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INQUA and Quaternary science at the Millennium: a personal retrospective☆

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In the late 1950s, when I was a graduate student, it was widely thought that the Earth had experienced four glaciations during the last one million years, the interval then assigned to the Pleistocene Epoch. Radiocarbon dating had just begun to show promise of providing a chronology for late Quaternary events previously assigned ages largely on the basis of informed guesswork. Geologists were struggling to explain the origin of mountain ranges, continents, and ocean basins in the absence of the unifying concept of plate tectonics, and ideas about the causes of climatic change were largely speculative and provisional.

The fundamental theme running through much of Quaternary science concerns climate and environmental change. I would like to call your attention to an often-overlooked paper by Richard Foster Flint, President of the VIIth INQUA Congress convened in Boulder in 1965 (Fig. 1). It appeared in the fourth volume of *Quaternary Research* as an editorial entitled "Three Theories in Time" (Flint, 1974). Flint reviewed the three fundamental aspects of our planet: the dynamics of the biosphere, expressed in the theory of organic evolution; the dynamics of the lithosphere, explained by the theory of plate tectonics; and the dynamics of the atmosphere, which concerns global climatic change. In writing this paper in the early 1970s, Flint concluded that a viable theory of climatic variation did not yet exist, and that its solution lay almost wholly in the future. He noted that whereas development of the theory of evolution essentially involved many individual observations spread over several decades, the theory of plate tectonics arose with a rapid synthesis of existing geologic and newly acquired geophysical data, and was decidedly a group effort. He suggested that, in many respects, a theory of climate is more difficult to derive because of the far-greater complexity and much-shorter time scales of atmosphere motions than those of lithospheric plates, and the many disciplines that necessarily would be involved in its formulation. A major manifestation of climate change during the late Cenozoic was the expansion of ice sheets and mountain glaciers during successive glacial ages. He pointed out that by 1960, 53 explanations, or "theories", about the causes of glaciation had been put forth, most being mere speculations.

Flint suggested that a viable theory of climatic change would require several fundamental conditions:

1. Adequate and reliable radiometric dating.
2. The involvement of a sufficient number of scientists, both in data acquisition and theoretical analyses.
3. Measurements using approaches not yet devised, and
4. Models that can be tested with geologic data.

He concluded that "our strong curiosity, our increasing manpower, and the rapid development of our technical skills lead me to expect that the theory of climatic variation will be with us before the end of the 20th century."

We have now reached that point, and a new millennium is at hand. How far have we come toward fulfilling Flint's prediction?

This presentation is advertised as "a personal retrospective," and so my focus will be on the post-WW II period. I would like to review briefly some of the major scientific advances during the past half century that have given us a more-comprehensive understanding of Quaternary environments and taken us progressively closer to a comprehensive theory of climatic change. I will do so by calling attention to work that I consider significant in

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The beginning of INQUA's last congress of the century is an appropriate time for me to reflect on more than three decades of association with friends and colleagues who comprise our unique organization. It is unique because unlike other major scientific unions, INQUA is an interdisciplinary mix of scientists from many diverse fields who have a common interest: how our modern environment has been shaped by the processes and events of the last several million years. Befitting the arrival of a calendric milestone, this seems an obvious time to review on how Quaternary science has developed and changed within the professional lifetime of each of us and to anticipate challenges that lie ahead as we enter a new century and millennium.

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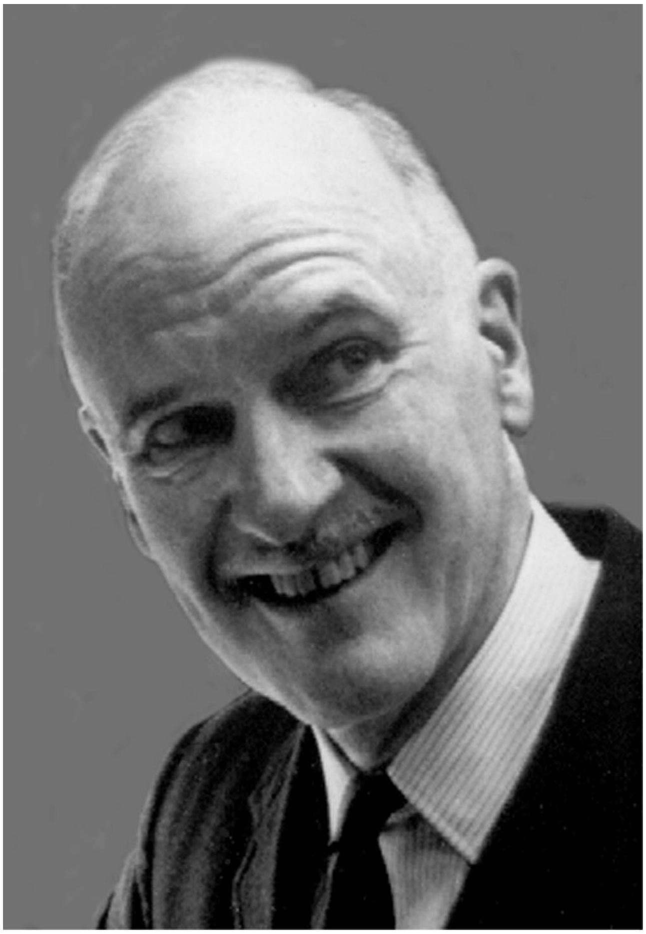

Fig. 1. Richard Foster Flint (1902–1976).

both these areas. In some cases, a cited work is representative of a series of papers that collectively have advanced a field of study. My own research interests and experiences influence my choices, as do my personal interaction with some of the players involved. Therefore, my list doubtless differs from the one that each of you might compile. In the brief time available, I cannot include all I might wish, and therefore hope you will forgive me if your favorite topics and personalities appear to be overlooked. The works mentioned here and in the list of references at the end are arranged chronologically within the time frame of the quadrennial INQUA congresses from 1957 to 1999.

V Congress (Madrid, 1957)

1957–1961: I will begin with 1957, the year of the Madrid Congress and the year I began a career in Quaternary science. During this year, three important syntheses of Quaternary geology had reached the bookstores: J.K. Charlesworth's (1957) monumental two-volume study of "The Quaternary Era," the second edition of Flint's (1957) textbook on "Glacial and Pleistocene Geology," and the first volume of a three-volume work by Paul Woldsted (1954, 1958, 1965) on "Das Eiszeitalter." Each included a synthesis of available information on Quaternary glaciation and environmental change, as well as speculations about the causes of the glacial ages. Each remains a valuable reference to the earlier literature.

In addition, I call attention to a paper in *Nature* by Louis Leakey (1959) which concerns a topic of major continuing interest to Quaternary scientists: the evolution of humans and their environment, the theme of this congress. In this paper, Leakey reported the discovery, by his wife Mary, of the *Zinjanthropus* skull. This was the first of many startling finds the Leakeys and other paleoanthropologists would make in Africa during the next several decades. Shortly after this discovery, Leakey described the fossil skull in an informal weekly Pleistocene seminar that I attended at Yale University; the audience of about a dozen persons included graduate students and several faculty members. A year later he returned to Yale where, because of the attention his work was receiving, a larger lecture room was required. The next year Leakey again visited Yale and presented a lecture to a standing-room-only crowd that filled the largest lecture hall on campus. By that time, coverage of the fossil find had appeared in *National Geographic* magazine, generating worldwide popular attention.

VI Congress (Warsaw, 1961)

1961–1965: Among the many papers and books that appeared between the Warsaw and Boulder congresses, several stand out. John Hollin's (1962) perceptive linkage of sea level and Antarctic ice-margin variations provided important insight about the dynamics of Pleistocene ice sheets. In the mid-1960s, a series of papers appeared that ultimately led to the theory of Plate Tectonics. Among the most frequently cited early papers is one by Vine and Mathews (1963) who used geophysical data to demonstrate the reality of sea-floor spreading in the Atlantic Ocean. I include this paper in my list because tectonic activity associated with the motion of lithospheric plates provides an important piece of the puzzle dealing with the onset of the Late Cenozoic glacial ages. The disclosure by Allan Cox et al. (1964) that the Earth's magnetic field had reversed repeatedly, not only was crucial to development of the concept of plate tectonics, but it opened an entirely new approach to dating Pleistocene events that would quickly find application to deep-sea cores. Liu Tungsheng et al. (1965) described the loess and paleosol stratigraphy of China's vast loess region which, during the next several decades, would be recognized as one of the most-detailed continuous records of terrestrial environmental change on the planet and provide important information about the causes of climate change.

In preparation for the VII congress in Boulder, American Quaternary scientists began assembling an array of papers, maps, guides, and monographs that synthesized many disciplinary and geographical aspects of Quaternary research in North America. Among them was the major compilation on "The Quaternary of the United States" edited by Herb Wright and Dave Frey (1965). This volume provided a model for similar national summary volumes that were assembled for many subsequent international congresses.

VII Congress (Boulder, 1965)

1965–1969: Shortly after the Boulder congress, a major synthesis volume on "The Bering Land Bridge" appeared, edited by Dave Hopkins (1967). This regional study was unique in the breadth of its interdisciplinary coverage, the relative remoteness of much of the region covered, and the international collaboration it involved. It would be followed in subsequent years by similar syntheses on the Quaternary history of other subcontinental regions in which political boundaries do not always coincide with geologic boundaries.

During the first half of this century, it was widely believed that the Pleistocene encompassed four glacial–interglacial cycles. The classic work on the Alps by Penck and Brückner (1909) was a standard reference. However, Gustav Arrhenius (1952), documenting the results of the 1947–1948 Swedish Deep-Sea Expedition, recognized nine carbonate cycles in the Pleistocene segment of the recovered cores (the last 1 million years). This was the first time evidence was presented suggesting more than the traditionally accepted four glaciations. However, Arrhenius was strongly influenced by the existing land record of glaciation and argued that the youngest four carbonate peaks, spanning the last half million years, were correlative with the Nebraskan, Kansan, Illinoian, and Wisconsin glaciations of the standard North American Quaternary glacial succession. A paper by Jim Hays et al. (1969) constituted an important milestone. Applying the paleomagnetic reversal chronology to Pacific marine sediments, they presented evidence of eight glacial–interglacial cycles during the Brunhes Chron — the last 780,000 yr. Before long, the Pleistocene would increase in length to 1.8 million years and encompass some 32 glacial–interglacial cycles — eight times the number perceived by Penck and Brückner more than a half century earlier.

VIII Congress (Paris, 1969)

1969–1973: So many important papers appeared in the decade of the 1970s that it is not easy to single out those of greatest significance. The first papers describing the analysis of ice-sheet cores appeared and would be followed in the coming decades by further reports that would revolutionize our understanding of the Quaternary atmosphere and the climate history of the polar regions. Among the earliest summary reports was a paper by Willi Dansgaard et al. (1969) on the Camp Century ice core from Greenland; it was followed by papers documenting evidence of high-frequency, high-amplitude variations in Greenland climate that would become known as Dansgaard–Oeschger oscillations. In a long and significant paper, Hubert Lamb (1970) called attention to the influence of volcanic aerosols on climate change and offered a guide to eruption magnitudes. John Imbrie and Nilva Kipp's (1971) important paper, which appeared in a festschrift for Professor Flint held in 1969, described the approach that would be used by the CLIMAP (Climate: Long-range investigation mapping and prediction) project to reconstruct Pleistocene sea-surface temperatures. Andy McIntyre and Bill Ruddiman (1972), using marine faunal evidence, demonstrated repeated shifts of the North Atlantic polar front during the last glacial–interglacial cycle. Nick Shackleton and Neil Opdyke's (1973) magnetically dated isotope record of equatorial Pacific core V28-238 is probably the most-cited paper that has appeared in the journal *Quaternary Research*. It established a chronology of glaciations for most of the last million years and called attention to the relationship between the marine isotope signal and global ice-volume fluctuations.

The initial issue of *Quaternary Research*, the interdisciplinary journal founded by Link Washburn, appeared in 1970. This was the first of an array of eight new journals that would focus on the Quaternary Period or disciplinary aspects of Quaternary research, the others being *Boreas* (1972), *Geographie physique et Quaternaire* (1977), *Quaternary Science Reviews* (1982), *Journal of Quaternary Science* (1986), *Paleoceanography* (1986), *Quaternary International* (1989), and *The Holocene* (1991). Within two decades, these eight leading journals, together with *Nature* and *Science*, were handling an ever-increasing number of research contributions on Quaternary topics.

IX Congress (Christchurch, 1973)

1973–1977: About the time of the IXth INQUA congress in New Zealand, Art Bloom et al. (1974) produced a eustatic sea-level curve spanning the last glacial–interglacial cycle that was based on a dated succession of emergent coral reefs in tectonically active New Guinea. During the next several years, major papers resulting from the CLIMAP project were published. These included a reconstruction of the surface of the ice-age Earth (CLIMAP Project Members, 1976), simulations of ice-age climates (Gates, 1976), and the affirmation of Milankovitch Earth–orbital theory to explain the timing of the glacial–interglacial cycles (Hays et al., 1976). Also at this time, George Kukla (1977) correlated the cyclic pattern of climate change seen in the loess and soil record of central Europe with the isotopic stratigraphy of marine cores. Similar land–sea correlations would be proposed a decade later using the long, continuous loess–paleosol record of China (e.g., Kukla, 1987).

X Congress (Birmingham, 1977)

1977–1982: A paper by André Berger (1978) that appeared shortly after the Birmingham congress was one of several detailing his calculations and assessment of orbital variations and climate. This year also saw publication of Geneviève Woillard's (1978) pollen analysis of the Grand Pile peat bog in the southern Vosges Mountains of France. Her study produced a detailed record of paleovegetation changes with a pattern that closely resembles the isotopic signal of the last glacial–interglacial cycle in ice- and ocean-core records. Claus Hammer et al. (1980) measured variations in acidity in the Greenland ice sheet that constitute a record of volcanic aerosols and they correlated peaks in acidity with major historic eruptions. "The Last Great Ice Sheets," a major CLIMAP volume edited by George Denton and Terry Hughes (1981) provided an up-to-date survey of mountain glaciers and ice sheets during the last glaciation, and handled uncertainties in ice-sheet geography by depicting minimum and maximum reconstructions.

XI Congress (Moscow, 1982)

1982–1987: Not long after the Moscow congress, a volume on the "Late Quaternary Environments of the Soviet Union" appeared, edited by Andrei Velichko (1983). This was the first major summary, in both Russian and English, of the current state of Late Quaternary research in this vast region of the Northern Hemisphere. Manabe and Broccoli (1985), key players in CLIMAP research, published their results of model simulations that provided insight into the importance of ice sheets and other glacial boundary conditions on ice-age climate. During this inter-congress period, the results of drilling and laboratory analysis of high-altitude, low-latitude ice cores were published by Lonnie Thompson, Ellen Mosley-Thompson et al. (1985). These were the initial results of a succession of investigations of high-mountain glaciers in South America and central Asia that extended the geographic range of ice-core studies. Culminating several years of concentrated effort in the world's major mountain ranges, Friederich Röthlisberger (1987) summarized his impressive global study of radiocarbon-dated Holocene glacier variations.

XII Congress (Ottawa, 1987)

1987–1991: A paper by Helmut Heinrich (1988) that appeared in *Quaternary Research* started a flurry of investigations on ice-rafted detritus in North Atlantic deep-sea cores and "Heinrich events." Within several years, new evidence of millennial-scale climatic oscillations that were correlated with massive discharges of icebergs into the North Atlantic Ocean was appearing almost on a weekly basis. A year later, Rick Fairbanks (1989) published a U-isotopic record of the postglacial rise in sea level at Barbados, which also aided in calibration of the older part of the radiocarbon time scale. Bill Ruddiman and John Kutzbach (1989) proposed that the uplift of vast plateaus in south-central Asia and western North America strongly influenced atmospheric circulation and Late Cenozoic climate. Wally Broecker, among the most imaginative and productive of Quaternary researchers, stressed the climatic importance of changes in the oceans thermohaline circulation system (e.g., Broecker et al., 1990). He linked these changes to periodic massive outbursts of meltwater and icebergs that reduced or shut down the ocean circulation system during Heinrich and Dansgaard–Oeschger events. Finally, a paper by Peter Molnar and Philip England (1990) pointed to a likely linkage between tectonic uplift and climatic change. Their provocative analysis stimulated an increase in denudation-related research and generated further speculations about the "trigger" for Late Cenozoic glaciation.

XIII Congress (Beijing, 1991)

1991–1995: Among the papers that appeared during the inter-congress period following the Chinese congress were two on the structure and causes of glaciations by John Imbrie and a long list of co-authors who participated in the CLIMAP project (Imbrie et al., 1992,1993). Minze Stuiver and Paula Reimer (1993) made available a user-friendly computer program that easily converts radiocarbon ages to calibrated ages, thereby improving the reliability of Late Quaternary correlations, as well as calculations of the rates of various surface processes. Years of field and laboratory studies, combined with extensive syntheses, produced some major summary reports by the COHMAP (Cooperative

Holocene Mapping Project) group. Among them was a paper by John Kutzbach et al. (1993) on climate simulations at 3000-yr intervals since the last glacial maximum, 18,000 yr ago. Chalmers Clapperton's (1993) book on the "Quaternary Geology and Geomorphology of South America" is an impressive one-man synthesis of the environmental history of a continent that extends from the humid tropics in the north to the frigid ice caps of southern Patagonia.

During these inter-congress years, evidence of millennial- and sub-millennial-scale climate events, both on land and in the oceans received increased attention. INQUA scientists collaborated actively with many PAGES (Past Global Changes) projects of the International Geosphere–Biosphere Program in generating high-resolution terrestrial paleoclimate records. Papers on North Atlantic iceberg-discharge events (i.e., Heinrich events) (e.g., Bond and Lotti, 1995), provided details of ice sheet and climate history of the last glacial–interglacial cycle, and proposed correlations between marine records and the detailed ice-core isotopic record from Greenland.

XIV Congress (Berlin, 1995)

1995–1999: It perhaps is too early to assess the long-term significance of papers that were published since the last congress in Berlin. My provisional candidates, however, include the synthesis by Bill Ruddiman (1997) and colleagues of evidence for "Tectonic Uplift and Climate Change," and a paper by John Kutzbach et al. (1998) on "Climate and biome changes for the past 21,000 yr." These two works indicate several of the new directions that Quaternary (and related pre-Quaternary) research is currently taking.

XV Congress (Durban, 1999)

Interestingly, the research that I have reviewed has moved in the direction that Dick Flint anticipated in his 1974 editorial. New and improved radiometric dating methods have been devised, the number and variety of Quaternary scientists have increased steadily, new methods to measure climate-related parameters have been developed, and modeling has become an increasingly important approach, the results of which are being tested with geologic data.

Let us return, then, to the question that I posed earlier: How far have we come toward fulfilling Flint's prediction that "a theory of climatic variation will be with us before the end of the 20th century"? The significant contributions I have just reviewed illustrate the course of progress that has been made (Fig. 2). The broad outlines of a theory of climate became possible only with the explosion of

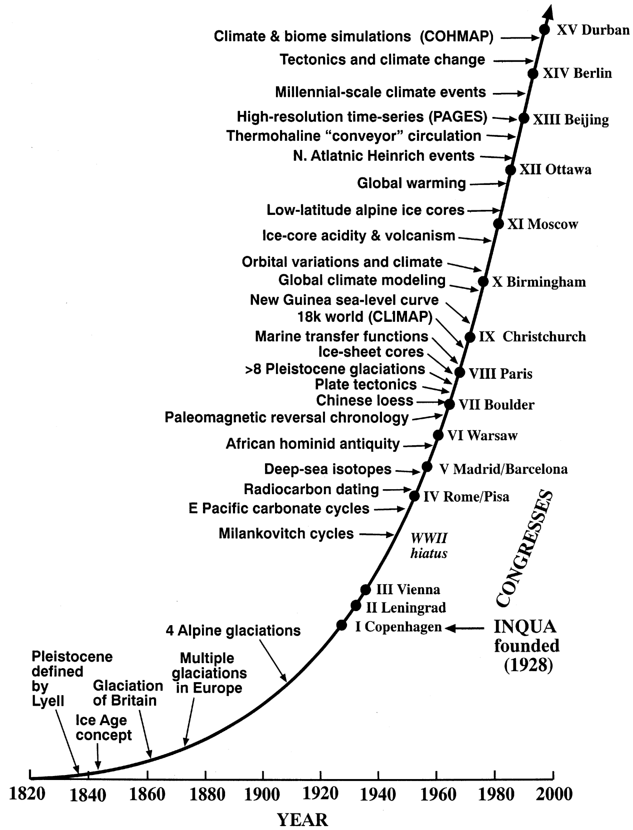

Fig. 2. Chronology of INQUA Congresses and some major advances in Quaternary science.

work on marine sediments and with an appreciation of the role of the ocean in climate change. With this research, orbital control of variations in insolation received at the Earth's surface could convincingly explain the timing of the glacial–interglacial cycles. Nevertheless, the origin of the 100,000-yr climate cycle has yet to be explained to everyone's satisfaction. Climatic events of shorter, millennial-scale frequency recognized in ocean, ice, dust, pollen, and glacial records are now reasonably well documented, if not all understood, and the importance of large sulfur-producing volcanic eruptions for modulating subdecadal-scale climatic events has been acknowledged. However, explanations of other high-frequency components of the climate record remain elusive. Just as the theories of evolution and plate tectonics are still being refined decades after the basic outline of each was formulated, so, too, a theory of climate will likely take additional decades of work before it becomes a viable one. Herein lies part of INQUA's challenge in the years ahead. Clearly, the climate system is far more complex than visualized a quarter century ago.

Let me conclude this presentation with an assessment of where Quaternary research may be headed in the first part of the 21st century. I should say *guess*, rather than *assess*, for predictions in science often are shortsighted and exclude some of the truly exciting work that will emerge. When I was a newly minted Quaternary scientist, I did not foresee the revolution that plate tectonics would soon bring, a Pleistocene Epoch with more than four glaciations, sophisticated computer models of past climate conditions, or an array of new methods for dating Quaternary deposits. The themes that will continue to interest and engage us include the following: the nature and cause of millennial- and sub-millennial-scale climatic events; global and regional paleoenvironmental reconstructions with finer spatial and temporal resolution; assessment of lags in various environmental systems in response to climatic changes; the roles of the greenhouse gases, atmospheric dust, and volcanic aerosols in Quaternary climate change; the nature and influence on climate of the tropical ocean and tropical atmospheric humidity during the glacial ages; the further development and application of reliable dating methods, including cosmogenic isotopes; the role of tectonics, weathering, and denudation in climatic change, as well as the importance of the Earth's biota in the climate system; modeling of Earth systems using improved higher-resolution models; and the fundamental question of how, when, and why the Late Cenozoic glacial ages began.

What role can and will INQUA have in this challenging research agenda? As you will see from the stimulating program of the XVth congress, INQUA is alive and well. As a result of changes instituted by the International Council during the Berlin congress, INQUA is now engaged in a variety of wide-ranging research projects that encompass an array of disciplines. Its geographic base is growing with the addition of new member nations and regions. Nevertheless, if it is to play a prominent role in the basic research themes I have outlined here, several opportunities must not be overlooked. INQUA must expand its membership to include greater participation by scientists living and working in the tropical and subtropical lands of Africa, the Middle East, and South America, which are regions of particular interest in the climate puzzle. More than two-thirds of our planet is covered by ocean, and we must encourage far greater participation in INQUA programs by Quaternary oceanographers. Recognizing, also, the increasing importance of modeling for understanding the dynamics of Quaternary environmental change, we must attract a young generation of scientists trained in modeling paleoclimates and encourage them to collaborate with INQUA field and laboratory scientists who are assembling data about past surface conditions. INQUA's major strength has always been its international and interdisciplinary character. Its importance will continue to lie in its ability to bring together scientists dedicated to understanding how the climate system works and how the Earth's environments have evolved.

A final comment: in addition to the intellectual stimulation of being involved in advancing an important and exciting science, one of the great benefits of working with the glacial ages and being involved in INQUA is meeting and interacting with such a varied, stimulating, and engaging collection of people. After three and a half decades of association, my friends and colleagues in INQUA are the equivalent of an extended family with whom I have shared a continually interesting and fascinating scientific career.

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