

# CHRONOSTRATIGRAPHIC CALIBRATION OF THE PACIFIC COAST CENOZOIC: A SUMMARY

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## ABSTRACT

The chronostratigraphic calibrations of key Pacific Coast Cenozoic biostratigraphic and lithologic units have been considerably modified by the advent of magnetic stratigraphy. The Paleocene record in California is much less complete than originally supposed, with almost no early Paleocene. The Pacific Northwest virtually lacks a Paleocene sedimentary record. The Eocene, Oligocene, and Miocene records in both regions are better represented, but many of the classic "complete" sections have significant hiatuses. Some of the biostratigraphic zonations based on benthic organisms (foraminifera and molluscs) turn out to be significantly time-transgressive, or overlapping in age by several million years, or completely co-extensive in age. In other cases, these allegedly continuous biochrons have large time gaps between them, or are so long in duration as to be useless for high-resolution correlations. Studies in this volume have shown that the future of Pacific Coast correlations lies with magnetic stratigraphy calibrated by planktonic microfossils, rather than with the molluscs and benthic foraminifera that are traditionally used.

## INTRODUCTION

As discussed in the introduction to this volume, the chronostratigraphy of the Pacific Coast Cenozoic has come a long way since its origins over a century ago. Before the current phase of research, the most recent efforts at a synthesis of Cenozoic time scales were published by Armentrout (1981), Armentrout et al. (1983), Brabb (1983), and in several charts produced by the COSUNA (Correlation of Stratigraphic Units of North America) project (e.g., Bishop et al., 1984a, b). In this chapter, I will summarize our current understanding of many of the correlations that were proposed over the last century, focusing especially on the correlation of the classic molluscan and benthic foraminiferal stages proposed by Clark and Vokes (1936), Kleinpell (1938), Mallory (1959), and later authors. Not every type section or critical

sequence has been studied in detail, but many of them have been, so it is appropriate that we place such a synthesis in this volume. Many more units remain to be studied, of course, and many more problems remain, but such is the nature of this dynamic research area that it is never stagnant, and always presents additional interesting problems to be solved.

## PALEOCENE

The Paleocene was a late addition to the standard Cenozoic time scale. Proposed by the paleobotanist Schimper in 1874, it was originally based on fossil plants, and was difficult to recognize in marine sections, or even terrestrial sections lacking plant fossils. Even in the early twentieth century, Paleocene rocks were still called "Lower Eocene" by most geologists, and the U.S. Geological Survey did not accept the term until 1939.

### Molluscan zones

The first recognition of "lower Eocene" (now Paleocene) fossils and rocks in the Pacific Coast came from the work on the Martinez Formation, east of the Berkeley Hills (Whitney, 1869; Stanton, 1896; Merriam, 1897; Weaver, 1905; summarized by Dickerson, 1911, 1914, and Weaver, 1953). This became the basis for the "Martinez Stage" of the Clark and Vokes (1936) time scale, which in turn was used in the Weaver et al. (1944) time scale. At the time, the term "Martinez" was widely used for all rock units with a Martinez molluscan assemblage, even if they were not lithostratigraphically connected to the type Martinez Formation, including rocks in the Coalinga area and even the San Francisquito Formation in southern California. Because these units are not truly referable to the Martinez Formation, they have since been renamed, but the confusion still persists, even in modern geologic maps which adopt the names from older maps without knowing their origin.

The type Martinez section (especially the Vine

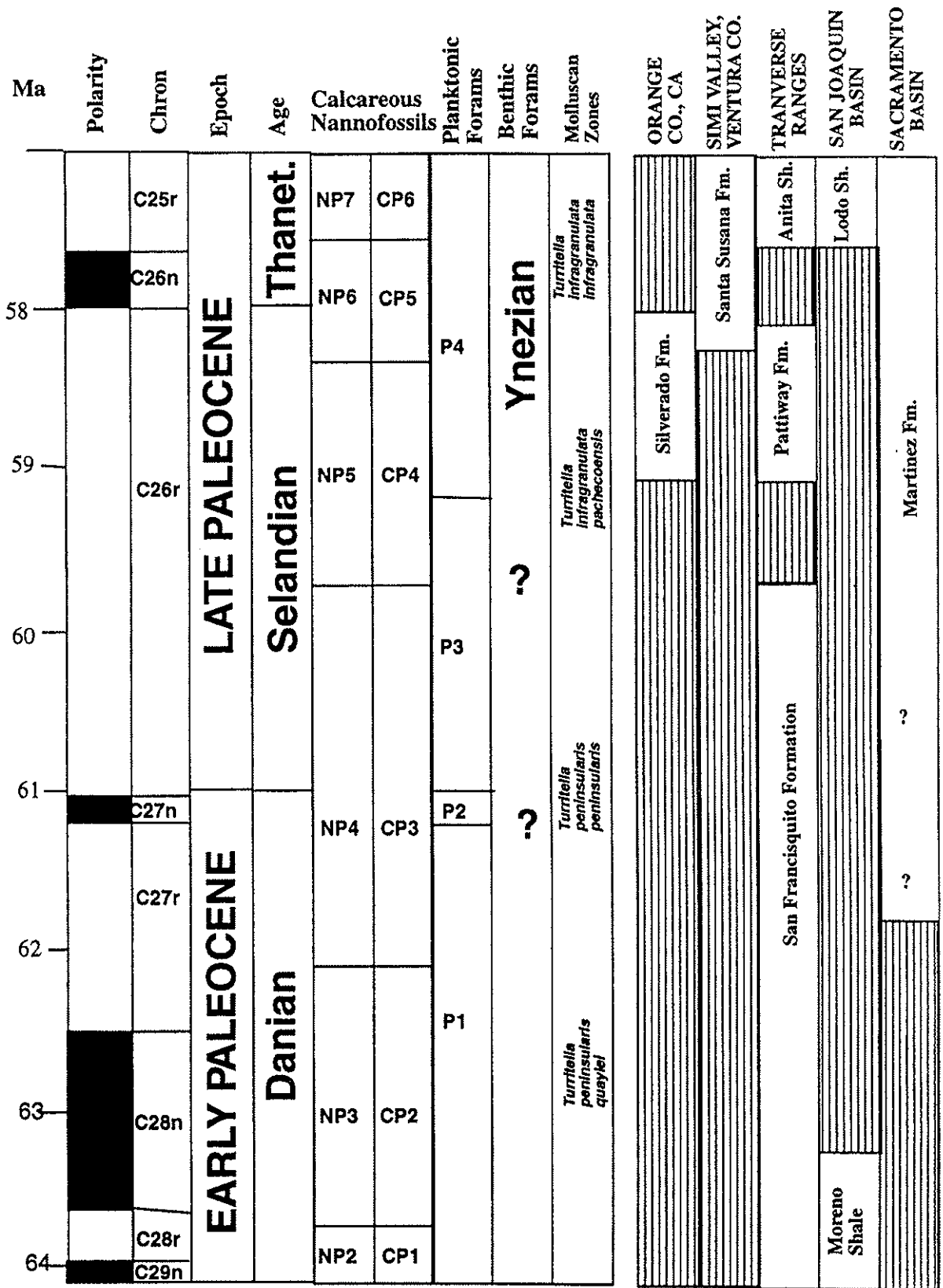


Figure 1. Correlation chart of Paleocene biostratigraphic zones and lithologic units. Time scale after Berggren et al. (1995) and Saul (1983). Vertical lines indicate temporal hiatuses between rock units (unshaded). Thanet. = Thanetian.

Hill Sandstone, which contains most of the molluscs that were the basis of the "Martinez Stage") is highly faulted, and very poorly exposed today, so it is impossible to do paleomagnetic sampling or make significant new collections of the fossils. Sullivan (1964) reported nannofossils from Zones CP6-7-8 from the Vine Hill Sandstone, which would place the unit in the latest Paleocene, but it is difficult to determine whether much older Paleocene rocks exist in the type area (Fig. 1). Saul (1983) proposed a zonation for the Paleocene based on the gastropod *Turritella*, and at present this is the highest-resolution biostratigraphic indicator for most of the Paleocene in the Pacific Coast. The early Paleocene (Danian) produces *Turritella peninsularis quaylei*, followed by *T. peninsularis peninsularis* in the latest Danian-early late Paleocene (Selandian), and then followed by *T. infragranulata pachecoensis* and *T. infragranulata infragranulata* in the late Paleocene (late Selandian-Thanelian) (Fig. 1). Unfortunately, there are no sections with thick and continuous records across the entire Paleocene to calibrate most of these zones, so their duration is still not well constrained at this point. Nevertheless, Saul (1983, fig. 14) showed that the lowest molluscan assemblages from the Vine Hill Sandstone include *T. peninsularis peninsularis*, which would suggest that the type Martinez Stage spans at least the early late Paleocene (Selandian) and possibly the late early Paleocene (late Danian).

#### **Benthic foraminiferal zones**

Laiming (1940, 1943) suggested that his benthic foraminiferal zone "E" was Paleocene in age, and this unit has proven its value in the subsurface rocks of the San Joaquin Basin (Almgren et al., 1988). Mallory (1959) proposed the "Ynezian" and "Bulitian" stages as benthic foraminiferal stages for the Paleocene of California. He (1959, p. 74) based the Ynezian Stage on the foraminifera from the lower Anita Shale in Arroyo el Bulito in the Santa Ynez Range, Santa Barbara County, California. The Bulitian Stage was based on foraminifera from slightly higher exposures in the Anita Shale in the same region. Almgren et al. (1988) indicated the numerous problems with Mallory's (1959) stages and zones. According to Sullivan (1964), the oldest nannofossils in the Anita Shale are no older than Zone CP6 (57.5 Ma and younger, or latest Paleocene), so the type section of the Ynezian Stage spans very little of the Paleocene (contrary to Mallory's concepts). Likewise, Mallory's principal

correlative for the Ynezian Stage, the Lodo Shale in the Panoche Hills of central California, is no older than Zone CP6 (Sullivan, 1964; Almgren et al., 1988). Although Ynezian benthic foraminifera are reported from older units in California, the type section is very short and spans very little of the Paleocene. Since ages do not have to be coextensive with their type sections, one could extend the concepts of Laiming's (1940, 1943) zone "E" or the Mallory's (1959) Ynezian Stage down to span the entire Paleocene, but this does little to resolve biostratigraphic problems within the Paleocene.

The supposedly Paleocene Bulitian Stage of Mallory (1959) has since been shown to be based on deep-water foraminiferal assemblages which were time-transgressive and correlative with the latest Paleocene to late early Eocene (Almgren et al., 1988, Fig. 2). Those authors redefined Mallory's Bulitian as equivalent of the earliest Eocene. Likewise, the supposedly late Paleocene Meganos molluscan stage of Clark and Vokes (1936) has also been shown to be earliest Eocene (Almgren et al., 1988).

#### **Paleocene correlations**

Nilsen (1987, p. 93-96) listed a number of Paleocene units in California. Unfortunately, many of these have been partially removed by pre-Eocene erosion, or do not crop out at the surface, and even fewer have good biostratigraphic control. Consequently, we cannot update the age assignments for many of the Paleocene units mentioned by Nilsen (1987). Some important units, however, have now been precisely dated. Rocks representing the early Paleocene (Danian Stage) are poorly represented in the Pacific Coast. Based on the presence of *Turritella peninsularis quaylei*, Saul (1983, Fig. 1) suggested that the upper part of the mostly Cretaceous Moreno Formation in the San Joaquin Valley and Coast Ranges is earliest Paleocene. The same is true of some of the lower San Francisquito Formation in the Warm Springs Mountain area. Unfortunately, it is too thin and discontinuous a section to be suitable for magnetic stratigraphy (Prothero and Vacca, this volume, a).

Later Paleocene units are much more widespread in California. The Silverado Formation in the Santa Ana Mountains of Orange County (Prothero and Lopez, this volume, a), the Pattiway Formation in the Caliente Range of San Luis Obispo County (Prothero and Vacca, this volume, b), and the Locatelli Formation of the Santa Cruz Mountains (Prothero and Lopez, this volume, b) all appear to be

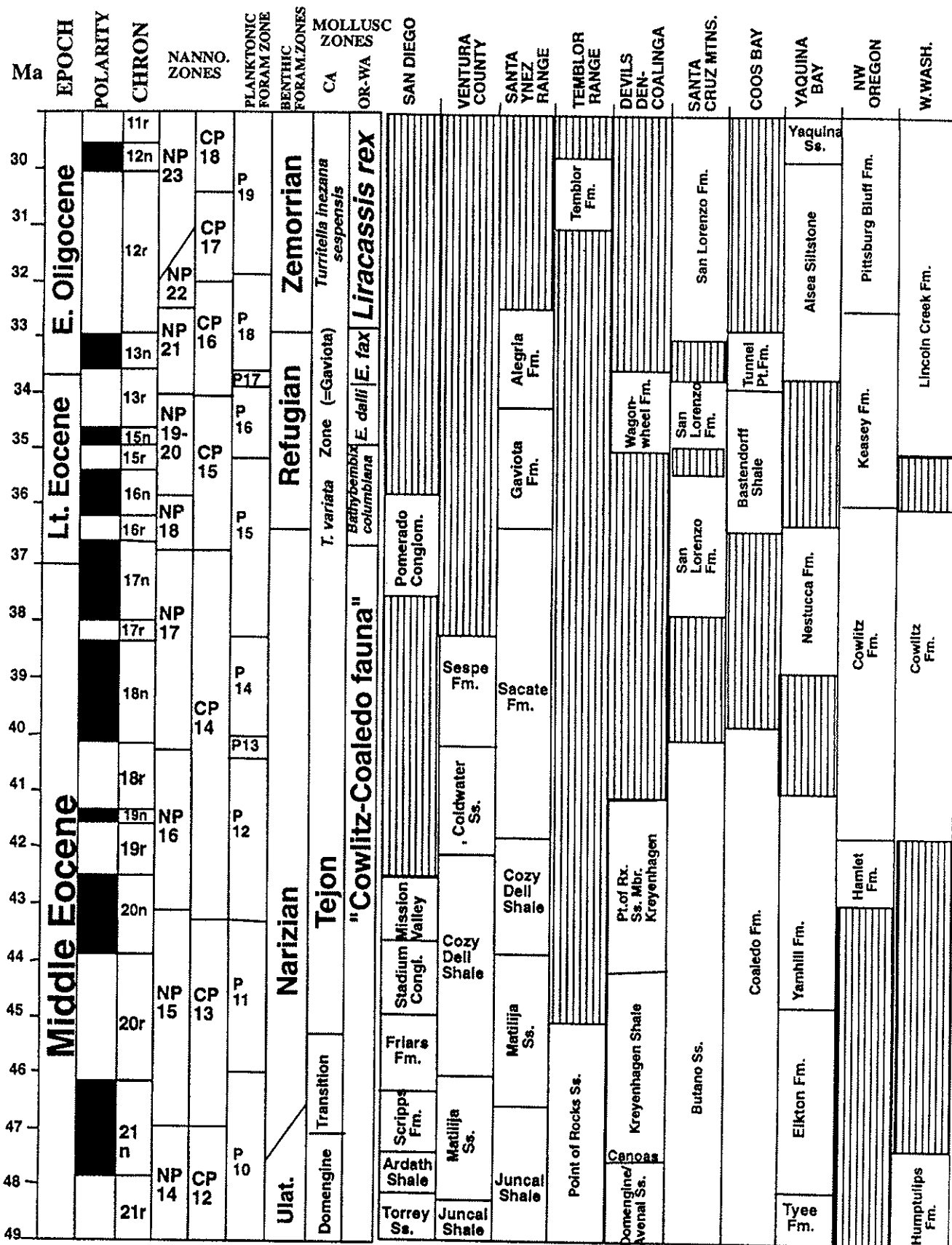


Figure 2. Correlation chart of middle Eocene to early Oligocene biostratigraphic zones and lithologic units. Time scale after Berggren et al. (1995), Squires (1988, 2002), Almgren et al. (1988), and Armentrout (1973, 1975, 1981). Vertical lines indicate temporal hiatuses between rock units (unshaded).

correlative with late Chron C26r (58-59 Ma), while the upper part of the San Francisquito Formation (members D, E, and F of Kooser, 1982) appears to correlate with early Chron C26r (59-61 Ma). Saul (1983, fig. 1) suggested that the Santa Susana Formation in the south side of the Simi Valley, Ventura County, might be as old as early Paleocene, but the planktonic microfossils and magnetostratigraphy of the upper part of the Santa Susana Formation from the north side of Simi Valley (Bottjer et al., 1991) show that it starts in late Chron C26r (59.5 Ma) and only spans the latest Paleocene. As discussed above, such crucial units as the Anita Shale, Lodo Shale, and most of the Vine Hill Sandstone are also latest Paleocene. Thus, the overall impression (Fig. 1) is that the Paleocene of California is very discontinuously represented. Only a few areas yield discontinuous early Paleocene sequences, and even the late Paleocene strata are rather patchy and discontinuous, even if there are more of them. Some of the units mentioned by Nilsen (1987) may improve the situation slightly, but since many of the classic well-sampled, fossiliferous sections have already been studied and yielded this discouraging picture, we are not optimistic than any of the less well-studied strata mentioned by Nilsen (1987) will produce a better Paleocene record. Rather, this suggests that Paleocene deposition was rather rare in California, ranging from almost non-existent (except in a few places) in the early Paleocene, to sparse in the late Paleocene. Unlike the thick and relatively continuous sections for the later Cenozoic epochs throughout the Pacific Coast, the Paleocene is much less well represented.

The Paleocene record in the Pacific Northwest is virtually non-existent. Armentrout et al. (1983) suggested that some of the Roseburg Formation of the Umpqua Group in southwestern Oregon might be Paleocene in age, but all the planktonic foraminifera described by Miles (1981) from this unit are early Eocene. Orr and Orr (1999, p. 126) report that Paleocene planktonic foraminifera were collected from a locality near Bandon, Oregon, but that elusive site has never been relocated. As Orr and Orr (1996) point out, coastal Oregon and Washington did not exist during most of the Paleocene, but was emplaced in the early Eocene when a series of basaltic seamounts joined with the Ancestral Cascade Arc, forming volcanic basement rocks such as the Siletz River, Roseburg, Crescent, and Tillamook volcanics.

## EOCENE

By contrast with the Paleocene, the Eocene is much longer (34.7-55 Ma, over 20 million years in duration, compared with only 10 million years of the Paleocene or Oligocene) and much better represented on the Pacific Coast. Rapidly subsiding forearc basins in Oregon and Washington (Orr and Orr, 1996) accumulated thick Eocene sequences in many places, and there were many basins subsiding in coastal California during the Eocene as well (Nilsen, 1987). The wealth of Eocene rocks (especially compared to the Oligocene or Paleocene) is apparent on any large-scale correlation chart (e.g., Armentrout et al., 1983; Bishop et al., 1984a, b). Consequently, there is a much more refined biostratigraphic zonation for much of the Eocene, based both on molluscs and on benthic foraminifera (Fig. 2).

### Molluscan zones

Clark and Vokes (1936) formalized the California molluscan stages that had developed over the previous 40 years, and their Eocene biostratigraphy was adopted in the Weaver et al. (1944) time scale. These stages are still being calibrated and refined (Squires, 1988, 2002; pers. communication) but some preliminary statements can be made here. The earliest of the stages, the Meganos, was correlated with the earliest Eocene. Almgren et al. (1988) showed that the deposits of the Meganos submarine canyon do indeed correlate with early Eocene nannofossil Zones CP9-CP11 (55-50 Ma). The second stage of the Eocene, the Capay, is based on assemblages from limited exposures of the Capay Shale near Winters, California, that are not amenable to magnetic stratigraphy. According to Almgren and Filewicz (1984) and Almgren et al. (1988), the type Capay Shale yields nannofossils of Zones CP9-11, so it is apparently overlapping in age with the type Meganos Stage. Redefinition of these stages to represent truly sequential time units (if this is possible) awaits further work by Richard Squires, and so will not be discussed here.

The succeeding Domengine Stage of Clark and Vokes (1936) has been sampled for magnetic stratigraphy in its type section (Prothero, this volume) and correlates with Chron C21r (48-49 Ma). Reference sections the Juncal-Matilija-Cozy Dell sequence in the Transverse Ranges (Prothero and Britt, 1998) suggest that the Capay/Domengine boundary occurs in Chron C22r (50.5 Ma), and the Domengine/"Transition" boundary early in Chron C21n (47.5 Ma, as calibrated by its position within

the Matilija Sandstone). The "Transition"/ Tejon Stage boundary occurs near the base of Chron C20r (46.0 Ma), based on calibration of the Friars Formation (which yields Domengine molluscs at the base and "Transition" molluscs at the top, and correlates entirely with Chron C20r) in the San Diego area (Walsh et al., 1996). Squires (1988) showed that the "Transition" Stage occurs entirely with nannofossil Zone CP13a (Fig. 2). The Tejon Stage of Clark and Vokes (1936), in turn, is extremely long, spanning most of the late middle Eocene to late Eocene (at least 10 million years, from 46 to at least 36 Ma). Clark and Vokes (1936) proposed a "Gaviota" molluscan stage for the latest Eocene (equivalent to the "*Turritella variata*" zone of Kleinpell and Weaver, 1963), based on the faunas of the Gaviota Formation in the Santa Ynez Range, western Santa Barbara County, California (Prothero and Thompson, this volume). But this stage has not held up to further scrutiny and is not used by current workers (e.g., Squires, 1988, 2002). In addition, Schenck and Kleinpell's (1936) original definition of the Refugian Stage for this same interval of time also included the molluscan component of the Gaviota Formation, so several terms have been proposed for the latest Eocene molluscan stages.

By contrast to the Eocene molluscan stages of California formalized by Clark and Vokes (1936), those of the Pacific Northwest have not been as well developed. Weaver et al. (1944) applied the molluscan stages of Clark and Vokes (1936) to the Pacific Northwest, but the correlations are not straightforward, since there is significant regional endemism between faunas. Instead, a partial local zonation has evolved for the Pacific Northwest Eocene molluscs (Fig. 2). No formal name has been proposed for the early Eocene, because molluscs of that age (and indeed, rocks of early Eocene age in general) are rare. The oldest well-defined faunas are those of the middle Eocene Cowlitz Formation of western Washington and Oregon, and the Coaledo Formation of southwest Oregon. Originally lumped into a "Cowlitz-Coaledo fauna" (e.g., Armentrout, 1981; Nesbitt, 1994), our subsequent studies have shown that the rocks which enclosed these faunas are not strict age equivalents. The Coaledo Formation is slightly older, spanning the interval from Chron C18r-C21r (40-49 Ma) (Prothero and Donohoo, 2001), while the Cowlitz Formation correlates mostly with Chrons C16r-C18r (36.5-41.0 Ma) (Prothero, Sanger, Nesbitt, Niemi and Kleibacker, this volume).

Together, the "Cowlitz-Coaledo fauna" spans the interval from 36.5-49 Ma (almost the entire middle Eocene), so it is not much use in resolving events within the middle Eocene. According to Nesbitt (pers. communication), the "Cowlitz-Coaledo fauna" is fairly homogeneous throughout this span of time, so there is not much hope of further subdividing this molluscan zone.

Weaver et al. (1944) used the lithologic terms "Keasey" and "Lincoln" as molluscan stages for the late Eocene in the Pacific Northwest. Durham (1944) proposed four molluscan zones for the same interval of time. Problems with this zonation led Armentrout (1973, 1975, 1981) to propose a series of molluscan zones for the late Eocene of Washington, replacing the earlier schemes, and this has become widely accepted. The "Keasey" stage of Weaver et al. (1944) and the "*Turricula columbiana*" zone of Durham (1944) are now called the *Bathybembix columbiana* zone of Armentrout (1973, 1975, 1981), the first zone of his Galvinian Stage. Based on the magnetostratigraphy of the Lincoln Creek Formation (Prothero and Armentrout, 1985), it correlates with Chron C15r-C16r (35.1-36.5 Ma), so it is early late Eocene in age. The lower "Lincoln" stage of Weaver et al. (1944) was originally subdivided into the "*Molopophorus gabbi*" and "*Molopophorus stevensoni*" zones by Durham (1944), but Armentrout (1973, 1975, 1981) recognized only the *Echinophoria dalli* zone. In the Lincoln Creek Formation (Prothero and Armentrout, 1985), it correlates with Chrons C13r-C15r (33.7-36.5 Ma), so it is latest Eocene in age (Fig. 2). It is also the basis for Armentrout's (1973, 1975) middle Galvinian Stage. The rest of Armentrout's molluscan zones are now considered Oligocene in age, and will be discussed in the next section.

### **Benthic foraminiferal zones**

Laiming (1940, 1943) and Mallory (1959) proposed a series of biostratigraphic zones for the Eocene of California based on benthic foraminifera. These have been the subject of much controversy, especially since many of Mallory's zones have proven to be based on time-transgressive deep-water species (McDougall, 1980; Almgren et al., 1988). For example, Almgren et al. (1988, fig. 2) showed that the early Eocene Penutian Stage of Mallory (1959) is based on taxa which are now known to occur from the latest Paleocene to the late early Eocene (nannofossil Zones CP7-CP11, 50-57 Ma). Likewise, the Ulatisian Stage of Mallory (1959) is

based on taxa that range from the earliest Eocene (nannofossil Zone CP9, 55 Ma) to early middle Eocene (CP13, 45 Ma). Almgren et al. (1988) redefined Mallory's (1959) zones to eliminate some of this problem of facies control, making the (formerly Paleocene) Bulitian Stage (Laiming's "zone D" emended) earliest Eocene, the Penutian Stage (Laiming's "zone C" emended) early Eocene (with a "persistent deep-water" facies that lasts until the middle Eocene, known as "Pseudo-C" in Laiming's terminology), and the Ulatisian Stage late early Eocene to earliest middle Eocene (Fig. 2). Under the criteria of Almgren et al. (1988), the Bulitian/Penutian boundary falls in mid-Zone CP9 (54.0 Ma), the Penutian/Ulatisian boundary in mid-Zone CP10 (52.0 Ma).

The Bulitian and Penutian stratotypes were not amenable to magnetostratigraphic analysis, but the type section of the Ulatisian Stage ("B" zones of Laiming, 1940) in the Vacaville Shale was studied by Prothero and Brabb (this volume). They found it spans the interval from mid-Chron C22r to mid-Chron C20r (46.0-50.5 Ma). Studies of the Ulatisian in Media Agua Creek in the Temblor Range (Prothero, this volume), on the other hand, found that it is time-transgressive (even as redefined by Almgren et al., 1988) from place to place. The base of the Ulatisian in the Vacaville Shale is 2 million years older (50.5 Ma) than it is in Media Agua Creek in the Temblor Range (48.5 Ma). The top of the Ulatisian is a million years younger (46.5 Ma) in the Vacaville type section than it is at Media Agua Creek (47.5 Ma) (see Fig. 2).

The Narizian Stage of Mallory ("A" zones of Laiming, 1940, 1943) was even more difficult to date than the previous stages. Its base is time-transgressive (46.5 Ma in the Vacaville section, but 47.5 Ma at Media Agua Creek). The Narizian type section in the Point of Rocks Sandstone near Devil's Den is now very poorly exposed and incomplete, so the magnetostratigraphic section spanned only a part of the Narizian time interval (Prothero, this volume). The Narizian/Refugian boundary falls within Chron C16n or C16r in the San Lorenzo Formation of the Santa Cruz Mountains (Prothero, Sutton, and Brabb, this volume) but clearly within Chron C16r in the Santa Ynez Range (Prothero and Thompson, this volume), so it is 36.5 Ma in age (very close to the middle-late Eocene boundary at 37.0 Ma).

The age of the Refugian Stage (based on both benthic foraminifera and molluscs by Schenck and

Kleinpell, 1936) has long been controversial, with various authors placing it in the late Eocene, the Oligocene, or both (see discussion in Prothero and Thompson, this volume). Almgren and Filewicz (1984) showed that most of the Refugian was late Eocene, with the uppermost part including earliest Oligocene, and this has been confirmed by our magnetostratigraphic analysis of the type section (Prothero and Thompson, this volume).

In Washington and Oregon, micropaleontologists (such as Rau, 1981) have generally tried to follow Mallory's criteria for recognizing the Eocene benthic foraminiferal stages of California. However, this has led to problems, as McDougall (1980) has demonstrated. For example, the criteria for the the Narizian, Refugian, and Zemorrian as defined in California by Mallory (1959) result in time-transgressive or partially overlapping stages in Washington; likewise, if the criteria of Washington foraminifera are applied to California, the same stages are time-transgressive or overlapping in age in a different way. As McDougall (1980) points out, the problem lies in using deep-water foraminifera which are tracking water depth locally, so that the local first appearance is controlled more by bathymetric changes than by true faunal evolution. McDougall (1980) redefined these foraminiferal stages for use in the Pacific Northwest, eliminating the foraminifera that caused the problems, so that they more closely represent true time-stratigraphic units.

### **Eocene correlations**

Correlations of some of the crucial middle-late Eocene units (based on the studies in this volume, and in other recent research) are summarized in Figure 2. Clearly, it is not possible to show every Eocene unit that might be found on the Armentrout et al. (1983) chart or the COSUNA charts. However, most of the classic units (e.g., those shown in Orr and Orr, 1996, p. 329, or Orr and Orr, 1999, p. 127) have been analyzed and more precisely correlated.

The most striking comparison between these older charts and Figure 2 is that the older charts were drafted as if each of the units spanned most of the available time, with relatively short unconformities and hiatuses between units. Our more precise correlations (Fig. 2) show that there are very few truly continuous sequences through much of the Eocene (only the Santa Ynez Range appears to meet this criterion), and most of the supposedly "continuous" sequences of strata are actually packages of rock representing relatively short intervals of time

with large hiatuses in between. This phenomenon is being discovered more and more often as high-resolution stratigraphic methods are applied to classic "continuous" stratigraphic sequences. As Ager (1973) pointed out almost 30 years ago, the stratigraphic sequence in any given place is "more gaps than record." Even in the relatively thick and rapidly deposited sequences of Pacific Coast forearc basins (which might be expected to be the most complete compared to passive margins or cratonic basins), the strata are still riddled with huge unconformities.

## OLIGOCENE

This theme of discontinuity is further reinforced when we consider the Oligocene record of the Pacific Coast. As reviewed by Prothero and Resseguie (this volume), even the presence of Oligocene beds in California has been questioned. Eames and others (1962) argued that "in the whole region we have considered (and even as far north as the state of Washington), there are no published records of stratigraphical successions of fossiliferous marine beds which can be dated as Oligocene." Lipps (1965) replied to Eames and others (1962), arguing that the type Saucian section in Los Saucos Creek, Ventura County, California, contains diagnostic late Oligocene planktonic foraminifera as recognized by Eames and others (1962). Lipps also showed that Kleinpell (1938) considered the Refugian, Zemorrian, and part of the Saucian stages to be correlative with the Oligocene (even though his book is entitled *Miocene Stratigraphy of California*), and Kleinpell and Weaver (1963) also thought that the Refugian-Zemorrian-Saucian succession in the Santa Ynez Range was partially correlative with the Oligocene.

Our recent studies have further confirmed that the Oligocene is indeed well represented in the Pacific Coast, but it is full of gaps and incomplete sequences in most places. Like the Eocene, there are very few successions that span much or most of the Oligocene, and unfortunately the regions that were chosen as stratotypes for biostratigraphic stages are among the most incomplete successions.

### Molluscan zonation

Unlike the formally established Eocene stages of Clark and Vokes (1936), no comparable molluscan zonation developed for the California Oligocene. But the molluscan zonation for the Oligocene of the Pacific Northwest is much more developed than it is in California. The Weaver Committee (1944) used

lithostratigraphic terms such as "Lincoln" and "Blakeley" for stage names, based on biostratigraphic zones erected by Durham (1944) for the Olympic Peninsula of Washington. These included the *Turritella olympicensis* and *Turritella porterensis* zones, which have since been merged into Armentrout's (1973, 1975, 1981) late Galvinian *Echinophoria fax* zone. Based on magnetostratigraphic calibration of the Lincoln Creek Formation (Prothero and Armentrout, 1985), this zone spans Chrons C13n-late C13r, or 33.0-34.7 Ma (earliest Oligocene). Above this, Durham (1944) recognized the early Oligocene "*Echinophoria*" (now *Liracassis*, *vide* Moore, 1984) *rex* zone (equivalent to the Matlockian Stage of Armentrout, 1981). According to Prothero and Armentrout (1985), the *Liracassis rex* zone and Matlockian Stage spans the interval from Chron C12r-C10n (32.5-28.5 Ma), or the rest of the early Oligocene.

According to Durham (1944), the late Oligocene is represented by the "*Echinophoria*" (now *Liracassis*) *apta* zone, whose type section was designated by Durham (1944) as the Pysht Formation on the northern Olympic Peninsula (also called the "Juanian Stage" of Addicott, 1976). Based on the magnetostratigraphy of the Pysht Formation (Prothero, Streig, and Burns, this volume) and the Lincoln Creek Formation (Prothero and Armentrout, 1985), we correlate the type Juanian Stage and *Liracassis apta* zone with Chrons C10n-C6Cr (24.0-28.5 Ma), so it is equivalent to the late Oligocene.

The only attempt at a molluscan zonation of the California Oligocene was presented by Kleinpell and Weaver (1963), who proposed an early Oligocene *Turritella inezana sespensis* and a late Oligocene *Turritella inezana inezana* zone, largely based on the Sespe-Alegria fossils in the western Transverse Ranges. However, Prothero and Thompson (this volume) and Prothero et al. (1996) showed that both the Sespe and Alegria formations are very incomplete, spanning only a small portion of the early Oligocene (late Chron C13r-early Chron C12r, 32-33.7 Ma), with a large hiatus followed by late Oligocene rocks (28.0 Ma and younger). So far as we know, there are no mollusc-bearing sequences in California which have a more complete record of the Oligocene. The San Lorenzo Formation is more complete, but yields molluscs in only a few places. Addicott (1973) described (but did not name) an early Oligocene molluscan zone based on the fauna of the Wygal Sandstone in the Temblor Formation of the Temblor



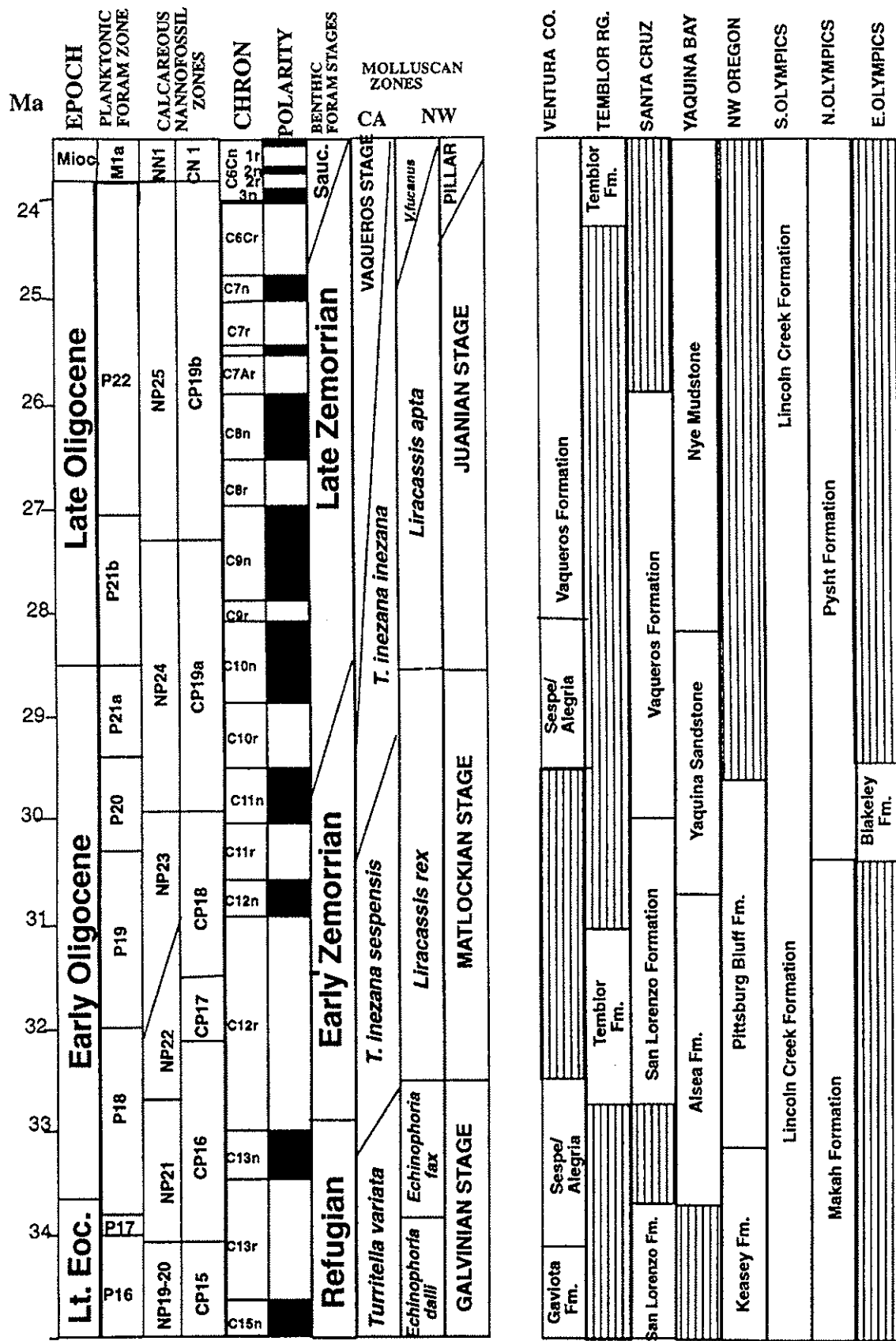


Figure 3. Correlation chart for Oligocene biostratigraphic zones and lithologic units. Time scale after Berggren et al. (1995), Kleinpell and Weaver (1963), and Armentrout (1973, 1975, 1981). Vertical lines indicate temporal hiatuses between rock units (unshaded). Pillar. = Pillarian.

Range. As Prothero and Resseguie (this volume) showed, the Wygal Sandstone spans only a very short portion of Chron C12r (32-33 Ma), so it is even less complete than the zonation suggested by Kleinpell and Weaver (1963).

The Vaqueros molluscan stage of Loel and Corey (1936) has long been equated with the early Miocene. However, as shown by Prothero et al. (1996), Vaqueros molluscs occur as early as Chron C9n (27.5 Ma) in the Simi Valley of Ventura County, California, and C11n (30.0 Ma) in the San Lorenzo-Vaqueros strata of Santa Cruz County. Thus, the Vaqueros Stage spans a significant portion of the late Oligocene.

### **Benthic foraminiferal zonations**

Only two benthic foraminiferal stages have generally been correlated with the Oligocene: the Refugian Stage of Schenck and Kleinpell (1936) and the Zemorrian Stage of Kleinpell (1938). As discussed above, recent work (Almgren and Filewicz, 1984; Prothero and Thompson, this volume) has shown that only the latest Refugian is Oligocene in age (earliest Oligocene, 33.0-33.7 Ma). The Zemorrian Stage is even more problematic. Kleinpell (1938) designated its type section as the lower part of the Temblor Formation in Zemorra Creek in the southern Temblor Range. As Prothero and Resseguie (this volume) demonstrated, this type section is very short and incomplete, spanning only a small portion of the earliest Oligocene (32-33 Ma) for the Cymric Shale and Wygal Sandstone, and a tiny portion of the latest Oligocene and early Miocene (23.7-24.7 Ma), with a hiatus between 24.7 and 32 Ma that spans almost the entire Oligocene. In retrospect, this was a very poor choice for a Zemorrian type section, but as Kleinpell (1938) noted, it was the best surface exposure of that stage available at the time, and represented much more thick and complete packages of Oligocene strata in the subsurface of the San Joaquin Basin. Tipton et al. (1973) described more complete Oligocene successions from the San Joaquin Basin, but unfortunately most of these are found only in the subsurface as well.

A much more complete sequence of Zemorrian strata was described from the San Lorenzo Formation of the Santa Cruz Mountains, which was the basis for the original "San Lorenzo" Oligocene stage of early time scales. In these strata, early Zemorrian foraminifera are found from Chrons C12r-C11r (30.2-32.0 Ma), while late Zemorrian foraminifera are found from Chrons C8n-C11n

(26.0-30.2 Ma). However, Prothero and Armentrout (1985) found that in the Lincoln Creek Formation of Washington, the early/late Zemorrian boundary occurred in Chron C10n (28.5 Ma), rather than the C11r/C11n boundary (30.2 Ma), which suggests that this boundary may be time-transgressive by almost 2 million years.

Studies of the planktonic microfossils have shown that in the Zemorrian type section at Zemorra Creek, Zemorrian benthic foraminifera are found in strata that yield earliest Miocene (Zone CN1) calcareous nannofossils. However, in the type section of Kleinpell's (1938) early Miocene Saucesian Stage in Los Sauces Creek, Ventura County (Lipps, 1965; Lipps and Kalisky, 1972), Saucesian strata yield latest Oligocene planktonic foraminifera. Thus, it appears that the Zemorrian and Saucesian are not successive stages as proposed by Kleinpell (1938), but in fact overlap in age across the Oligocene/Miocene boundary (Fig. 3).

### **Oligocene correlations**

Some correlations of important Oligocene units are shown in Figure 3. Unlike the Eocene, there are several sequences (the Canyon River Lincoln Creek sequence and the Pysht Formation of Washington, the Alsea-Yaquina-Nye sequence of Oregon, and the San Lorenzo-Vaqueros Formations of California) which appear to span much or most of the Oligocene. Ironically, the type sections of Oligocene zones and stages (such as the type Zemorrian in the Temblor Range, and the types of Kleinpell and Weaver's molluscan stages in the Santa Ynez Range) are among the more incomplete sequences now known. Nevertheless, the overall impression of the Oligocene is that in most regions, it is much thinner and less complete than portrayed on earlier correlation charts (e.g., Weaver et al., 1944; Armentrout, 1981; Armentrout et al., 1983; Bishop et al., 1984a, b). As we have mentioned already, incompleteness is the rule rather than the exception, even in the Pacific Coast forearc basin settings.

### **MIOCENE-PLIOCENE**

The Miocene and Pliocene of the Pacific Coast have been the focus of research interest for many years. This is largely because Miocene-Pliocene rocks are the source of much of the oil wealth in California, and are widely exposed with many thick sections in many parts of the Pacific Coast. The siliceous shales of the Monterey Formation in particular have been studied very intensively, not only

because of their oil, but also because of their paleoceanographic implications.

By contrast, the Miocene and Pliocene of the Pacific Northwest were much less completely studied and represented. Ironically, the first Cenozoic fossils described from the West Coast of North America were molluscs collected by J.K. Townsend between 1834 and 1837 from the Astoria Formation, near Astoria, Oregon. Conrad (1848) described these fossils and correctly realized that they were of Miocene age (even though the concept of Miocene was still poorly defined in the type areas of Europe at that time).

The Miocene, like the Eocene, is also a very long interval of time (23.7-5.3 Ma, according to Berggren et al., 1995), almost 18.5 million years in duration. This long interval is marked by many biostratigraphic zones on the global time scale, and an extraordinarily busy magnetic polarity signal, so it lends itself to very precise correlation if the appropriate chronostratigraphic tools are present. Unfortunately, the biostratigraphic zonations developed for the Pacific Coast are relatively low in resolution, and prone to the same problems of time-transgression that we have seen elsewhere in the Cenozoic.

### Molluscan zonation

The California Miocene-Pliocene molluscan zonation was never formally established by a single author, but instead grew haphazardly as shallow marine units bearing distinctive faunas were described. As in the case of other zonations, the original biostratigraphic stage terms were actually the names of lithologic units, on the assumption that the fossil content is homogeneous throughout. By the time of the Weaver Committee report (1944), the "Vaqueros Stage" was used for the early Miocene, the "Temblor Stage" was used for the middle Miocene, and the "Briones Stage" was equivalent to the late Miocene. The Weaver et al. (1944) time scale also added the "Cierbo," "Neroly," and "Jacalitos" Stages to the late Miocene. Later time scales have used only the "Margaritan Stage" (based on the molluscs of the Santa Margarita Formation) and the "Jacalitos Stage" as late Miocene zones in California (Bishop et al., 1984a, b). Lithostratigraphic units such as "Etchegoin" and "San Joaquin" are used as Pliocene molluscan stage names in California (Bishop et al., 1984a, b).

The Vaqueros Stage has proven particularly problematic. The distinctive Vaqueros molluscan

assemblage (Loel and Corey, 1936), including such taxa as *Turritella inezana* and *Rapana vaquerosensis*, is very widespread and long-ranging in California. As discussed above, in some places the Vaqueros Formation and its molluscs occur in strata as old as Chron C9n (27.5 Ma) in the Simi Valley of Ventura County, California, and C11n (30.0 Ma) in the San Lorenzo-Vaqueros strata of Santa Cruz County (Fig. 3), so the Vaqueros Stage begins in the late Oligocene. In the Santa Ana Mountains of Orange County, Vaqueros molluscs occur in strata overlying mammal-bearing Sespe redbeds that are dated at 18 Ma (Prothero and Donohoo, this volume). Thus, it appears that the Vaqueros Stage spans a very long interval of time (at least 30-18 Ma), or 12 million years of the late Oligocene and early Miocene (Prothero and Hoffman, this volume). Instead of being restricted to the early Miocene, as geologists once thought, it now appears that the Vaqueros Stage is so long in duration that it is meaningless for high-resolution studies.

The Temblor Stage is also based on the faunas from a very long-ranging lithologic unit, and so offers little resolution regarding the early or middle Miocene. The lower Temblor Formation produces the type Zemorrian benthic foraminiferal zone, and Addicott's (1973) "unnamed zone" of Refugian or early Zemorrian molluscs, so it is not relevant here. The upper members of the formation (Carneros Sandstone, Media Shale, and Buttonbed Sandstone) yield their own distinctive molluscan assemblages that were the original basis of the Temblor Stage (Stewart, 1946; Adegoke, 1969). In the type area in the southern Temblor Range, Mark Filewicz (pers. communication) has documented early Miocene Zone CN1 nannofossils in the Carneros Shale, Zone CN2 nannofossils in the Media Shale, and Zones CN3-CN5 nannofossils in the upper Media Shale and Buttonbed Sandstone. Apparently most of the type Temblor Stage is early Miocene (as old as 23 Ma), and overlaps in age with the Vaqueros Stage. The upper parts may just barely reach into the middle Miocene, as previous authors have suggested. Other Miocene molluscan faunas (such as those of the Topanga Formation, or those from the San Joaquin Basin described by Stewart, 1946) that have been referred to the Temblor Stage may be slightly younger than the type Temblor faunas. However, the total age span of the Temblor Stage (23 Ma to at least as young as 16 Ma) is so long as to be virtually useless as a biochronologic unit, since it overlaps

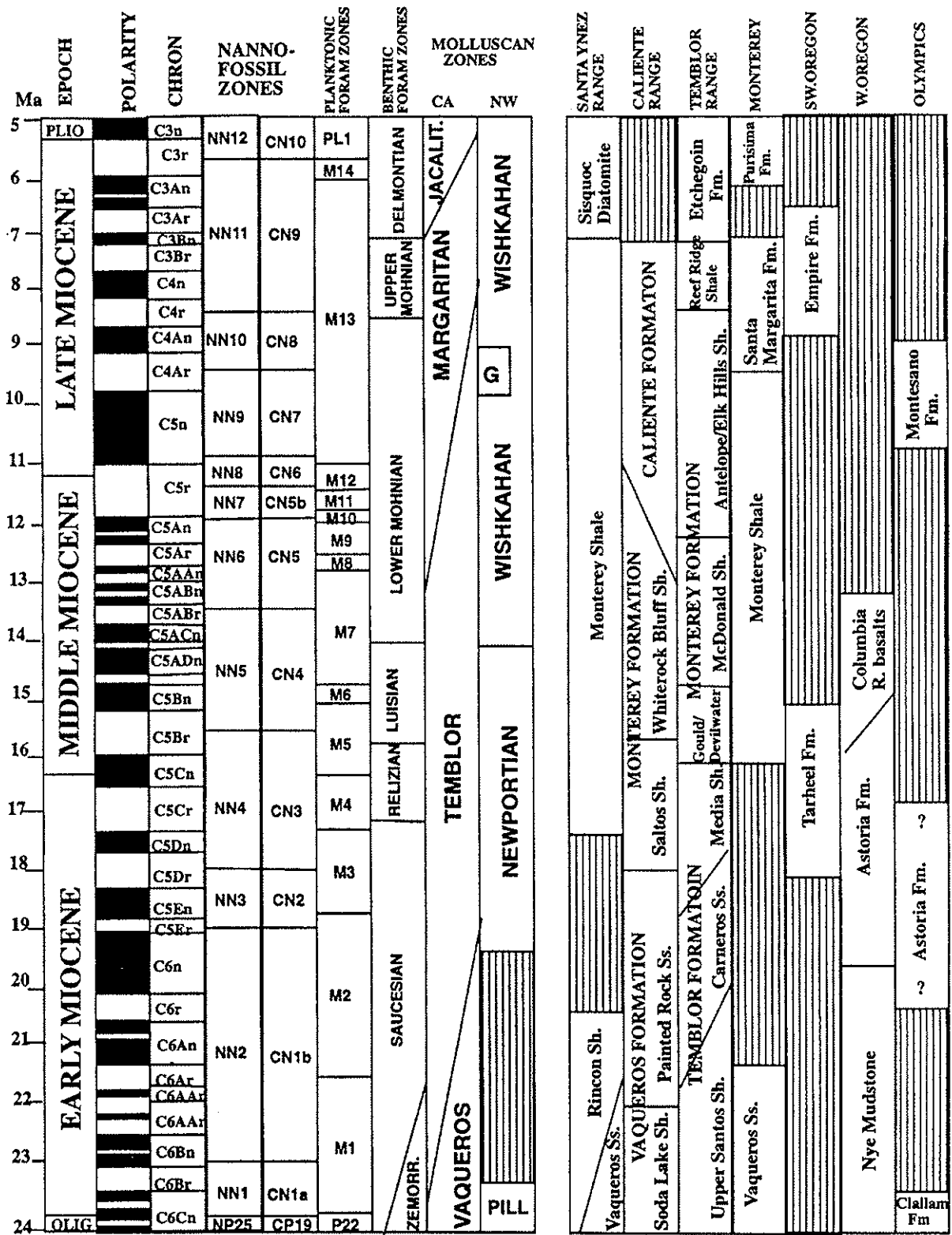


Figure 4. Correlation chart for Miocene-Pliocene biostratigraphic zones and lithologic units. Time scale after Berggren et al. (1995), Barron (1976), Barron and Isaacs (2001). Benthic foraminiferal stages follow Blake (1991), although they are actually time transgressive (see discussion in text). Lithologic units follow chapters in this volume, and correlations by Bishop et al. (1994a, 1994b) and Armentrout et al. (1983). Vertical lines indicate temporal hiatuses between rock units (unshaded). G = Graysian Stage; PILL = Pillarian Stage of Addicott (1976).

with much of the Vaqueros Stage, and spans most of the early and a bit of the middle Miocene.

The Margaritan Stage is based on the abundant molluscan faunas of the Santa Margarita Formation, widespread in the Coast Ranges and the southern San Joaquin Basin, as well as parts of the Transverse Ranges. In the southern San Joaquin Basin (Wilson and Prothero, 1997), the Santa Margarita Formation has been dated by magnetic stratigraphy to span parts of Chrons C5Cn to C5Br (17-15.5 Ma), making it early middle Miocene, not late Miocene as once supposed. Barron (1976) used diatom zonations to show that Santa Margarita exposures range in age from 13 to 8.5 Ma (late middle to early late Miocene).

In contrast to California, the molluscan zonation of the Miocene of the Pacific Northwest was formalized by Addicott (1976; see also Moore and Addicott, 1987). Addicott recognized the Juanian Stage (now considered late Oligocene—see above) and Pillarian Stage as early Miocene, the Newportian Stage as middle Miocene, and the Wishkahan and Graysian stages as late Miocene. The Moclipsian Stage was proposed as a Pliocene molluscan biozone, based on the faunas of the Quinault Formation. In his diagram (Addicott, 1976, fig. 1), he suggests that these stages are continuous and span most of Miocene and Pliocene time, but our recent studies do not support this contention. For example, the Pillarian Stage (based primarily on the faunas of the Clallam Formation in the northern Olympic Peninsula) may correlate with latest Oligocene Chron C6Cn3n-C6Cn2r, or 24.2-23.8 Ma (Prothero and Burns, this volume). If this interpretation is correct, the type Pillarian is latest Oligocene and spans only about 0.4 million years, not the 7 million years of the early Miocene as once thought. The upper Nye Mudstone (Prothero, Bitboul, Moore, and Niem, this volume), also Pillarian in age, may extend up into more of the early Miocene and provide a more complete Pillarian section than the type Clallam section, but it has proven too discontinuously exposed for detailed paleomagnetic sampling.

The Newportian Stage, based on the molluscs of the Astoria Formation near Newport, Oregon, spans part of the early Miocene to part of the middle Miocene, based on the magnetostratigraphic correlation with Chron C6n to C5Bn2 (19.2-15.1Ma) (Prothero, Bitboul, Moore, and Moore, this volume).

The allegedly late Miocene Wishkahan and Graysian Stages, on the other hand, turned out to be

problematic. As first recognized by Armentrout (1981) and Barron (1981), they are not true successive stages as conceived by Addicott (1976). Instead, type Wishkahan and Graysian section correlates with mid-Chron C5n to Chrons C4Ar (10.5-9.1 Ma). The referred Wishkahan faunas from the Empire Formation in Oregon are considerably younger (8.5-6.5 Ma) than the supposedly younger Graysian faunas in the type section in the Montesano Formation (Prothero, Lau, and Armentrout, this volume; Prothero and Lau, this volume). It appears that the "Graysian Stage" molluscs are a local shallow-water facies equivalent to part of the Wishkahan, instead of successive stages as suggested by Addicott (1976). The stratotypes of both stages span only a small part of the total duration (11.3-5.3 Ma) of the total late Miocene.

### **Benthic foraminiferal zonations**

The Miocene benthic foraminiferal zones of Kleinpell (1938, 1980) were the first attempt at a truly modern range zone biostratigraphy in the Pacific Coast, in contrast with the older zonations which equated rock units with biostratigraphic units (Berry, 1999). Kleinpell (1938) established six provincial stages (Fig. 4) for the Miocene: Saucesian and Relizian for the early Miocene; Luisian and Mohnian for the middle Miocene; Delmontian and Repettian for the late Miocene. In addition, he originally thought his Zemorrian Stage was Miocene, although as discussed above, it is now considered mostly Oligocene in age.

Although Kleinpell's benthic foraminiferal zones have been generally quite successful in correlating Miocene strata across much of California, they have some of the same problems of incompleteness and time-transgression seen in the Paleogene benthic foraminiferal zonations. Crouch and Bukry (1979) studied samples from cores drilled from the California offshore region. They showed that most of Kleinpell's (1938) zones are overlapping in age when they are calibrated by planktonic microfossils, such as coccoliths. For example, coccolith samples suggested that the Saucesian and Relizian stages overlap in nannofossil Zones CN3 and CN4, and the Relizian and Luisian overlap completely in Zones CN3, CN4, and CN5. According to their coccoliths, the lower Mohnian overlaps with the Luisian in Zones CN4, CN5, and CN6, and the upper Mohnian overlaps with the lower Mohnian by several nannofossil zones. In their study, they found samples which all had Zone CN4 coccoliths, but could be

assigned to the Relizian, or Luisian stages, and other samples with yielded Zone CN4-CN5 coccoliths, but foraminifera from the Saucesian, Relizian, or Luisian stages.

For this reason, Miocene biostratigraphers have begun to adopt a modified form of Kleinpell's zonation, based on planktonic microfossil calibrations of the type sections (where possible). Presumably this refined zonation avoids some of this time-transgression (e.g., Blake, 1991). Some of these stratotypes of stages, however, have proven to be problematic. As discussed above, the type Saucesian Stage in the Rincon Shale in Los Sauces Creek, Ventura County, California, may overlap in age with the type Zemorrian, with each stage spanning the Oligocene/Miocene boundary. Magnetostratigraphic studies of the best available sections of the normally poorly exposed Rincon Shale at Tajiguas Landfill, Santa Barbara County, showed that the section is very short in duration, and correlates with either magnetic Chrons C6Aa-C6Br (23.2-22.2 Ma), or with Chrons C6r-C6An (21.5-20.0 Ma) (Prothero and Rapp, this volume). No matter which correlation is adopted, however, it is clear that this section of the Rincon Shale spans at most 1.0-1.5 million years of the total of 8 million years of the early Miocene.

Poore et al. (1981) studied the diatoms and calcareous nannofossils of the type section of the Relizian in Reliz Canyon in the central Coast Ranges, and found that it spanned part of nannofossil Zones CN2 and CN3, as well as diatom zones which indicated a temporal span of 18-16 Ma, or late early Miocene. However, there is a considerable temporal gap between the oldest type Relizian at 18 Ma and the youngest type Saucesian at 20 or 22 Ma.

Poore et al. (1981) and Baldauf and Barron (1982) examined the diatoms and nannofossils of the type Luisian Stage, near San Luis Obispo. Its duration was restricted to nannofossil Zone CN4 (15.5-13.5 Ma, or early middle Miocene).

The Mohnian Stage has proven to be highly problematic. Its type section in the Modelo Shale along Topanga Canyon Road near Mohn Springs is now completely overgrown and unsuitable for sampling for further fossils or paleomagnetism. As discussed by Ford (1972) and Blake (1991), there are numerous problems with the definition of the Mohnian Stage as well, mostly due to the problematic benthic foraminiferal taxa. In some zonations, the Mohnian Stage includes the entire middle and late Miocene. Using planktonic microfossils, Blake

(1991) suggested a correlation with the interval from 14-7 Ma (middle to early late Miocene). Finally, the Delmontian Stage is partially overlapping with the upper Mohnian Stage using some criteria. Based on diatoms, Barron (1976) showed that the type Delmontian near Monterey, California, is about 11-9 Ma, or late middle to early late Miocene. However, Kleinpell (1938) designated the type *Bolivina obliqua* subzone as the lower subzone of his Delmontian Stage. Blake (1991) recognized the Delmontian Stage by the *Bolivina obliqua* subzone, assigning it an age of 7-5 Ma. In its type area in the Santa Monica Mountains near Los Angeles, the *Bolivina obliqua* subzone is about 7-5 Ma, or latest Miocene to earliest Pliocene (Barron, 1976; Barron and Isaacs, 2001).

In contrast to the differences in Miocene molluscan zonations between California and the Pacific Northwest, the benthic foraminiferal zonation of Kleinpell (1938) has also been applied in Oregon and Washington, with some modifications (Rau, 1981; Armentrout et al., 1983). Different key taxa are used to define the Saucesian, Relizian, Luisian and Mohnian in Washington, but Kleinpell's names are still used despite these fundamental differences in definition. However, Miocene deep marine rocks are much less common in this region than they are in California, so there has been correspondingly less use of benthic foraminifera (or detailed study of their correlation to planktonic microfossil zones) than there has been in California.

### Miocene correlations

Correlation of some of the more important Miocene biostratigraphic zonations and lithologic units is shown in Figure 4. As was apparent in our discussion of the Paleogene epochs, the overall pattern is "more gaps than record." Few places have strata that record very long intervals of time, and even between the standard biostratigraphic stages and zones (especially the molluscan zones of Addicott, 1976), there are long hiatuses. However, due to the long, continuous slow deposition of units such as the Monterey Formation, there are some places where a nearly continuous Miocene record exists. In addition, the high silica content of many of these rocks makes them amenable to diatom biostratigraphy, complementing the biostratigraphy of the calcareous plankton that have been traditionally used in global correlations.

## DISCUSSION AND CONCLUSIONS

The chronostratigraphy of the Pacific Coast Cenozoic has come a long way since the early time scale of Arnold (1906) (see the first chapter of this volume). Early stratigraphic concepts used rock units interchangeably with biostratigraphic units, focused on benthic organisms such as molluscs, and considered the stratigraphic record of the Pacific Coast Cenozoic to be relatively complete and continuous. Correlation to the global standard of Lyellian epochs was problematic at best, since few of the molluscan taxa could be reliably correlated to the type faunas in Europe. By the time of the Weaver Committee report (1944), the complexity of the zonation had increased (especially with the addition of benthic foraminiferal zonations), but the time scale still confused rock units with biostratigraphic units. However, the summary correlation chart in the Weaver Committee Report (1944) began to suggest that the Pacific Coast marine record was much less complete than originally thought. Correlation with the global standard, however, was still as difficult as it had been since the beginning of the century. The major breakthrough occurred in the 1960s, 1970s, and 1980s, when planktonic microfossils were used to calibrate sections whose ages were based largely on benthic foraminifera. These provided not only the first reliable correlation to the global time scale and the Lyellian epochs, but also showed that biostratigraphic zonations based on benthic organisms can be grossly time-transgressive.

The last decade of paleomagnetic studies has further confirmed many of these realizations. Magnetic stratigraphy has made it possible to correlate these sections to the global standard at a resolution of less than 100,000 years, and provide precise local positions of the boundaries between European epochs and ages, finally resolving over a century of confusion and controversy. High-resolution magneto-biostratigraphic correlations have also further reinforced the evidence that many or most of the benthic zonations have time-transgressive boundaries, or overlap in age, or have long hiatuses between supposedly continuous stages.

Even more impressive is the strong evidence (Figs. 1-4) that the stratigraphic record in the Pacific Coast Cenozoic is very incomplete, "more gaps than record," in Ager's (1973) words. This might be expected in passive margin and cratonic basins, which have relatively low sedimentation rates and high probability of unconformities, but it is also true

of the active margin forearc basins of the Pacific Coast, which have huge hiatuses despite their long histories of subsidence and high rates of sedimentation. Instead of the simplistic representation of the Pacific Cenozoic formations as continuous sedimentation, and the biostratigraphic zones as continuously covering all of Cenozoic time, our modern conception (Figs. 1-4) shows that for a given area, most time is *not* represented by rocks, and the classic "continuous biostratigraphy" is full of gaps and overlaps.

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