Climate change from the perspective of physics and geology

<u>Part 6</u>

Dr.-Ing. Alexander Koewius and Prof. Dr. Christopher J. Rhodes.

5. Paleo-Climatologic Findings and the Insights to be derived from them; or: What the last 2 Ice-Age Cycles of Earth's History can tell us

5.1 Introduction: a brief overview of earth's history

If you allow yourself a deeper look into the approximately 4,6 billion year history of the earth – the issue (unfortunately) does by no means belong to the standard curricula - , many profound impressions may strike you, which also impact on areas beyond paleo-climate change per se; a change which appears quite astounding as viewed from a contemporary perspective. The tables 1 and 2 permit us an initial and rudimentary overview:

Table 1: Brief overview of earth's history from the beginning

Geologic Eras (**Eonothems**) - [<u>duration</u> in 10^9 year units], - <u>from start to end</u> (numbers indicate temporal distance from present in 10^9 year units)	Biosphere or stage of the **evolution** of life	Earth's system and **Paleo-climate**
Hadean [0,6] 4,6 bis 4,0	No living beings	Formation of the planet as a glowing sphere; formation of the moon; Numerous and heavy impacts of asteroids; essentially no stable Earth's crust yet; early atmosphere of igneous origin, consisting of H_2O-vapour, CO_2, N_2,... . *<u>No</u>* O_2!
Archean [1,5] 4,0 bis 2,5	Appearance of early forms of organic life in the Oceans; **~3,5**: formation of structurally primitive, heterotrophic protozoa without cell nucleus (= **Prokaryotes**); among these later on, too, O_2-producing Cyanobacteria	Appearance of solid crust; formation of the oceans; still an O_2-free atmosphere showing great amounts of N_2 and CO_2 (before the formation of the oceans also large amounts of H_2O-vapour)
Proterozoic [ca. 2,0] 2,5 bis 0,542 (or ~ 0,6 after other indications)	Increasing appearance of protozoa with complex cellular structures (nucleus, organelles, cell membrane), i.e. similar to the modern cell (= so-called **eukaryotes**); On the basis of Eukaryotes from **~ 0,7** on: first appearance of multi-cellular life (= i.e. rather small animals <u>without</u> hard components like a shell or a skeleton); <u>no life on land yet</u>	**~ 2,5**: beginning of the O_2-enrichment of the atmosphere; great climate changes, presumably having led to the glaciation (ca. between **0,85** and **0,63**) of nearly the whole surface of the globe; high CO_2 -content (several 1000 ppm)
Phanerozoic (means something like: „<u>Eon in which</u> <u>life became apparent</u>" – in face of the innumerable macroscopic fossils out of this eon) [0,54 or 0,6] 0,542 (or0,6) until **0** (i.e. until present)	At the beginning: „Cambrean Explosion" of the multitude of – especially greater – life forms (i.e. animals, now among them also those <u>with</u> hard components; *but also* plants); **~ 0,5**: the first fish (in the Cambrian); **~0,43**: <u>plants conquer the land</u> (in the Silurian); **~ 0,4**: <u>animals enter the land</u>; first insects, first amphibians (in the Devonian); **~ 0,3**: first reptiles (in the Carboniferous); **~ 0,22** (in the Triassic): the first crocodiles and mammals; start of the Dinosaur era (which ends up in **0,065** by a mass extinction) after **0,065** (in the Cenozoic): Rise of the mammals; after **~ 0,01**: Appearance of hominids; later on then (during the Quaternary): <u>homo sapiens</u>	At the beginning *a-cryogenic phase*; high atmospheric ***CO_2-content*** (several 1000 ppm), which later (i.e. till **~0,34** in the Carboniferous) went down to ~ 500 ppm due to an intense propagation of the land flora (associated with an O_2-rise to over 30 % at times), and due to an increasing weathering; hence in **0,33** till **0,27**: *cryogenic phase*; afterwards: „recovering" of the CO_2-content and start of *the last a-cryogenic phase*, which lasted till **~ 0,03**; afterwards (due to a decreasing CO_2-content): *youngest cryogenic phase*; *formation (and decay)* of *„super-continents*" like Gondwana and Pangäa; during the Phanerozoic several sudden *mass extinctions* , presumably due to volcanism, big meteors, ...

Table 2: Brief overview of the Cenozoic

Erathem:	System:	Series:	≈ Duration (in 10^6 years) 0 means Present "	paleo-geological and -climatologic events in the Cenozoic:
Cenozoic	Quater-nary	Holocene	0,0117 – 0	= the present interglacial
		Pleistocene	2,588 – 0,0117	Appearance of ice age cycles on the Northern hemisphere
	Neogene	Pliocene	5,332 – 2,588	continuity of the cryogenic period
		Miocene	23,03 – 5,332	
	Paleogene	Oligocene	33,9 – 23,03	~ **30**: start of the Antarctic glaciation, i.e. of the last cryogenic period
		Eocene	55,8 – 33,9	from ~ **40** on: decrease of CO_2-content of ~500 (since ~ **65**) to ~300 ppm (since ~ **25**); ~ **65**: the end of the dinosaurs (generally: the last mass extinction)
		Paleocene	65,5 – 55,8	

Table 2: The **Cenozoic**, which comprises ca. 65 million years, represents one of the 3 main subdivisions (= ‚Erathems') of the Phanerozoic.

Annotation: Formerly the Neogene and the Paleogene (= ‚systems') with their corresponding sections (= ‚series') had been subsumed under the heading „Tertiary".

In contrast to table 1 the most recent time interval is now mentioned first. Absolute numbers stand for „time intervals/points of time" in the unit „millions of years", unlike in table 1, where we chose the unit „billions of years" (equally: "Ga" = Giga-Annus) for the absolute numbers.

Definition of some terms, which appear in the tabels 1 and 2:

– *heterotrophic*=feeding on organic matter. Bacteria in the water were also feeding on polyatomic chemical compounds (at least in the early days of the earth). Heterotrophic are all animals; plants to the contrary are usually autotrophic, i.e. not dependent on the ‚consumption' of other organisms.

– *a-cryogenic* periods = time intervals (in earth's history), which did *not* know *any* areas on earth being covered with ice and snow in appreciable quantities *all over the year*, be it on the land or – as an ice sheet – on the water surface. These periods are those most prevailing in earth's history. The opposite is: 'cryogenic' periods = Ice Ages. The adjective ‚cryogenic' for a geological period however is unusual in the German speaking countries (compared with engl. ‚cryogenic period'), because it is normally restricted to cryogenics and low temperature physics. On the other hand the Geologic Time Scale contains a time interval named „Cryogenium" (in engl.: Cryogenian).

– Gondwana = a big continent, which was mainly settled on the Southern hemisphere and which has contained Antarctica. G. came into being $0{,}6*10^9$ years ago, i.e. in the Proterozoic era. About ~ $0{,}3*10^9$ a ago (Permian→Triassic transition) it became (like several other, smaller land masses close to G.) part of the super-continent Pangea.

– Pangea = a super-continent, which comprised all of today's continents and stretched from the south pole into the arctic regions. P. came into existence about ~ 0,3 to $0{,}25*10^9$ a before present mainly by the unification of Gondwana with Laurasia (in the English speaking countries one finds also: ‚Euramerica'). Pangea again broke apart ~ $0{,}15*10^9$ a before present, leading to a drifting apart of single land masses, which – apart from others like Gondwana – correspond with the continents of today. The actual year-numbers given for these events vary from source to source. Gondwana for its part disintegrated later on (in the Cretaceous, 0,144 till $0{,}065*10^9$ a before present), whereby Antarctica emerged as an independent landmass (or more explicitly, continent).

5.2 Insights into climate events in the Phanerozoic before the start of the Quaternary

The uncertainties, which accompany data from paleo-geologic and -climatologic investigations, increase the further back these investigations reach into earth's history. Hence all the many number indications, which are cited in this part of the essay from numerous sources, may be taken as more or less rough estimates.

N.B.: This statement does **not** apply to the duration, temporal position and the succession of geological time periods, which are all well defined and named/labelled in order to render a subdivision of earth's history that is uniform and mandatory internationally. The subject is covered by the International Geologic Time Scale, which was (and is being) developed by the ICS (= International Commission on Stratigraphy).

However these uncertainties are not so great, that certain issues or connections remain totally in the dark. Take for example the connection between the atmospheric **CO_2**-content, **k**, and the occurrence of cryogenic periods, which make themselves felt by continental ice sheets, see the black columns in **Fig. 17**. The diagram is indeed extended solely over the latest 10 % of the geologically penetrable history of the earth; however it already provides an impression of the extraordinary dynamism, which governed the geologic/climatologic course of events in the past of our planet if we observe this course against a temporally large background scale. However, the use of such a long yardstick means that we are no longer in a position to reveal short, drastic changes or events of global nature (i.e. events within very long time intervals, which comprise many tens of million years), in such a diagram as is shown below.
The figure demonstrates – among other things – how persistently a tendency to lower **k**-values tries to win through time after time. Before (and at) 400 Ma B.P. (= 'before present') **k** had attained values of likely several 1000 ppm (= 0.1 %), which is extremely high as viewed against the present level. **CO_2**-consuming, chemical weathering processes (in the presence of water) lowered **k** to some 500 ppm within an interval from 540 to 320 Ma B.P. What contributed to that descent (from ~ 400 Ma on) was the strong development and propagation of the terrestrial plants. It is interesting but obvious , that the (trend-like) descent rate of **k** was always small in absolute numbers. We may read out something like „0,2 ppm per 5000 yrs.", which roughly corresponds to the length of the time interval, within which human culture has developed; - hence we realize that notions like 'dynamism' are quite relative, i.e. a matter of the subject regarded and the temporal frame of observation chosen.

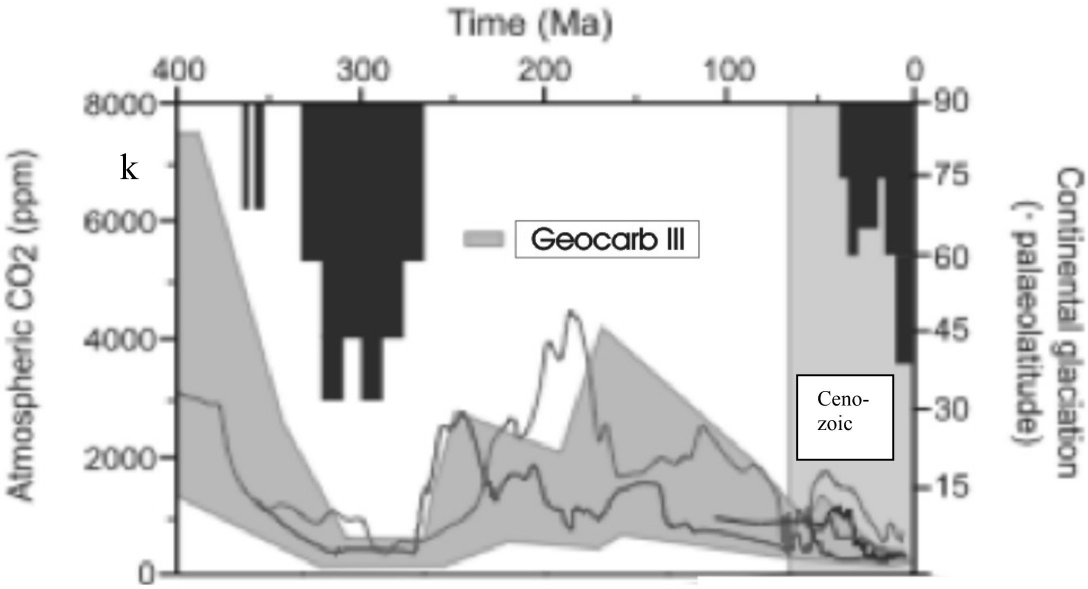

Fig. 17: Development of the atmospheric **CO_2**-content and the appearance of continental glaciations during 400 millions of years (Ma = Mega-Annus) of the Phanerozoic. The last 65 Ma of this Eon (= in Greek: ‚eternity') account for the Cenozoic, which subsists still today.
The light grey tinted, toothed area corresponds to (plausible) ranges of variation after the geo-chemical *Model* „Geocarb III" to the carbon-cycle (after Berner and Kothavala, 2001). The dark grey courses of the atmospheric **CO_2**–content over the time are based on so-called proxy-data*), which have partially been obtained by means of organic matter deep in the (ocean) grounds.
The black columns reaching into the diagram from above, indicate those periods, in which the latest two permanent glaciations took place, and on the other hand the extension of the continental ice sheets stretching from the poles into more southerly (or northerly in the case of the south pole) latitudes.
Source: 4th AR (= Assessment Report) of the IPCC, WG (= Working Group) I, Report „The Physical Scientific Basis", chapter 6 „Paleoclimate", S. 441.

----

*) These are „substituting features", which allow certain inferences on the atmospheric **CO_2**-content in the earth's past, hence in those times far before present, for which that content **cannot** be directly determined.

It seems actually remarkable, that **k** never became marginal or even zero during all the eons, which followed the creation of the planet. A change of **k** is based on several opposing processes, which take place continually, and which become effective globally with varying intensity. For example: Provided that the (**CO_2**–consuming) weathering of rocks prevails, the atmosphere is deprived of more **CO_2** than is added to it by igneous (more precisely: tectonic) activities within the same (large-scaled) period; and vice versa.
Apart from other influences, which determine the average temperature on the earth's surface (MGT), a high **k**–value generally provides evidence that MGT tends to greater values, too, and vice versa. So, if **k** were approaching more or less today's levels, the chances are improved for the beginning of a permanent, extended glaciation in the region of one pole at least, i.e. for the change from an a-cryogenic stage to a cryogenic one. **Fig. 17** bears eloquent witness to this issue by referring to the latest 2 cryogenic stages of the geological past. While we presently live in the latest of these cryogenic phases, the immediately previous one *ended* after a duration of about 60 to 70 Ma; and we may wonder „Why?" We have found only one answer to this question – despite intensive source studies. In the book of R. Walter, „Erdgeschichte – Die Entstehung der Kontinente und Ozeane" (Earth's History – the Formation of the Continents and Oceans) one finds reference to that issue on p. 95; we cite:
[>> At the end of the Paleocene (= end of the Carboniferous, ca. 300 Ma B.P.) an extreme decline of the sea level by several 100 m exposed organic matter to an **oxidizing** atmosphere; a matter, which formerly was bound en masse in sediments. As a consequence the content of free oxygen decreased in the atmosphere. **<<]**.
Something like this sounds plausible in our context insofar as „oxidation" of course means „formation of **CO_2**", too. Hence one could perhaps explain (partly at least) the fresh rise of **k** since the time point ~ 270 Ma till 250 Ma, see Fig. 17.

Finally we wish to devote our attention to the latest cryogenic phase, which began ~35 to 30 Ma back and which we still live in. This phase started with the glaciation of **Antarctica**, which – as an independent continent – had already been 'harboured' by the South Pole for a long time. In a time interval starting from the Cretaceous -(= an ice-free 'warm stage' lasting from 140 till 65 Ma B.P., thus experiencing the existence of dinosaurs also in the polar regions)- and ending up in the Oligocene (34 until 23 Ma B.P.) the atmospheric **CO_2**-content had decreased slowly but continuously (i.e. from more than 1000 ppm down to ca. 400 or 500 ppm). That decrease still continued even to the point, when an ice-cap also appeared on the North Pole. With regard to the latter ice-cap different number indications are to be found. Following the report „Arctic Climate Impact Assessment" (Cambridge University Press, 2005) one should assume – as is allegedly not improbable – the following: The first little ice-sheet presumably was already formed (e.g. on Greenland) in the Pliocene. A fast advance of the arctic glaciation (roughly to the present extent) however were to be assumed not until ~3,5 Ma B.P. And this number would correspond to something, which is commonly apostrophized as „beginning of the glaciation of the Northern polar region".
Other sources, e.g. [D. Archer], indicate – for good reasons – ~2,6 Ma for this, hence the beginning of the Quaternary (2.6 till 0.0 Ma). Either way, there is a recognisable temporal difference between the start of the glaciation of the South and the North Pole.

Hence it may be maintained that the beginning of the formation of a polar ice-cap also depends on which one of the 2 poles is taken into consideration. With respect to the poles – from the geographic point of view – there is indeed no symmetry, as was also the case in the geological past. Hence many factors may come into play, e.g. the distribution, form and size of land-masses in a polar region, the development of ocean currents and air circulations on a large scale, which the meridional temperature setoff **) depends on, the amount of precipitation, etc. A decreasing atmospheric **CO_2**-content is of importance for when and where in the Phanerozoic a pole glaciation had to be expected, to be sure, but not solely significant in this regard.

) This means a **T-setoff occurring between equatorial and polar regions. Supposed, that there were no setoff of this kind at all (or too small a one). Hence ice sheets at both poles would likely have been the rule and not the vastly extended a-cryogenic periods in the earth's history.

In some publications on the web (yes, we draw our „wisdom“ from the internet here and there!) the view or thesis is held, that the formation of a polar ice-cap **[3*)]** was mainly favoured – or even initiated – by the (formerly dry) land, provided that the land is located sufficiently close to the pole. Whether the land is harbouring the pole directly or whether it lies – separated by water – sufficiently close to the pole, does not really matter. We must admit, there is much which supports this view, especially when the said land includes more elevated mountainous regions (or had included such regions in a past long ago). As is commonly accepted, an ice sheet comes into being by the fact that snow, which has fallen in the winter, does not melt completely during the ensuing summer. The effect is enhanced by relatively cool summers, provided that these become the rule over a certain geological time interval (we will dwell on this aspect in a sub-chapter 5.3). However it will likely take substantially more time to initiate a permanent ice cover on the sea (adjacent to a polar land region) due to the high heat capacity of water, which furthermore extends to considerable depths. And when the sea ice had finally formed, then the said heat capacity also resulted in ice thicknesses being less than can be formed on land.
Though the thesis above cannot really be inferred from features like longitudinal groove patterns on (very) old rock formations (e.g. in Africa) due to the abrasive action of former glaciers, one would nevertheless be inclined to appreciate a statement like
“If one of the 2 poles was situated on the land and the other one in an ocean then it is quite clear to everybody, which of them would win the race as initiator of a cryogenic period!”

To be sure, paleo-geologic findings suggest, that – in the Phanerozoic (i.e. since 542 Ma) – the South Pole was – in contrast to its counterpart – settled most of the time on the land (Gondwana, Pangea). As is still the case today with the South Pole: it lies in the middle of the antarctic continent; however the North Pole is in the middle of an ice covered ocean. But can a wonderfully simple picture like this be sufficient to assess e.g. the start/course of the next-to-latest global glaciation some 300 Ma back (see Fig. 17)? At this time practically all of the current land masses were united in a single super-continent called ‘Pangea’ . Pangea stretched – in contrast to the priorly existing southern continent Gondwana – far into the northern latitudes. The matter of how far seems - among other things - to be still a matter of suppositions (beyond solid scientific knowledge); a “guesswork”, as is also mirrored by the diversity of those paleo-geographic world maps, which have been (and are being) drawn everywhere on the globe for such distant times as we have alluded to. This is especially true for the paleo-geographic extension of the ice sheets at these times. Indeed, all the corresponding illustrations have only one common factor: that the southern region of Pangea was hidden under an enormous ice cover. On the other hand the northern polar region is sometimes depicted as being ice-free, and at other times as covered with sea ice. How far the sea ice – which certainly was present, too, at that time – had stretched in the direction to the equator is not exactly known. Since it leaves no geological

----

[3*)] We want to understand by this any permanent and coherent ice cover on the land (in the form of ice sheets/glaciers due to accumulating snow) as well as on the surface of waters (in the form of pack ice and ice shelves).

- *Ice shelves* consist of ice masses which are connected with feeding glaciers in a coastal region, but which mainly extend to the ocean, hence coherently floating on the ocean surface.
- The colloquial ‚*pack ice*’ corresponds to the scientific notion ‚*sea ice*’.
- On the other hand the notion ‚*drift ice*’ means the entirety of single floating ice floes being driven by water currents. To this kind of ice are belonging not only the minor ice floes but actually also the big icebergs.

The present stage of the Antarctic glaciation is above all characterized by a huge, kilometres thick ice sheet, as well as by extended ice shelves in the very large bays of Antarctica. In contrast the northern polar ice-cap definitively consists of the Greenlandic ice sheet on the one hand, and on the other of the Arctic Ocean, as far as it is permanently covered with sea ice. N.B.: The extension (and the thickness, too) of the sea ice cover sensitively reacts on temperature variations. The latter in turn are not only induced by the seasons, but are also a consequence of a changing climate.

signature and hence cannot be evaluated paleo-geologically. As we have already stated: the farther one goes back into earth's history, the more uncertain are both the hard numbers in scientific publications and the abundance of more qualitative assumptions, theories and even speculations. With respect to those paleo-geologic events, which allow little more than a merely qualitative ventilation or nothing else than mere surmises, the community of the paleo-geologists/-climatologists who are mainly involved in scientific research are rather reserved in their publications/comments/presentations; especially in terms of such details as we are promoting here.

5.3 The ice-age cycles within the Quaternary (2,6 Ma until present)

Introductory remarks: Once one has delved sufficiently deeply into the subject of „ice-ages in the quaternary and their reasons" and has a sense of close connection with nature, it is almost impossible not to be left smitten with a sense of almost helpless amazement. Indeed, it seems unnecessary to continually refer to the „mystery of life and its formation" in order to become absolutely fascinated by the Earth's history; many other events in that long-lasting chronicle are similarly able to meet a profound desire for (mental) adventures.

The ice-age cycles of the Quaternary since 2,6 Ma B.P., might appear to us as something like "Close Encounters of the Third Kind" (Steven Spielberg) with regard to their occurrence and progress over time. There is an impressive series of scientifically ensured findings/results regarding the paleo-climate of the Quaternary, the events of which are increasingly striking as the particular time intervals investigated become closer to the present time. There are, nevertheless, a number of aspects attendant to the ice ages which are less clearly understood, and for which only more or less plausible surmises or interpretations are offered. Given the wealth of information about the phenomenon of ice ages, it is difficult to be concise without being vague. We shall nonetheless attempt to do so, merely to exemplify the complexity of the issues involved – attended by all kinds of intellectually demanding *subtleties* - which climatologists and their colleagues from other geo-scientific fields must deal with, to undertake their meticulous research work.

b1) Some remarks on the beginnings of ice-age research: At the end of the 18th century, the idea had yet to be generally accepted that bone and skeleton finds **(**e.g. in difficultly accessible caves, and in the permafrost-soils of Siberia**),** along with particular geological findings (e.g. large erratic rock fragments far from every high mountain and every glacier, the terminal moraines, and the glacial valleys) must be witnesses to a geologically distant past. The seeds of ice-age research were sown in Switzerland in the 1920s and 1930s, where Swiss natural scientists were the first to recognize and to promote the only possible explanation for the very large rock fragments observed in the alpine regions which lie dispersed on the ground far away from the slopes of any mountain, i.e. that these boulders must have been moved by ice masses, which were far more extended in former times than any of the present alpine glaciers. Of course it had long been known that the glacial ice moves (albeit slowly) from the mountain down the valley, and is accordingly able to carry with it, not only detritus and boulders but also to grind those rocky surfaces, which confine a glacier from its bottom and sides. Now, such "sander marks" (for which the technical term is "Gletscherschliff" in German) were also observed on those rocks which were located at some distance from any glacier, which further endorsed the "Thesis of the Great Ice", which arose during this time. Similar observations of sander marks such as those the alpine regions (the Alpine foreland included) were shortly discovered (after [Hofbauer]) in Great Britain too, although *not* with the tertiary layers of unconsolidated rock as in the North German low lands; layers, which the ice (having descended from more northern latitudes in the latter case) must have scraped across. However, the erratic blocks ("erratica") in particular, which can be found dispersed at random across the North German Plain, proved to be comparable with typical Scandinavian rocks, in terms of their chemical composition. The chains of terminal moraines, too, which can be identified at various locations in the North German regions (terminal moraine = material pushed together at the rim of an ice sheet during its greatest extension) provided irrefutable evidence for the ice-age process. The idea that compact, extended ice masses had moved down from far northern latitudes to deep into the North German plain, having first cut their way across the Baltic Sea and Denmark, seemed too far-fetched to most of those living at that time. Nevertheless the concept, known as the "ice age", became generally accepted during the second half of the 19th century. In prehistoric times, large parts of the European mainland (including the alpine regions and parts of the British Isles) must have been periodically covered by continuous ice shields. Furthermore, it became clear that there had not been merely a single ice age, but several, which succeeded one another at particular points and durations in time; however, these temporal issues were then uncertain or unknown. In this regard one may think of such designations as "Günz" - "Mindel" - "Riss" - and "Würm" – (glacial stage), being connected with certain regions at the foot of the Alps (see Fig. 18 b-1).

b2) Some remarks on the more recent ice-age research: Whilst climate research was already more or less orientated globally at the beginning of the 20th century, the ice-age research still remained restricted for quite a while – and on the whole – to certain land regions, especially those in the north. There was indeed a perception of a (relative) succession developed; the (absolute) dating of single ice- age events was however – as far as we can see – not possible. But the situation changed around the middle of the 20th century: by and by also the paleo-climatic research (hence ice-age research, too) became for their part a "globally oriented matter". The following 3 points should be mentioned in this context:

- The veracity of **global plate tectonics** was demonstrated by intensive field-studies, and more recently supported by satellite measurements, which also included the area of the vast oceans. Thus, not only was A. Wegeners theory confirmed, that continents drift, but the speed and direction of the movement of the land masses could be determined, so enabling a validation of various conclusions that had been made regarding the previous locations/distribution of the continents. It is now clear that the present distribution was achieved approximately before the beginning of the Quaternary, e.g. the Panama land bridge rose about 3 million years ago.

- The development of deep-sea drilling technologies enabled samples to be taken from **deep-sea sediments** (which may be several hundreds of metres in thickness) allowed proxy data to be determined about the paleo-climatic development which had occurred over many millions of years. Here, the term "proxy" means a value that is directly measured (e.g., the oxygen-isotope relation, discussed in a later section), so allowing conclusions to be drawn about a critical parameter, such as temperature, **T**, which existed many millennia past, and hence cannot be measured *per se*.

- **Ice cores** have also been taken from the ice shields in the northern and southern pole areas (Greenland, Antarctica), using deep-sea drilling techniques, thus enabling samples to be taken to a depth of several kilometres. By analysing tiny air bubbles that are trapped in the ice, the atmospheric composition and its variation over time, can be monitored, most importantly greenhouse gases (GHGs), e.g. $\mathbf{CO_2}$, $\mathbf{CH_4}$ and also $\mathbf{N_2O}$. Using established proxy relations between isotopic composition and temperature, the temperature profile over many ice age cycles can be determined, going back to 800,000 years BP ("Before Present"); see project EPICA, Antarctica. Ice cores contain demonstrably more paleo-climatic information than sediment samples do. As a result of the unambiguously recognizable delineation between the individual ice layers, which had been formed by an accumulation of snowfall, year on year, it became possible to date single events directly, as can be expressed in terms of the variables shown in **Fig 18a**. This permits the data to be arranged collectively on an "absolute" time scale, which extends from our present and into the past. Ice cores taken from the Greenland ice shield proved to be especially valuable in this regard for the last ice age cycle, i.e. for the time interval of ~ 123,000 to ~10,000 years BP, along with a very fine temporal resolution within the data files, [Hofbauer] and [Svensson et al.].

c) To the results from ice drillings, Fig.s 18a and b, and their interpretation:
Fig. 18a shows the variation in the concentration of 3 greenhouse gases, GHG's, over time (see the 3 uppermost curves) and those of 2 proxy dates, whereas $\mathbf{\delta^{18}O}$ (see explanations further below) indicates specifically changes in the global ice volume. **δD** represents a measure of the change in temperature **T**, that the ice has undergone during its history "on site", i.e. here, in Antarctica. The data embrace a time interval of 650 000 a, which encompasses the final stages of the "bipolar ice age", i.e. that which is encompassing both of the Earth's poles. All the curves, other than that uppermost, can be seen to run in synchrony with the temporal changes.

Evidence for this synchronous running was also obtained from measurements of ice cores drilled from the Greenland ice sheet, despite that fact that only the time interval between the last warm stage (the "Eemian interglacial period") ~123000 a BP and the present is covered by them. The timescale could be confirmed simply by boring down to the bedrock, which may extend to a depth of 3085 m below the surface of the ice sheet, as was demonstrated by the project NGRIP (= North Greenland Icecore Project).

The very jagged course of events might suggest that many, more or less violent changes occurred over relatively short time intervals. On the timescale of a human life, e.g. 100 years, however, such intervals are perceived to be rather lengthy. For example, if the abscissa is extended mentally by a factor 10, so that 1 mm corresponds to 100 a, rather than 1000 a, these changes appear to proceed tortuously slowly. As an example, we can consider the rise in the global atmospheric CO_2 – concentration, which began at the end of the last glacial period, i.e. after the LGM = Last Glacial Maximum (ca 20 000 a BP), up to the beginning of the Holocene (i.e. the present inter-glacial which began about 10 000 a BP). According to the Figure, this amounts to: (260 -180) ppm/4000 a = **2 ppm per 100 a**, which might appear practically negligible in comparison with the present rise of **~ 2 ppm per 1 a**! In addition, the Greenland ice cores show some differences in the temperature in the northern latitudes, where a significantly faster rise occurred: these differences are termed Dansgaard-Oeschger-events, which occurred during the previous glacial period (100 to 20 ka BP), see among others [Rahmstorf].

We may now consider the last 4 or 5 ice age cycles, which are represented in the diagram with grey vertical bars, each of which indicates the duration of the comparatively warm period within a single cycle. The latter are known as interglacial periods, and these intersperse the substantially longer and colder "glacial periods". Thus, each ice age cycle begins with a warm period and ends with a subsequent cold period.
From a consideration of the **δD** trends, the following features become evident:

- Warm periods occupy a minority duration of the cycle, overall, averaging at around 20% of those shown in the diagram. A complete ice-age cycle takes the order of 100 000 years to complete.
- During a cold period considerable **T**-variations appear. However, these variations tend to decrease as a cold period progresses, until the **T**-minimum point is reached, whereupon the next dramatic **T**-increase begins, from which the next inter-glacial follows. Thus, the overall T-course in an ice-age cycle can be seen to resemble a "sawtooth", which is characterised, according to common knowledge, by the noticeably different slopes of its 2 dental flanks.

Although it is not obvious in Fig. 18a, we should note an important fact, i.e. that the decline in the atmospheric $\mathbf{CO_2}$ concentration (and presumably that of $\mathbf{CH_4}$ too) lags behind the decline in temperature at the beginning of a glacial period within an ice-age cycle, by about 800 to 1000 years. Hence, the **GHG** concentrations cannot be the immediate cause of a T-decline, which begins immediately at the end of an inter-glacial, and so there must be some other factor at play.

As we have already noted, those variations in various parameters relevant to climate, do not depend on influences that are confined exclusively to the global system itself, but on others which originate from beyond it, and which are accordingly termed forcings, in the climatological nomenclature. It is the periodic nature of these forcings, that is reflected in the ice-age cycles, which must be the most impressive, virtually classical examples, of these phenomena.

It is now generally accepted that periodic variations occur in the earth's orbit around the sun and also in the tilt of the earth's rotation axis (relative to the ecliptic). These effects, in combination with a phenomenon called precession, provided natural external forcings, which precipitated both the start of a glacial period at the end of an inter-glacial one.

It is necessary to seek the causes of the periodic climatic variations that occur during the entire ice-age period, within the realm of those astronomical features, which are contained in the notion of "**Milankovich-cycles**", abbreviated here by "M-cycles". These cycles have been determined from calculations made within the field of celestial mechanics, and take account of those perturbations which are a consequence of the gravitational influence of the other planets (mainly Jupiter and Saturn)*). The most important features of the M-cycles may be summarized as follows:

- (relative) *eccentricity*: The 'eccentricity of an ellipse' is the distance **e** between the centre of the ellipse and one of its two focal points on the major axis 2a. Since **e = SQR ($a^2 – b^2$)**, where **a** is the semi-major axis and **b** is the semi-minor axis, we obtain

$$e/a = SQR (1 – b^2/a^2),$$

This is the *relative* eccentricity, which is normally designated by **ε,** rather than **e**. In case of the Earth **ε** varies continually within the limits $0.005 \le \varepsilon \le 0.058$, while leaving the semi-major axis **a** unaffected. The present value for the Earth is **ε** = 0.017, and the variation follows a period of about 100,000 years, which corresponds closely with the duration of each of the past 4 or 5 ice age cycles, see Fig. 18a.

- *Tilt* or *obliquity*, **φ**, of the Earth's rotation axis: **φ** varies within the limits $22.1° \le \varphi \le 24.5°$, and its present value is 23.5°. The continuous change of **φ** occurs over a period of 41000 years, which is sometimes manifested in the temporal distance between adjacent T-peaks within an ice-age cycle, see Fig. 18-b2.

Note: In our use of the term "peaks" we are not only referring to the so-called inter-glacials but also the so-called inter-stadials, i.e. smaller T-peaks, which follow one other during the cold period of an ice-age cycle.

- The *precession* of the Earth's rotational axis: This effect is caused by the combined gravitational pull of the Moon and the Sun, which results in a torque that acts on the planet due to its equatorial bulge. Hence the Earth's axis is forced to alter its direction by precessing on the surface of a cone, in the same way as the axis of a fast spinning, slanted top precesses in relation to the ground. Note: the effect alone does not affect the value of **φ**.

This continuous change of the orientation of the axis follows a period of around 26,000 years, if we ignore the rotation of earth's elliptical orbit itself. However, once this is included, cycles of 23,000 and 19,000 years are manifested.

Within the above mentioned range of values for **ε**, the Earth's elliptical orbit can hardly be distinguished from a circle. Accordingly, the overall radiation energy which the Earth receives from the sun during the period of one year, is barely affected by such small **ε** variations. However, over shorter time periods, say a quarter of a year, then there may be an effect, in terms of the intensity of the solar radiation and according seasonal aspects, e.g. whether the earth is situated in the aphel or in the perihel** phase of its orbit.

It is well known that the terrestrial seasons occur as a consequence of the tilt **φ**, the value of which appears to vary more or less independently of **ε**. We may note that a zero value for **φ** (i.e. no tilt) would lead to the absence of any seasonal variation at higher latitudes in both northern and southern hemispheres. We might envisage a scenario in which the value of **φ** diminishes, so that the summers become permanently colder from year to year and the winters warmer until the difference between winter and summer vanishes, in contrast with our experience in the equatorial region with a moderate **φ** value of 23.5°. The opposite case (**φ** tending to greater values) needs no further comment.

Nonetheless, the question arises of why, on the southern hemisphere, there were no ice-age cycles with their growing and dwindling ice volumes on the land and water, since the celestial conditions principally are entirely equal for both hemispheres?

---

*) Note: If there were no other planets in our solar system, the shape of earth's slightly elliptical orbit (parameter e or **e/a** = **ε**), as well as the orientation of this orbit would remain entirely invariant with time. This is also true for the value of the tilt (or obliquity) **φ,** of the Earth's rotation axis in relation to the pole of the ecliptic (= the plane of earth's orbit). It is only in this hypothetical case that Johannes Kepler's laws of planetary motion be perfectly accurate! Hence "perturbation" means nothing other than the (temporally varying) deviation from that idealistic scenario.

**) Aphel = greatest distance from the sun; perihel = smallest distance.

(to be continued; please refer to the German text for the moment!)