AAPG Landmark Papers

Paleontology Tools

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INTRODUCTION

This compilation of landmark papers complements the Applied Biostratigraphy case histories. We have selected nine foundational publications that have enabled micropaleontologists and palynologists to assist in geologic interpretation. These works are historical contributions that have led to the modern interpretation and application of subsurface microfossil assemblages. They are sorted into three categories: 1) biozonation and chronostratigraphy, 2) biofacies models, and 3) application of graphic correlation.

Readers wishing to delve deeper into this subject are directed to the following publications containing excellent examples of value-added studies:

Berggren, W. A., D. V. Kent, M.-P. Aubry, and J. Hardenbol, eds., 1995, Geochronology, time scales and global stratigraphic correlation: Tulsa, Oklahoma, SEPM Special Publication, v. 54, 386 p.

Bolli, H. M., J. B. Saunders, and K. Perch-Nielsen, eds., 1985, Plankton stratigraphy: Cambridge, UK, Cambridge University Press, 1032 p.

Bowden, A. J., F. J. Gregory, and A. S. Henderson, eds., 2004, Landmarks in foraminiferal micropaleontology: history and development: London, UK, Geological Society, The Micropalaeontological Society, Special Publications, 360 p.

Bown, P. R., ed., 1998, Calcareous nannofossil biostratigraphy: London, UK, Chapman and Hall, British Micropalaeontological Society Publication Series, 315 p.

Gradstein, F. M., J. G. Ogg, M. D. Schmitz, and G. M. Ogg, eds., 2012, The geologic time scale 2012: New York, Elsevier, 1176 p.

Two quantitative works not included among our top 10 references are worthy of mention for their significance in biostratigraphic correlation:

Forgotson, J. M., Jr., and C. F. Iglehart, 1967, Current uses of computers by exploration geologists: AAPG Bulletin, v. 51, no. 7, p. 1202–1224.

Shaw, A. B., 1964, Time in stratigraphy: New York, McGraw-Hill, 365 p.

SELECTED FOUNDATIONAL PUBLICATIONS

1. Biozonation and Chronostratigraphy

***Applin, E. R., A. E. Ellisor, and H. T. Kniker, 1925**, Subsurface stratigraphy of the coastal plain of Texas and Louisiana: AAPG Bulletin, v. 9, p. 79–122.*

In 1921, Ester Applin gave a presentation at a meeting in Amherst, Massachusetts, in which she proposed using microfossils in oil exploration, specifically for the dating of the rock formations in the Gulf of Mexico region. Although disputed by a professor from University of Texas at Austin, her contention was shared by Joseph Cushman, a native resident of Massachusetts whose name was about to become synonymous with foraminiferal research. A few years later, the landmark publication by Applin, Ellisor, and Kniker, as well as Cushman's successful application of foraminiferal biostratigraphy for an oil well in Mexico, established the utility of this new geologic tool, which was embraced by the American oil industry (Finger, 2013; Martin, 2013).

This paper was the first to document the application of foraminiferal biostratigraphy in subsurface geologic correlation and it represented the first step towards the extensive modern biozonation of the U.S. Gulf Coast. The authors used diagnostic taxa to define their "faunal" or assemblage zones, which they integrated with wireline log data to create a regional stratigraphic framework. It was a vast improvement over the prior method of geologic correlation, which relied solely on lithologies interpreted from well logs. This new approach was particularly beneficial in coastal areas, where reliable correlations were often elusive due to rapid facies changes and repetitive lithologies.

As Howe (1959, p. 511) stated in his review of the history of micropaleontology, "Credit for the resolution which took place in the use of foraminifera properly goes to three ladies, Esther Richards Applin [Rio Bravo Oil Company], Alva C. Ellisor [Humble Oil and Refining], and Hedwig T. Kniker [The Texas Company]. Their paper on the subsurface stratigraphy of the coastal plain of Texas and Louisiana (1925) had been presented before the Annual Meeting of the American Association of Petroleum Geologists in Shreveport, Louisiana and the discussion which followed opened the eyes of oil company executives." Soon thereafter, micropaleontological biostratigraphy "bloomed" in both academia and industry.

***Kleinpell, R. M., 1938**, Miocene stratigraphy of California: Tulsa, Oklahoma, AAPG, 450 p.*

Kleinpell's seminal publication was the first book documenting the biostratigraphic zonation for an entire region with multiple contemporaneous basins. It provided a major advancement in unraveling the complex stratigraphy of the hydrocarbon basins in California. His focus was benthic foraminiferal biostratigraphy. Being both abundant and relatively large, benthic foraminifera are the most conspicuous microfossils in California and their application as a correlation tool in the "oil patch" was still in its infancy when Kleinpell began working on his dissertation at Stanford University in 1931. He used these fossils to develop a biostratigraphic framework for the California Miocene that served as the major reference for most micropaleontologists working on the West Coast for many years. The Miocene section was of particular interest to the oil industry because it consisted predominantly of the Monterey Shale, a geographically extensive source-and-reservoir rock unit. Kleinpell's work was strongly influenced by fieldwork with his older brother William (an oil company geologist), his fellow Stanford student Hollis Hedberg, whose name later became synonymous with American stratigraphic principles, and biostratigraphic methods of the 19th Century German geologist Albert Oppel, who developed a Jurassic ammonite zonation for Europe. After completing his dissertation, Kleinpell applied the principles he had set forth to his consulting work in the oil industry with considerable success. He became widely recognized as the West Coast's leading expert on foraminifera and their biostratigraphy.

This book reflects the extensive taxonomic and biostratigraphic familiarity Kleinpell had with the benthic microfauna. He used this knowledge to formulate a zonation that emulated what Oppel had done with ammonites. Kleinpell divided the Miocene into six stages named for their respective type localities, which in turn were divided into 15 zones, each bearing the name of a prominent species and most being defined by the first appearance of a species at its base and the last appearance of a species at its top. Which and how many of the diagnostic species had to be present to identify a zone was a matter of subjectivity. In essence, each zone was a type of range zone, later termed "Oppel Zone", characterized by the occurrence of certain species within the interval, regardless of their associations in individual assemblages. This was the only viable means for interbasinal correlation of benthic faunas in the Miocene of California, and Kleinpell's application of it received worldwide recognition.

In 1946, Kleinpell joined the Department of Paleontology at the University of California in Berkeley where he supervised V. Standish Mallory's complementary dissertation on the California Paleogene, which in 1959 was also published in book form by the AAPG. This completed the benthic foraminiferal framework for the California Cenozoic as Natland (1952, 1957) had already named the Pliocene-Pleistocene stages in which he incorporated the zones that had been defined by Wissler (1943).

Imperfections of the California benthic foraminiferal composite scheme became increasingly evident as micropaleontologists often had difficulty applying both the taxonomic and zonal concepts of its authors. Each stage was described from its type locality in one depositional basin, so interbasinal correlations were often problematic.

Beginning in the early 1970s, more accurate planktic biostratigraphies, specifically those of calcareous nannoplankton and diatoms, revealed that Kleinpell's stages were plagued by time transgressions and overlaps. It also became evident that they could not be used to correlate two contrasting depositional environments, which supported Natland's long-held conviction that all of the benthic stages were based on paleoenvironmental changes that varied in time and space. Nevertheless, application of Kleinpell's benthic foraminiferal framework for California led to the recovery of billions of barrels of oil and its stage names are engraved in the regional geologic vernacular.

Martini, E., 1971, *Standard Tertiary and Quaternary calcareous nannoplankton zonation,* in *A. Farinacci, ed., Proceedings, 2nd International Conference Planktonic Microfossils Roma: Rome (Edizioni Technoscienza), v. 2, p. 739–785.*

Martini's publication was the first compilation of Tertiary and Quaternary nannofossil assemblages and stratigraphic ranges. His zonation was based primarily on his own research (i.e., Martini, 1970; Martini and Worsley, 1970) and that of others, including Bramlette and Wilcoxon (1967), Hay et al. (1967), and Gartner (1969). Martini's paper provides a comprehensive framework of zones bearing letter-number designations (NP 1–25 and NN 1–21) and defines the zonal boundaries. This zonation was widely adopted and is still considered the global "standard" for nannofossil zonation. Martini included useful range charts of the zone-defining species, charts comparing his zones to those for planktic foraminifera and silicoflagellates, and images of key taxa.

Although subsequent studies indicate that a few of the nannofossil taxa that Martini used to define zonal boundaries are not widely recognized or have diachronous datums, most have stood the test of time. Several amendments or additions have been proposed to improve the utility of his 1971 zonation. Some biostratigraphers now prefer the newer nannofossil zonation by Okada and Bukry (1980) that is based on low-latitude nannofloral assemblages. Martini's scheme, however, has been largely adopted by investigators in the DSDP, ODP and IODP research programs, which have expanded the application of calcareous nannofossils as a fundamental biostratigraphic tool in deep-marine deposits.

Hardenbol, J., and W. A. Berggren, 1978, *A new Paleogene numerical time scale: Tulsa, Oklahoma, AAPG Studies in Geology, v. 6, p. 213–234.*

Stratotypes represent the formal basis for relating time and rock units. Hardenbol and Berggren closely examined the relationship of the Paleogene stage stratotypes, all located in Europe, to a global chronostratigraphic framework in order to facilitate numeric basin modeling. Significantly, they correlated the Paleocene, Eocene, and Oligocene biozonations of planktic foraminifera and calcareous nannoplankton that were established in these stratotypes to magnetic polarity history and radiometric ages. The authors accomplished this by drawing on the global results of the Deep Sea Drilling Project. The result was a robust global chronostratigraphy for the middle and low latitudes.

This paper was published during the time that the development and application of "Exxon-style" sequence stratigraphy was shifting stratigraphic paradigms. Hardenbol and

Berggren were the first to take the multi-fossil group approach with microfossils instead of invertebrate macrofossils that were previously used to define biozonations of the European stratotype sections. Their high-resolution chronostratigraphy was of particular value to the newly emerging techniques of basin modeling and geohistory analysis that were applied to the Paleogene.

Similar methods incorporating additional types of data led to the more refined and chronologically extensive framework of Berggren et al. (1995), which stood as the standard chronostratigraphy until that of Gradstein et al. (2012).

2. Biofacies Models: Paleobiologic Maps of Depositional Environments

Natland, M. L., 1933, *The temperature and depth ranges of some Recent and fossil foraminifera in the southern California region: Scripps Institute of Oceanography, Bulletin, Technical Series, v. 3, no. 10, p. 225–230.*

Natland's paper is fundamental to micropaleontology because it was the first to show that benthic foraminifera are sensitive environmental indicators and, conversely, that the environment exercises primary control on their stratigraphic distribution. Focusing on foraminiferal depth assemblages and using the present as key to the past, Natland designed a study that became a model for others of its kind. He and a colleague collected 153 bottom samples in the channel between Long Beach and Santa Catalina Island, recording the bottom depth and temperature at each station. He augmented that collection with a dozen samples from greater depths in the region giving him a sample set ranging from an ebb-tide depth of one foot in a brackish lagoon to more than 8,000 feet (2,438 m) offshore. He showed that the foraminiferal assemblages change in accordance with the decrease in temperature that accompanies increasing depth. Natland divided the faunal distribution into five "life-zones", each represented by characteristic species. These distinct groups are now referred to as biofacies. He then applied his modern foraminiferal data to interpret a Neogene sequence exposed in Hall Canyon near Ventura. His study indicated that the lowest beds were deposited in the coldest water, and there was a gradual warming from there to the top of the section. Natland was uncertain if the warming was entirely from shallowing, so, unlike those who followed in his footsteps, he refrained from correlating the interpreted water temperatures with depth.

Natland (1944) also recognized mixed assemblages of warmer (shallow) water forms with those characteristic of cooler (deep) water, leading him to explore the sedimentary dynamics off California, and he later recognized the major role played by turbidity currents (Natland and Kuenen, 1951; Natland, 1957). Those investigations have been vital to our modern understanding of gravity-flows and deep-water deposition, which is now of particular importance in the exploration for oil and gas in many parts of the world.

Natland's work had a profound influence on foraminiferologist Orville Bandy at the University of Southern California. At a time when most foraminiferal research was taxonomic or biostratigraphic, Bandy and his students used Natland's work as a springboard from which they delved into ecological and paleoecological studies of foraminifera. Their publications include the first biofacies maps on stratigraphic horizons (e.g., Bandy and Arnal, 1960; 1969), several of the earliest studies that used biofacies to map polluted environments (Bandy et al., 1964a, 1964b, 1965a, 1965b), and the first thorough compilation of regional biofacies and their integration with the environmental factors that have shaped them throughout the Cenozoic (Ingle, 1980).

Phleger, F. B, and F. L. Parker, 1951*, Ecology of foraminifera, northwest Gulf of Mexico, parts I & II: Boulder, Colorado, Geological Society of America Memoir 46, Part I, p. 1–88 and Part II, p. 1–64.*

Phleger and Parker's two-volume publication was a major advancement in the study of living foraminifera that fundamentally set the ecology and environmental/bathymetric zonation standard for the Gulf of Mexico. This work also established a foundation for paleowater-depth biofacies currently used by biostratigraphers in the Gulf of Mexico and in other basins worldwide. Phleger and Parker's compendium was the "gold standard" for subsequent studies of a similar nature worldwide.

Having analyzed foraminifera from 550 bottom samples and 55 cores collected in the northwest Gulf of Mexico, Phleger and Parker delineated six bathymetric zones based on foraminiferal assemblages within middle neritic to abyssal depth interval of 263 feet (80 m) to more than 6,562 feet (>2,000 m). The authors presented the data and described the methodology used for their bathymetric zonation, and showed the value of using and refining ecologic/bathymetric zones for biofacies and sedimentary analysis. In addition, they used the planktic/benthic ratios of foraminiferal assemblages to help determine relative rates of sedimentation.

Phleger and Parker's work led to many additional studies on foraminifera in the Gulf of Mexico, most notably those of Albers et al. (1966), Pflum and Frerichs (1976), Poag (1981), Tjalsma and Lohmann (1983), Van Morkhoven et al. (1986), Poag (2015), and Denne and Sen Gupta (1993).

Bandy, O. L., and R. E. Arnal, 1960*, Concepts of foraminiferal paleoecology: AAPG Bulletin, v. 44, no. 12, p. 1921–1932.*

This classic paper pioneered the application of foraminiferal biofacies in basin analysis. Biofacies are now integrated with seismic stratigraphic systems tracts in order to interpret depositional environments with greater confidence.

Bandy and Arnal synthesized previously published studies on modern foraminiferal biofacies to develop and test multiple criteria in order to paleobathymetrically analyze ancient basins. They recognized seven criteria of greatest importance: (1) the general trends in species abundance and total benthic specimens relative to water depth and distance from shore; (2) the utility of porcelaneous foraminifera as indices of nearshore conditions; (3) the abundance of simple-walled agglutinated species in some brackish areas vs. the complexly structured tests of other agglutinated species in deep water; (4) the abundance of planktic foraminifera on the outer shelf and upper slope; (5) the validity of using fossil homeomorphs of modern species as paleoenvironmental indicators; (6) the recognition of displaced species; and (7) the utilization of upper-depth limits of the deepest-dwelling species in an assemblage to indicate the minimum depth of deposition.

Bandy and Arnal used the seven occurrence patterns as internal checks to validate their paleobathymetric maps of California's petroliferous San Joaquin Basin during the Luisian Stage (middle Miocene). They preview their much more extensive analysis (Bandy and Arnal, 1969) of this basin based on more than 5,000 core samples. Bandy and Arnal's maps appear to be the first basin-wide paleobathymetry maps based on subsurface biofacies data. Their 1960 paper also shows how paleobathymetric changes between two successive time-slices (beginning and end of the Luisian) can be used to quantify patterns of subsidence and uplift, which are key components for understanding relationships between oil fields and basin development.

This publication has been one of the most influential contributions to California micropaleontology. It laid the groundwork for their later studies (i.e., Bandy and Chierici, 1966; Bandy and Arnal, 1969; Arnal, 1976) and inspired others (e.g., Ingle, 1967, 1980; Lagoe and MacDougall, 1986; Finger et al., 1990; Olson, 1990) to adopt and further investigate the micropaleontologic criteria they recognized as useful tools in paleoenvironmental analysis.

3. Additional Selected Biozonations Used by Industry and Academia

Ziegler, W., 1962*, Taxonomie und phylogenie Oberdevonischer conodonten und ihre stratigraphische Bedeutung (Taxonomy and phylogeny Upper Devonian conodonts and their stratigraphic significance): Abhandlungen des Hessischen Landesamtes für Bodenforschung, v. 38, 166 p.*

Conodonts are phosphatic teeth-like structures of pelagic 'eel-like' aquatic animals that are found in Paleozoic marine sedimentary rocks. Ziegler recognized that their abundance and rapid evolution gave them biostratigraphic utility. His landmark paper provides a case history of their Paleozoic biozonation, and his conodont zonation represents one of the earliest Paleozoic biochronologies useful in the subsurface. In this monograph, Ziegler established the standard for Devonian conodont biostratigraphy, which remained in force until updated by Ziegler and Sandberg (1990). Working principally on sections in Germany and Belgium, while considering stratigraphic distributions in North America and elsewhere, Ziegler established a series of zones based on evolutionary inceptions and he defined each zone by its characteristic conodont assemblage. The conodont biostratigraphy devised by Ziegler and updated by Ziegler and Sandberg includes 32 zones for the Late Devonian, each with a duration less than 500,000 years. This level of stratigraphic precision makes conodonts a valuable tool for both local and intercontinental correlations of Devonian sediments. As a result, the event stratigraphy and eustasy of the Devonian period is well understood (House and Ziegler, 1997). Devonian stages were amongst the first to be defined on the basis of their stratotypes (Becker et al., 2012).

Klemme and Ulmishek (1991) attributed approximately 25% of recoverable oil and gas reserves to three Paleozoic source rock intervals: Silurian, Upper Devonian, and Pennsylvanian–Lower Permian. These intervals are now being intensely investigated as resource plays in the United States (e.g. Bakken Shale) and elsewhere. In addition, there are key conventional hydrocarbon reservoir intervals of Paleozoic age. These include the giant gas fields of the Khuff Formation and its equivalents in the Middle East. There has been a critical need for biostratigraphic tools to provide correlation and age calibration of Paleozoic basin models. Conodonts, as well as acritarchs, chitinozoa, and fusulinids, are the microfossils that have been vital tools in calibrating the Paleozoic.

Germeraad, J. H., C. A. Hopping, and J. Muller, 1968*, Palynology of Tertiary sediments from tropical areas: Palaeobotany and Palynology Review, v. 6, p. 189–348.*

Biostratigraphic correlation is most often applied to marine strata, but many sedimentary basins have nonmarine successions that contain hydrocarbon resources. Winds widely distribute pollen and spores (palynomorphs), making them particularly useful in correlating sedimentary rocks deposited in nonmarine, transitional, and marine environments. This paper serves as a prime example of applied palynology.

In their paper, Germeraad et al. present the results of nearly 20 years of intensively studying Tertiary palynomorphs from wells and outcrops across the Tropics. They show how palynology is applied as a tool for age dating and correlation, and establish biostratigraphic zones based on the stratigraphic and geographic extent of 49 tropical pollen and spore species. Their zonation extends from Maastrichtian to Pleistocene and includes six pantropical zones recognized in the Caribbean and across tropical Africa, and Southeast Asia. Within the same framework are transatlantic and regional zonations for the Caribbean and Borneo. They also included palynological correlation panels across northern and western Venezuela, Trinidad, and Colombia, and species distribution charts for key sections in Venezuela, Trinidad, and Nigeria.

The Germeraad et al. zonation is so robust that, after almost 50 years, it is still used by palynologists working tropical terrestrial floras. While the biostratigraphic framework is the most obvious contribution of this paper, the authors extended the application of palynology as a stratigraphic tool by: 1) demonstrating the importance of quantitative and statistical analysis of pollen and spore assemblages for zonation recognition in the tropics, 2) discussing the transport and climate effects on the final characteristics of the assemblages, and 3) proposing botanical affinities for many of the key species to support their stratigraphic significance and geographic distribution. All of these attributes make this is a unique and timeless contribution on “terrestrial” palynology in biostratigraphy, which is of particular value to the oil and gas industry.

This paper built on the pioneering and historic papers of Kuyl et al. (1955), who demonstrated the application of palynology in oil exploration, and Muller (1959), which dealt with the distribution of palynomorphs in recent deltaic sediments. From the many papers that have been subsequently published that partially address in more detail the palynology of specific tropical areas, it is also relevant to mention Muller, Di Giacomo and Van Erve (1987).

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