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Evolution of the Late Cretaceous forearc basin, northern and central California

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ABSTRACT

The Upper Cretaceous part of the Great Valley Sequence of California provides a unique opportunity to study deep-marine sedimentation, petrologic evolution, and tectonic evolution of a forearc basin. Actualistic models of submarine fan sedimentation and arc-trench evolution provide the basis for unraveling the complex depositional history of the bathyal to abyssal sediment deposited between the Sierra Nevada volcano-plutonic arc to the east and the Franciscan subduction complex to the west. Submarine fan components are lenticular stratigraphic units which can be correlated along strike on the basis of both paleontologic and petrologic data. The following depositional components are present: basin plain, outer fan, midfan, inner fan, slope, and shelf. Vertical successions of fan facies associations constitute retrograding and prograding suites that correspond, respectively, to onlapping and offlapping relations in the basin. Sedimentation rates are similar to those of other tectonically active flysch basins. Paleocurrents are predominantly southerly and westerly in the Sacramento Valley, and predominantly westerly in the San Joaquin Valley. Microfossil evidence and the lack of carbonate material suggest deposition below the Late Cretaceous calcite compensation depth.

Dimensions and geometries of tectono-stratigraphic components of the Late Cretaceous arc-trench system are similar to those of modern arc-trench systems. The Late Cretaceous arc-trench gap widened by the prograde accretion of the Franciscan Assemblage (subduction complex) and the retrograde migration of the Sierra Nevada volcanic front (arc). Sediment dispersal systems expanded as the basin widened. The Java arc-trench system provides a modern analogue for the Late Cretaceous forearc basin, with sediment fed laterally from the arc and dispersed longitudinally along the basin axis.

INTRODUCTION

The plate-tectonics setting of California during the Late Cretaceous has been described by Dickinson (1970, 1974a, 1976), Ernst (1970), and Hamilton (1969), among others. In addition, many sedimentologic and petrologic studies have clarified stratigraphic, structural, and tectonic relations within the Great Valley Sequence (GVS) and among the GVS, Franciscan Assemblage, and Sierra Nevada magmatic complex (Dickinson and Rich, 1972; Lowe, 1972; Mansfield, 1971, 1972; Ojakangas, 1964, 1968; Perkins, 1974; Rich, 1968; Schilling, 1962; Swe and Dickinson, 1970; Tamesis, 1966). Nevertheless, unraveling of the complex depositional and tectonic history of this forearc basin has had to await sufficient study of modern arc-trench systems and deep-marine clastic environments so that actualistic models of such systems could be utilized (Ingersoll, 1975, 1976, 1978c; Ingersoll and others, 1977). Ojakangas (1964, 1968) suggested three possible models to explain sedimentary characteristics and dispersal patterns in the Sacramento Valley. Others (Lowe, 1972; Mansfield, 1971, 1972; Perkins, 1974; Shawa, 1970) attempted inferences concerning basin geometries and dispersal routes based on local

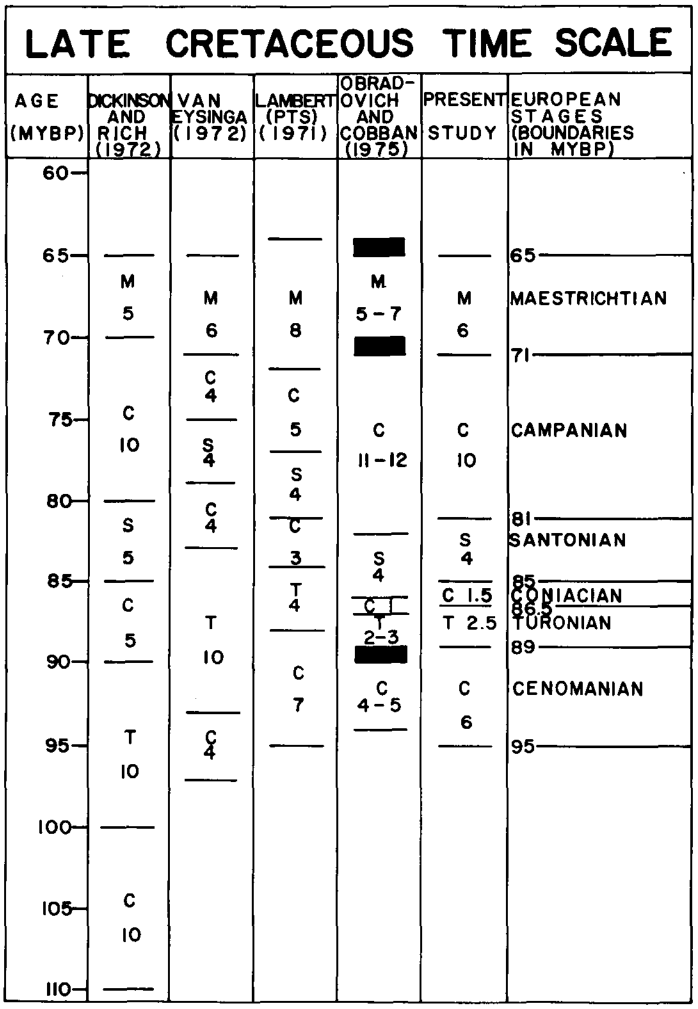

Figure 1. Comparison of some previously published time scales for the Late Cretaceous and the time scale used in the present study. The time scale used in the present study differs from that of Obradovich and Cobban (1975) by no more than 1 m.y. at any stage boundary.

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studies. One model of Ojakangas (I of his Fig. 11, 1968) is in accord with the conclusions of the present study.

TIME SCALE AND CORRELATIONS

A reliable radiometric time scale is essential if a coherent picture of volcanism, plutonism, metamorphism, and basin evolution is to be realized. Determination of a radiometric time scale for the Cretaceous involves numerous problems of correlation and reliability of dating methods (Baldwin and others, 1974; Van Hinte, 1976). Paleontologic correlations based on extrapolation of European molluscan stages to the deep-marine forearc environment of California involve many assumptions of continuity and age equivalence of diverse faunas. Moreover, the GVS contains few interbedded bentonite beds that are well suited for radiometric dating and has a scarcity of megafossils readily correlatable with those of Europe or the North American interior. As a result, microfossils usually provide the most reliable correlations within the GVS. Figure 1 contains four previously published time scales for the Late Cretaceous and the time scale adopted in the present study. Use of this time scale results in a consistent picture of sedimentary, metamorphic, and igneous events in northern and central California.

Extreme lenticularity of stratigraphic units characterizes the GVS, and classical correlation and naming procedures are difficult to apply over significant distances. On the other hand, stratigraphic divisions based on petrofacies have proven useful throughout the GVS (Dickinson and Rich, 1972; Ingersoll, 1978a; Ingersoll and others, 1977; Mansfield, 1971, 1972). The most useful lithologic mapping has utilized sandstone-to-shale ratios and bedding characteristics to differentiate depositional units (for example, Bailey and Jones, 1973; Brown and Rich, 1961; T. W. Dibblee, Jr., unpub. data; Mansfield, 1971, 1972; Rich, 1971) within larger petrostratigraphic units. Figure 2 is a correlation chart of stratigraphic and age-equivalent units within the study area.

Displaced faunas within the GVS have resulted in age designations that tend to be too old. The occurrence of Early Cretaceous fossils in Upper Cretaceous strata (Brown and Rich, 1960) is a classic example of this situation. Stratigraphic zonation has been improved through the use of planktic microfossils (Douglas, 1969; Pessagno, 1974). Goudkoff's (1945) provincial foraminiferal zones are based largely on benthic faunas that are known to be facies-controlled and time-transgressive (Douglas, 1969; Edmondson, 1962). Careful attention to accurate paleontologic correlations as well as utilization of "unconventional" lithologic criteria such as petrofacies (Dickinson and Rich, 1972; Ingersoll and others, 1977) facilitate the temporal and physical reconstruction of the tectonostratigraphic components of the GVS and related features.

SUBMARINE FAN FACIES ASSOCIATIONS

Facies analysis (Ingersoll, 1978b), correlations discussed above, and detailed lithologic maps (for example, Bailey and Jones, 1973; Brown and Rich, 1961; T. W. Dibblee, Jr., unpub. data; Mansfield, 1971, 1972; Rich, 1971) were used to construct schematic columnar sections at intervals along the GVS outcrop belts (Ingersoll and others, 1977, Pl. 2). Mutti and Ricci-Lucchi (1972, 1975), Ricci-Lucchi (1975a), and Ingersoll (1978b) have discussed the significance of vertical progressions of fan facies associations in terms of basin evolution and changing sea level. The ideal prograding sequence has the following vertical sequence of facies associations: basin plain–outer fan–midfan–inner fan–slope; whereas the ideal retrograding sequence is the opposite (Ricci-Lucchi, 1975a). Possible examples of prograding sequences in the GVS include: the Coniacian interval along Cache Creek, the Turonian interval on Nye Creek, the Venado on Cache Creek, Unit IVC in the Clear Lake area, the Coniacian-Santonian interval in the East Bay area, and Units KP V through KP VI along Del Puerto Creek. Possible examples of retrograding sequences include: the Turonian–lower Coniacian interval along Putah Creek, the entire Upper Cretaceous section along Stone Corral Creek, Units KP A through KP III along Del Puerto Creek, the Turonian interval in the San Luis Reservoir area, and the Cenomanian interval in the Panoche Hills area (see Pl. 2 of Ingersoll and others, 1977). The scale and details of the fan associations vary considerably in the above examples.

Prograding and retrograding sequences reflect the complex interplay of tectonic activity, sediment supply, and sea-level change. In general, prograding sequences correspond to offlapping relations in the basin, and retrograding sequences correspond to onlapping relations in the basin (Ricci-Lucchi, 1975a; Ingersoll, 1978b) regardless of the mechanisms causing these progressions. Prograding sequences show gradual changes in facies associations, whereas retrograding sequences tend to show marked changes, commonly with erosion of underlying sequences (Ricci-Lucchi, 1975a). Basin setting may control whether prograding or retrograding sequences predominate at specific localities. For instance, a prograding fan may appear in the stratigraphic record in a former basin plain setting, but there may be no record of this event near the former shoreline. In contrast, a fan that retrograded onto a former slope and shelf environment would preserve a record of this event, whereas the basin plain beyond the former fan fringe might not show any significant effect other than a decline in the frequency or size of turbidity deposits. In general, more proximal deep-marine environments contain more retrograding sequences, and more distal deep-marine environments contain more prograding sequences. These generalizations are based on the assumption that relative sea-level changes are sufficiently gradual that the slope-fan-basin plain system remains in dynamic equilibrium. If relative sea-level rise is too rapid, submarine canyons that feed fan systems may be cut off from their sediment sources in near-shore areas, and the fan system may be starved, with no retrogradational sequence preserved. If relative sea-level fall is too rapid or if the sediment supply increases dramatically, entirely new fan systems may develop in place of the gradually prograding older system.

In general, the GVS in the Sacramento Valley contains sediment deposited in more distal environments and a higher proportion of prograding sequences than does the GVS in the San Joaquin Valley (Ingersoll and others, 1977, Pl. 2; Figs. 3 through 6 of this paper). The Sacramento Valley GVS is characterized by association progressions such as: basin plain–outer fan–midfan-slope (prograding) and slope-inner fan-midfan–outer fan–basin plain–slope (retrograding followed by prograding slope). In contrast, the San Joaquin Valley GVS is characterized by: slope–inner fan–midfan-slope (retrograding followed by prograding slope). The primary cause of the differences in the sequences of the two parts of the Great Valley is that the present outcrop belts of the San Joaquin Valley are closer to presumed paleoshorelines (Figs. 3 through 6). The present outcrop belt of the GVS turns eastward more rapidly in a southerly direction than do the eastern limits of the strata, which are the presumed western possible locations of the paleoshorelines. This geometry and interpretation can explain four characteristics of the San Joaquin Valley GVS that contrast with those of the Sacramento Valley GVS: (1) Late Cretaceous facies associations are more proximal, (2) retrogradational sequences predominate over progradational sequences, (3) paleocurrent trends are more transverse and less longitudinal, and (4) the Lower Cretaceous and Jurassic parts of the GVS usually are not present in outcrop.

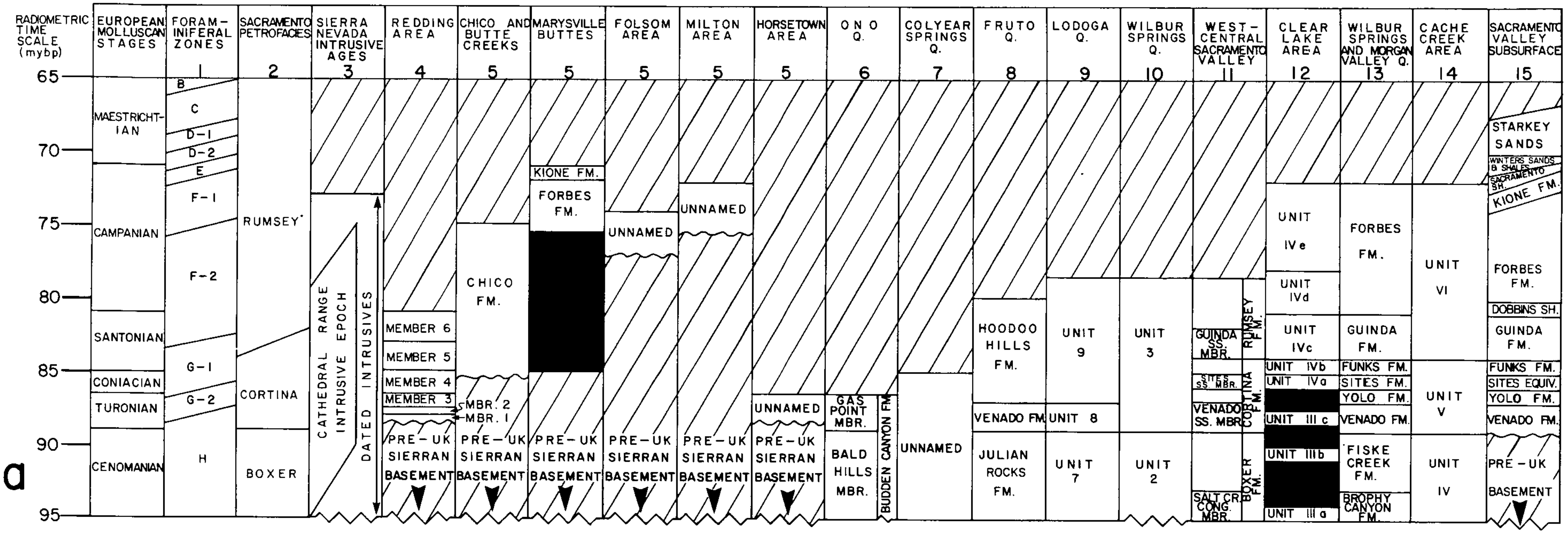
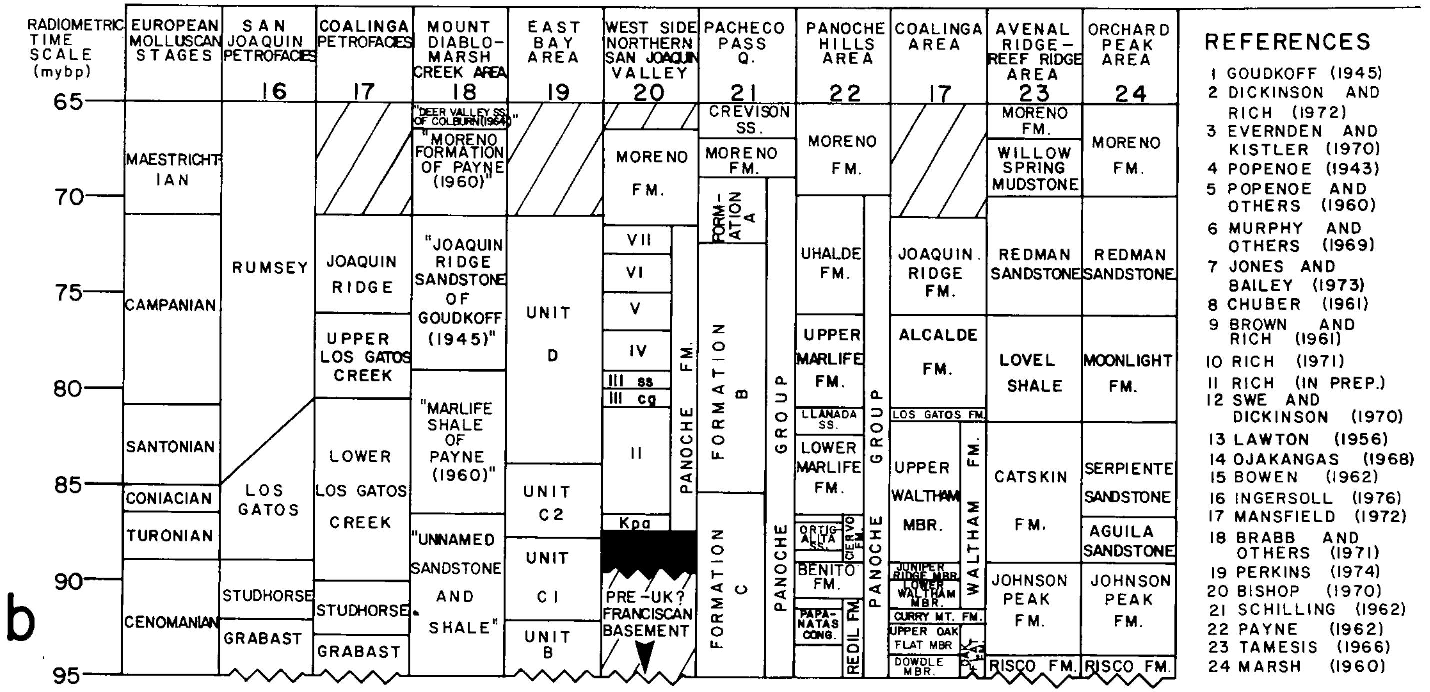


Figure 2. Correlation chart of the Upper Cretaceous part of the Great Valley Sequence and age equivalents. North is to the left for both the Sacramento Valley (a) and the San Joaquin Valley (b). Black areas indicate strata missing for tectonic reasons; slanted lines indicate strata missing due to nondeposition, erosion, or burial.



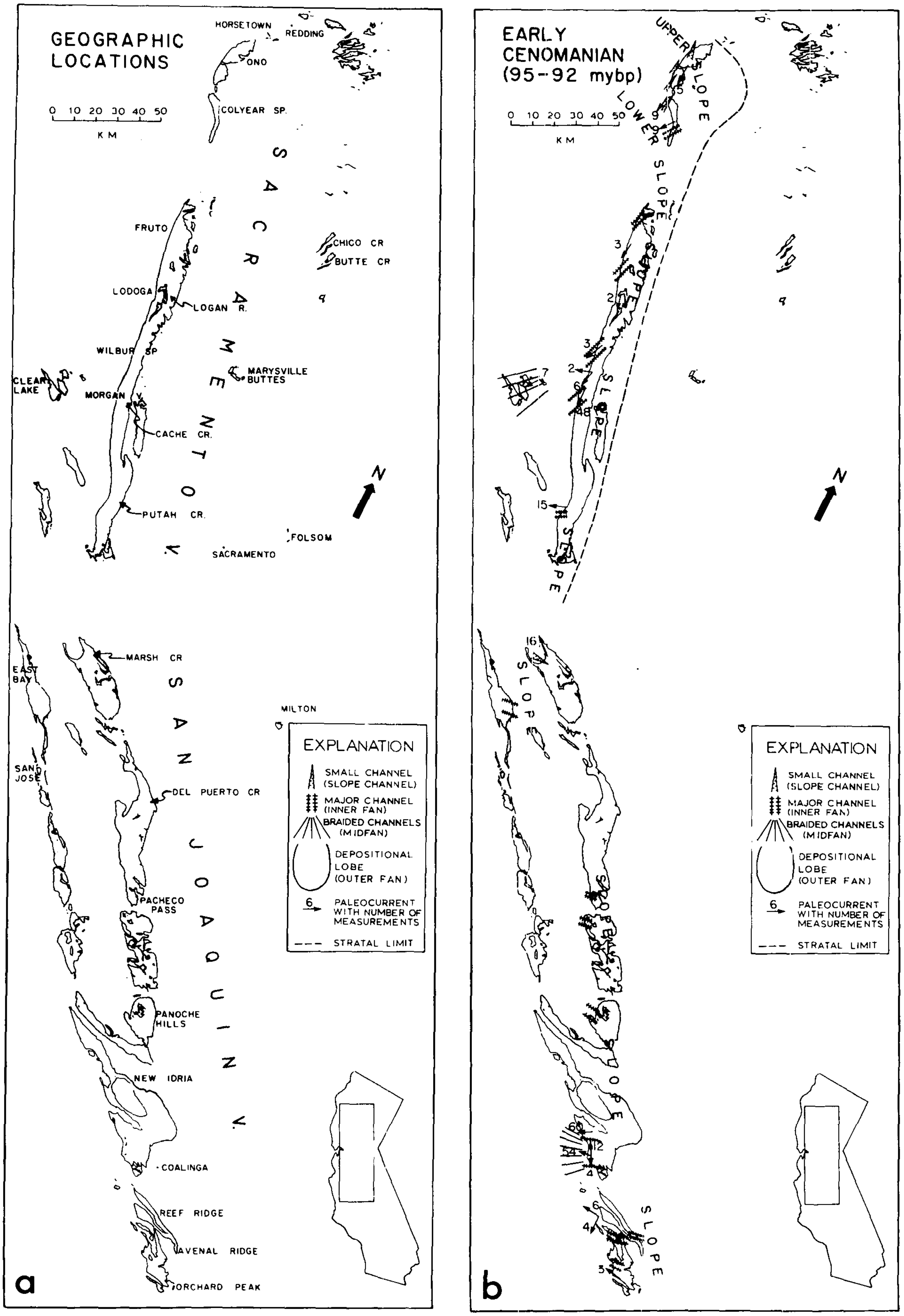


Figure 3. (a) Map showing geographic locations. Upper Cretaceous outcrops are delineated by solid lines. Stratal limits are determined by surface exposures as well as subsurface data from Bowen (1962, Pls. 5, 14, 15, 16, 17, 18). The Great Valley consists of the Sacramento Valley in the north and the San Joaquin Valley in the south. (b) Schematic paleogeographic map for the early Cenomanian.

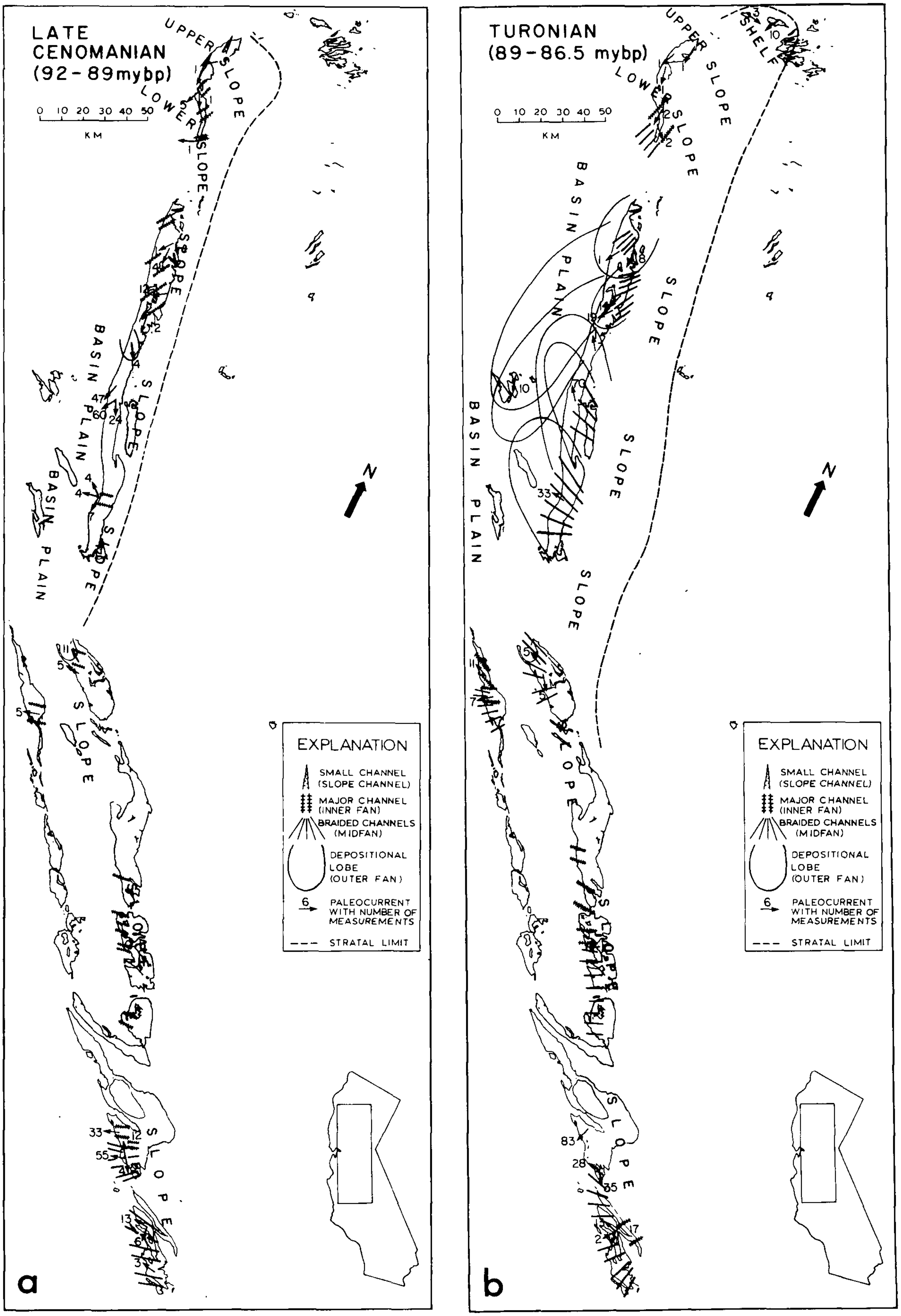


Figure 4. (a) Schematic paleogeographic map for the late Cenomanian. (b) Schematic paleogeographic map for the Turonian.

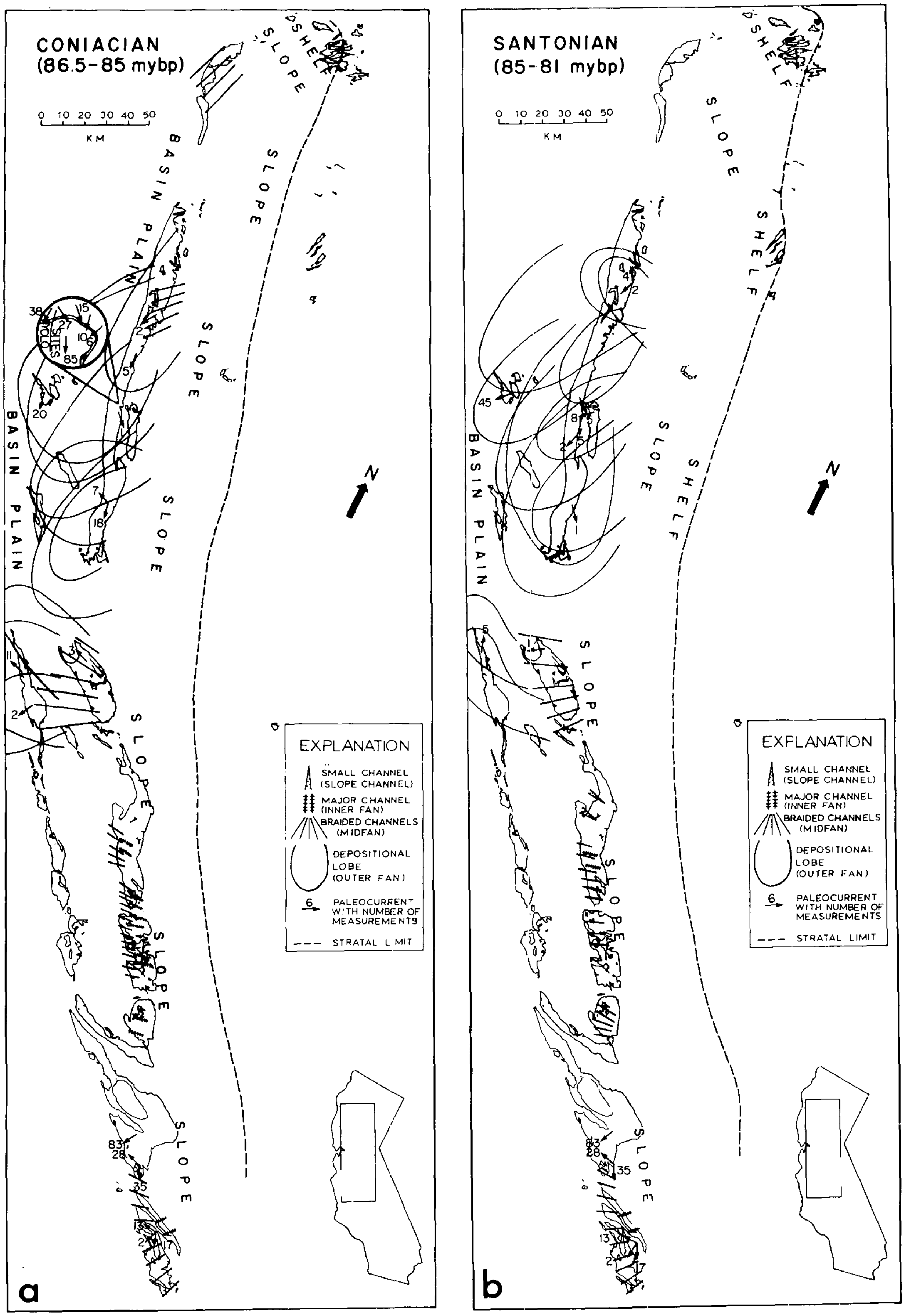


Figure 5. (a) Schematic paleogeographic map for the Coniacian. (b) Schematic paleogeographic map for the Santonian.

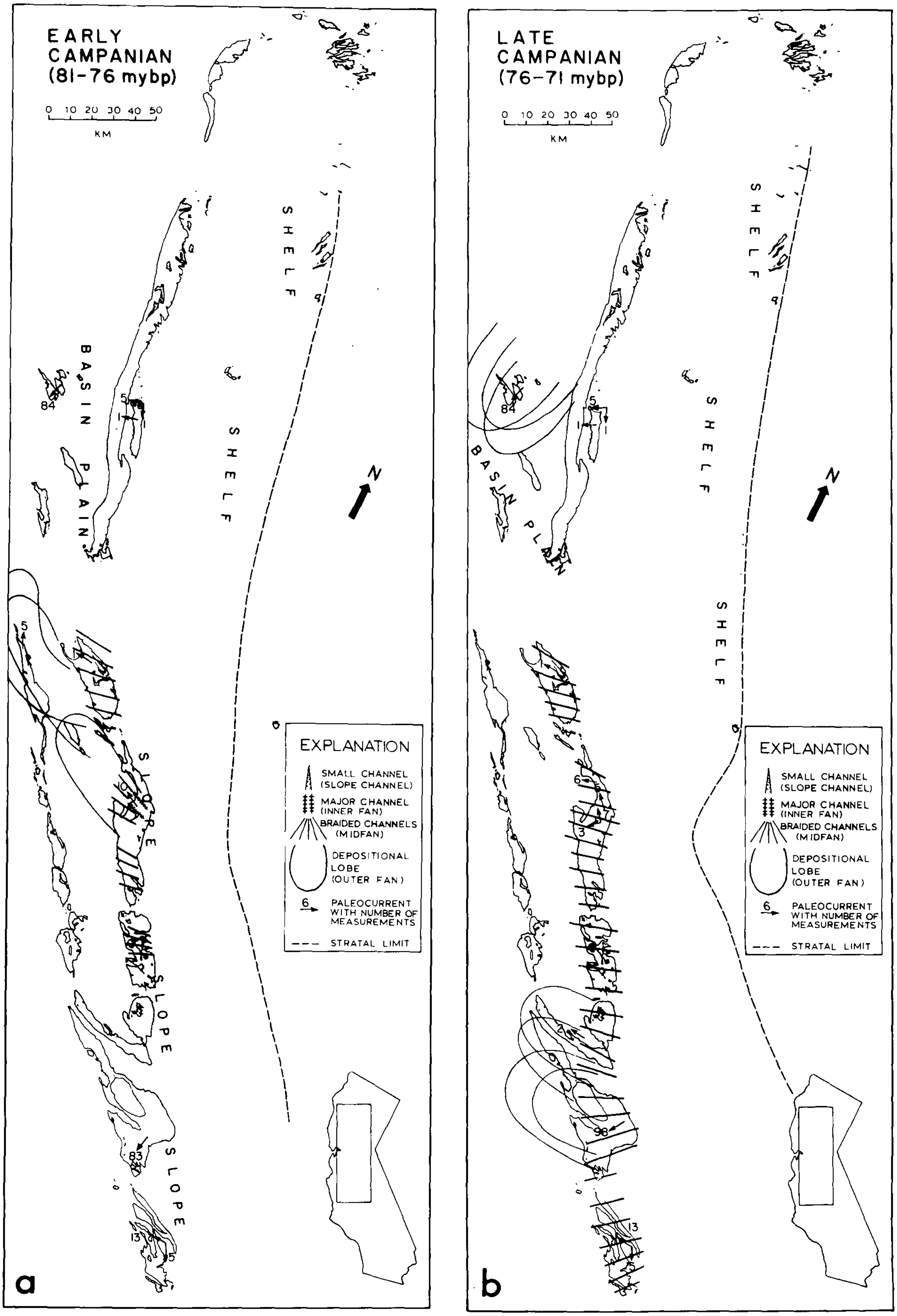


Figure 6. (a) Schematic paleogeographic map for the early Campanian. (b) Schematic paleogeographic map for the late Campanian.

SEDIMENTATION RATES

Average sedimentation rates (more properly termed net accumulation rates) for each facies association and for each European molluscan stage within the GVS (Tables 1 and 2) are similar to sedimentation rates calculated for flysch basins of the Apennines (Ricci-Lucchi, 1975b; Sagri, 1975). Compaction factors are ignored in both of these studies and in the present study. The average sedimentation rates for the GVS are highest for outer fan associations and lowest for shelf and slope associations (Table 1). The fact that sedimentation rates are higher for outer fan facies associations than for channelized facies associations (inner fan and midfan) supports the inferences that most sediment gravity flows traveled through channels before most deposition occurred, and that only unusually coarse detritus came to rest in the main channels. Relatively high sedimentation rates of basin plain associations suggest that most of the studied basin plain associations contain numerous fan fringe deposits, and that the basin plain was not starved. High sedimentation rates of overbank associations suggest that depositional fan channels predominated over erosional fan channels (following the usage of Normark, 1970), and that levee construction was an important component of fan sedimentation. Another factor that can cause such a high rate for these overbank deposits is that I use overbank in its broadest context in Table 1, and include considerable material deposited on inner fan and midfan surfaces as interchannel deposits. In any case, the high sedimentation rates of overbank associations confirm the importance of these facies in the development of fan geometries and in the filling of flysch basins.

Table 2 documents a general decrease in sedimentation rates following Turonian time. This trend may be explained by the increasing dimensions of the basin and individual fans from Coniacian through Maestrichtian time (Ingersoll, 1975, 1976; and Figs. 3 through 6). Wider dispersal of the available sediment resulted in a smaller vertical accumulation in the present outcrop belt of the GVS. Widespread retrogradation of fan systems (the predominant effect during the early Late Cretaceous), coupled with increasing fan and basin dimensions, resulted in increasing sedimentation rates along the outcrop belt (Cenomanian through Turonian) followed by a gradual decrease (post-Turonian, Table 2). The highest sedimentation rates occurred during the Turonian and Coniacian when depositional lobes were common in the outcrop areas, but before the basin had widened significantly. As the basin continued to widen after the Coniacian, a higher proportion of sedimentation probably occurred to the east in deltaic and shelf environments, thus lowering the rates along the outcrop belt. An additional factor that induced the gradual decline in sedimentation rates during the Late Cretaceous was the lessening of volcanic and plutonic activity during this time, resulting in a lowered total sediment supply to the basin (Ingersoll, 1978a).

PALEOCURRENT DATA

Ojakangas (1964, 1968) noted the predominance of south-directed paleocurrents within the Sacramento Valley GVS, but with more common west-directed paleocurrents in Turonian strata. However, paleocurrent studies of flysch sequences tend to be biased in favor of longitudinal paleocurrents because easily measured flute and scour marks are formed by true turbidity flows more easily than by liquefied flows or grain flows (Middleton and Hampton, 1973). Consequently, more easily measurable paleocurrent indicators occur more commonly in outer fan or basin plain associa-

TABLE 1. AVERAGE SEDIMENTATION RATES BY FACIES ASSOCIATION

Facies association	Total number of sections included	Total thickness (m)	Total elapsed time (m.y.)	Sedimentation rate (m/m.y.) or (mm/10^3 yr)
Shelf	4	1,400	7.75	181
Slope	21	14,410	69.25	208
Overbank	7	7,235	21.5	337
Inner fan	13	13,015	46.5	280
Midfan	23	22,185	83.75	265
Outer fan	17	14,440	34.0	425
Basin plain	12	7,110	22.5	316

Note: Original data for both Table 1 and Table 2 can be found in Ingersoll (1976, Table 19).

TABLE 2. AVERAGE SEDIMENTATION RATES BY STAGE

European molluscan stage (UK)	Total number of sections included*	Total thickness (m)	Total elapsed time (m.y.)	Sedimentation rate (m/m.y.) or (mm/10^3 yr)
Maestrichtian	9	6,250	32.0	195
Campanian	17	18,730	79.0	237
Santonian	21	14,725	55.0	268
Coniacian	19	16,645	46.75	356
Turonian	21	21,825	59.75	365
Cenomanian	26	22,820	84.50	270

* Some sections overlap stage boundaries and are included in more than one calculation. As a result, total thicknesses and total elapsed times from this table differ from those of Table 1.

tions than in more proximal associations where nonturbulent flow mechanisms are important (Ingersoll, 1978b). In addition, sole marks tend to be more visible on sandstone beds deposited in more distal environments because of the presence of interbedded mudstone that erodes easily, thereby exposing overlying soles in outcrop. Examination of the detailed location and facies association of each paleocurrent measurement from the GVS indicates that longitudinal paleocurrents (primarily from basin plain facies associations) apparently were less common during the Late Cretaceous than Ojakangas suggested. Late Cretaceous paleocurrent indicators point predominantly southward in the Sacramento Valley GVS and westward in the San Joaquin Valley GVS, but they exhibit considerable bimodality and local dispersion (Figs. 3 through 6). Significantly, eastward-directed paleocurrent indicators are absent.

Direction of pinch-out of sandstone or conglomerate bodies must be used cautiously as an indicator of source direction. The predominant accumulation areas for coarse-grained sediment are at the base of slopes or within channel complexes eroded into the lower slope. Fine-grained slope and outer shelf deposits commonly lie between this coarse-grained sediment and sources in near-shore environments. Source directions determined on the basis of changes in average grain size or sandstone-to-shale ratios are suspect unless it can be documented that individual sedimentation units or paleocurrent indicators show the same trends.

PALEOBATHYMETRY

The general scarcity and displaced nature of megafossils within the GVS have caused difficulty in both correlation and paleoenvironmental studies. However, recent work with the more abundant microfossils has resolved some of these problems. Most microfossil assemblages from the Upper Cretaceous GVS of the main outcrop belt are characterized by Radiolaria and arenaceous and calcareous benthic Foraminifera, but sparse planktic Foraminifera (Pessagno, 1974). Presumably, the scarcity of planktic Foraminifera indicates deposition below the Late Cretaceous calcite compensation depth (CCD), and the few observed calcareous Foraminifera were preserved due to rapid transport and burial by turbidity currents (Pessagno, 1974). Correlations based on these displaced fauna are misleading, at best. Pessagno (1974) suggested that the GVS microfossil assemblage indicates bathyal to abyssal accumulation depths (below the CCD). To test this hypothesis, the benthic Foraminifera reported in the GVS were examined in light of the bathymetric model for Cretaceous genera described by Sliter and Baker (1972).

All available published and unpublished lists of benthic Foraminifera from the Upper Cretaceous of the GVS were tabulated and grouped by stratigraphic position and geographic location. The resulting table (Ingersoll, 1976, Table 21) confirms deposition at bathyal to abyssal depths. All faunas from the main outcrop belt contain bathyal (usually lower bathyal) genera, and the only stratigraphic unit that contains no exclusively bathyal genera is the Crevision Formation, which probably was deposited at shelf depths (see discussion below). All of the stratigraphic units that contain no exclusively middle or lower bathyal fauna occur either in the Redding and Ono areas where water depths were shallower (see Figs. 3 through 6; and Jones and others, 1979), or in stratigraphic units from which only one of the genera of the model has been reported, either due to insufficient work or because dissolution has removed tests of all but the most resistant genera.

The benthic foraminiferal data and the microfossil assemblage suggest that deposition of most of the Upper Cretaceous of the GVS was below the Late Cretaceous CCD which Van Andel (1975) has calculated to be ~4 km. A 4-km depth near the present boundary between the Sacramento and San Joaquin Valleys would necessitate an average basin paleoslope of ~0.8° from there to the presumed paleoshoreline near Redding, a distance of ~300 km. This minimum average slope would be sufficient to cause the deflection of fan systems toward the center of the basin as well as to allow turbidity flows to travel great distances along the basin plain. Slopes of 5° to 10° from the east would be needed to accommodate shorelines within less than 50 km of the present outcrops during the early Late Cretaceous (Figs. 3 through 5). For instance, near Pacheco Pass and the Panoche Hills, the Cenomanian section contains numerous lenses of pebbly sandstone and conglomerate with clasts up to 50 cm that were probably deposited by debris flow mechanisms (Ingersoll, 1976, 1978b). The oldest strata that have been penetrated in the subsurface east of these outcrops are Coniacian beds that onlap basement (Figs. 3, 4a and 5a). Following the reasoning presented below, this requires that the Cenomanian shoreline was less than ~30 km east of the channel deposits which formed at depths greater than 4 km. This geometry requires a paleoslope of at least 8°, and likely quite higher, because the distance to the paleoshoreline is a maximum and the depth is a minimum. This slope is in excellent agreement with the minimum value of 9° calculated as necessary for the transport of part of the Juniper Ridge Conglomerate (see Lowe, 1976). Distance of subaerial transport of clasts may have been as much as 125 km, which is the distance from the outcrop belt to the Cenomanian volcanic front (Fig. 7).

PALEOGEOGRAPHIC MAPS

Figures 3 through 6 are schematic paleogeographic maps for approximately equal time intervals of the Late Cretaceous. Locations of major fan channel, channelized midfan, and outer fan depositional lobe complexes are shown as well as average paleocurrent directions, general environmental settings, and the eastern and northern limits of strata of each time period as determined from surface occurrences and published subsurface correlations. These eastern and northern stratal limits represent westernmost and southernmost limits, respectively, of paleoshorelines, assuming all preserved strata were deposited in or near marine environments. Dimensions of fan components shown on the paleogeographic maps suggest relative sizes of such features, but are generalized for the scale and time periods of the maps.

A Maestrichtian paleogeographic map was not constructed because of the scarcity of exposures and the predominance of slope and shelf deposits in exposed Maestrichtian sections. Progradation of muddy slope sediment capped by shelf sand was predominant during this time in the outcrop area (see Ingersoll, 1978c). The Deer Valley, Crevison, and Laguna Seca Formations of the San Joaquin Valley probably represent these capping shelf sediments.

The northern limit of the basin is north of the outcrops of shallow marine strata near Redding. Upper Cretaceous strata near Hornbrook, California, and in the Klamath Mountains of Oregon were deposited in a separate marine basin open to the northwest (Elliott, 1974; Ojakangas, 1964, 1968). The southern and, in part, western limits of the study area are determined by termination of the outcrop belt by the San Andreas fault zone. Right-lateral strike-slip offsets within the Clear Lake and East Bay areas probably are not sufficient to necessitate significant palinspastic reconstruction at the scale of Figures 3 through 6.

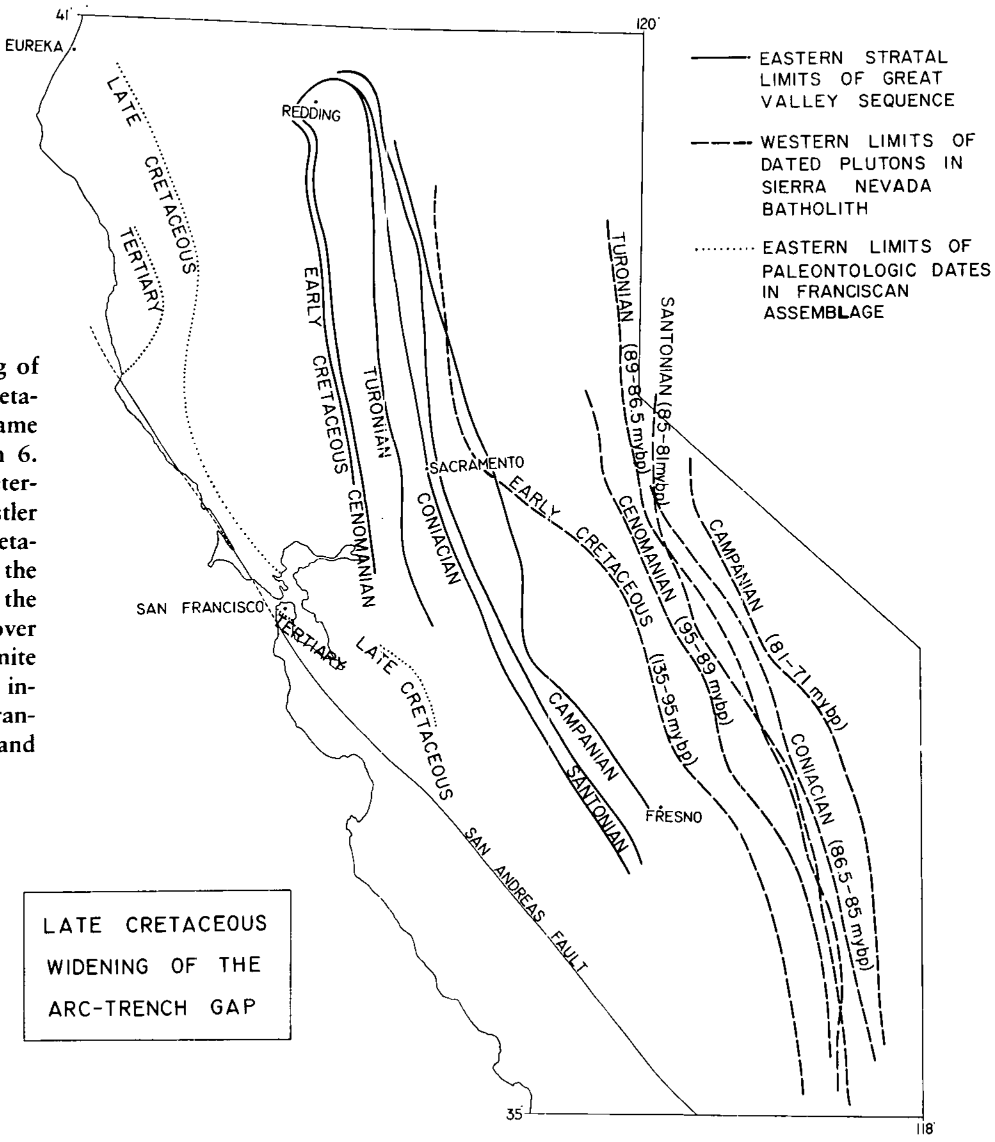


Figure 7. Map illustrating widening of the arc-trench gap during the Late Cretaceous. Stratal limits of the GVS are the same as those shown on Figures 3 through 6. Plutonic fronts (volcanic fronts) are determined by data from Evernden and Kistler (1970). The location of the Early Cretaceous plutonic front is controlled by the lack of exposures along the east side of the San Joaquin Valley where sediments cover the southern equivalents of the Yosemite and older part of the Huntington Lake intrusive epoch. Age limits within the Franciscan Assemblage are from Ingersoll and others (1977).

A major problem in construction of the paleogeographic maps is the scarcity of exposures that allow examination of east-west variations. The Clear Lake and East Bay areas are the only areas west of the main outcrop blet that have sufficiently good exposures and that have been studied sufficiently to yield significant paleoenvironmental information. Exposures of shallow marine Campanian and slightly older strata to the east and published subsurface data on primarily post-Turonian strata yield little information that helps resolve problems within the main outcrop belt.

Along the west side of the Sacramento Valley, the Cenomanian and Turonian strata are repeated in outcrop by the Sites anticline and the Fruto syncline. Recent lithologic mapping (Brown and Rich, 1961; Ingersoll and others, 1977) indicates that the base of the Venado Member (Turonian) in eastern exposures primarily consists of sandstone deposited in a channelized midfan setting. In contrast, the base of the Venado exposed within the Fruto syncline to the west contains lower sandstone-to-shale ratios, has more distal characteristics, and was deposited on the outer part of the same fan system as the eastern equivalents. Paleocurrent directions toward the southwest support this interpretation (Fig. 4b). This is one of the few locations where three-dimensional stratigraphic relations are clearly exposed.

The action of contour currents has been invoked by Ojakangas (1964, 1968) and Shawa (1970) as a possible explanation for the predominance of southward-directed paleocurrents in the Sacramento Valley and for the presence of paleocurrent directions perpendicular to the predominant westward transport directions in the San Joaquin Valley. A more likely explanation for the southward-directed paleocurrents, as suggested above, is the presence of a trough sloping southward from the area of Redding to the south end of the Sacramento Valley. Paleocurrent directions perpendicular to the predominant flow direction are explained best by the action of overbank processes near channels (Colburn, 1971; Lowe, 1973). The present study has found no evidence suggesting the presence of contourites within the GVS. In fact, strong contour currents are uncommon on the eastern margins of the Pacific Ocean, as oceanic circulation is less constricted than along the western margins (Bouma and Hollister, 1973). If contour currents were present along the eastern margins, they would be flowing northward (opposite to surface currents), not southward! Southward deflection of fan components and paleocurrents within the Sacramento Valley probably was accomplished both by the regional slope to the south and by the Coriolis deflection of fan channels to the left in the northern hemisphere (Nelson and Nilsen, 1974).

With the development of wider shelves during the late Late Cretaceous, more sediment accumulated in shallow water before traveling through submarine canyons and fan systems. As a result, the average size of individual gravity flows may have increased during the Late Cretaceous along with average fan and canyon dimensions. In the early part of the Late Cretaceous, the lack of significantly wide shelves may have prevented the formation of deeply incised canyons and, therefore, resulted in a large number of smaller fan systems that migrated rapidly. By Campanian time, numerous canyons probably had incised the shelf and slope, thus localizing sediment sources and favoring the building of broader fans that remained relatively fixed through time.

MODERN BASIN ANALOGUES

Geometry and dimensions of the Java arc-trench system (Hamilton, 1974) probably closely resemble those of the Late Cretaceous of California. Back-arc areas of the two arc-trench systems differ in that the Java back-arc area is completely submerged by shallow seas, whereas the California back-arc area probably had an Andean-type setting with shallow seas farther to the east (Dickinson, 1976). However, both of the arcs are continental margin arc-trench systems (Dickinson, 1974b; Dickinson and Seely, 1979; Ingersoll, 1978c; Ingersoll and others, 1977). The Java system contains an active volcanic arc, a deep forearc basin, an outer-arc ridge (that is exposed above sea level only in the Sumatra arc-trench system to the north where sediment supply to the trench is greater), and an actively subducting trench (Hamilton, 1974). Bathymetric depths of the Java forearc basin exceed 4 km, and stratigraphic thicknesses within the basin exceed 6 km (Hamilton, 1974). The bathymetric basin is elongate and segmented by bathymetric ridges. These smaller basins are bordered on the north (toward the arc) by steep slopes and shelves of varying widths. Each basin plain within the basin axes shallows gradually to the east and west. This trough geometry favors introduction of sediment laterally from the north and dispersal of sediment longitudinally to the east and west, toward the basin centers. The forearc basins of the Java system are between 100 and 200 km wide and between 500 and 1,000 km long (Hamilton, 1974).

Modern arc-trench gaps widen with time by the prograde accretion of subducted material above and behind the trench, and by the retrograde migration of the volcanic arc away from the trench (Dickinson, 1973). Karig and Sharman (1975) and Dickinson (1975) discussed the nature of the tectono-stratigraphic contact between the subduction complex and the undeformed sediment of the forearc basin. As the accretionary prism builds upward and outward, the forearc basin sediment onlaps the tectonically stable flank of the subduction complex near the trench-slop break. Periodic reactivation of thrusts within this area causes deformation of the base of the onlapping sediment so that the contact between the subduction complex and the forearc basin sediments has both depositional and tectonic characteristics (Dickinson, 1975). Forearc basins of modern arc-trench systems tend to evolve from steep-sloped, narrow zones with little sediment accumulation to wider and shallower basins within which great sedimentary thicknesses accumulate (Karig and Sharman, 1975). As the forearc basin widens, most sediment derived from the arc is deposited within the arc-trench gap, with little reaching the trench. Eventually, the forearc basin may be filled to near sea level, and arc-derived sediment again may be deposited primarily within the trench or within trench-slope basins (Moore and Karig, 1976). This latter situation is more likely to occur within continental margin arc-trench systems with high rates of sediment supply than in island-arc systems with low rates. The Java arc-trench system probably has intermediate rates of sediment supply to the arc-trench gap. The tectonic boundary between the forearc basin and the arc terrane has been termed the upper slope discontinuity (Karig and Sharman, 1975), and is a zone of weakness that usually consists of nearly vertical faults along which sediment of the forearc basin may be deformed. Presumably, the upper slope discontinuity marks the location of the former continental margin that existed before subduction was initiated (Karig and Sharman, 1975).

LATE CRETACEOUS BASIN TECTONICS

All of the features of modern arc-trench systems described above also characterized the Late Cretaceous arc-trench system of northern and central California. The Franciscan Assemblage (the subduction complex) contains evidence of prograde accretion throughout the late Mesozoic with westward decreases in age, degree of deformation, and grade of metamorphism (Blake and Jones, 1974; Blake and others, 1967; Cowan, 1974; Dickinson, 1975; Evitt and Pierce, 1975; Ingersoll, 1975, 1978c; Ingersoll and others, 1977). The Great Valley Sequence (sediment of the forearc basin) was deposited in a widening basin, which was bordered on the west by a presumably time-transgressive thrust contact with the subduction complex, and which onlapped arc terranes to the east (Dickinson, 1975; Ingersoll, 1975, 1978c; Ingersoll and others, 1977). The western limit of plutonism and, presumably, related volcanism of the Sierra Nevada batholith (the magmatic arc) migrated eastward (retrograde migration) during the Late Cretaceous (Evernden and Kistler, 1970; Ingersoll, 1975, 1976, 1978c; and Fig. 7). The boundary between the base of the GVS and Sierra Nevada basement is hidden beneath younger GVS strata, but, by inference, locally may have the characteristics of an upper slope discontinuity (high-angle reverse or normal faulting, and juxtaposition of magmatic arc terrane with oceanic basement and overlying sediment) (Ingersoll, 1978c; Ingersoll and others, 1977). The present location of this feature may correspond to the magnetic and gravity anomalies underlying the Great Valley (Cady, 1975).

Figure 7 illustrates the Late Cretaceous widening of the forearc basin by the prograde accretion of the Franciscan Assemblage and the retrograde migration of the volcanic front (represented by the plutonic front of the Sierra Nevada batholith). Eastern limits of GVS strata (from Figs. 3 through 6) show an eastward migration paralleling the migration of the volcanic front. The sea apparently transgressed eastward as the recently inactivated western part of the arc cooled, subsided, and was eroded. Eustatic sea-level rise during the Late Cretaceous probably increased the extent of transgression but cannot by itself explain the several kilometres of post-Turonian sediments deposited eastward of the eastern limit of Turonian sediments (for example, see Bond, 1976). Tectonic complexities and difficulties in dating make construction of Upper Cretaceous stage limits within the Francisacan Assemblage impossible. Therefore, only the eastern limits of Tertiary fossils and Late Creta-

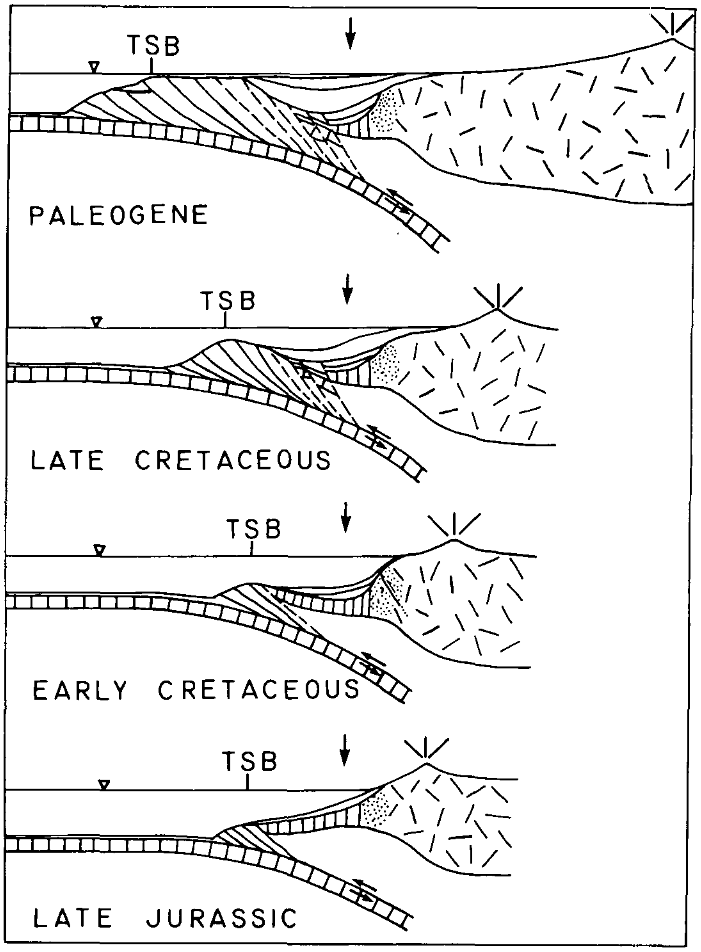


Figure 8. Schematic cross sections of the late Mesozoic forearc area of northern and central California. Vertical arrows indicate location of present outcrops along west side of the Sacramento Valley. These are used as a fixed reference point for successive cross sections. Dotted patterns represent the upper slope discontinuity. TSB is the trench slope break. Volcanoes show the location of the volcanic front. Note that little arc-derived sediment reached the trench during the Cretaceous (after Ingersoll, 1978c).

ceous fossils are shown on Figure 7. The time of the widest extent of the forearc basin (Late Cretaceous) was probably the time during which accretion of arc-derived material into the Franciscan Assemblage was slowest (Ingersoll, 1978c); consequently, the Late Cretaceous and Tertiary limits within the Franciscan are close to each other in Figure 7. Thus, during the Late Jurassic, much of the sediment derived from the arc likely was deposited in the trench or in basins near the trench-slope break that were subsequently incorporated into the subduction complex. As this subduction wedge grew, a bathymetric ridge (outer-arc ridge) prevented most of the arc-derived sediment from reaching the actively deforming part of the subduction complex, and the forearc basin sediment thickened more rapidly. Eventually, the forearc basin filled to near shelf depths, and arc-derived sediment again was able to traverse the arc-trench gap and be incorporated into the subduction complex, by the latest Late Cretaceous or Paleogene in most locations (Ingersoll, 1978c). Figure 8 contains suggested schematic cross sections for different stages of evolution of the late Mesozoic-Paleogene arc-trench system.

The present study suggests that apparent stratigraphic discontinuities within the Upper Cretaceous of the GVS (Brown and Rich, 1967; Lowe, 1972; Peterson, 1965, 1967a, 1967b) were formed by sedimentary processes and are more apparent than real. There is no evidence within the GVS for a major depositional discontinuity during the Late Cretaceous, although relative changes in sea level and tectonic movement along the basin margins may have triggered changes in the deep-marine sedimentary systems of the forearc basin. Controversy regarding the meaning of apparent strike-slip and possibly reverse faulting near the north end of the Sacramento Valley during the Early Cretaceous (Ingersoll, 1978c; Ingersoll and others, 1977; Jones and Irwin, 1971; Jones and others, 1969) might be resolved by a detailed basin and facies analysis study of the Jurassic and Lower Cretaceous parts of the GVS.

DISCUSSION

The present study demonstrates the value of actualistic sedimentary and tectonic models in deciphering the complex history of ancient arc-trench systems. Through careful application of these models and analysis of tectonic, structural, paleoecologic, stratigraphic, sedimentologic, and petrologic relations, it is now possible to document the history of this forearc basin from its inception in the Late Jurassic following arc-arc collision (Schweickert and Cowan, 1975), through the widening and filling of the basin during the Cretaceous and Paleogene (Dickinson and Seely, 1979; Ingersoll, 1978c), and into the Neogene termination of subduction by the migration of a triple junction along the coast (Atwater, 1970). The forearc basin of northern and central California is the most thoroughly studied and best understood ancient basin of its type in the world. This knowledge should prove useful in studies of similar basins.

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