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Reports

Pleistocene Chronology: Long or Short?*

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Introduction

Although coring devices capable of collecting stratified samples from the deep sea floor were developed forty years ago, it is mainly in the last decade that major syntheses of stratigraphic data from many such cores have been undertaken. The recognition of alternating "warm" and "cold" microfaunas in the cores invites comparison with the records of glacial and interglacial events on the continents and it might be anticipated that correlations would soon emerge. This has indeed been the case, but the correlations suggested by different authorities are so widely divergent that it is difficult to determine their relative degrees of probability. Nor are the uncertainties confined to the ocean floor record, for the glacial events themselves are poorly dated and there is still disagreement about various aspects of intra-continental relations, as well as intercontinental correlation. The problems will not be resolved without further observations, but it seems worthwhile at this stage to consider some of the evidence afforded by a number of different lines of study and to attempt a "first approximation" towards a reconciliation of the conflicting chronologies.

Glaciation on the Continents

The classic studies of Penck in the Alps (1882) subsequently led to general adoption of the "four glacial" concept of the Pleistocene and the Alpine glacial stages, Günz, Mindel, Riss and Würm, have tended to form reference standards even beyond Europe. Although a pre-Günz glacial episode was named the Donau by Eberl (1930) and a still earlier phase called the Biber (Schaefer, 1956) these terms have not been as widely used. In point of fact it is only the main Alpine sequence that is firmly established in its type region and the subdivisions, and correlations so widely accepted elsewhere are regarded as highly controversial by those most familiar with the area. Nevertheless, the existence of several pre-Günzian glacial episodes may be regarded as established, although the details are not agreed.

Northern Europe and the British Isles were invaded by the Scandinavian ice sheet, which at its maximum extent was still 500 km from the Alpine ice cap. Although an independent nomenclature is employed in Britain, the North German plains and the receptive basin of the Netherlands have formed the basis for a "standard" sequence that has acquired (through usage rather than formal adoption) the effective status of provincial stages. Faunal and floral correlations of the interglacial deposits have led to reasonably firm correlations of the Mindel, Riss, and Würm with the Elster, Saale (plus Warthe) and Weichsel respectively. The pre-Elster interglacial constitutes the Cromerian stage, the Elster/Saale is the Holsteinian, and the Warthe/Weichsel is the Eemian. The pre-Cromerian terminology is based on the Netherlands sequence which, in descending order, is Menapian, Waalian, Eburonian, Tiglian, Praetiglian and Reuverian. The terrestrial faunas in the Waal and Tegelen beds suggest their general equivalence to the Upper Villafranchian "stage" of the Mediterranean region (Azzaroli, 1970). The Villafranchian began about 4 million years ago. It is roughly coeval with the Blancan landmammal age of North America.

In North America four continental glacial advances have long been recognized and it has been more or less tacitly assumed that they correspond to the four "classic" glacials of the Alps, thus:

N. America	Europe
WISCONSIN	WEICHSEL (WÜRM)
Sangamon	Eemien
ILLINOISAN	SAALE
Yarmouth	Holsteinian
KANSAN	ELSTER
Aftonian	Cromerian
NEBRASKAN	[GÜNZ]

Even Flint (1971) does not challenge this concept, although he does give a realistic assessment (p. 658) of its degree of reliability. One of the few challengers has been Richmond (1965, 1970), who proposed equating the Illinoisan with the Elster (Mindel) rather than the Saale (Riss), a view supported here.

Dating Glacial Events in Europe

In Europe, various estimates of the duration of "glacial" time have been made. Penck and Brückner (1909) assessed rates of deposition and depths of weathering during interglacials, arriving at a total estimate for the duration of the four alpine glaciations and three interglacials of about 600,000 years. Various other estimates for the corresponding span have ranged mainly from a minimum of about 300,000 years to a maximum rarely more than one million. The availability since 1950 of C^{14} dates has served to define more clearly the duration of the last glacial but has not led to radical changes in the earlier estimates. Other radiometric methods, such as K/Ar dating, have been largely frustrated by lack of suitable volcanic materials in association with deposits readily correlated with the European glacial/interglacial sequence. K/Ar dating has, however, been of considerable value for the Villafranchian and the data are summarized by Savage and Curtis (1970) and by Azzaroli (1970). The latest Villafranchian fauna is no younger than one million years and the oldest is close to 4 my. (Azzaroli, personal communication). Some notable dated landmarks related to the Middle and Upper Villafranchian faunas are Roca Neyra, Mt. Coupet and Valros, shown in Table 1.

Two younger volcanic episodes in Italy are of some value for dating glacial-related events. Eruptions of the Volcano Albano at 270,000 years ago are probably of Mindel/Riss age (Flaminian/Nomentanan of Blanc). A "tuff with black pumices" from Volcano Bracciano is interbedded between deposits correlated with the Flaminian and Nomentanan glaciations and is dated at 430,000 years (Evernden and Curtis, 1965). This tuff occurs in deposits burying tools of an Abbevillian-Acheulean culture (Blanc, 1957).

The only other European K/Ar dates available are estimates of the ages of terraces in the Rhine valley based on the occurrence in them of pebbles from clearly recognizable volcanic rocks that have been dated radiometrically (Frechen and Lippolt, 1965). These are shown in Table 1 but the correlation of the terraces with the glacial/interglacial events is not entirely satisfactory.

Recognition of the fact that periodic inversions have taken place in the polarity of the Earth's magnetic field (Rutten, 1959) has led to the development of a "palaeomagnetic time scale" well controlled by numerous radiometric dates (Cox, Doell and Dalrymple, 1963; Cox, 1969). The rapid evolution of the time scale has been reviewed recently by Dalrymple (1972) and the time scale given in Table 1 is basically that of Cox (1969), modified to fit better with comments made by Dalrymple.

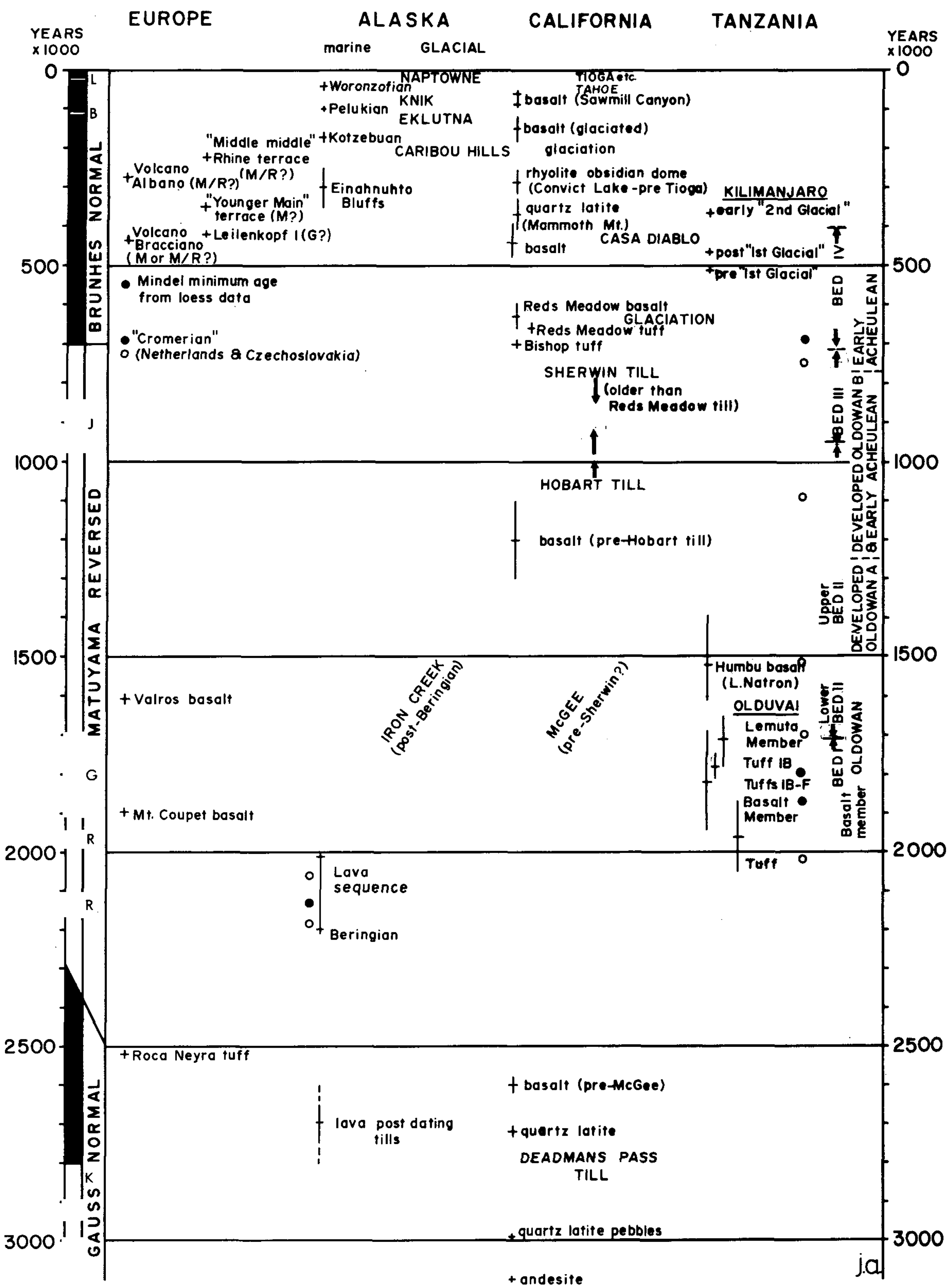
The palaeomagnetic time scale has been a powerful tool for correlation and dating marine sediments, where deposition is essentially continuous and the magnetic "fingerprint" can be matched with some assurance. It has also, of course, been misused. Terrestrial deposits present much greater problems as there is considerable room for uncertainty. However, in Europe Kukla (1970) has not only worked out the loess stratigraphy for Czechoslovakia and Austria but has shown that a rich Cromerian fauna is embedded in soil virtually at the Brunhes/Matuyama boundary. The same dating of the Cromerian was arrived at by Van Montfrans and Hospers (1969) in the Netherlands. Kukla (1970) also arrived at a probable relative minimum age for the Mindel which is shown in Table 1. Although Kukla questions the reliability of the dating of the Brunhes/Matuyama boundary at 0.69-0.70 my, his arguments in this regard are not such as to represent a serious challenge.

Accordingly, it seems highly probable that the European Cromerian stage lies astride the first major reversal boundary at 700,000 years ago. An age of around 500,000 years for the Mindel/Elster glaciation would be reasonably consistent with the Rhine terrace data (except for Leilenkopf) and with the Italian volcanic ages. It is interesting to note that Richter (1958), using fluorine as a means of estimating relative ages --a technique unfortunately somewhat open to criticism-- suggested an age of 0.64 my for the Cromerian and 1.5 my for the Tiglian. Kurten (1960) using C^{14} dates and a K/Ar date of 230,000 years for the Holsteinian, calculated faunal turnover rates and estimated ages for the Cromerian of 480,000 and Late Villafranchian of 700,000 years. These now seem rather too short but nevertheless tend to confirm the order of magnitude of the new dating for the Cromerian. Most European geologists have assumed the age of the Günz (or its equivalent) to be no more than 0.5 my and favour a "short" Pleistocene chronology.

Dating Glacial Events in North America

As in Europe, the areas occupied by the major ice sheets in North America were devoid of volcanic materials that could readily be dated radiometrically. Numerous C^{14} determinations for the later Wisconsinian showed a striking parallelism to the details of fluctuations in the Weichselian of Europe, thus tending to reinforce the concept of simple one-to-one equivalence. However, beyond the age limits of C^{14} it is only in the mountainous regions of the west that volcanics are present and it is only there that glacial/interglacial events have been "bracketed" by radiometric dates. Unfortunately the number of dated events is extremely limited and the glacial episodes of the mountains have not been linked with assurance to the phases of advance and retreat of the major ice sheets to the east. Nearly all the dates available are summarized in

TABLE I



KEY: + = Radiometric date ● = Normal polarity o = Reversed polarity

Table 1.

The most interesting, and in the long run the most promising, area is Alaska, where Hopkins and his collaborators have shown that marine stages of deposition can be related both to terrestrial events and to datable volcanics. The basis for the interpretation is summarized by Hopkins et al (1965). A lava dated at 2.7±0.6 my has two tillites between it and a flow dated at 8.4±0.7 my in the Wrangell Mountains of Southern Alaska and one tillite adjoins a 3.6±0.2 my old lava flow, (Denton and Armstrong, 1969). There is also evidence of other glaciations in Alaska in the late Miocene, at least 8 my ago. Although these are mountain glaciations and thus do not either require or imply contemporaneous ice sheets, it is clear that there was substantial atmospheric cooling long before the "classic" Glacial Period.

In the Rocky Mountains and Sierra Nevada areas, there is abundant evidence for numerous glacial advances, although many of the occurrences are too localized for correlation to be reliable. The oldest firmly dated occurrence is the Deadmans Pass till which rests on an andesite with a K/Ar age of 3.1 my and is overlain by a quartz latite with a good age of 2.72 my. The age range is further narrowed by the occurrence in the till of angular boulders of another quartz latite with an age of 3.0 my (Curry, 1966). The relative stratigraphy of the other Californian tills is shown in Table 1 and is fully discussed by Dalrymple (1972). An excellent authoritative consideration of the stratigraphy has been given recently by Birkeland, Crandall and Richmond (1971), which should be consulted for additional information and a few dates not included in Table 1. However, correlation of these mountain events with those of the plains areas remains uncertain.

Ocean Floor Sediments

The literature on the interpretation of cores from sediments of the ocean floor is vast and it has been necessary here to be highly selective. Discussion will be confined essentially to the data summarized in Table 2. Although the actual inorganic particles of the sediments themselves provide useful data on weathering, erosion and other climate-related phenomena (see McManus, 1970) most of the discussion on inferred climatic changes has centered on analyses of the organic content. In the circumpolar region, the distribution of ice-rafted sands is obviously important and more studies are needed; Margolis and Kennett (1970) have thereby shown that the Antarctic was glaciated through most of the Cenozoic, but comparable observations are not available for most of the northern region (but see Kent, Opdyke and Ewing, 1971). Much excellent work, such as that of Arrhenius and Olausson cannot be included here because of difficulties in placing the curves as they do not give dating controls. Olausson's scepticism regarding isotopic dating and the palaeomagnetic time scale (Olausson, 1971) makes it difficult even to suggest that his curves can be matched by those of other workers.

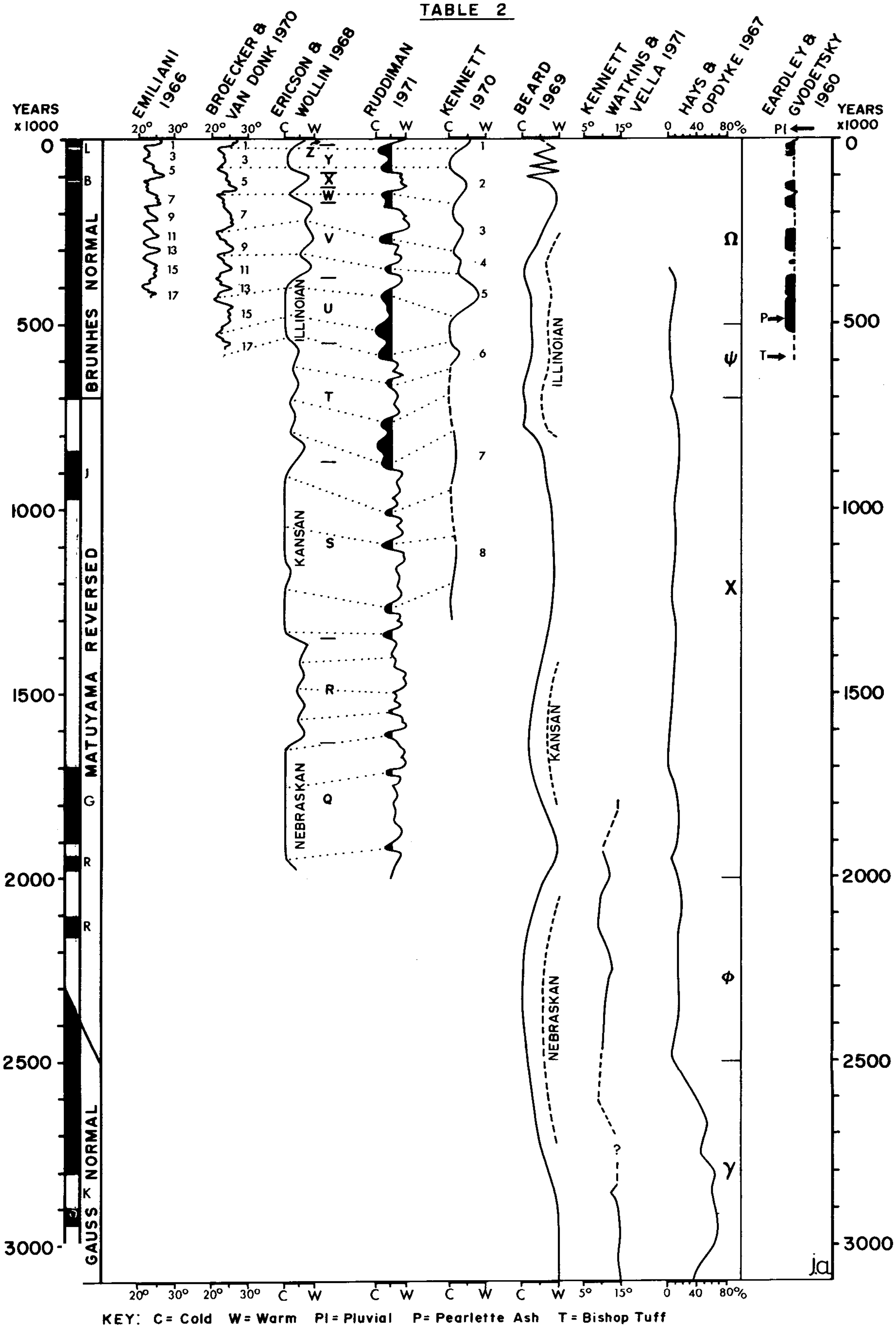
Climatic interpretations of organic remains from cores have been made essentially by four methods: (1) ratios of warm-water to cold-water species (whether foraminifera, radiolaria, nannoplankton, or diatoms); (2) coiling directions in particular foraminiferal species, notably *Globorotalia truncatulinoides* and *Globigerina pachyderma*; (3) productivity and (4) oxygen isotope ratios (O^{18}/O^{16}) determined in the $CaCO_3$ of planktonic foraminifera as a measure of effective water temperature during the growth of the calcite of the test.

The oxygen isotope method (developed by Urey) was first applied by Emiliani (1955) to cores from the tropical Atlantic and the Caribbean. Mediterranean observations were added and the curve later refined; the version given in Table 2 is from Emiliani's generalized curve of 1966. In 1958 numbers were used to designate the successively older warm intervals, but as far back as 1955 he had proposed to correlate cold periods 2 and 4 with the Würm and Wisconsin, 6 with the Riss/Illinoisan, 10 with the Mindel/Kansan and 14 with the Günz/Nebraskan, although subsequent papers were somewhat more cautious in this regard. However, Emiliani's isotope curve has come to typify the "short chronology" and has been employed by others to support correlation with astronomically controlled radiation factors generally called the "Milankovitch hypothesis".

The time scale for Emiliani's curve was derived from C^{14} dates, extended by sedimentation rates, but later checked by several Th^{230}/Pa^{231} determinations on the two "type" Caribbean cores (Rona and Emiliani, 1969). These dates were challenged by Broecker and Ku (1969) who suggested a 25% increase in the age estimates and an acrimonious and inconclusive debate ensued. Emiliani's curve, as "stretched" by the dates given by Broecker and Van Donk (1970), is also shown in Table 2.

Using a different technique, initially involving mainly warm/cold faunal ratios, Ericson and his collaborators at the Lamont-Doherty Geological Observatory produced climatic interpretations for cores from the Atlantic Ocean; later they relied more on the coiling directions of *Globorotalia truncatulinoides*. The first major synthesis involving a "long" chronology (Ericson, Ewing and Wollin, 1964) placed the four North American glacials (matched by the four European Alpine terms) with the Riss/Illinoisan about 400,000 years ago, the Mindel/Kansan about 1.1 my and the Günz/Nebraskan at 1.5 my. With the availability of palaeomagnetic controls for the calculation of sedimentation rates in different parts of the cores, the curve was modified to the form shown

TABLE 2



KEY: C = Cold W = Warm Pl = Pluvial P = Pearlette Ash T = Bishop Tuff in Table 2 (Ericson and Wollin, 1968); the base of the "Nebraskan" is put at close to 2.0 my and the "Kansan" considerably stretched by comparison with the 1964 version. The letters shown alongside the curve designate the major climatic zones recognized by Ericson and Wollin, as reflected in percentages of the *Globorotalia menardii* complex present.

Although the Ericson and Wollin curves show considerable detail for individual cores, they are rather drastically smoothed out in the generalized presentation. This obscures the fact that the upper parts actually match very well with the Emiliani isotope curve (particularly with the "stretched" version) but reconciliation between the "short" and "long" chronologies has not been achieved so far.

Similar studies by Ruddiman (1971) on a suite of 15 cores from the equatorial Atlantic, using the warm/cold foraminiferal fauna ratio technique, confirmed in general both the upper part of the Ericson and Wollin curve and that of Emiliani, although there are differences in detail. Two long cores enabled this work to be extended to the base of the Gilsa[1] palaeomagnetic event and the entire composite curve is shown in Table 2. It is worth quoting from the abstract an important conclusion: "This analysis pinpoints two prominent, large-scale climatic shifts: (1) at 1.3 my B.P., the mean climatic situation deteriorated, and short but severe cold pulses began to punctuate the previous moderate warmth of the late Matuyama; (2) following 900,000 yrs B.P., the duration of cold intervals increased. Prior to the Jaramillo, no cold pulse exceeded 30,000 yrs; three post-Jaramillo cold intervals ranged in duration from about 50,000 to 150,000 yrs. The shortest and most recent of these correlates with the Wisconsin glaciation." Ruddiman's conclusions thus suggest that a different kind of weighting should be given to the potential influence on glaciation of pre-Jaramillo as compared with post-Jaramillo cold phases. This would not be inferred from the Ericson and Wollin curve as presented.

In the subantarctic region, Kennett (1970) has studied the biostratigraphy of 11 cores from the central Pacific sector and evaluated the palaeoclimatic trends, primarily through coiling directions and frequencies of *Globigerina pachyderma*. In three of the cores the trends matched closely the inferences made by Hays (1965, 1967) on radiolaria, and Kennett's generalized curve is presented in Table 2; the small numbers refer to warm intervals. Kennett notes that the relative magnitude of the climatic warmings was considerably greater during the last half million years than during the period from 0.5 to 1.3 my, when conditions were generally cooler. Interval 5 (about 0.4 my) was significantly warmer than the Recent. A broad correlation with the curves of Ruddiman, Ericson and Wollin, and Emiliani is apparent.

Rather different in character is a climatic curve by Beard (1969) based on abundances and coiling directions of planktonic foraminifera from deep-water sediment cores from the northern Gulf of Mexico (Table 2). Palaeomagnetism was used as a control but some uncertainties apparently exist. The "cold" sections of the core are regarded as coincident with lowered sea levels and there seems to be good agreement between bathymetry and climate. This curve exhibits little similarity to those from the open oceans and, as the details of the individual cores are not published, it is difficult to guess the reasons for the differences. If the correlations with glacial events are correct, Beard's chronology is even "longer" than that of Ericson and Wollin.

Beard's cores apparently provide data back to 3 my and are thus of interest for the earlier part of the climatic record. Two other sets of observations covering this earlier period are also included in Table 2. One of these is taken from a short paper by Kennett, Watkins and Vella (1971) who established the palaeomagnetic stratigraphy for cores from the southern end of the North Island of New Zealand. Foraminiferal palaeotemperature curves had already been constructed by Devereaux, Hendy and Vella (1970) and the particular one shown in Table 2 is derived from O^{18}/O^{16} values in the planktonic foraminifera; benthonic foraminifera and abundance curves for *Globigerina pachyderma* are essentially very similar. These data show that marked cooling began shortly after the Kaena event (2.8 my). Even stronger evidence of this transition from generally warm to generally cool conditions is shown by radiolaria in a study by Hays and Opdyke (1967) of long cores from Antarctic waters between New Zealand and South America. In a previous study of radiolarian stratigraphy, Hays (1965) had recognized a number of radiolarian faunal zones and designated them by Greek letters (see Table 2). The curve (Fig. 2) represents the percentage of individuals of species not found in Recent Antarctic sediments in core E14-8. Both the radiolarian zones and the palaeomagnetic stratigraphy permitted good correlation of the cores and the same trends were shown in each of them. Before 2.8 my the fluctuations of non-Recent species fluctuated between 35% and 80%, but following a "warm" spell at 3.0-2.8 my the percentage of Recent (or "cold") forms increased very rapidly so that since the end of the Gauss normal epoch the non-Recent forms fell to 0-20% only. The relatively small fluctuations shown for the past 2.5 my have not been analyzed in sufficient detail to provide

[1] Re-evaluation of the Olduvai data by Grommé and Hay (1971) shows that the long polarity event younger than 2.0 my is the main event at Olduvai and they suggest that this should be designated as the "Olduvai event" and the term Gilsa event abandoned. The two short events are renamed the "Reunion events" In order to avoid unnecessary confusion, the latter proposal is adopted here but the term "Olduvai event" is dropped in favour of retention of Gilsa event for the longer episode to which this name has become firmly linked in the literature.

details of later climatic events.

Included in Table 2, although not based on a marine sequence, is a curve derived from a 650-foot deep boring (the "Saltair" core) in the Great Salt Lake, Utah (Eardley and Gvodetsky, 1960). A careful study of the sediments led to inferences about the salinity of the Lake and the shaded areas represent periods of fresh water, supposedly associated with "pluvials". Near the bottom of the core are two ash layers, the upper (marked P in Table 2) being of Pearlette type; almost at the base is another tuff (marked T) that is probably a correlative of the Bishop tuff. As the time scale used was based on sedimentation rates estimated from C^{14} dates in the upper part of the core, it would seem that the estimates for the deeper parts are about 15% low and that the curve should be "stretched" by that amount. The upper part of the Saltair curve matches closely the shorter record from Searles Lake, California (Flint and Gale, 1958) which accords very well with the Wisconsin glaciation.

Synthesis

An attempted synthesis is presented in Table 3 and is largely self-explanatory. However, some comments on various aspects of the reasoning involved may be desirable.

In the first place, it is assumed that the changes shown in the Atlantic and Antarctic oceans are due to real changes in the temperatures of the water masses, either because of atmospheric influences or because of glacially induced changes in the surface circulation. It is realized that there is some evidence that in the central Pacific, faunal changes may not be synchronous with those of the Atlantic (Ericson and Wollin, 1970), but there are other criteria that do seem to match, so consideration of the Pacific data must be left open for the moment. Assuming that the oceanic effects are real, it is logical to try to fit the glacial/interglacial events to them in so far as this is compatible with the terrestrial evidence itself.

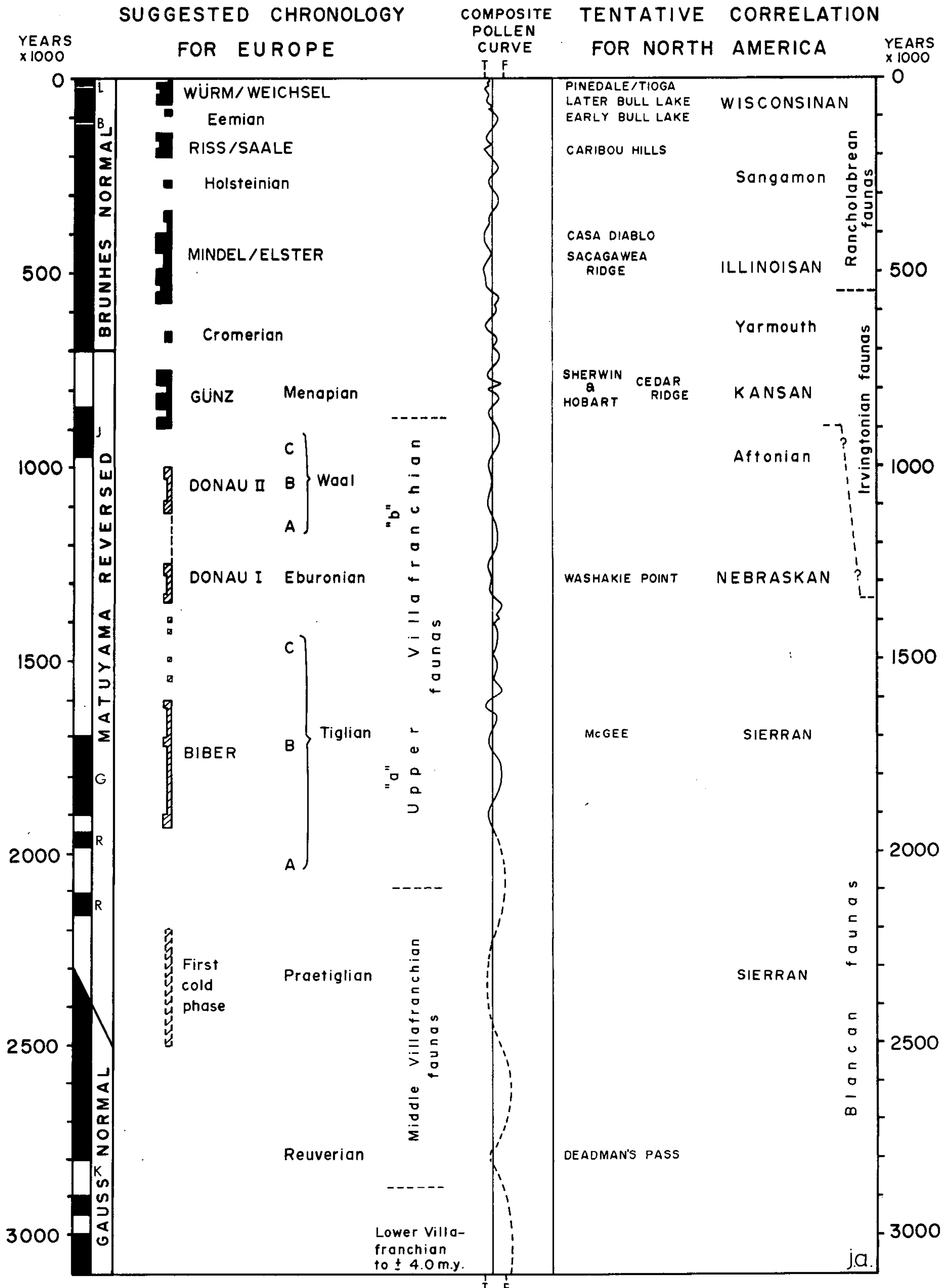
For the European chronology, the evidence for placement of the Cromerian at about 700,000 years is good. This dictates a younger position for the Mindel, for which the U Zone of Ericson and Wollin's curve is appropriate; this is in accord with other dating evidence, only the Leilenkopf data failing to fit, but the criteria for suggesting that it was of Günz age are in any case too tenuous for this conflict to be regarded as significant. The Riss has been placed as corresponding to the W phase of Ericson and Wollin's curve. The Günz glacial of the Alps is not matched by a known extension of the Scandinavian ice sheet, thus suggesting that it was weaker than the succeeding glacials. Although Ericson and Wollin's curves do not show a strong climatic event at an appropriate time, Ruddiman does record a substantial cool period during and after the Jaramillo event, in a very suitable position.

Placement of the Donau and earlier glacial events is very problematical. No ice sheet counterparts are known and these glaciations were most probably of the magnitude of montane Alpine ice caps only; the Scandinavian mountain core may also have had a similar ice cap that did not extend into the plains. The four short "peaks" of Ruddiman's curve have been rather arbitrarily grouped into two phases of the "Donau", thus giving some weight to the extended "Kansan" of Ericson and Wollin's curve. A similar argument applies to the "Biber" in relation to Ruddiman's data and the "Nebraskan" of Ericson and Wollin. The placement of the Netherlands stages is adjusted to a "best fit" with the inferred glacials and fits the relationship between the mammalian faunas and those of the rather well controlled Villafrachian time scale.

Perhaps unnecessary is the "composite pollen curve" given in Table 3. Basically it consists of the pollen-derived temperature curves given by Zagwijn (1963) for the Netherlands, fitted by surprisingly small adjustments to the inferred chronology. Some account has been taken of other data, such as the Leffe cores from Italy (Lona, 1963).

As far as correlation with the North American glaciations is concerned, the problem is more complex. There are few departures from the correlation for the western United States proposed by Birkeland, Crandell and Richmond (1971). The early stage of the Bull Lake glaciation seems to be earlier than the base of the classical Wisconsin. It is problematical whether the Hobart till is the equivalent of the Sherwin or not, but it is certainly pre-Tioga. The position of the McGee is questionable and it may well be equivalent to the Washakie Point till, as Birkeland and his co-authors suggest. For correlation between the Rocky Mountain region and the eastern United States, the suggestions of Richmond (1970) are followed in the main. The principal problem is the apparent absence of a true equivalent of the Alpine Riss, for Richmond equates it to the Bull Lake, the base of which does not extend beyond 130,000 years. The apparent absence of a Riss equivalent in the eastern areas of North America could be explained by its extent being so much less than that of the Wisconsin that its edge moraines and other debris have been overlooked or included with the early Wisconsinan stages. The Riss equivalent does seem to be represented in Alaska bv the Caribou Hills and by glaciation in California.

TABLE 3



KEY: T= Tundra flora F= Forest flora

On the one hand, the Kansan seems certainly older than the 700,000-year old Bishop tuff. The Kansan mammal fauna includes the elephant *Mammuthus* and the species (*M. imperator*) is almost certainly descended from *M. meridionalis* of the late Villafranchian or Cromerian of Europe. This is characteristic of the Irvingtonian landmammal age in North America. The dating of the Seger fauna as belonging to the earlier Kansan, and late Blancan in character, may require review. The upper Kansan fauna (Cudahy) is overlain by a Pearlette-type ash and, although three such ash levels are now known, this is the "O-type" ash, with normal magnetic polarity, dated at 0.6 my (Izett, Wilcox, Powers and Desborough, 1970). A very similar Pearlette-type ash, the "S-type" (with reversed polarity) has an age of 1.2 my. There is also a third similar ash of age close to 2.0 my, known as the B-type (Naeser, Izett and Wilcox, 1971), directly underlying the sediments that contain the Borchers fauna of Hibbard (1941). This fauna was classified as late Irvingtonian because it was apparently younger than the Cudahy, a conclusion that no longer holds. The relationship to the Seger (late Blancan) fauna also requires review.

As THE "Pearlette Ash" has been used as a stratigraphic marker and reference horizon, the existence of three virtually identical ash beds of such widely different ages demands that the stratigraphic and other interpretations linked to this type of ash be critically reviewed. Fortunately the O-type ash seems to be the most widespread. Nevertheless, it seems certain that the Kansan is pre 0.6 my. However, the S-type ash (1.2 my) is so designated because it occurs in the type Sappa Formation which, though periglacial, has long been regarded as later than the Kansan till. However, S-type ash was found below Kansan till in sediments assigned to the Fullerton Formation in Butler County, Nebraska (Izett, Wilcox, Obradovich and Reynolds, 1971). Thus the Kansan till has limiting ages somewhere between 1.2 and 0.6 my, so its position in Table 3 is not unreasonable.

A problem concerning the base of the Irvingtonian is at present unresolved. In Idaho lenses of fossil-bearing sediments are sandwiched between flows of the Bruneau Basalts, the youngest of which is dated at 1.36 my (Evernden, Savage, Curtis and James, 1964); polarity is reversed. The scrappy fauna includes fragments of an undoubted *Mammuthus* molar and a piece of humerus of *Gigantocamelus*, as well as a large *Equus*, *Paramylodon* and cervids (Malde and Powers, 1962). Apart from not being Blancan, the assemblage is not diagnostic. The molluscan fauna is almost completely modern and suggests a much younger age than does the radiometric date. While it is not impossible that *Mammuthus* arrived as early as this, it is odd that the Aftonian faunas remained typically Blancan. It is possible that the date is spurious but if this is not the case then the Aftonian and Nebraskan should be older. As the Nebraskan was a continental ice-sheet, an older date would be difficult to reconcile with the apparently montane character of the earlier glaciations. Even the position shown in Table 3 would make the Nebraskan the oldest northern ice sheet, a view not well supported by the marine data or by the pre-Günz glacial episodes. Closer study of this issue is required in conjunction with the re-evaluation of the stratigraphy in which Pearlette-type ash has been used as a reference horizon.

Archaeological aspects

Penck's original estimate of the total duration of the four Alpine glaciations as 600,000 years was confirmed by Zeuner in two publications, "The Pleistocene Period" (1945) and "Dating the Past" (1946), that have had a considerable influence on the thinking of prehistorians. Zeuner linked the geological data to Milankovitch's astronomical theory, as also for example, have Emiliani (1955) and Broecker and Van Donk (1970), usually with a shorter chronology than that of Zeuner. Stone tools are not reliably known in the Cromerian, although Heidelberg Man may belong to the final Cromerian or earliest Mindel/Elster. The first plentiful hand-axes of the Abbevillian, Acheulean and Clactonian cultures are in deposits of Holsteinian age, although there are scattered localities that belong within the Mindel/Elster period. The antiquity of Man in Europe has been looked upon as less than half a million years.

In Africa the story is very different. At Olduvai Gorge in Tanzania pebble tools ("Oldowan culture") were found in Bed I, giving place in Bed II to more advanced Oldowan artefacts and to Early Acheulean cultural remains. It came as something of a shock to European prehistorians when Bed I was dated at 1.8 my and it was widely assumed that the upper part of Bed II and the overlying Bed III and Bed IV must be roughly contemporary with the Holstein. Recent evidence suggests that this is not so, for the upper part of Bed III has reversed polarity and is thus still within the Matuyama Epoch, whereas a sample from near the base of Bed IV has normal polarity (M.D. Leakey, 1971). This serves to equate the Bed III/Bed IV boundary with the Cromerian, although it is possible that Bed IV may in part be substantially younger. The inferred sequence is set out in Table 1. Isaac (1972) has recently reviewed the problem from the viewpoint of the prehistorian and it must be admitted that the greater antiquity assigned here to the European glacial sequence does not wholly meet his needs, although it helps. At least the dates here suggested are feasible.

Periodicity of Glacial Events

As the various observational and dating techniques are refined, it becomes clear that the simplistic division of later Cenozoic time into "glacial" or "interglacial" does not work. The isotope analyses of Emiliani, the fluctuations shown by Ruddiman, the multiplicity of loesses demonstrated by Kukla (1970), and the complexities of the pollen curves all show that in reality the temperature factor, and other factors as well, fluctuate considerably through time. The Antarctic had some glaciers at least as far back as the Eocene and the onset of continental glaciation in the northern hemisphere seems likely to have developed through a preceding phase of montane glaciation only. There are probably more montane glaciations than ice sheets and it seems likely that a continental glaciation results only when the duration of the appropriate conditions (temperature as well as other meteorological parameters) continues long enough. The geological grouping into "glacials", with various substages, may well be somewhat arbitrary. It is even possible to imagine that the particular meteorological conditions in North America and in Europe need not always produce exactly synchronous geological glacial events. Similarly, interglacials are not periods of continuous warmth but are essentially only periods when the cold spells were not of sufficient intensity or duration to produce detectable "glaciation".

Broecker and Van Donk (1970) have made a very interesting analysis of Emiliani's data, thus demonstrating the apparent asymmetry (or "sawtoothed" as they term it) shape of the major oscillations. They show that the passage from cold to warm is very abrupt compared with the gradual onset of the cold conditions; these rapid warmings they call O^{18} "terminations". Kukla (1970) has observed rather sharp boundaries between the successive eastern European loesses and has called them "marklines", noting that they match remarkably well with the O^{18} terminations. There are at least eight such cycles within the Brunhes Normal Epoch and it would not be difficult to match the "marklines" with Ruddiman's (1971) curve. Further research in these areas should make a notable contribution to the details of Pleistocene chronology and, if the loess studies can be extended farther back in time, may well solve some of the problems that exist at present. Similar work on the loesses of North America is highly desirable. The marine data and the application of the palaeomagnetic time scale are changing our perspective and suggest that the prime need is for further studies in the terrestrial areas. In the meantime the best that we can do is to attempt to reconcile the data from different disciplines, recognizing that the resulting correlations are far from perfect.

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