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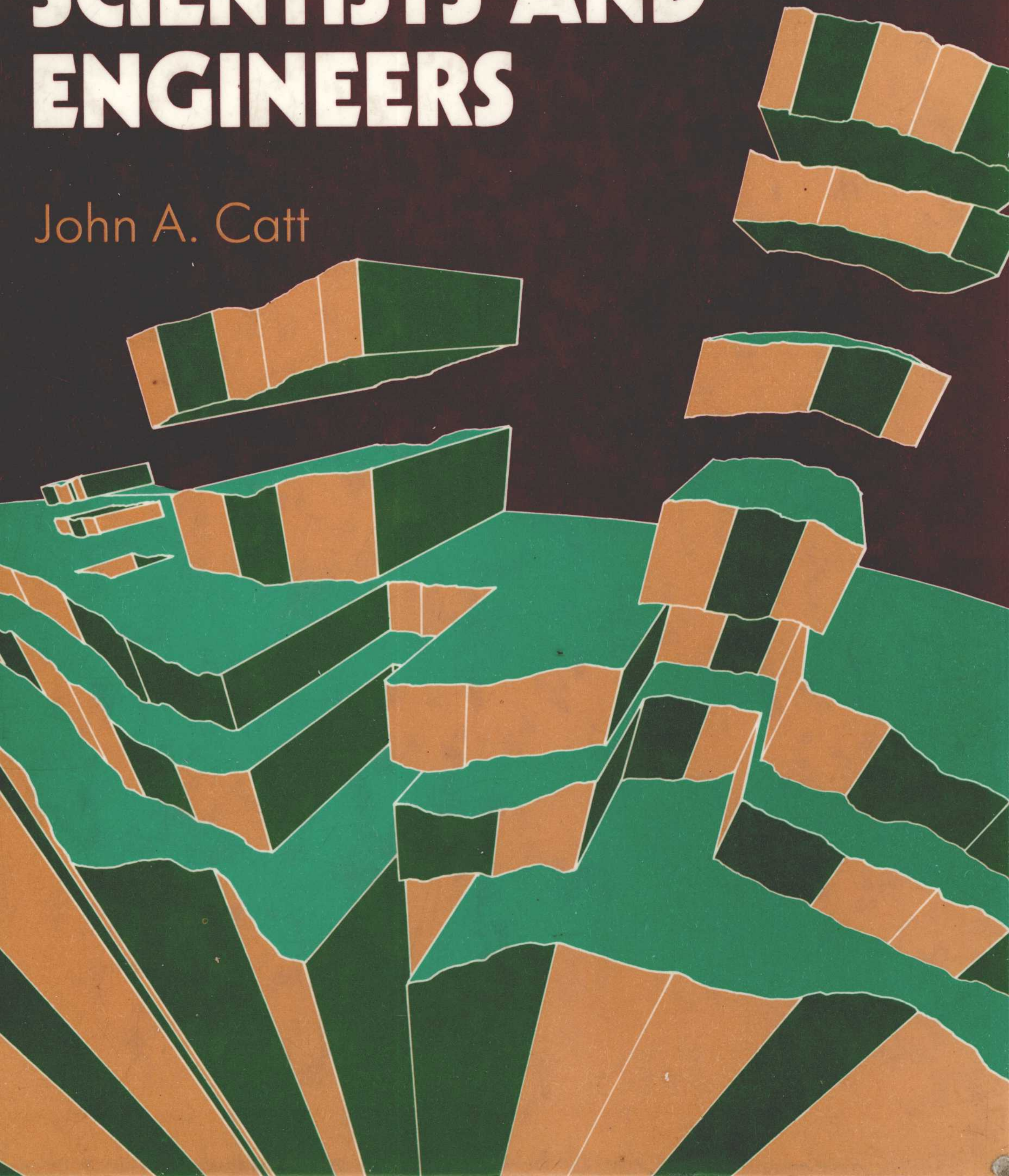
QUATERNARY GEOLOGY FOR SCIENTISTS AND ENGINEERS

John A. Catt



QUATERNARY GEOLOGY FOR SCIENTISTS AND ENGINEERS

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Preface

The study of the Quaternary period has expanded over the last twenty years from an insignificant part of geology (the 'Ice Age') to an important multidisciplinary activity. It is now an indispensable part of geomorphology, climatology, archaeology, soil science, plant and animal ecology, oceanography and mineral exploration. In return these and other subjects, such as astronomy, have had significant impacts upon our understanding of events during the last few million years, especially in clarifying the rapid changes of climate, sea level, soil and vegetation characteristics, and the associated animal and human migrations.

In recent years there has also been an increasing awareness of the economic significance of Quaternary studies. A major focus is now the prediction of future climatic and climate-related environmental changes. This has demonstrated very clearly the value of the multidisciplinary approach to Quaternary studies, because changes in the earth's orbit and processes operating in the atmosphere, oceans, glaciers and biosphere (including soils and human activities) all seem to be involved in the working of a very complex natural system determining climate.

Because of its multidisciplinary nature, Quaternary science is hardly ever adequately taught. For example, in Britain there are at present only two MSc/MPhil courses in Quaternary studies, one taught at Cambridge University and the other run jointly by City of London Polytechnic and North-east London Polytechnic, and only one university sub-department (part of the Botany School at Cambridge) conducts multidisciplinary research into Quaternary history. Restricted aspects of the Quaternary are included in many undergraduate courses in archaeology, physical geography, botany and soil science, but the subject is rarely accorded more than a few lectures in geology courses. From an educational viewpoint this is pity, because the Quaternary is useful for relating geological principles to other sciences. In terms of practical training for a geologist it is a disaster, because almost all practising geologists soon encounter Quaternary deposits in the field, and then realize that they are often much more variable in lithology and thickness than pre-Quaternary deposits. Failure to recognize Quaternary features can lead, for example, to misunderstanding of surface outcrops or misinterpretations of borehole information.

The purpose of this book is to explain the effects of Quaternary processes of erosion, deposition and soil development, so that practising geologists can recognize and interpret them correctly. Methods of classifying, correlating, mapping and dating Quaternary deposits are described, and the useful interrelations with other disciplines involved in Quaternary studies are explored. The wide range of analytical laboratory techniques applicable to Quaternary deposits cannot be described in detail, but their uses and limitations are discussed so that the field geologist can decide when it is worth calling upon the services of an expert analyst.

The book was written at the suggestion of colleagues in the Institution of Geologists, the organization representing professional geologists in Britain. It is intended primarily for this readership, but will I hope be read and used by practising scientists and engineers from a much wider range of backgrounds, anyone in fact who feels that a knowledge of the immediate geological past with its climatic vicissitudes might help resolve present or future problems.

I wish to thank Jeremy Joseph for encouraging me in the preparation of the book, Mrs Patricia Ashcroft and Mrs Joyce Munden for drawing many of the figures and Miss Jeanette Gooding for typing the manuscript. Among the many publishers and authors who have readily given permission for reproduction of their figures, I thank especially Professor Hans Jenny, who kindly allowed me to use many graphs from his book *Factors of Soil Formation* (McGraw-Hill, 1941), namely Figs 3.12 to 3.20.

Harpenden John A. Catt
February 1988

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Nature of the Quaternary period

1.1 INTRODUCTION

For many geologists the Quaternary is the most recent part of geological time, when glaciers deposited chaotically mixed deposits in mid-latitude regions which now have temperate climates. Though broadly true, this is a considerable over-simplification, because in these regions the climate fluctuated between cold and temperate many times, with the result that some areas were glaciated repeatedly.

By both deposition and erosion, glaciations greatly modified land areas and many shallow shelf seas. Also beyond the ice margins land areas were much modified by periglacial processes of aeolian deposition, slope erosion and frost disturbance.

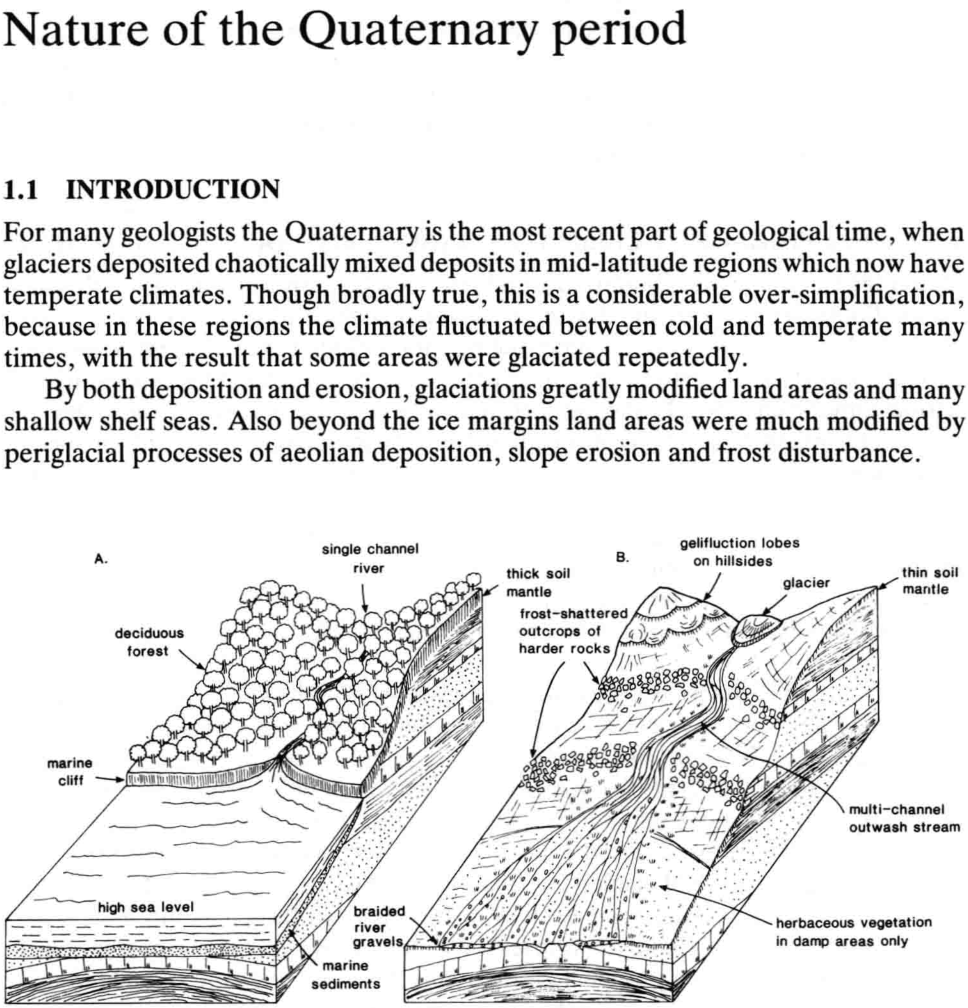

Fig. 1.1 — Typical warm (A) and cold (B) stage landscapes of mid-latitude regions during the Quaternary.

During the cold periods the proportion of land to sea was increased, as the incorporation of large amounts of water into glaciers lowered the sea-level worldwide. In contrast, the intervening warm periods or interglacials were times of high sea level, decreased land areas and greatly diminished deposition and erosion (Fig. 1.1).

Because the interglacial land surfaces were stable, usually under a forest cover, soils developed beneath them, often to depths of several metres. The physiography of the present land surface, the soils beneath it, and modern natural floral and faunal assemblages were all determined by events and processes in later parts of the Quaternary. So, although the climatic fluctuations and their various effects are usually grouped together as "Quaternary geology", this discipline is distinctly multifaceted, and includes aspects of meteorology, zoology, botany, pedology and geomorphology. It also embraces anthropology and archaeology, because the appearance of man as a toolmaker was a Quaternary event in most parts of the world, and stages in his subsequent development are useful to some extent for dating purposes. In addition, applied aspects of Quaternary studies are important in civil engineering, mineral exploration and agriculture.

1.2 THE EVIDENCE OF CLIMATIC CHANGE FROM OCEANIC DEPOSITS

Croll (1864) was the first Quaternary geologist to suggest that sediments on the deep ocean floors would provide the most complete palaeontological record of past climatic changes. However, this potential was not realized until sediment cores could be retrieved with the piston corer, and methods were developed for evaluating and dating climatic changes. In the first oceanic cores to be examined, climatic changes were determined from the relative abundance of individual foraminiferal species indicating warm or cold surface water; the layers containing them were dated by the radiocarbon method (see 5.2), and by extrapolation assuming constant sedimentation rates of 1–3 mm per century for horizons beyond the range of this dating method. Later, multifactorial methods of estimating water temperature from assemblages of foraminifera (Imbrie and Kipp 1971) and other microfossil groups were developed, and some older horizons were dated by the palaeomagnetic method (see 5.10).

The method of determining palaeotemperatures from $^{18}O/^{16}O$ ratios in foraminifera (Emiliani 1955) gave similar results to the multifactorial methods, but usually indicated larger temperature changes; for example, foraminiferal assemblages indicated a fall of 2°C in the temperature of Caribbean surface waters at the beginning of each cold stage, but the isotopic measurements suggested a 6°C drop. Shackleton (1967) showed that the difference results from the concentration of ^{16}O relative to ^{18}O in the ice of glaciers, so that most of the isotopic variation is caused by differences in the total volume of glaciers on the earth's surface, and only a small part results from the local water temperature component. Originally planktonic foraminifera were used for oxygen isotope measurements, because they were thought to show the effects of both these components. However, their isotope ratios are also affected by differences in surface salinity and other factors. More recently benthic species have been used instead, because they avoid these problems, and were thought to provide a purer record of changes in global ice volume, as the deep ocean should be less affected by temperature changes than the surface waters. However, Chappell and Shackleton (1986) showed that even the deep waters of the Pacific Ocean varied by about 1.5°C during the later Quaternary.

During cold periods the glaciers were enlarged quite slowly, but they melted and decreased in size more rapidly at the beginning of warm periods, so the curves for change in the oxygen isotope ratio with time have a typical saw-tooth shape. The alternating cold and warm stages are conventionally given arabic numerals working backwards in time from the present (stage 1), and the steeper parts of the saw-tooth, known as 'terminations', are identified by capital roman numerals, again working backwards in time from Termination I at the Pleistocene/Holocene boundary (Broecker and Van Donk 1970).

Emiliani (1955, 1966) originally recognized 16 oxygen isotope stages in sediment cores from the Caribbean Sea and Atlantic Ocean. Shackleton and Opdyke (1973) analysed another core (V28-238) from the western equatorial Pacific, and recognized 22 stages over the last 800 000 years, the first 16 of which were similar to those of Emiliani. A stratigraphically longer core (V28-239), also from the Pacific, extended the succession continuously back to 2.1 million years ago (Shackleton and Opdyke 1976); this showed that over the last 1.5 million years there have been at least 17 major cold periods separated by warmer episodes (Fig. 1.2). Similar complex successions have been established in other cores from the Atlantic Ocean (e.g. V16-205, Fig. 1.2) and Indian Ocean, so there is no doubt that the numerous changes recorded were worldwide in effect. Cores covering even longer periods of time show that the climatic fluctuations extended well back into the Tertiary. Large glaciers first affected oxygen isotope ratios in the north Atlantic and Pacific about 3.2 million years ago (Shackleton and Opdyke 1977), though it is thought that small mountain glaciers began forming in the northern hemisphere in the late Miocene (10 million years ago). The Antarctic ice cap has also existed for at least as long as this, and even may have begun forming in the early Oligocene about 38 million years ago (Mercer 1983).

As well as the micropalaeontological and oxygen isotope record of Quaternary climatic change, it is also possible to use the calcium carbonate content of deep ocean sediments as a palaeoclimatic indicator. This is because during cold stages lower sea surface temperatures depressed biological productivity of calcareous plankton, and ice-rafted clastic material diluted any carbonate precipitated from the water. Analyses of several Atlantic cores have shown that the three methods give approximately similar results. A sudden strong decrease in the carbonate content of some north Atlantic cores, such as 552A (Shackleton *et al.* 1984), in the late Pliocene about 2.4 million years ago suggests this was a time of increased ice rafting of clastic sediment, and therefore of increased continental glaciation in N. America and Europe.

1.3 CAUSE OF THE CLIMATIC CHANGES

Many different theories have been put forward to explain why the Quaternary was generally much colder than most earlier periods of geological time and why the climate fluctuated from cold to warm in many parts of the world. The earlier of these were summarized by Charlesworth (1959, p. 1532), but most are not worth repeating because the evidence from deep sea cores has recently shown that one particular theory (the astronomical theory) can account for most of the climatic change inferred from oceanic successions. In the nineteenth century, pioneer workers such as Croll

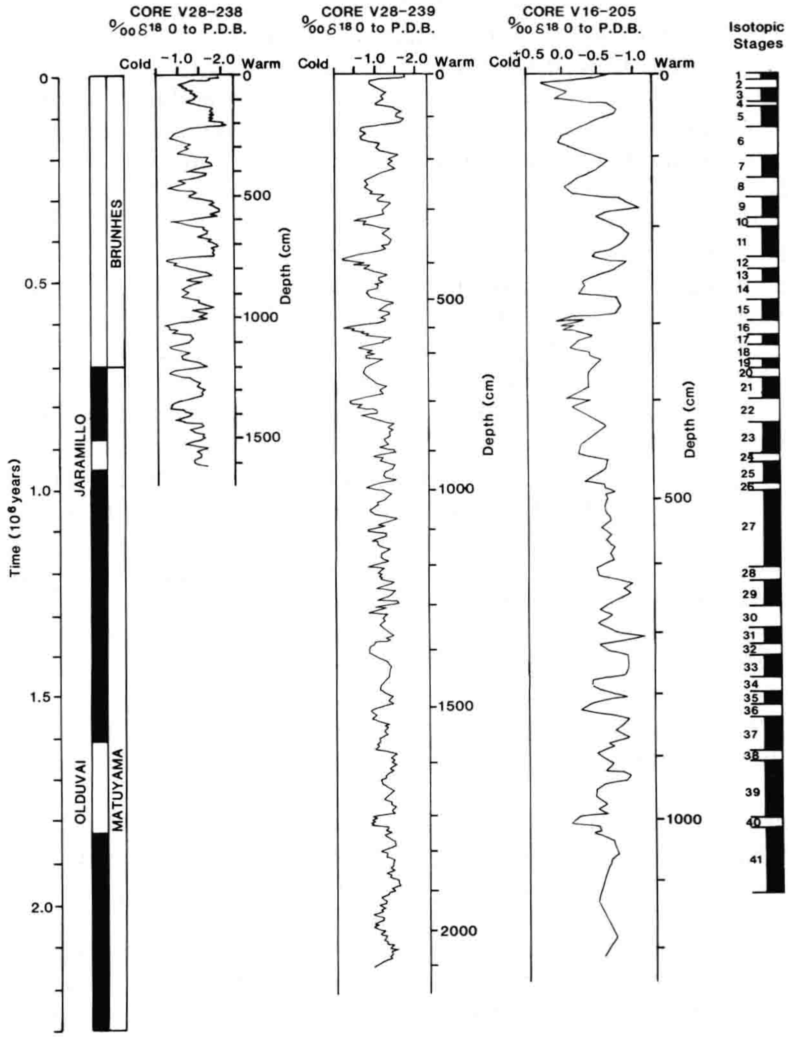

Fig. 1.2 — Oxygen isotope curves for oceanic cores covering long periods of Quaternary time and drawn to a common time scale (from Shackleton and Opdyke 1973, 1976 and Van Donk 1976). Originally published in part by Geological Society of America.

(1864, 1867) suggested that various perturbations of the earth's orbit around the sun affect the amount of solar radiation it receives and thus influence its climate. These insolation changes are related to cycles with periods of approximately 19 000, 23 000, 41 000 and 100 000 years, resulting from changes in the longitude of perihelion (precession of the equinoxes), the earth's obliquity (tilt of the axis of rotation relative to the plane of the orbit) and the eccentricity of the orbit (Lockwood 1980). Later Milankovitch (1920, 1930) calculated radiation curves for various latitudes, and although his results suggested dates for Quaternary ice ages very similar to those estimated previously for alpine areas by Penck and Brückner (1909), the theory was soon abandoned by most Quaternary geologists.

However, improved dating of the oxygen isotope changes in foraminiferal tests from deep ocean cores allowed Hays *et al.* (1976) to match cyclic changes in the isotope ratio with insolation changes at 65°N attributable to three of the four orbital cycles over the past 468 000 years, using frequency or spectral analysis (Fig. 1.3). This

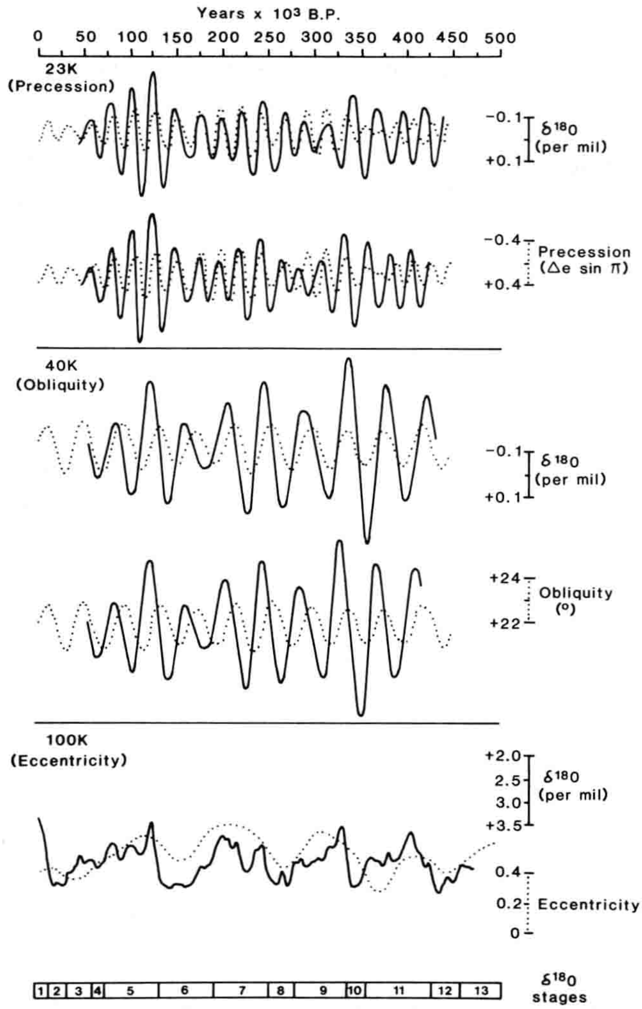

Fig. 1.3 — Variations in orbital data (precession, obliquity and eccentricity) for the last 500 000 years (dotted lines, from Vernekar 1972) compared with frequency components of climate derived from $\delta^{18}O$ variations (from Hays *et al.* 1976). The curves for $\sigma^{18}O$ for precession and obliquity are frequency components extracted by digital band-pass filters; that for eccentricity is the original unfiltered curve. The two sets of curves for precession and obliquity are for alternative time scales based on different interpolations between dated horizons in selected sediment cores.

led to a revival of the astronomical theory for climatic change, though it seems unlikely that there is a direct relationship between orbital cycles and climatic change because the maximum difference in total insolation over the last million years has been <0.6%. Imbrie *et al.* (1984) reported further evidence for a close relationship between orbital cycles and isotopic changes which enabled them to present a revised chronology for isotopic stage boundaries in core V28-238 over the past 780 000 years. Their dates are given in Table 1.1. Spectral analysis of the oxygen isotope ratios and

Table 1.1 — Revised dating of oxygen isotope stage boundaries in core V28-238 (from Imbrie *et al.* 1984)

Oxygen isotope stage boundary in V28-238	Revised dating (years B.P. $\times 10^3$)
1/2	12
2/3	24
3/4	59
4/5	71
5/6	128
6/7	186
7/8	245
8/9	303
9/10	339
10/11	362
11/12	423
12/13	478
13/14	524
14/15	565
15/16	620
16/17	659
17/18	689
18/19	726
19/20	736
20/21	763
21/22	790

carbonate content in dated Atlantic cores has shown that the climate of approximately the last 600 000 years has been dominated by the 100 000-year cycle related to orbital eccentricity. However, before about 600 000 years ago the 41 000-year tilt cycle dominated the climatic fluctuations. The change at approximately 600 000 years ago also led to stronger glaciations, which is puzzling because the 100 000-year cycle has an even weaker effect on insolation than the 41 000-year cycle. The increased glaciation may therefore have been related to rapid uplift of mountain ranges in Asia and western America at this time; the elevated surfaces would have extended the