Chapter 18

North American Mammalian Chronostratigraphy: The Contributions of Malcolm C. McKenna

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ABSTRACT

Mentored by Don Savage at the University of California, Berkeley, in the 1950s, Malcolm C. McKenna was instrumental in bringing about a revolutionary change in dating the North American mammalian time scale. In 1973, he became involved with the revision of the Eocene part of the Wood et al. (1941) land mammal ‘‘ages’’. Finally published in 1987 (Krishtalka et al., 1987), this revision laid the foundation for our modern understanding of Eocene mammalian stratigraphy. McKenna was, and still is, one of the most interdisciplinary of mammalian paleontologists, constantly synthesizing disparate data sources and integrating new developments (such as K-Ar dating and magnetic stratigraphy) into the poorly understood Cenozoic chronostratigraphy of North America. Through his work, and that of his students and several other Berkeley-trained paleontologists, the North American mammalian time scale has been radically revised, so that many events can now be dated to the nearest 100,000 years and reliably correlated to the Lyellian epochs based in Europe and to the global time scale.

INTRODUCTION

Many of the papers in this volume focus on the areas of research most associated with Malcolm C. McKenna: his mastery of mammalian systematics and classification, his pioneering work in cladistic hypotheses of mammalian relationships, his innovative work in biogeography, and so on. Not so well known are McKenna’s crucial contributions to the development of the mammalian time scale in North America during the 1960s, 1970s, and 1980s, particularly for the Paleocene and Eocene epochs. During those decades, he was the foremost synthesizer of mammalian biochronologic data with other geochronologic techniques, such as radiometric dating and magnetic stratigraphy. Although he published only a few papers on the subject, his ‘‘behind the scenes’’ influence was much greater, as seen in the contributions made by many of his students.

In 1941, a committee chaired by Horace Wood II (Wood et al., 1941) established a time scale for North American Cenozoic land mammals. They proposed a series of ‘‘provincial stages’’ that were an unfortunate mix of lithostratigraphic and biostratigraphic units (see Tedford, 1970, and Woodburne, 1977, 1987, for discussions). However, the report of the Wood Committee was a product of the times and of the training of its members. Most mammalian fossils had been collected with little regard to detailed stratigraphic ranges, so the classic Oppelian range-zone biostratigraphy widely used by invertebrate paleontologists was not used by mammalian paleontologists. In addition, the early collections tended to come from a few quarries or well-sampled horizons, with large gaps of unsampled (and usually unfossiliferous strata) between localities, so mammalian paleontologists were not inclined to make Oppelian range zones out of such data.

The Wood Committee also attempted to tie its provincial North American mammalian time scale to the standard Cenozoic time scale and Lyellian epochs, based on European marine sections. Here, they ran into even greater problems. First of all, most of the European stratotypes were still poorly defined and highly controversial, so there was little agreement even among European marine stratigraphers (see discussion by Hardenbol and Berggren, 1978). This problem wasn't solved until the Deep Sea Drilling Project and the development of a planktonic marine time scale, based on foraminifera and calcareous nannofossils during the 1970s and beyond (Berggren, 1971; Berggren et al., 1985, 1995). A bigger problem for the Wood Committee was that few of the European marine stratotypes interfingered with mammal-bearing strata, so the correlation of European mammalian biostratigraphy with the marine time scale was problematic. Finally, even when European mammals could be reliably correlated to the marine time scale (e.g., during the early Eocene), there were few time intervals during which they freely exchanged with North America, allowing correlation of North American provincial mammalian biochronology with the European standard. Hence, most of the Lyellian epoch assignments presented by Wood et al. (1941) were tentative. Nevertheless, several generations of vertebrate paleontologists memorized ''Uintan and Duchesnean are late Eocene'', ''Chadronian is early Oligocene'', ''Clarendonian and Hemphillian are Pliocene'' or ''Arikareean is early Miocene'', and were slow to unlearn those ideas when better data in the 1980s and 1990s showed those assignments to be incorrect.

The preliminary correlations of the Wood Committee (Wood et al., 1941) were satisfactory for their generation, but a decade later they began to be challenged. Donald E. Savage, who was McKenna's graduate advisor at Berkeley, was a pioneer in trying to apply rigorous biostratigraphic techniques (used by his invertebrate paleontologist colleagues at Berkeley) to the mammalian time scale. Savage (1951) described the Irvingtonian and Rancholabrean land mammal ages and later (Savage, 1955) published a paper proposing two formal biostratigraphic stages and ages (Cerrotejonian and Montediablan) for the California ''Pliocene'' (now considered middle to late Miocene; see Tedford et al., 1987; Woodburne and Swisher, 1995; Wilson and Prothero, 1997; Prothero and Tedford, 2000). These stages were consistent with the codes of stratigraphic nomenclature then in use. Savage's stages had clearly designated type sections that were based on biostratigraphic ranges and first and last occurrences (unlike most of the ''stages'' and ''ages'' in the Wood Committee report). Savage (1962) published (in an Argentinian journal) a classic paper that pointed out the problems with the Wood Committee time scale and advocated the use of Oppelian range zone biostratigraphy for North American Cenozoic mammals wherever possible. Savage himself (1977) proposed just such a zonation for the early Eocene, and several other former Berkeley students (e.g., Rensberger, 1971, 1973; Lindsay, 1972; Tedford, 1970) tried to apply standard biostratigraphic methods to certain intervals of the mammalian time scale.

MALCOLM McKENNA AND THE CENOZOIC TIME SCALE

Clearly, Malcolm McKenna was influenced by his advisor Don Savage during this period when much of the Berkeley program was breaking new ground in biostratigraphy. McKenna's dissertation project on the Wasatchian Four Mile Fauna of Colorado (McKenna, 1960a) was essentially a biostratigraphic/faunal study, although it also made important contributions in mammalian systematics and paleoecology. When he arrived at the American Museum of Natural History in 1960 to replace George Gaylord Simpson, McKenna focused first on projects in mammalian systematics, especially the systematics of insectivorous mammals and many other poorly understood groups. Still, his love of fieldwork and dedication to solving stratigraphic problems were apparent even then. His early exposure to the puzzling Goler Formation in California, and his persistent collecting of that unit, paid off when he found the first age-definitive fossils (McKenna, 1960b). By the late 1950s and 1960s, he had largely moved beyond his graduate fieldwork in the Four Mile area and was actively collecting in the Cretaceous (especially in the Lance Formation, which became the subject of dissertations by Richard Estes and William Clemens, launching both of their careers) and the Paleocene and the Eocene all over the Rocky Mountains. Those of us who were his graduate students, and spent a field summer with him, usually received the ‘‘grand tour’’ of nearly every important early Cenozoic mammal locality in Wyoming and Colorado. Some were localities that Simpson had collected, or that McKenna had visited with other paleontologists, but many were ones that he himself had discovered. Although he occasionally worked in well-studied areas, such as the Bighorn Basin, McKenna was particularly fond of collecting in areas where few other paleontologists had the patience or resources to collect (such as the East Fork Basin and Togwotee Pass—McKenna, 1980; Flynn, 1986). These areas may not have yielded the most abundant fossils, but in their unusual faunas and their implications for biostratigraphic zonations based on better studied areas they were crucial. For example, his work on the early Uintan faunas of the East Fork Basin showed that this currently high-elevation assemblage was distinct from the classic Uintan faunas of the Uinta Basin of Utah and the Washakie Basin of Wyoming. Eventually it was given its own land mammal ‘‘subage’’, the Shoshonian, by McKenna’s student John Flynn (Flynn, 1986; but see Walsh, 1996).

By the late 1960s and early 1970s, McKenna’s first-hand familiarity with nearly every Paleocene and Eocene mammal locality in North America placed him in a position to be the ‘‘grand synthesizer’’ of early Cenozoic mammalian biochronology. In addition, McKenna was highly conscious of the development of potassium-argon dating and its implications for the North American provincial time scale. Once again, this technique was largely pioneered at Berkeley (by Garniss Curtis, Jack Evernden, and Brent Dalrymple). Evernden and Curtis collaborated with Savage and his student Gideon James to publish the first Cenozoic mammalian chronology of North America based on K-Ar dating (Evernden et al., 1964). These early dates showed that there were problems with many of the correlations proposed by the Wood Committee, and as more dates were obtained, further problems emerged. McKenna was always on the cutting edge, incorporating the new dates into the evolving time scale and frequently finding datable ash samples in crucial localities and personally paying to have them analyzed. Those of us who were his students in the 1970s and 1980s remember the large blackboard in his office, immediately behind his desk. It was always neatly ruled with horizontal lines representing time lines, and in chalk were the latest dates and correlations of nearly every unit McKenna was keeping track of. The data were continually changing, so the correlations were constantly being erased and revised. It was like a ‘‘situation board’’ in a military facility—at a glance, one could quickly gauge the current status of any early Cenozoic fauna in North America and the basis for its correlation.

McKenna’s pre-eminence in Eocene mammalian biochronology placed him in prime position when it came time to formally revise the Wood Committee report. He participated in a symposium at the annual meeting of the Geological Society of America, held in Dallas in November 1973. In that symposium, a number of informal committees reported on the status of mammalian biochronology for the Lyellian epochs. McKenna was the first author among a large committee of paleontologists working on the Eocene (McKenna et al., 1973). From that initial effort, a long-term project was launched to publish a volume updating and improving the Wood Committee’s report. At first, Malcolm and Robert M. ‘‘Mac’’ West were the principal authors of the Eocene chapter. By the late 1970s, the project had grown so large that McKenna no longer had time to supervise it, and Mac West assumed first authorship. The volume on Cenozoic mammalian biochronology continued to evolve into the 1980s. By the mid-1980s, a younger generation of workers (Leonard ‘‘Kris’’ Krishtalka and Richard Stucky) had added more recent contributions and taken over the Eocene chapter; West and McKenna became third and fourth authors. It was in that form (Krishtalka et al., 1987) that it finally was published in 1987, more than 14 years after it was initially conceived. The chapter occupies 40 pages in the Woodburne (1987) volume, one of the longest and most detailed in the book. Once it appeared, it immediately became the standard for all Eocene work in nonmarine strata of North America. In addition, when Bill Berggren sought expertise on Paleogene stratigraphy to publish an update of the time scale (Berggren et al., 1978), he sought out McKenna as a coauthor.

Although McKenna was primarily interested in late Cretaceous and early Cenozoic fossils and stratigraphy, he also took a role in understanding the later Cenozoic. When Childs Frick died in 1965, McKenna was instrumental in making sure that Frick's enormous collection of late Cenozoic fossil mammals came to the American Museum. He also recommended the hiring of Richard Tedford as Curator of Fossil Mammals so that Tedford could contribute his expertise to the study of mammals in the Frick Collection. McKenna made a point of visiting and studying many of Frick's Oligocene and Miocene localities, and supervised Bob Emry's (1973) dissertation project on Frick localities in the White River Formation in Wyoming.

McKenna had become interested in the Miocene at a young age. As he wrote (McKenna, 1965), he first befriended Harold Cook in 1947 and learned about the complicated Miocene stratigraphy in western Nebraska. In the process of trying to sort out the age of Arikareean and Hemingfordian deposits and fossils in the Bighorn Basin of Wyoming (McKenna and Love, 1972), he realized that the Miocene nomenclature of C. Bertrand Schultz (Schultz and Stout, 1941, 1961) was in need of revision. Typical of Malcolm, when he found a puzzling problem, he figured it out for himself, and once he had solved it, he published it. He untangled the confusion that Schultz and Stout had created and published his own interpretation of Hemingfordian stratigraphy (McKenna, 1965). He also arranged to have Harold Cook's description of the Runningwater Formation (Cook, 1965) published in *American Museum Novitates.* McKenna's student Bob Hunt later replaced Schultz at the University of Nebraska, and has since gone on to make important contributions to the stratigraphy of these same beds. In the mid-1970s, McKenna supervised students who did magnetic and biostratigraphic work on the Miocene Santa Fe Group in New Mexico (MacFadden, 1977; Barghoorn, 1981).

McKenna's interests were not restricted to the Cenozoic. In addition to his work on the Upper Cretaceous Lance Formation of Wyoming (mentioned above), he studied numerous other Cretaceous mammal-bearing deposits in North America. This culminated in the first attempt to define North American land mammal ages in Cretaceous rocks (Lillegraven and McKenna, 1986).

McKENNA'S LEGACY FOR THE CENOZOIC TIME SCALE

Although McKenna continued to be active in the time scale revision process after the publication of Krishtalka et al. (1987), his primary influence was through the work of his students. American Museum–Columbia University graduate students had the option of choosing from a wide variety of dissertation projects. Some worked on the systematics of the immense collections of fossil mammals available to them; many others chose to do biostratigraphic and/or chronostratigraphic work. In part, this was influenced by Malcolm's own attitude and interests in synthesizing disparate data, his dedication to solving fundamental problems like the age of fossils, and his gift for promoting intellectual inquiry. Every graduate student received ''the pep talk'' soon after his or her arrival at Columbia. Malcolm would challenge the new student to tackle interdisciplinary problems, to take advantage of all the geochemical and geophysical opportunities at Columbia and Lamont-Doherty Geological (now Earth) Observatory, and to break new ground by finding techniques or insights that had never been applied to fossil mammals.

Consequently, many of Malcolm's students did stratigraphic research. Examples include Bob Emry's (1973) study of the Chadronian Flagstaff Rim section of Wyoming and Bob Hunt's work on the classic Oligocene-Miocene deposits of western Nebraska (Hunt, 1985). When paleomagnetic projects first became feasible at Lamont, Malcolm's students were the first to sample classic localities. Starting with MacFadden's (dissertation, 1976; published in 1977) and Barghoorn's (dissertation, 1979; published in 1981) research on the Miocene of the Santa Fe Group in New Mexico, they were followed by my research (Prothero, 1982, dissertation; Prothero et al., 1983; Prothero, 1985, 1996) on the Eocene-Oligocene White River Group in the High Plains and Flynn's (dissertation, 1983; published in 1986) research on the Bridgerian and Uintan of Wyoming and California. Later students (such as Dan Bryant) pursued geochemical investigations of mammalian fossils, again with McKenna's encouragement.

Today, that legacy continues, particularly in the many magnetostratigraphic investigations undertaken by MacFadden, Flynn, and myself. Among us, we have done magnetostratigraphic studies on most of the important Cenozoic mammal-bearing deposits not only in North America, but also in South America and other continents. Only a handful of published studies were *not* done by one of us or by one of MacFadden's students. Consequently, the mammalian time scale has undergone tremendous changes since the Woodburne (1987) volume, which was published just as magnetic stratigraphy was becoming practical. As summarized by Woodburne and Swisher (1995) and by Prothero (1995, 1998) and Prothero and Emry (1996), nearly all of the ''provincial land mammal ages'' of Wood et al. (1941) have been recalibrated, most in several different localities. They can now be dated precisely (using the new $^{40}Ar/^{39}Ar$ dating method) and correlated to the nearest 100,000 years to the global time scale, finally resolving many stratigraphic problems and puzzles that had existed for decades.

Although some of the Wood Committee's (Wood et al., 1941) correlations were correct, the major contribution of the last decade of work has been the revised correlations to the Lyellian epochs. For example, the Uintan and Duchesnean were thought to be late Eocene by the Wood Committee, although this correlation was questioned by Krishtalka et al. (1987). Subsequent work (summarized by Prothero and Emry, 1996) showed that they were both middle Eocene in age. The Chadronian was always considered early Oligocene by the Wood Committee, and that correlation was unchallenged until 1989, when Carl Swisher produced the first $^{40}Ar/^{39}Ar$ dates that clearly showed it was late Eocene (Swisher and Prothero, 1990; Prothero and Swisher, 1992). Ever the skeptic, Malcolm at first challenged these results when they were presented at the 1989 meeting of the Society of Vertebrate Paleontology, but he accepted them when the quality of the new $^{40}Ar/^{39}Ar$ dates became apparent. Moving the Chadronian to the late Eocene meant that the Orellan (''middle Oligocene'' of the Wood Committee) and Whitneyan (''late Oligocene'' of the Wood Committee) both became early Oligocene.

The Wood Committee (Wood et al., 1941) considered the Arikareean to be early Miocene, but by the 1970s (Obradovich et al., 1973; Naeser et al., 1980), K-Ar and fission-track dates on the Gering Formation showed that at least some of it was late Oligocene. This was incorporated into the paper by Tedford et al. (1987). The situation was further clarified when a previously undiscovered unit, the ''brown siltstone'' of Swinehart et al. (1985), was documented between the Whitney Member and the true Gering Formation. More detailed magnetostratigraphic and biostratigraphic studies (MacFadden and Hunt, 1998; Tedford et al., 1996) have clearly shown that more than half of the Arikareean is Oligocene. The Barstovian, once thought to be late Miocene, is now middle Miocene, and the Clarendonian and Hemphillian, originally considered early and middle Pliocene by Wood et al. (1941), are now middle to late Miocene (Tedford et al., 1987), largely based on changes in the Miocene/Pliocene boundary in Europe (Berggren and Van Couvering, 1974). Only the Wood Committee's Blancan land mammal ''age'' still remains in the Pliocene, and it is nearly coextensive with the global view of the Pliocene Epoch.

Finally, the indirect influence of Don Savage on many of McKenna's students, and many other mammalian paleontologists, has been shown by the application of classic Oppelian range zone biostratigraphy to the biochronological concepts of the Wood Committee. Archibald et al. (1987) proposed formal range zones and interval zones for most of the Paleocene, although these zones were not based on type sections and so did not fully meet the requirements of the 1983 North American Stratigraphic Code. Savage himself (1977) proposed formal biostratigraphic zones for the early Eocene, and Prothero and Emry (1996) and Prothero and Whittlesey (1998) proposed biostratigraphic zonations for the Uintan through Whitneyan interval. Rensberger's (1971, 1973) zonations for the Arikareean have not been applied widely outside the John Day Formation in Oregon, although the potential to do so remains. The resolution of Miocene mammalian chronostratigraphy is now excellent, although formal biostratigraphic zones have not been proposed to subdivide the Hemingfordian through Hemphillian interval (with the exception of Savage's (1955) Cerrotejonian and Montediablan for the Clarendonian of California, and Whistler and Burbank's (1992) zones for the Barstovian-Clarendonian-Hemphillian of California). However, the detailed lithostratigraphy, biostratigraphy, and magnetic stratigraphy have now been completed in numerous areas, such as the Hemingfordian-Barstovian strata of the Barstow Formation (MacFadden et al., 1990) in California, the Barstovian-Clarendonian-Hemphillian beds of the Ricardo Group (Whistler and Burbank, 1992) of California, or the Barstovian-Hemphillian formations in the Santa Fe Group (Barghoorn, 1981) of New Mexico, so that such a formal zonation is possible. Through the influence of Malcolm McKenna, Don Savage's (1955, 1962) dream has been largely realized, with higher resolution and better correlations to the European standards than anyone thought possible only 15 years ago.

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