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Cesare Emiliani (1922–1995), pioneer of Ice Age studies and oxygen isotope stratigraphy

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Abstract – Cesare Emiliani established that the ice ages of the last half million years or so are cyclic phenomena, which gave strong support to the hypothesis of Milankovitch. He discovered the cycles when analyzing foraminifers from long deep-sea cores for their oxygen isotope composition (cores were from the Swedish Deep-Sea Expedition, from the Lamont collection and later from collections made at Miami). Emiliani's method has become the standard procedure for interpreting the deep-sea record in terms of ocean and climate history. Emiliani introduced a time scale suggesting that the cycles are typically 40 000 years in duration, and he defended this scale for almost 20 years. He also thought that temperature was a more important influence on oxygen isotope variations of the ocean than the buildup and decay of northern hemisphere ice sheets. Both these notions proved incorrect. However, his insistence that the Milankovitch mechanism, in conjunction with ice dynamics and crustal response to loading, is the driving force behind the climate cycles of the Quaternary proved well founded. ***To cite this article: W.H. Berger, C. R. Palevol 1 (2002) 479–487.*** © 2002 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

Cesare Emiliani / Ice Age / oxygen isotope stratigraphy

Résumé – Cesare Emiliani (1922–1995), pionnier des études sur l'Âge glaciaire et sur la stratigraphie par analyse des isotopes de l'oxygène. Cesare Emiliani a établi que les âges glaciaires du dernier demi-million d'années sont des phénomènes cycliques, ce qui va dans le sens de l'hypothèse de Milankovich. Il a découvert les cycles, en analysant la composition en isotopes de l'oxygène de Foraminifères en provenance de longues carottes de forage en mer profonde (carottes de l'expédition suédoise, de la collection Lamont et, plus tard, d'autres collections faites à Miami). La méthode d'Emiliani est devenue la procédure standard pour interpréter l'enregistrement en mer profonde, en termes d'histoire de la température et de l'océan. Emiliani a introduit une échelle de temps, suggérant que les cycles ont une durée de typiquement 40 000 ans et a défendu cette échelle pendant environ 20 ans. Il pensait aussi que la température avait une influence plus importante sur les variations de la composition isotopique de l'oxygène que la formation et la disparition des couches de glace de l'hémisphère nord. Ces deux notions se sont révélées incorrectes. Cependant, son insistance sur le fait que le mécanisme de Milankovich, en conjonction avec la dynamique de la glace et la réponse crustale à la charge, était la force motrice des cycles climatiques au Quaternaire, s'est révélée tout à fait fondée. ***Pour citer cet article : W.H. Berger, C. R. Palevol 1 (2002) 479–487.*** © 2002 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

Cesare Emiliani / Âge glaciaire / stratigraphie / analyse isotopique / oxygène

1. Introduction

In my opinion, three great revolutions in the Earth Sciences profoundly changed our thinking during the second half of the last century: (1) the Plate Tectonics revolution, (2) the Milankovitch revolution, (3) the Impact revolution. In all three of these, information from the deep-sea record was a key ingredient in establishing the new paradigm [23]: (1) during Leg 3, it was established, from microfossils, that ages of basal sediments support seafloor spreading, (2) isotopic micropaleontology delivered a viable time scale for the Late Quaternary, providing a useful yard stick for spectral analysis, (3) the original evidence for widespread and

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Fig. 1. Cesare Emiliani.

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sudden extinction came from planktonic nannofossils and microfossils, and verification of a global scale came from deep-sea drilling.

It is in this context of pelagic stratigraphy that the work of the Italian-American paleontologist and isotope geochemist Cesare Emiliani (Fig. 1) attains its outstanding importance. He introduced isotopic paleontology and stratigraphy to deep-sea studies and thereby opened the way to detailed and quantitative studies of the history of climate and ocean. His single most important contribution was the demonstration, in 1955, that the ice ages are part of long-term cyclic climate change, as Milankovitch theory predicts [10]. However, the confirmation of Milankovitch theory is commonly placed at a time 20 years later. The reason is that Emiliani introduced a time-scale for the Late Quaternary that proved incorrect. Ironically, he did so believing that Milankovitch theory was obviously confirmed and could therefore be used to support the time scale. A tight link between Milankovitch insolation and the record is no generally assumed and used to find time scales for cores, a practice known as 'orbital tuning'. The pitfalls inherent in the method have been emphasized in [25].

The most important thing in Quaternary research is to get the time scale right, so that one can pursue the problem of how the Milankovitch forcing is translated into climate change. There is no question that the correlation between high-latitude summer insolation and the oxygen isotope record within deep-sea sediments is the crucially important tool allowing this research to proceed, as first suggested by Emiliani. Thus, when commemorating Emiliani's wide-ranging contributions, the focus has to be on oxygen isotope stratigraphy. Emiliani's success in providing the basis for interpreting the isotope record, and his failure in getting the time scale right, are major themes in this story. A nearly correct time scale for the last third of the Quaternary was first given by Shackleton and Opdyke [28]. The basis for the time scale was the determination of the Brunhes–Matuyama boundary in this Lamont core. At the time, the age of the boundary was off by 15%, but the distortion of the piston core was such that this error was largely compensated for, as far as the upper portion of the core.

2. Claims to fame

Emiliani's contributions are well-recognized in the literature on paleoceanography. In my article (see [4]), I cite more first-author papers by Emiliani [17] than for any other colleague. B. Haq, in his review of paleoceanography, cites three of Emiliani's papers (all different from those cited by Berger) [4]. W. Hay, in his centennial review of paleoceanography [4], cites nine of Emiliani's contributions. Also, Emiliani himself was aware of his role as an innovator in the Earth sciences, and was not shy in making the corresponding claims. In his delightfully irreverent yet scholarly book 'Planet Earth' [16], he introduces himself as follows: "Cesare Emiliani holds a doctoral degree from the University of Bologna, Italy, and a PhD from the University of Chicago. *[Emiliani earned his first doctorate in geology (micropaleontology) from the University of Bologna, in 1945. He earned his second doctorate in 1950, working with the doyen of isotope chemistry Harold C. Urey in Chicago – author's note.]* At Chicago, he pioneered the isotopic analysis of deep-sea sediments as a way to study the Earth's past climates. He then moved to the University of Miami where he continued his isotopic studies and led several expeditions at sea. His work has revolutionized our understanding of climate dynamics and the ice ages. He was instrumental in initiating the Deep-Sea Drilling Project, now in its 25th year of operation, a project that finally revealed how the Earth works. *[Emiliani here combines the Deep-Sea Drilling Project, managed by Scripps Insti-*

tution of Oceanography, University of California, San Diego, and its successor, the Ocean Drilling Program managed by Texas A & M in College Station, Texas – author's note]. He is the recipient of the Vega Medal from Sweden and the Agassiz medal from the National Academy of Sciences of the United States. Cesare Emiliani is the author of several books and well over one hundred research papers."

This introduction is enlivened with a photograph that shows Emiliani's portrait at the center of an electronic transmission image of *Emiliania huxleyi*, a coccolithophorid that has evolved in the Latest Quaternary and is now widespread in all oceans. Of this species, Emiliani says ([16], p. 423): "The most abundant species living today in the world ocean is the coccolithophorid *Emiliania huxleyi*, with a standing crop of about 1 avogadro – *i.e.* 6×10^{23}, *the number of nucleons (protons and neutrons) in a gram of matter, author's note* – of cells. The total, worldwide number of living human cells is similar, also about 1 avogadro. Extinctive evolution predicts that both *Emiliania huxleyi* and *Homo sapiens* are candidates for extinction." Emiliani here implies that there is a price to be paid for success, in terms of high population density. Emiliani [17] makes the point that the negative feedback commonly assumed to control species populations through factors related to population density is not a smoothly operating mechanism in the case of virus infection, but is more likely related to a threshold density combined with rapid evolution of the virus. This instability produces 'extinctive evolution', he suggests.

In Part VI of his book ([16], p. 553), *The Historical Perspective*, Emiliani lists (by order of birth) "the people most responsible for producing the view of the world we now hold, together with their achievements." This sequence of entries allows us a ready view of what Emiliani considered important in the natural sciences, and especially the sciences that bear on his own interests. The entry for Alcide Desalines d'Orbigny (1802–1857) reads as follows (p. 569): "French specialist on Foraminifera, recognized 27 successive faunas and proposed 27 successive creations." Emiliani's list is not entirely reliable. The text for the entry for Friedrich Wilhelm von Humboldt actually refers to the travels and explorations of his brother Alexander. The name of Hans Pettersson, leader of the Swedish Deep-Sea Expedition 1947–1948, is misspelled. Other entries relevant in the present context are those for Milutin Milankovitch (1879–1958), Motonori Matuyama (1884–1956), Hans Pettersson (1888–1966), Harold Clayton Urey (1893–1981), Harry H. Hess (1906–1969), Willard Frank Libby (1908–1980), Luis Walter Alvarez (1911–1988), Alfred O. Nier (b. 1911), Sam Epstein (b. 1919), Cesare Emiliani (b. 1922), Harmon Craig (b. 1926), Neil Opdyke (b. 1933), Christopher G. A. Harrison (b. 1936), Nicholas John Shackleton (b. 1937), and Stephen Jay Gould (b. 1941).

Emiliani states the following about these scientists: Milankovitch proposed that "changes in insolation at different latitudes" were "the cause of the ice ages (this was confirmed by isotope analysis of deep-sea cores)." Matuyama "discovered that the Earth's magnetic field was reversed in the Early Pleistocene (1929)". Pettersson "led the Swedish Deep-Sea Expedition of 1947–1948, which opened the postwar era of oceanographic exploration". Urey "discovered a method for measuring paleotemperatures by oxygen-isotope analysis of marine carbonates". Hess "discovered guyots (1946) and proposed the theory of sea-floor spreading (1962)". Libby "developed the radiocarbon dating method at the University of Chicago (1948–1950)". Alvarez "discovered, together with his son Walter, the iridium excess at the Cretaceous–Tertiary boundary at Gubbio (Italy) and developed a theory of asteroidal impact (1978) to explain the observed extinctions at the end of the Cretaceous". Nier "improved the mass spectrometer, measured the isotopic compositions of many elements, and developed several dating methods". Epstein "developed the isotopic method of paleotemperature analysis and pioneered the study of stable isotopes in nature". Emiliani "applied oxygen-isotope analysis to deep-sea sediments and demonstrated the cyclic nature of the ice ages (1955)". Regarding this entry, Emiliani writes as follows ([6], p. 579: "After a brief battle between modesty and thoroughness, I decided to include my own name in this list, taking the description of accomplishments from Millar D., Millar I., Millar J., and Millar M. 1989. *Concise Dictionary of Scientists*. Chambers/Cambridge University Press, Cambridge, England, 461 p. This work profiles what those authors deem to be the 1,000 most prominent scientists of all time. Buy a copy of the book and see if your name is in there. If it is not, you may complain to Millar, Millar, Millar, and/or Millar." Craig "pioneered the application of stable-isotope analysis to the hydrosphere, to the biosphere, and to statuary". Opdyke "established a firm chronology for the Quaternary, in collaboration with Shackleton (1973)". Harrison "discovered magnetic reversals in deep-sea sediments". Shackleton "established a firm chronology for the Quaternary, in collaboration with Opdyke (1973)". Gould "proposed the theory of punctuated equilibrium, jointly with Niles Eldridge".

These scientists, we may infer, form Emiliani's peer group in his own judgment.

3. Interaction with the Foram experts

In a letter to the author (one-page letter, on the letterhead of the University of Miami, Department of Geological Sciences, P.O. Box 249176, Coral Gables, Florida 33124, dated February 11, 1994. Four lines of personal message concerning W.H.B. deleted, the rest given verbatim), Emiliani gives the following summary of his work as it concerns foraminifers and interactions with Fred B. Phleger and Frances L. Parker, leading experts on the biogeography and ecology of modern foraminifers:

"I was drafted into Urey's paleotemperature project by Heinz Lowenstam who wanted to know the isotopic composition of planktic forams (I was the only one in Chicago at that time who knew anything about forams). When, in 1951, Hans Pettersson came to Chicago and gave a talk about his famous expedition, I saw that deep-sea cores were the way to go. I visited him in Stockholm the following summer and he was most generous with samples from his cores – *the Albatross Expedition (1947–1948) is to paleoceanography what the Challenger Expedition was to oceanography; a total of 299 cores, with a combined length of 1.6 km, had been collected by the Albatross, using the new piston corer invented by B. Kullenberg. The other pioneers of paleoceanography working on these samples were Gustaf Arrhenius, Fred Phleger, Frances Parker, and Eric Olausson, author's note*.

"Because temperature drops fast with depth in the ocean, I was most interested in finding out the oxygen isotopic composition of planktic forams from plankton tows. Enter Fred B (no period) Phleger – *Fred B. Phleger (1909–1993); Phleger preferred using this form to using the name of his father, with the appendix 'Jr.', author's note* – (who had participated in the Caribbean leg of Hans Pettersson's cruise). He had tows from the Gulf of Mexico, which was just what I needed. He sent me the samples, I ran them, and quickly discovered that different species lived at different depths, mostly within the thermocline (which, as we all know, is well mixed). Neither Fred nor Frances Parker – *Frances Parker (1906–2002), micropaleontologist at Scripps, working in Phleger's laboratory, author's note* – could swallow that. In fact, after a brief talk I gave about this story at some meeting in the early 1950's I was ridiculed by Frances Parker, who could not stop laughing. If there was any notion of collaborating on a paper (of which I have no recollection, but it is possible – I have no access to my early correspondence because we are in the process of moving to Palm Beach and everything is packed), that was the end of it – *Emiliani here answers my question why no collaboration came about between him and the scientists at Scripps. Regarding the same question, Phleger told me that the amount of material needed by Emiliani was a problem, and that it was frustrating if a sample gave invalid results and a substitute had to be prepared all over, author's note*. I distinctly remember that I pointed out that the isotopes only indicated the depth at which shell deposition took place, not the depth at which the forams 'lived' as I had said in my talk. That was not enough, though. Some 15 years later Jim Jones, using opening and closing nets [22], showed that the forams actually lived at different depths. If I remember correctly, Fred did not buy this notion in his book on Recent Foraminifera (my copy of the book is packed away), even though I pointed out to him that the distribution of forams in sediments in his Gulf of Mexico transects fit the differential depth distribution that my isotopes indicated. Phleger [27] quotes Emiliani rather extensively (p. 218) but is critical of Emiliani's suggestions concerning the depth stratification of planktonic foraminifers.

"I should say that the discovery that forams are stratified came as a big surprise to me, like the cyclic nature of the isotopic record downcore. But then again, surprises in science are usually heralding interesting discoveries. If one dismisses the surprising evidence, one surely misses out on the discovery.

"Please note that the above story is according to my best recollection and without the help of the documentation (which is packed away)."

Emiliani also interacted with the micropaleontologist D.B. Ericson at the Lamont Geological Observatory. In fact, it appears that Ericson's assistance was of vital importance in producing the classic paper *Pleistocene temperatures*. Emiliani writes ([10], p. 547): "Isotopic analyses have been made of 12 cores. Eight were raised by the Swedish Deep-Sea Expedition of 1947–1948 and samples were furnished by Hans Pettersson of the Oceanografiska Institutet of Göteborg. The other four, identified by prefix 'A', were obtained from David B. Ericson, of the Lamont Geological Observatory. [...] The weight percentage of the fraction larger than 62 or 74 μ[m] was determined for all samples of the Atlantic and Caribbean cores. This was done for the fraction larger than 74 μ[m] by Ericson at the Lamont Geological Observatory for the Caribbean cores and Atlantic core A180–73." In the Acknowledgments ([10], p. 570), Emiliani thanks "Maurice Ewing and his associates D.B. Ericson and B.C. Heezen, for having made available and sampled the cores"; further, one reads that "the availability of the two Caribbean cores, which offer the best record of the Pleistocene temperature variations, was due to the efforts of Ewing and Heezen to obtain a section as undisturbed and as long as possible from the stratigraphic point of view, on the basis of their studies on deep-sea regional sedimentation in the Atlantic and adjacent basins".

D.B. Ericson provided the samples (rather than Ewing or Heezen). Ericson had generated standard profiles for the Late Quaternary of the tropical Atlantic of the presence and absence of *Globorotalia menardii* (d'Orbigny), a tropical planktonic foraminifer that thrives during warm periods but is absent during much of the cold periods (W. Schott, Die Foraminiferen in dem äquatorialen Teil des Atlantischen Ozeans, Wiss. Ergebn., Deut. Atlant. Exped. Meteor, 1925–1927 3 [1935] 43–134). By noting whether a core had a typical sequence of *G. menardii*, Ericson could check the stratigraphic quality of a tropical core (D.B. Ericson, G. Wollin, Correlation of six cores from the equatorial Atlantic and the Caribbean, Deep-Sea Res. 3 [1956] 104–125). This knowledge was invaluable in selecting cores for analysis, because of the effort involved in producing an isotope stratigraphy. Emiliani's decision to be sole author on his classic paper must have generated some disappointment at Lamont.

4. Major contributions and difficulties

The paper that made Emiliani famous was the article entitled, with studied simplicity, *Pleistocene Temperatures* [10]. Few contributions to the problem of ice age climates are equal in importance to this article, yet much of the interpretation is now considered incorrect, from the time scale to the range of temperature variation. Thus, the importance of the paper was not in the particular results it presented, but in the way it opened an entirely new field of investigation with immense opportunities for learning about climate change.

The heart of the new science is the oxygen isotope method for determining paleotemperature, invented by Urey, refined by McCrea, and further refined by Epstein and colleagues by experimentation with shells of molluscs grown in controlled conditions [29]. The method is based on the fact that when in thermodynamic equilibrium calcite and seawater differ in their ratios of ^{18}O to ^{16}O, and this difference decreases with increasing temperature. Shells precipitated in equilibrium with seawater are enriched in ^{18}O relative to seawater, but less so at higher temperatures. The equation relating temperature of precipitation to the oxygen isotopic composition of the mollusc shells was found as:

$$T = 16.5 - 4.3\,(\delta - A) + 0.14\,(\delta - A)^2 \qquad (1)$$

This is the equation used by Emiliani [2], based on the work by Epstein et al. (see [29]). It is still in use today. The δ-value is the difference in the isotope ratios of sample and standard, as permil of the standard:

$$\delta = 1000\,(R_{\text{sample}} - R_{\text{standard}})/(R_{\text{standard}}) \qquad (2)$$

where R stands for the ratio between the two isotopes $^{18}O/^{16}O$.

The term A is the δ of the seawater within which the sample (calcitic shell, foraminifer) was precipitated. It is usually not known and must be guessed at, before the temperature T can be calculated. The standard usually is taken as 'PDB', for a belemnite from the Pee Dee formation in South Carolina that was originally analyzed by Urey's group.

On the scale of ice-age climate fluctuations, **A** varies because polar ice caps are impoverished in ^{18}O (or enriched in ^{16}O, which is saying the same thing), which has the effect of changing the isotopic composition of seawater, since the overall average ratio between the two isotopes is preserved. Emiliani was well aware of this effect, as well as of direct effects of evaporation and precipitation – he acknowledges Harmon Craig, then in the same laboratory in Chicago, for "much helpful advice and fruitful discussion on isotope chemistry and geochemistry, and for having critically read the manuscript" ([10], p. 571). He applies a 'correction' to the measured foraminifer δ-values, based on modern deviations of surface water δ-values from the ocean average. The justification for this, by today's standards, is a bit of a stretch ([2], p. 551): "Application of modern values to fossil samples seems reasonable on the basis of the apparent constancy of oceanic circulation through time (Schott, 1935; Arrhenius, 1952; Ericson, 1953)." The cited works can be equally well read as an argument for changes in circulation, rather than constancy.

Emiliani carefully lists the various problems that interfere with reading the oxygen isotope record in terms of paleotemperature (the ice effect, geographic variation in isotopic composition, vital effects, seasonal growth of shells, growth of foraminifers at depth in the water). Nevertheless, he presents his data as indices of 'isotopic temperature' in his graphs. The uncertainty about the glacial-interglacial contrast in each of the different factors introduces errors somewhere between 0.3 and 2 °C, and the errors are more or less additive. Thus, when Emiliani plotted, say, a range of 7 °C for the glacial–interglacial contrast in the Caribbean, the uncertainty was of the order of 3 °C – making the quantitative aspect questionable. This problem was well appreciated by the community at large, and especially by critics. It was pointed out to me in a geology freshman course, in 1959, in Germany, that the temperature ranges were unsubstantiated. This uncertainty affected acceptance of the other aspects of Emiliani's work as well, including the notion of cycles.

The glacial effect, that is, the amount of global change in δ-value of seawater, as a consequence of the buildup and decay of polar ice, proved to be the bugbear of Emiliani's interpretation. Emiliani estimated an overall increase of about 0.4 permil over present values for this effect. With an isotopic range near 2 permil for the contrast between warm and cold periods in the Caribbean, this left 1.6 permil to be explained by temperature (assuming all other factors did not change the range, but merely offset absolute values). From this emerges the seven-degree range in temperature seen in the surface-water species (*Globigerinoides ruber, Globigerinoides sacculifer*) in Emiliani's graph ([10], fig. 2). In the abstract of "Pleistocene Temperatures", Emiliani writes ([2], p. 538): "Oxygen isotopic analyses of pelagic Foraminifera from Atlantic, Caribbean, and Pacific deep-sea cores indicate that the temperature of superficial waters in the equatorial Atlantic and Caribbean underwent periodic oscillations during the Pleistocene with an amplitude of about 6 °C. The temperature record of the Pacific cores was much affected by local oceanographic conditions."

In fact, it was the values found for the Pacific cores that proved especially difficult to reconcile with a glacial effect larger than about 0.5 permil. The values obtained for material from the equatorial Pacific (supplied by Gustaf Arrhenius) were based on the analysis of *Globorotalia tumida*, presumably because this species was still present in considerable quantity after others had been dissolved. The warm-to-cold-period ranges seen are between 0.5 and 0.8 permil, approximately, suggesting very small temperature fluctuations, even when applying the minimal 0.4 permil glacial effect. Of course, if a greater glacial effect were to be applied, the temperature in the region would fluctuate in reverse to the glacial-interglacial cycles. The paradox may have arisen because of the stronger preselection of heavy shells by increased dissolution during interglacial periods (see discussion in [5]). Emiliani ([10], p. 544) writes: "The figure of 0.4 per mil depends upon an estimate of the amount of ice formed during the ice ages, and therefore it may not be correct. There are good reasons, however, to believe that it cannot be far from the true value. Apart from the geological evidence [...], certain isotopic temperatures to be presented later indicate that the isotopic composition of sea water could not have undergone a change greater than that mentioned, or true glacial temperatures would be higher than interglacial ones."

The generally accepted value for the ice-linked range (near 1.2 permil in the ocean) was suggested by Eric Olausson in 1965, and again by N.J. Shackleton (in 1967) [26]. Ironically, this same value of 1.2 permil emerges when analyzing the delta-values for benthic foraminifers given by Emiliani ([10], table 14). The minimum and maximum values (average of two extremes) listed are as follows: Atlantic interglacial, 2.6 permil; Atlantic glacial, 4.2 permil, for a difference of 1.6 permil. Pacific interglacial, 3.15 permil; Pacific glacial, 3.95 permil; for a difference of 0.8 permil. The average change is 1.2 permil, and presumably largely reflects the glacial effect, assuming little change in deepwater temperatures. (In fact, such an assumption would be arbitrary, of course.) Emiliani used mixed species for the benthic determinations, which makes results questionable. Only the ice cores themselves could give some confidence that the value of 1.2 permil is indeed a good one to work with, assuming that the remaining ice masses on Greenland more or less reflect the composition of the ice masses once covering northern North America and Scandinavia. The isotopic composition of Greenland ice was established through deep sampling [9]. To get the glacial effect from this one needed to assume that the Greenland isotopic composition reflects the composition of the vanished northern ice sheets. But the mass of these sheets still had to be estimated from sea-level change. The uncertainty in this estimate at the time Emiliani grappled with the question was around + 30 percent. Emiliani put the most likely sea-level range at 100 m (a round number reflecting the large uncertainty). A value near 120 m with an uncertainty near 10% would include most modern estimates.

In the discussion of the glacial effect, Emiliani showed a remarkable resistance to adjusting his low estimate, presumably because of the constraints posed by the Pacific samples, with their small glacial-interglacial range. In the 1966 paper of reference [13], he states that the glacial–interglacial variation of the Pacific bottom waters (and hence probably of the ocean as a whole) could not have exceeded 0.5 permil by very much (p. 120). This is repeated in the 1971 article of reference [13]. As late as 1970, he writes ([14], abstract): "The generalized isotopic paleotemperature curve reproduces absolute temperatures to within 1 °C; it closely reflects faunal changes; and its time scale is correct to within a very few percent back to at least 175 000 years. The average oxygen isotopic composition of the North American and European ice caps was about –9 per mil." Inspection of his graph ([14], fig. 1) shows that his time scale is off somewhere near 30 percent, for this interval. The ice cap composition is now taken as near –30 per mil, which means his estimates for temperature ranges were off by roughly three degrees.

However, the stages he assigned to glacials and interglacials, back to Stage 17, are now part of the master stratigraphy of Quaternary history. Also, the fact that correlation between cores from different regions is excellent [11] has become indispensable in doing paleoceanography, including the production of synoptic maps for “time slices”.

Emiliani’s problem with the time scale stemmed largely from his conviction that Milankovitch theory would provide a template for the chronology (a concept now widely accepted and used). Thus, whenever someone questioned his time scale, he reacted as though they were attacking Milankovitch theory. Unfortunately, his original attempts to extrapolate sedimentation rates downcore, from radiocarbon dates, had a low chance of success, because the upper portion and lower portion of cores tend to be disturbed in different ways during the coring process. Emiliani made the transition toward the modern time scale in 1974 [20], when realizing that Broecker’s reef-based scale was supported by the results of Shackleton and Opdyke [8, 28]. The relevant text reads as follows ([20], p. 512): “[The] age of 120 000 years for the temperature peak of stage 5 [from V28-238] [...] compares favorably with the age of 120 000 years for the fossil coral reefs dated by various authors [citing Broecker et al. 1968; Veeh, 1966; Veeh and Chappell, 1970] and interpreted as representing high stands of sea level.” As mentioned, this fit between the time scales was in part a matter of good luck [28]. The modern value for the Barbados III datum (first and warmest substage of Stage 5) is 125 000 years. This date is supported by the data compiled by Emiliani and Rona (1969) as plotted in Berger (1977) [3].

Emiliani was concerned with time resolution and the effects of mixing, and considered that “reworking by bottom organisms reduces the time resolution of deep-sea cores of normal ‘Globigerina-ooze’ facies to a few thousand years”. ([11], p. 264). The transitions from cold to warm intervals, in many of his isotope stratigraphies, are clearly rather abrupt. It appears that Emiliani was inclined to think of sediment disturbance as a way to produce sudden change ([12], p. 531). He doubts that observations on cores, purporting to document extremely rapid change [7], have a basis in reality (ibid.): “Broecker et al. (1958, 1960) have marshalled evidence suggesting that an abrupt temperature rise may have occurred within a few hundred years about 11 000 years ago. The deep-sea cores, generally, do not show such an abruptness, probably a result of sediment reworking by bottom animals.” At the same time, he realizes that rapid change clearly needs to be addressed, given the evidence from the oxygen isotope stratigraphies (ibid.): “Disappearance of sea ice in the northern North Atlantic and elsewhere, causing a decrease of albedo, may explain the rapidity of the temperature rise (Emiliani and Geiss, 1959). Sea ice, in fact, is thin and can be melted away very rapidly.” Perhaps his familiarity with the last deglaciation prevented him from following this idea further. The last deglaciation, of course, is a poor example for sudden change, since it shows a complicated isotopic signal with two or three steps ([10], fig. 8). Concerning sudden change, then, Emiliani apparently erred on the side of caution. It was left to Broecker [6] to boldly draw the ‘terminations’ on top of Emiliani’s stratigraphy, thus introducing this very fruitful concept into the thinking about the ice ages. Emiliani subsequently elaborated on the sudden release of meltwater to the Gulf of Mexico, late during deglaciation [21].

Milankovitch had proposed that the ice ages were cyclic and that they were a result of changing summer insolation in high latitudes (that is, of seasonality). When insolation in summer is relatively strong, snow and ice melts; when weak, some of it stays till next winter and helps build up ice [24]. Emiliani was aware that insolation changes alone (the Milankovitch mechanism sensu stricto) are not sufficient to produce ice ages. In a paper with Geiss [18], he proposed an expanded theory, including ice-sheet and earth-crust dynamics, with the Milankovitch mechanism as a triggering and timing agent. This combination of factors is now considered correct, in principle [2]. It contains the ‘slow physics’ necessary to explain why the spectrum of the response is greatly shifted toward longer periods, compared with the spectrum of the forcing, and especially toward multiples of precession and of obliquity. The abstract of [18] summarizes the theory, and the introduction disclaims originality, as follows (p. 576): “The Pleistocene, and possibly also other, older glaciations, are believed to have resulted from a combination of terrestrial and astronomical factors. Preceding glaciations, orogenesis and uplift increased the Earth’s albedo and decreased temperature. Lowering of temperature below a certain threshold value permitted the astronomical cause to become operative. While smaller glaciations may have been largely or entirely patterned by the astronomical cause or causes, terrestrial factors had an important effect in determining the course of the larger glaciations. Two time-delay factors are believed to have been responsible for the oscillatory pattern of glaciation: these are plastic ice-flow, and crustal warping. Summer insolation variation in the high latitudes is believed to be a more likely astronomical cause than variation of solar radiation.” And further: “No claim of originality is made for many of the ideas discussed below, which have been presented in one way or another by many different authors during the last 50 or 100 years."

Many other contributions could be cited here, to round out the remarkable career of this Renaissance man among Earth scientists. Emiliani was very interested in the cooling of the planet since the Eocene, and he played an important role in stimulating progress concerning deep drilling for paleoceanographic purposes, a role he has described in the epilog to the tome *The Oceanic Lithosphere* [15]. Working with Earth systems all through his professional life, he became very concerned with human impacts on the environment, and the feedback of this impact on the quality of life. Thus, in the preface to his book Planet Earth [6], he writes:

"Our planet is at risk. The current explosion in the human population is forcing us to a simple but pivotal choice: stabilize the planet or perish. The first few decades of the next century will bring grave crises – environmental, economic, human. Only if we achieve a close understanding of the system of which we are part – how it came about and how it works – will the next generation be positioned to cope with the emerging problems."

5. Conclusions

In lieu of a summary of the many contributions of Emiliani, here is his own view of how our understanding of the Quaternary was impacted by developments in his days ([19], p. 126): "The invention of the piston corer by B. Kullenberg (1944–1945), the discovery of the ^{14}C dating method by W.F. Libby (1946–1951), and the discovery of the $^{18}O/^{16}O$ method of paleotemperature measurement by H.C. Urey (1947–1951) have drastically changed our picture of the Pleistocene period. While, before, this period was viewed as consisting of four great glaciations separated by four interglacials, ranging across the past million years or so, we have seen emerging a picture of rapidly alternating glacial and interglacial ages each lasting only a few tens of thousands of years. The first intimation toward this picture was provided by Arrhenius' analysis of the piston cores from the eastern equatorial Pacific (Arrhenius, 1952) [1], and more conclusive evidence was provided by $^{18}O/^{16}O$ analysis of piston cores from the Atlantic and the Caribbean (Emiliani, 1955)."

References

[1] G.O.S. Arrhenius, Sediment cores from the east Pacific, Rep. Swed. Deep-Sea Exped. 1947–1948 5 (1) (1952) 1–227.

[2] A. Berger, J. Imbrie, J. Hays, G. Kukla, B. Saltzman (Eds.), Milankovitch and Climate, 2 vols, Reidel, Dordrecht, The Netherlands, 1984 895 p.

[3] W.H. Berger, Carbon dioxide excursions and the deep-sea record: aspects of the problem, in: N.R. Andersen, A. Malahoff (Eds.), The Fate of Fossil Fuel CO_2 in the Oceans, Plenum Press, New York and London, 1977, pp. 505–4542; C. Emiliani, E. Rona, Caribbean Cores P6304-8 and P6304-9: new analysis of absolute chronology. A reply, Science 166 (1969) 1551–1552.

[4] W.H. Berger, Paleoceanography: the deep-sea record, in: C. Emiliani (Ed.), The Oceanic Lithosphere. The Sea, Vol. 7, John Wiley and Sons, 1981, pp. 1437–1519; B.U. Haq, Paleoceanography: a synoptic overview of 200 million years of ocean history, in: B.U. Haq, J.D. Milliman (Eds.), Marine geology and oceanography of Arabian Sea and coastal Pakistan, Van Nostrand Reinhold, New York, 1984, pp.201-231; W.W. Hay, Paleoceanography: a review for the GSA centennial, Geol. Soc. Am. Bull. 100 (1988) 1934–1956.

[5] W. Berger, J.V. Gardner, On the determination of Pleistocene temperatures from planktonic foraminifera, J. Foraminifer. Res. 5 (2) (1975) 102–113.

[6] W.S. Broecker, J. van Donk, Insolation changes, ice volumes, and the O^{18} record in deep-sea cores, Rev. Geophys. Space Phys. 8 (1970) 169–198.

[7] W.S. Broecker, M. Ewing, B.C. Heezen, Evidence of an abrupt change in climate close to 11 000 years ago, Am. J. Sci. 256 (1960) 503–517.

[8] W.S. Broecker, D.L. Thurber, J. Goddard, T.L. Ku, R.K. Matthews, K.J. Mesolella, Milankovitch hypothesis supported by precise dating of coral reefs and deep-sea sediments, Science 159 (1968) 297–300.

[9] W. Dansgaard, H. Tauber, Glacier oxygen-18 content and Pleistocene ocean temperatures, Science 166 (1969) 499–502.

[10] C. Emiliani, Pleistocene temperatures, J. Geol. 63 (6) (1955) 538–577.

[11] C. Emiliani, Paleotemperature analysis of Core 280 and Pleistocene correlations, J. Geol. 66 (1958) 264–275.

[12] C. Emiliani, Cenozoic climatic changes as indicated by the stratigraphy and chronology of deep-sea cores of Globigerina-ooze facies, Ann. N. Y. Acad. Sci. 95 (1) (1961) 521–536.

[13] C. Emiliani, Paleotemperature analysis of Caribbean cores P6304-8 and P6304-9 and a generalized temperature curve for the past 425 000 years, J. Geol. 74 (2) (1966) 109-126; C. Emiliani, The amplitude of Pleistocene climatic cycles at low latitudes and the isotopic composition of glacial ice, in: K.K. Turekian (Ed.), The Late Cenozoic Glacial Ages, Yale Univ. Press, New Haven, Connecticut, 1971, pp. 183-197; C. Emiliani, Quaternary paleotemperatures and the duration of the high temperature intervals, Science (1972) 398–400.

[14] C. Emiliani, Pleistocene paleotemperatures, Science 168 (1970) 822–825.

[15] C. Emiliani, A new global geology, in: C. Emiliani (Ed.), The Oceanic Lithosphere. The Sea, vol. 7, Wiley-Interscience, New York & Chichester, 1981, pp. 1687–1728.

[16] C. Emiliani, Planet Earth – Cosmology, Geology, and the Evolution of Life and Environment, Cambridge University Press, Cambridge and New York, 1992, 717 p.

[17] C. Emiliani, Extinction and viruses, BioSystems 31 (1993) 155–159.

[18] C. Emiliani, J. Geiss, On glaciations and their causes, Geol. Rundsch. 46 (2) (1959) 576–601 (1957).

[19] C. Emiliani, J.D. Milliman, Deep-sea sediments and their geological record, Earth-Sci. Rev. 1 (1966) 105–132.

[20] C. Emiliani, N. Shackleton, The Brunhes, Epoch: isotopic paleotemperature and geochronology, Science 183 (1974) 511–514.

[21] C. Emiliani, S. Gartner, B. Lidz, K. Eldridge, D.K. Elvey, T.C. Huang, J.J. Stipp, M.F. Swanson, Paleoclimatological analysis of Late Quaternary cores from the northeastern Gulf of Mexico, Science 189 (1975) 1083–1088.

[22] J.I. Jones, Significance of distribution of planktonic foraminifera in the Equatorial Atlantic Undercurrent, Micropaleontology 13 (1967) 489–501.

[23] A.E. Maxwell, R.P. von Herzen, K.J. Hsü, J.E. Andrews, T. Saito, S.E. Percival, E.D. Milow, R.E. Boyce, Deep sea drilling in the South Atlantic, Science 168 (1970) 1047–1059; J.D. Hays, J. Imbrie, N.J. Shackleton, Variations in the Earth's orbit: pacemaker of the ice ages, Science 194

(1976) 1121–1132; N.G. Pisias, Late Quaternary variations in sedimentation rate in the Panama Basin and the identification of orbital frequencies in carbonate and opal deposition rates, Geol. Soc. Am. Mem. 145 (1976) 375–391; W.A. Berggren, Some planktonic foraminifera from the Maestrichtian and the Danian stages of southern Scandinavia, Stockholm Univ. Contrib. Geol. 9 (1962) 1–106; H.P. Luterbacher, I. Premoli-Silva, Biostratigrafia del limite Cretaceo–Terziario, Riv. Ital. Paleontol. 70 (1964) 67–128; M.N. Bramlette, Massive Extinctions in the Biota at the End of Mesozoic Time, Science 148 (1965) 1696–1699; H.R. Thierstein, H. Okada, The Cretaceous/Tertiary boundary event in the North Atlantic, Initial Rep. Deep Sea Drilling Proj. 43 (1979) 601–616.

[24] M. Milankovitch, Mathematische Klimalehre und astronomische Theorie der Klimaschwankungen, Handbuch der Klimatologie, Bd 1, Teil A, Bornträger, Berlin, 1930, 176 p.

[25] R.A. Muller, G.J. MacDonald, Simultaneous presence of orbital inclination and eccentricity in proxy climate records from Ocean Drilling Program Site 806, Geology 25 (1) (1997) 3–6.

[26] E. Olausson, Evidence of climatic changes in North Atlantic deep-sea cores, with remarks on isotopic paleotemperature analysis, Prog. Oceanogr. 3 (1965) 221–252; N. Shackleton, Oxygen isotope analyses and Pleistocene temperature reassessed, Nature 215 (1967) 15–17.

[27] F.B. Phleger, Ecology and Distribution of Recent Foraminifera, The Johns Hopkins Press, Baltimore, 1960, 297 p.

[28] N.J. Shackleton, N.D. Opdyke, Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific Core V28–238: oxygen isotope temperatures and ice volume on a 10^5-year and 10^6-year scale, Quat. Res. 3 (1973) 39–55; W.H. Berger, T. Bickert, H. Schmidt, G. Wefer, M. Yasuda, Quaternary oxygen isotope record of pelagic foraminifers: Site 805, Ontong Java Plateau, Proc. Ocean Drilling Program, Scientific Results 130 (1993) 367.

[29] H.C. Urey, 1947. The thermodynamic properties of isotopic substances, J. Chem. Soc.(1947) 562–581; J.M. McCrea, On the isotopic chemistry of carbonates and a paleotemperature scale, J. Chem. Phys. 18 (1950) 849–857; S. Epstein, R. Buchsbaum, H.A. Lowenstam, H.C. Urey, Carbonate-water isotopic temperature scale, Geol. Soc. Am. Bull. 62 (1951) 417–426; H.C. Urey, Revised carbonate-water isotopic temperature scale, Geol. Soc. Am. Bull. 64 (1953) 1315–1325.