INTRODUCTION: A CENTURY OF PACIFIC COAST CENOZOIC CHRONOSTRATIGRAPHY

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ABSTRACT

Although Cenozoic fossils and strata from the Pacific Coast were documented and described as early as 1839, the first true Pacific Coast Cenozoic marine time scale was that of Arnold (1906). The early time scales of Arnold and Hannibal (1913) and Weaver (1912, 1916) were based on molluscan faunas from surface outcrops and did not distinguish between lithostratigraphic and biostratigraphic units. This work culminated with the Clark and Vokes (1936) molluscan zonation for the California Eocene. In the 1930s, benthic foraminifera were used to construct another type of time scale, much more useful for oil prospecting and deciphering monotonous shales from core samples. Kleinpell (1938) not only established the first benthic foraminiferal time scale for California, but also introduced many key biostratigraphic principles, including Oppelian range-zone biostratigraphy, which subdivided rock units into biostratigraphic zones. A conflict between the two approaches was apparent when the Weaver Committee formalized the Pacific Coast Cenozoic time scale in 1944. Not only was there disgreement about local correlation, but there were enormous difficulties in correlation of the local zonation to the Lyellian epochs and stages, based on European type sections. In the 1960s and 1970s, planktonic microfossil biostratigraphy solved many of these correlation problems with Europe, and also showed that many of the benthic foraminiferal stages on the Pacific Coast were time-transgressive. Because benthic foraminifera can track water depth, while plankton float freely in surface waters around the world, they are much better zonal indicators. Limited radiometric dating has been applied to Pacific Coast Cenozoic marine strata, but most rocks either have no volcanics or their volcanics are too altered for reliable dating. In the past decade, many of the classic sedimentary sections on the Pacific Coast have been analyzed using magnetic stratigraphy, allowing not only better correlation to local and global time scales, but also to stratigraphic resolution of events to less than 100,000 years.

INTRODUCTION

The first collections of Cenozoic marine strata and fossils from the Pacific Coast were published over 160 years ago (Townsend, 1839) from the Miocene Astoria Formation near Astoria, Oregon. These fossils were described by Timothy Conrad of the Academy of Natural Sciences in Philadelphia (1848, 1849). Conrad correctly realized that these fossils were Miocene in age, based on their similarities to the molluscs of the Calvert Cliffs (only 15 years after Lyell had coined the term "Miocene"). Over the next fifty years a number of paleontologists (mostly based on the East Coast) described additional faunas from the Pacific Northwest as they were collected and sent east for study. At the same time, reconnaissance geologic mapping (spurred by surveys for transcontinental railroad routes) proceeded rapidly in California, Oregon, and Washington. In 1875, the discovery of oil in California, and shortly thereafter, the discovery of important coal deposits in Oregon and Washington, also spurred further geological exploration. By the end of the nineteenth century, many key lithostratigraphic units were recognized, and their fossil contents described.

However, the integration of lithostratigraphy and fossils to construct a composite geological column for the Pacific Coast was primarily a twentieth-century development. As that century ends and a new one begins, it is appropriate to place the papers in this volume in historical context.

PHASE ONE: MOLLUSCAN STAGES

Two institutions figured prominently in the next phase of Pacific Coast Cenozoic biostratigraphy. Most of the activity took place at the University of California, Berkeley, which became dominant in West Coast paleontology once J.C. Merriam founded the Department of Paleontology in 1912. Merriam, a 1898 Berkeley graduate, returned to the Univesity of California after he obtained his doctorate in Munich under Karl von Zittel. While he was an undergraduate at Berkeley, Merriam worked on Cenozoic invertebrates, but when he returned he focused on building the department, supporting paleontological

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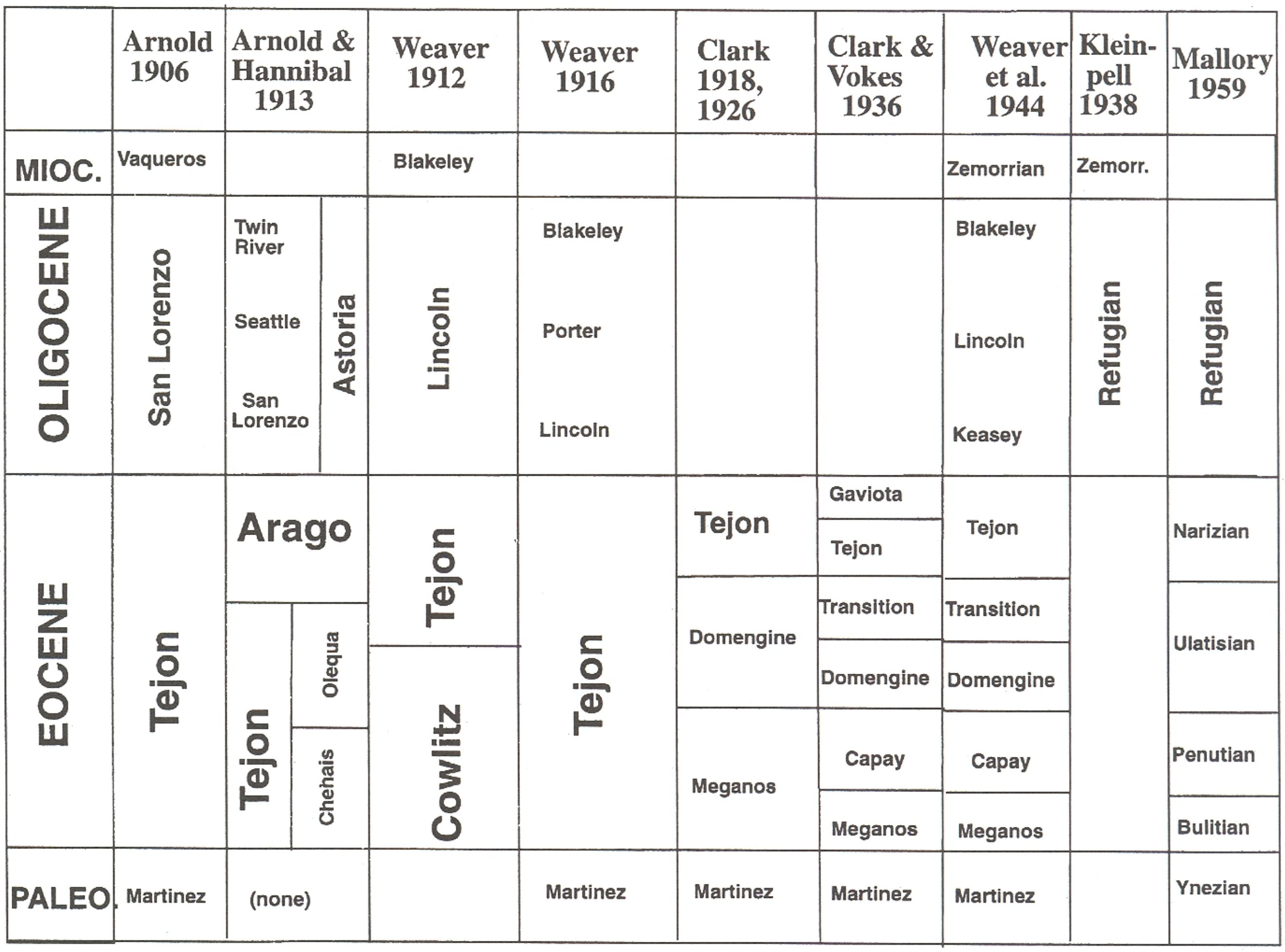
Figure 1. John C. Merriam and his students, Berkeley, California, 1915. From left to right: J.P. Buwalda, Earl L. Packard, Merriam, W.S.W. Kew, Jorgen Nomland, Chester Stock, and Bruce L. Clark. (Photo courtesy University of Californa Museum of Paleontology).

research, teaching, and eventually shifted his own research interests to fossil mammals. Many of the key figures (Fig. 1) in the early history of West Coast paleontology were (directly or indirectly) students or colleagues of Merriam, including Charles Weaver, Bruce Clark, Earl Packard, and Harold Vokes, along with pioneering West Coast vertebrate paleontologists such as Chester Stock and W.S.W. Kew. Weaver (Fig. 2) went on to found the paleontology program at the University of Washington in 1907, and trained many other influential paleontologists, including J.P. Buwalda (who spent many years at Berkeley, and then helped Chester Stock establish geology and paleontology at Caltech), Earl Packard (who became the paleontologist first at the University of Oregon, then later at Oregon State University), and distinguished Stanford malacologist Katherine V.W. Palmer.

Figure 2. Charles Edwin Weaver

The third key institution at the this time was Stanford University. With the arrival of James P. Smith (trained in Göttingen, Germany) in 1892, Stanford produced many of the pioneers of Pacific Coast Cenozoic biostratigraphy, including Ralph Arnold, Wayne Loel, and Harold Hannibal. Hubert Schenck, trained by Packard at Oregon, and got his doctorate from Bruce Clark at Berkeley in 1926. He came to Stanford in 1924, initially working on Oligocene molluscs and formations of Oregon. He eventually became one of the first to train micropaleontologists on the West Coast.

The first significant step toward constructing a Cenozoic time scale for the Pacific Coast was taken by Ralph Arnold, who spent the period from 1900-1909 at the U.S. Geological Survey. Basing his work



	Arnold 1906	Arnold & Hannibal 1913	Weaver 1912	Weaver 1916	Clark 1918, 1926	Clark & Vokes 1936	Weaver et al. 1944	Klein-pell 1938	Mallory 1959
MIOC.	Vaqueros		Blakeley				Zemorrian	Zemorr.	
OLIGOCENE	San Lorenzo	Twin River Seattle San Lorenzo Astoria	Lincoln	Blakeley Porter Lincoln			Blakeley Lincoln Keasey	Refugian	Refugian
EOCENE	Tejon	Arago Olequa Chehalis Tejon	Tejon Cowlitz	Tejon	Tejon Domengine Meganos	Gaviota Tejon Transition Domengine Capay Meganos	Tejon Transition Domengine Capay Meganos		Narizian Ulatisian Penutian Bulitian
PALEO.	Martinez	(none)		Martinez	Martinez	Martinez	Martinez		Ynezian

Figure 3. Evolution of stratigraphic terminology in the Pacific Coast Cenozoic.

primarily on the succession of fossil pectinid bivalves from California formations, Arnold (1906) constructed what might be considered the first true Pacific Coast Cenozoic time scale. In that paper, he recognized a "Martinez horizon" as early Eocene (the Paleocene was still not widely accepted in North America, and would not be adopted by the U.S.G.S. until 1939), and a "Tejon horizon" (a term originally proposed by Gabb, 1869) as late Eocene (Fig. 3). He considered the "San Lorenzo horizon" to be Oligocene, and the "Vaqueros," "Monterey", and "San Pablo" were successive horizons of the Miocene. Arnold (1906) used the names "Purisima" and "Merced" for the lower and upper Pliocene respectively, and "San Pedro" for the Pleistocene. This was a preliminary relative time scale, based on a small part of the fauna and on a few units in California, although Arnold (1906, p. 10) did indicate possible correlatives elsewhere in California, and in the Pacific Northwest. Fossils were known from only a few localities within the formation, so there was no attempt to zone fossils *within* a formation, nor to distinguish lithostratigraphic units from their biostratigraphic content (those concepts would be developed later). However, Arnold's work helped lay the foundation for all later time scales on the Pacific Coast, even though many of his terms have become obsolete or subdivided, or their correlation has changed. Arnold also constructed the first paleogeographic maps of the Pacific Coast (recognizing the different biogeographic provinces in California, and in Oregon and Washington), and made the first paleoclimatic inferences based on molluscs.

Meanwhile, Charles Weaver (Fig. 2) began his own research after he arrived in Seattle in 1907, mapping the stratigraphy of western Washington and accumulating large fossil collections. Weaver is one of those legendary figures about whom many stories are still told, even though he died in 1958. He did his dissertation at Berkeley on the Paleocene and

Miocene beds around Mt. Diablo (including the type "Martinez Stage" Paleocene strata). He was famous for his prodigious stamina, walking 30 to 50 km from Berkeley to Martinez on weekends to do his field work, then sleeping on the ground wherever he ended up at night. As Addicott (1981) put it, "even after retirement, he had the reputation of being able to walk a much younger man into the ground." Weaver worked on a shoestring budget, taking the train or bus to his field area, or hitching rides on logging railroads, and eating cheaply as well (Barksdale, 1974). He stopped driving altogether in the 1920s with the introduction of traffic lights, because he was color blind. However, he was somehow able to teach optical mineralogy at Washington for years. Weaver was also known for his amazing memory and his ability to teach entire courses without notes. He was so shy that early in his teaching career, he taught courses from the back of the room to avoid facing the students.

With his preliminary mapping of key units in Washington (1912), Weaver established the first time scale for the Pacific Northwest. He recognized seven horizons: the upper Eocene Cowlitz and Tejon formations (mixing in California names because the horizons were partially defined on fossil content, and the term "Tejon" was as much faunal as it was lithostratigraphic), the Oligocene Lincoln formation, the lower Miocene Blakeley, Wahkiakum, and Chehalis formations, and the upper Miocene Montesano formation. In 1912, Weaver thought that the lower Eocene (including Paleocene in later parlance) and the Plio-Pleistocene were missing in the region, although the latter would be found not long afterwards.

After Arnold left the U.S.G.S. in 1909 to take up a career in consulting, he began collaborating with Harold Hannibal. Trained at Stanford by J.P. Smith and then by Weaver at the University of Washington, Hannibal was an exceptional fossil collector and field geologist. Unfortunately, he was also a rather reclusive person who alienated most of his peers (Taylor and Smith, 1971), and after 1914, suffered worsening bouts of mental illness which soon ended his career. After learning all about Weaver's ongoing work on the Pacific Northwest in 1910-1911, and doing extensive fieldwork there himself, Hannibal returned to California and collaborated with Arnold on a massive project which summarized most of what was then known about the Pacific Coast Cenozoic, both in California and the Pacific Northwest. Arnold and Hannibal (1913) used a mixture of rock units from both California and the Pacific Northwest to construct a more detailed time scale (Fig. 3). The California name "Tejon" was retained for the upper Eocene, but it was subdivided based on Washington units: Chehalis, Olequa (= Cowlitz), and Arago (= Coaledo). The Oligocene still included the San Lorenzo (from the 1906 Arnold California time scale), along with Oregon-Washington units such as the Astoria, Seattle, and Twin River formations, and the Sooke formation from British Columbia. The lower Miocene consisted of the Monterey (California) and the Clallam (Washington) horizons, while the upper Miocene was typified by the Empire formation (Oregon). The Pliocene was subdivided into (from oldest to youngest) the Merced, Elk River, and Admiralty Till, and the Pleistocene represented by the Vashon Drift and the Saanich formation.

In 1916, Weaver (1916a, 1916b, 1916c) published a much more detailed subdivison of the Cenozoic of western Washington, also mixing California and Washington terms. The "lower Eocene" was still called the "Martinez Stage," while the upper Eocene was called the "Tejon." The Oligocene was divided into the Lincoln, Porter, and Blakeley horizons. The lower Miocene was called the Wahkiakum, whereas there was no middle Miocene; the upper Miocene was typified by the Montesano formation. Unlike previous authors, however, Weaver (1916) also gave biostratigraphic names to these horizons as well, although it is clear that each biostratigraphic zone is coextensive and interchangeable with the formational name. He also specified type sections for his faunal horizons, and listed characteristic species, practices that were not widely adopted until much later. Weaver continued to map and collect fossils extensively over much of western Washington, summarizing a massive amount of work conducted over the next 20 years in two reports (Weaver, 1937, 1942).

After this burst of activity early in the century, progress in this area of research slowed down in the 1920s and 1930s. Interest shifted to other fields after Arnold and Hannibal's work, and Weaver spent much of the period after 1919 doing geological field work and consulting in California and South America. The most important figure in Pacific Coast Cenozoic molluscan biostratigraphy during this period was Bruce Clark, who spent his entire career at Berkeley. He was famous for his enormous energy and enthusiasm, and for inspiring many students in their research, and even helping them financially during the Depression. According to Addicott (1981), Clark "is said to have had so very active a mind that his thoughts raced well ahead of his ability to write them down. His office was cluttered, and he had the habit of using any available item as book marks—especially rock and fossil specimens and old pipes." In a series of publications (Clark, 1918, 1926), he refined the Eocene molluscan stratigraphy of California, which up to then was simply all considered "Tejon." Clark collected and studied many important molluscan faunas in California, introducing the "Meganos" and "Domengine" stages for the lower and middle Eocene respectively. In 1936, Clark collaborated with his student Harold Vokes on a revision of the marine Eocene of the Pacific Coast, which formalized the sequence of stage names (from oldest to youngest): "Meganos," "Capay," "Domengine," "Transition," "Tejon," and "Gaviota." They based their stage sequence entirely on faunas from California strata, even though they indicated their ideas of correlations with units in the Pacific Northwest. Each stage was also typified by a characteristic molluscan zone, while some stages (e.g., "Capay," "Tejon") had two successive molluscan zones within them.

PHASE II: MICROPALEONTOLOGY COMES OF AGE

Throughout most of this period, biostratigraphy on Cenozoic marine beds was done exclusively with molluscs, because they were by far the most abundant and distinctive macrofossils in most areas. This worked well for outcrops of shallow to intermediate-depth deposits, but most of the deep-marine deposits found in such abundance in this region yielded few, mostly non-diagnostic, molluscs. After World War I, the growth of the oil industry (especially in California) required even more refined stratigraphic techniques to improve the chances of success. Many of the richest oil-bearing strata are thick shales and turbidite sandstones found in deep basins, rarely exposed at the surface, and usually accessible only by drilling. Naturally, molluscs were not much help in correlating these strata, but a number of workers soon began to realize that foraminifera (especially benthic foraminifera) were abundant in drill cuttings as well as surface outcrops, and could be used for biostratigraphy. This effort was led by the pioneering micropaleontologist Joseph Cushman, who demonstrated the utility of benthic foraminiferal biostratigraphy for the Atlantic Coast in 1914, and for the Gulf Coast in 1922. On the Pacific Coast, the effort was originally led by G Dallas Hanna of the California Academy of Sciences (e.g., Hanna and Hanna, 1924), and Hubert Schenck at Stanford (e.g., Cushman and Schenck, 1928). Schenck in particular was very influential and progressive in his stratigraphic thinking. By this time, he and many other geologists were bothered by the common practice of blurring the distinction between rock terms and time terms, or using lithostratigraphic and biostratigraphic units interchangeably. Eventually, Schenck and Muller (1941) published their famous paper that formalized the separate hierarchies of lithostratigraphic, chronostratigraphic, and chronologic terms, and showed that lithostratigraphic terms should not be equated with time terms. That principle has since been incorporated into western stratigraphic thinking, and is at the heart of the more recent North American stratigraphic codes.

However, the most important figure in Pacific Coast micropaleontology was Robert M. Kleinpell. After obtaining his undergraduate degree in history at Occidental College in 1926, Kleinpell began working for oil companies and soon realized the problems they faced correlating similar-looking shales known only from well cores. He also found that the cores were rich in benthic foraminifera, and eventually came to Stanford to study the problem under the supervision of Schenck. At the suggestion of Ralph Reed, Kleinpell read extensively from the European biostratigraphic literature, and soon became familiar with the works of Quenstedt, d'Orbigny, and Albert Oppel on Jurassic ammonite biostratigraphy. Kleinpell realized that Oppel's method of biostratigraphic zonation was ideal for his purposes and could help finely subdivide the monotonous Cenozoic shales of California into fine-scale biostratigraphic units that would be immensely useful in exploration. With his access to hundreds of oil-company cores, he tackled the problem of the California Miocene for his dissertation, presenting it for the first time in 1933. It was eventually published by the A.A.P.G. as the landmark book, *Miocene Stratigraphy of California* (1938). As Berry (1999) pointed out, it was much more than the title suggested. In this work, Kleinpell laid down the foundation for his biostratigraphic principles, and extensively discussed the work of Oppel and others, introducing their biostratigraphic concepts for the first time in

North America. Like his advisor Schenck, Kleinpell (1934) was an early advocate of the separation of lithostratigraphy and biostratigraphy. Through Kleinpell, these concepts became so influential that they are now the basis for nearly all modern biostratigraphy, and are integral to the currently used North American Stratigraphic Code.

Kleinpell (1938) erected a series of biostratigraphically defined benthic foraminiferal stages in California, specifying type sections, indicating the different biostratigraphic zones, and giving lists of characteristic taxa, as well as suggesting correlative strata—all practices that are now required by modern stratigraphic codes. In succession, his "Miocene" stages were the Zemorrian (now considered mostly Oligocene), the Saucesian, Relizian, Luisian, Mohnian, and Delmontian. Slightly before this, Schenck and Kleinpell (1936) named the upper Eocene to lowermost Oligocene Refugian Stage, using both molluscs and foraminifera in its definition. Kleinpell's biostratigraphy was quickly adopted by the oil companies working in California, and soon they were using his methods to find oil. Kleinpell himself went to explore for oil in the Philippines in the early 1940s, where he was captured by the Japanese after World War II broke out, and spent four years in a Japanese prison camp. He kept up his spirits by teaching fellow prisoners, and when the war ended, he returned to oil exploration. In 1946, he joined the faculty at Berkeley, where "Doc" Kleinpell soon became one of the most beloved and influential professors. There he propagated his biostratigraphic concepts, and trained a new generation of micropaleontologists, most of whom went to work in the oil industry. Some, however, went on to academic jobs and pure research. One of these students was Stan Mallory, whose dissertation was published in 1958 and completed Kleinpell's work by creating benthic foraminiferal stages for the Paleogene in California. Mallory, in turn, went on to replace Weaver at the University of Washington, where he trained many of the paleontologists still active in this research area.

MID-CENTURY SYNTHESIS: THE WEAVER COMMITTEE REPORT

In the late 1930s, the Geological Society of America organized a series of committees to standardize stratigraphic nomenclature and correlation in the United States. The job of correlating Pacific Coast Cenozoic strata was given to a committee chaired by Charles Weaver. This committee included most of the prominent invertebrate paleontologists who worked on Cenozoic molluscs in the Pacific Coast, including Clark, Durham, Grant, Putnam, Taliaferro, and others, as well as field geologists such as Mason Hill and Tom Dibblee, and micropaleontologists such as Schenck, Bramlette, Kelley, Beck, Carlson, Forest, Hill, and of course, Kleinpell. Their report was published in the *Geological Society of America Bulletin* in 1944 (Weaver et al., 1944), and consisted mostly of a large correlation chart, with each individual region being the responsibility of a different author or authors. In the introduction, however, Weaver noted that a tension had developed between the correlations based on molluscs and on microfossils. The older school of thought (the molluscan school, led by Weaver, Clark, Durham, Vokes, and others) based their work on comparisons of molluscs between formations, attempting to find common species of molluscs with the type sections in Europe, so that the local zonation could be correlated to the global standard. The other school (led by micropaleontologists such as Kleinpell) focused on detailed local zonations based on benthic foraminifera. As Weaver (1944, p. 571) wrote, "The cleavage into two schools, due partly to the preference of some stratigraphers for one set of material and techniques and of others for a different set, springs largely from the inexorable fact that parts of the Cenozoic stratigraphic record in the West Coast province are rich in microfossils and almost lacking in mollusks or other large, shell-bearing groups, whereas other parts of the record are marked by abundant megafossils and few Foraminifera." As Weaver noted, the biggest problem arose when the two schools attempted to correlate their strata to the Lyellian epochs. Because both benthic foraminifera and most benthic megainvertebrates are highly endemic to the Pacific Coast, few species could be confidently correlated to the type sections in Europe, so the positions of the epoch boundaries on the chart were difficult to determine and highly controversial. On the right side of the chart (Weaver et al., 1944, Fig. 1), for example, are two different standard time scales (one based on molluscs, the other on foraminifera), which differ in many ways. The molluscan Oligocene (based on the Lincoln and Blakeley Stages) was much shorter and more restricted than the foramiferal Oligocene (more or less equivalent to the Refugian Stage). The foraminiferal time scale even had a transitional "Eo-Oligocene" for the early Refugian. (Ironically, most of the Refugian is now considered Eocene in age, and Kleinpell's Zemorrian now spans most of the Oligocene, not the early Miocene as he originally thought—see Prothero and Thompson, this volume; Prothero and Resseguie, this volume).

PHASE III: PLANKTONIC MICROFOSSILS TO THE RESCUE

As these two parallel schools of thought continued their research after 1944, their results became increasingly irreconcilable, and their arguments unresolved. In particular, the vexatious issue of correlation with the European standard caused endless debates. The Refugian continued to bounce back and forth between the Eocene and Oligocene, or straddled the boundary (Prothero and Thompson, this volume). Some authors even doubted whether there was any true Oligocene in the Pacific Coast at all. 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 by showing that Oligocene planktonic foraminifera do occur in California, and since then the Oligocene age of many formations has been well documented.

Another problem was that the biostratigraphy of benthic organisms could be hampered by facies problems. Benthic foraminiferal zonations, in particular, were potentially time-transgressive, because many key taxa are sensitive to water depth, and their first and last occurrences could be a reflection of paleobathymetric changes rather than of faunal evolution. Although workers such as Kleinpell knew of this problem and discussed it (Kleinpell, 1938, 1972, 1980), its significance was not fully appreciated until another standard of correlation could be brought to bear. This was the use of planktonic microfossils (especially planktonic foraminifera and calcareous nannofossils, and to a lesser extent, diatoms) for biostratigraphy. Initially, these groups had been neglected because they were relatively scarce in the Pacific Coast marine sections, with their high sedimentation rates that tended to swamp the planktonic component. In addition, the planktonic time scale was a relatively late development (see Berggren, 1971, for a discussion), and there were many initial mistakes (mostly in foraminiferal taxonomy) that gave benthic foraminiferal specialists reason to distrust it (e.g., Kleinpell, 1972, 1980). However, as planktonic microfossils became much bette
(especially due to the impetus from scienti
ing on the Deep Sea Drilling Project) in th
the bugs were eventually worked out of the system. It soon became apparent that planktonic microfossils, which live in pelagic waters around the world and evolve quite rapidly, were a much better standard for global correlation than benthic organisms, which were tied to changes in the bottom water depth.

The pioneering work in Pacific Coast planktonic foraminifera (Loeblich, 1958; Parker, 1964; Lipps, 1964, 1967; Fowler, 1965; Ingle, 1967; Orr et al., 1971; Orr, 1971; McKeel and Lipps, 1972, 1975) and in nannofossils (Bramlette and Sullivan, 1961; Sullivan, 1965) soon began to bear fruit as many correlation problems were pointed out and solved. One of the first problems to be solved was the controversy over correlation to the European standard for the Lyellian epochs. Berggren (1971; Hardenbol and Berggren, 1978; Berggren et al., 1978, 1985) and other micropaleontologists studied the plankton of most of the type sections in Europe, and soon were able to tie these sections to the global pelagic standard developed by the D.S.D.P. research. This was not an easy task, because most of the European type sections (particularly in the Paleogene) were very shallow-water deposits and contained few planktonic microfossils. In addition, they were typically very short, incomplete, unconformity-bounded packages of Cenozoic sediment, so most of the European stratotypes represent only a small part of the total time spanned by their respective stages (Berggren and Van Couvering, 1978). Once the time scale had been standardized and most of the controversies over European stratotypes had been resolved, it was possible to use Pacific Coast planktonic microfossils and settle long-controversial issues. A number of micropaleontologists (e.g., Sullivan, 1965; Lipps, 1967; Lipps and Kalisky, 1972; McKeel and Lipps, 1972, 1975; Poore, 1976, 1980; Poore and Bukry, 1983; Bukry et al., 1977; Warren and Newell, 1980; Almgren et al., 1988, among many others) documented enough planktonic foraminifera and nannofossils in key sections to finally resolve the issue of what was Eocene, Oligocene, and Miocene on the Pacific Coast.

Through the study of planktonic microfossils, it soon became apparent than many benthic foraminiferal zones and stages were time-transgressive (Milow and Ennis, 1961; Bandy and Kolpack, 1963; Sullivan, 1965; Lipps, 1967; Lipps and Kalisky, 1972; Steineck and Gibson, 1971; Schmidt, 1975; Poore, 1976, 1980; Poore and Brabb, 1977; Poore and Bukry, 1983; Bukry et al., 1977; Warren and Newell, 1980; Almgren et al., 1988). For example, Poore (1980) and Almgren et al. (1988) showed that the upper Paleocene to lower Eocene Ynezian, Bulitian, and Penutian benthic foraminiferal stages of Mallory (1959) were significantly time-transgressive. In some places the Penutian stage contains late Paleocene (Zone CP8, 56 Ma) nannofossils, while in others it contains late early Eocene (Zone CP12, 47 Ma) nannofossils, a difference of 9 million years. Comparing the Eocene benthic foraminiferal zonations of Mallory (1959) and Rau (1958), McDougall (1980) found that the Narizian, Refugian, and Zemorrian stages were inconsistently defined and demonstrably time transgressive between California and the Pacific Northwest. Many other examples were documented, so that the protests of the older generation of benthic foraminiferal specialists (e.g., Kleinpell, 1972) were countered by overwhelming evidence, and benthic foraminifera are now treated with caution when used purely for biostratigraphy.

The culmination of this phase of research came with several papers published in the 1980s (especially McDougall, 1980, 1983; Poore, 1980, 1983; Warren and Newell, 1980; Barron, 1981; Almgren et al., 1988). This work laid a firm foundation for correlating many Pacific Coast Cenozoic stratigraphic units to the global time scale. Much of this understanding was synthesized in volumes edited by Armentrout (1981a) and Brabb (1983), and in several correlation charts (Armentrout, 1981b; Armentrout et al., 1983). Then this research almost completely ceased as the oil industry went through a crisis, and many oil company micropaleontologists were laid off or diverted to other areas of research. The costs of exploration and environmental regulation caused most of the major oil companies to pull out of California, further hampering research. In addition, the cutbacks in the U.S. Geological Survey in the 1980s caused many micropaleontologists to retire early or change their fields of research, so that very few are still working on these problems. Sadly, the potential for this research area is still enormous, but few people are being trained to replace the workers who once made such great strides in solving so many problems.

RADIOMETRIC DATING

When K-Ar dating was developed in the late 1950s and 1960s, it seemed to offer the potential to resolve many of these correlation problems. In 1970, Orville Bandy edited a *GSA Special Paper*, "Radiometric Dating and Paleontologic Zonation," which summarized the dates that had been analyzed up to that point (especially those of Turner, 1970, for the California Miocene). Despite the long history of Cenozoic volcanism in and around the Pacific Rim, however, reliable radiometric dates are relatively scarce in Cenozoic marine deposits. This is because the suitable volcanic materials are typically too altered for dating, even though many individuals and laboratories have tried repeatedly with limited success. Since Turner's (1970) pioneering efforts on K-Ar of basalts from the California Miocene, there have been a handful of successes (e.g., Berry, 1991, on the Eocene Mission Valley Formation in San Diego; Irving et al., 1996, on the Eocene Cowlitz Formation in Washington; Niem et al., 1994, on the Oligocene Pittsburg Bluff Formation in Oregon), but in general, radiometric dates are so few and far between that they have not replaced biostratigraphy, and their primary value has been to calibrate the biostratigraphic zonations.

THE FUTURE?

Although the potential of planktonic microfossil biostratigraphy and radiometric (particularly ^{40}Ar/^{39}Ar) dating has still not been fully realized, new methods of chronostratigraphy have also developed which have improved our correlations immensely. The development of the strontium isotope stratigraphy offers potential as a dating tool, but so far the limited efforts on dating Pacific Cenozoic strata have been hampered by problems of diagenesis, so no successful strontium correlations have yet been published. The biggest strides have been made with magnetic stratigraphy, the subject of this volume. Unlike other methods of correlation, magnetic stratigraphy offers the potential of globally isochronous correlation independent of facies and lithology, with resolution to less than 100,000 years (Prothero, 1988). By contrast, most biostratigraphic zones are several million years in duration. Coupled with other means of calibration (primarily planktonic microfossils, but occasionally radiometric dates), the papers in this volume and elsewhere have led to a much more refined understanding of the stratigraphy, with much more accurate correlations and much finer resolution of events. Such fine-scale correlation will allow not only better exploration for oil, but also fine-scale correlation of the climatic and tectonic history of the Pacific Coast to the global record of climate change and plate activities. We hope that the papers in this volume will lead to a new renaissance in the geological study of the Pacific Coast Cenozoic.

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