### QUATERNARY CHRONOSTRATIGRAPHY — A REVIEW

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Ouaternary development is characterized by strong climatic fluctuations associated with repeated glacier expansions. Consequently the Quaternary chronostratigraphy is largely based on the dating of climatic fluctuations which have led to large-scale, often global, environmental changes. The cooling episode around 2.5 million years ago that swept forests away from large areas and rapidly increased the ice volume in the Northern Hemisphere marks the beginning of the Quaternary Period. The Milankovitch, or astronomical, theory of climatic change is today commonly accepted as the explanation for the rhythms of Quaternary climatic fluctuations. Climatic variability is controlled by small periodic or quasiperiodic changes in the Earth's orbit around the Sun, which in turn lead to changes in the intensity of the seasonal solar radiation reaching different latitudes. Small variations in the insolation trigger events which eventually lead to enormous climatic and environmental changes. Different orbital periodicities have dominated the climatic variability at different times during the Quaternary, for example, the 41-ka-long cycle of the tilt of the Earth's spinning axis and on the average 22-ka-long precession and 100-ka-long eccentricity cycles. During the last 800 ka, however, the eccentricity cycle of the orbit stands out clearly. It has set the pace for the largest Quaternary glaciations, all of which fall into the latter part of the Quaternary. The validity of the Milankovitch theory has been confirmed by many proxy records, including deep-sea oxygen isotope stratigraphy, Chinese loess records and many palaeobotanical studies on long lacustrine sequences; the present chronostratigraphical division of the Quaternary Period is largely based on these data. However, the lack of good dating methods still poses a major problem in many Quaternary stratigraphical studies. In some cases the shortcomings and methodical uncertainties can be avoided and accuracy improved by comparing dates obtained with different techniques. The comparison of K/Ar ages with climatic events dated by calculations of astronomical periodicities and the comparisons of radiocarbon ages with U/Th dates and varved sediment counts serve as examples of how the reliability and applicability of chronostratigraphy can be checked and further improved in this way.

Key words: glacial geology, chronostratigraphy, palaeoclimatology, glaciation, Milankovitch theory, absolute age 0—18, Quaternary.

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### Introduction

Quaternary stratigraphical research has made rapid advances in the past few decades, leading to major changes in the earlier picture of Quaternary climatic and environmental development. Unfortunately Finland has no natural archives containing long, continuous Quaternary stratigraphical records. Ice sheets have covered this country several times during the Quaternary Period each time eroding most of the soft strata deposited during the thermomers. The sediments deposited after the last deglaciation are well preserved, but the events can only be studied on the fragmentary sequences discovered between and below the Pleistocene till beds (Hirvas & Nenonen 1987, Hirvas 1991).

Regional correlations are clearly needed to put the Finnish Quaternary findings into their natural historical perspective. Correlations over different regions are indeed an essential part of all geological research, as the UNESCO sponsored International Geological Correlation Program (IGCP) shows in a very convincing way. The present paper discusses the main features of Quaternary chronostratigraphy and closely related issues, with a view to providing researchers working here, close to the central area of northern European glaciations, some background knowledge of global development.

The principles, terminology and international rules of stratigraphical classification are presented in Hedberg (1976), and there are also several national or regional stratigraphical guides. A suggestion for the stratigraphical division of the Quaternary in Norden was published by Mangerud *et al.* (1974) and has since been elaborated further in Mangerud & Berglund (1978), Mangerud (1982) and Mangerud *et al.* (1982). The rules for the formal stratigraphical division and terminology can be found in the above books and these subjects are not discussed at length in this paper. Instead, attention is paid to the key records and sites and to the dating of deposits, which together form the basis of Quaternary stratigraphy and chronology.

In the chronostratigraphical classification the strata are organized into units according to their age relationships. The Quaternary development is characterized by substantial climatic changes and thus climatostratigraphy largely coincides the chronostratigraphy in this system. Litho- and biostratigraphical units form the traditional basis of the general division, but during the past few decades measurements of physical properties of the deposits such as oxygen isotope (<sup>18</sup>O/<sup>16</sup>O) ratios and palaeomagnetism have made important contributions to the general stratigraphical classification and dating.

Selected type sections, called stratotypes, are used to demonstrate defined stratigraphical units. The stratotypes represent units or boundaries or a combination of geological strata and they are of great importance in Quaternary as in other studies (cf. Bowen 1978).

### The Plio/Pleistocene boundary

The basal part of the Quaternary System in chronostratigraphical terms is commonly called the Plio /Pleistocene boundary. The Pliocene is the uppermost Series in the Tertiary System underlying the Quaternary Pleistocene Series (the corresponding geochronological unit being the Pleistocene Epoch).

The first attempt to define the base of the Quaternary was made in 1913 by M. Gignoux, who suggested that the first appearence of »northern guests» in certain fossil- bearing strata in Italy should mark the start of the ice age period. The »northern guests» refer to some cold-water marine organisms, first of all the mussel *Arctica* (Cyprina) *islandica*, which partly replaced the former Tertiary warm-water marine species. This faunal shift was found in the basal part of the tectonically uplifted marine Calabrian strata. At the International Geological Congress held in London in 1948 the Plio/Pleistocene sedimentation area in Italy was chosen as the type area for that important geological boundary (Nilsson 1983, Kukla 1991).

It soon became evident, however, that the correlation of other sequences with the Italian strata was very often problematic. The result was a longlasting dispute about the »correct» Plio/Pleistocene boundary, and a consistent picture of the climatic events connected with it has begun to emerge only relatively recently.

The climatic cooling associated with temperature oscillations was well under way as the Tertiary Period drew to an end 4—3 million years (ma) ago. About 2.5—2.3 ma ago a very pronounced drop in global temperatures took place, as is documented in several long Quaternary stratigraphical records from different parts of the world (Kukla 1989, and references in that paper). It is no wonder that many researchers interpret this distinct shift towards cooler conditions in world climate as the Plio/Pleistocene boundary.

The stratotype for the Plio/Pleistocene boundary is defined in the Vrica section in Italy, where it is dated by radiometric methods to around 1.6— 1.8 ma ago. That time span should mark the arrival of the »northern guests» in the Mediterranean waters. It has now been proved, however, that some »northern guests» were present in Santerno, Italy, as early as 2 ma ago (Kukla 1991). Thus the Italian stratotype is clearly not the best possible one to represent the base of the Quaternary System.

Detailed stratigraphical and palaeobotanical studies, especially those made in The Netherlands (Zagwijn 1975, 1985, see also De Jong 1988), show that European land areas were afflicted by a very cold and also dry climatic event which swept the forests awary from vast regions around 2.5—2.3 ma ago. At about the same time (2.4 ma ago), the quantity of sediments transported by icebergs in the North Atlantic area increased markedly, as can be seen from the deep-sea stratigraphy (Shack-leton et al. 1984). That led to a substantial expansion of land-locked ice in the northern latitudes. The deposition of loess in China also started at about the same time, 2.5 ma ago (cf. Fig. 1 and discussion below).

Even though there are so many pieces of evidence demonstrating that the major global cooling marking the beginning of the Quaternary took place around 2.5 ma ago, it should be noted that the development was characterized by oscillations in temperatures. Stratigraphic data from Europe indicate that by 1.9 ma ago the first Quaternary cool episode was over and mild climatic conditions had returned (Zagwijn 1975, 1985, see also Kukla 1989). Another cold pulse (called the Eburonian in western Europe) hit the Earth about 1.6 ma ago, but it was far less significant than the 2.5-ma cold burst and thus cannot be regarded as marking any major geological boundary.

## Dating the Quaternary with a combination of radiometric control and orbital cycles

Several methods for dating Quaternary deposits are available, and innovations in this field are frequently reported, but still the dating presents a major problem in Quaternary studies. The general Quaternary chronostratigraphy is largely based on radiometric dating, the K/Ar method in particular. This method, however, is best applied to volcanic rocks; marine and continental sediment sequences are the most useful deposits for Quaternary stratigraphical studies.

An extremely important link in dating is the magnetostratigraphy, as this can be applied to volcanic and water-lain deposits as well as to windblown loess. It is possible to date sediments using the palaeomagnetic boundaries obtained with radiometric methods from volcanic deposits as fixed points. In this way the whole sedimentary record can be dated with reasonable accuracy, provided there have been no marked changes in the longterm sedimentation rate.

The deep-sea oxygen isotope stratigraphy forms the skeleton of Quaternary chrono- and climatostratigraphy today. The recently established Chinese loess stratigraphy is also of the utmost importance. The oxygen isotope stages and loesspalaeosol seqences (Fig. 1) are dated by linking the palaeomagnetic boundaries to radiometric dates as described above. However, the Milankovitch theory shows how the accuracy of age determination can be improved by correlating the climatostratigraphy with orbital cycles.

According to the astronomical, or Milankovitch, theory of climatic change, celestial mechanics has been the pacemaker for the comings and goings of the Quaternary ice ages and thermomers. Slight periodic or quasiperiodic changes in the Earth's orbit trigger chains of events which eventually lead to enormous global climatic changes. These orbital changes include the 41-ka-long axial tilt cycle, the 22-ka-long precession cycle, and the 100-kalong cycle in the eccentricity of the Earth's orbit (Berger 1989). Global climatic variations during the Quaternary have followed the orbital rhythms amazingly accurately. Climatic cycles corresponding to astronomical periodicities have also been documented from the earlier history of the Earth (Berger et al. 1992).

The dominant periodicities of climatic variation have changed during Quaternary time, which means that the climatic effects of the different orbital elements vary in the long term (Fig. 1, Berg-



Fig. 1. The deep-sea oxygen isotope record of Williams et al. (1988) compared with the Chinese loess-palaeosol section at Baoji. The timescale is largely based on palaeomagnetic measurements, of which the principal reversals are shown here (according to Rutter 1992).

er 1989, Rutter 1992). Orbital variations can be calculated accurately both far back in time and into the distant future. Climatic changes on the  $10^3$ — $10^5$ -year time scales follow the orbital cycles enabling us to calculate the ages and durations of past and future climatic cycles. The astronomical theory of climatic change can thus be used to predict the oc-

currences of future ice ages and warm intervals (Kukla *et al.* 1981, Berger *et al.* 1981, Matthews 1984, see also Eronen *in press*). Calculations of past orbital variations have been extended to 500 ma ago (Berger *et al.* 1992).

Deep-sea oxygen isotope stratigraphic studies conclusively have corroborated the theory that global Quaternary climatic cyclicity was controlled by celestial mechanics. As the climatic cycles of the latter part of the Quaternary are reasonably well known, the associated orbital cycles can be used to improve the time scale. The SPECMAP working group has elaborated orbitally tuned time scales for the past hundreds of thousands of years and so has established a very detailed chronostratigraphy for the past 300 ka (Imbrie *et al.* 1984, Martinson *et al.* 1987).

Despite of some problems with connecting all the early Quaternary climatic fluctuations to specific astronomical periodicities, Shackleton et al. (1990) have extended the orbital time scale calculations to include the whole Quaternary Period. The resulting time scale deviates somewhat from the earlier one, as can be seen in Table 1. The time scales are more or less concordant until close to the Brunhes/Matuyama palaeomagnetic boundary, but further back in time the orbitally determined ages deviate from the earlier ones by 5-7%. The earlier time scale is based on K/Ar dating, and Shackleton et al. (1990) conclude that there is systematic error in the method, giving ages that are too young. The <sup>40</sup>Ar/<sup>39</sup>Ar dating method used by Baksi et al. (1992) has yielded results supporting this view, dates from the Brunhes/Matyama boundary lava giving an age of 783-11 ka. The detailed Quaternary chronology and chronostratigraphy are thus taking shape step by step.

### Oxygen isotope stratigraphy and long continental records

Continuous and regular sedimentation in certain marine environments makes deep-sea cores a very useful source material for Quaternary stratigraphical studies. In continental environments, sedimentation typically does not last for a long time in one particular place and so the terrestrial stratigraphical evidence tends to be more fragmentary, albeit usually more detailed, than the marine record. There are, however, some continental environments where sedimentation has continued without any major breaks throughout Quaternary time. Detailed studies have been made in Colombia by H. Hooghiemstra, who has investigated the biostratigraphy of a lake sediment record over 3 ma long. Similar studies have been made in Israel (by A. Horowitz) on lake deposits covering a time span of approximately the same length. The deposits at Tenaghi Phillipon in Greece (studied by T.A. Wijmstra *et al.*) demonstrate variations in vegetation and climate during the past 900 ka. An extremely important record of botanical and climatic changes since the late Tertiary has been compiled by W. Zagwijn who has collected evidence from many different sites in The Netherlands. (For references to the above studies, see Kukla 1989.)

Climatic phases corresponding to the oxygen isotope stages of the deep-sea stratigraphy have been found in the continental records, but until recently reliable correlations were difficult to make because of the dating problems discussed above. This shortcoming has now been overcome with the discovery and establishment of the excellent Chinese loess stratigraphy, which marks a major step forward in the correlation of marine and continental Quaternary stratigraphical records.

Intensive Quaternary stratigraphical studies on the Chinese loss plateau started in the1980's, with the opening the area to Western research groups. Since then the volume of palaeoclimatic information from that region has accumulated rapidly. The exposed loess sections reveal a distinct stratification characterized by light loess and dark palaeosol layers. Loess deposition started about 2.5 ma ago (cf. Fig. 1) and has continued throughout the Quaternary Period. The »soils», or palaeosols, also consist of loess, but they contain more organic matter than the proper loess layers. It is now known that light loess was deposited during cold ice ages, or stadials, whereas the »soils» accumulated during warm interglacials and temperate interstadials (Kukla & An 1989, Rutter 1992).

There is also a difference in grain size between the light and dark layers, the proper loess containing more coarse aeolian material than the palaeosols. The best way of distinguishing between these two types of accumulation, though is by measuring their magnetic susceptibility (Fig. 2, Rutter et al. 1990). It is clearly stronger in the palaeosols than in the light loess layers. Different explanations have been sought for this finding, the most recent being magnetic autigenesis in the soil processes during thermomers (Maher & Thompson 1992).

# Orbital cycles controlling the global climatic variations

When loess-palaeosol sequences are compared with the oxygen isotope curves of deep- sea cores, it is easy to see that the changes in both records are regularly contemporaneous (Fig. 1). The similarity between these two records is really striking when the huge difference in depositional environments is taken into consideration. The <sup>18</sup>O/<sup>16</sup>O variations in deep-sea sediments are thought to represent in the first place changes in the global ice volume (Shackleton & Opdyke 1973). The alternations in the loess stratigraphy indicate the variability in strength of the summer monsoons in China. Strong summer monsoons bring abundant rains to the interior parts of eastern Asia, increasing the vegetation cover in semiarid and arid areas, whereas weaker summer monsoons lead to droughts and reduced plant growth in central China (An et al. 1991). The dark palaeosols were formed during thermomers associated with strong summer monsoons, but the light loess layers deposited during ice ages and stadials, when cold winds carried aeolian dust from the interior of the continent and the summer monsoons bringing rains were weak.

Spectral analysis of the climatic records of both loess and deep-sea cores reveals that the variations were due to orbital forcing. The 100-ka-long eccentricity cycle has determined the occurrences of ice ages during the past 800 ka. Before that time, between 800 ka and 1.6 ma ago, the 41-ka-long axial tilt cycle controlled the climatic variability. The 23- to 19-ka-long precession cycle also shows up clearly in the records of the whole Quaternary, regionally being so prominent that in some paleoceanographic sedimentary sequences it dominates

Table 1. Comparison of ages obtained previously (in the 1980's) for selected magnetic reversal boundaries (ages 1 and 2) with the ages (3) resulted from the astronomical calibration of the radiometric timescale by Shackleton *et al.* (1990).

Oxygen isotope stage	Correlative palaeomagnetic reversal	Age 1 ma	Age 2	Age 3
base 19	base Brunhes	0.73	0.73	0.78
mid 27	top Jaramillo	0.92	0.90	0.99
mid 31	base Jaramillo	0.98	0.97	1.07
base 35	Cobb Mountain	1.10	1.10	1.19
base 63	top Olduvai	1.66	1.65	1.77
base 71	base Olduvai	1.88	1.82	1.95
104	top Gauss	2.47	2.48	2.60

the variance (Berger 1989). The 100 -ka cycle can be found in the climatic variability in the early part of the Quaternary, 1.6—2.5 ma ago, but there is an even stronger 400-ka eccentricity cycle, which seems to form an outline, but the time span is too short for this periodicity to become clear. What is clear, however, is that the orbital cycles dominating the Quaternary climatic variability have changed over time. For some reason the mode of 100-ka-long strong swings from severe ice ages to temperate interglacials was established in the climatic variability around 800 ka ago (Rutter 1992, see also Fig. 1).

Some palaeobotanical records also indicate the orbital forcing of climatic variation. These include the reconstructions based on pollen studies made in The Netherlands and Greece which were mentioned earlier. In the former data, the changes were controlled by temperatures and in the latter largerly by variations in humidity. Even taking into account these different environmental constraints, though the orbital cycles still play the decisive role in the background (Kukla 1989).

### The large glaciations

The »classical model» of four main Quaternary ice ages designed by Penck and Brückner (1909)



Fig. 2. Comparison of the deep-sea oxygen isotope record with the magnetic susceptibility and grain size variations in the Chinese loess-palaeosol sequences. These curves of three variables run largely parallel, even though deep-sea and loess records indicate different environmental changes (after Rutter 1992).

had to be abandoned in 1970's, when studies on deep-sea sediments resulted in a totally different picture of events (Bowen 1978). Oxygen isotope stages pointed to nine cold periods during the Brunhes palaeomagnetic stage, and to many more during the Quaternary Period (cf. Fig. 1).

As the »valleys» in the oxygen isotope curves represent the maximum volumes of the glacier ice during glaciations, rough estimations of the severity of each ice age can be made from the magnitude of these »valleys». According to this reasoning, the largest glaciations occurred during oxygen isotope stages 2, 6, 12 and 16, and the ice sheets of stage 10 grew almost as large as the stage 2 (Weichsel/Wisconsin) ice masses (Porter *et al.* 1992 cf. Fig. 3).

It is still not known which ice ages of the »classical model» correspond to the above cold oxygen isotope stages. Difficult correlation problems are encountered in the European stratigraphy immediately beyond the Eem interglacial (stage 5). This was preceded by the Saale ice age, which is generally divided into Drenthe and Warthe glaciations in northern Europe. The Saale ice age was preceded or interrupted by the Holstein interglacial, the age of which is still being debated. It has been correlated with oxygen isotope stage 7, 9, or 11 (Schwarz & Grün 1988, Marks 1991.)

The picture of Quaternary ice ages is partly returning to the »classical model», suggesting that there really were only 4—5 large glaciations covering vast areas of northern Europe and North America. The outer limits of these ice sheet expansions must bear some correlation with the cold episodes indicated by oxygen isotope curves. On the other hand, the end moraine chains defined as showing the maximum extents of ice advances can be somewhat diachronous. Even admitting this, it



Fig. 3. Magnitudes of glaciations estimated from the shape of deep-sea oxygen isotope curves. The Weichsel/Wisconsin glaciation (stage 2) has been taken as the index (100) against which the other glaciations are compared (according to Porter *et al.* 1992).

is still acceptable to use the names of the »classical» ice ages (Günz, Mindel, Riss and Würm in the Alps; Elster, Saale and Weichsel in northern Europe; Nebraskan, Kansan, Illinoian and Wisconsinan in North America) as morphostratigraphical terms. Chronostratigraphy indicates that the most extensive Quaternary glaciations began only around the Brunhes/Matuyama palaeomagnetic boundary 800—700 ka ago (Figs. 1 and 3).

### The last interglacial/glacial cycle

The abundant stratigraphical and chronological evidence accumulated from Quaternary studies during the past few decades unequivocally shows that the last, or Eem (Sangamon in North America), interglacial corresponds in terrestrial environments to oxygen isotope substage 5e of the deepsea record. It's age has also been reliably determined, the warmest peak being dated to 125—120 ka ago. During the Eemian optimum the climate was generally a few degrees warmer than during postglacial time (Mangerud 1991a,b, Dawson 1992, Frenzel *et al.* 1992).

The lower boundary of the Eemian thermomer

and substage 5e (130 ka B.P.) also marks the beginning of the late Quaternary section of the Quaternary Period and thus forms an important fixed point for many stratigraphical studies. The stratigraphy of the Late Quaternary is in every way far better known and dated than that of the Early (2.5 ma — 780 ka ago) and Middle (780—130 ka ago) Quaternary. There are, however, many uncertainties and gaps in knowledge when it comes to the details of regional developments in the Late Quaternary (Dawson 1992).

The results of different stratigraphical studies on the Late Quaternary are shown in Fig. 4, and as can be seen they are in good agreement with each other. Further evidence supporting the scheme of Fig. 4 is given by the Antarctic Vostok ice core studies (Lorius *et al.* 1985) and from the Chinese loess stratigraphy (Kukla & An 1989). The climatic variations of the Late Quaternary, like those during earlier parts of this period are strongly affected by the Milankovitch cycles, and thus the dates of events can be checked by means of the orbital periodicities as shown in Fig. 4 (data from Martinson *et al.* 1987).

During the Eem interglacial temperate deciduous forests grew in mainland Europe. This warm episode was followed by strong temperature oscillations, including two cold stages (5d and 5b) and two temperate interstadials: the Brørup and Odderade (stages 5c and 5a in the oxygen isotope stratigraphy). Note that in the marine stratigraphy the interglacial time comprises the entire stage 5, while in the continental stratigraphical division the stadials and interstadials following the Eem are included in the Weichselian glaciation.

The extent of the early Weichselian (5d and 5b) glaciations is debated, and conflicting results have been presented, especially from the northern European glaciation area, where the suggested southernmost positions of the ice margin vary from north-central Finland (Hirvas & Nenonen 1987) to Denmark (Petersen *et al.* 1990).The Weichselian interstadial deposits indicating forest cover found below till beds in northern Europe should be correlated with the Brørup or Odderade, because after these thermomers there were no coniferous for-



Fig. 4. Chronostratigraphical divisions of the last interglacial/glacial cycle based on different proxy data. The oxygen isotope stages and palaeobotanical studies made in France (Grande Pile), Germany (NW Europe) and the Netherlands (the vegetation curve) all indicate similar climatic trends, which are also in accordance with the orbital variations, cf. discussion in text, (according to Mangerud 1991a,b).

ests in mainland Europe until the onset of the warm late Weichselian interstadials (Fig. 4).

Traditionally, Late Weichselian (also called late glacial) time has between defined as covering the few thousands of years of the last glaciation, and in the proposal for a chronostratigraphical division of Norden by Mangerud *et al.* (1974) it is bracketed between 13,000 and 10,000 radiocarbon years B.P. The use of this rigid classification clarified the then prevailing jumble of terminology but it has since proved to be somewhat lacking, because it has failed to serve as a good framework for bioand climatostratigraphy. Amendments to the original division have been proposed, as can be seen in Fig. 4 (see also Mangerud & Berglund 1978). The Late Weichselian Substage is now extended to around 25 ka B.P., which corresponds to oxygen isotope boundary 2/3. Accordingly the Late or Upper Weichselian includes the maximum stage of the Weichselian glaciation. It is somewhat confusing that, according to this chronostratigraphical division, a single substage comprises the growth of an ice sheet to its maximum extent plus the bulk (but not all) of its subsequent decay. The crucial Late Weichselian unit from the Bölling through the Alleröd to the Younger Dryas remains without a proper definition in this classification. When the problems with radiocarbon dating of that period are also taken into consideration, it is clear that the present terminology is far from satisfactory. The recent call by W. S. Broecker (1992) for the creation of a more suitable chronostratigraphi-



Fig. 5. Calibration curves for the radiocarbon ages around the Late Weichselian/Holocene transition based on dendrochronology (left) and varved lake sediments (right), cf. discussion in text.

cal classification for the Bölling- Alleröd-Younger Dryas section is certainly warranted, and a revision of the terminology for some other parts of the Weichsel/Wisconsin glaciation should also be considered (cf. e.g. Dawson 1992, p. 45).

### Calibration of the radiocarbon dates

Radiocarbon dates constitute the most important basis for the chronostratigraphical division of Late Weichselian and Holocene times and even for the chronostratigraphical boundaries in the Mangerud *et al.* (1974) division, which is still commonly used despite repeatedly expressed criticism (discussion above, Watson & Wright 1980, see also Mangerud 1982, Mangerud *et al.* 1982).

It has long been known that radiocarbon years deviate markedly from sidereal or calendar years. Today <sup>14</sup>C dates can be conveniently calibrated by computer programs to about 5200 B.C. (van der Plicht & Mook 1989). The calibration can be extended still further back with calibration tables

(Stuiver & Kra 1986), and recently the dendrochronological calibration has been extended to the late Younger Dryas Substage. A 9928-year long absolutely dated tree-ring record of oak has been combined with a 1604-years-long late glacial and early Holocene pine record constructed from subfossil trees (Becker *et al.* 1991). The <sup>14</sup>C dated pine record crossmatched with the absolute scale by means of the »wiggles» of the radiocarbon calibration curve is presented in Fig. 5 together with the results obtained from radiocarbon dates of varved sediments from a lake in Switzerland.

The curves in Fig. 5 show that the radiocarbon ages form two distinct plateaus at around 9500 and 10,000 B.P., in other words, there are intervals up to 450 years long in the radiocarbon curves with constant <sup>14</sup>C dates. It is extremely harmful to the chronostratigraphical division that there is a plateau at the point defined as representing the Holocene/Late Weichselian boundary. Even though roughly dated, in absolute years the boundary is some 1000 years older than indicated by uncorrected radiocarbon dates. The shapes of the

The deviations of <sup>14</sup>C dates from »absolute» ages are depicted in Fig. 6. The dendrochronological dates, the U-Th dates from <sup>14</sup>C dated coral deposits and the ages derived from Swedish clay varves and the annual laminae of Swiss lake sediments all indicate a similar trend. The radiocarbon dates are consistently younger than the »absolute» dates, although some differences in the magnitude of deviations lead to inaccuracies in the results.

### **Concluding remarks**

Well-preserved long continental records have recently added considerably to our knowledge of Quaternary development. A coherent picture of the main outline of global Quaternary history is clearly taking shape. The astronomical theory of climatic change seems to explain a major part of the climatic variations on Earth tens and hundreds of thousands of years long.

Many of the climatic events documented in the long marine and continental records should be detectable in the numerous organic layers preserved below and between till beds in Finland. The lack of suitable dating methods, though, often hampers the age determination of those fragmentary findings. Nonetheless, progess is possible in the Finnish Quaternary because the dating methods are being improved step by step, and our rapidly expanding knowledge of Quaternary climatic and environmental evolution is helping to put the pieces of evidence in their right place in the general picture. The regional correlations are an integral part of this work.

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Fig. 6. Comparison of radiocarbon dates (without statistical limits of error) and dendrochronological ages, Uranium/ Thorium dates against the radiocarbon dates from the same corals, and radiocarbon dates of the varved clays and laminated lake sediments. The radiocarbon ages are consistently younger than the dates obtained by other methods. The dendrochronological data permit conversion of the conventional <sup>14</sup>C dates to more or less accurate calendar ages, but at present this control extends only slightly beyond the Late Weichselian/Holocene boundary.

literature relevant to this paper. Thanks are also due to Kirsti Kyyrönen for drafting the figures and to Vuokko Karttunen for the word processing.

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