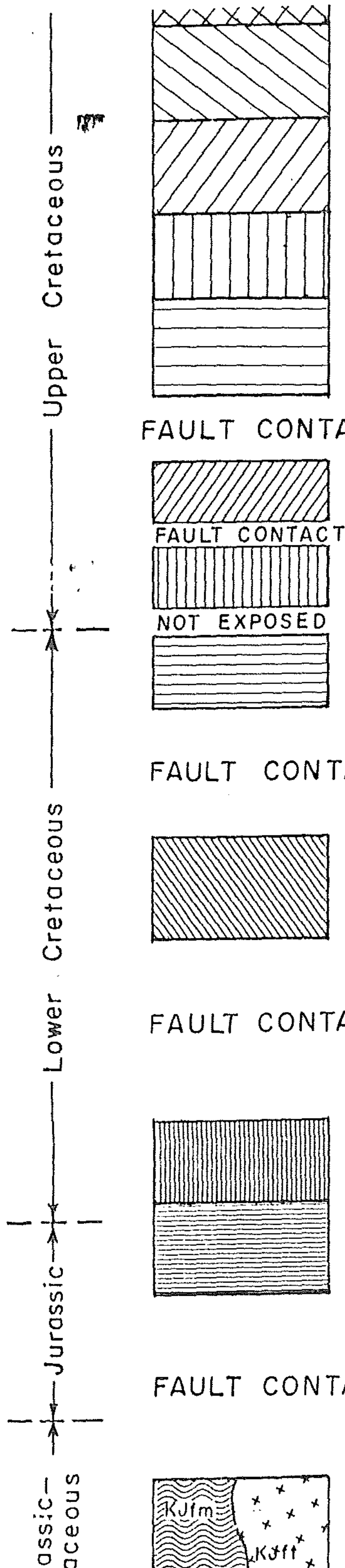
…e Map: *Parts of Lower Lake & Calistoga 15' Quadrangle topographic Maps of U.S. Geological Survey (1958).*

…gy by Win Swe, 1967



38° 45'

122° 30'



IVd *(Dominantly mudstone)*

IVc *(Dominantly sandstone)*

IVb *(Siltstone with some interbedded massive fine-grained white sandstone)*

IVa *(Dominantly massive feldspatho-lithic sandstone)*

Conformable Upper Cretaceous Succession; exposed discordant base is the Harbin Mountain Thrust

FAULT CONTACT

IIIc *(Dominantly massive litho-feldspathic, brownish weathering sandstone)*

FAULT CONTACT

IIIb *(Dominantly mudstone)*

NOT EXPOSED

IIIa *(Dominantly feldspathic, brownish to tan-weathering sandstone) with conglomerate lenses*

Isolated, fault-bounded exposures of "Mid"-Cretaceous strata (Upper Lower and/or Lower Upper Cretaceous)

FAULT CONTACT

II *(Mudstone with thin interbedded quartz-rich sandstone)*

Lower Cretaceous Strata

FAULT CONTACT

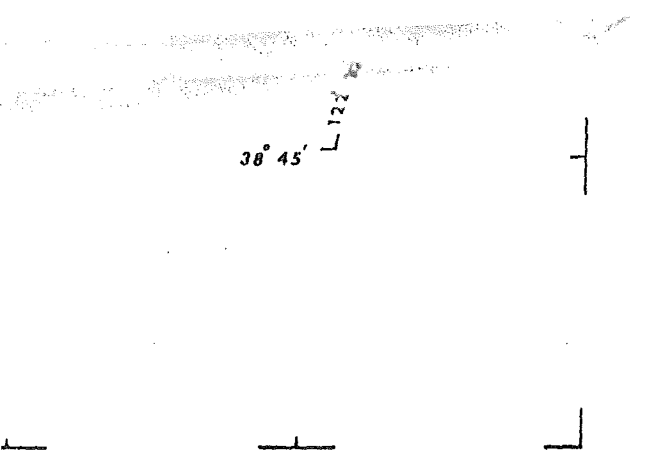
Ib *(Conglomerates and sandstone with some interbedded mudstone)*

Ia *(Dominantly mudstone with some lithic graywacke, thin-bedded chert associated with pillow lava present in lowest part)*

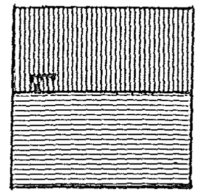
Conformable Upper Jurassic and Lower Cretaceous Succession; exposed discordant base is the Soda Creek Thrust.

FAULT CONTACT

FRANCISCAN ASSEMBLAGE *(Eugeosynclinal assemblage of diverse*



Jurassic



Ib (*Conglomerates and sandstone with some interbedded mudstone*)

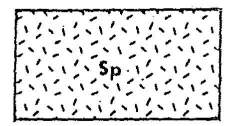
Ia (*Dominantly mudstone with some lithic graywacke, thin-bedded chert associated with pillow lava present in lowest part*)

Conformable Upper Jurassic and Lower Cretaceous Succession; exposed discordant base is the Soda Creek Thrust.

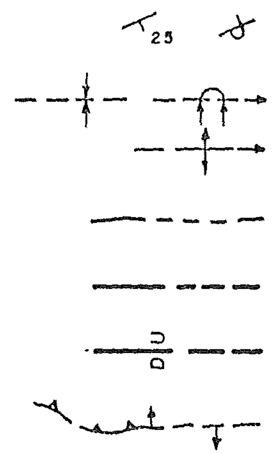
FAULT CONTACT

Jurassic—Cretaceous

FRANCISCAN ASSEMBLAGE (*Eugeosynclinal assemblage of diverse rock types including graywacke, shale, bedded chert, greenstone and low grade metamorphic rock) Separated into two units — metasedimentary rocks (KJfm) and tectonic breccia (KJft)*)



SERPENTINITES (*Includes related mafic and ultramafic rocks and their altered products*)



Dip and Strike, Overturned

Syncline, Overturned
Anticline
} Showing plunge

Stratigraphic contact

Fault displacement not known

Fault displacement shown

Folded thrust, dip <45° and >45°; arrow indicate dip and hachures denote upper plate

} Dashed where approximately located

Palyn = Palynomorph