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The Tooth of Time: Cesare Emiliani

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It's funny how a seemingly minor event in graduate school can take on deeper meaning later on. We had a day to kill after a long drive from Baltimore to Miami through the Deep South. It was 1967 and we had long hair. Carbonate sedimentologist Bob Ginsburg had come to Johns Hopkins two years earlier, bringing Paleozoic limestones back to life in Florida Bay, the Florida Keys and Great Bahama Bank. He had to spend the day bartering with boat operators but he suggested we attend a talk on forams at the Institute of Marine Science (University of Miami). To be honest, I don't remember much about the substance of the talk, except that the shells of one foram species coil to the left where it is cold and to the right where it is warm—just like American politics. But I remember the speaker, a fast-talking, high-voltage Italian whose presentation was so charged with conviction that for years afterwards I gave all Linnean names an emphatic Bolognese accent in his honour. Only decades after the fact did I begin to appreciate the historic circumstances of Emiliani's talk in Miami.

Emiliani studied micropaleontology and published on Cretaceous and Pliocene forams in wartime and post-war northern Italy. He won a Fellowship to University of Chicago in 1948 and was recruited by Harold Urey into his research group, which was dedicated to realizing the dream that "such a transient physical quantity" as the temperature of seawater could be faithfully recorded in rocks for a hundred million years or more (1). The group included engineer Charles McKinney (who supervised the construction of a duplicate mass spectrometer to the one designed by Al Nier in Minneapolis), Urey's graduate student John McCrea and Sam Epstein, a postdoctoral chemist with an interest in geology from Winnipeg by way of McGill. Urey, a Nobel laureate in chemistry in 1934 (age 41), was the most important American Earth scientist of the 20th century, remarkable considering that he devoted only a dozen papers and a tiny fraction of his career to Earth science. As Karl Turekian recently remarked, "Geochemists are often accused of acting like God. There are good reasons for this."

In 1946, Urey had been asked (by Paul Niggli) after a talk at ETH in Zürich whether it might be possible, given that rainwater was isotopically lighter than seawater, to distinguish marine and continental carbonates by isotopic analysis. Urey did some calculations and discovered that there was a measurable temperature effect to contend with. "I suddenly found myself with an isotopic thermometer in my hands." he said (2). Not quite. The resolution of their mass spectrometer had to be improved by a factor of ten. And they had to figure out how to extract CO_2 gas from carbonate shells without contamination from the embedded organic matter, a problem Epstein solved by a method still used today (3). By 1951, Urey's group had perfected the measurement of paleotemperatures in ancient carbonates and were able to show that a 150-million-year old belemnite from the Isle of Skye had lived for four winters and three summers at temperatures ranging from 15 to 21°C, and that the winters grew progressively colder during its lifetime. Urey hoped to test the idea that climate change was responsible for the extinction of the dinosaurs, but the results were inconclusive. Emiliani would take Urey's paleothermometer in a new direction.

Emiliani reasoned that younger carbonate would be better preserved and that the Pleistocene was a logical target because of large temperature changes associated with the ice ages. He had studied a Pleistocene foraminiferal section near Bologna and had proposed a paleoenvironmental proxy based on foram dimensional variability (prosperity brings uniformity). In 1951, he sampled a Lower Pleistocene section in the Palos Verdes Hills of Los Angeles, finding strong oxygen isotope variations. But correlation with existing ice age chronology, hopelessly tied to 50-year-old work on the north slope of the eastern Alps—Günz, Mindel, Riss, Würm—was impossible. The same year, he heard a lecture by Hans Pettersson describing recent Swedish innovations in deep-sea piston coring. Cores from the Swedish Deep-Sea Expedition of 1947-48 showed quasi-periodic variations in calcium carbonate content, which Gustaf Arrhenius had interpreted in terms of glacial (higher content) and interglacial (lower content) cycles. Arrhenius numbered the glacial (even numbers) and interglacial stages (odd numbers) counting backward from the present interglacial, a scheme later transferred to isotope records. Emiliani saw his chance and visited Göteborg, obtaining samples from a number of Atlantic and Pacific deep-sea cores. These were supplemented by samples Urey obtained from Maurice Ewing at Lamont from the Atlantic and Caribbean. In two of the Swedish cores, much sediment was missing and the core tops, the first samples to be analyzed, turned out to be Miocene and Oligocene in age, based on their benthic forams. Isotopic analysis of these same forams showed that deep-ocean bottom water temperature was 7°C in the Miocene and 10°C in the Oligocene, compared with 2°C today. Emiliani had found a first-order climate change in deep time in spite of himself (4).

Not everything would come so easily. The problem for Pleistocene paleotemperature is that the isotopic composition of seawater is neither uniform nor invariant over time. Epstein and Toshiko Mayeda had shown that the subtropical surface waters are heavy, due to net evaporation, while equatorial waters, estuaries and the Arctic Ocean (a large estuary) are light. During an ice age, the entire ocean becomes heavier in proportion to the volume and degree of isotopic depletion of the ice sheets. Emiliani was acutely aware that temperature and ice volume have complementary isotopic consequences for foraminiferal calcium carbonate, but in what proportions? He went to great lengths to show that the saw-tooth changes in the oxygen isotopes of specific pelagic forams he observed down-hole correlate with changes in foraminiferal speciation and size, then the more established proxy for environmental stress. He studied the depths at which different foraminiferal species live as a means of disentangling temperature from ice volume isotopically. He reasoned that temperature change during glacial-interglacial cycles was greater in surface waters than at depth. Deeper-dwelling species should therefore show less isotopic change than shallower ones if temperature was the main determinant, but all depths should change in lock-step if ice volume was in sole control. He selected four species of planktonic forams that live at different depths and analyzed them independently. Comparing the down-hole curves, Emiliani concluded that about 60% of the variance was temperature and 40% was ice volume (5).

This was not the first time invertebrate paleontology played a pivotal role in the struggle to understand the ice ages. In 1836, the celebrated Scottish yachtsman, conchologist and Biblical scholar James Smith (1782-1867) of Glasgow—not to be confused with the English map-maker—first used the term “till” in a geological sense, for a “stiff unstratified clay, confusedly mixed with boulders” (6). Together with overlying stratified clays and gravels, till forms what was then called the Diluvium, or Drift, of Newer Pliocene age. (The name Pleistocene was introduced by Lyell in 1839 but he disavowed it. The name was not used during the great controversy over the glacial theory of 1837-1865.) Smith sailed extensively and dredged for shells in the Clyde Estuary and the Arctic North Atlantic. He observed that indigenous (not reworked) marine fauna, mainly molluscan, occur sparingly in the tills and abundantly in the stratified Drift, up to hundreds of feet above contemporary sea level. He also pointed out that the

Drift fauna of Scotland more closely resembled his Arctic collections than those of the Clyde (7), an inference subsequently confirmed by Edward Forbes (8). The first observation created a major stumbling block for the glacial theory, which predicted a large sea-level fall just when the fauna in the lowland Drift indicated submergence (9). There were no marine fossils in the Alpine glacial deposits and hence the Swiss proponents the glacial theory had no explanation for submergence, a problem not resolved until long after the glacial theory was finally accepted (10). Smith's second observation created a problem for climate physics. It was then widely assumed that global climate could only get colder over time as the Sun grew dimmer through the loss of radiant heat. Europe was experiencing the last advance of the Little Ice Age, so there was historical as well as geological (paleobotanical) evidence for climatic cooling. The faunal evidence for a geologically recent warming implied that climate change was bidirectional, a challenge to physics that led explicitly to the experimental demonstration of the so-called greenhouse effect by the Irish-English physicist John Tyndall in 1861 (11). Never underestimate the power of humble mollusca.

Fast forward 100 years to 1961. Teddy Bullard, head of Geodesy and Geophysics at Cambridge University was now convinced that Emiliani's application of Urey's paleothermometer held great promise, and a new stable isotope lab dedicated to paleotemperatures was established in the Quaternary Research unit at Cambridge. The lab would reflect nearly 15 years of technical improvements since Urey's mass spectrometer was installed at Chicago. Setting up the new lab would be the PhD project(!) for a recent Cambridge physics graduate and son of the East Africa field geologist Robert Shackleton. Nick Shackleton was up to the task and by 1967, the year of his PhD (and my trip to Miami), the Cambridge lab was producing data more precise than the Chicago lab (12). But the crux of the problem wasn't precision, it was the same uncertainty plaguing Emiliani, now at the University of Miami: the effect of seawater temperature versus global ice volume on oxygen isotopes in carbonate. Both Emiliani and Shackleton did mass-balance calculations, based on estimated volumes and isotopic compositions for peak glacial and interglacial ice sheets: Emiliani's estimate of the mean isotopic depletion of the Laurentide ice sheet was –15‰ PDB, less than half the value calculated by Eric Olausson in Göteborg (based on Wili Dansgaard's data from Greenland), subsequently confirmed by Shackleton (13). The result was that Emiliani's calculation underestimated the ice-volume effect by a factor of two.

Shackleton reasoned that abyssal bottom water could not have been much colder during ice ages because it is close to the freezing point today. So he measured the compositions of coexisting planktonic and benthic forams in two samples spanning the last glacial-interglacial transition in a tropical South Pacific deep-sea core. He supplemented his data with paired benthic-planktonic results from Atlantic and Caribbean cores published by Emiliani. Because benthic forams are larger and less abundant, fewer individuals contributed to each analysis: the result was scatter in the data because bioturbation can disturb the mean age of a few shells more readily than a few hundred, leading to asynchroneity between the two populations in a sample. Nevertheless, the best-fit line in a benthic-planktonic cross-plot of the data had a slope close to unity—as much isotopic change in bottom water as surface water (14). This meant that ice volume was the dominant factor.

Shackleton's paper (14) appeared in Nature on 01 July 1967 and was a direct attack on Emiliani's assertion that foram isotope change was predominantly a paleotemperature record. Despite the uncertainty as to whether I heard Emiliani on my first trip to Miami with Ginsburg (Spring 1967) or my second (Spring 1968), it is likely that Emiliani knew what was coming, even if it hadn't yet arrived. Moreover, the dagger had a twist. Shackleton needed to explain why Emiliani's planktonic species from different depths did not change in lock-step, as they should do if the composition of seawater, not its temperature, was in control. Recalling an argument put forward by oceanographer Wally Broecker, Shackleton suggested that because the glacial ocean was saltier, planktonic forams had risen into warmer waters due to buoyancy. Emiliani appears to have neglected this factor and it must have galled the foram specialist to be caught out by a newly-minted PhD geochemist. But then Shackleton showed his class. In conclusion, he wrote, Emiliani's curves become even more valuable because they constitute a direct record of the ice ages, not an indirect record through seawater temperature (14).

The ice-volume only paradigm prevailed for twenty years before the tide turned again in the 1990s as data from terrestrial climate records (palynology, tropical snow-line elevations, noble gases in tropical groundwater), porewaters from deep-sea cores, and new paleothermometers (Mg/Ca, Sr/Ca, alkenone unsaturation index) confirmed that the tropics did cool significantly during glacial maxima after all. Today the respective contributions of temperature and ice volume to the foram isotope record are thought to lie about halfway between Shackleton's estimate and Emiliani's.

Both went on to greatness. In 1967, Emiliani was appointed Chairman of Geology and Geophysics at the Marine Institute (later Rosenstiel School of Marine and Atmospheric Sciences) and of Geological Sciences on the main campus of the University of Miami, positions he held until his retirement in 1993. He was instrumental in the establishment of the Deep-Sea Drilling Project by NSF in 1968, with its emphasis on paleoenvironmental records (15). Versed in the classics and virtually all of science and its history, he was a spell-binding teacher and his textbook, Planet Earth (1992), and The Scientific Companion (1987, 1995) filled a niche now occupied by Wikipedia.

Shackleton became a key participant in CLIMAP, a multi-institutional NSF project to reconstruct LGM (last glacial maximum) sea-surface temperatures globally, as a boundary condition for climate models. Resulting collaborations at Lamont led to the recognition with magnetostratigrapher Neil Opdyke of Pacific Core V28-238 from the Solomon Plateau, which yielded a beautiful isotope record of 22 stages, tied for the first time to the Brunhes-Matuyama geomagnetic reversal (0.78 Ma) in stage 19 (16). The isotope record from V28-238 could be correlated stage by stage with Emiliani's records from the opposite side of the globe (17). CLIMAP also spawned Shackleton's collaboration with Jim Hays (Lamont) and John Imbrie (Brown), resulting in the spectral analysis of deep-sea records that resurrected the Milankovitch theory as the pacemaker of the ice ages (18). This turn of events brought joy to Emiliani, who had been an outspoken supporter of the Milankovitch theory during its eclipse (19).

Neither Emiliani nor Shackleton are alive to correct my reconstruction of events, but Bob Ginsburg remembers. His off-hand suggestion that a bunch of travel-weary graduate students go to a talk on forams was anything but. He knew Emiliani from his own graduate-school days at Chicago. He knew what we were in for, if we took the bait. Thanks Bob.

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