

Tertiary Paleoclimatic Trends in the San Joaquin Basin, California

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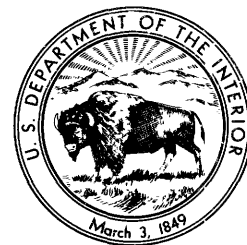
Tertiary Paleoclimatic Trends in the San Joaquin Basin, California

By WARREN O. ADDICOTT

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

GEOLOGICAL SURVEY PROFESSIONAL PAPER 644-D

*Distributional patterns of shallow-water
molluscan genera reflect Eocene and
Miocene episodes of warm marine climate
separated by a middle Oligocene climatic
deterioration*



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CONTENTS

	Page		Page
Abstract	D1	Discussion—Continued	
Introduction	1	Gaps in the record	D11
Paleogeographic setting	2	Middle Oligocene anomaly	12
Paleoclimatic analysis	4	Eocene amelioration	13
Eocene	7	Climatic change and extinction	13
Oligocene	7	Other California basins	14
Miocene	8	Oregon and Washington	14
Pliocene	10	Paleoclimatic inferences from Foraminifera	15
Discussion	11	Summary and conclusions	16
Sample size	11	References	16

ILLUSTRATIONS

		Page
FIGURE 1.	Index map showing physiographic features of central California	D2
2.	Maps showing Oligocene and Miocene paleogeography of the San Joaquin basin	3
3.	Map showing modern shallow-water molluscan provinces of the marginal northeastern Pacific Ocean	4
4.	San Joaquin basin zoogeographic profiles	5
5.	Santa Cruz basin and southern Coast Range zoogeographic profiles	9
6.	Graph showing middle Oligocene latitudinal faunal gradient	12
7.	Idealized zoogeographic profiles for the San Joaquin basin	13

TABLES

		Page
TABLE 1.	Faunal data	D6
2.	Extralimital warm-water molluscan genera	6

TERTIARY PALEOCLIMATIC TRENDS IN THE SAN JOAQUIN BASIN, CALIFORNIA

By WARREN O. ADDICOTT

ABSTRACT

Early and middle Tertiary molluscan faunas of the middle latitudes of the northeastern Pacific are characterized by taxa now living in tropical and subtropical latitudes far to the south. Unusually large percentages of warm-water molluscan genera in Eocene and Miocene faunas of the San Joaquin basin, California (lat. 35°–36.5° N.), reflect episodes of Tertiary marine climate substantially warmer than at present. Sharp decreases in warm-water genera and in taxonomic diversity during the middle Oligocene seem to represent an intervening climatic deterioration. Parallel faunal trends occur in other Tertiary basins of the California Coast Ranges.

INTRODUCTION

The San Joaquin basin (fig. 1), roughly coincident with the southern third of the Great Valley of California (lat 35°–36.6° N.), has the most complete sequence of shallow-water marine molluscan faunas of the Pacific Coast Tertiary. These central California faunas have been the subject of intensive paleontologic study during the past 60 years. Thus, they are particularly well suited for zoogeographic-based study of Tertiary climatic change in the near-shore marine environment.

Lower Tertiary molluscan faunas are well developed along the west side and the south margin of the San Joaquin basin. Oligocene and Miocene molluscan assemblages occur around the south and southeast margin of the basin. Late Miocene and Pliocene faunal succession is best developed in the northwestern part of the basin near Coalinga.

Tertiary molluscan faunas of central and southern California include a persistent element of taxa now living in warm-water regimes far to the south. During the late Pliocene and Pleistocene this warm-water element is defined by species occurring far north of their modern distributional limits; during the Miocene and older parts of the Tertiary, it is identified at higher taxonomic levels because of high percentages of extinct species. Mollusks constituting the warm-water element are referred to as extralimital taxa.

The first students of west coast Tertiary marine climate (Arnold, 1909a; Smith, 1910) noted a decrease of warm-water elements following the diverse, cosmopolitan faunas of the Eocene and thereby inferred progressively cooling post-Eocene marine climate. Extralimital late Cenozoic molluscan taxa are mostly from the warm-temperate Californian molluscan province (lat 28°–34.5° N.), whereas early and middle Cenozoic faunas include many taxa now restricted to subtropical and tropical molluscan provinces farther to the south. This concept went through two stages of refinement (Smith, 1919, and Durham, 1950) but remained essentially unchanged from Arnold's original inference. Studies of marine climate of specific parts of the California Tertiary based upon marine mollusks have been made by Dickerson (1913; 1917), Barbat and Galloway (1934), Vokes (1940), Woodring, Stewart, and Richards (1940), Woodring and Bramlette (1950), Hall (1960, 1962a), and Addicott and Vedder (1963). Other workers have commented on the climatic implications of individual molluscan faunas. Recent studies of mid-Tertiary San Joaquin basin faunas (Addicott and Vedder, 1963; Addicott, 1965, 1970; DeLise, 1967) and work in progress now permit more refined analysis of mid-Tertiary molluscan assemblages. From these new faunal data a reversal of the post-Eocene cooling trend, with warming during the beginning of the late Oligocene and a peak in the middle Miocene, has been recently identified (Addicott, 1968a). The purpose of this report, then, is to document climatically controlled changes in middle and late Tertiary molluscan zoogeography of the San Joaquin basin. This analysis does not permit assignment of specific temperature values to the fossil faunas such as oxygen isotope studies do. Accordingly, emphasis is placed upon identification of relative change in the shallow-water climatic regime as reflected by distributional patterns of Tertiary mollusks.

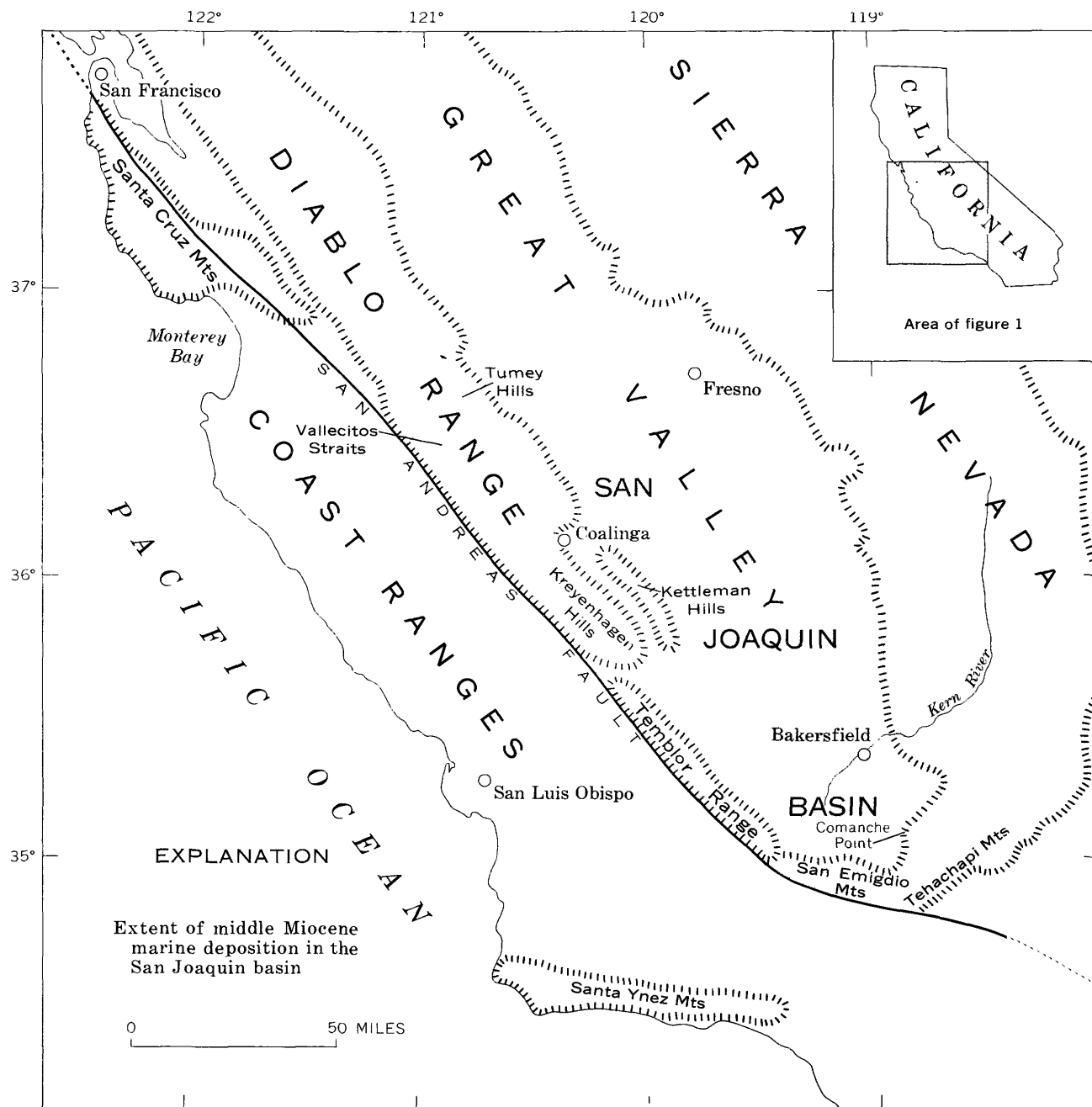


FIGURE 1.—Index map showing physiographic features of central California referred to in text.

PALEOGEOGRAPHIC SETTING

The San Joaquin basin, centered in the southern part of the Great Valley of California, is today separated from the Pacific Ocean by the central California Coast Ranges, which average about 40–50 miles in width. During the Tertiary the basin was connected to the Pacific along much of its west margin, now approximately defined by the San Andreas fault. The relationship to Coast Range geology to

the west has been obscured, however, by subsequent diastrophic movement along the San Andreas fault, notably large cumulative right-lateral slip (Hill and Dibblee, 1953).

Following the broad inundation by Late Cretaceous seas, the San Joaquin basin formed a narrow, kidney-shaped embayment during the Paleocene and early part of the Eocene. During this part of the early Tertiary, the basin was connected to the ocean

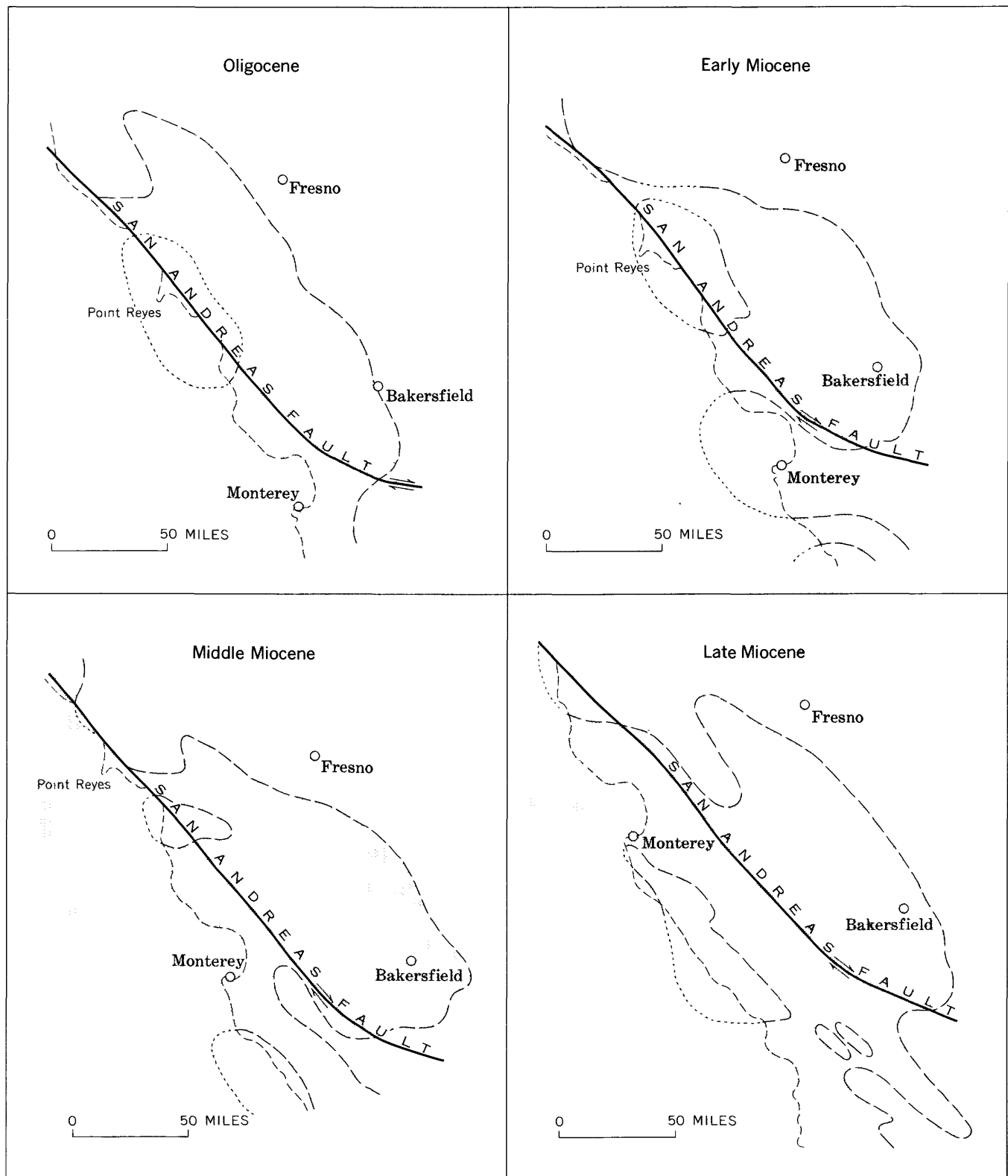


FIGURE 2.—Oligocene and Miocene paleogeography of the San Joaquin basin prior to lateral displacement on the San Andreas fault. Pattern indicates area of deposition.

by a narrow passage northwest of Coalinga, the Vallecitos Straits of Hoots, Bear, and Kleinpell (1954). A major marine transgression occurred in the later part of the Eocene; the basin was broadened and deepened. It presumably had a broad oceanic connection on the west margin, suggested by the marine upper Eocene strata which are now truncated by the San Andreas fault (from the Tehachapi Mountains northwestward to the middle part of the Diablo Range (Repenning, 1960)).

The sea withdrew from most of California during the Oligocene, giving way to extensive nonmarine deposition, but a narrow marine basin remained in the southernmost part of the Great Valley. Seaward connections at the ends of the linear Oligocene depositional basin are indicated by the apparent truncation of marine Oligocene strata along the San Andreas fault (Addicott, 1968b). A transgressive cycle reinitiated during the late Oligocene foreshadowed broad expansion of Miocene seas in the southeastern part of the basin. Oceanic connections during this period were principally along the southwestern part of the basin. Lake Miocene orogeny in the Coast Range area gave rise to the Temblor Range, diverting the Pliocene oceanic connection northward to what is now the southern part of the Diablo Range southwest of Coalinga. The basin shoaled during the Pliocene; brackish water conditions that developed during the later part of the epoch were followed by nonmarine deposition during the Pleistocene.

Restoration of Oligocene and Miocene paleogeography, in keeping with postulated cumulative right-lateral slip along the San Andreas fault (Hill and Dibblee, 1953; Addicott, 1968b; Grantz and Dickinson, 1968), suggests that the San Joaquin basin was bordered on the west through most of the Tertiary by insular and peninsular masses (fig. 2). Nevertheless, the basin seems to have been an open deepwater marine embayment during the Oligocene and Miocene, according to bathymetric inferences from benthonic foraminiferal assemblages in its central and western parts (Bandy and Arnal, 1964, 1968, 1969). Adjoining basins west of the San Andreas fault were at least as deep as the upper part of the bathyal zone during the Oligocene (Brabb, 1964) as well as throughout most of the Miocene (Cummings and others, 1962). Thus, there is no reason to suspect that the tropical aspect of Miocene molluscan faunas could have been caused by abnormal warming of the basin owing to shallow-water or silled conditions. Moreover, evidence from other California basins and Tertiary sequences around the Pacific rim, discussed

subsequently, indicate that the Miocene warming was an oceanwide phenomenon.

PALEOCLIMATIC ANALYSIS

The premise of this study is that paleoclimatic inferences can be made by interpreting the composition of fossil assemblages in the light of modern molluscan zoogeography. The modern latitudinal gradient along the Pacific Coast of North America, expressed by a series of distinctive molluscan provinces (Valentine, 1966), provides a convenient frame of reference for evaluating zoogeographic change in Tertiary faunas. As indicated earlier, middle-latitude Tertiary benthic invertebrate faunas include a significant proportion of warm-water taxa that live today in low latitudes of the eastern Pacific. The object of this investigation is to quantitatively determine changes in the proportion of this warm-water element in successive Tertiary molluscan faunas.

Zoogeographic-based paleoclimatic analyses of fossil assemblages necessarily assume that constituent taxa have not subsequently changed their tem-

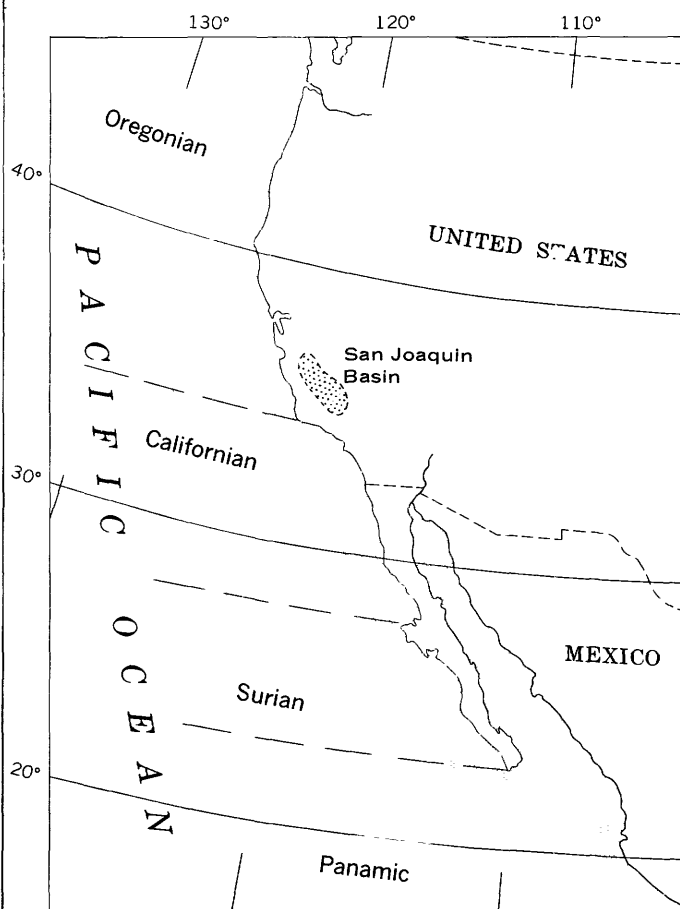


FIGURE 3.—Modern shallow-water molluscan provinces of the marginal northeastern Pacific Ocean.

perature tolerance. The composition of Tertiary fossil assemblages generally seems to bear this out— assemblages usually can be readily categorized as of warmer or cooler aspect than the modern fauna of the same latitude. Sometimes, however, there are anomalous occurrences of one or more warm-water mollusks in assemblages composed of temperate mollusks, or vice versa, suggesting that some taxa may have had different temperature tolerances in the past. It is important, therefore, to utilize an entire fauna, rather than individual taxa, in making paleoclimatic inferences. Accordingly, a simple means of characterizing the composition of Tertiary molluscan faunas of warm-water aspect has been devised. Warm-water elements are expressed as percentages to permit comparison of faunas of differing size. Faunal assemblages included in this analysis are believed to have inhabited the higher reaches of the inner sublittoral zone, depths of less than 15 fathoms.

The procedure is to classify each molluscan genus

in a fauna according to the modern zoogeographic province (fig. 3) in which its north end point of range occurs. Classification is based on range data mainly from Burch (1944–46), Smith and Gordon (1948), Fitch (1953), Keen (1958; 1963), and Olsson (1961). From these data, percentages of genera now restricted to warm-water molluscan provinces—Panamic (6°S – 23°N), Surian (23°N – 28°N), and Californian (28° – 34.5°N)—are readily determined. Genera that are extinct or are no longer living in the northeastern Pacific Ocean are excluded.

Cumulative percentages of warm-water genera have been plotted on a time scale (fig. 4) based upon the Pacific Coast megafaunal “stages” of Weaver and others. (1944). Boundaries on the chart have been adjusted in consideration of available radiometric ages on volcanic rocks interbedded in the California marine sequence. These are mainly from Turner (1968a, b); other dates are from Bandy (1967a), Clark (1966), Ingle (1967), Obradovich (1968), and Yeats (1965). Plotting values as cumu-

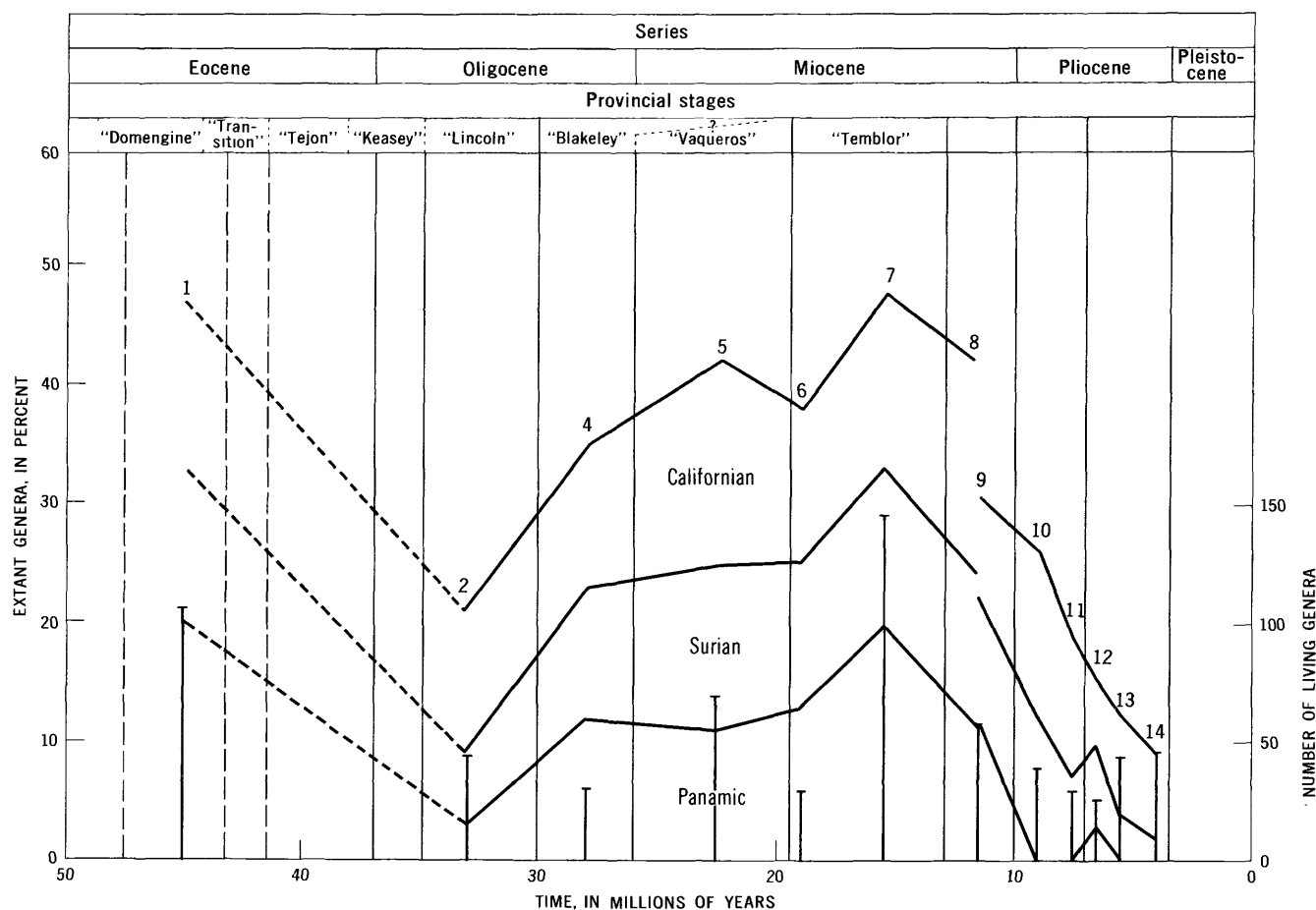


FIGURE 4.—San Joaquin basin zoogeographic profiles. Numbers refer to faunal data in table 1. The inclined dashed line between the “Blakeley” and “Vaqueros Stages” of Weaver and others (1944) indicates the partial age equivalence of these units (Addicott, 1967).

lative percentages has the advantage of permitting visual combination of tropical (Panamic) and subtropical (Surian) values as well as tending to smooth some of the irregularities in individual curves. The number of genera in each fauna is indicated by vertical lines in figure 4. Faunal data from which these percentages were determined are listed in table 1.

TABLE 1.—Zoogeographic indices for selected northeastern Pacific Tertiary molluscan faunas

[Genera with north end points of range in modern warm-water molluscan provinces indicated by cumulative percentages: P (Panamic), S (Surian), C (Californian). Genera no longer living in eastern Pacific are considered extinct. "Stages" are of Weaver and others (1944). Formational names not yet adopted by the U.S. Geological Survey are indicated by an asterisk (*); usage is in the sense of the authors cited]

Formation or "Stage" and Source	Number of genera		Warm-water genera (cumulative percent)		
	Total	Extinct	P	S	C
San Joaquin basin, California					
1. Domingine Formation, southern Diablo Range—Vokes (1939)	112	52	20	33	47
2. San Emigdio and Pleito Formations* ("Lincoln Stage")—Wagner and Schilling (1923), DeLise (1967), Alex Clark (unpub. paleontological reports, Calif. Univ., Riverside), Schenck and Reinhart (1938)	43	10	3	9	21
3. Tumey Sandstone—Zimmerman (1944), USGS collections	32	5	0	7	11
4. So-called "Phacoides" reef—USGS locs. 5149, M3578, M3579	31	5	12	23	35
5. "Vaqueros Stage" southeast San Joaquin basin—Loel and Corey (1932), Addicott (1965; 1970), USGS collections	69	12	11	25	42
6. Lower part of the Olese Sand, Kern River area—Addicott (1970), USGS collections	28	4	13	25	38
7. Upper part of the Olese Sand and lower part of the Round Mountain Silt—Loel and Corey (1932), Keen (1943), Addicott (1965; 1970), USGS collections	146	20	20	34	48
8. Santa Margarita Formation, San Joaquin basin—Preston (1931), Addicott and Vedder (1963)	66	4	11	24	42
9. Santa Margarita Formation, Coalinga anticline—Nomland (1917a), Adegoke (1967)	55	4	12	22	31
10. Etchegoin Formation, Chione emmerensis zone—Nomland (1917b)	39	5	0	12	26
11. Etchegoin Formation, Turritella nova zone—Nomland (1917b)	30	3	0	7	19
12. Etchegoin Formation, Siphonalia zone—Woodring and others (1940)	43	3	3	10	15
13. San Joaquin Formation, Cascajo Conglomerate Member—Woodring and others (1940)	27	1	0	4	12
14. San Joaquin Formation, Peeten zone—Woodring and others (1940)	47	1	0	2	9
Southern part of the Coast Ranges, California					
15. Middle member of the Gaviota Formation*—Kleinpell and Weaver (1963)	25	6	11	26	47
16. Upper member of the Gaviota Formation*—Kleinpell and Weaver (1963)	19	6	8	15	31
17. Vaqueros Formation—Loel and Corey (1932; locs. UCMP A494-496, A499)	39	3	14	33	53
18. Temblor Formation, La Panza Range—Anderson and Martin (1914); USGS locs. M3813, M3814	52	10	24	38	60
19. Santa Margarita Formation, eastern San Luis Obispo County—Hall (1960), Woodring (1926)	30	0	10	33	43
20. Pancho Rico Formation, Salinas Valley—Durham and Addicott (1965)	80	3	4	13	30
21. Careaga Sandstone—Woodring and Bramlette (1950)	132	5	2	8	13
Santa Cruz basin, California					
22. San Juan Bautista Formation*—Allen (1945)	25	7	0	11	22

TABLE 1.—Zoogeographic indices for selected northeastern Pacific Tertiary molluscan faunas—Continued

23. Vaqueros Formation—Clark (1966), Loel and Corey (1932), Allen (1945), Arnold (1908), USGS collections	41	7	6	29	44
24. "Temblor Stage"—Clark (1966), Bowen (1966)	27	3	8	42	50
25. Purisima Formation, lower part—Addicott (1969a)	25	2	4	13	17
26. Merced (?) Formation—Addicott (1969a)	34	0	0	6	9
Mount Diablo area, California					
27. Sandstone member of the Kirker Formation*—Primmer (1964)	22	4	6	17	28
Western Oregon and Washington					
28. Eugene Formation—Vokes and others (1951), Hickman (1968)	53	11	5	12	17
29. Lincoln Creek Formation, Porter Bluffs, Washington—Durham (1944)	50	17	3	6	9

Extra-limital warm-water genera and subgenera in middle and late Tertiary faunas of the San Joaquin basin and the California Coast Ranges are listed according to their northernmost latitudinal occurrence within modern zoogeographic provinces in table 2.

Inspection of the zoogeographic profiles (fig. 4) indicates that many genera now restricted to tropical

TABLE 2.—Extralimital warm-water genera in California Coast Range Neogene molluscan faunas classified according to modern molluscan province in which their north end point of range occurs

[Classification based on data from Burch (1944-46), Fitch (1953), Smith and Gordon (1948), Keen (1958, 1963), and Olsson (1961)]

Panamic	Surian	Californian
<i>Bornia</i>	<i>Anadara</i> s.s. <i>Anomalocardia</i>	<i>Amiantis</i> <i>Anadara</i> s.l.
<i>Clementia</i>	<i>Arca</i> s.s.	<i>Anatina</i>
<i>Miltha</i>	<i>Crassostrea</i>	<i>Anomia</i>
<i>Pinna</i>	<i>Chionopsis</i>	<i>Atrina</i>
<i>Tropithaca</i>		
<i>Arcularia</i>	<i>Cunearca</i> <i>Dosinia</i>	<i>Crassatella</i> <i>Florimetus</i>
<i>Cirsostrema</i>	<i>Lirophora</i>	<i>Here</i>
<i>Cymatium</i>	<i>Lyropecten</i>	<i>Isognomon</i> <i>Pteria</i>
<i>Disputaea</i>	<i>Macrocallista</i>	<i>Tellinella</i>
<i>Eucilia</i>	<i>Solecurtus</i>	<i>Agathotoma</i>
<i>Ficus</i>	<i>Antillophos</i> <i>Architectonica</i> <i>Cancellaria</i> s.s.	<i>Austrotrophon</i> <i>Besla</i>
<i>Hastula</i>		
<i>Knefastia</i>		
<i>Melongena</i>	<i>Catilon</i>	<i>Bulla</i>
<i>Polystira</i>	<i>Gemmula</i> <i>Lithoconus</i> <i>Natica</i> s.s.	<i>Costoanachis</i>
<i>Ptycheulimella</i>	<i>Nerita</i>	<i>Clavus</i>
<i>Pyrucilia</i>	<i>Oliva</i> <i>Strombina</i> <i>Solenosteira</i>	<i>Forreria</i>
<i>Scalina</i>		
<i>Semicassis</i>		
<i>Trochita</i>	<i>Thaisella</i>	<i>Kelletia</i>
<i>Triumphis</i>	<i>Torcula</i>	<i>Morula</i>
<i>Turricula</i> s.s.		<i>Neverita</i>
<i>Turritella broderipiana</i> stock.		<i>Niso</i>
<i>Typhis</i>		<i>Pomaulax</i>
<i>Vitrinellops</i>		<i>Strioterebrum</i> <i>Terebra</i>

latitudes ranged far north of their modern north limits during the Tertiary. The proportion of these warm-water genera in San Joaquin basin faunas increased from a low point during the Oligocene to a middle Miocene peak and gradually decreased thereafter. Tropical, or Panamic, molluscan genera dropped out of the San Joaquin basin fauna by the end of the Miocene and subtropical genera toward the end of the Pliocene. The relatively high percentages of genera now restricted to tropical and subtropical latitudes suggest water conditions much warmer than today; the San Joaquin basin lies inland from the southern part of the Oregonian molluscan province (southern boundary 34.5° N.), the climate of which is generally considered temperate (Hall, 1964). The post-middle Oligocene increase of warm-water genera, together with a sharp increase in faunal diversity, suggests climatic warming. Post-middle Miocene decrease in these parameters is likewise taken to indicate a more or less systematic decrease in marine surface-water temperatures. Faunal evidence upon which these inferences are based is discussed in the following section.

Eocene

The tropical aspect of shallow-water Eocene molluscan faunas of the San Joaquin basin has been discussed by several paleontologists (Dickerson, 1913; 1917; Smith, 1919; Vokes, 1940; Durham, 1950). Their inferences were based upon the relatively large number of genera that are either living or are represented by modern analogs in tropical seas. Vokes (1940), for example, listed 31 such genera from the middle Eocene Domengine Formation, and Durham (1950) listed 20 molluscan genera from the Eocene Tejon Formation. Clark and Vokes (1936) observed that, without exception, all the California Eocene genera that can be compared with modern taxa have living representatives in tropical seas.

Quantitative zoogeographic analysis at the generic level is not suited for early Tertiary faunas because of the high percentage of extinct genera. Middle and late Tertiary molluscan faunas have about 5–20 percent extinct genera, whereas between 45 and 50 percent of the genera of the early and middle Eocene "Capay" and "Domengine Stage" faunas (Vokes, 1939) are extinct. Moreover, the composition of the classic late Eocene molluscan fauna of the south margin of the San Joaquin basin ("Tejon Stage") is incompletely known owing to stratigraphic lumping of middle and late Eocene assemblages in Anderson and Hanna's (1925) definitive paleontologic study of the Tejon Formation (Marks, 1943). Nevertheless, the thoroughly studied middle Eocene "Do-

mengine Stage" fauna from the southern part of the Diablo Range (Vokes, 1939) has been tentatively incorporated in the zoogeographic chart (fig. 4) to indicate qualitative differences between Eocene and Oligocene molluscan faunas. Percentages of warm-water middle Eocene genera doubtless are much higher than shown because many of the extinct genera excluded from the analysis have closely related modern counterparts in tropical and subtropical seas.

A small pelecypod assemblage from the lower part of the San Emigdio Formation of Wagner and Schilling (1923) near the south margin of the San Joaquin basin may be of late Eocene age, judging by associated foraminifers. The molluscan fauna, consisting of *Thyasira* and lucinoid pelecypods (Wagner and Schilling, 1923), is too small and represents a habitat too deep to reflect surface water temperatures. Associated benthonic foraminifers of the Narizian Stage are of upper bathyal or lowermost neritic aspect according to DeLise (1967).

OLIGOCENE

Molluscan assemblages referable to the Oligocene "Lincoln Stage," the limits of which are coincident with the biozone of *Acila shumardi*, occur at scattered localities along the west side of the San Joaquin basin from Tumey Hills (Atwill, 1935; Zimmerman, 1944) to the northern Temblor Range (Simonson and Kreuger, 1942). The largest faunas, however, are from the upper part of the San Emigdio Formation of Wagner and Schilling (1923) and the lower part of the Pleito Formation of Wagner and Schilling (1923), near the south margin of the basin. Molluscan assemblages are known from many localities in the 1,500 feet of strata assigned to the Refugian Stage of Schenck and Klempell (1936) (= "Lincoln Stage") by DeLise (1967). Although molluscan fossils are abundant, faunal diversity is greatly reduced from that of the Eocene. Whereas Clark and Vokes (1936) recognized 130 species of mollusks from the upper Eocene part of the Tejon Formation in the San Emigdio Mountains and 182 species from the type locality of the "Domengine Stage" near Coalinga, Wagner and Schilling (1923) listed only 70 species from their San Emigdio and Pleito Formations. Moreover, less than 10 percent of the still-living genera from the *Acila shumardi* zone of the San Emigdio Mountains can be classified as tropical or subtropical (fig. 4).

The comparatively cool aspect of the middle Oligocene fauna of the San Joaquin basin, suggested by low faunal diversity and low proportion of warm-water genera (fig. 4), has not been noted in previous

analyses of marine climate. However, an unusually cool middle Oligocene terrestrial climate in Oregon, Washington, and in southern Alaska has been postulated from paleobotanical evidence (Wolfe and Hopkins, 1967). Smith (1919) failed to recognize the Oligocene climatic deterioration because he utilized the fauna of the Astoria Formation of Oregon as his sole Oligocene control. This fauna is now regarded as middle Miocene; it is relatively warmer in zoogeographic aspect than the molluscan faunas of the middle and late Oligocene of the Pacific Northwest (Addicott, 1969b). Durham's (1950, fig. 3) analysis did not include Oligocene faunas from California; the relationship of his Oligocene paleotemperature estimates to those of this report are discussed subsequently.

The late Oligocene molluscan fauna of the San Joaquin basin is poorly known. The only definite occurrence is in the basal part of Anderson's (1905) type Temblor [Formation]—the so-called Phacoides sandstone of the central Temblor Range. Although few mollusks have been reported from the so-called Phacoides sandstone (Anderson, 1905, p. 170; Kleinpell, 1938, p. 39, 106; Curran, 1943, p. 1372), recent collections have yielded shallow-water assemblages large enough to be included in this analysis. The fauna is here referred to the lower part of the "Blakeley Stage" of Weaver and others (1944), the type section of which is in northwestern Washington, based upon its apparent position between faunas of the "Lincoln Stage" (*Acila shumardi* zone) and the lower Miocene "Vaqueros Stage."

Olequahia lorenzana (Wagner and Schilling), a gastropod restricted to the Oligocene "Lincoln Stage," has been collected from the so-called Salt Creek shale, about 10–30 feet stratigraphically below molluscan assemblages from the so-called Phacoides sandstone (California University, Riverside, loc. 1106). A larger Lincoln fauna occurs in a landslide block about 12 miles to the southeast (Simonson and Kreuger, 1942, p. 1614). The so-called Phacoides sandstone contains no species restricted to either the "Lincoln Stage" or to the "Vaqueros Stage." The lowest stratigraphic occurrence of "Vaqueros" mollusks in this part of the Temblor Range is in the stratigraphically higher Agua Sandstone of Clark and Clark (1935). The Phacoides fauna occurs within the type section of the lower part of the Zemorrian Stage (Kleinpell, 1938) of the microfaunal sequence; the type section of the lower part of the "Blakeley Stage" on Bainbridge Island, Wash., is also referred to the lower part of the Zemorrian Stage by Kleinpell (1938).

Although somewhat smaller than the fauna of the "Lincoln Stage" from the southern part of the San Joaquin basin, the combined percentage of Panamic (tropical) and Surian (subtropical) genera in the late Oligocene fauna is more than twice as great as that of the middle Oligocene. Some of the Panamic and Surian genera characteristic of the late Oligocene of the San Joaquin basin are: *Anadara*, *Clementia*, *Crassostrea*, *Dosinia*, *Miltha*, and *Ficus*. All of these warm-water genera had pre-late Oligocene origins. Similar middle to late Oligocene zoogeographic trends have been observed in benthonic foraminiferal faunas of California; Kleinpell (1938, p. 102) observed that the Refugian (= *Acila shumardi* zone) fauna contains fewer benthonic foraminifera with southern affinities than does the fauna of his overlying Zemorrian Stage.

Faunas of this age are also known from the upper part of the San Lorenzo Formation and lower part of the Vaqueros Formation of the Santa Cruz Mountain area west of the San Andreas fault (Cummings and others, 1962). Fossils are abundant in these formations (Brabb, 1964) but, like the associated benthonic foraminifera (Sullivan, 1962), are indicative of outermost inner sublittoral or bathyal depths and, therefore, are excluded from this analysis.

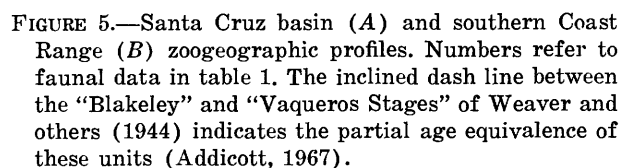
MIocene

Early Miocene faunas are known from only three areas in the San Joaquin basin—the northern Temblor Range (Arnold, 1909b; Clark and Clark, 1935; Heikkila and McLeod, 1951), the San Emigdio Mountains at the south edge of the basin (Loel and Corey, 1932), and the Kern River area northeast of Bakersfield (Loel and Corey, 1932; Addicott, 1965, 1970). Assemblages from the basal part of the Jewett Sand near Kern River are the only ones large enough to be included in this analysis.

The sharp increase of warm-water genera from middle to late Oligocene in the southern part of the San Joaquin basin did not continue into the early Miocene. Rather, the percentage of Panamic and Surian molluscan genera remained almost constant from the lower part of the "Blakeley Stage" to the "Vaqueros Stage" (the upper part of the "Blakeley Stage" of Washington and the "Vaqueros Stage" of California are considered to be contemporaneous (Addicott, 1967)).

A small molluscan assemblage from near the lower Miocene–middle Miocene boundary (No. 6 in fig. 4) seems to reflect conditions essentially unchanged from the early Miocene. This control point is based upon meager assemblages from the lower part of the Olcese Sand of the Kern River area. The

Comparable peaks in the percentage of warm-water mollusks occur in Miocene basins of the Coast Ranges west of the San Andreas fault (fig. 5). Middle Miocene faunas of eastern San Luis Obispo County directly west of the fault contain the highest percentage of warm-water elements. Smaller faunas from the Santa Cruz basin to the northwest have a similar combined percentage of Panamic and Surian genera, but the proportion of subtropical (Surian) genera is much higher. According to recent postulates of post-middle Miocene lateral slip along the San Andreas fault (Addicott, 1968b; Grantz and Dickinson, 1968), the Santa Cruz basin lay directly across the fault from the southern part of the San Joaquin basin during the middle Miocene. The somewhat cooler aspect of the middle Miocene fauna of



the Santa Cruz basin suggested by the lower proportion of tropical genera may be the result of its more seaward, less protected setting and the possible influence of upwelling. However, the Santa Cruz basin fauna is so small that intensive collecting

could conceivably alter the percentage composition of warm-water elements.

Further evidence of the middle Miocene peak in the post-middle Oligocene warming of marine climate is apparent from diversity trends within some important middle and late Cenozoic warm-water molluscan lineages: *Cancellaria*, *Anadara*, and *Turritella*. Species of *Cancellaria* in the San Joaquin basin, for example, increase from six during the early Miocene (Clark, 1918; Loel and Corey, 1932; Addicott, 1970) to 18 during the middle Miocene (Anderson, 1905; Arnold, 1909b; Addicott, 1970) but decline to about seven during the late Miocene (H. R. Gale, in Preston, 1931; Addicott and Vedder, 1963) and only three during the early Pliocene (Nomland, 1917b). Similarly, the *Turritella* stocks of Merriam (1941) increase from two in the California early Miocene to five in the middle Miocene but decline again to only two during the late Miocene and during the Pliocene. Species of *Anadara* (Reinhart, 1943; Hall, 1962a) likewise rise from a low of one during the middle Oligocene to six during the middle Miocene but decline to three during the late Miocene and two during the Pliocene.

Late Miocene assemblages occur at scattered localities in the southern part of the Diablo Range, the southern Temblor Range, and along the southeast margin of the San Joaquin basin. The largest faunal assemblages are from the Comanche Point area south of Bakersfield (B. L. Clark, in Merriam, 1916; Addicott and Vedder, 1963) and the Coalinga area (Nomland, 1917a), about 125 miles to the northwest. Both assemblages are shown in figure 4; the Comanche Point assemblage marks the highest stratigraphic occurrence of marine Tertiary in surface exposures around the southeast margin of the San Joaquin basin. There are subsurface records of Pliocene assemblages from the southern part of the basin (H. R. Gale, in Preston, 1931; Howard, 1935) and small assemblages reported from the foothills of the San Emigdio Mountains (Hoots, 1930), but faunal data are too meager to include in this analysis. Pliocene faunal analysis is based, therefore, on the thoroughly studied faunas of the Kreyenhagen Hills-Kettleman Hills area (Arnold, 1909b; Nomland, 1917b; Woodring and others, 1940) in the northwestern part of the basin.

Percentages of Panamic and Surian genera dropped sharply from the middle Miocene peak into the late Miocene. Cumulative percentages of warm-water late Miocene genera of the Coalinga area are lower than those in the southern part of the basin. Presumably this is due to the occurrence of a late

Miocene latitudinal faunal gradient. This gradient was initially inferred by Hall (1960) in his recognition of latitudinal differentiation of late Miocene molluscan faunas in California. Hall's inferences were questioned by Addicott and Vedder (1963) on the basis of warm-water genera from the southern part of the San Joaquin basin not considered in his paleotemperature analysis. Their argument was that paleotemperatures in the southern part of the San Joaquin basin probably were much warmer than those postulated by Hall and at least equally as warm as those west of the fault in San Luis Obispo County. Their reasoning was based upon the much larger number of tropical and subtropical genera in the late Miocene fauna of the southern San Joaquin basin. The problem of accurately comparing these faunas is still unresolved; much of it stems from the much smaller taxonomic diversity of molluscan assemblages west of the San Andreas fault which is in large part due to selective preservation of calcitic-shelled mollusks. Aragonitic-shelled mollusks are well represented in the much larger San Joaquin basin late Miocene assemblages. Although there are many more warm-water genera in the San Joaquin basin fauna, the percentage of warm-water genera is actually somewhat higher in the San Luis Obispo County faunas west of the fault (fig. 5). This relationship is in accord with postulated post-late Miocene lateral slip along the fault (summarized by Grantz and Dickinson, 1968) and the concept of temperature-controlled middle and late Tertiary latitudinal differentiation of molluscan faunas.

The last significantly large occurrence of Panamic (tropical) molluscan genera in the San Joaquin basin occurred during the late Miocene. Only two Panamic genera are recorded from the Pliocene. An occurrence of *Euclia* as *Cancellaria fernandoensis tribulis* (Nomland, 1917b, p. 238), from an isolated lower Pliocene locality on Warthan Creek southwest of Coalinga was not assigned to either of the Pliocene zones by Nomland (1917b) and is, therefore, not represented in figure 4. An unnamed turritellid genus, commonly known as the *Turritella broderipiana* stock (Merriam, 1941), that seems to be restricted to the modern Panamic fauna is represented by a species in the lower part of the Etchegoin Formation (Woodring and others, 1940).

PLIOCENE

Pliocene faunas of the San Joaquin basin are less diverse than those of the Miocene and are characterized by greatly reduced percentages of warm-water genera. Cumulative curves (fig. 4) depict a progressive decrease in the percentage of Surian and

Californian genera although individual percentages of these are subject to variation. The Pliocene curves are based upon five faunas: two each from the Jacalitos and Etchegoin Formations and one from the San Joaquin Formation. These have received intensive study (Arnold, 1909b; Nomland, 1916, 1917b; Woodring and others, 1940). Tropical genera are all but missing from the San Joaquin basin Pliocene as indicated above. Subtropical (Surian) genera systematically decrease from 12 percent in the early Pliocene to only 2 percent in the late Pliocene. The smaller percentage, based upon the pelecypod *Anadara* s.s., probably represents a relict population. This seems to be a case in which a single genus that is now restricted to a distant warm-water province probably does not indicate temperature fully as warm as those in which it now lives (the northernmost occurrence of *Anadara* s.s. is in the Surian molluscan province). By the end of the Pliocene, only a few extralimital genera remained in the San Joaquin basin. These are warm temperate genera referable to the California molluscan province, the north boundary of which is today less than 200 miles south of the Kettleman Hills area.

Barbat and Galloway (1934) inferred an abrupt late Pliocene cooling, based upon the occurrence of abundant *Mya* (*Arenomya*) in the fauna of the San Joaquin Formation. With the exception of brief warm-water phases represented by their *Pecten-Mytilus-Scalex* and *Pecten coalingensis* faunal zones near the base and the middle parts of the formation, they considered the marine climate to be significantly cooler than the modern climate of this latitude. However, a fairly large, self-sustaining population of *M. (A.) arenaria* inhabits Elkhorn Slough in nearby Monterey Bay (Fitch, 1953); it seems doubtful therefore, that this taxon reflects significantly cooler marine temperatures. Zoogeographic analysis of the *Pecten coalingensis* zone fauna of Woodring, Stewart and Richrads (1940) and qualitative evaluation of the much smaller assemblages from their other San Joaquin faunal zones suggest that marine surface-water temperatures were comparable to those occurring in the southernmost part of the modern Oregonian molluscan province off central California. In other words, the marine climate was as warm as or perhaps slightly warmer than occurs at this latitude today.

The present analysis is in accord with Barbat and Galloway's (1934) belief that the succession of Jacalitos and Etchegoin faunas evidence progressive cooling and with Durham's (1950) similar conclusion on the relationship of Etchegoin to San Joaquin

faunas. The slight late Pliocene climatic warming inferred by Durham (1950, p. 1259, fig. 3) based upon mollusk and coral identifications from northern California, was negated after reidentification of the supposed warm-water taxa and a zoogeographic analysis of the associated fauna indicated that the fauna as a whole suggested somewhat cooler temperatures than occur at that latitude today (Allison and others, 1962). Stanton and Dodd (1969) seem to hold a contrasting view that there were no significant climatic trends or fluctuations during the later part of the Pliocene in the Kettleman Hills area of the San Joaquin basin. Their faunal analysis and strontium paleotemperature estimates based upon the bivalve *Crenomytilus* did, however, indicate that water temperatures were warmer than occur at this latitude today.

DISCUSSION

SAMPLE SIZE

Although the molluscan sequence of the San Joaquin basin is much more complete than in other California Tertiary basins, zoogeographic analysis is hampered by gaps in the fossil record and sparse assemblages in parts of the sequence. Faunal size for example, varies from less than 30 to nearly 150 genera. These differences may be in part the result of inadequate sampling (Durham, 1967); the Miocene fauna of the lower part of the Olcese Sand, for example, has not been thoroughly sampled. Most of the faunas utilized in the analysis, however, have been rather intensively collected suggesting that the apparent relationship of low Oligocene and Pliocene generic diversity to much higher middle Miocene levels probably is real. Species diversity trends in Oligocene to Pliocene molluscan faunas of California exhibit similar relationships (Keen and Benton, 1944, fig. 3). Changes in generic diversity in San Joaquin basin faunas presumably reflect climatic change, judging by the occurrence of high levels of taxonomic diversity in modern warm-water equatorial seas (Fischer, 1960; Stehli and others, 1967). Similar trends in diversity of molluscan genera and subgenera occur in the western Atlantic part of the Tertiary Caribbean faunal province; the number of taxa increases dramatically from a low point during the Oligocene to a peak during the middle Miocene and then declines (Woodring, 1966).

GAPS IN THE RECORD

Biostratigraphic control is adequate to discern only general faunal trends. Climatic maximums suggested by peaks at 40 to 50 and 10 to 20 million years in the San Joaquin basin zoogeographic profile (fig. 4) appear to agree well with the 30-million-year

Mesozoic and Cenozoic climatic cycle advanced by Dorman (1968). Clearly, the existence of subsidiary cycles, or changes associated with minor climatic fluctuations, cannot be ruled out with presently available control. The spacing of faunal control is better for the Pliocene—five faunas in approximately 7 million years—than for the Oligocene and Miocene—only six faunas during a span of about 25 million years. Furthermore, one of the mid-Tertiary faunas, as previously mentioned, is inadequately known. Biostratigraphic study of the type Tejon Formation of the south margin of the San Joaquin basin must be completed before the Eocene climatic peak can be accurately identified.

Shallow-water molluscan faunas occur in many of the apparent stratigraphic gaps on the chart. Potential stratigraphic control is at least twice as dense as shown, but, unfortunately, many of the faunas are too small for quantitative analysis. Oxygen isotope study of the faunal sequence could provide much denser control, in addition to a better indication of actual marine temperatures.

MIDDLE OLIGOCENE ANOMALY

Zoogeographic indices from middle Oligocene molluscan faunas of the Pacific coast indicate that the climatic minimum suggested by low percentages of warm-water middle Oligocene genera of the San Joaquin basin may not have been as much lower than late Oligocene and early Miocene values as is shown in figure 4. Percentages of warm-water genera between latitude 34° and 48° N. are plotted in figure 6; data from the Santa Ynez Mountains west of the San Andreas fault are adjusted for post-Oligocene lateral slip in keeping with recent postulates of Ad-dicott (1968b). Although the faunas of the Gaviota Formation of Kleinpell and Weaver (1963) and the sandstone member of the Kirker Formation of Primmer (1964) were the subject of recent taxonomic study, the much larger middle Oligocene faunas of Oregon, Washington, and the San Joaquin basin suggest that these key faunas may still be incompletely known. The zoogeographic indices from them are based, in both cases, on less than 25 genera. Accordingly, the middle Oligocene latitudinal graph should be considered tentative. The data are sufficient, however, to suggest latitudinal organization of middle Oligocene molluscan faunas of the eastern Pacific. The straight-line profiles also disclose anomalously low values for San Joaquin basin faunas. Accordingly, smoothed curves utilizing interpolated values from figure 6 have been constructed for the San Joaquin basin Tertiary (fig. 7). Much stronger contrasts between Miocene faunas of California and the

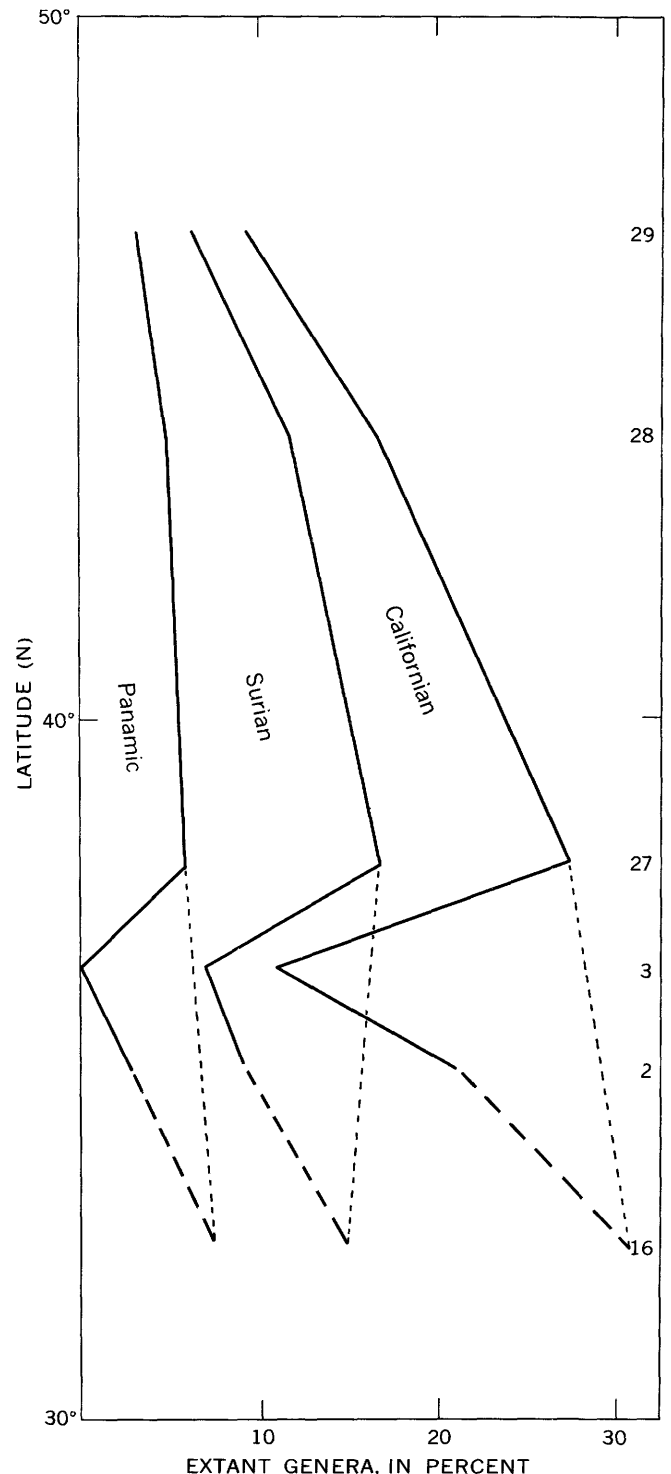


FIGURE 6.—Middle Oligocene latitudinal faunal gradient. Numbers refer to faunal data in table 1. The fauna of the upper member of Kleinpell and Weaver's (1963) Gaviota Formation (no. 16) west of the San Andreas fault (lat 34° N.) is adjusted for post-Oligocene lateral slip (Grantz and Dickinson, 1968).

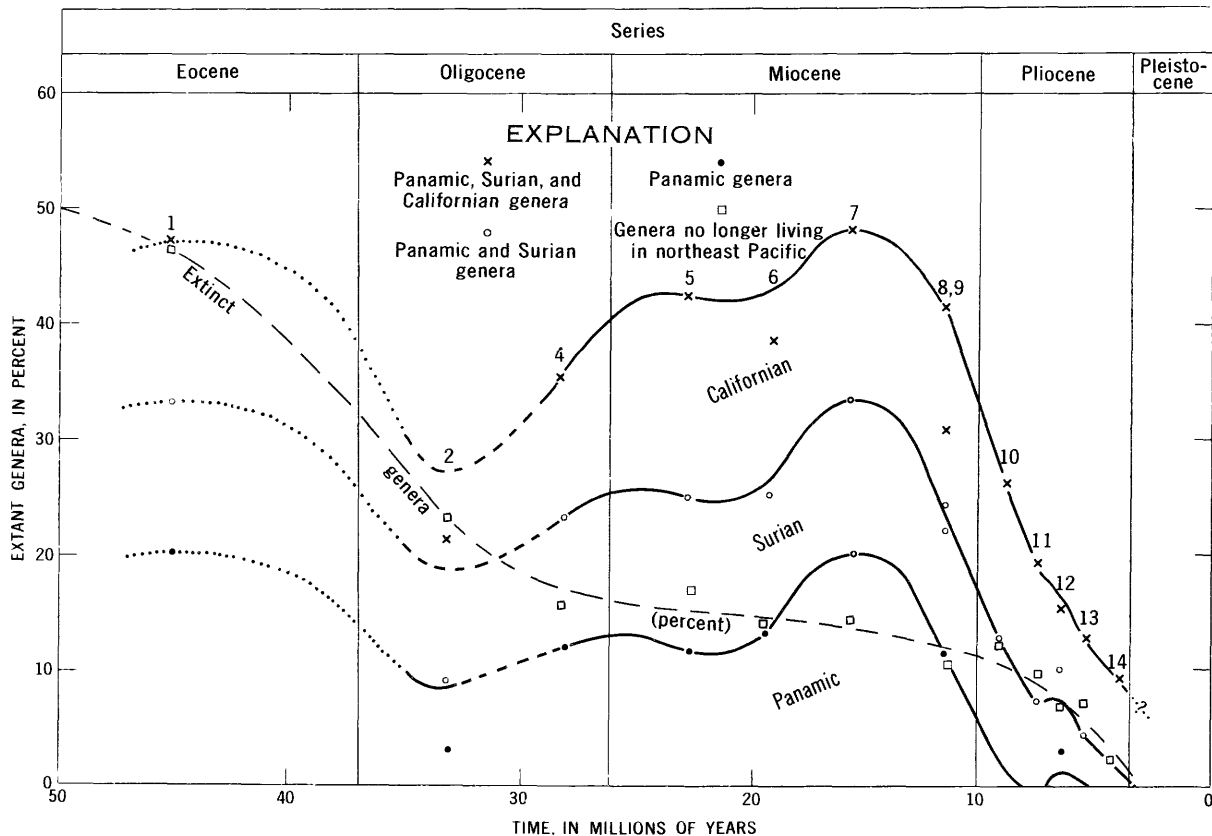


FIGURE 7.—Idealized zoogeographic profiles for the San Joaquin basin utilizing interpolated middle Oligocene values from figure 6. Single dashed curve shows changes in the percentage of genera no longer living in the eastern Pacific Ocean, herein considered to be extinct. Numbers refer to faunal data in table 1.

Pacific Northwest (Addicott, 1969b) are indicative of more distinct latitudinal gradients; there is no evidence of a Miocene continuation of unusually low middle Oligocene zoogeographic indices in San Joaquin basin molluscan faunas.

Reasons for the San Joaquin basin anomalies in the middle Oligocene latitudinal faunal gradient are not readily apparent. They could be the result of inadequate sampling or local upwelling of cold water. The possibility of upwelling at this time but not in later stages of deposition, in the San Joaquin basin seems favored by the high Oligocene relief, evidenced by extensive deposition of nonmarine strata in California and by the fact that the basin was more open to the Pacific than during subsequent stages (fig. 2). It is notable that the faunas of the San Juan Bautista Formation of Allen (1945) near Monterey Bay, west of the San Andreas fault, and the San Emigdio and Pleito Formations of Wagner and Schilling (1923) of the southern San Joaquin basin have almost identical percentages of warm-water genera (table 1). The two faunas initially lived at the same latitude and in proximity according

to recent postulates of cumulative right-lateral slip along the San Andreas fault (Addicott, 1968b; Grantz and Dickinson, 1968).

EOCENE AMELIORATION

Although the relationship of middle Oligocene to later Tertiary values is perhaps better portrayed by the adjusted curves, the dramatic late Eocene or early Oligocene climatic deterioration is minimized. Moreover, its configuration cannot be defined because of inadequate biostratigraphic control. As stressed earlier, the Eocene peak doubtless was much higher than shown because of the many extinct Eocene genera of warm-water affinities not included in the analysis. Many of the excluded gastropod genera, for example, are spinose forms suggestive of warm-water conditions. The Eocene peak was probably much higher than the middle Miocene peak.

CLIMATIC CHANGE AND EXTINCTION

Increased rates of extinction at the generic level during the Oligocene and the Pliocene in the San Joaquin basin seem to be related to the climatic deterioration that followed the principal Eocene and

Miocene warm pulses. The close correlation between zoogeographic evidence of warming climate and a slowing of the apparent rate of extinction is indicated by curves in figure 7. Eocene and Oligocene data are scant; in the much better controlled Neogene faunal sequence, however, a plateau in the extinction curve occurs during the Miocene. It is followed by a sharp decline during the Pliocene. In this study, extinct genera are defined as those no longer living in the eastern Pacific Ocean.

OTHER CALIFORNIA BASINS

Zoogeographic profiles from Tertiary basins in the central California Coast Ranges west of the San Andreas fault (fig. 5) are similar to the San Joaquin basin profile although based on sparse faunal control. Of these, the southern Coast Range profile (fig. 5B) assembled from faunal data in San Luis Obispo and Santa Barbara Counties has better stratigraphic control. Oligocene faunas of the Gaviota Formation of Effinger (1935) of the Santa Ynez Mountains (Kleinpell and Weaver, 1963) seem to define the mid-Tertiary climatic deterioration much better than the San Joaquin basin faunas. Unfortunately, the late Oligocene fauna of the Alegria Formation of Dibblee (1950) in the Santa Ynez Mountains (Kleinpell and Weaver, 1963) is too small to be included in this analysis. Late Oligocene control is also lacking in the Santa Cruz basin profile to the north.

Both the southern Coast Range and the Santa Cruz basin (= La Honda basin of Cummings and others, 1962) profiles have prominent middle Miocene peaks which correspond to a similar peak in the San Joaquin basin profile. The Santa Cruz basin peak differs from the southern Coast Range peak, however, in having a much smaller percentage of Panamic (tropical) genera and a relatively larger percentage of Surian (subtropical) genera. Presumably this is a reflection of the Santa Cruz basin's more northern position in relation to the middle Miocene latitudinal faunal gradient.

OREGON AND WASHINGTON

The Miocene climatic peak is further reflected by a northward migration of many warm-water genera along the Pacific Coast during the middle Miocene (Addicott, 1968b). Several genera now restricted to the Panamic, Surian, and Californian molluscan provinces advanced northward from early Miocene distributional limits in central California to Oregon and Washington during the middle Miocene. All of these tropical, subtropical, and warm temperate genera, except *Anadara* s.s., disappeared from Oregon and Washington by the end of the middle Miocene, their

northernmost late Miocene limits occurring once more in California.

Durham's (1950) Oligocene paleoclimatic curves for Washington differ from the California zoogeographic profiles (fig. 4 and 5) in picturing a gradual transition from near-tropical early Oligocene climate to subtropical late Oligocene climate. The middle Oligocene climatic deterioration evident in the California profiles and from paleobotanical evidence in Oregon and Washington (Wolfe and Hopkins, 1967) probably occurred between Durham's two Oligocene faunas. Presumably the intervening middle Oligocene fauna of the upper part of the "Lincoln Stage" in Washington was excluded from his diagram because of its "slightly deeper facies" (Durham, 1942). That the late Oligocene fauna of western Washington was relatively cooler than the early Oligocene fauna seems perfectly clear, but the zoogeographic relationship to California faunas, which have much larger proportions of tropical and subtropical molluscan genera, suggests that the initial estimates of marine climate were too warm. In the context of this analysis, mollusks of the lower part of the "Lincoln Stage" (Durham, 1950), p. 1255) would be classified as marginally subtropical to warm temperate and those of the lower part of the "Blakeley Stage," warm temperate. Durham (1940) initially considered corals from the lower part of the "Blakeley" to be of "a decided warm temperate aspect."

More than half of the molluscan genera from the lower part of the "Lincoln Stage" in Washington, once regarded as indicative of near-tropical condition (Durham, 1950, p. 1255), are now known to range northward into the temperate Oregonian molluscan province (lat 34.5°–48° N.); several other genera are not represented in modern eastern Pacific faunas. None of the remaining genera are today restricted to the tropical Panamic molluscan province, and the three that today live in subtropical latitudes—*Gemmula*, *Nerita*, and *Macrocallista*—constitute an even smaller percentage of warm-water elements than occurs in the middle Oligocene fauna of California Coast Range basins.

Paleoclimatic inferences from the late Oligocene molluscan fauna of Washington, the *Echinophoria* zone of Durham (1944), are conflicting. Late Oligocene marine climate was considered temperate by Dickerson (1917) and Bentson (1940), temperate to warm temperate by Addicott (1967), and subtropical by Tegland (1933) and Durham (1942, 1950). Molluscan evidence suggests that the late Oligocene climate was more likely warm temperate

than subtropical, as less than 5 percent of the molluscan general are now restricted to subtropical or tropical provinces.

The significance of one or two taxa of hermatypic (reef-building) corals upon which Durham (1942, 1950) based his interpretation of subtropical conditions for the upper part of the Oligocene (type Blakeley Formation of Tegland, 1933) and lowermost part of the Miocene (upper part of the Twin River Formation) is of critical importance. Because of the absence of vigorous coral growth (reefs) and low taxonomic diversity, it has been postulated (Addicott, 1967) that the two hermatypic genera in the "Blakeley Stage" may have been acclimated to a cooler environment than the subtropical 18°–18.5° C minimum for vigorous growth cited by Vaughan and Wells (1943, p. 55).

PALEOCLIMATIC INFERENCES FROM FORAMINIFERA

Whereas a similar warming trend seems apparent from reported abundance and diversity of planktonic Foraminifera during the California Oligocene and Miocene, Pliocene planktonic foraminifers seem to indicate an entirely different picture.

Planktonics are characterized by low species diversity and are of relatively rare occurrence during the Oligocene to early Miocene Refugian to Saucesian foraminiferal stages (Smith, 1956; DeLise, 1967; Bandy and Arnal, 1968). They become diverse and relatively abundant during the middle Miocene (Lipps, 1967a; Bandy and Arnal, 1969). During the late Miocene they are apparently less diverse and constitute the coolest water assemblages of the California Miocene (Lipps, 1967a; b). A simple diversity curve fitted to these observations closely parallels molluscan data and would seemingly have similar paleoclimatic significance. A similar peak in the diversity of planktonic Foraminifera occurred during the middle Miocene in New Zealand (Jenkins, 1968). Berggren (1968) has also noted the striking similarities between taxonomic diversity in planktonic Foraminifera and climatic fluctuations during the Tertiary (Devereux, 1967), but his diversity peak is somewhat later in the Miocene than Jenkins'.

The paleoclimatic significance of Miocene benthonic foraminifers has been interpreted in a much different manner, closely paralleling Smith's (1919) concept of progressively cooling surface-water temperatures during the Tertiary. Kleinpell (1938, p. 104–134) described a more or less gradual withdrawal of tropical and subtropical foraminiferal elements from California basins during his Zemorrian to Delmontian Stages. Recently Ingle (1967) postulated systematic cooling of bottom waters during the

Miocene based upon similar observations of progressive latitudinal restriction of tropical and subtropical benthonic foraminiferal elements during successive Miocene stages.

A contrasting interpretation closely aligned with paleoclimatic inferences from San Joaquin basin molluscan faunas seems to be indicated by middle Tertiary species diversity trends in San Joaquin basin foraminiferal faunas. Bandy and Arnal (1969, fig. 26) indicate significantly higher levels of species diversity in the early and middle Miocene Saucesian, Relizian, and Luisian Stages than in the late Oligocene to early Miocene Zemorrian Stage and the late Miocene Mohnian Stage. The shape of their curve is generally similar to the middle Tertiary zoogeographic profiles and generic diversity of San Joaquin basin molluscan faunas (fig. 4).

The relationship to paleoclimatic inferences from Pliocene planktonic foraminifers is less clear. Bandy (1967c, 1968) and Ingle (1967) picture early and late Pliocene surface-water temperatures off California as having been much warmer than at present and middle Pliocene temperatures much cooler, based principally upon changes in the coiling direction of the planktonic foraminifer *Globigerina pachyderma*. Their interpretations differ markedly from the repeated inferences of progressively cooling Pliocene marine climate of the San Joaquin basin based on shallow water mollusks (Smith 1919; Barbat and Galloway, 1934; Durham, 1950; Addicott, 1969b; Stanton and Dodd, 1969). Molluscan evidence presented herein points to Pliocene water temperatures consistently warmer than at present. There is, however, a slight suggestion of a middle Pliocene warming (fig. 7). The inferences from foraminifers cannot be directly related to the molluscan sequence of the San Joaquin basin because planktonics are found only in deeper water sediments. *Globigerina pachyderma*, for example, lives today suspended in the water column below depths of 100 meters (Casey, 1963; Lidz, 1966; Bandy, 1967b; Ingle, 1967), a much cooler and deeper environment than nearshore inner sublittoral environment represented by the Pliocene mollusks.

Both the molluscan and foraminiferal evidence are equivocal. The shallow-water climatic regime of coastal sites might not have been reflected in the San Joaquin basin during the Pliocene because of shallow depths and the protection afforded by its deeply embayed configuration. The planktonic foraminifers, on the other hand, clearly do not reflect surface-water temperatures. The relatively deep-water habitat of *Globigerina pachyderma* normally ex-

cludes it from all but the outermost shelf sediments. Although evidence from other basins (fig. 5) supports the inference of progressively cooling shallow-water temperatures during the Pliocene, detailed study of other California faunal sequences, including oxygen isotope studies, is needed to better evaluate this discrepancy.

SUMMARY AND CONCLUSIONS

The Oligocene and Pliocene distributional profile of San Joaquin basin molluscan faunas is based upon a more detailed faunal succession than was previously available for the northeastern Pacific. Zoogeographic trends and their inferred paleoclimatic significance are mirrored not only in other California Tertiary basins but also, more significantly, by recent paleoclimatic studies from other areas around the Pacific margin. Paleontologic studies of corals and other invertebrates from New Zealand (Squires, 1958; Hornibrook, 1967), land floras and various marine paleontologic data from Japan (Tanai and Huzioka, 1967; Kobayashi and Shikama, 1961), and leaf floras from southern Alaska (Wolfe and Hopkins, 1967) and the Western United States (Dorf, 1955) all show parallel trends. Moreover, paleotemperature curves inferred from recent oxygen isotope studies of New Zealand and Australian marine invertebrates have remarkable similarities (Dorman, 1966; Devereux, 1967) to paleoclimatic inferences from California. The succession of climatic peaks in the Eocene and the Miocene seem to support Dorman's (1968) 30-million-year Mesozoic and Cenozoic climatic cycle. Comparable studies of marine mollusks have not been made in other Tertiary sequences around the Pacific rim, although qualitative analysis of the Tertiary of Japan by Saburo Kanno (oral commun., 1968) indicates similar trends.

This simple analysis should prove useful in defining paleoclimatic trends in similar Tertiary sequences around the Pacific rim. Requirements are: (1) Adequate sequences of shallow-water Tertiary molluscan faunas, and (2) the frame of reference provided by a north-south segment of coast where modern molluscan faunas exhibit temperature-related latitudinal differentiation similar to that of the northeastern Pacific.

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