The Classical European Glacial Stages: Correlation with Deep-Sea Sediments

George Kukla
Columbia University

Follow this and additional works at: http://digitalcommons.unl.edu/tnas
Part of the Life Sciences Commons

http://digitalcommons.unl.edu/tnas/334

This Article is brought to you for free and open access by the Nebraska Academy of Sciences at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Transactions of the Nebraska Academy of Sciences and Affiliated Societies by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
THE CLASSICAL EUROPEAN GLACIAL STAGES:
CORRELATION WITH DEEP-SEA SEDIMENTS

GEORGE KUKLA
Lamont-Doherty Geological Observatory
Of Columbia University
Palisades, New York 10964

Four glacials and three interglacials, recognized by classical Alpine and North-European subdivisions of the Pleistocene, were correlated with continuous oxygen-isotope records from the oceans using loess sections and terraces as a link (Fig. 15). It was found that the Alpine “glacial” stages are represented by sediments formed during both glacial and interglacial climates, that the classical Alpine “interglacial” stages do not represent episodes of interglacial climate but probably intervals of accelerated crustal movements, and that the physical evidence on which the North-European classical subdivision is based is misinterpreted due to lengthy gaps in the record.

It is recommended to discontinue the use of classical terminology in all interregional correlations and to base the chronostratigraphic subdivision of Pleistocene on the $\delta^{18}O$ record of deep-sea sediments. It is believed that, as in Europe, the loesses and terraces in Nebraska will eventually provide the link needed for correlation of deep-sea sediments with the classical American glacial stages.

THE OXYGEN ISOPTOE RECORD

The ratio of oxygen isotopes $O^{18}$ and $O^{16}$ in foraminiferal tests provides the most complete record of global climatic changes known to date (Emiliani, 1955). It is ideally suited for a standard with which all other records can be compared. The isotopic variations in benthic foraminifera is controlled predominantly by fluctuations in the total amount of ice deposited on land (Shackleton and Opdyke, 1973, 1976). This record is almost independent of the geographic location of studied cores. It was also shown that the benthic $O^{18}$ record is closely paralleled by that of planktonic foraminifers, first described by Emiliani (1955, 1958, 1966, 1972; Emiliani, et al., 1961). Emiliani used it to subdivide deep-sea sediments in several Caribbean and North Atlantic cores into numbered stages. His system, commonly referred to as the “oxygen isotope stratigraphy” or “delta $O^{18}$ stratigraphy,” is now widely used by deep-sea researchers.

Piston core V28-238 can conveniently serve as a type locality of the $O^{18}/O^{16}$ record (Shackleton and Opdyke, 1973; Geitzenauer, et al., 1976). It was taken from the equatorial Pacific at Long. 01°01’N and Lat. 160°29’E, from a water depth of 3120m. It is deposited at the Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York. As seen in Figure 2 the upper 14m of the core are
<table>
<thead>
<tr>
<th>System</th>
<th>Interval</th>
<th>Interpreted Climate</th>
<th>Type Unit</th>
<th>Type Locality</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpine</td>
<td>Postglacial</td>
<td>Temperate</td>
<td>---</td>
<td></td>
<td>Penck and Brückner (1909)</td>
</tr>
<tr>
<td>Würm</td>
<td>Glacial</td>
<td>Low Terrace</td>
<td>---</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Riss-Würm</td>
<td>Interglacial</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Riss</td>
<td>Glacial</td>
<td>High Terrace</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mindel-Riss</td>
<td>Interglacial</td>
<td>Younger Cover Gravel</td>
<td>Ille-Loch Platte,</td>
<td>Eberl (1930)</td>
<td></td>
</tr>
<tr>
<td>Mindel</td>
<td>Glacial</td>
<td>Older Cover Gravel</td>
<td>Germany</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Günz-Mindel</td>
<td>Interglacial</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Günz</td>
<td>Glacial</td>
<td></td>
<td></td>
<td>Eberl (1930)</td>
<td></td>
</tr>
<tr>
<td>Donau-Günz</td>
<td>Interglacial</td>
<td>---</td>
<td></td>
<td>Eberl (1930)</td>
<td></td>
</tr>
<tr>
<td>Donau</td>
<td>Glacial</td>
<td>Donau Gravel</td>
<td></td>
<td>Schaeffer (1953)</td>
<td></td>
</tr>
<tr>
<td>Biber-Donau</td>
<td>Interglacial</td>
<td>---</td>
<td></td>
<td>Schaeffer (1953)</td>
<td></td>
</tr>
<tr>
<td>Biber</td>
<td>Glacial</td>
<td>Highland Gravel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North European</td>
<td>Flandriaan</td>
<td>Temperate</td>
<td>Marine and Brackish Brackish deposits</td>
<td>Netherlands</td>
<td>Dubois (1925)</td>
</tr>
<tr>
<td>Weichsel</td>
<td>Glacial</td>
<td>End-Moraines</td>
<td>North Germany, Poland</td>
<td>Keilhack (1926)</td>
<td></td>
</tr>
<tr>
<td>Eem</td>
<td>Interglacial</td>
<td>Marine and Brackish deposits</td>
<td>Vicinity of Amersfoort, Netherlands</td>
<td>Madsen (1929)</td>
<td></td>
</tr>
<tr>
<td>Warthe</td>
<td>Glacial</td>
<td>End Moraines</td>
<td>Central Germany</td>
<td>Keilhack (1926)</td>
<td></td>
</tr>
<tr>
<td>Holstein</td>
<td>Interglacial</td>
<td>Marine deposits</td>
<td>Schleswig-Holstein</td>
<td>Penck (1922)</td>
<td></td>
</tr>
<tr>
<td>Elster</td>
<td>Glacial</td>
<td>Glacial-lacustrine</td>
<td>Central Germany</td>
<td>Keilhack (1926)</td>
<td></td>
</tr>
<tr>
<td>Cromer</td>
<td>Interglacial</td>
<td>Marine and Brackish deposits</td>
<td>East Anglia, G.B.</td>
<td>Reid (1882)</td>
<td></td>
</tr>
<tr>
<td>American</td>
<td>Recent</td>
<td>Temperate</td>
<td>Lake, alluvial and colluvial deposits on top of Wisconsin</td>
<td>North-Central USA</td>
<td>For American usage: Kay and Leighton (1933)</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>Glacial</td>
<td>End Moraines</td>
<td>Eastern Wisconsin</td>
<td>Geikie (1894)</td>
<td></td>
</tr>
<tr>
<td>(originally East Wisconsin)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sangamon</td>
<td>Interglacial</td>
<td>Black mud with (alluvial clay?), gummy clay (accretion gley?), sand, gravel and peat, ferreto (red soil).</td>
<td>Vicinity of Rochester, Sangamon County, Illinois</td>
<td>Leverett (1898)</td>
<td></td>
</tr>
</tbody>
</table>
subdivided into 22 oxygen isotopic stages numbered in order of increasing age. Odd-numbered units are relatively deficient in $\delta^{18}O$ and correlate with cold intervals characterized by increased volume of land-based ice. The boundaries, defined by depth in the core, are placed near the level of fastest change of the isotopic ratio, mostly halfway between the neighboring maxima and minima. Boundaries separating especially pronounced isotopic maxima from exceptionally pronounced minima were called "terminations" by Broecker and Van Donk (1970). The segments bounded by two consecutive terminations and composed of commonly two or up to four basic stages represent units of higher rank labeled "glacial cycles." Terminations are numbered by Roman numerals and glacial cycles by capital letters in order of increasing age.

Stage 5 was further subdivided by Shackleton (1969) into five substages labeled 5a to 5e in order of increasing age. Substage 5e has the lowest isotopic ratio of the five. It corresponds to the minimum volume of ice and is considered to represent the last interglacial. Similarly, stage 7 was subdivided into substages 7a, 7b and 7c (Ninkovich and Shackleton, 1975). Cores where the subdivisions were described are listed in Table II. The last termination, within the limits of dating precision, correlates with the last deglaciation (Ruddiman and McIntyre, 1973). Correspondingly earlier terminations are interpreted as representing earlier deglaciations. The climatic interpretation of $\delta^{18}O$ record is abundantly supported by independent climatic indicators present in deep-sea sediments such as faunal assemblages (Ericson and Wollin, 1968; Imbrie and Kipp, 1971), coccoliths (Ruddiman and McIntyre, 1973, 1976), ice rafted detritus (Kent, et al., 1971), and total carbonate content (Gardner and Hays, 1976; Kellogg, 1976).

In theory the $\delta^{18}O$ ratio in forams should provide an accurate measure of past ice volume. However, the resolution of the method is limited by a number of factors such as delay in ocean mixing, varying sedimentation rates, different sampling intervals, burrowing, redeposition of shells into younger sediment, selective dissolution, etc. (Shackleton and Opdyke, 1976). As a result the precision of the method greatly decreases with age, and the amplitudes of correlative peaks in different cores diverge to a significant degree. At present, the shapes of $\delta^{18}O$ curves, rather than the absolute values of isotopic ratios, are used for stratigraphic interpretations. Records of several cores must be compared before confident climatostratigraphic correlations are made.

The reversal of the earth’s magnetic field, K/Ar dated in land-based volcanics to about 0.7 million years (Dalrymple, 1972), was recognized in a number of deep-sea cores (Opdyke, 1972). In V28-238 it was located at the base of isotopic stage 19. In V28-239 it was found below termination IX in isotopic stage 20. Undoubtedly the reversal occurred in the vicinity of stage 19/20 boundary. Younger sections of deep-sea sediments are extensively dated by radiocarbon (Ericson, et al., 1961; Broecker and Van Donk, 1970; Ruddiman and Glover, 1972).

<table>
<thead>
<tr>
<th>System</th>
<th>Interval</th>
<th>Climate</th>
<th>Type Unit</th>
<th>Type Locality</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinoian</td>
<td>(originally</td>
<td>Glacial</td>
<td>Tills</td>
<td>Southwestern Illinois</td>
<td>Chamberlin (1896)</td>
</tr>
<tr>
<td></td>
<td>Illinois)</td>
<td></td>
<td>Sand, clay and peat with twigs and</td>
<td>Well in Yarmouth,</td>
<td>Leverett (1898)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bones of hare on till</td>
<td>exposure in West</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Point, Iowa</td>
<td></td>
</tr>
<tr>
<td>Yarmouth</td>
<td>Interglacial</td>
<td></td>
<td>Sand, clay and peat with twigs and</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bones of hare on till</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kansan</td>
<td>Glacial</td>
<td></td>
<td>Tills</td>
<td>Northeastern Kansas</td>
<td>Geikie (1894)</td>
</tr>
<tr>
<td>Afton</td>
<td>Temperate</td>
<td></td>
<td>Gravel and sand, muck with vegetation</td>
<td>Exposures in Afton</td>
<td>Chamberlin (1895)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(= organodetritic silts)</td>
<td>Junction, Iowa</td>
<td></td>
</tr>
<tr>
<td>Nebraskan</td>
<td>Glacial</td>
<td></td>
<td>Tills</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Exposures in the vicinity of Omaha,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nebraska</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE II

Key Sites of Oxygen Isotope Stratigraphy

<table>
<thead>
<tr>
<th>Core</th>
<th>Ocean or Sea</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Water Depth (m)</th>
<th>Length (cm)</th>
<th>δO&lt;sup&gt;18&lt;/sup&gt; Stages</th>
<th>Remarks</th>
<th>References</th>
<th>Place of Deposit</th>
<th>Site No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A172-6</td>
<td>Caribbean</td>
<td>14°59'N</td>
<td>68°57'W</td>
<td>4290</td>
<td>935</td>
<td>1-14</td>
<td>Orig. definition of O&lt;sup&gt;18&lt;/sup&gt; stages 1-14</td>
<td>Emiliani, 1955</td>
<td>Lamont</td>
<td>4</td>
</tr>
<tr>
<td>P6304-8</td>
<td>Caribbean</td>
<td>14°59'N</td>
<td>69°20'W</td>
<td>3927</td>
<td>1054</td>
<td>1-11</td>
<td>Definition of 15-17; Radiometric ages of stages 2-7</td>
<td>Rona-Emiliani, 1969</td>
<td>Miami</td>
<td>5</td>
</tr>
<tr>
<td>P6304-9</td>
<td>Caribbean</td>
<td>14°57'N</td>
<td>68°55'W</td>
<td>4126</td>
<td>1429</td>
<td>1-17</td>
<td></td>
<td>Broecker and van Donk, 1970</td>
<td>Lamont</td>
<td>3</td>
</tr>
<tr>
<td>V12-122</td>
<td>Caribbean</td>
<td>17°00'N</td>
<td>74°23'W</td>
<td>2800</td>
<td>1095</td>
<td>1-14</td>
<td>Orig. definition of terminations &amp; Glacial Cycles</td>
<td></td>
<td>Lamont</td>
<td>6</td>
</tr>
<tr>
<td>V16-205</td>
<td>Atlantic</td>
<td>15°24'N</td>
<td>43°24'W</td>
<td>4043</td>
<td>1232</td>
<td>1-14</td>
<td>Orig. definition of stages 23-41</td>
<td>van Donk, 1976</td>
<td>Lamont</td>
<td>2</td>
</tr>
<tr>
<td>V28-238</td>
<td>C. Pacific</td>
<td>01°01'N</td>
<td>160°29'E</td>
<td>3120</td>
<td>1609</td>
<td>1-22</td>
<td>Orig. definition of stages 17-22 proposed O&lt;sup&gt;18&lt;/sup&gt; type core</td>
<td>Shackleton &amp; Opdyke, 1973</td>
<td>Lamont</td>
<td>8</td>
</tr>
<tr>
<td>V28-239</td>
<td>C. Pacific</td>
<td>03°15'W</td>
<td>159°11'E</td>
<td>3490</td>
<td>2102</td>
<td>1-23→</td>
<td>Detailed O&lt;sup&gt;18&lt;/sup&gt; record for ± 2 m.y.</td>
<td>Shackleton &amp; Opdyke, 1973</td>
<td>Lamont</td>
<td>9</td>
</tr>
<tr>
<td>RC11-120</td>
<td>S. Pacific</td>
<td>43°31'S</td>
<td>79°52'E</td>
<td>3135</td>
<td>954</td>
<td>1-9</td>
<td>Cycle analysis and correlation with astronomic chronol.</td>
<td>Hayes et al., 1976</td>
<td>Lamont</td>
<td>11</td>
</tr>
<tr>
<td>E49-18</td>
<td>S. Pacific</td>
<td>46°03'S</td>
<td>90°09'E</td>
<td>3256</td>
<td>1459</td>
<td>5-13</td>
<td></td>
<td>Ruddiman and McIntyre, 1976</td>
<td>Lamont</td>
<td>10</td>
</tr>
<tr>
<td>K708-7</td>
<td>N. Atlantic</td>
<td>53°56'N</td>
<td>24°05'W</td>
<td>3502</td>
<td>1280</td>
<td>not defined</td>
<td>Orig. names of Glacial cycles A-H in deep-sea sed.</td>
<td></td>
<td>Lamont</td>
<td>1</td>
</tr>
<tr>
<td>Sw Exp-58</td>
<td>Eq Pacific</td>
<td>6°44'N</td>
<td>129°29'W</td>
<td>4440</td>
<td>991</td>
<td>not defined</td>
<td>First downward numbered stages in a deep-sea core. Concept followed by Emiliani.</td>
<td>Arrhenius, 1952</td>
<td>Uppsala</td>
<td>7</td>
</tr>
</tbody>
</table>
Figure 2. Key oxygen isotope records. Location of the cores in Figure 1. Formal numbering of δ¹⁸O stages in Arabic numerals after Emiliani (1955, 1966) and after Shackleton and Opdyke (1973, 77), informal below stage 22 after Van Donk (1976) terminations in Roman numerals after Broecker and Van Donk (1970), major cycles in capital letters after Ruddiman and McIntyre (1976). Faunal and floral markers mainly after Geitzenauer, et al. (1976), Thierstein, et al. (1977), and Briskin and Berggren (1975) showing: A: beginning dominance of *Emiliania huxleyi* over *Gephyrocapsa caribbeanica* in transitional waters; B: first appearance of coccolith *Emiliania huxleyi*; C: last appearance of radiolaria *Stylactractus universus*; D: last appearance of coccolith *Pseudoemiliania lacunosa*; E: appearance of abundant foraminfer *Sphaeroidinella dehiscens*; F: last appearance of foraminifer *Globigerinoides fistulosus*; G: last discoasters; H: emergence of *Globorotalia menardii-tumida* group and of the foraminifer *Globorotalia truncatulinoides*; I: last appearance of *Globigerinoides obliqua*; J: last appearance of foraminifer *Globorotalia exilis*; Y-Q: Faunal zones of Ericson defined by the lack of the *Globorotalia menardii-tumida* group in the Atlantic.

Warm oxygen isotope stages stippled, estimated age of terminations from Table III. Normal polarity in black, reversed blank.
Uranium-decay series were used to calibrate uneven sedimentation rates back to approximately 0.3 million years (Rosholt et al., 1961; Rona and Emiliani, 1969; Ku and Broecker, 1966). The ages derived by this method are subject to large systematic uncertainty. Oxygen isotope variations in corals made it possible to accurately date, by the uranium/thorium method, the O\textsuperscript{18} peaks of stages 5, 7 and 9 in coral reefs at Barbados (Shackleton and Matthews, 1977). The U/Th dates on corals are considered accurate because the aragonitic skeleton of corals are almost impermeable to radioactive isotopes and maintain a closed geochemical system. Age determinations of corals were extensively cross-checked by repetitive sampling at a number of localities by several laboratories.

Table III summarizes the recently published estimates of the age of terminations within the last one million years, obtained by interpolations to the Brunhes/Matuyama reversal and by radiometric dating of corals.

The O\textsuperscript{18} record shows eight completed glacial cycles, namely B through I, and nine terminations, I through IX in the last epoch of normal polarity which lasted approximately 0.7 million years. Ten glacial cycles, B to K, separated by eleven terminations, I to XI, were completed in the past one million years from the Jaramillo normal polarity event.

The ice-volume oscillations as recorded by O\textsuperscript{18} ratio within each glacial cycle seem generally to follow a sawtooth pattern, progressing from an early minimum to a late maximum. Apparently the glaciers have grown in steps interrupted by temporary regressions. The O\textsuperscript{18} record does not show where the ice was deposited and where the retreats took place. It remains unclear whether the changes of ice volume proceeded in phase or out of phase between the two hemispheres or between the North American and Euro-Asian continents.

The number of secondary isotope fluctuations recognized within each glacial cycle, depending on the sedimentation rate and sampling interval of the particular core studied, varies commonly between 4 and 6. In each of the well-known last two glacial cycles, B and C, five secondary oscillations took place. A typical O\textsuperscript{18} curve of cycle B is shown in Figure 5.

In general it was observed that during the past approximately one million years the general shape and amplitude as

### TABLE III

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>11,000</td>
<td>10,500</td>
<td>13,000</td>
<td>11,000</td>
<td>13,500</td>
<td>10,000</td>
<td>11.5 ± 1 +2</td>
</tr>
<tr>
<td>II</td>
<td>127,000</td>
<td>128,000</td>
<td>128,000</td>
<td>128,000</td>
<td>127,000</td>
<td>127,000</td>
<td>128.0 ± 1 +0</td>
</tr>
<tr>
<td>III</td>
<td>225,000</td>
<td>243,000</td>
<td>251,000</td>
<td>245,000</td>
<td>220,000</td>
<td>247,000</td>
<td>240.0 ± 20 +10</td>
</tr>
<tr>
<td>IV</td>
<td>300,000</td>
<td>333,000</td>
<td>347,000</td>
<td>335,000</td>
<td>315,000</td>
<td>336,000</td>
<td>330.0 ± 30 +20</td>
</tr>
<tr>
<td>V</td>
<td>380,000</td>
<td>370,000</td>
<td>440,000</td>
<td>415,000</td>
<td>380,000</td>
<td>425,000</td>
<td>400.0 ± 30 +40</td>
</tr>
<tr>
<td>VI</td>
<td>485,000</td>
<td>502,000</td>
<td>480,000</td>
<td>455,000</td>
<td></td>
<td></td>
<td>480.0 ± 20 +20</td>
</tr>
<tr>
<td>VII</td>
<td>600,000</td>
<td>592,000</td>
<td>575,000</td>
<td>515,000</td>
<td></td>
<td></td>
<td>570.0 ± 55 +30</td>
</tr>
<tr>
<td>VIII</td>
<td>647,000</td>
<td>635,000</td>
<td>605,000</td>
<td></td>
<td></td>
<td></td>
<td>630.0 ± 25 +20</td>
</tr>
<tr>
<td>IX</td>
<td>726,000</td>
<td>706,000</td>
<td>700,000</td>
<td></td>
<td></td>
<td></td>
<td>710.0 ± 10 +20</td>
</tr>
<tr>
<td>X</td>
<td>845,000</td>
<td>782,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>810.0 ± 30 +35</td>
</tr>
</tbody>
</table>
Figure 3. Foraminiferal assemblages in North Atlantic core K708-7 after Ruddiman and McIntyre (1976), compared with the pollen record in the Tenaghi-Phillipon peat bog in Macedonia, after Van der Hammen, et al. (1972). Percentage of subtropical and transitional foraminifera in K708-7 and oak pollen in Macedonia shown in black. Forams other than a polar type and total tree pollen stippled. Position of terminations, correlation with oxygen isotope stages and glacial cycles modified after Ruddiman and McIntyre (1976). Recently confirmed by an $\delta^{18}$O analysis of the core by Shackleton (personal communication).
Figure 4. Key loess areas around Brno, Praha and Krems (3) and the maximum extent of Pleistocene glaciers in Europe (stippled).

Rivers, which the north European glacial stages were named after, or those with dated terraces are also shown. 1: type locality of the Alpine glacial stages (crosshatched); 2: type region of the north European glacial stages.

as well as internal structure of the $^{18}O$ record did not markedly change. This conclusion takes into account that the limited climate history during each one of the glacial cycles C-J is likely to have displayed about the same degree of complexity as the last glacial cycle B.

Cold stages 2, 6, 10, 12, 16 and 22 were found to be marked on the average by deeper and/or longer-lasting isotopic highs than were the remaining cold stages. On the contrary, cold stage 14 is poorly expressed and points to an exceptionally low ice volume. The warm peaks of odd-numbered stages 1 to 21 (except stage 3) all seem to approach a closely similar level, at least within the precision limits of the $^{18}O$ method. This indicates that the global ice volume and sea surface temperatures in peak interglacials were similar to those of today and also that during the past 0.9 million years there were at least nine episodes with global climate comparable to the present one, which can be labeled “interglacial.” Stage 7 shows two pronounced warm peaks of interglacial rank. This is a characteristic difference from other odd-numbered isotopic stages which only allow recognition of single $^{18}O$ peak. Thus the interglacial of stage 7 may have been doubled. Whether some of the warm stages older than 13 displayed similar two-fold structures is impossible to determine because of insufficient resolution of available cores.

In summary, the isotopic record of deep-sea cores provides the most accurate hitherto known information on Pleistocene climates, unique in its continuity and global extent. Validity of any other climatostratigraphic system of Pleistocene must be tested by comparison with the deep-sea record.
Figure 5. Summarized loess stratigraphy of the last 130,000 years in the area around Praha and Brno. PMG: polarity of remanent magnetization, black: normal, stripped: interpreted as reversed (after Kukla and Kočí, 1972). Radiocarbon dates on charcoals and soils after Klíma, et al. (1962) and Kukla (1975), abbreviations of type localities of the soils after Kukla (1975), lithologic symbols same as in Figure 9. Roman numerals designate marklines and terminations. Vertical scale proportional to relative thickness, not time. Curves of reconstructed environment show (C) cold, (N) normal, (M) mild loess steppe; barren badlands; (R) sparse marginal grasslands; (T) thick grasslands; (BE) coniferous or short-lived mixed forests on braunerde; (PB) deciduous, long-lasting forests on parabraunerde. Cold and normal loess steppe in studied area is characteristic for full glacial (GLAC); parabraunerde for full interglacial (INTGL). Tentative correlation with δ^{18}O record also shown. After Kukla (1975).
THE LOESS RECORD
IN CENTRAL EUROPE

Loess is a yellow-calcareous, porous, wind-blown silt, characteristic of Pleistocene sequences all over the world. Its thickest deposits, several tens of meters thick, accumulated in periglacial areas along the course of major rivers (Smalley, 1975). The bulk of deposits is of glacial age. Largest are in China (Liu and Chang, 1961) and Ukraine (Veklitch, 1969; Velichko, 1969). The best studied and the most important for Pleistocene stratigraphy are deposits lying closest to formerly glaciated areas of Europe.

The advantage of loess sequences is that they are essentially continuous. With the help of magnetostratigraphy and observed parallels in climatic history, they can be directly correlated with deep-sea sediments (Kukla, 1970, 1975). They are also stratigraphically related to the terraces of rivers flowing through formerly glaciated areas. In this way a link is provided for a direct correlation of the deep-sea record with classical glacial stages.

The periglacial area around Prague, Brno and Nitra in Czechoslovakia, as well as around Krems and Vienna in Austria (Fig. 4) was never glaciated. When the Alpine and Fennoscandinavian ice sheets reached their maximum extents, loess accumulated in this region, influenced by highly continental periglacial climate. During the interglacials the climate was of the Atlantic type, similar to the present one, or warmer and wetter. Deciduous forests spread, leaving behind the characteristic parabraunderde soils. Thus in favorable depositional basins, glacial-interglacial cycles were recorded by repeated alternations of loess and forest soils. The loess is frequently deposited on river terraces behind steep cliffs of abandoned river banks. These were ideal sedimentary traps for the wind-blown dust. The terraces around Prague were formed by a tributary of the Labe (Elbe) River which flows into the region of Fennoscandinavian glacial deposits. The terraces around Brno, Nitra, Krems and Vienna belong to the tributaries of the Danube River which also drains the Alpine foothills where classical Alpine glacial stages were defined by Penck and Brückner (1909). Thus, the correlation of loss sequences with glacial deposits in northern Europe and in the Alps is possible.

More than one hundred selected localities, with especially well developed sequences, have been described in Czechoslovakia and Austria during this century (Penck and Brückner, 1909; Götzinger, 1936; Schönhäls, 1951; Žebera, 1949; Fink 1954, 1969; Musil, et al., 1955; Průšek and Ložek, 1957; Kukla and Ložek, 1961; Demek and Kukla, 1969; Kukla, 1975). The two most important key localities are Červený Kopec (Red Hill) in Brno and the Kremser Schiesrattke in Krems.

Glacial loess in central Europe differs from any known eolian deposit of contemporary origin because of its fine network of secondary carbonate, which coats the rock detritus and sheets of clay minerals, partly filling the dense system of fine grass root-holes. Stratigraphic relations and micromorphology prove beyond doubt that the calcareous network is syn-genetic. A special type of arid weathering called “Loessification,” acting in both the source area as well as in the accumulation zone, is believed responsible for this feature (Ganssen, 1922; review by Marosi, 1970).

The depositional environment of loess can be fairly well reconstructed. Extensive, barely or poorly vegetated, seasonally dry surfaces exposed to loessification must have existed in the deflation areas. Sparse patches of grass and sedges in the accumulation areas were necessary to pick up the dust and prevent further erosion of the surface. Indeed, pollen of Gramineae and Cyperaceae were found in the loess by Frenzel (1964). Sandy interlayers and wind-moved rock fragments on the slopes prove that winds were occasionally very strong (Žebera, 1949).

Valuable information on the loess environment is provided by gastropodes. These are found largely intact, and there is no doubt that animals lived at the time of loess deposition.

The typical autochthonous assemblage of central European loesses is dominated by the Pupilla group and called the Puppilla fauna (Ložek, 1964). Some of its elements still live in the steppes of Europe, while others such as Pupilla loessica are extinct. No place is known today where the living elements of Pupilla fauna dwell together. The environment indicated by Pupilla fauna is sometimes referred to as a “cold loess-steppe” (Ložek, 1964, 1969).

Another loess assemblage, dominated by a cold resistant species Columella columella, is called Columella fauna. It is frequently accompanied by Vertigo paracenttata, Vallonia tenuisulabris, or Pupilla loessica. Elements of wet and cold environments such as Suceinea putris, Vertigo arctica, and Vertigo pseudosubstriata are also present. Elements of this assemblage today live in the Alpine zone of the Tien Shan Mountains of central Asia, under an extremely cold and highly continental climate. At the paleolithic sites of Vestonice and Pavlov, the wet Columella fauna is accompanied by lynx, wolverine (Gulo gulo), arctic fox (Allopex lagopus), reindeer, mammoth and wody rhinoceros (Musil, 1959), and in Bojnice by lemming (Dicrostonyx torquatus) (Prošek and Ložek, 1957). Also related to this assemblage are the frost gley soils indicative of permafrost. Obviously the Columella fauna was able to persist in a subarctic environment with a very low winter temperature, sometimes referred to as loess-tundra.

The Striata fauna is climatically the most demanding assemblage known from loess (Ložek, 1964, 1969). It is represented, among others, by Helicopsis striata, Chondrula tridens,
*Pupilla muscorum*, *Vallonia costata* and in some areas by *Abiola frumentum*. All its elements today live in central Europe, and the assemblage as a whole is closely related to the Holocene steppe faunas of southeastern Europe. The *Striata* fauna is characteristic of what could be called a “warm loess-steppe” (Ložek, 1969). Presence of *Striata* fauna does not necessarily imply that the climate was mild. The assemblage may resist much harsher winters than those occurring today in eastern Europe. Nevertheless, it requires relatively warm and dry summers.

Obviously the loess of central Europe was deposited under a variety of climatic conditions which have only this in common: expressed continentality, low precipitation and a short, if any, rainy season. Mean annual temperatures may have been as low or even lower than in northern Siberia today but also as high as they are now in the Black Sea Basin.

Two specific types of sediments are commonly found in the loess-filled depressions of Czechoslovakia, the “pellet sands” and the “marker.” The pellet sands, sediments composed of sand-sized pellets made of silt or clay, are deposits of torrential rains that followed a prolonged warm and dry season. They are at least partly contemporaneous with gravel aggradation in neighboring rivers. “Markers” are thin bands of light-colored silt probably deposited by dust storms of continental magnitude (Kukla, 1961b). Snail assemblages of the pellet sands and of markers are closely related to the *Tridens* and *Striata* faunas.

Soils interstratified with loess and hillwash sediments record intervals of dense vegetation established at a locality for a period of at least several centuries. The quality of soil horizons depends directly on the type, density, and duration of vegetational cover and in such a way indirectly on climate. Because most of the studied localities lie on slopes, the soil surfaces have not become fully stabilized, and the soil material from higher elevations continued to be slowly redeposited into the depressions.

The soils in the loess belt of central Europe are of two main groups: (1) biologically reworked steppe (prairie) soils, showing an accumulation of organic matter but little chemical change of mineral matrix; and (2) leached soils of braunerde type with evidence of in situ redeposition of carbonate, iron, and manganese as well as clay plasma. These are not reworked to any significant degree by pedofauna.

Under unaltered conditions, the loess belt in central Europe today would be thoroughly vegetated, its surface stabilized, and the occasional limited airborne increments reaching the surface would be assimilated in soils without interrupting the pedogenetic process. Actually, however, large areas have been denuded by man and are now subject to extensive soil erosion and redeposition. Thus, modern allochthonous soils and loess-derived floodloams are frequent in the region.

Leached soils, called *parabraunerdes*, with clay-enriched B-horizons have the highest stratigraphic value. They are the product of deciduous forests, which in this part of Europe are, by definition, interglacial. Today they border the southern periphery of the loess belt and reach their present northern limits in central Europe.

Correlative recent snail faunas of the forested borders of the loess belt are richly diversified with *Monachoides incan- nata*, *Ena montana*, *Discus perspectivus*, *Helicodonta obvoluta*, and *Helix pomatia*. Ložek (1964) refers to these assemblages as the *Helix* faunas.

The *parabraunerde* of Czechoslovakia and Austria, which developed on calcareous loess of the last glacial age, in undisturbed environments, always associated with mixed hardwood forests and *Helix* faunas. Fossil parabraunerde are also associated with *Banatica* snail assemblages. These, in addition to forms known from recent broadleaf forests, include species such as *Helicigona banatica*, *Soosia diodonta*, and *Aegopinella rossmani*, requiring higher winter temperature and wetter summers than present. Gastropods are typically found in *krotovinas* reaching into the Oca horizons of this soil or in carbonate-rich, hillwash loams, immediately underlying such soils. They are not present within the soil itself since it is strongly leached. In the *parabraunerde* of the last interglacial, Frenzel (1964) found pollen of oak, linden elm, and hazel, providing independent proof of an interglacial origin for this soil. Stones of *Celtis* (cherry) are common in the older *parabraunerdes* and braunlehms (Ložek 1964).

Braunlehms are fossiliferous, strongly-weathered, argillitic forest soils and frequently have large carbonate concretions with a high proportion of clay plasma. They are interpreted as a polygenetic formation produced by alternations of warm-wet and warm-dry climates. Their snail assemblages are essentially the same as those of the *parabraunerde*.

Chernozems, rich in humus, calcareous, well-granulated biogenic soils are the postglacial climax soils of the drier loess belts. They are preserved north of Prague, south of Brno and east of Vienna and Bratislava. Chernozems stretch today from central Germany and Czechoslovakia to the Ural and central Asia, reaching as far north as 57° latitude. They are present soils of continental climates with cold to very cold winters, rainy springs, and dry summers.

Recent snail faunas in the driest parts of the basins with thick chernozems, are dominated by such species as *Chondrula tridens* and *Abiola frumentum*. They differ from similar *Heistocene Tridens* faunas of buried chernozems by the presence of exothermic elements like *Cepea vindobonensis* or *Oxychilus inopinatus* and by the presence of southern immigrants like *Helicella ceciloides*, whose expansion was facilitated by man (Ložek, 1972).
The so-called frost-gleys or pseudogleys are fossil soil horizons that differ from the raw loess only by the greenish-grey stains and frequent ochre-brown limonitic concentrations. These features are believed to be due to repeated saturation of the soil by groundwater. As the soils are often associated with cold, tolerant *Columella* faunas and since the gley phenomena run parallel to the surface and are accompanied by small involutions and signs of solifluction, it is assumed that they formed in the summer melt on top of the permafrost (Klima, et al., 1962).

Common braunerde soils are also found in the loess sequences. They are leached and oxidized but do not show signs of clay illuviation. Temperate snails were not found accompanying such soils in any of the studied localities. Smolkova (1971) studied the micromorphology of fossil braunerdes in the neighborhood of Brno and Prague and compared them to arctic braunerdes, commonly found under boreal coniferous forests.

**Climatostratigraphic Value of Loess and Soils**

As the preceding discussion indicates, the paleoclimatic information that can be derived from loess sequences comes from characteristic types of sediments or soils and, independently, from snail assemblages. Both soils and snails depend upon the type of established vegetation cover and on its persistence. They are specific to the loess belt, which is relatively narrow in Europe. Thus, unlike marine faunas which can be followed moving north and south during the glacial cycles, the characteristic soils and gastropod assemblages of the loess belt alternately appear and disappear.

Interglacials are defined as intervals of warm and wet climate during which temperate deciduous forests were established in northwestern Europe (Turner and West, 1968; Farrowbridge, 1972; Kukla, et al., 1972; Turner, 1975). In the neighborhood of Prague, Brno and Krems the development of hardwood forests was practically synchronous with the type region. Thus, parabraunerdes, braunlehms, and the accompanying *Helix* and *Banatica* faunas are the approximate equivalents of the temperate phases II and III of interglacials as described in pollen records. Their presence in the sequence proves an interglacial proper. On the other hand, the full glacial conditions, during which the glaciers in the Alps, northern Germany, and Poland reached their last maxima, are recorded in the Prague and Brno area by frost-gley soils and by *Columella* snail faunas.

A surprisingly close correspondence of sedimentary sequences of different ages has been observed in the region around Prague and Brno. This observation led to the definition of sedimentary cycles of the first and second order (Kukla, 1961a) and later to a regional lithostratigraphic system naming the soils according to their cyclic position in the sequence (Kukla, 1975). Cycles of the first order are called “glacial cycles” and are delimited by marklines. Those of the second order are “stadial cycles” or “subcycles” and are delimited by submarklines (Fig. 5). Each cycle and subcycle starts with a thin deposit of hillwash loam (phase 1), succeeded in turn by a forest soil of braunerde type (phase 2), steppe soil of chernozem type (phase 3), marker (phase 4), pelletal sand (phase 5), and loess (phase 6). Some members of the sequence may be missing, but within the studied area the successive order of the phases always remains identical. The detailed, cyclic repetitions of chernozems, markers, and pelletal sands have only been reported from the last three glacial cycles, reflecting the fact that relatively few localities with older sediments are known.

Marklines are the boundaries between a thick layer of loess, commonly containing *Columella* or *Pupilla* faunas, and the overlying parabraunerde or braunlehm. Where the hillwash of phase 1 is present beneath the soil, the markline is drawn at the boundary of the hillwash with the loess.

Each glacial cycle delimited by two successive marklines is labeled by a capital letter. The elapsed part of the Holocene glacial cycle is labeled A, the last completed Pleistocene cycle B, the next order one C, and so on, in order of increasing age.

Within each glacial cycle an oscillatory but gradual change is evident between environments of a pronounced climatic optimum and of the most severe continental climate. Whereas the optimum occurs at the beginning of each cycle, the coldest environment is recorded shortly before its end. In this respect the loess cyclothems resemble the sawtooth glacial cycles in marine O\(^{18}\) records (Broecker and Van Donk, 1970) or the oscillations of foraminiferal assemblages and coccoliths in the North Atlantic (Ruddiman and McIntyre, 1976).

Submarklines (Kukla and Kočí, 1972) are the boundaries of loess of any kind with overlying parabraunerde, braunerde, or chernozem. Each unit delimited by two successive submarklines is called a “stadial cycle” or a “subcycle” and labeled with the capital letter of the corresponding glacial cycle followed by an Arabic numeral (Fig. 5).

Individual lithologic units recognized in the studied area are so numerous that the original attempt to name them after the type localities (Klima, et al., 1962) was abandoned. Instead, the soils are labeled by a lower case letter combined with the designation of the corresponding stadial or glacial cycle. The intention is to use the same designation for horizons considered to be of equal age throughout the region. However, because a correct correlation cannot always be guaranteed, the complete reference needs to include the abbreviated symbol of the locality. Also, where correlations are made with units from outside the loess system, the prefix L
(for loess) is used to avoid confusion with similar labels of other authors.

Thus the designation \textit{L-CK-C3j} refers to the soil labeled as \textit{j} observed within the subcycle \textit{C3} (youngest section of glacial cycle \textit{C}) at the locality Červený Kopec (symbol CK). Correspondingly, the soil \textit{L-DK-C3j} in Dolní Kounice (symbol DK) shows the same stratigraphic position and presumably is of the same age.

Apart from dividing the glacial cycle into three or five stadial cycles, there also are good reasons for a twofold subdivision. Under such a scheme, a sedimentary sequence of every glacial cycle is divided into a "Lower" and "Upper" series. In the lower one, dark-colored soils and soil sediments predominate, while in the upper one, light-colored loess is the predominant deposit (Fig. 5). Typical arctic vertebrates like arctic fox, lemming, or wolverine are either missing or very rare in the lower series but are abundant in the upper one, giving it a pronounced glacial character. Thus the composition of vertebrate faunas in this part of Europe parallels the twofold rather than the multifold subdivision of the glacial cycle. The twofold subdivision is applicable for young as well as old deposits and is useful for correlation with deposits outside Czechoslovakia and Austria. Similar twofold units are common in loess areas of Hungary, Yugoslavia, Bulgaria, Romania, the Soviet Union, or in the United States, and are widely utilized in geologic mapping.

The Time Control

The chronostratigraphic setting of the loess sequences is based on radiocarbon dates of charcoal and soil humus extending back over 50,000 years (Klima et al., 1962; Fink, 1969, 1976; Vogel and Zagwijn, 1967); positions of magnetostratigraphic boundaries correlated with the Brunhes/Matuyama, the Olduvai/Matuyama reversals, and the Jaramillo and the Blake event. Time coincidence of marklines with the

Figure 6. Červený Kopec (Red Hill-CK) section at Brno, Czechoslovakia. Exposed in an excavation front of a brickyard pit and in boreholes (vertical bars). Terraces CK 1-5, the fossil-bearing section of Stránská Skála (SS) and the Židenice brickyard (ZD) are also shown. Horizontal scale shows distance from the Svatka River. 1: Brunhes/Matuyama reversal; 2: soil with Biharian vertebrates; 3: cave fill with Biharian fossils; \( A-K \): baselines of corresponding glacial cycles. Location in Figures 1 and 4. Detailed stratigraphic column in Figure 7.
terminations in oceanic sediments makes it possible to use the age estimates of terminations directly as the age estimates of corresponding marklines (Table I). The summary of the available radiocarbon control is shown in Figure 5.

The record of the Brunhes/Matuyama reversal was located in two sequences in Krems, Austria (Fink and Kukla, 1977), two at Červený Kopeck (Figs. 6 and 7), Czechoslovakia (Bucha, et al., 1969; Bucha, 1973; Kočř, unpublished), one on Granska Skala at Brno and one in Unetice (Fig. 8) near Prague (Kočř and Sibrava, 1976). Independent paleontologic and morphostratigraphic correlations confirmed the same relative age of five out of the six locations mentioned (Kukla, 1975). The reversal occurs in sediments of late glacial J, or possibly in the earliest layers of the interglacial I, in a very close vicinity of markline IX.

Global synchrony of gross climate changes results in the synchronicity of terminations with marklines (Kukla, 1970). Independent observations support such correlation. The age of markline I around Brno falls close to 10,000 years B.P. judging from the final occurrences of autochthonous wind-blown loess at C 14 dated Magdalenian occupation levels in local caves (Valoch, 1968). Termination I, marking the last deglaciation, was dated in the cores of the equatorial Atlantic to about 11,000 B.P. (Broecker, et al., 1960). Thus, the ages of markline I and termination I are very close. Termination II, 127,000 years old according to Barbados coral reefs, predates by about 5,000 years the interglacial optimum in the O 18 record. Markline II which is more than 115,000 years old because of its relation of the reversed magnetostratigraphic unit in Modrice correlated with the Blake event, predates by a few thousand years the climax soil BIB of the deciduous forests of the last interglacial. Thus the synchrony of markline II with termination II is highly probable.

The number of distinguishable layers developed and preserved in the sequence, and thus the quality of climatostratigraphic information, depends critically on the local morphology. Serious miscorrelations were frequent in the loess belt in former decades when Pleistocene stratigraphers did not pay sufficient attention to this fact. In the absence of independent correlation criteria, the authors dated the strata by counting them down from the surface and labeling them in terms of Soergel's and Milankovitch's chronology. This “count from top” method produced, for instance, the notorious hypotype soil of the Riss/Wurm interglacial, the Kremser paleosol (Gross, 1957; Brandtner, 1956; Movius, 1960), which as we now know is about one m.y. old, older than the whole of Penced's classical Pleistocene. Also, by similar miscorrelation, a polygenetic soil at Paudorf was chosen to represent a Late Pleistocene interstadial 30,000 years old. It later yielded one of the richest known snail assemblages of the last interglacial (Fink, 1976).

Most of the studied sections in central Europe rest on abandoned river terraces and fill sheltered depressions cut deep into the subsurface by meandering streams. As the streams gradually cut deeper, the high lying relief became increasingly exposed to denudation. As a result, loess and soils immediately overlying fluvial sediments are thicker, better subdivided, and less affected by retrograde weathering or destruction. Each time the river cut to a deeper terrace level, space was provided for the well-stratified younger fill. Thus, a “telescopic superposition” of strata (Kukla, 1961b), exemplified in Figure 6 is commonly observed in the downwind western banks of Czech and Moravian rivers.

**Stratigraphy**

Stratigraphy of several hundred loess sections in Europe has been described in the literature. Stratigraphic columns of some of them with brief descriptions are contained in special volumes edited by Fink (1969) and by Demek and Kukla (1969).

Figures 6 and 7 show the stratigraphy in one of the key sites exposed in the brickyard of Červený Kopeck (Red Hill), Czechoslovakia. Sediments and soils of ten completed glacial cycles B-K and of the Holocene rest in telescopic superposition on top of five terraces of the river Svatka labeled locally as CK1-CK5. The Brunhes/Matuyama (B/M) paleomagnetic boundary, 0.7 m.y. old, is on top of the high terrace CK4 and is overlain by a soil with remains of Biharian vole Pitymys. On the nearby locality of Stranska Skala in a similar position above a high terrace, the B/M reversal is overlain by soil sediments with rich Biharian vertebrate assemblage (Kurten, 1960; Musil, 1969). The youngest part of the Red Hill sequence is paralleled at another nearby locality, Modrice, where an anomalously magnetized unit correlated with the Blake event was identified above the forest soil of the last interglacial (Kukla and Kočř, 1972). Chernozems are the most abundant soils of the last five glacial cycles A-E. The climax interglacial soils are parabraunerdes in the older cycles F-I: the soils are clayey braunlehm rich in large carbonate. Soils of cycles F and K are distinguished by strikingly red hues.

Numerous boreholes and exposures in the vicinity of Brno demonstrate the stratigraphic relation between the loess sequence and the terraces. Each terrace is a morphostratigraphic unit identified by relative elevation of its fluvialit sediment incorporated into the terrace body. In order to date the terrace with respect to the loess sequence, exposures from several localities have to be compared because deposition and erosion in a river bed occur simultaneously and give each terrace body a complicated internal structure. Sediments of greatly divergent ages may coexist at the same level.

It was found in several localities that the deposition of river gravels was contemporaneous with the pellet sands. The earliest recognized deposit of the lowermost terrace in the
Figure 7. Stratigraphy of the Červený Kopec (Red Hill) sequence in Czechoslovakia (cf. Fig. 6). Composed of segments with highest resolution. Lithologic symbols same as in Figure 5. BL—braunlehm. Levels of deep erosional incision in cycles C, F, I and K marked as breaks. VF 1–VF 3: vertebrates of Biharian faunal wave; VF 4: vertebrates of Steinheim faunal wave. Reconstructed environment: same symbols as in Figure 5. Details in Kukla (1975).
Figure 8. Terrace sequences of Vltava and Elbe around Praha, Czechoslovakia. Ilm and Saale around Leipzig, Germany and lower Rhine around Köln (Cologne), Germany. Designation of Vltava terraces after Záruba (1942), Ilm after Soergel (1939), and Rhine after Brunnacker (1975). Terrace gravel stippled, floodloam marked with horizontal stripes, interglacial soils and silts black, ice deformed sections zig-zagged, loess blank, B–D glacial cycle baselines. After Kukla (1975).
vicinity if Brno, CK1, correlates with the pellet sands of subcycle C2 (Kukla, 1975). Correspondingly, the time span during which CK1 terrace has been deposited is bracketed between the next-to-the-last glacial of cycle C and the present. Gravels and floodloams are still being incorporated into the body of CK1 (Fig. 6). It should be noted that during subcycle B2 the river cut to a considerable depth. But because of subsequent aggradation returned to previous and even higher levels, a separate terrace unit did not develop.

In a similar manner the CK2 terrace, whose surface is about 20 to 30 meters above the present river, is younger than the floodloams of subcycle GI and older than the pellet sands of cycle C. The oldest-known loess covering this terrace is that of cycle F (Fig. 6). The CK3 terrace, whose surface is 40 to 50 meters above the river, is younger than subcycle J3 and older than the loess of subcycle F3. The oldest-recognized fluvial sediments of this terrace were deposited either during cycle H or I. CK3 is the youngest terrace in the vicinity of Brno bearing highly weathered braunlehms, including the markedly red soils of cycle F. The CK4 terrace lies 60 meters above the river. Reversely magnetized, water-reworked loess of cycle J with fluvial gastropodes covers the terrace gravels at both Cerveny Kopec and Stranska Skala. The age of this oldest terrace could not be bracketed because of the lack of suitable localities, but it is probable that downcutting from the CK5 to CK4 level occurred during cycle K.

Thus we recognize in the vicinity of Brno three terraces of Brunhes age. Each one of the three was deposited during glacial as well as interglacial climate and represents deposition of more than one glacial cycle. The oldest of the three Brunhes terraces is capped by a highly-weathered, clayey-red polygenetic soil of cycle F. The next older terrace CK4 is overlain by reversely magnetized floodloam derived from reworked loess and therefore dates from Matuyama time.

The Krems Schiesstatte (Krems Shooting Range)

The Krems Schiesstatte (Krems, symbol KR) is the exposure in the loess fill of an abandoned river meander elevated 60 meters above the Danube (Fig. 9). The site was described among others by Göttinger (1936), Fink (1955), and Brandtner (1956). The two best-developed soil groups were considered to represent the R/W interglacial (soils KR7-9) and the early Wurm Gottweiger interstadial (soil KR4). Demek and Kukla (1969) and Fink and Kukla (1977), showed that the main soil complex is embedded in reversely magnetized sediments of Matuyama age. The interglacial snails at the base of KR4 overlying the Brunhes/Matuyama reversal include Biharian Heli­cigona capeki and are closely related to the assemblage in the basal interglacial soil at Stranska Skala. Another Biharian interglacial snail assemblage is found in KR5. The soils KR7, KR9, and KR10 contain Late Villafranchian voles Mimomys plioaeanicus, Mimomys hungaricus, and Lagurus sp. (Fink, 1976).

The Krems soil complex consists of rubefied braunlehms, representing the most intensely weathered Pleistocene polygenetic soils known from central Europe. The Cca horizon, at the base of KR7a, is a hard, compact limestone crust penetrated by vertical rootcasts filled with red braunlehm plasma (Lehmstangen). Almost no loess, only pellet sand, is preserved from the end of the glacial cycle M. It is unclear whether the soil group KR7a-8 represents three glacial cycles as shown in the diagrams or only two. However, because of the high degree of weathering of the soils and because of the exceptional thickness of the basal carbonate horizon, the former alternative was considered the more probable.

The loess separating the soils KR9 and KR10 and the soils KR12 and KR13 seems to be, on the average, thicker than other early Pleistocene loess units in Krems.

A relatively thick, positively magnetized unit found under soil KR13 is interpreted as correlative with the top of the Olduvai magnetozone. A unit with anomalous polarity in the KR7 soil was interpreted as a result of normal fossil remagnetization of an originally reversed layer. It is understood that the latter process took place when the soil weathered during the Jaramillo normal event.

Krems is the only hitherto known site where the glacial cycles of Mid-Matuyama age are exposed in an apparently continuous sequence. At least 9 full glacial cycles were completed in the Middle and Upper Matuyama Epoch between the end of the Olduvai and the Brunhes/Matuyama boundary. The combined record of Cerveny Kopec and Krems therefore documents 17 full glacial cycles which occurred in central Europe in the last 1.7 m.y. During each of them the environment shifted from a temperate broadleaf forest to a highly continental loess tundra. As unrecognized gaps may exist in the Krems stratigraphic column, this number has to be considered a minimum.

Paleoclimatic Information Derived from the Loess Record in Central Europe

The main conclusions on European climates, derived from numerous loess sequences studied in detail (Demek and Kukla, 1969), can be summarized as follows:

1. The complexity of climate history on land is similar to that in the oceans. The number of full interglacials of Pleistocene age approaches twenty. Although the well subdivided early Pleistocene sequences are rare, there are no indications that the detailed climatic development of any glacial/interglacial cycle was less complicated than that of the last one. Thus, the total number of major Pleistocene stadial-interstadial cycles can be estimated to be on the order of a hundred. Each such cycle probably included several climatic oscillations.
Figure 9. Stratigraphy of the Krems sequence, Austria. KR1-16: local soil designations. Levels studied for gastropods marked with a snail-like symbol giving characteristic species after Loeck (unpublished). Symbols for environment same as in Figure 5. BL-braunlehm. Vertebrates after Fink (1976); K and U breaks: levels of deep erosion. Krems 010 to 0100 M.Z.: local designation of magnetohorizons. Further details in Fink and Kukla (1977).
significantly exceeding the range of variability observed in meteorological records of the past two or three centuries (Fig. 10).

2. The sequence of environmental changes recorded in central Europe during the last three completed glacial cycles $B$, $C$ and $D$ closely followed a uniform, repetitive pattern.

3. Environments of the last four interglacials of cycles $B$ to $E$ resemble that of the Holocene. Mixed deciduous forests were present in the highlands of central Europe, while temperate grasslands on top of chernozem soils stretched further east.

4. Two oldest soils of glacial cycle $C$ were formed under deciduous forests. By comparison, only a single basal soil in each of the cycles $B$ and $D$ corresponds to such conditions. Thus the interglacial of cycle $C$ was doubled. The timely correlative $O^{18}$ stage 7 of the deep-sea sediments shows the same character.

5. Basal polygenetic soil of cycle $F$, as well as soils of cycles $G$–$L$ with the exception of cycle $J$, are more strongly weathered than the younger soil groups and contain large carbonate concretions, partly filling rootcasts. This indicates longer and/or repetitive occurrence of forests at the sites in central Europe alternating with warm xerophytic steppes or savannas.

6. The sedimentary features and faunal assemblages point to the exceptionally mild glacial intervals of cycles $G$, $L$, and $M$. This correlates well with the poor expression of the $O^{18}$ cold peak of stage 14 and with the $O^{18}$ record below stage 23.

7. Intensive and widespread rearrangement and downcutting of the river network during cycles $F$ and $K$ lead to separation of distinct terrace levels. Because both episodes do not seem accompanied by any indications of an exceptionally cold climate, it is speculated that they may have been caused by a temporary intensification of crustal movements. Similar but less pronounced episodes occurred in cycles $C$ and $I$ (or $H$).

8. The Late-Villafranchian faunal elements were replaced by the typical biharian faunal elements in cycle $K$. These in turn gave way to a successive Young Pleistocene faunal wave during or before cycle $F$.

9. The Pleistocene climatic cycles of Matuyama age in central Europe had basically the same amplitude as those of the Brunhes Epoch. The environment repeatedly alternated between a continental cold loess steppe or semi-desert and a temperate interglacial forest. Mean duration of the cycles was close to 0.1 m.y.

### The Alpine Glacial Stages

The four classical glacial stages, Würm (W), Riss (R), Mindel (M), and Günz (G), and the three interglacials Riss-Würm (RW), Mindel-Riss (MR) and Günz-Mindel (GM), were named by Penck (in Penck and Brückner, 1909) after the four Bavarian tributaries of the Danube (Donau) and Isar. The system was later extended by adding two older glacial stages—Donau (Eberl, 1930) and Biber (Schaefer, 1953)—and two corresponding interglacials—Donau-Günz (DG) and Biber-Günz (BG). The type locality of all the stages is the Ilmtal, Lech Platte in the northern foothills of the Alps, south of Ulm, Augsburg, and Munich (Fig. 4).

The type units of the glacial stages are gravel terraces called Niederterrasse (Lower Terrace, NT) for Würm, Hochterrasse (High Terrace, HT) for Riss, Jüngere Deckenschotter (Younger Cover Gravel, JDS) for Mindel, Ältere Deckenschotter (Older Cover Gravel, ADS) for Günz, Donauschotter (Danube gravel) for Donau, and Höhenschotter (Height gravel) for Biber glacial. The Lower Terrace is connected with morphologically fresh-looking Young Moraines (Jüngermoränen) whereas the High Terrace is connected with poorly preserved Old Moraines (Ältemoränen). The surfaces of Mindel and Günz terraces, contrary to the younger two, are strongly weathered into the red-clayey zone called "Ferretto." While the terraces represent the glacial, the interglacials are represented by the erosional steps separating the terraces and interpreted as intervals of downcutting and removal of sediments. The vertical distance of Riss and Mindel terraces is in many areas especially great. Because the depth of the incision from one terrace to the next was considered to be a measure of time, it was concluded that the M/R was substantially longer than the R/W interglacial.

Although Penck clearly stated that each of the four glacials is documented by the corresponding "glacial series" which includes moraines and glacial outwash deposited during the outermost stands of piedmont glaciers in the type area, his stratigraphic system rests entirely on the four gravel terraces. Penck believed that their formation was fully contemporaneous with the glaciations (Penck and Brückner 1909). As the terraces are well-defined and mappable morphostratigraphic units, they proved ideal for regional extension of the system all over the Alps. Thus, in practice, Penck and Brückner and their numerous followers established and used the terraces as type units of Würm, Riss, Mindel, Günz, Donau, and Biber glaciations (see also discussion by Zeuner, 1946).

The four terraces of Penck and Brückner represent widespread morphostratigraphic correlation units which can be readily differentiated over much of the Alpine foreland. After several decades of intensive study and revisions, the value of Penck's Alpine stages as first-class morphostratigraphic correlation units remains intact.
Figure 10. Environmental changes around Brno and Krems as reconstructed from the loess record. Symbols are the same as in Figures 5 and 9. RL, crosshatched: warm savannah type environment favoring development of exceptionally red polygenetic soils. Symbols of snail assemblages explained in the legend. In the local faunal column, crosses mark single faunal occurrences, full dots first faunal occurrences in the loess sections. Breaks are levels of deep erosional incisions. Modified from Kukla (1977).
Under the influence of Milankovitch’s insolation chronology, Eberl (1930) described the so-called ‘‘Vollgliederung’’ or ‘‘full delineation’’ of the Alpine Pleistocene system. Within the original type area he recognized three substages of the Würm, two of the Riss, two of the Mindel, two of the Günz, and three of the Donau, and differentiated them by numerals. The substages are numbered in order of decreasing age. Eberl’s approach combined geomorphic mapping with lithostratigraphic observations. While some of his conclusions were later found to be based on miscorrelations, the finding on at least two generations of Riss gravels separated by a weathering interval of possibly interglacial rank was supported (Woldstedt, 1958). Also, the existence of two moraine generations in the Würm and two in the Mindel, each probably separated by a non-glacial interval of considerable length, were reasonably well demonstrated. What remains unclear, however, is the stratigraphic relation of the non-glacial interlayers within the terrace bodies to individual end moraines and terrace surfaces. Eberl’s substages were never successfully extended outside the type area.

Whereas the geomorphologic setting of the Alpine terraces was properly described and stratigraphically exploited, its climatic interpretation was incorrect. As we today know the gravels accumulated not only during glacials but also during interglacials. The erosional intervals which separate the terraces were, for the most part, glacial rather than interglacial events (Schaefer, 1953).

Present knowledge on the stratigraphy of the forealpine terraces in Bavaria, Switzerland, and lower Austria is synthesized in the composite diagram shown in Figure 11. The numbered features show:

1. Rolled Roman brick dredged from the submergel base of coarse gravels of the Niederterrasse in Vienna during recent engineering operations (Fink 1976).
3. Logs of oak (Quercus, cf. robur), C14 dated at 3165 ± 115 Y.B.P. and 3130 ± 65 Y.B.P., found in coarse gravel in Trubensee east of Krems (Piffl 1971).
4. Logs of pine and birch up to 8.5 meters long, C14 dated at 9660 ± 115, and 9185 ± 95 Y.B.P., in Neustift east of Krems (Piffl 1971). Logs of similar age dated to 9480 Y.B.P. and 9700 Y.B.P. in the gravels of Niederterrasse in Ulm and Linz (Graul, 1973).
5. The subhorizontal layer of parabraunerde on top of the lower terrace gravel in Murnau, overlain by a Würm moraine (Kaiser, 1963). (Improbable alternative explanation proposes that the soil plasm leaked through the moraine in Holocene.) Two generations of Würm gravels separated by till in the...

Figure 11. Schematic cross section showing classical Alpine Pleistocene stratigraphy in the Iller-Lech Platte type area in lower Austria and in the vicinity of Zurich. Gravel blank; soils, interglacial clays and silts black; loess stippled. Moraines marked M 1-2, R 1-2, W 1-2. Numbers 1-14 on top denote sites discussed in the text.

78
same area (Penck, 1922); interglacial peats correlate with the Eemian (Frenzel, 1973) within the low laying so-called Laufen gravel at Zeifen.

6. Three localities close to Munich with gastropods of deciduous forests in fine grained interlayers of the high terrace (Brunnacker and Brunnacker, 1962).

7. Parabraunerde and loss of glacial cycles $D$, $C$, and $B$, in part accompanied by interglacial snail faunas, overlying local terrace, correlate with the high Hochterrasse and merging with its floodloams in Senftenberg and Thallern near Krems.

8. The deep weathering horizon capping the thick accumulation of Pre-Riss gravels of Zink (1940) in northern Switzerland around Basel and Zurich, overlain by gravels locally labeled as Riss-1 (Altriss) and still younger gravels of Riss-2. In Riss-1, the glaciers presumably attained their maximum extent in this part of Switzerland. The Reidmatt forest bed from the Pre-Riss/Riss-1 interval and the Grunholz black clays with remains of temperate flora presumably corresponding to Riss-1/Riss-2 interval (Woldstedt, 1958).

9. The M/R erosional gully which at Zurich cuts 500 meters beneath the Mindel terrace and far beneath the present river alluvia filled by rapidly deposited "Rinnenschotter" (Zink, 1940).

10. The red-clayey soil Ferretto on top of the Mindel terrace at numerous locations throughout the Alps (Penck and Brückner, 1909); it is by an order of magnitude stronger than any younger soil known in the region.

11. At least two generations of Mindel moraines, also two levels of Mindel gravels, in the Iller-Lech Platte, described by Eberl (1930).


13. Two surfaces of the Günz terrace recognized by Eberl (1930) in the type area.

14. Lignite lenses in clays capping the Donau gravel at Uhlenberg, west of Augsburg, containing interglacial flora with *Pterocarya* and *Carya*. These latter elements are abundant in the Waalian interglacial but not in the following Cramer-type interglacials (Fälzer and Scheuerpfugl, 1970).

The authority of Penck was respected to such a degree that the interglacial layers within the terrace bodies were interpreted as local anomalies rather than an indication of a partly interglacial age of Alpine terraces at large. Because fossils within gravels are very rare and because only a few species of vertebrate fauna are specific for interglacials, some geologists still believe in the glacial origin of any coarse river gravel.

It clearly follows from Figure 11 that the gravels of the Niederterrasse, which by definition represent Würm, must have accumulated during Late Pleistocene as well as Holocene, in glacial as well as the postglacial and interglacial climates. The logical conclusion of our discussion, therefore, is that Würm, as originally defined, includes Late Pleistocene and Holocene, glacial and postglacial. In a similar way, the older glacial stages were also deposited during both glacial and interglacial epochs. Obviously, the climatic concept of classical Alpine glacial stages is in serious error.

A question could be raised as to whether the use of the terms "Würm," "Riss," "Mindel," and "Günz" should be restricted only to sediments deposited during the glacial phases and thus correlate with the corresponding moraines. This probably was the original climatostratigraphic concept of Penck. Unfortunately, there is no safe way to distinguish sterile interglacial from glacial gravels within one terrace body. Furthermore, it is too late for any substantial revision of the system since terraces were extensively used as type units of the four glaciations for several decades.

To avoid further confusion, the terms "Würm," "Riss," "Mindel," and "Günz" as well as "Donau" and "Biber" should only be used in connection with either the terraces or with the moraines in the Alps, and reference should be made in full to either "Würm terrace" or "Würm moraine." Different time stratigraphic and climatostratigraphic setting of moraines and terraces must be taken into account. The terrace sequence completely covers time, irrespective of glacial or interglacial, while the moraines and their related outwash gravels are correctly interpreted as glacial features but represent only a few millennia of maximum expansion of the piedmont glaciers.

**Correlation of the Loess Sequence with Classical Alpine Glacial Stages**

Four major terraces, *CK1, CK2, CK3*, and *CK4*, underlie sediments of the eight glacial cycles of the Brunhes epoch at Červený Kopec in Brno (Fig. 6). The oldest one is of Matuyama age. The upper two are overlain by strongly weathered brunlehmns. Four terraces—Niederterrasse, Hoehterrasse, Jungere Deckenschotter, and Alterer Deckenschotter—represent the four classical Alpine glacial stages—Würm, Riss, Mindel, and Günz—of Penck and Brückner (1909). The oldest one, Günz terrace in Linz, Austria, is of Matuyama age. The upper two terraces, namely the Jungere and Altere Deckenschotter, locally bear a strongly weathered soil Ferretto. Both Brno and Linz lie in a similar tectonic position at the border of the Bohemian Massif and the forealpine depression. Both belong to the Danube watershed. Therefore the broad correlation of three Brunhes terraces at Brno with the three Brunhes terraces of the Danube and of its Alpine tributaries is reasonably well justified. We may conclude that with high probability the Alpine Würm, as represented by its type unit Niederterrasse, correlates with *CK1* and thus covers the younger half of
cycle C, the whole of cycle B, and the elapsed section of cycle A. Using parallels between the loess system and the deep-sea record, we further conclude that Würm correlates in time with O^{18} oceanic stages 1-6, Riss with CK2, and thus with cycles F, E, D, and the older part of C or with oceanic O^{18} correlates 7-12. Mindel probably correlates with CK3 and thus with cycles F, G, H, and I. It is represented in the ocean by O^{18} stages 13-18. Günz correlates with K, J, ..., a part of cycle F and with O^{18} stages 19-22 (Fig. 15). The exact stratigraphic position of the breaks between individual terraces of the Alpine system may locally differ from the proposed scheme, for reasons explained in the discussion of the Brno area, but the evidence at hand strongly points to cycles C, F, H (or I) and K as episodes of accelerated crustal movements north of the Alps, correlative with the R/W, M/R, G/M, and D/G Alpine interglacials.

THE CLASSICAL NORTH EUROPEAN GLACIAL AND INTERGLACIAL STAGES

The classical glacial stages in the area formerly covered by the Fennoscandinavian continental ice sheet are named “Weichsel,” “Warthe,” “Saale,” and “Elster” (Table I). They were recognized from the end-moraine system, crossing Denmark, Netherlands, northern Germany, and Poland (Fig. 12), and are named after the rivers of this area. Moraines of the Weichsel and Warthe have a fresh hummocky constructional topography; moraines of the Saale are dissected and flattened; and the moraines of the Elster have lost their original morphology completely. The former extent of the Elster glacial advance was, for the most part, reconstructed from tills and from the distribution of erratics. As the type units of each of the four glacial stages are moraines, the resulting system is a morphostratigraphic one. The naming of the moraines is attributed to Keilhack (1926) who mapped them in north-central Germany. The Warthe moraine was originally grouped with the Weichsel, then regrouped with the Saale by Woldstedt (1954). Finally, it was singled out as a separate glacial stage by Picard (1964). It should be observed that the older moraines lie progressively further south. This was a principal condition of their preservation and recognition.

The classical interglacial stages of northern Europe are, in order of increasing age, the Eem, Holstein, and the Cromer. They are represented by the deposits of marine transgressions and by peat bogs whose pollen content documents the presence of temperate hardwood forests in northwestern Europe.

The stratigraphic position of the Eem transgression is established by the fact that its sediments overlie Saale and Warthe tills but are overridden by Weichsel (Fig. 13). In a similar way Holstein deposits overlie the Elster but are buried by Saale. The Eem interglacial is recognized and named after the marine clays containing shells of the mollusc Tapes aureus var. eemienstis accompanied by other molluscs of temperate lusitanian fauna (Madsen, 1928). Today a similar assemblage is found along the coast of Portugal in much warmer waters than those of the present North Sea.

The Holstein marine transgression is morphologically related to the Elster advance whose glaciofluvial sands it overlies (Fig. 12). The pollen sequences in the lake beds of Holstein age, frequently with a characteristic water fern Azolla filiculoides, point to the presence of forests dominated by conifers with low proportion of hardwood trees. Molluscs Pala­dina diluviana and Corbicula fluminalis are the abundant fossils of the Holstein river beds. Marine molluscs and foraminifers of Holstein epicontinental seas point to relatively chilly waters, similar to those of the present North Sea.

The Cromer Forest Bed, the type unit of the Cromer interglacial, is exposed in the cliffs of the North Sea in the vicinity of East and West Runton, England (Reid, 1882). Oscillating freshwater, brackish and marine layers, contain rich assemblages of Biharian vertebrates and pollen of mixed forests. The Cromer local fauna is of the Biharian type. It has numerous extinct elements and is well distinguishable from a younger faunal wave accompanying the post-Elster strata. Forests and vegetational history of type Cromer resemble the Postglacial (Turner, 1975). The Lowestoft till overlying the Cromer forest bed is believed to correlate with the Elster advance. In Germany there are several interglacial deposits containing biharian fauna, broadly correlative with Cromer. The annually banded lake deposit in Bilshausen records the change from the reversely magnetized late glacial lake beds of Matuyama age to normally magnetized full interglacial beds of Brunhes age (Fromm, unpublished; H. Muller, personal communication).

This is, in short, the basic framework of classical Pleisto­cene stratigraphy of the glaciated parts of northern Europe. The present knowledge on the stratigraphy of principal units in northwest Europe was summarized in Figure 13. The figure shows:

1. The boreholes made in recent years which revealed the existence of two successive transgressions with temperate assemblages of marine microfaunas formerly believed to represent Eem in North Germany (Wiegank, 1972). They are separated by deposits of glacial origin.
2. Holocene sediments of Baltic Sea transgressive over the Late Weichsel tills.
3-5. Fresh Weichsel moraines overlying the buried inter­glacial lake and riverine deposits in the vicinity of Berlin. The lower one with mollusc Pala­dina diluviana was correlated with Holstein.
7. Fresh terminal moraines of Warthe. Outside of Warthe on top of the terrace cut into Saale deposits.
the fossiliferous travertines of Ehringsdorf, next to Weimar. Though long held as representing the last interglacial, they were dated to over 200,000 years and correlate with the lower series of cycle C and with the O$_{18}$ stage 7 (Goddard, et al., in preparation).

8 & 10. Two tracks of dissected terminal moraines of Saale. The inner so-called Rehburg moraine track was possibly overridden by the main Saale.

9. Marine clays and peats overlying the Saale ground-moraine. The type Eemian.

11. Marine clays and peats of type Holstein overlying the Lauenburger Clay. Two interglacials in superposition with floral succession of Holstein type were recently described in the region. The older one corresponds to the type Holstein (Ducker, 1969).

12. Buried channels of Late Elster filled with fluvioglacial sands and occasional layer of till.


14. Biharian vertebrates in Voigstedt, Germany. Here the Elster till and pro-glacial varves cap a thick unit of loess, with sand and gravel at the base. Fossiliferous silts and sands with Biharian mammals *Trogontherium cuvieri*, *Diceros rhinus etruscus*, etc., underlie the gravel. These, in turn, are underlain by two gravel beds, separated by clay with the interglacial mollusc *Mellanopsis acicularis*. Layers of two interglacials are probably present at this site.


Several were buried until sheets differing in composition from the embedded rock debris were found in a number of...
boreholes and excavations. They enabled local subdivisions of Saale and Elster to be made into three substages each (Cepek, 1967). At least three separate interglacials in stratigraphic position of Cromer were described from the Netherlands (Zagwijn, 1975). Multiple interglacial horizons with Cromer-type fauna are also known from Germany.

In Mosbach in the Rhine Valley fossiliferous gravels, sands, and silts accumulated in the 10 km-wide depression which continuously subsided during the early and a part of middle Pleistocene. The basal gravels yielded young Villafranchian vertebrates with *Archidiskodon meridionalis*. The younger main fossiliferous layer overlying the reversely magnetized silts (Koč, et al., 1973) contains typical Biharian vertebrates such as *Canis lupus mosbachensis*, *Panthera gombaszoensis*, or *Ursus deningeri* (Bruning, 1972; Kahlke, 1975). The youngest deposits of the Mosbach basin are correlated with the Upper Middle Terrace of the Rhine. Afterwards the subsidence ceased and the basin was gradually uplifted (Wagner, 1930).

There is no doubt today that more than two interglacials took place between Elster and Weichsel and that numerous till sheets were deposited in Europe. But it still remains unclear what is the relation of the tills to the surface moraine tracks and which of them represents the first order advances as opposed to only local intersections of contemporaneous ice lobes.

One of the great discoveries of recent decades is the yearly laminated interglacial deposits. The duration of interglacial environment at such sites has been relatively accurately counted (review by Turner, 1975). The length of the Eemian interglacial in Bispingen, Germany was in such a way found to be 10,000 ± 1,000 years. By a similar method, the temperate deciduous forest of the Holstein interglacial lasted for 13,000 ± 1,000 years, and the so-called Ruhme interglacial of Cromer type in Bilshausen lasted 30 to 32,000 years (Müller, 1974a, 1974b, 1965). The latter, however, was interrupted approximately in the middle by a 400-year-long expansion of pine and birch. During this short episode the temperate species almost disappeared from the area. The Bilshausen deposit closely overlies the B/M boundary.

The varved deposits revealed how little time is actually represented by the type units of north-European interglacials. Out of the 700,000 years known to have elapsed since the end of the Matuyama epoch, the Postglacial together with Eem...
Figure 14. Buzzard Roost loess section in south central Nebraska, U.S.A. Location in Figure 1. Lithologic symbols same as in Figures 5 and 9. Fauna above 34m from Frankel (1956), below 34m depth section is sterile. Local marklines, not necessarily time-correlative with those in Europe, are recognized as boundaries between porous eolian loess and decalcified soil (or immediately underlying colluvial silt). Encircled plus sign: paleomagnetic samples with normal polarity. Further details in Schultz and Stout (1961, and other publications).
by exceptionally deep erosion which was followed by deposition of channel gravels of the Rhine and Elbe. With high probability, this erosional episode correlates with Alpine M/R. The erosion has been explained as a result of intensified crustal movements north of the Alps (Graham, 1933; Genieser, 1962; Quitzow, 1959). It may correlate with the Ortenau orogenetic phase as recognized by Wittmann (1939) in the upper Rhine basin.

7. Cromer: Correlation of the Cromer forest bed with the loess sequence and with the $Q^{18}$ stages is difficult. Paleomagnetic study of Montfrans (Zagwijn, et al., 1971) and of Kukla (unpublished) revealed only normal polarity, but the samples are weakly magnetized and the remanence may be entirely due to secondary overprint. Biharian vertebrates indicate that type Cromer is close in age to the Brunhes/Matuyama paleomagnetic boundary, as are the localities Stranska Skala, Bilshausen and Mosbach. However, Biharian faunal elements are also reported from deposits younger than type Elster (Heller and Brunnacker, 1966) and from an interglacial considerably older than the Brunhes/Matuyama boundary (Fink and Kukla, 1977; Ložek, 1972). In agreement with these observations the alternative position of type Cromer is bracketed by cycles F and J (Fig. 14).

A glaciation older than Cromer is claimed from Poland (Rozycki, 1969; Mojski and Ruhle, 1965). It is called the "Podlasice" or "Elbe glaciation" and documented by tills and varved lake deposits encountered in the subsurface. It is difficult to prove convincingly that the tills are older than the type Elster; therefore, their correlation with either $Q^{18}$ stage 16 or possibly 20 remains open.

Comments to Correlations in Northern Europe

The north-European Pleistocene subdivision is based on a sound climatostratigraphic concept. The principal units are the interglacials. Their climate related lower and upper boundaries are clearly fixed in continuous pollen-bearing sequences by the appearance and disappearance levels of abundant pollen of temperate trees (Turner and West, 1968; Kukla, et al., 1972; Turner, 1975; Zagwijn, 1975). Type area of the interglacials is the north-western Europe (Fairbridge, 1972). The north-European interglacials are the only widely recognized Pleistocene land-based stratigraphic units whose boundaries occur in continuous sequences and thus comply with the principal requirement for a definition of formal chronostratigraphic unit (Hedberg, 1972). Since by convention the Pleistocene is divided into glacial and interglacial, all strata underlying and overlying interglacials are glacial. Hence, type sections of the interglacials contain all the boundaries of the classical north-European Pleistocene units.

Unfortunately, glacial units are represented and named after the moraine tracks which, for the most part, cannot be related to type interglacial sites. Unknown gaps exist in the physical evidence left by glaciers. In practice it is impossible to prove the continuity of a glacial environment between two consecutive interglacial deposits. The repetitive nature of glacial and interglacial deposits, the common lack of distinguishable fossils, and the common truncations of Pleistocene strata are further deficiencies of the north-European subdivision.

In such a situation Pleistocene stratigraphers working in Europe commonly apply a stratigraphic approach that can be labeled a "count from top" (CFT) method. In essence each unit is assigned a minimum possible age by comparing the studied section with the accepted climatostratigraphic mode and assuming an uninterrupted deposition.

The CFT method has produced a remarkable number of miscorrelations. A single till, for example, was frequently assigned to two different glaciations depending on how complete the overlying section was. Similar miscorrelations occurred with interglacials as well. Frenzel (1973) argues that for botanical reasons several interglacial deposits formerly believed to represent a single warm interval could not have actually coexisted.

After many years of widespread miscorrelations, the classical north-European terminology cannot be saved. The sooner it is abandoned in interregional correlations the better.

RELATION OF EUROPEAN AND NORTH AMERICAN CLASSICAL GLACIAL STAGES

The limited scope of the present manuscript does not permit an attempt to correlate, with the deep-sea sediments, the four classical American glacial stages, i.e. Wisconsin, Illinoian, Kansan and Nebraskan, and the three interglacial stages Sangamon, Yarmouth, and Afton (Table 1). As the Pleistocene gross climatic changes were globally synchronous and as the four-fold subdivision of European Pleistocene was shown to be in conceptual error, the obvious conclusion is that the four-fold subdivision of American Pleistocene is also incorrect.

The American glacial stages are, according to their original definitions (Geikie, 1894; Chamberlin, 1895; Shumak, 1909), represented by moraines and tills in much the same way as the north-European glacial stages. Although not specified by the authors, the American glacial stages were understood as times when continental ice was present in the type area, which is the Midwest. For the same reasons given in the discussion of north-European glacial stages, it is highly improbable that the continental ice sheets remained in the Midwest for continuously longer periods than approximately 10,000 years. It is probable that, as in Europe, the end moraines of
Wisconsin and Illinoian, and the outermost tills of Kansan and Nebraskan, were formed close to the end of a glacial cycle during the cold peaks which immediately preceded a termination. It is furthermore improbable that a moraine or till preserved in the Midwest would correspond to the exceptionally mild O18 stage.

There are morphologic parallels between the Wisconsin and Illinoian drifts, and the Weichsel, Warthe, and Saale moraines. The Wisconsin drifts and the Buffalo Hart moraine (Leverett, 1899) of late Illinoian age display a fresh and hummocky surface (William and Frye, 1970). The Weichsel and Warthe in Europe have similar morphology. Both groups were originally viewed as products of a single glaciation, namely Weichsel and Wisconsin respectively. Buffalo Hart moraine (Leverett, 1899) is separated from Wisconsin by a decalcified interglacial weathering horizon (Johnson, 1964). Similarly, Warthe is separated from Weichsel by the Eemian interglacial deposits in Schleswig-Holstein. Early- and mid-hummocky surface (William and Frye, 1970). The Weichsel-Leverett, and Illinoian drifts, and the Weichsel, Warthe, and Saale moraines show weathered and dissected surfaces similar to the type Saale and Saale-Rehburg moraines in Europe.

A major rearrangement of the hydrographic net occurred between Kansan and Illinoian and between Saale and Elster.

The type units and the underlying concept of classical American interglacials differ substantially from the European ones. Type units of Sangamon, Yarmouth (Leverett, 1898) and Afton (Chamberlin, 1895) are sediments and soils whose only climatic implication is the ice-free surface at the type localities. It is probable that much of the Midwest was ice-free during the formation of the soils, accretion gleys, and the sandy fills of buried channels originally representing the classical American interglacials. However there is nothing to indicate that the Sangamon, Yarmouth, and Afton deposits were limited to peak warm climates correlative with European interglacials typically marked by the presence of deciduous forests in northwest Europe. Obviously the classical American interglacials, as originally defined, represent much longer intervals of time than any of the European ones, and, therefore, in terms of the European climatostratigraphic concept, include both the glacial and the interglacial climates.

Would an approach, similar to the one used in Europe, be applicable in correlation of the American glacial stages with the deep-sea stratigraphy, using loess, terraces, and lake beds outside the formerly glaciated areas as a link?

Differences between the two continents partially disfavor such an approach. There are fewer artificial exposures in loess and fewer, less-accurate studies of terraces made in critical areas. On the other hand, the widespread presence of radiometrically dated mid- and early-Pleistocene Pearlette ashes compensates for the deficiencies.

We believe that the detailed study of loess sequences, especially those in Nebraska, is a worthwhile objective which should be further pursued. A large amount of data is already available on loess sequences in the North Platte vicinity. Figure 14 shows the recently updated stratigraphic column of the Buzzard Roost section, with six major polygenetic soils separated by loess, and covering the interval of the last 0.6 m.y. (Schultz and Stout, 1961; Frankel, 1956). The Pearlette “O” ash outcropping at the bottom of the section is radiometrically dated to about 0.6 m.y. (Boellstorff and Te Punga, 1977; Naeser, et al., 1971) and is known to be younger than the Kansan tills. The Buzzard’s Roost section therefore corresponds in time to Illinoian, Yarmouth, and Wisconsin. The strongly developed soils, weathered to a substantially higher degree than the local climax Holocene soil, are more numerous than the classical paleoclimatic model predicts. The number matches, perhaps by coincidence, that of the Pleistocene terminations of the last 0.6 m.y.

Obviously the prospect of west Nebraskan loess sections linking the glacial stratigraphy in the Midwest with the deep-sea record is promising. More effort should be spent in research in this area.

**FINAL REMARKS**

Our present results in correlation of deep-sea sediments with the land-based Pleistocene deposits of Europe is summarized in Figure 15. The diagram covers the last 0.9 m.y., about half of the Pleistocene. The early Pleistocene sequences older than approximately 1 m.y. were not included because the O18 stratigraphy of this interval is not yet worked out in sufficient detail. Tentative correlations of the early Pleistocene older than 1 m.y. in Europe were published by Zagwijn (1975) and Menke (1975).

Our correlation, still quite fragmentary and inaccurate, demonstrates that the paleoclimatic models of European Pleistocene are in serious error. Because the paleoclimatic reconstruction was the underlying concept of both the Alpine and the north-European stratigraphic systems, these cannot be correct either.

The mistaken simplistic subdivision of the Middle and Late Pleistocene into three classical interglacials and four glacial is largely the result of a climatic misinterpretation of Alpine terraces, of the repetitive nature of incomplete physical evidence in the glaciated areas of northern Europe, and of common persistent violations of basic stratigraphic principles by Pleistocene geologists. Stratigraphic terms were indiscriminately used outside the type areas with meanings different than those originally intended. Time content of the chronostratigraphic units was commonly extended far beyond the boundaries actually represented in the type deposits. Due to the repetitive nature of Pleistocene sediments, this practice...
leads to wide overlaps of the chronozones composing the system.

After decades of misinterpreted usage of the Alpine and the north-European terminology, it is doubtful whether either can be saved. Few stratigraphers would like to use a system in which the units overlap in time or in which inter-glacials and glacials were labeled by one name. The sooner the classical terminology is abandoned in interregional correlations, the better. Future global subdivision of the Quaternary must be based on continuous sequences such as those in the oceans or lakes.

REFERENCES


Goddard, J., W. S. Broecker and G. J. Kukla. (In preparation.)


Zárubka, Q. 1942. Längsprofil durch die Moldauterrassen zwischen Kamik und Weltrus, Mitteilungen tschechoslovakischer Forscher.
