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HOLOCENE — its lower boundary and stratigraphical aspects **Part 2**

THE PLEISTOCENE-HOLOCENE BOUNDARY: AN EVALUATION OF THE VARIOUS CRITERIA USED FOR DETERMINING IT ON A PROVINCIAL BASIS, AND SUGGESTIONS FOR ESTABLISHING IT WORLD-WIDE

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INTRODUCTION

The question of defining an international boundary between the Pleistocene and Holocene is on the agenda of the 8th INQUA Congress in Paris in 1969. The INQUA Subcommission for Study of the Holocene, in its role advisory to the INQUA Congress, has been studying this question for several years, seeking viewpoints of delegates from many countries. At its annual meeting in October 1968 in Holland, this subcommission met jointly with the INQUA Subcommission on Baltic and North Sea Shorelines, and both subcommissions reached a consensus that the international boundary between the Pleistocene and Holocene should occupy the time-stratigraphic interval between the Bölling/Older Dryas and the Younger Dryas/Pre-Boreal pollen-zone boundaries of northern Europe, and equivalents elsewhere of this interval. It is believed that this interval provides sufficient time-span, from about 12,000 to 10,000 years ago, to accomodate various regional preferences for provincial boundaries at somewhat different time-stratigraphic levels and to provide latitude for the inevitable time-transgression of the key beds or stratigraphic discontinuities by which this boundary is mapped and correlated over large regions.

Unfortunately, there is greater diversity of opinion on placement of this boundary in the United States than now exists in Europe. Quaternary geologists in the U.S. have the same attitude toward this boundary as they do about morality. They all agree that a line has to be drawn somewhere, but they haven't been able to agree on where the line should be drawn.

The different stratigraphic levels at which various U.S. geologists would place this boundary are as follows:

(1) At the glacio-eustatic minimum of sea level during the late Wisconsin glacial maximum. This boundary is advocated by workers in the Mississippi River delta region (e.g., Fisk and McFarlan, 1955; Le Blanc and Bernard, 1954; Bernard and Le Blanc, 1965, who formerly dated this episode at about 30,000 years ago, but recently (Saucier, 1968) revised its age to 20,000 or 18,000 years ago—i.e., synchronous with the maximum of the "Main Würm" Glaciation.)

(2) At one of the following stratigraphic markers (local to widespread) caused by several rapid climatic fluctuations (cold to warmer and vice-versa) toward the close of the Wisconsin Glaciation, dating from about 12,000 to 10,000 years ago:

(a) The following time-equivalent soil-stratigraphic units that record a brief warm interval: the Harmon School Soil in the Lake Lahontan area, Nevada, the Graniteville Soil in the Lake Bonneville area, Utah, the Brady Soil in the Great Plains, and a weak weathering profile (and also peat and a forest bed) of the Twocreekan Substage in the Midwest. This warm interval commonly has been correlated with the Allerød warm interval of Europe, but perhaps it should be correlated with the Bölling warm interval (see Broecker and Farrand, 1963). I now believe that the upper contacts of the full weathering profiles of this interval, marking its end about 12,000

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years ago, would make excellent provincial markers for the Pleistocene-Holocene boundary in at least the Western and Midwestern U.S.

(b) At the top of the Valders Till at a proposed type locality in northeastern Wisconsin, which marks the end of the maximum of the Valders readvance of the Lake Michigan glacial lobe, dated at 11,500-11,000 years ago (H.E. Wright, Jr., written communications, 1968).

(c) At the top of a generalized spruce-pollen zone, dated at 11,000 ± 1,000 years ago, that is marked by a catastrophic decrease in abundance of *Picea* pollen—a change sharper than any other in the entire pollen sequence—that can be recognized from Manitoba to New England and south at least to Nebraska (H. E. Wright, Jr., in press and written commun., 1968).

(3) At one of the manifestations of the postglacial "thermal maximum" ("altithermal") interval (correlative with the Atlantic warm interval of Europe), either:

(a) A marker at the beginning of this interval. Frye, Willman, Rubin, and Black (1968) recently redefined the end of the Valderan Substage, and consequently of the Wisconsinan Stage (and implicitly the Pleistocene-Holocene boundary), at the contact of the Cochrane Till with thin overlying and discontinuous deposits in the James Bay Lowland of Ontario. This boundary dates from about 7,000 radiocarbon years ago, according to these authors. Richmond (1962, p. 87; 1964) draws the boundary at the top of the till of the late stade of the Pinedale Glaciation in the Rocky Mountains, and also infers it to be about 7,000 years old.

(b) The postglacial maximum of sea level, about 5,500 to 5,000 years ago, presumably correlative with complete deglaciation of North America. This boundary is suggested by Karlstrom and Ray (1968) and formerly by Frye and Willman (1960).

(c) At the top of the weathering profile that formed during the later part of this interval. I formerly (1961, 1965c) advocated (but no longer advocate) a provincial Pleistocene-Holocene boundary for the Great Basin region; only about 4,000 years ago, to be drawn at the upper of this weathering profile (the Toyeh Soil of the Lake Lahontan area, and its equivalents).

Thus, U.S. Quaternary geologists have suggested that this boundary be placed at age levels ranging from about 20,000 to 4,000 years ago. It is well to note, however, that already there is substantial support in the U.S. for placing the boundary at the 12,000 to 10,000-year level recommended by the INQUA Holocene Subcommission.

In view of the differences of opinion on placement of the Pleistocene-Holocene boundary, particularly in the U.S., and on the criteria appropriate for its recognition and definition, I will review some of the theoretical and pragmatic considerations that should govern the selection of the stratigraphic level for this boundary if it is to be truly international. (I should explain that this discussion represents only my own personal views on the boundary question. The Geologic Names Committee of the U.S. Geological Survey has not yet decided upon a particular stratigraphic level for the Pleistocene-Holocene boundary; it probably will follow the recommendation of the INQUA Congress.) Crucial topics to consider are:

1. The rank of the Holocene.
2. Whether the Pleistocene-Holocene boundary should be defined on a time-stratigraphic (chronostratigraphic) or a geologic time (geochronologic) basis.
3. What are the requirements for time-stratigraphic definition of the boundary?
4. What criteria are applicable to recognizing and correlating this boundary with the necessary precision?
5. Finally, what is the best time-stratigraphic level (and time-span) for this boundary on an international basis?

RANK OF THE HOLOCENE

The rank of the Holocene in time-stratigraphic (and geologic time) classification is germane only incidentally to this discussion. The Holocene presently holds series/epoch rank by usage of most geologists and all the official Geological Surveys of Europe and the United States*. A few geologists in the U.S. and Europe, however, advocate reducing the Holocene to stage/age rank (e.g., Flint, 1947, p. 205-10; 1957, p. 282-285; see, however, Morrison *et al.*, 1957, for reasons for retaining the Holocene (Recent) as a

*In early 1968 the American Commission on Stratigraphic Nomenclature and the Geologic Names Committee of the U.S. Geological Survey recommended that Holocene replace Recent as a series subdivision of the Quaternary System.

series/epoch). If the Holocene is retained as a series/epoch, the recommendation of the INQUA Congress on placement of its lower boundary must be referred to the International Geological Congress for final decision, but such referral is not needed if the Holocene is relegated to a lower rank. Regardless of what rank the Holocene has, however, we still are faced with the problem of defining its lower boundary.

REASONS WHY THE PLEISTOCENE-HOLOCENE BOUNDARY SHOULD BE DEFINED ON A TIME-STRATIGRAPHIC (CHRONO-STRATIGRAPHIC), RATHER THAN ON A GEOLOGIC TIME (GEOCHRONOLOGIC) BASIS

A few geologists advocate simply agreeing to place the international Pleistocene-Holocene boundary at a certain "absolute" (true-time) or radiocarbon date, without tying the boundary to any specific sequence of rock strata. This proposal seemingly has merit, because this boundary can be dated much more accurately than any other series/epoch boundary. For example, radiocarbon dating is so widely applicable, relatively accurate, and offers so close an approximation to true time, that it is tempting to define the boundary simply by picking an arbitrary date; for example 10,000 radiocarbon years B.P. Radiocarbon dating obviously will be of great importance as an *aid* to local identification and long-distance correlation of this boundary. However, it would be unwise to define the boundary primarily on time, as a certain number of absolute or radiocarbon years, for the following reasons:

1. The only feasible operational way at present of determining the boundary in local sequences would be by radiocarbon dating. Sites that provide materials suitable for radiocarbon dating are relatively uncommon, and those having C-14-dateable material in enough different beds of a sequence of strata so that the boundary can be located accurately are rare indeed. Moreover, the C-14-dated boundary at a particular site is essentially just a point in time and space; "spot" time datum, and generally it cannot be extended by normal stratigraphic means beyond this locality as a reliable isochronous marker.

2. Radiocarbon dates aren't "absolute" dates, because they have appreciable inherent errors. Ages determined by carbon-14 measurements deviate from true-year dates because they are subject to analytical errors, errors due to contamination, and those caused by changes in the C-14 content of the atmosphere. The analytic error is conventionally expressed in so-called "finite" dates as the "standard error", which states the numerical uncertainty as a certain plus or minus value. This value is judged solely on physio-chemical grounds and does not include other sources of error. Contamination (dilution of original C-14 by older or younger radiocarbon or by "dead" carbon) may cause serious errors. Aquatic plants and mollusks may incorporate C-14-deficient ("old") carbon as all or part of their original carbon, leading to ages that are too old. Finally, it is well established that the C-14 content of the atmosphere has fluctuated during the last 6,000 years, and even larger fluctuations are considered likely during the larger climatic cycles of the late Quaternary. These fluctuations are believed to have been caused by variations in production of C-14 as a result of changes in cosmic-ray flux (C-14 is produced by bombardment of nitrogen in the earth's atmosphere by cosmic rays), and by alternating periods of slower and faster mixing of the oceans.

3. The most important objection to defining the boundary primarily in terms of time alone is that this procedure would violate generally accepted practice among stratigraphers the world over that *the divisions of geologic time are based upon the rock record, not primarily on abstract divisions of non-material time.* A recent development of fundamental importance in clarifying and organizing the semantics of stratigraphic classification with respect to time was the establishment of separate classifications for time-stratigraphic (chronostratigraphic) and geologic time (geochronologic) units in the new American Stratigraphic Code and in the reports of the International Subcommission on Stratigraphic Terminology (1961, 1964). According to the revised American Stratigraphic Code (Amer. Comm. on Stratigraphic Nomenclature, 1961, p. 659-660):

Geologic time units are divisions of geologic time distinguished on the basis of the rock record, *particularly as expressed by time-stratigraphic units.* They are not material units.....The units of geologic time are no more valid than the time-stratigraphic units on which they are based. (italics added) Time-stratigraphic and geologic time units are like opposite sides of the same coin, but geologic time units, being non-material, are more highly inferential, and therefore must be derivative from time-stratigraphic units.

Thus, in my opinion, tó define Quaternary stage and epoch boundaries primarily from isotopic dates would be pragmatically most unsound. It would set up arbitrarily chosen, nonmaterial time boundaries instead of material time-stratigraphic boundaries that can be traced through terrestrial sequences. Although the material boundaries admittedly are not perfectly time parallel in all cases, well-chosen ones are reasonably so and they provide a far more useful working framework for the field stratigrapher.

GUIDELINES FOR DEFINING THE PLEISTOCENE-HOLOCENE BOUNDARY ON A TIME-STRATIGRAPHIC BASIS

The time-stratigraphic interval suggested by the INQUA Holocene Subcommission for this boundary has a much shorter time-span than any other series/epoch boundary. (For example, it is unlikely that the Pliocene-Pleistocene boundary can be defined within a time-span as narrow as 100,000 years—whenever the true age of this boundary finally is established.) The brief time-span of the proposed Pleistocene-Holocene boundary will require a unique degree of precision in time-stratigraphic concepts and methodology if this boundary is to be identified, mapped, and correlated reliably around the world. For a workable boundary, it is important to consider carefully the requirements for its proper definition on a time-stratigraphic basis. Two quotations from a leading U.S. stratigrapher, H. D. H e d b e r g (1965, p. 460; 1968, p. 198), are appropriate:

For true progress in chronostratigraphy, it is essential to develop clear concepts and accurate definitions of stratigraphic terms, and, in so doing, to avoid being enticed away from reality by convenient assumptions, attractive as they may seem.

...for any chronostratigraphic unit it is only the boundaries in the rock strata which it is important to define locally by stratotypes, since it is these alone which fix the essential features of the unit—its time-scope in the rocks and its relations to adjacent units. ...the important task of chronostratigraphy is to agree upon the position of boundary stratotypes.

The international stratotype

An international stratotype for the boundary must be selected. This must define the boundary at a specific horizon or key bed at a particular locality (or small area) which will serve as a tangible reference. Although provincial stratotypes probably also will be selected (to facilitate correlation in regions at a distance from the international stratotype), there can be only *one* international stratotype because in case of conflict one of the stratotypes must be controlling.

The international stratotype should be a continuous depositial sequence of strata (rock-stratigraphic, biostratigraphic, soil-stratigraphic, and/or geologic climate units) representing the entire time span for a zone extending some distance above and below the designated Pleistocene-Holocene boundary, with very limited or no unconformities caused by non-deposition or erosion. This sequence must be on land, and preferably it should be continuously exposed; in other words, it should not be a submarine, a sublacustrine, nor, preferably, a subsurface sequence. This stratotype should be situated in an area where its stratigraphic relations are easily determinable in relation to other "standard" well-studied sequences that represent other parts of the late Quaternary; it should not be in a part of the world remote from such sequences.

The Pleistocene-Holocene boundary at this stratotype ought to be *mappable.* A certain key bed or horizon of distinctive lithology (but not an unconformity) should be chosen to mark the boundary. It is very desirable that this key bed or horizon be amenable to accurate dating by radiocarbon or other isotopic means. It is important that, traced away from the stratotype, this key bed or horizon be essentially time parallel over a reasonably large region, and it is very desirable that it be of fairly common occurrence and readily identifiable throughout this region.

At the international stratotype the Pleistocen-Holocene boundary probably can be dated within several hundred radiocarbon years. This will serve as the primary international reference date for the boundary. It must be recognized, however, that the key bed or horizon that marks the boundary at the international stratotype probably will not maintain exactly the same age as it is traced away from the international stratotype. It is even more unlikely that other key beds or horizons used to identify and map the boundary locally at a distance from the international stratotype, or a provincial stratotypes, will have exactly the same age as the boundary at the international stratotype (see below).

Provincial stratotypes

It would be very fortunate if the Pleistocene-Holocene boundary could be identified by some single stratigraphic feature that is both isochronous and occurs in an wide variety of depositional terranes throughout the world. Such a stratigraphic feature probably does not exist. The various kinds of stratigraphic markers that can be used for time-stratigraphic mapping and correlation of this boundary (such as a pollen-zone boundary) are of limited areal extent. It therefore will be necessary to use different kinds of stratigraphic markers in different regions. Moreover, although the boundaries of time-stratigraphic units, extended away from the type section, ideally are isochronous surfaces, representing everywhere the same horizon in time (that is, having zero time-span), they never are so in reality. Inevitably some time transgression occurs in the biostratigraphic, rock-stratigraphic, or other material boundaries that are used to define, map, and correlate time-stratigraphic units in actual practice. It is possible that a certain kind of stratigraphic marker may transgress time to so great an extent that it can be used only in a certain region, but not in others, for locating the boundary within proper bounds of accuracy. For these reasons, in order to facilitate local correlations in regions far removed from the international stratotype, it should be expected, indeed encouraged, that provincial stratotypes be established—for instance, in eastern and/or midwestern North America, in western North America, Australia, Japan, Siberia, and the like. Such provincial stratotypes should meet all the requirements of the international stratotype—and, of course, the stratigraphic level selected for the provincial Pleistocene-Holocene boundary should lie within the designated time-span for the international boundary.

A BRIEF EVALUATION OF SOME OF THE CRITERIA THAT MIGHT BE USED TO IDENTIFY AND CORRELATE THE BOUNDARY

The criteria that have been been proposed for identifying and correlating this boundary are relatively few and comprise: (1) evolutionary change in organisms, particularly mammalian extinction; (2) record of climatic change, as manifested by (a) glacial oscillations, (b) ocean-temperature changes, (c) glacioeustatic changes, and (d) pollen stratigraphy; (3) weathering profiles (soil-stratigraphic units); and (4) radiocarbon dating. (A few other criteria, such as varve chronology and volcanic-ash stratigraphy (tephrochronology), although valuable and precise locally, are of too limited application to be considered here.)

Evolutionary change in organisms

In pre-Quaternary sequences, time-stratigraphic division and correlation is mainly based on evidence of a significant stage of evolutionary change in the bioseries (development of new forms and extinction of old), typically identifiable by a widespread, relatively abrupt faunal change. However, evolutionary changes in all organisms are far too slow to provide the degree of time resolution needed for differentiating between the Pleistocene and Holocene (M o r r i s o n, 1968, p. 13-17, 72-74). Even the supposedly "sudden" extinction of large mammals during the late Wisconsinan and early Holocene was much too slow to provide the presision necessary for differentiating this boundary.

Glacial oscillations

The general late-glacial recession of the North American and Scandinavian ice sheets was interrupted by several stillstands or small readvances. Certain of these episodes have been proposed to mark the boundary between the Pleistocene and Holocene; for example, the parting of the Scandinavian ice sheet at Ragunda Pass in central Sweden and the terminations of either the Valders or the Cochrane readvance maxima in northeastern Wisconsin and Ontario, respectively. However, there are serious disadvantages to using such criteria to define the Pleistocene-Holocene boundary in either the international or provincial stratotypes:

(1) It is well established by detailed stratigraphic studies that different lobes of the continental ice sheets of Europe and North America did not fluctuate in unison. C u s h i n g (1967), for example, comments: "Geomorphic and stratigraphic evidence indicates that the four glacial lobes that were active in the state (Minnesota) during the period (15,000 to 10,000 years ago) did not all reach equilibrium at the same times..." Concerning the Ragunda event, N i l s s o n (1965) comments: "As a dividing point between the major divisions of the late Quaternary...it was too

incidental a character to be really appropriate. The activity of the ice-sheet apparently did not change at that point of time as De Geer has led us to believe."

(2) The drifts that record these glacial oscillations, including the readvance maxima, are highly time transgressive, and generally there are no other stratigraphic units coeval with the readvance maxima that are reasonably time parallel. Thus, if a glacial maximum at a particular locality is designated as a stratotype for the Pleistocene-Holocene boundary, generally the only way of tracing and correlating this boundary away from the type locality is by radiocarbon dating.

Consequently, in my opinion, it would be inappropriate to define the pleistocene-Holocene boundary primarily from the stratigraphic record of glacial oscillations themselves.

Ocean-temperature changes

A number of oceanographers, marine geologists, and geochemists (e.g., B r o e c k e r et al., 1961) have proposed placing the Pleistocene-Holocene boundary at the mid-point of the rapid warming of the surface layer of the oceans about 11,000 or 10,500 years ago, as recorded in deep-sea cores. Two things are wrong with this proposal:

(1) The ocean-temperature records are not on land. They cannot have terrestrial type localities that can be readily inspected, and they are not keyed reliably to widespread stratigraphic markers in nonmarine sequences.

(2) As B r o e c k e r (1965, p. 742) says: "The climatic curves for the deep-sea cores fail to show the detailed climatic fluctuations revealed in other records." The ocean-temperature curves show a pronounced, apparently steady, warming trend over a span of several thousand years during the period in question, without recognizable minor fluctuations. The smoothing of the ocean-temperature curves may be caused by the heat-storage characteristics of the oceans, mixing by currents within the surface layer, mixing of sediment at the ocean bottom by benthonic organisms, and other factors.

The ocean-temperature record, although important as an ancillary criterion, therefore does not seem suitable as a primary criterion, or for an international stratotype, for the boundary.

Glacio-eustatic changes

Various proposals have been made to base the boundary on the record of glacio-eustatic changes in sea level. They range from the afore-mentioned sea-level minimum at the maximum of late Wisconsin glaciation, to a pronounced flattening of the gradient of the sea-level curve between about 6,000 and 8,000 years ago (C u r r a y, 1965, p. 733) and to a presumed postglacial sea-level maximum about 5,000 years ago (F r y e and W i l l m a n, 1960). These proposals also have serious drawbacks:

(1) All the possible glacio-eustatic boundaries, except the postglacial maximum, are below present sea level, and they therefore have the same weaknesses mentioned under (1) in the preceding section.

(2) The time range for the Pleistocene-Holocene boundary that is suggested by the INQUA Holocene Subcommission was one of rapidly rising sea level, and hence it is represented in the submarine sequences on the continental shelves by a markedly time-transgressive unconformity.

Pollen stratigraphy

Probably the most widely advocated criterion for *precise* placement of the Pleistocen-Holocene boundary, particularly in Europe, is pollen stratigraphy. The pollen zones of northeastern Europe are so well known and highly regarded as valid time-stratigraphic units, as well as sensitive detailed climatic-stratigraphic units, that it is common practice to regard them as time-stratigraphic standards and to relate proposals for the Pleistocene-Holocene boundary at various stratigraphic levels to them.

The pollen fallout reacts quickly to climatic changes, far more quickly than ocean surface temperatures, glaciers, and sea level; thus the pollen stratigraphy provides an exceptionally sensitive and relatively unambiguous climatic record. Although some geologists maintain that the pollen zones are significantly time transgressive, a chief objective of European palynologists has been to define the pollen zones so that they record synchronous climatic changes in various regions as manifested by the varying components of the different floras of these regions. Stress has been placed on evidence of temperature changes, in preference to precipitation changes, because the temperature changes tend to be less local and time transgressive. Radiocarbon dating

has demonstrated that the pollen zones are almost time parallel, and that some pollen-zone boundaries are especially so; thus, they probably constitute the best time-stratigraphic markers other than volcanic ash beds. The pollen-zone boundaries are not everywhere isochronous, however, because they are transitional and must be defined arbirarily and also because they are designated according to differing criteria by individual palynologists.

The pollen-zone boundaries in northeastern Europe that have been proposed as markers for the Pleistocene-Holocene boundary are (1) the Bölling/Older Dryas boundary, about 12,000 years ago, (2) the Older Dryas/Allerød boundary, about 11,300 years ago, (3) the Allerød/Younger Dryas boundary, about 11,000 to 10,600 years ago, and (4) the Younger Dryas/Pre-Boreal boundary, about 10,300 to 10,000 years ago. The latter boundary has been identified as far south as the southern Alps, and also has been found in southwestern Iran.

In the U.S. intensive study of pollen stratigraphy has centered in the northern Midwest, the Northeast, and the Pacific Northwest. The sensitivity and detail of the pollen record appears to vary considerably between the various regions and with time, and in some areas certain climatic fluctuations are more poorly recorded than in other areas. The most ubiquitous and marked pollen boundary is the top of the spruce pollen zone, marked by an abrupt decrease in spruce pollen (characteristically from more than 50% to less than 5%) and registering the rapid deterioration of the boreal forest. This pollen boundary has been indentified from Manitoba to New England and south to Georgia, Ohio, and New Mexico. It records a climatically controlled event that was remarkably synchronous at about 11,000 ± 1,000 years throughout this very large area (Ogden, 1967).

Pollen zones obviously are limited to the floral zones they represent, which change with regional climatic patterns. Thus the pollen stratigraphy of northeastern Europe and northern U.S. probably is limited to these regions. The Late Pleistocene-Holocene pollen stratigraphy of other parts of the world is little known, except for pioneer studies in Japan, New Zealand, Columbia, and Hawaii. In the tropics climatic changes probably were smaller than in the middle latitudes, and the pollen record may be less sensitive. Pollen is quickly destroyed by weathering; therefore, pollen records are best preserved in lakes and bogs and are poor or absent in subaerial sediments and soils formed in oxidizing environments.

Weathering profiles (soil-stratigraphic units, geosols)

A few geologists, including myself, advocate using weathering profiles as at least provincial markers for the boundary between the Pleistocene and Holocene. These weathering profiles formed during the warmer intervals of late-glacial and postglacial time and qualify as soil-stratigraphic units under the 1961 American Stratigraphic Code and as geosols of my usage (Morrison, 1967; Morrison and Frye, 1965, p. 7). The ones that have been proposed in the U.S. for marking the lower boundary of the Holocene comprise two age groups of correlative geosols: (1) A group whose formation ended about 12,000 years ago, that includes the Harmon School Soil of the Lake Lahontan area, Nevada (Morrison, 1964), the Graniteville Soil of the Lake Bonneville area, Utah (Morrison, 1965a, b), the geosol between the middle und late stades of Pinedale Glaciation in the Rocky Mountain region (Morrison and Frye, 1965), the Brady Soil of the Great Plains region (Morrison and Frye, 1965; Frye and Leonard, 1965; Frye, Willman, and Glass, 1968), and an unnamed geosol of Twocreekan age in the midwestern U.S, (Farnham *et al.*, 1964). I now propose using the upper contacts of the full (uneroded) profiles of the geosols of this group as a possible marker for the Pleistocene-Holocene boundary in the western and midwestern U.S. (2) A group that formed during the later part of the postglacial thermal maximum, ending about 4,000 years ago. This group includes the Toyeh Soil of the Lake Lahontan area, the Midvale Soil of the Lake Bonneville area, the post-Pinedale Soil of the Rocky Mountain region, and unnamed geosols in the Great Plains and Midwest. I formerly (1961, 1965c), but no longer, believed that the Pleistocene-Holocene boundary might properly be placed at the top of the Toyeh Soil and its equivalents. In Europe, weathering profiles (geosols) of Allerød and/or Bölling age, equivalent to group 1 above, have been widely identified. Less common, but probably present at least locally are those of group 2 age.

I consider geosols to be among the most useful time-stratigraphic markers in Quaternary non-marine sequences because they are widespread and readily

identifiable in most types of such sequences and are essentially time parallel throughout at least the temperate zones of the earth – much more isochronous than any common sedimentary deposits, such as glacial, alluvial, and lacustrine units. Geosols are more widely distributed than good pollen-profile sequences and are at least equally time parallel. I believe that their remarkable time parallelism probably is because they formed during episodes of accelerated weathering induced by climatic thermal maxima (likely caused by increase in solar radiation) that probably were synchronous over the entire earth.

Radiocarbon dating

It has been explained earlier that radiocarbon dating ought not be used as a primary basis for defining the Pleistocene-Holocene boundary. On the other hand, C-14 dating is a tool of utmost importance for recognizing the boundary and for obtaining independent checks on and improving the reliability of correlations over long distances and between dissimilar depositional environments, particularly where different time-stratigraphic markers are used to identify and map the boundary (such as different pollen-zone boundaries, geosols, and the like). Without such a tool it is very doubtful whether it would be possible to achieve worldwide correlations of this boundary within the accuracy of its proposed time-span.

Conclusions on criteria

Summarizing, it appears that evolutionary change in organisms is the least satisfactory criterion for identifying and defining the Pleistocene-Holocene boundary; ocean surface temperature and glacio-eustatic data, though better, still will not provide precise time-stratigraphic markers usable by geologists working on land, and hence are inadequate for the international stratotype. The applicable glacial oscillations have no time-stratigraphic character because these minor fluctuations were nonsynchronous in different glacial lobes. The most reliable time-stratigraphic markers are the pollen-zone boundaries and the upper contacts of uneroded geosols.

CONCLUSION

It appears to me that the time-stratigraphic interval dating from about 12,000 to 10,000 years ago is the most appropriate one for the Pleistocene-Holocene boundary, and that the boundary should be defined to have approximately this time span. This is the interval that was tentatively suggested for the boundary at the October 1968 meeting of the INQUA Holocene Subcommission. It contains a greater number and variety of widely recognizable stratigraphic markers than other parts of the late-glacial and postglacial record. These stratigraphic markers are suitable for precise time-stratigraphic definition, mapping, and long-distance correlation. Notable among these time-stratigraphic markers are 4 pollen-zone boundaries in northeastern Europe, at least 1 pronounced widespread pollen-zone boundary in the U.S., amd a weathering profile that occurs widely in the U.S. and Europe. The mid-point of this interval coincides approximately with the mid-point of the steepest part of the late-glacial-postglacial rise in ocean surface temperatures and is recorded by a sharp lithologic and faunal change in the deep-sea core records from oceans throughout the world.

Opinion among European geologists, palynologists, and oceanographers appears to be virtually 100% in favor of placing the Pleistocene-Holocene boundary at this interval, and there is considerable (though by no means unanimous) support in the U.S. for this proposal. I believe that it is unrealistic to expect that any other time-stratigraphic interval will be adopted for this boundary when it is defined internationally.

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