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PRESENT KNOWLEDGE OF LATE CENOZOIC GLACIATION

Traditionally the Pleistocene Epoch has been thought of as a glacial time. Its recurrent cold climates and even its warmer interglacial climates have been held to contrast with conspicuously warm-temperate climates of the Pliocene as indicated by land floras, marine- and terrestrial faunas, and possibly also zones of deep, mature weathering of rocks. The Pleistocene has been regarded as marked by glaciation not matched by any known similar events since the rather widespread glaciation in the Permian Period.

Recent discoveries, however, have introduced a new element into concepts of late-Cenozoic climatic history: the occurrence of cool-climate fluctuations, accompanied by glaciation at least in some regions, at times that clearly antedate the Pleistocene. Likewise strata that had been widely thought Pleistocene were shown by Potassium/Argon dating to be substantially older than had been supposed. For example the Blancan Faunal Age, based on fossil mammals in western North America and generally regarded as Pleistocene, dates back at least 3.5 milion years (Evernden, *et al.*, 1964), although the Pleistocene Epoch had been supposed to have begun only about one milion years ago. Soon afterward the diamict named Deadman Pass Till in the Sierra Nevada, California, was shown by K/Ar dating (Curry, 1966) to be $>2.7<3.1$ million years old. If the diamict is of glacial origin, this early date is significant.

Meanwhile research is northern Iceland (Einarsson, Hopkins, and Doell, 1965) revealed evidence of glaciation at least 1.9 million and possibly 3.0 million years old, followed by at least nine more glaciations. In the McMurdo sound region, Antarctica, glaciations are known to have occurred more than 2.7 million years ago (Armstrong, Hamilton, and Denton, 1968) and more than 3.4 million years ago (Denton and Armstrong, 1968); in another area 3.7 to 3.9 million years ago (Denton, Armstrong, and Stuiver, 1970, *in press*). A preliminary date indicates that in the Jones Mountains, West Antarctica, tillites (Rutford and others, 1968) are 6 to 10 million years old (R. L. Armstrong, unpublished). Finally, in coastal mountains

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in southeastern Alaska, a succession of tillites interbedded with lava flows indicate a number of glaciations ranging in age from about 3 million to at least 10 million years ago (Denton and Armstrong, 1970, *in press*).

Although it is not yet possible to fix the date of the Pliocene/Pleistocene boundary, numbers such as 10 million years clearly refer to pre-Pleistocene events. It seems to be established, therefore, that glaciation occurred at least at places in high latitudes, well before the beginning of Pleistocene time. Certain records of fossil plants and animals indicate climatic cooling that is at least compatible with the glacial record. Conspicuous cooling in the Miocene and again in the Pliocene is inferred from fossil plants in Japan (Takai and Hurioka, p. 93, *in* Hatai, ed., 1967), western Europe, and western United States (Dorf, p. 20, *in* Nairn, ed., 1964). Comparable cooling in the Pliocene is indicated by marine molluscs in Pacific North America (Durham, 1950, p. 1259). Tertiary climatic cooling is implied also by the forms of the margins of arboreal leaves (Wolfe and Hopkins, p. 72, *in* Hatai, ed., 1967). Likewise data set forth by Wolfe and Leopold (p. 203, *in* Hopkins, ed., 1967) support the concept of rapid cooling through about 7° in the July average, around 15 million years B. P., in later Miocene time.

Apart from these data, Bandy (1968) found evidence, in planktonie microfaunas, of cold episodes in late Miocene and mid-Pliocene time. Emiliani (1966) noted, from a variety of data, similar episodes in northern and southern Italy, and Zagwijn (1967) found pollen evidence, in the Mio--Pliocene of the Netherlands, of fluctuaction between warm-temperate and cool-temperate climate, possibly repeated once or twice. Ronai (1968) inferred from pollen data in Hungary a long cool interval in the late middle Pliocene. Whatever may have been the sequence of climatic events, it follows that as to the presence of glaciers the Pleistocene was not unique among Cenozoic epochs, although it may have been unique as to the presence of mid-latitude ice sheets.

This fact reduces the options open to us in choosing a Pliocene/Pleistocene boundary. Formerly we had the option of choosing a boundary based on the state of evolution of organisms (implicit in the proposal of Reboul, 1833), or one based on evidence of the onset of climatic cooling (implicit in the concept of Forbes, 1846). It now appears that the concept based on cooling is not unique to a single stratigraphic horizon and is therefore not practicable. We are consequently left with organic evolution, perhaps fortunately in that that is the basis of all pre-Pleistocene stratigraphic boundaries.

Another aspect of the existence of glaciers in later Tertiary time concerns the causes of glacial ages, about which many hypotheses have been framed. The data listed above disfavor hypotheses based on rather sudden, unique (or at least very infrequent) events. They are compatible, however, with hypotheses based in part on the existence of highlands. It has been proposed (Flint, 1957, p. 499–503) that where either orogeny or regional uplift causes highlands to interesect the snowline, glaciers can result. There is much evidence independent of glaciation that such uplifts occurred widely in Miocene and Pliocene time, subdividing continental areas into compartements and reducing average temperatures independently of the effects of changes, if any, that may have occurred in the flux of solar radiation.

The time/temperature curves in the references cited in this paper show an overall downward trend, amounting to several degrees, in Cenozoic surface temperatures. Superposed on the general trend is fluctuaction of several degrees' amplitude, at least in Miocene, Pliocene, and Pleistocene time. From our scanty information on the extent and distribution of glaciation, we might surmise that at first, episodes of low temperatures produced glacial responses in topographically high parts of high latitudes. As yet we have no evidence that large middle-latitude ice sheets appeared before Pleistocene time. Indeed they may not have appeared until well after its beginning, for there is available no direct radiometric dating of „Nebraskan" and other „early" drift layers of ice-sheet origin. If middle-latitude ice sheets were slow in appearing, the cause may have been that lands in or adjacent to those latitudes were not sufficiently high, or that secular temperature had not yet declined enough to push the snowline down below the tops of nearby highlands.

With present information all we can be sure of is that glaciers formed, and even in middle latitudes substantial fluctuation of climate made itself felt, long before Pleistocene time began.

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