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Clarkforkian Land-Mammal Age: Revised Definition, Zonation, and Tentative Intercontinental Correlations

Abstract. *New faunal and stratigraphic evidence documents the validity of the North American Clarkforkian Land-Mammal Age. Its limits are defined by the initial appearances of immigrant taxa. In the type area (northwestern Wyoming), the Clarkforkian is subdivided into three zones. Clarkforkian faunas are approximately correlative with latest Paleocene–earliest Eocene faunas of the Paris Basin of Europe and in part with the Gashato–Naran Bulak faunas of Mongolia.*

Wood *et al.* proposed the Clarkforkian as the last of the North American Paleocene provincial ages—now more widely termed land-mammal ages (*1*, *2*)—and based it "on the Clark Fork Member (and faunal zone) of the Polecat Bench Formation" (*3*, p. 9) (type area in the Clark's Fork Basin, northern Bighorn Basin, Wyoming). Their faunal characterization of the Clarkforkian, including first and last appearances, index fossils, and characteristic taxa, was drawn mainly from earlier studies that had suggested the presence of a distinctive Clark Fork assemblage in this basin (*4–7*).

Until recently, collections of Clarkforkian age were small and few in number, and precise stratigraphic data for most specimens were inadequate. As a result, the original definition of the Clarkforkian (*3*) included inaccuracies both in faunal indicators and stratigraphic details [for example, the "Clark Fork" is not a valid member of the Polecat Bench Formation, nor is the Clarkforkian fauna restricted to that formation (*8*)]. In addition, the misconception that the limits of the Clarkforkian should coincide with epoch or formation boundaries led to dispute over the exact age of the Clarkforkian. For these reasons, the validity of the Clarkforkian came into question (*9*), and a reassessment became mandatory.

Since 1975, personnel of the University of Michigan (UM) Museum of Paleontology, Ann Arbor, under the direction of P. D. Gingerich, have conducted intensive paleontological and stratigraphic investigation in the Clark's Fork Basin. Vertebrate fossils have been systematically collected from a richly fossiliferous section approximately 1000 m thick. The lowest part of the section yields fauna of late Paleocene (late Tiffanian) age (*6*, *10*); the upper part, mammals of early Eocene (early Wasatchian) age (*5*). Clarkforkian mammals occur in the intervening interval, about 450 m thick, in the uppermost Polecat Bench Formation and the lower part of the Willwood Formation (*8*, *11–14*). Thousands of mammalian fossils have now been collected from nearly 300 UM localities, about half of which are Clarkforkian in age (*8*). Although the Clarkforkian fauna is dominated by mammals of Paleocene aspect, it also contains taxa characteristic of the early Eocene. Thus it is an important transitional fauna that spans the time during which many archaic mammals were supplanted by mammals of more modern aspect, including the earliest members of several extant higher taxa.

The beginning of the Clarkforkian can now be defined by the first appearance of Rodentia (*Paramys*) and the mutual first occurrence of Tillodontia (*Esthonyx*), the pantodont *Coryphodon*, and the condylarth *Haplomylus*. The end of the Clarkforkian (beginning of the Wasatchian) is indicated by the first appearance of Artiodactyla (*Diacodexis*), Perissodactyla [*Hyracotherium* (*15*)], adapid and omomyid primates, and hyaenodontid creodonts, and by the first common occurrence of the condylarth *Hyopsodus* (*8*, *12*, *14*). The suites of taxa that define the boundaries of the Clarkforkian appear essentially simultaneously in the fossil record, suggesting that they represent waves of immigrants (Fig. 1). Several species of Clarkforkian index fossils are now known (*8*), including the common primate *Plesiadapis cookei* [listed by Wood *et al.* (*3*) but now known to be restricted to middle Clarkforkian]. Stratigraphic ranges and precise stratigraphic occurrences of all Clarkforkian mammal species from the Clark's Fork Basin are detailed by Rose (*8*).

Assemblages of definite Clarkforkian age are now recognized from several localities in Wyoming, Montana, and Colorado (*8*, *16*). More than 80 species of mammals are recorded in these assemblages; of these, 70 were found in the Clark's Fork Basin (*8*, *17*, *18*). Most are new records for the Clarkforkian, and about 25 percent are new species described since the inception of the UM project.

Ranges of Clarkforkian mammals in the Clark's Fork Basin permit subdivision of the type Clarkforkian into three biostratigraphic zones. According to Gingerich's zonation of the middle and late Paleocene of North America (based on evolution of plesiadapid primates), the late Tiffanian *P. simonsi* Zone was followed by the *P. cookei* Zone, then believed to occupy all of Clarkforkian time (*11*, *19*). A new species of *Plesiadapis* is now known from strata of latest Tiffanian and early Clarkforkian age, above beds yielding *P. simonsi* and below those yielding *P. cookei* (*8*). The new species is part of the *P. simonsi*–*P. cookei* lineage but is easily distinguished from both. Thus the stratigraphic range of the new species defines a new *Plesiadapis* zone of latest Tiffanian–early Clarkforkian age. This zone corresponds with about the upper 100 m of strata of Tiffanian age and the lowest 100 m of strata of Clarkforkian age. (The concurrent range zone of the rodent *Paramys* and the new species of *Plesiadapis* delimits the early Clarkforkian.) Immediately above the new *Plesiadapis* zone, and occupying an interval about 200 m thick, is the *P. cookei* Range Zone. It is now evident that *P. cookei* became extinct well before the end of Clarkforkian time, and a second new zone, here designated the *Phenacodus-Ectocion* Acme Zone, is proposed to encompass rocks of late Clarkforkian age [the upper 150 m of Clarkforkian strata in the type area (*8*)]. The lower two Clarkforkian zones are based on the ranges of species of *Plesiadapis*, whereas the uppermost zone is recognized partly by persistence of the Clarkforkian fauna in the absence of these species. Species of other genera, particularly *Esthonyx* (*8, 18*) and the primate *Phenacolemur* (*8*), also characterize these zones. Larger collections and better stratigraphic control are required to determine whether this zonation is applicable or precisely time-equivalent in other areas.

Gingerich (*11*) observed very close resemblances between *P. simonsi* and late Paleocene (Thanetian) *P. tricuspidens* from Cernay, France, and between *P. cookei* and early Eocene (earliest Ypresian) *P. russelli* from France. The new North American species corresponds closely to specimens of *P. tricuspidens* from Berru, France, which are intermediate in size between *P. tricuspidens* from Cernay and *P. russelli,* and slightly younger than the Cernay sample. Hence there is close agreement between the North American lineage *P. simonsi-Plesiadapis,* new species-*P. cookei*, and the European lineage *P. tricuspidens* (older)-*P. tricuspidens* (younger)-*P. russelli*. This similarity suggests that the corresponding North American and European species may eventually prove to be better regarded as geographic subspecies. In view of the resemblance of North American late Paleocene and early Eocene mammalian faunas to those from Europe (*20*), evidence from plesiadapid evolution and zonation strongly supports a tentative intercontinental correlation. If the lineages are approximately contemporaneous, as is suggested, latest Tiffanian-early Clarkforkian time (characterized by the new species) is correlated with late Thanetian (very late Paleocene) time. The remainder of the Clarkforkian is correlated with very early Ypresian (earliest Eocene), or perhaps with (unfossiliferous) latest Thanetian (Fig. 2). More precise correlation is hindered by the less continuous and less complete European sections. The correlation proposed here suggests that the Clarkforkian Land-Mammal Age is in part latest Paleocene, as was long believed, and in part earliest Eocene, as recent studies indicated (*11, 12, 19*).

Mammalian faunas from at least four localities in the Gobi Desert of Mongolia also bear similarity to those of the Clarkforkian and early Wasatchian of North America (*8, 21, 22*). About half of the mammalian genera from the Gashato-Naran Bulak assemblages (also found at Ulan Bulak, Tsagan Khushu, and possibly Khaitchin Ula-II) have close relatives in Clarkforkian or Wasatchian faunas. Some of them are generically identical to North American forms, and others are so similar that they may prove to be congeneric. Although some taxa found on both continents are unknown before the Wasatchian in North America (*Hyopsodus*, *Coryphodon*, Omomyidae,

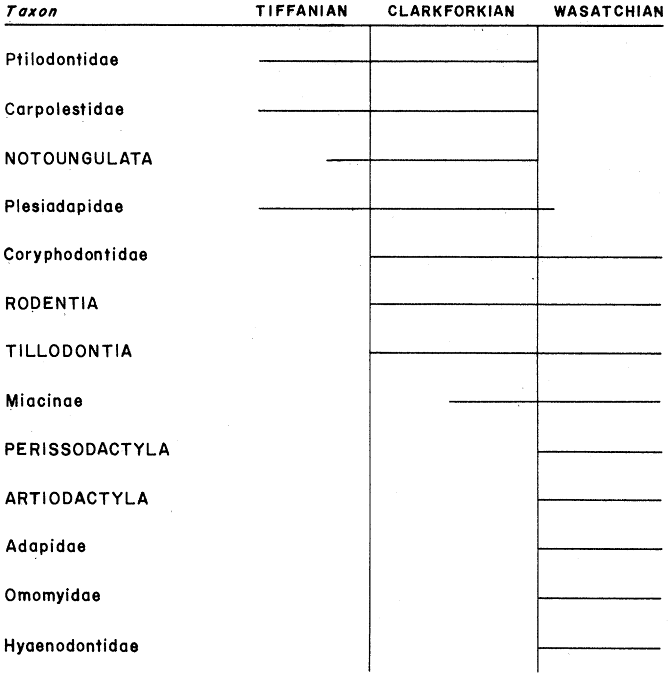

Fig. 1. Ranges of some important higher taxa of mammals that are useful for defining the limits of the Clarkforkian. Families and subfamilies are given in initial capitals; orders in all capitals.

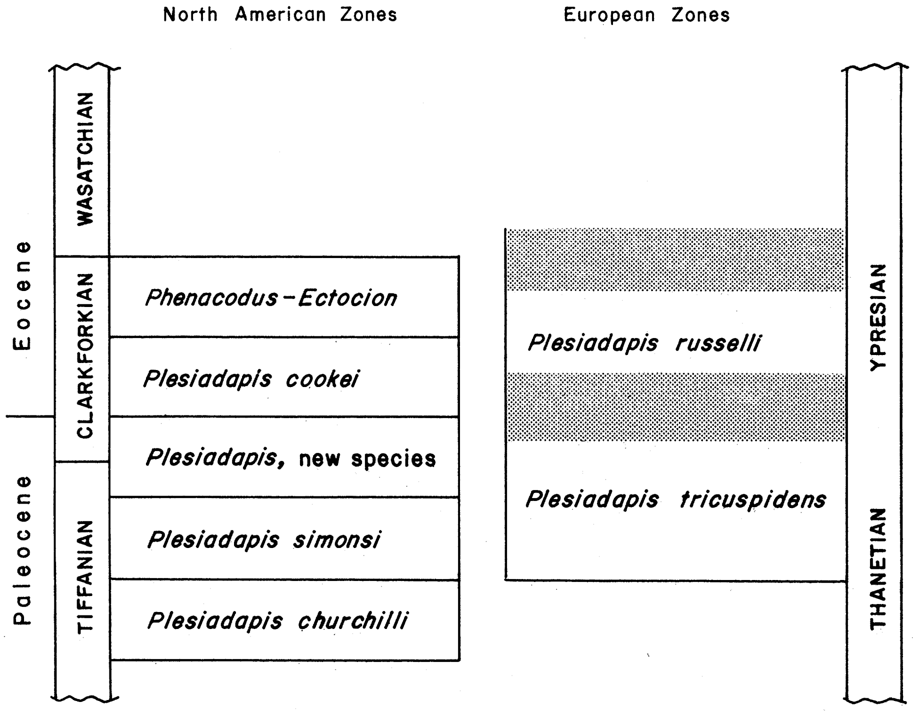

Fig. 2. Late Paleocene and earliest Eocene faunal zones in western North America and the Paris Basin, showing a tentative intercontinental correlation. Shaded areas reflect the uncertain position of the zone boundaries in Europe.

Hyaenodontidae), others are more indicative of pre-Wasatchian age (Arctostylopidae, certain uintatheres and pantodonts). The Gashato fauna was long considered to be of late Paleocene age (*21*), but it is probably earliest Eocene and at least partly correlative with the Clarkforkian (*8, 12, 22*).

Our much-improved knowledge of the Clarkforkian Land-Mammal Age and its fauna allows better correlation with European and Asian faunas and demonstrates that the Paleocene-Eocene transition was a time of substantial faunal interchange between North America and both Europe and Asia.

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Saturn's Luminosity and Magnetism

Abstract. *The Pioneer 11 results for Saturn's large heat output, small magnetic field, and near-axisymmetry of the field may all be explained by an interior model in which the helium is undergoing phase separation and is nonuniformly distributed. Substantial depletion of helium from the atmosphere is predicted.*

All published models for Saturn are essentially similar to those for Jupiter: they consist of a rock and ice core (or central concentration) of order ten Earth masses, surrounded by a shell of fluid, metallic, uniformly mixed hydrogen and helium, surrounded in turn by a fluid envelope of a molecular hydrogen-helium mixture (*1*). Three aspects of the Pioneer 11 results lead to doubts concerning this supposed similarity of Jupiter and Saturn. First, the conventional explanation of Jupiter's excess heat output (gradual homogeneous cooling) does not appear to explain Saturn's observed excess heat output (*2*). Second, the observed magnetic field at Saturn (*3*) is smaller than expected on the basis of scaling from Jupiter. Third, the magnetic dipole is aligned to within 1° of the rotation axis, unlike the substantial dipole tilt that characterizes other planets.

It is proposed to explain all these observations by an ongoing gravitational differentiation of helium from hydrogen within Saturn. The potential importance of differentiation as an additional energy source has long been known (*4*) and the essential features of the process have been described by Salpeter (*5*). Differentiation not only provides energy, but limits the convecting metallic region to deeper within the planet, thereby reducing the external field. Furthermore, an inhomogeneous, stably stratified metallic fluid layer above the dynamo region (see Fig. 1) is in differential rotation because of the equator-to-pole temperature difference. This flow tends to make the external field axisymmetric. These assertions are elaborated below.

The difficulty of reconciling Saturn's heat output with a homogeneous evolution (one in which the composition at each point within the planet does not change with time) is indicated by detailed evolutionary calculations (*6*) but can be readily understood in terms of quite simple considerations (*7*). To a good approximation, the "age" of a homogeneously evolving Jupiter or Saturn (defined as the time the planet takes to cool from an initially hot state to its present observed effective temperature) is proportional to the Kelvin time, defined as the ratio of present heat content to present excess heat output. (The constant of proportionality is about 0.25.) For Jupiter (*8*), the present excess heat output is $(4 \pm 1) \times 10^{24}$ erg/sec and the present heat content can be calculated from interior models (*9*). The resulting age for Jupiter is $(5 \pm 1.3) \times 10^{9}$ years, consistent with the age of the solar system. For Saturn, the excess heat output (*2*) is $(1.1 \pm 0.3) \times 10^{24}$ erg/sec, and the heat content of Saturn can be evaluated from published models (*1*). The resulting homogeneous age of Saturn is $(2.8 \pm 1.2) \times 10^{9}$ years, less than the solar system age. The error includes observational error, the assumption of an interior adiabat based on a temperature (T) of 140 K at a pressure (P) of 1 bar, the uncertainty in the specific heat of dense molecular hydrogen, and all the corrections and sources of error discussed by Hubbard (*10*). For the reasons discussed by Stevenson and Salpeter (*7*), an even larger uncertainty is possible, so the failure of a homogeneously cooling model is not certain. Nevertheless, these calculations suggest the need for an additional energy source.

The largest and most likely additional source is the gravitational energy release from a downward partitioning of the more dense helium. Theoretical calculations (*11*) show that insolubility of helium must eventually occur, beginning at the lowest pressure at which hydrogen is pressure-ionized [around 2 Mbar (*12*)] and for $T \lesssim 10^4$ K. Helium raindrops form, grow to ~ 1 cm in size, and fall under the influence of gravity, releasing energy by viscous dissipation on a small length scale. These raindrops dissolve deeper down where the temperature is higher. The molecular envelope (including the atmosphere) is in convective communication with the region of phase separation and is progressively de-