气候演变的周期性与黄道倾斜的关系

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在《关于冰期成因问题的探讨》一文中，我们提出，在地质历史上，ε 的变化至少包括两种型式。其一是以 $200—300 \times 10^6$ 年为周期，振幅达 $10°—15°$ 的大波动；其二是以 41,000 年为周期，振幅仅 $2°—3°$ 的小波动。造成地质历史上大冰期(如第四纪大冰期、晚古生代大冰期等)和非冰期(如中生代非冰期)交替的主要原因是 ε 的大波动；而造成第四
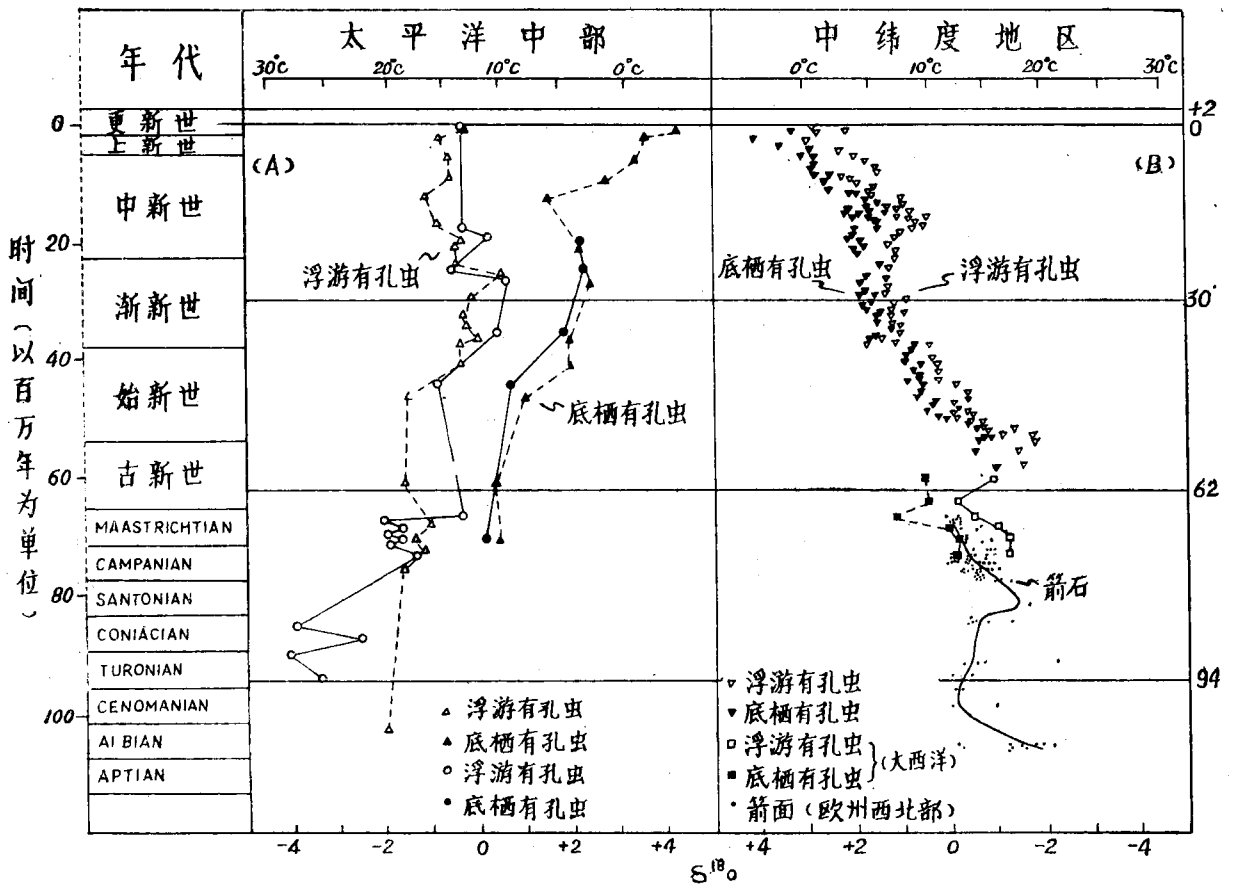

图 1 根据钙质的化石介壳中的氧同位素含量的变化所测定的古温度变化曲线。

A. 根据底栖及浮游有孔虫群落所分别测定的太平洋热带地区的洋底及洋面的古温度变化曲线。

B. 太平洋及大西洋的中纬度地区。 根据底栖、浮游有孔虫群落及箭石所分别测定的洋底及洋面的古温度曲线。

在新生代,洋底及高纬度地区洋面的古温度值是逐渐地下降的。在下降的过程中出现了温暖期（相当于繁种幕）与寒冷期（相当于稀种幕）的反复交替。

（按 Fischer and Arthur, 1977）

纪大冰期中冰期和间冰期交替的主要原因是 ε 的小波动。

在《地球轨道与气候演变的关系》一文中，我们着重研究了第四纪大冰期中气候演变的主要原因。天体力学的计算结果表明：在距今 2×10^6 年的范围内，在地球轨道三要素中，黄道倾斜（ε）变化的周期平均长 41,000 年，偏心率（e）变化的周期平均长 90,000 年，而岁差运动（π）变化的周期平均长 21,000 年。三者在数量级上大致是相等的。在第四纪大冰期中，寒冷期（相当于氧同位素偶数阶段）和温暖期（相当于氧同位素奇数阶段）的持续时间的长短；各个寒冷（或温暖）期的寒冷（或温暖）程度的深浅正是受上述地球轨道三要素的变化所控制的。由天体力学计算所取得的理论曲线（即北纬 35° 地区天文辐射冬半年总量的变化曲线）与实测所得到的古温度变化曲线非常吻合。这项事实雄辩地证明：在第四纪大冰期中，世界上气候的巨大变化确实是与地球轨道要素的微妙的变化联结在一起的

1977 年 Fischer and Arthur 写了一篇很值得注意的论文《远洋区的长期变化》。他们收集了近几十年来在海洋学研究中所涌现出来的大量资料，令人信服地证明：在上述两级气候波动之间，还存在着一级以 32×10^6 年为周期的气候波动（图 1, 3）。

这一级气候波动不仅直接表现在古温度的波动上，而且还间接地表现在许多其它的方面。

1. 在远洋区内，生物类别的数量在地质历史上是有变化的。有的时期种类繁多，叫做繁种幕（Polytaxic）；有的时期则种类稀少，叫做稀种幕（Oligotaxic）。前者的持续时间很长；后者则非常短。这种变化的周期恰好也是 32×10^6 年。繁种幕相当于温暖期，稀种幕则相当于寒冷期（图 2）。

繁种幕与稀种幕交替出现的事实不仅存在于远洋区，而且如 Flessa（1973）所论证的，它也存在于大陆上。

2. 大洋的开阔的洋底环境曾经历过周期性的变化。有的时期以氧化环境为主，有的时期则以还原环境为主。黑色的，薄层状的，缺乏底栖生物的海相沉积物，在现代的大洋中是很少见的。然而在某些地质时期中，例如在部分奥陶系、志留系、泥盆系中，在下侏罗统，以及在白垩系的中部（Aptian-Albian），它们都曾广泛地遍布全球。过去的地质学家总是以封闭的，或半封闭的海湾环境来解释这种现象。实际上，它们是在开阔的大洋中沉积的。Fischer 等认为，这是大片洋底处于还原环境的缘故。造成这个现象的根本原因在于气候的变化。在寒冷时期，两极与赤道之间的温差（即地理上的温度梯度）比较大，它使大洋中的对流加剧。其结果是大洋深处的水流通畅，由它们所提供的氧就比较多，于是大片洋底处于氧化环境之中；相反，在温暖时期，两极与赤道之间的温差比较小，它使大洋中的对流缓慢。其结果是大洋深处的水体长期滞留，由它们所提供的氧就比较少，于是大片洋底处于还原环境之中。事实正是如此，大量黑色的，薄层状的，缺乏底栖生物化石的海相层的地质时代都恰好相当于地质历史上的温暖期（图 3）。

3. 在大陆上，沉积过程是常有小间断的。这样的现象也出现在大洋中。例如在大西洋西部的巴哈马群岛附近的洋底上，至今尚裸露着白垩纪的地层。Fischer 等认为，这个现象也是由气候变化所造成的。在寒冷时期，大洋中的对流加剧，它不仅使大片洋底处于氧化环境之中，而且它也冲走了大洋底部相对隆起区上的松散沉积物，于是造成沉积小间
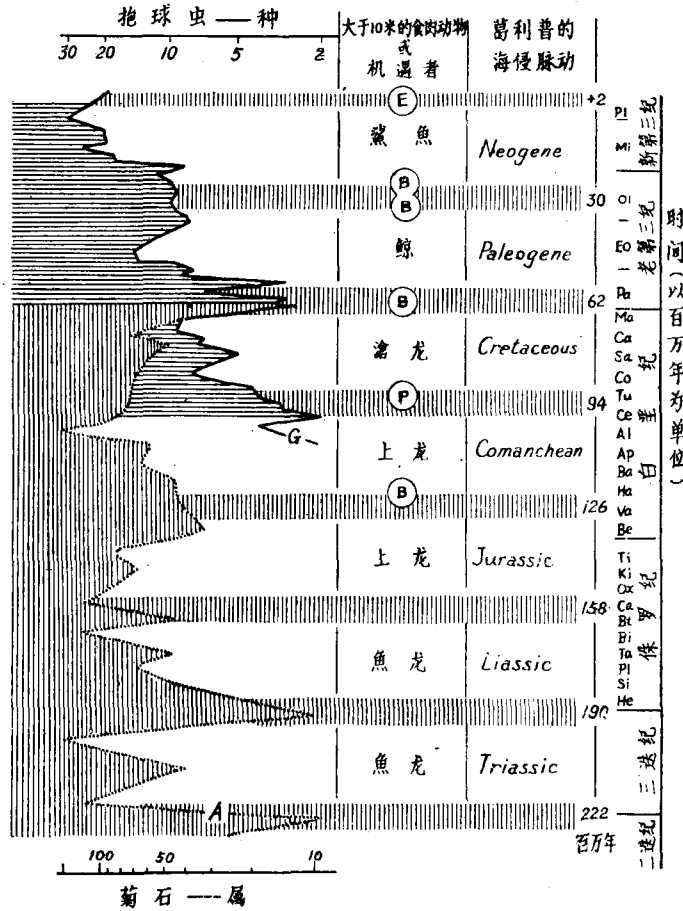
图2　在过去 220,000,000 年内，远洋区生物类别的数量、大型食肉动物或"机遇者"的盛衰情况。

　　　左列表示全球性的生物类别的数量的变化。菊石的属数（A）和抱球虫的种数（G）分别按对数的尺度标出。繁种幕与稀种幕交替出现，每隔 32,000,000 年重复一次。它恰好与右列所示的葛利普的海侵脉动相对应。

　　　在繁种幕，出现了身长超过 10 米的大型食肉动物，如中列所示，它们是鱼龙、蛇颈龙类的上龙、沧龙、鲸及鲨鱼。

　　　中三迭纪的鱼龙为 *Cymbospondylus and Shastasaurus*；早侏罗纪的鱼龙为 *Stenopterygius*；晚侏罗纪的上龙为 *Stretosaurus*；早白垩纪的上龙为 *Kronosaurus*；晚白垩纪的沧龙为 *Hainosaurus*；始新世的鲸为 *Basilosaurus*；中新世——上新世的鲨鱼为 *Carcharodon megalodon*。

　　　生物的危机是与某些远洋生物（即"机遇者"）的局部的大量出现相伴随的，它们在普通的生物群中是少见的。B, *Braarudosphaera*; p, *Pithonella*; E, *Ethmodiscus rex*.

　　　（按 Fischer and Arthur, 1977）

断。相反，在温暖时期，沉积小间断就比较少见（图3）。

　　4. 在地质历史上，海面的升降，或海侵与海退的交替，也存在着周期性的变化，其周期恰好也是 32×10^6 年。温暖时期与海侵相对应，而寒冷时期则与海退相伴随（图2，3）。

　　5. 碳同位素的比例：c^{13}/c^{12} 的值在地质历史上有着周期性的变化。在温暖时期，此值较大；在寒冷时期，此值较小（图3）。在繁种幕或温暖时期，有机碳的含量较高，而碳酸盐的含量较低；在稀种幕或寒冷时期，情况恰好相反。

　　海洋占全球总面积的 2/3 以上，人类对海洋的研究已经开始了。虽然目前这项研究

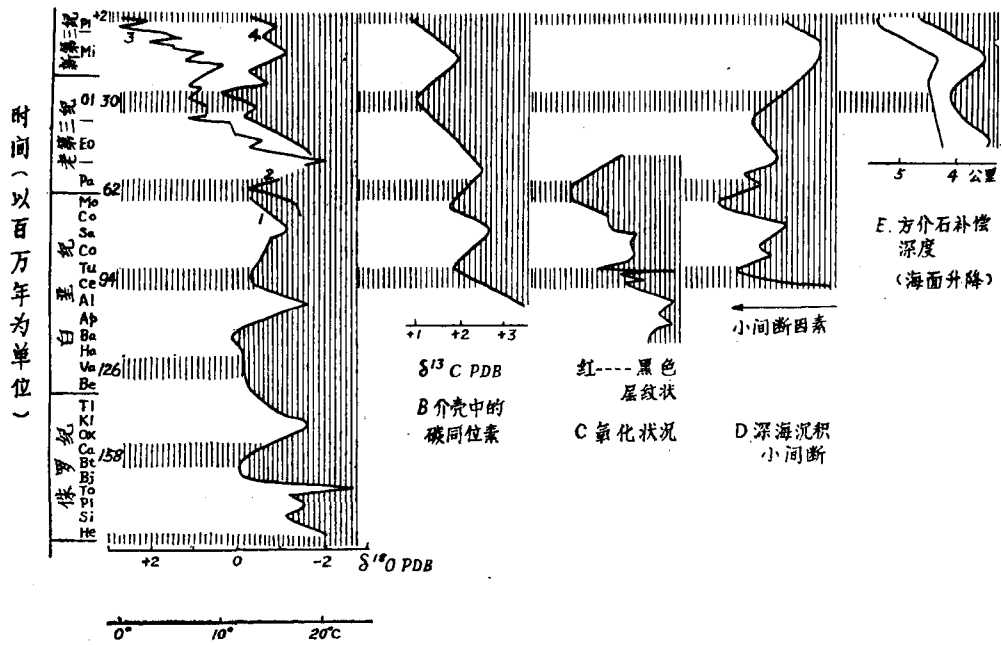图 3　与 32×10^6 年的周期性变化相联系着的各种化学、地质参数的变化概况。

　　A. 自从早侏罗纪以来的古温度变化曲线，这是根据化石中氧同位素含量的变化所测定的。1) 箭石(欧洲西北部)；2) 抱球虫(南大西洋)；3) 抱球虫(南太平洋，显示出高纬度地区海水的逐渐变凉)；4) 抱球虫(太平洋热带地区)。

　　B. 远洋区生物的钙质壳体中的碳同位素含量的变化。

　　C. 远洋区的沉积序列中沉积物的氧化状况，即根据沉积物的颜色、有机碳的含量及层纹结构。我们认为，在这里所显示的波动在全球各大洋的远洋区是有普遍意义的。

　　D. 深海沉积小间断。深海钻孔显示了远洋区沉积记录中的许多小间断；它们产生的时代和持续时间的长短都是随时间而变化的。越靠左侧，表示小间断越多。

　　E. 根据深海钻孔资料重建的方介石补偿深度的波动。它反映了海面的升降。

　　(按 Fischer and Arthur, 1977)

尚处于初级阶段，但是近几十年来，从大洋深处所揭示出来的许多事实已使人们的耳目为之一新。大陆漂移说的复活，被誉为地质革命的板块理论和海底扩张学说的问世，都是和海洋研究的进展紧密关联的。人们对第四纪气候演变史的认识，主要也是来自对海洋的研究结果。在陆地上或近岸的沉积物中，由于受构造运动、地貌变化等严重的干扰，上述的长期变化在地层中所留下的信息往往被许多表面现象所掩饰，以致于这种长期变化一直未被地质学家所认识。远洋区远离大陆，因而得以免除上述种种干扰。正是由于在近几十年来开展了对远洋沉积物的研究，才揭示出前述的大量事实。这一切使我们确信：在地质历史上，确实存在着以 32×10^6 年为周期的长期变化。Fischer 等指出，这种变化与大陆漂移或板块构造之间并没有直接的因果关系。他们认为，只有根据气候波动，即寒冷时期和温暖时期的交替，才能给这一系列变化以合理的解释。

　　在《关于冰期成因问题的探讨》一文中，我们根据冬、夏温度的估算法，得到了这样的结论，当 ε 从 $10°$ 增大到 $23°$ 时，其气候变迁的规律应为：1) 各地的年平均温度逐渐下降。2) 南北温差逐渐扩大。3) 各地的较差(即冬夏温差)也逐渐扩大。

　　在《评米兰柯维奇理论——兼论黄道倾斜 ε 变化对气候的影响》一文中，我们根据气

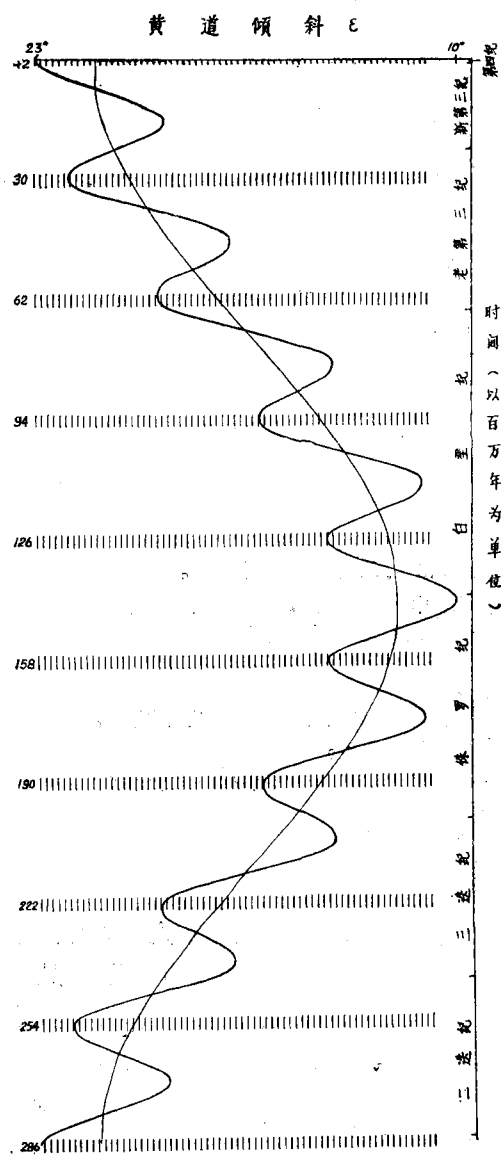候学原理强调指出：在讨论地球轨道要素的变化对气候的影响时，只考虑北纬 65° 地区天文辐射夏半年总量的相应变化是不够的。我们认为，1）不仅要考虑天文辐射夏半年总量的变化，还必须考虑天文辐射冬半年总量的相应变化。2）不仅要考虑北纬 65° 地区的变化，还必须考虑其它各纬度地区的相应变化。

黄 道 倾 斜 ε

图 4　根据 Fischer and Arthur (1977) 所提供的资料，在过去 286,000,000 年内黄道倾斜 ε 变化的情况。

3）不仅要考虑各纬度地区辐射量的变化，还必须考虑经向的热量输送。因为地球是一个统一的整体，所以低纬度地区（即低于 35°）会不断地把热量输送到纬度较高的地区（即高于 35°）去。4）不仅要考虑天文辐射量的变化，还必须考虑大气和地表反射率对不同地区天文辐射量的影响是完全不同的。纬度越高，其衰减的量就越多。5）不仅要考虑射入辐射量的变化，还必须考虑由此所引起的冬、夏温度的相应变化是完全不同的。因为能量（E）与温度（θ）之间不是线性关系，而是 $E = \sigma\theta^4$。综合地考虑了上述五因素后，我们得到了如下结论：当 ε 从 0° 增大到 30° 时，1）冬夏差异会扩大。2）地理上的差异（即南北差异）也会扩大。3）全球各地的平均气温会随着上述差异的扩大而下降。与前述结论完全一致。

根据这个原理，我们认为：造成以 32×10^6 年为周期的气候波动的最主要的原因是 ε 的波动（图 4）。

从另一个角度讲，如果离开 ε 的波动，能否解释上述事实呢？我们认为是不可能的。在《恐龙为什么能在古纬度75°的地方生活?》一文中，我们对此作了具体的分析。在晚白垩世时的古纬度 75° 地方，即加拿大的育空地区（现在该地位于北纬 66° 附近），不仅发现了恐龙化石，还发现了大量代表亚热带或暖温带气候环境的孢粉化石。一般的生物之所以能在地球的生物圈内生活，除了空气、水分等必要的条件外，太阳光也是一项必不可少的条件。因为太阳辐射几乎是地表热量的唯一来源，又是植物进行光合作用的必不可少的条件。倘若 ε 在地质历史上没有发生过较大幅度的变动，即其变动范围只是象近代那样局限于 22.08° 到 24.43° 之间的话，那么在纬度 75° 的地方就会有 90 多天极夜。显然，在连续 90 多天得不到一点点太阳辐射的条件下，靠什么热量来维持那里的亚热带或暖温带的地表温度呢？大量代表亚热带或暖温

带的气候环境的植物群落和恐龙又如何能在这样的漫漫长夜中生活呢？这些植物又如何能普遍地出现于晚白垩世时的古北极周围的高纬度地区，如格陵兰、加拿大、阿拉斯加及西伯利亚等广大地区呢？总之，如果离开 ε 的变化，那么对于上述一系列古气候现象是根本不可能给予解释的！只有当 $\varepsilon \leqslant 15°$ 时，那么在纬度 75° 地方才能每天都见到太阳光，上述一系列古气候问题才都可以得到合理的解释。所以我们认为：在晚白垩世时，恐龙能在古纬度 75° 地方生活的必要条件是当时的 ε 的值比现代（23°27'）小得多，甚至可能小于 15°。在图 4 上，晚白垩世时的 ε 的值恰好在 15° 左右。

我们的结论是，在地质历史上，ε 的变化至少包括三种型式：1）振幅仅 2°—3° 的小波动。据天体力学的计算，其周期平均为 41,000 年。地球轨道三要素（ε, e, π）的变化造成了第四纪大冰期中寒冷期（即氧同位素偶数阶段）和温暖期（即氧同位素奇数阶段）的交替（图 5）。 2）振幅约 5°—6° 的中波动。据 Fischer 等提供的大量证据，自三迭纪以来，其周期约为 32×10^6 年。3）振幅达 10°—15° 的大波动。根据最近几次大冰期（即第四纪大冰期、晚古生代大冰期、震旦纪大冰期等等）的间隔时间，其周期约为 $200—300 \times 10^6$ 年。上述三种波的叠加便反映了震旦纪以来 ε 变化的情况。
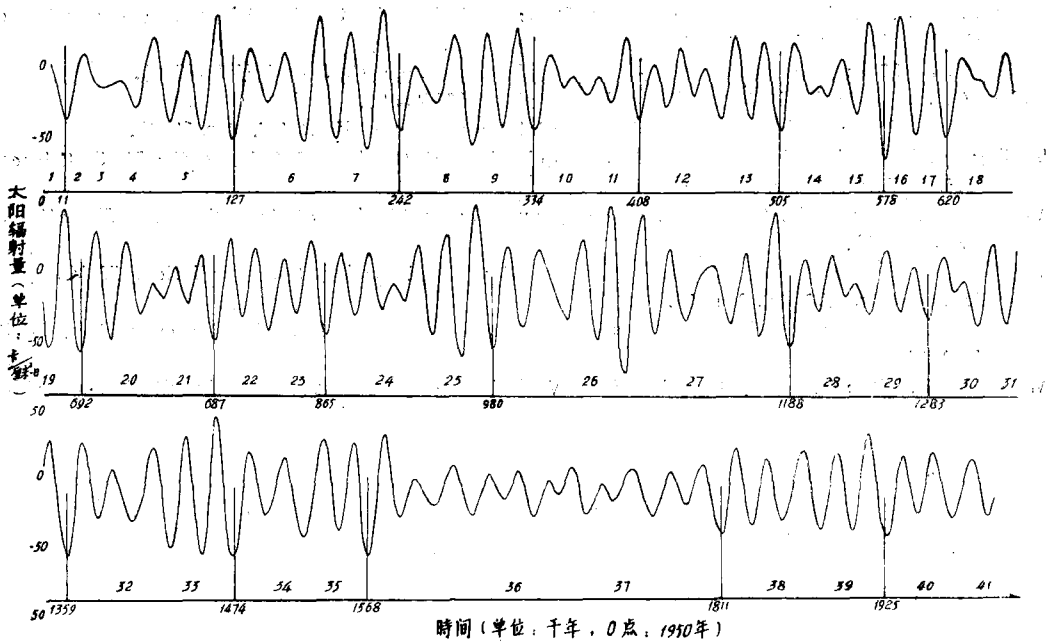

图 5 在过去 2,000,000 年内北纬 35° 地区天文辐射冬半年总量的变化曲线。其中奇数阶段代表温暖期，偶数阶段代表寒冷期。这些阶段的划分和深海钻孔中所揭示的古温度记录完全吻合。根据这条曲线，我们可以知道：哪些时期应属于寒冷期；哪些时期应属于温暖期；哪些时期的寒冷（或温暖）程度较深或持续时间较长；哪些时期的寒冷（或温暖）程度较浅或持续时间较短。

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CLIMATIC VARIATION AND THE OBLIQUITY

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Abstract

There were three kinds of climatic variation in earth-history. The first kind is the alternation of glaciation and nonglaciation with an average period of 200 to 300 million years. Glaciation or kryogene defiined as climate with "much ice", such as Quaternary Glaciation, Permo-Carboniferous Glaciation and so on. While nonglaciation or akryogene defined as climate with "a little ice", such as Mesozoic Era, during which there was only a little ice in the world. From Mesozoic Era to Quaternary Glaciation or during the Tertiary period the climatic variation included three characteristics: 1. The annual range of temperature was gradually widened (Axelrod and Bailey, 1969). 2. The latitudinal temperature gradient was gradually increased (Figs. 1, 3). 3. The mean annual temperature of the whole world dropped gradually (Figs. 1, 3). The first characteristic is the most important for understanding the cause of such climatic variation.

The second kind is the alternation of polytaxic and oligotaxic with an average period of 32 million years. Polytaxic times of maximal diversity coincide with higher and more uniform oceanic temperature, with continuous pelagic deposition and with widespread marine anaerobism, eustatic sea-level rises, and heavier carbon isotope values in marine calcareous organisms and organic matter. Pelagic communities reach maximal complexity, expressed in numbers of taxa and in predator size. While oligotaxic episodes are characterized by lower marine temperature and sharper latitudinal and vertical temperature gradients, by interruptions of submarine sedimentation caused by intensified current systems, by marine regression, by a lack of anaerobic marine carbonate skeletons and organic compounds. Degradation of pelagic communities is reflected by loss of large predators and lowered diversity; blooms of opportunistic species occur during these intervals. This oceanic cycle appears to be linked to continental climates expressed in the paleobotanical record (Figs. 1,2,3) (Fischer and Arthur, 1977).

Fischer and Arthur said correctly, "This alternation is not directly correlated with plate tectonics and patterns of continental distribution." They pointed out further, "The ultimate cause remains unknown, bu the link with sea-level ossillations and possible correlations with periodicity in magmatism suggest that it is internal to the earth, rather than tied to variations in solar or cosmic processes." (Fischer and Arthur, 1977).

The third kind is the alternation of warm stage and cold stage with an average period of 100,000 years during the Quaternary Glaciation. The isotopic record of deep-sea cores provides the most accurate hitherto known information on Quaternary climates, unique in its continuity and global extent (Kukla, 1977).

It is well known that the variations in the earth's orbital elements (obliquity, eccentricity and longitude of perihelion) can cause the redistribution of winter as well as summer insolation at all latitudes. The incoming solar radiation was computed for every 5° of latitudes from pole to pole over the last 2 million years by Vernekar (1972). In order to understand the details of the machanism through which insolation changes climate, we would like to point out: 1. We must consider the distribution of winter as well as summer insolation. 2. We must not only consider the distribution of insolation at 65°N, but also that at all latitudes. 3. As the earth is an entity, heat has been transporting from the lower latitudes ($< 35°$) to the higher ones ($> 35°$), therefore we must also consider the meridional heat transport. 4. When insolation reaches the earth's surface, it will be reduced by the albedo of the earth's surface and the reflective, absorptive and scattering of the earth's atmosphere. The higher the latitudes, the more the depletion. Therefore we must not only consider the variation received at the top of the atmosphere, but also take notice of the factors mentioned above. 5. We must not only examine separately the variation of the radiant energy of the entire winter or summer, but also observe separately the corresponding variation of temperature of each. The energy(E) is related to temperature(θ) by $E = \sigma\theta^4$, not a linear function. Considering the five factors mentioned above, we have drawn conclusions as follows: When the obliquity increases from 0° to 30°, 1. the annual range of temperature would be gradully widened; 2. the latitudinal temperature gradient would be gradully increased; and 3. as a result the mean annual temperature of the whole world would drop gradually (Xu Qinqi, 1980). The three points are exactly identical with the three characteristics of the climatic variation during the Tertiary period or from Mesozoic Era to Quaternary Glaciation. Therefore the variation of obliquity is the fundamental cause of the first kind of climatic variation. So is the second one.

The fossils of dinosaurs and many species of pollen and spores were found in Yukon, Canada (Rouse, 1972). During the late Cretaceous the locality was at 75°N (Van Valen, 1977), but it is about 66°N today as a result of continental drift. It is probable that these species lived in the subtropical or warm temperate zone. Late Cretaceous floras from Alaska and Siberia indicate that a moderately large area was so warm as subtropical or warm temperate zone. All these areas were at high latitudes during the late Cretaceous according to all kinds of palaeogeographic maps (Samoilovich, 1967; Krassilov, 1975; Van Valen and Sloan, 1977). Paleotemperatures derived from oxygen isotope ratios in clacite fossil skeletons (Figs. 1,3) show that during the late Cretaceous the climate at high latitudes was also as warm as that of subtropical or warm temperate zone (Fischer and Arthur,1977). If the obliquity had been about 23.5° then, there would have been 97 continuous polar nights at 75°N as today. In such conditions there would have been no sunlight at all during 97 continuous days. It is well known that the sun is the single noteworthy source of heat for the earth's atmosphere. If there had been no sunlight at all during 97 continuous days, it is impossible that the climate there could have been so warm as that of subtropical or warm temperate zone. I am afraid both dinosaurs and plants of the late Cretaceous could not have lived in such conditions. Only if the obliquity was quite small, such as about 15°, was there no polar night at 75°N and could these facts mentioned above be explained

reasonably. These facts are conclusive evidence, demonstrating that the obliquity once became quite small during the late Cretaceous. In Fig. 4 the obliquity is about 15° during the late Cretaceous exactly.

According to the analysis in my previous paper, when the obliquity increases from 0° to 30°, the amount of summer insolation at 65°N would be greatly increased, while that of the winter at 35°N would be gradually decreased. At the same time the mean annual temperatre of the whole world would drop gradually. Obviously the fall of the mean annual temperature is in correspondence only with the decrease of the amount of winter insolation at 35°N, and not with the increase of the amount of summer insolation at 65°N. As a matter of fact, during the pleistocene the curve of the distribution of winter insolation at 35°N is exactly identical with the paleotemperature curve provided by Hays, Imbrie and Shackleton (1976). So are many other paleotemperature curves from the deep-sea sediments. The curve in Fig. 5 can tell you what period belonged to the cold stage; what period belonged to the warm stage; and in what period the cold (or warm) stage was colder or longer than the others; in what period the cold (or warm) stage was poorly expressed. I now feel more confident than ever that the fundamental cause of the third kind is the variations in the earth's orbital elements.

The conclutions are that there were at least three type of variation of obliquity. 1. Obliquity varied between 22.08° and 24.43°, with an average period of about 41,000 years (Vernekar, 1977). It was the variations in the earth's orbital elements (obliquity, eccentricity and longitude of perihelion) that caused the alternation of warm stage and cold stage during Quaternary Glaciation. 2. Obliquity fluctuated with an amplititude of about 5°—6° and with an average period of 32 million years (Fig. 4). It is the fundamental cause of the alternation of polytaxic and oligotaxic. 3. Obliquity fluctuated with an amplititude of about 10°—15° and with an average period of about 200 to 300 million years (Fig. 4). It is the fundamental cause of the alternation of glaciation and nonglaciation. The superposition of the three fluctuations represents the law of the variation of the obliquity in earth-history.