GOLD MEDAL LECTURE

Penrose Medal

by Paul F. Hoffman

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My first geological conference was a Northeastern Section Meeting, my first talk was at a GSA Annual Meeting, a Penrose Conference was my international debut, and my first Plenary Lecture was at The Decade of North America Geology (DNAG) Meeting in Denver. GSA is my home Society. This high honor is therefore unique.

I wanted to be a geologist from an early age, scarcely realizing what an ideal vocation it would be for a kid who liked to be out-of-doors, on his own, indulging in arguments with himself. My parents, an industrial paint chemist and a primary school art teacher, gave me every encouragement. We lived in Toronto city but spent all summer and every weekend throughout the year in the country. Along with my three siblings, we learned to be self-reliant in both places. I liked sports (ice hockey and running), mineral collecting and daydreaming.

McMaster University in nearby Hamilton, Ontario, had a policy of admitting 100 students a year with high-school grades below 60%, the provincial standard floor for college admission. I was one of the 100. Mac was strong in natural science and had an excellent geology department. Herb Armstrong told me to see ‘Jet’ Thompson at the Ontario Geological Survey (then Department of Mines) about summer work. When I tell you that ‘Jet’ Thompson was the Survey Director and that it was not unusual for him to personally interview prospective junior field assistants, you will understand that this was a different world from today. Trust and personal responsibility stood then where now there is administrative overburden. Thompson looked me up and down, and told me to buy two pairs of boots and a train ticket to Sioux Lookout in northwestern Ontario, departing in mid-May and returning in mid-September. Four months in a paddle canoe mapping lakeshore geology in the Archean Wabigoon Belt was sublime, but inland the dense forest was like a prison. The next year I applied to the Geological Survey in Ottawa (GSC) in hopes of a summer job in the Canadian Rockies, but got posted instead to the barren lands north of Great Slave Lake, Northwest Territories. Tony Davidson still remembers me as the junior assistant who threw a discus made from Archean greywacke through the party chief’s tent. One day we looked out over the East Arm of the lake, which Tony described as a

Proterozoic sedimentary basin, folded and faulted on the side opposite the Slave craton, which was last mapped by Cliff Stockwell of GSC in the late 1920's.

Despite small enrollments (accounting for the graduation award Ray mentioned), undergraduate courses at McMaster were taught by outstanding researchers like geochemist Jim Crockett, petrologist Neil Irvine, geochemist Henry Schwarcz and paleontologist Gerd Westermann. One of them had a lasting impact on my own research strategy. The year he graduated from Rutgers, Vint Gwinn was a hard-hitting outfielder for the New York Giants affiliate in Lake Charles, Louisiana. He gave up baseball for geology and during his brief stay at McMaster, published a detailed affirmation, using industry bore-hole data, of blind, thin-skinned, thrust faults beneath the Appalachian Plateau, as hypothesized by John Rodgers. Gwinn was passionate that stratigraphy was the key to paleogeography, tectonics and Earth history. His 3rd-year students mapped thin-sections of Montana Group sandstone grain-by-grain, believing it would enable them to visualize western North America in Upper Cretaceous time. He argued that mountain belts are best understood from the stratigraphy and structure of the sedimentary basins along their borders. I knew from summer field work that sedimentary basins and fold belts within the Canadian Shield were well-preserved, but limited in size by erosion. After class one day, Gwinn held up a newly-published textbook and deliberately left it in the classroom. It was *Paleocurrents and Basin Analysis*, by Paul Potter and Francis Pettijohn, and one of the points it made was that paleoflow patterns in most formations are broadly uniform over large areas: regional paleoslopes and shoreline orientations could therefore be determined even where areas of preservation are small. A plan was born.

A deep interest in Precambrian geology made Pettjohn a rarity as a sedimentologist, so I applied to graduate school at The Johns Hopkins University in Baltimore. Pettjohn and structural geologist Ernst Cloos led Appalachian field trips every weekend for first-year graduate students (I went every year). Coming to Hopkins with 12 months of field experience in geology made a good impression and saved my skin later on when Cloos and Pettijohn courageously opposed those on my orals committee for whom illiteracy in mathematics was an automatic disqualifier. The arrival of Bob Ginsburg from Shell Development in Miami was an enormous bonus, opening up opportunities to compare Holocene coastal carbonates around the world with the 2-billion-year-old carbonate formations in my thesis area. After flirting with Neoproterozoic successions in the northern Canadian Cordillera and the East Greenland Caledonides, I had settled on the Paleoproterozoic basin in the East Arm of Great Slave Lake, which borders the Churchill orogenic province. It had the simplest logistics of the three areas and, with GSC support, I could operate with complete independence. The thesis was somewhat unorthodox for GSC because it wouldn't produce a map, and also for Pettijohn because instead of studying one formation over a great area, my study involved a 12-km-thick succession in a limited region. The goal was to compare the 2-billion-year-old succession with those in the Appalachians and other Phanerozoic 'geosynclines', where pre-orogenic sediment was shed toward the geosynclinal axis, post-orogenic transport was directed in the opposite direction, and syn-orogenic (mainly deepwater) sediment flow typically paralleled the orogenic axis. I spent two summers in Great Slave Lake (1966-67) measuring stratigraphic sections and nearly 8000 paleocurrent directions, but the main conclusions were apparent early on. The overall succession bore a striking developmental resemblance to the Appalachians, but the paleoflows were not associated with the Churchill orogen to the southeast as I anticipated, but with an orogen hidden beneath flat-lying Devonian carbonates southwest of Great Slave Lake. The Wopmay orogen sees daylight 500 km to the north, in the region east of Great Bear Lake. Before 1960, most of this region had never been geologically mapped at any scale.

When my three-year NSERC scholarship for study outside Canada ran out in 1968, I gratefully accepted a one-year, half-time lectureship at Franklin and Marshall College in Lancaster, Pennsylvania, a department that boasted petrologist Tony Morse and structural geologist Don Wise among others. The very next day I was offered Al Donaldson's vacated position at GSC, which I felt obligated to decline. Combining Appalachian field trips, my Holocene carbonate travels and thin sections from my thesis collection, I experienced thrills in teaching I was never able to recreate elsewhere. Sadly, Vint Gwinn was killed by the collapse of a point bar he was excavating in 1968, soon after being appointed head of the geology department at the University of South Carolina. In 1969, I was offered Hans Hofmann's vacated position as GSC Precambrian paleontologist, which I gladly accepted. No one complained that I never wrote a paleontology paper, although a senior GSC paleontologist did object to my using the word "correlation" in reference to Precambrian strata.

My student days coincided with the plate tectonics revolution of 1962-67. McMaster was alert to the new developments: as an undergraduate I heard Harry Hess and Tuzo Wilson present their ideas on ocean basin development. Johns Hopkins, despite its strong emphasis on field work, frowned on geotectonic speculation. A seminar by Bob Dietz linking geosynclines to the collapse of oceanic plates was not well received. Translating a paper on continental drift for my scientific German test was brash and insensitive. By the time I joined GSC in 1969, however, it was clear that plate tectonics was the appropriate template for Phanerozoic geodynamics. But what about earlier times? Interpreted in terms of plate tectonics, the Wopmay orogen should represent a 2-billion-year-old continental margin, 1400 km inboard from the present margin. I proposed to investigate a transect of the orogen, raising eyebrows again at GSC because no map-sheet would result. The project was approved and a rifted continental margin was soon found. An invitation from Brian Windley and John Sutton to present the work at a Royal Society meeting in London was a boost for my career. There was some grumbling about non-domestic publishing but in fact a plain-clothes version had already appeared in a GAC Special Paper in 1972, co-edited by Ray Price. The birth and death of the resulting paleocean were later dated by Sam Bowring at 2014 and 1882 Ma, respectively: the 132 Myr lifespan of the Wopmay passive margin is indistinguishable from the average duration of the 30-odd extinct Phanerozoic passive margins as compiled by Dwight Bradley.

I now had an interesting decision to make. Should I investigate the third and last of the structural basins around the Slave craton, continuing an effective methodology, or should I plunge into the volcano-plutonic and metamorphic belts in the interior of the orogen? From my reconnaissance transect, I knew the internides would require years of systematic regional mapping. To this day, northern Wopmay orogen has neither a road nor a human inhabitant. On the other hand, the area abounded with potential thesis projects, which would contribute to and be supported by a systematic GSC mapping program. Well-known Phanerozoic orogens were being completely reinterpreted in light of plate tectonics and Wopmay orogen, with its relatively shallow, but variable, depth of erosion and excellent exposure, was as good a place as any to see if plate tectonics could make sense of orogenesis in the truly deep past. The decision to go west, not east, was an easy one.

Geological mapping is the most intensely scientific activity I know. Pettijohn used to say that there was nothing “so sobering as an outcrop”, but that’s only the beginning. After you’ve come to grips with the outcrop you're standing, you must decide which of the many outcrops within walking distance to visit next. You can’t see to them all, so the next one should be the one that would be the devastating to your world-view if it isn’t what that vew predicts. Synthesis, hypothesis and test—in real time, for hours on end. The importance of retrospection drives good mappers to plot-up as infrequently as possible, a tendency encouraged by aerial haemotrophy, which is the price of admission to the Canadian Shield in summer.

PhD projects by Mike Easton (volcanology-geochemistry at Memorial of Newfoundland), John Grotzinger (carbonate sedimentology-stratigraphy at Virginia Tech), Janet King (structure-tectonics at Queen's), André Lalonde (igneous geology at McGill), Marc St-Onge (metamorphic geology at Queen's) and Rein Tirrul (structure-tectonics at UC-Santa Barbara) were incorporated in mapping projects, and those by Sam Bowring (geochronology-tectonics at Kansas) and Robert Hildebrand (igneous geology-tectonics at Memorial) operated independently with support from the Geology Office in Yellowknife, directed by Bill Padgham. I invited Denis St-Onge (GSC), who discovered and studied Quaternary Glacial Lake Coppermine, named for the canoeable river that drains diagonally across the orogen. Between field seasons, I cycled through the Calgary and Vancouver offices of GSC, taught at UC-Santa Barbara (thanks to Preston Cloud), UT-Dallas (thanks to Dave Eby) and Lomont-Doherty (thanks to Charlotte Schreiber), and was a Fairchild Scholar at Caltech (thanks to Lee Silver).

In 1980, I interpreted Wopmay orogen as a continent-arc-continent collision zone. But I quoted Rudy Trumpy's line that, "One could make a convincing interpretation of the Alps from rocks alone, and it would collapse the moment the first fossil was found." In 1980, there was not a single reliable radiometric date in Wopmay orogen. Zircons are our fossils, and zircon dating, in the hands of an astute geologist like Sam Bowring, proved to be highly effective in falsifying tectonic models. Dating proved that we had misinterpreted the tectonic significance of a number of key igneous suites. Nevertheless, the generic continent-arc-continent collision model held up, greatly refined by Robert Hildebrand. The exact location of the arc-continent geosuture remains uncertain, but modern analytical tools and the right samples could pin it down. Hildebrand has compiled all of the Wopmay maps and the Coppermine Homocline in a single 1:500K-scale map, recently published as *GSC Open File 6390*. The finding of a collided, west-facing, continental margin in the Canadian Shield paralleled the simultaneous recognition of 'suspect terranes' in the Cordillera.

As an advocate for early and continuous plate tectonics, I shouldn't have been surprised that this view was initially more approved of by Mesozoic-Cenozoic workers than by Precambrian geologists. The latter didn't want to have to read the huge new literature on Mesozoic-Cenozoic tectonics, and they didn't want to loose a distinct field in which they were the acknowledged experts. They cannot be blamed for this. Besides, they had an unlikely ally. Paleomagnetism, the field that in the 1950's set the table for the plate tectonic revolution of the 1960's, was increasingly assertive that the Archean cratons were mutually fixed in Proterozoic time. To me this made a mockery of Proterozoic geology, not to mention theoretical geodynamics. In 1981, a thick book was published on *Precambrian Plate Tectonics*: of the 28 chapters by different authors, not more than two were sympathetic to plate tectonics before the latest Proterozoic. The recognition of widespread low-temperature remagnetization led to improvements in paleomagnetism and the chimera of fixed cratons slowly dissolved.

The mapping in Wopmay orogen consisted of three-year projects (1:250,000-scale quadrangle), with a year off in between. In 1976, one of the off years, I returned to map my thesis area with six students, Ian Bell, Robert Hildebrand, Linda Thorstad, Scott Dallimore, Ian de Bie and Mike Flanagan. The East Arm of Great Slave Lake is a fjord-like system of channels and bays 250 km long. It exists because the Laurentide Ice Sheet preferentially eroded the large synclinorium of soft sedimentary strata I had studied for my thesis. Subsequently, at UC-Santa Barbara, I realized that the prominent linear faults that chopped up the synclinorium belonged to a strike-slip system of large displacement. In order to palinspastically restore the basin, I needed to work out displacements across the fault system. We started mapping in early May, a month before break-up, with two weeks of helicopter support in the relatively inaccessible and poorly mapped country southeast of the main waterways. At the end of the first week I told the crew that we were dealing with a stack nappes, with "all that that entails". A multi-tiered stack of basement and cover nappes, refolded in the big synclinorium and again during transpressional right-slip faulting, extends the length of the East Arm. We finally left the field in late September, with a small sample in each pocket collected after dark at the end of the final traverse. In 15 weeks, we had taken four days off (for weather), burned 1500 gallons of kicker gas, and remapped the East Arm of Great Slave Lake (*GSC Map 1628A*).

The continuation of the East Arm transpressional orogen was discovered 400 km to the northeast by Rein Tirrul and John Grotzinger in 1984, the year after they completed their PhD projects in the externides of Wopmay orogen (*GSC Open File 3251*). The Thelon orogen has its own passive-margin to foredeep transition, studded with mappable tuff horizons. Zircon dating by Otto van Breemen (GSC) in the plutonic arc of the orogen, combined with Sam Bowring's dating of tuffs within the sedimentary basins, led to the recognition of the Thelon orogen as a pre-Wopmay collision zone on the east side of the Slave craton. The East Arm basin is a composite basin, situated where the dueling foredeeps of the Thelon and Wopmay orogens converge. It is not an aulacogen, my postulate before mapping it. The Thelon and Wopmay orogens, although partly overlapping in age, are different in nearly all other respects. Combining paleomagnetic data, volcanic ash distribution, stromatolite orientation and carbonate platform asymmetry, we could account for the constrasting orogens and their changes in development in terms of trade-wind driven exhumation, as well as resolving the global polarity. A *Geology* reviewer described this as a “good example of bad science”, a quote I unsuccessfully lobbied the Editor to publish along side the complimentary quote he preferred. What better way to goad readers to reach their own conclusion?

The last Wopmay mapping project had begun in 1981, the same year Bert Bally and John Wheeler invited me to participate in the *Decade of North American Geology* (DNAG) project. My responsibility would be the Canadian Shield beyond the Superior and Grenville provinces, and a synthesis of the Precambrian geology of North America and Greenland for the Overview volume. The invitation was an expression of confidence in a mobilistic interpretation of Precambrian geology. I would have time to complete the Wopmay mapping project and to submit either a final map or a report, but not both. I opted for the map (*GSC Open File 3251*). DNAG meant curtailing major field projects for a decade, but at 35 I had unexpectedly fallen in love and now had a three-year-old son. From that perspective, the break was welcome. Erica Westbrook would be a constant source of practical support, friendship and sound advice for the next 35 years to the present. Guy Hoffman married the vivacious Clare Stephenson of Boston and they live nearby in Victoria, BC. I didn’t entirely give up field work and thanks to Mike Searle saw a transect of the Karakoram-Himalaya in 1985 after seeing part of the western Tien Shan the previous year.

Compiling a 1:5M-scale map was surprisingly similar to mapping a 1:250K sheet: I dug out all the original maps, theses and reports, and photo-reduced them for compilation at 1:1M-scale (e.g. *GSC Open File 2559*). The timing of DNAG was auspicious for the Precambrian because it caught the flowering of precise and reliable U-Pb geochronology stemming from Tom Krogh’s analytical innovations. DNAG-inspired compilations of potential-fields data helped locate potential sutures (paired gravity anomalies) and parallel magmatic arcs (positive magnetic anomalies) under sedimentary cover and in poorly mapped parts of the composite Churchill province. The basic story swiftly emerged—a rapid amalgamation in late Paleoproterozoic time of at least six, formerly independent, Archean cratons (*DNAG Special Publication 1*, 1982). Like all my good titles, *United Plates of America* came to me when I was out running. Running is good for the brain.

Strange to say, mining and fossils fuels were seen as ‘sunset’ industries for most of the 1980’s and 90’s. Support for geological mapping and teaching sank, tracking the price of oil. McMaster and GSC were among the victims. Arguably the best Geological Survey of its size in the world was scattered. Some took other jobs, in and out of geology; some took early retirement, and some stayed on hoping for a turnaround that has yet to occur. In 1991, I transferred to the GSC office outside Victoria (BC) on the understanding that the following year I would take a faculty position at the University of Victoria in the new School of Earth and Ocean Sciences, directed by Chris Barnes. My last job at GSC was a distillation of my 1:1M-scale compilation map for John Wheeler’s 1:5M-scale *Geological Map of Canada* (*GSC Map 1860A*). I was quite stunned by John Wheeler’s adept use of color in this map, which attains the standard of that great artist of North American geology, Philip B. King. Nothing I did at GSC gives me as much satisfaction as *Map 1860A*.

Like a map sheet, the Precambrian ‘collage’ of Laurentia is rudely truncated at its margins, so formerly adjacent continents must also be known. This led naturally to an interest in Rodinia and the grand procession of supercontinents—Nuna, Rodinia, Pangea and Amasia. However, it is only recently that radiometric and paleomagnetic data from mafic dike swarms has allowed this line of research to thrive. For my part, pondering life after DNAG, I couldn’t help but notice that the Quaternary was becoming the most exciting period in Earth history because of climate proxy records held in deep-sea sediments, ice sheets, lakes and caves. Might the Precambrian prosper from this wave of climate-focused activity, as it had from the plate tectonic revolution 30 years earlier?

The breakup of Rodinia and assembly of Gondwana had sparked my interest in late Neoproterozoic-Cambrian Earth history. Andy Knoll and Malcolm Walter had shown that carbon isotopes held promise both as a tool for correlation and a gauge of geochemical carbon cycling. I was familiar with Holocene and Paleoproterozoic carbonates, and was puzzled by the occurrence of glacial and especially glacial marine deposits within thick, shallow-water, non-skeletal, carbonate successions, which could only represent the warmer parts of the surface ocean. Stranger still, complex multicellular animals first appear soon after the last major Neoproterozoic glaciation. In 1990, the tectonic, climatic and biogeochemical sides of the Neoproterozoic puzzle were poorly integrated. Furthermore, the geologists who studied the glacial deposits were largely unaware of climate science and modelling. Joe Kirschvink had told me his ideas about a Neoproterozoic 'snowball' Earth in 1989, and also about large, rapid, oscillatory true-pole-wander. I thought all these problems should be studied jointly, so I looked around for a new long-term project area. With GSC out of the picture, northern Canada was prohibitively expensive. John Grotzinger, then at MIT with Sam Bowring, had just begun a long-term study of the fossiliferous Ediacaran carbonate succession (Nama Group) in southern Namibia, and he suggested that the Geological Survey of Namibia (GSN) would look favorably on a similar project involving the glacial-bearing Cryogenian carbonate succession (Otavi Group) in northern Namibia. Every mineral collector has heard of the Otavi Group and, as a kid growing up in Toronto, I was no exception. One of my father's older brothers owned a tannery in South West Africa (as it then was) and told enchanting stories of life there. I had met Henno Martin, the William Logan or John Wesley Powell of Namibian geology, at a Penrose Conference organized by Preston Cloud. In 1992, GSN geologists Roy Miller, Brian Hoal, Gabi Schneider, Charlie Hoffmann and Roger Swart gave me a tour of northern Namibian geology and logistics. Little geological work had been done during the preceding 15 years of political unrest, but a number of PhD thesis projects were conducted in the 1960's and 70's. The maps in these theses proved to be invaluable, even if the texts were outdated and unrewarding. I've now done more field work in Namibia than I did in Wopmay orogen. Namibia has a lot going for it—exceptional geology, awesome exposure, well-maintained roads, complete air photo and topographic map coverage, modern geological and geophysical data, cloud-free winter weather, the best beer in the world and, since independence, political stability as a multi-racial, representative democracy with a voice of its own.

The Otavi project began in 1993 while I was at the University of Victoria and relied on a GSN field vehicle and fuel vouchers. The next year Mike McElroy asked if I would consider an offer from Harvard. Erica and Guy loved Victoria and it broke their hearts to leave, but it was the right decision for a host of reasons. Harvard students are exceptional, the faculty outstanding and supportive, and with startup funds I could buy my own field vehicle in Namibia, a truck that is still going strong 16 field seasons later. As a Canadian, I find the U.S. energizing despite having lived there during the two most politically divisive decades in modern American history, the 1960’s and 2000’s. The Otavi project involved a lot of stable isotope measurements and my education in this field (first touted at McMaster) was aided by post-doc Jay Kaufman and by Jan Veizer’s invitation to join his Canadian Institute for Advanced Research (CIFAR) project Earth System Evolution. It took five field seasons to sort out the regional stratigraphy and facies before I dared to publish a paper. This would be impossible for an untenured academic.

The coming of geochemical oceanographer Dan Schrag to Harvard in 1997 was propitious. By this time it was clear that glaciers had racked the low-lying Otavi platform during two discrete intervals of Neoproterozoic time, otherwise dominated by shallow-water carbonate sedimentation. Along with strong paleomagnetic data from the younger (Marinoan) glaciation in Australia, it was evident that glaciers had reached sea level in the warmest zone. Colder areas must therefore have been frozen as well. No correlation is assumed *a priori*; correlation just logically follows from the premise. Virtually all climate models, then and now, respond to reduced solar or greenhouse radiative forcing by switching suddenly at a certain point to a fully-glaciated state. Planetary atmospheric scientists had shown that a fully-glaciated Earth could be self-terminating on a timescale of millions to tens of million of years, through feedback from the geochemical carbon cycle. The strong greenhouse forcing required for deglaciation seemed to be reflected by carbonate beds with unique features that ‘cap’ the glacial sequences in most areas, including those otherwise lacking carbonate. Carbonates bracketing the glacial sequences display anomalous swings in carbon isotope composition, implicating the carbon cycle in the climate changes. Midnight brainstorming with Dan Schrag during his first year at Harvard forged links between these phenomena I would have never reached on my own: brilliant geochemist meets phenomenal geological problem. Dan fought our 1998 paper on a Neoproterozoic snowball Earth through to publication in *Science*, in spite of just one favorable review (Ken Caldeira) out of four. The paper kindled broad interest in Neoproterozoic climate and caused consternation among Neoproterozoic geologists. Wrestling with the snowball Earth hypothesis has been by far the most intense learning experience of my life: it links geophysics, geochemistry and geobiology; from the core dynamo to stratospheric photochemistry, from phylogenetics to isotopologues.

I was fortunate to attract four graduate students who conducted independent, regional-scale projects on exciting problems in Neoproterozoic and early Paleozoic global change. Galen Halverson came from University of Montana, Adam Maloof and David Jones from Carleton College, and Francis Macdonald from Caltech. They accounted for over 60 months of field work between them while at Harvard, mostly in Svalbard, Morocco, Arctic Alaska, Mongolia and Canada. As strong field geologists who are operationally engaged with geophysics, geochemistry and geobiology, they now have their own flourishing research programs at McGill, Princeton, Harvard and Amherst. Snowball Earth will not be the last astounding phenomenon to be discovered in Proterozoic Earth history.

The continuity of plate tectonics and rare discontinuities in climate are features of the geological record to which I contributed. The two are ultimately connected. A sure way to create a snowball Earth would be a shut-down of plate tectonics, disabling the geochemical cycle of carbon, but if that had ever happed, the snowball would still be here, and we would not.

The first technical session ever devoted to the snowball Earth hypothesis was a Pardee Symposium I convened at the Annual Meeting in Denver 12 years ago. Thank you, GSA, for a lifetime of support.

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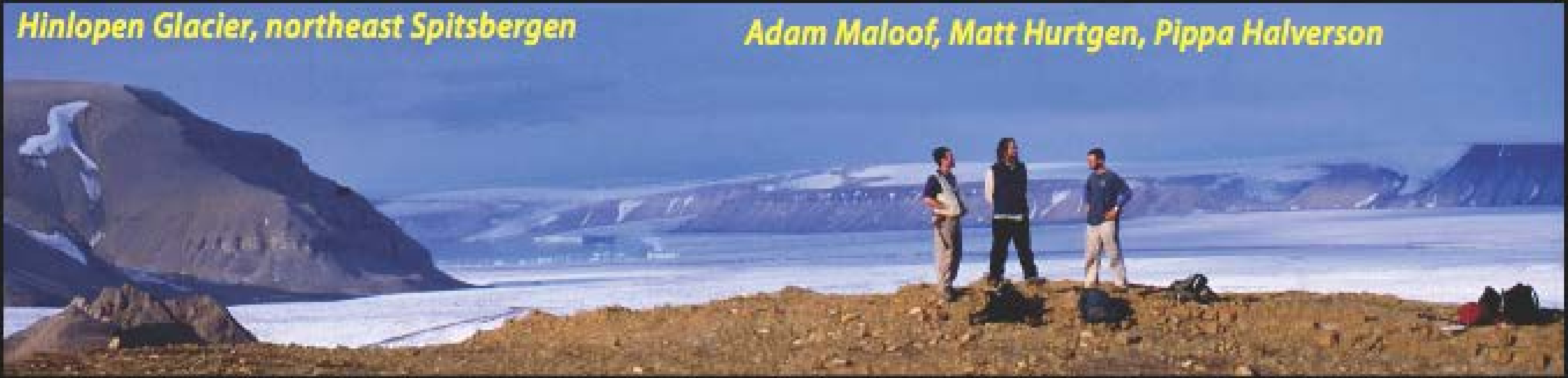
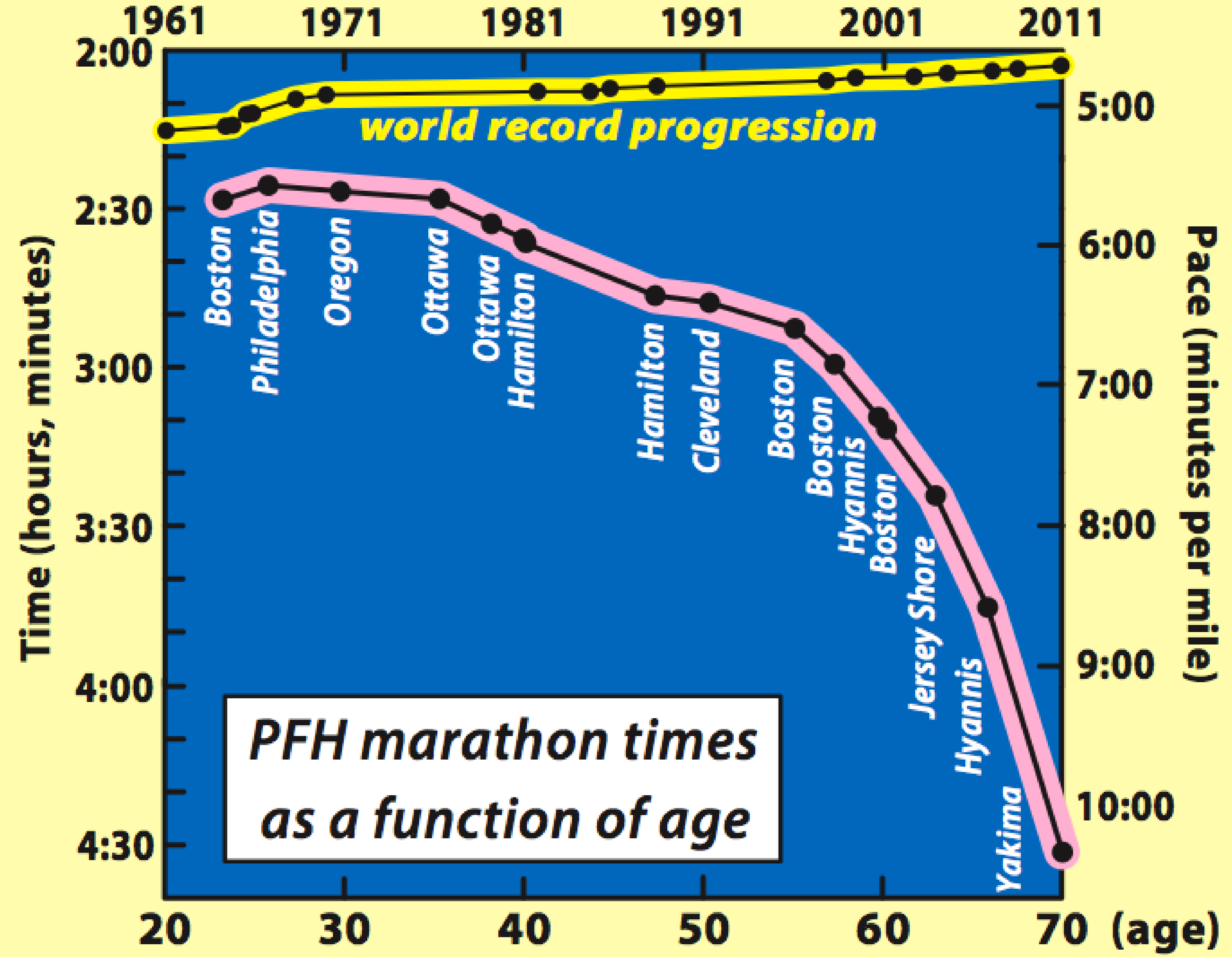


How adolescent Earth made continents but messed up the carbon cycle

Paul F. Hoffman



1961
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1981
1991
2001
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7:00
8:00
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Time (hours, minutes)
Pace (minutes per mile)
world record progression
Boston
Philadelphia
Oregon
Ottawa
Ottawa
Hamilton
Hamilton
Cleveland
Boston
Boston
Hyannis
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Jersey Shore
Hyannis
Yakima
PFH marathon times as a function of age
20
30
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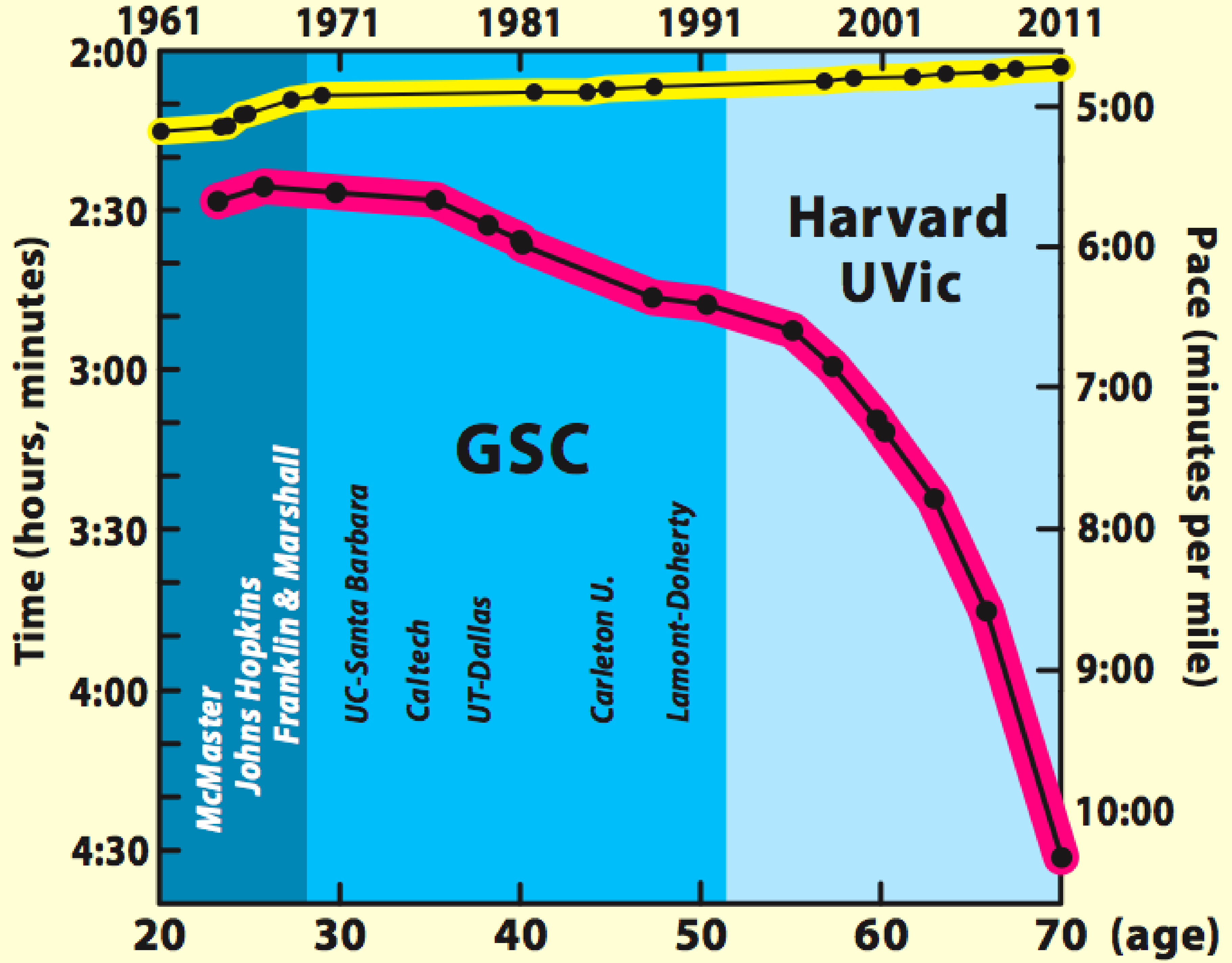
60
70
(age)



1961
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Time (hours, minutes)
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Pace (minutes per mile)
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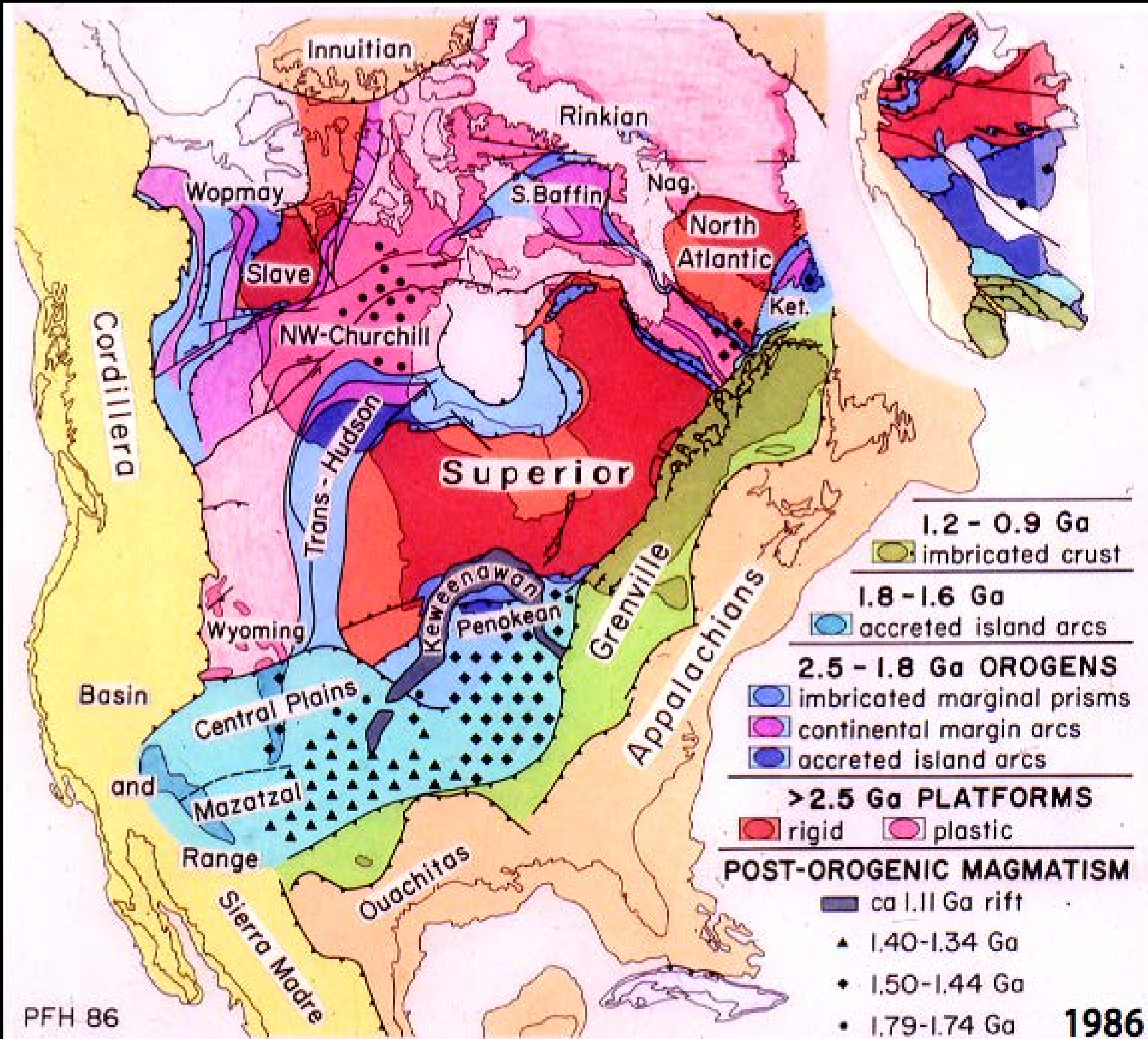
30
40
50
60
70 (age)
McMaster
Johns Hopkins
Franklin & Marshall
UC-Santa Barbara
Caltech
UT-Dallas
Carleton U.
Lamont-Doherty
GSC
Harvard
UVic



Innuitian
Rinkian
Wopmay
S.Baffin
Nag.
North Atlantic
Slave
Ket.
NW-Churchill
Cordillera
Trans-Hudson
Superior
Keweenawan
Penokean
Wyoming
Grenville
Appalachians
Basin
and
Range
Central Plains
Mazatzal
Ouachitas
Sierra Madre
1.2 - 0.9 Ga
imbricated crust
1.8 - 1.6 Ga
accreted island arcs
2.5 - 1.8 Ga OROGENS
imbricated marginal prisms
continental margin arcs
accreted island arcs
>2.5 Ga PLATFORMS
rigid
plastic
POST-OROGENIC MAGMATISM
ca 1.11 Ga rift
1.40-1.34 Ga
1.50-1.44 Ga
1.79-1.74 Ga
PFH 86
1986

Mesoproterozoic

brown - flood basalt

yellow - sandstone

Paleoproterozoic

red - granitoids

light green - seds

dark green - volcs

Archean

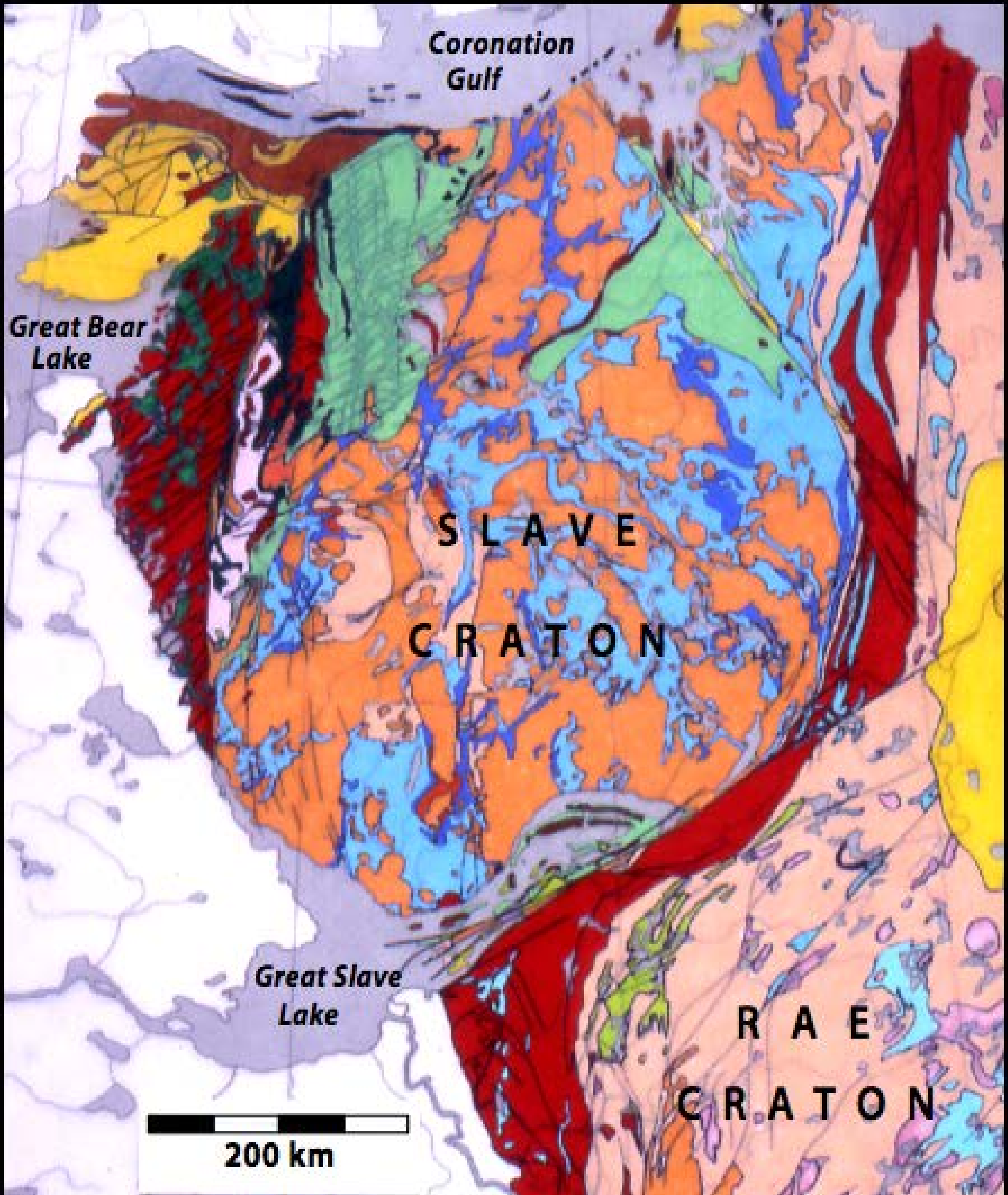
mauve - granulite

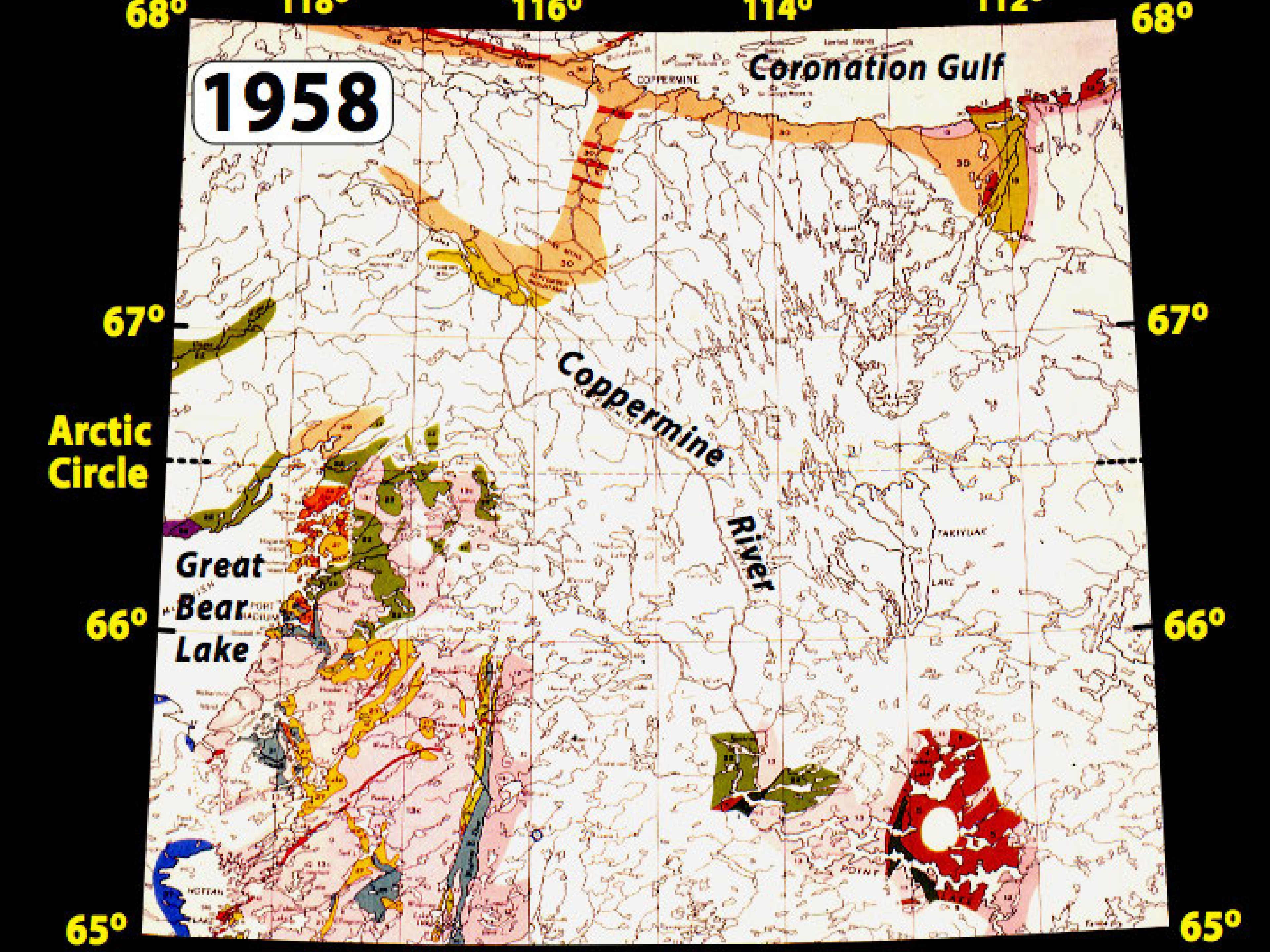
flesh - gneisses

orange - granitoids

light blue - clastics

dark blue - volcanics




1958
68°
118°
116°
114°
112°
68°
Coronation Gulf
COPPERMINE
67°
67°
Coppermine
Arctic
Circle
River
Great
Bear
Lake
66°
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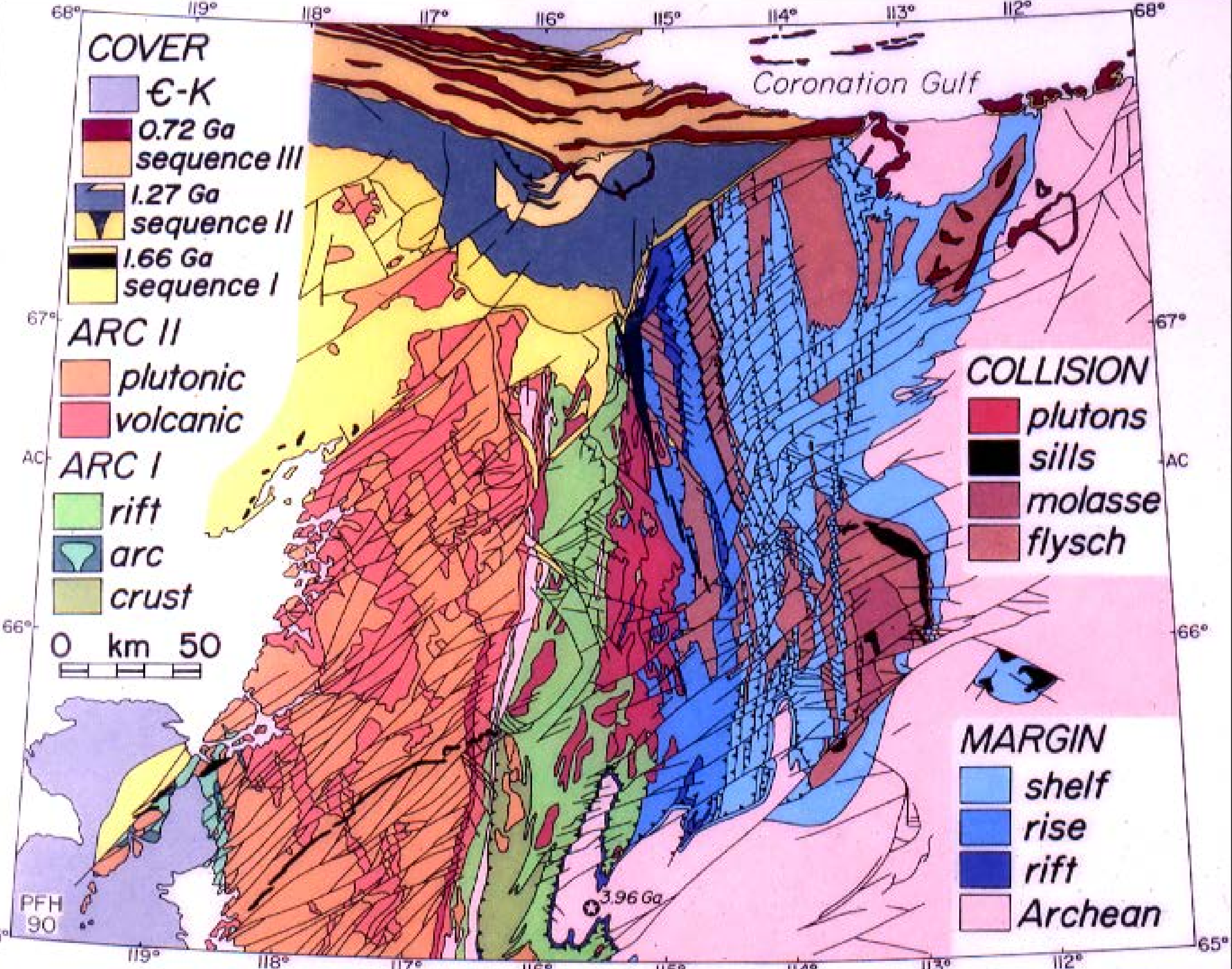
65°
65°


COVER
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sequence III
1.27 Ga
sequence II
1.66 Ga
sequence I
ARC II
plutonic
volcanic
ARC I
rift
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0 km 50
Coronation Gulf
COLLISION
plutons
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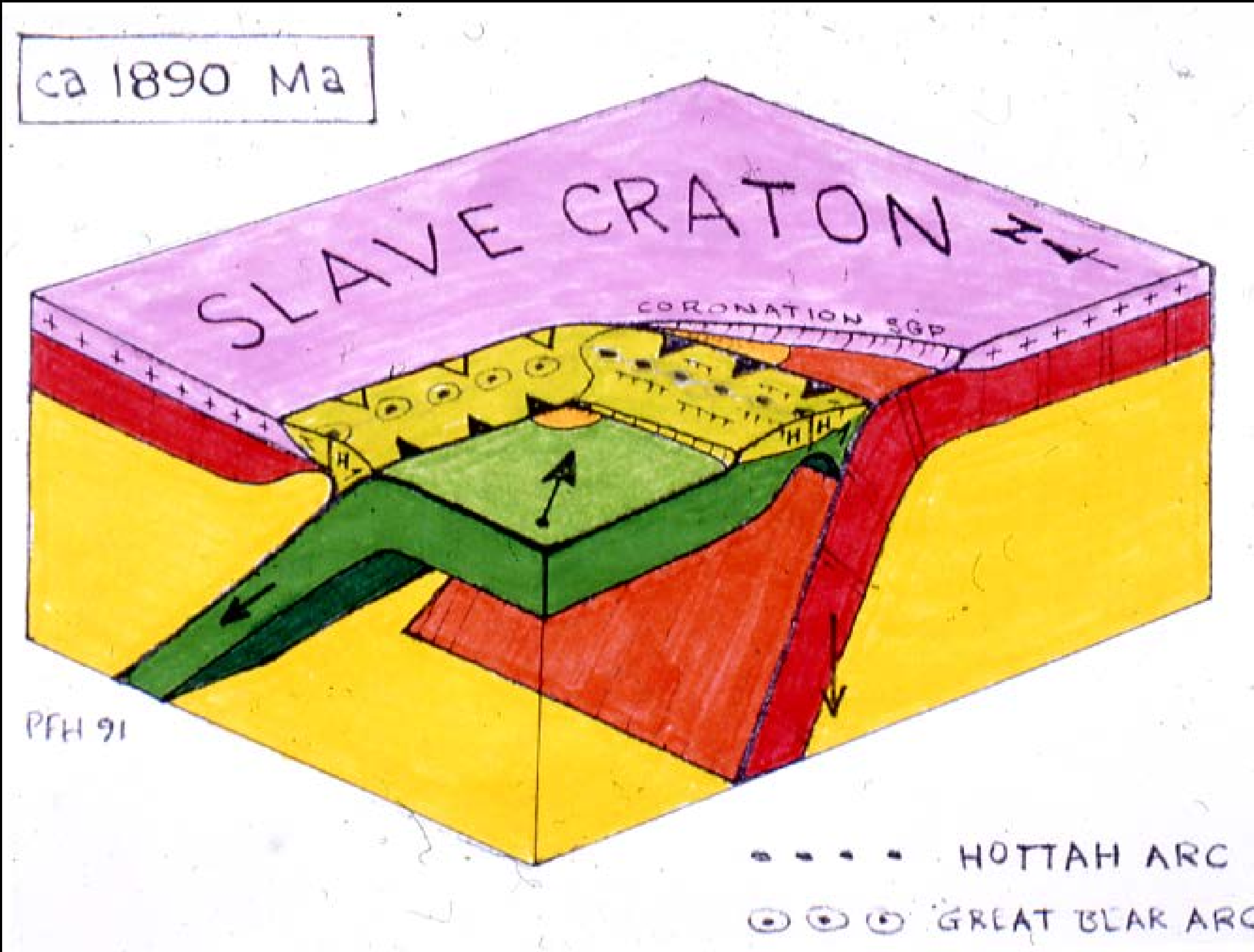
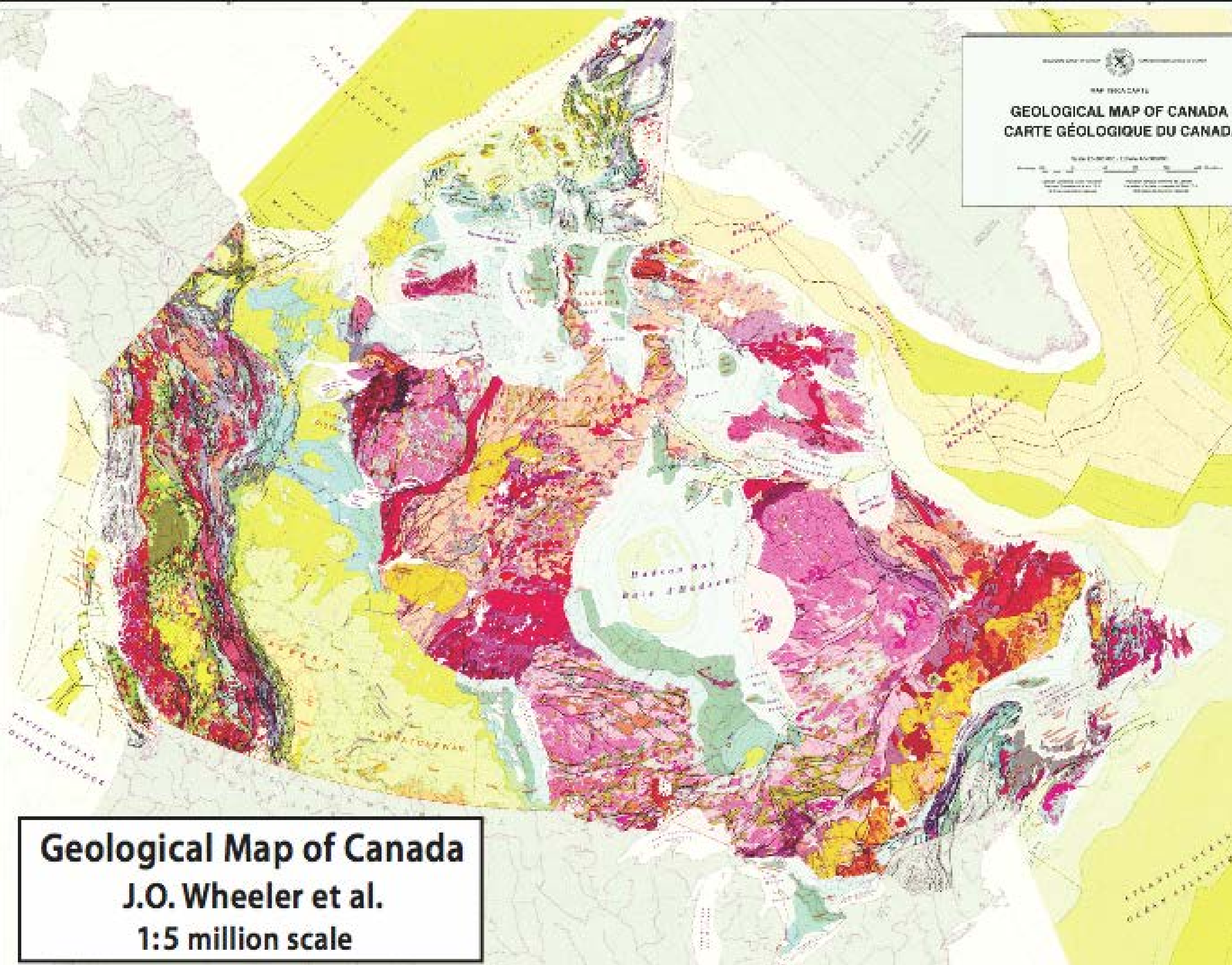
MARGIN
shelf
rise
rift
Archean
3.96 Ga
PFH 90
AC
68°
119°
118°
117°
116°
115°
114°
113°
112°
67°
66°
65°

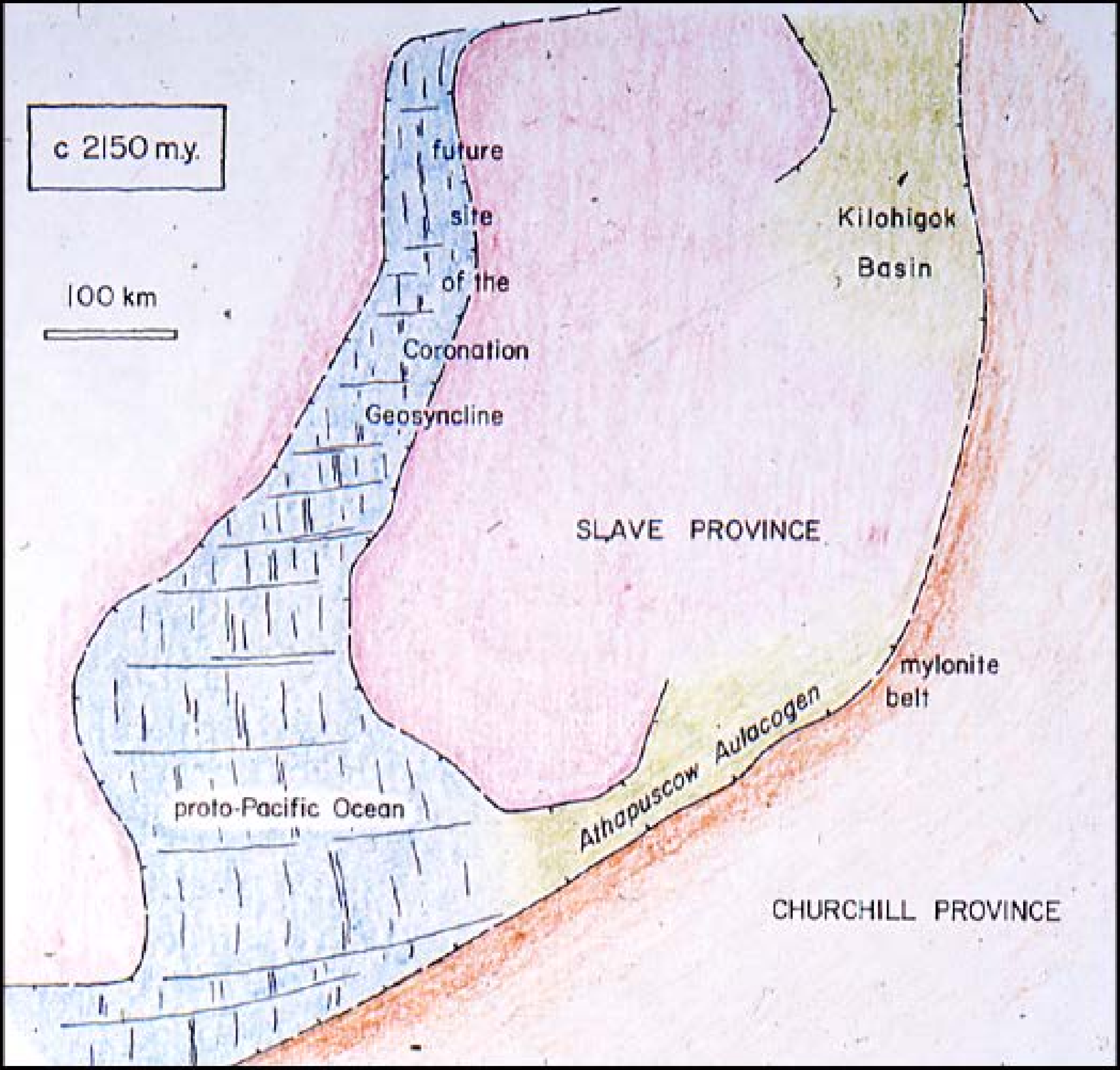
Calderian orogeny: arc-continent collision & subduction-polarity reversal

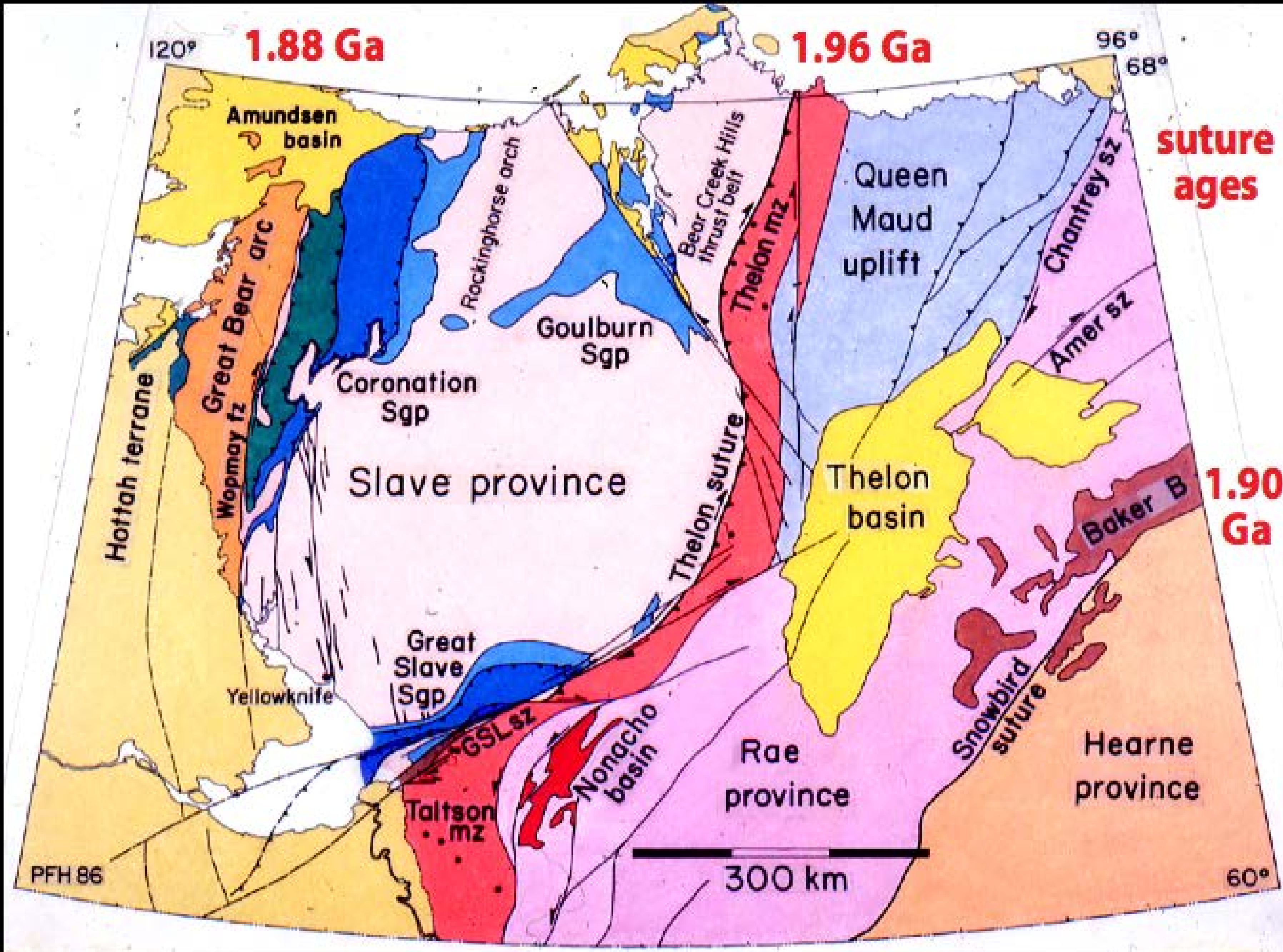


Mike Easton, Paul Hoffman, Marc St-Onge in 1979



Geological Map of Canada
J.O. Wheeler et al.
1:5 million scale

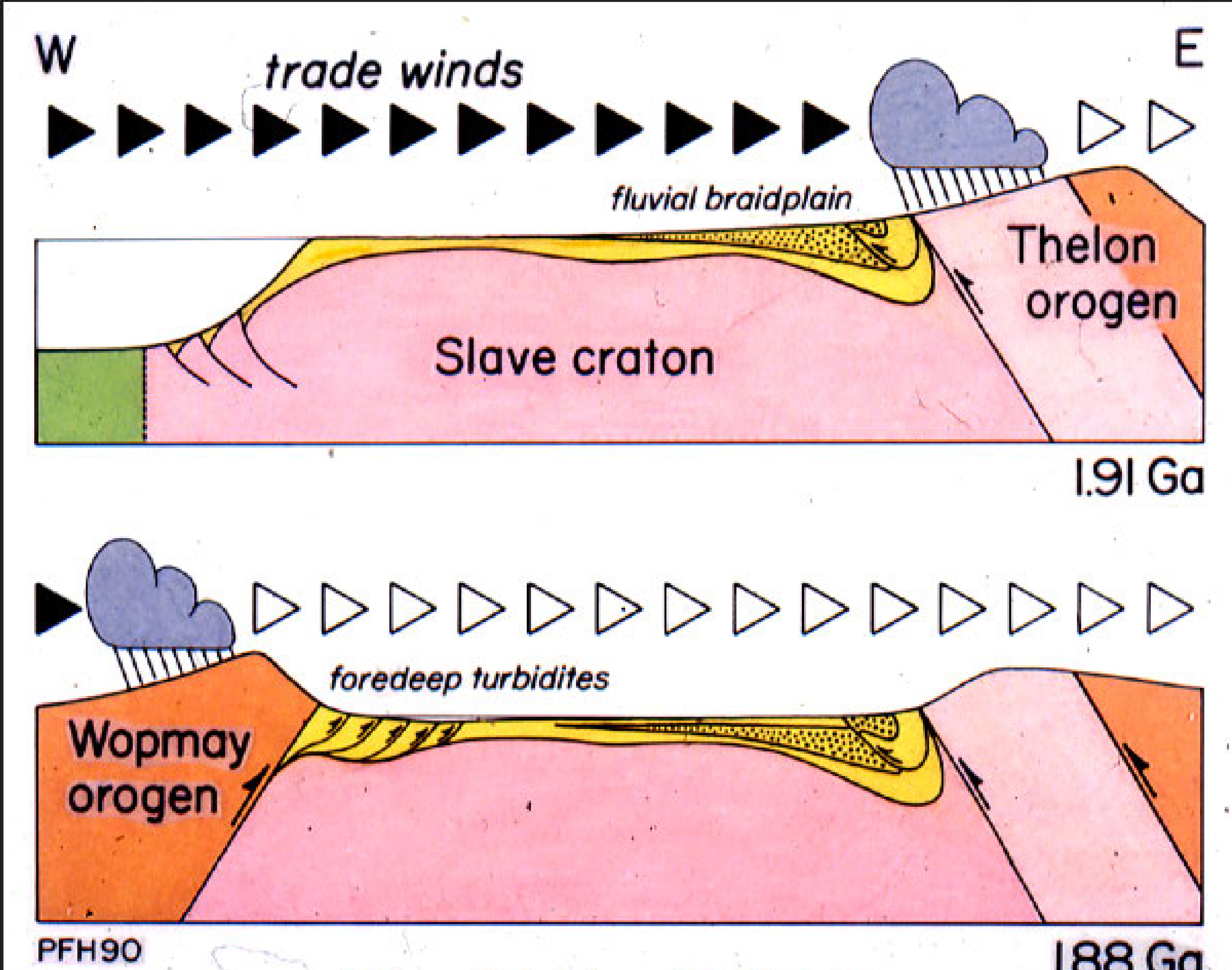

c 2150 m.y.
100 km
future site of the Coronation Geosyncline
Kilohigok Basin
SLAVE PROVINCE
mylonite belt
Athapuscow Aulacogen
proto-Pacific Ocean
CHURCHILL PROVINCE



Tectonic element map of the northwest of the Canadian Shield

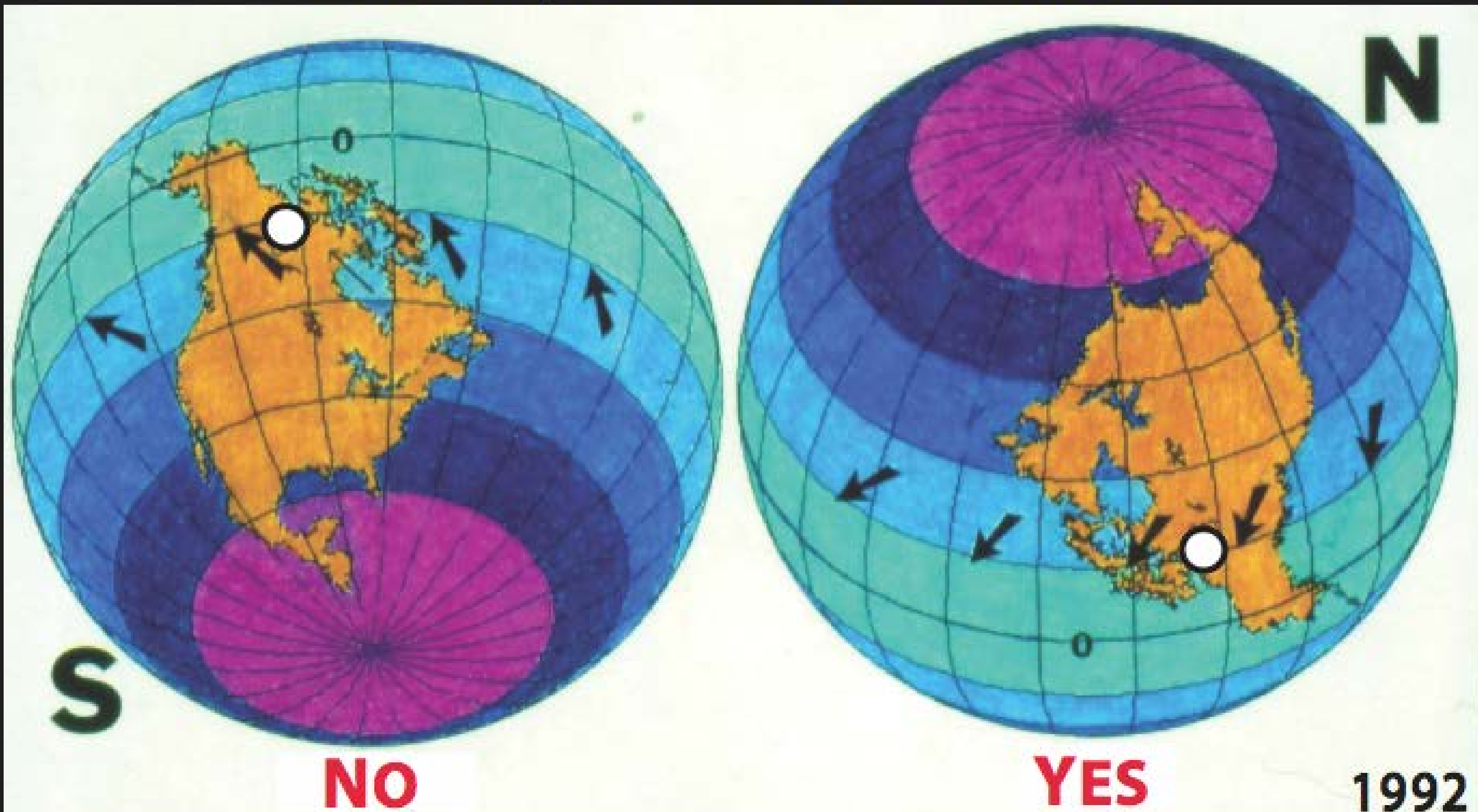
John Grotzinger and 1961-Ma ash in the Bear Creek foredeep (1987)
U-Pb zircon geochronology by Sam Bowring

Orographic precipitation model for the contrasting foredeeps and foreland thrust-fold belts of Thelon and Wopmay orogens



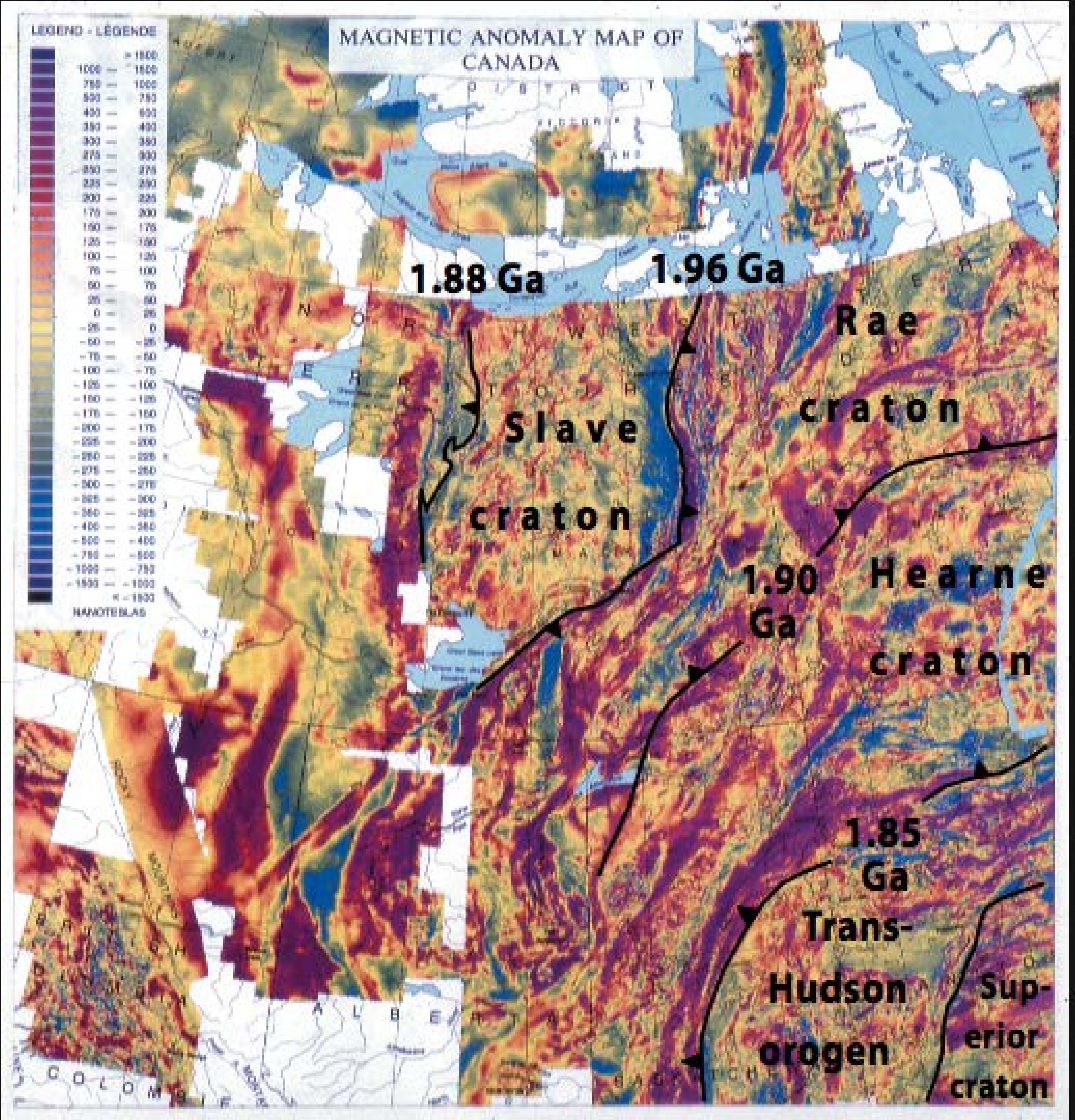
Hoffman & Grotzinger (1993) Geology

Determining paleomagnetic hemisphere polarity using Paleoproterozoic trade wind indicators in Wopmay and Thelon orogens

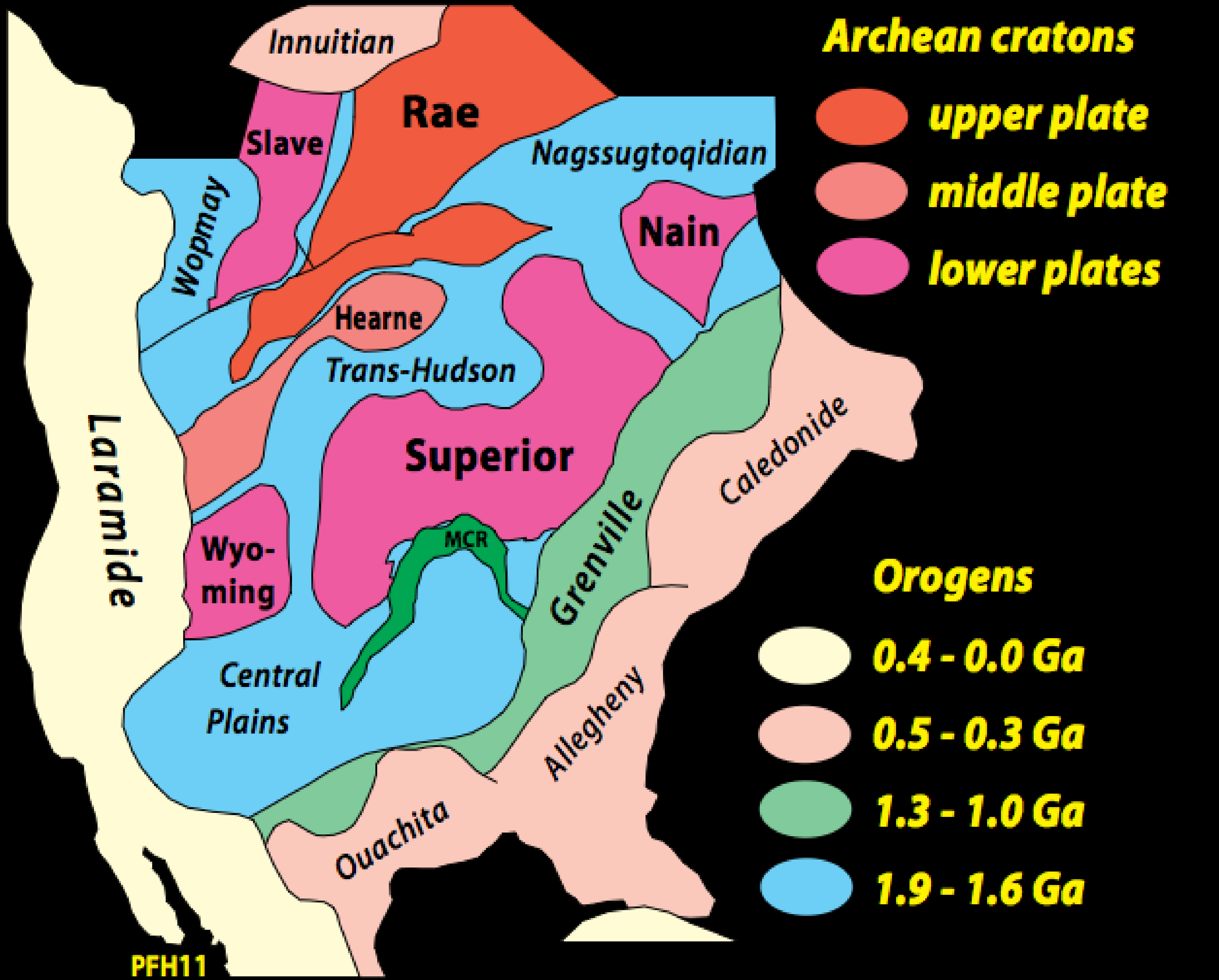


Aerial view of WSW-plunging Tree River folds in Rocknest Formation

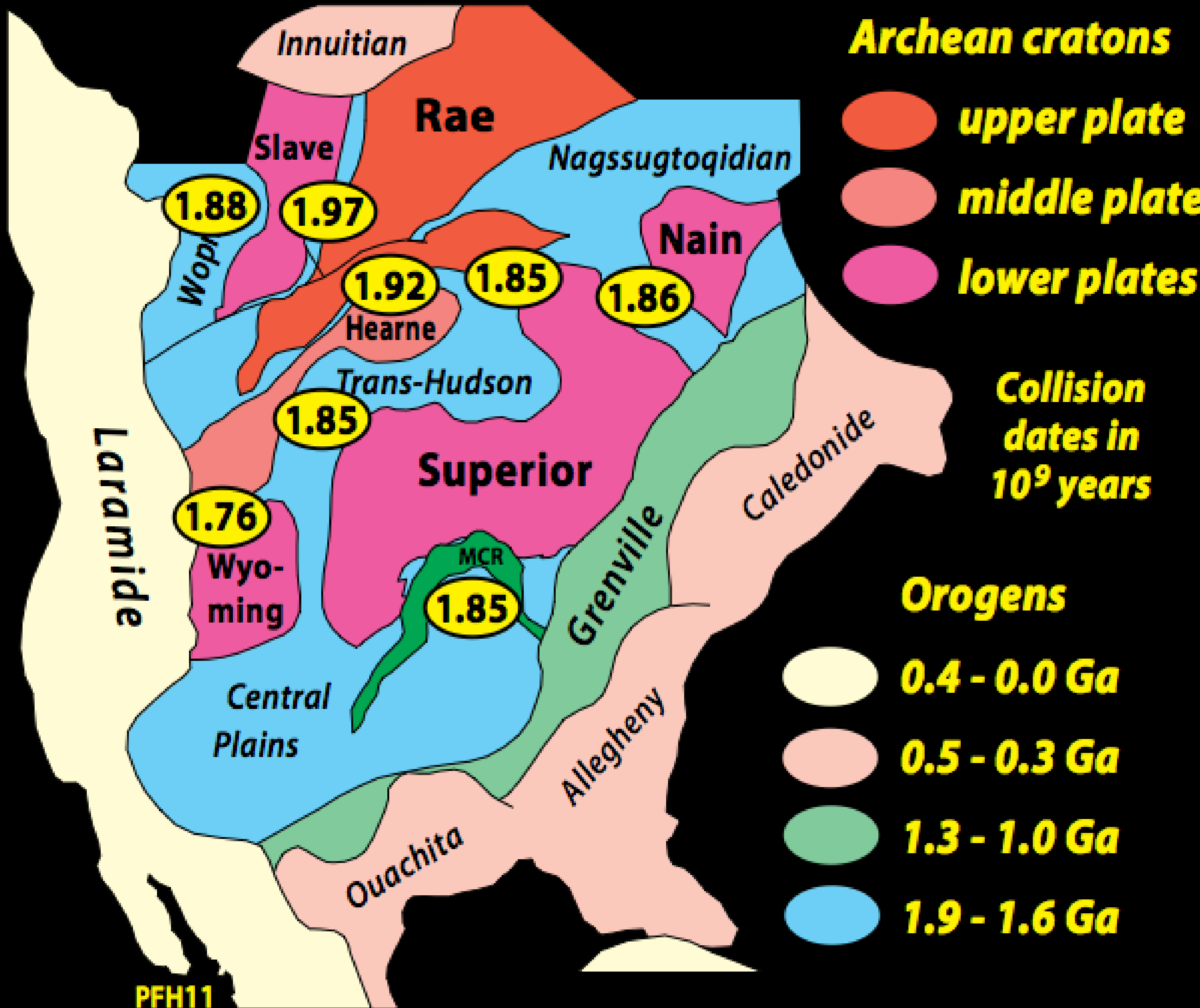
Guy, Paul and Erica Westbrook, Ottawa, 1982


MAGNETIC ANOMALY MAP OF CANADA
LEGEND - LÉGENDE
NANOTESLAS
1.88 Ga
1.96 Ga
Rae craton
Slave craton
1.90 Ga
Hearne craton
1.85 Ga
Trans-Hudson orogen
Sup-erior craton

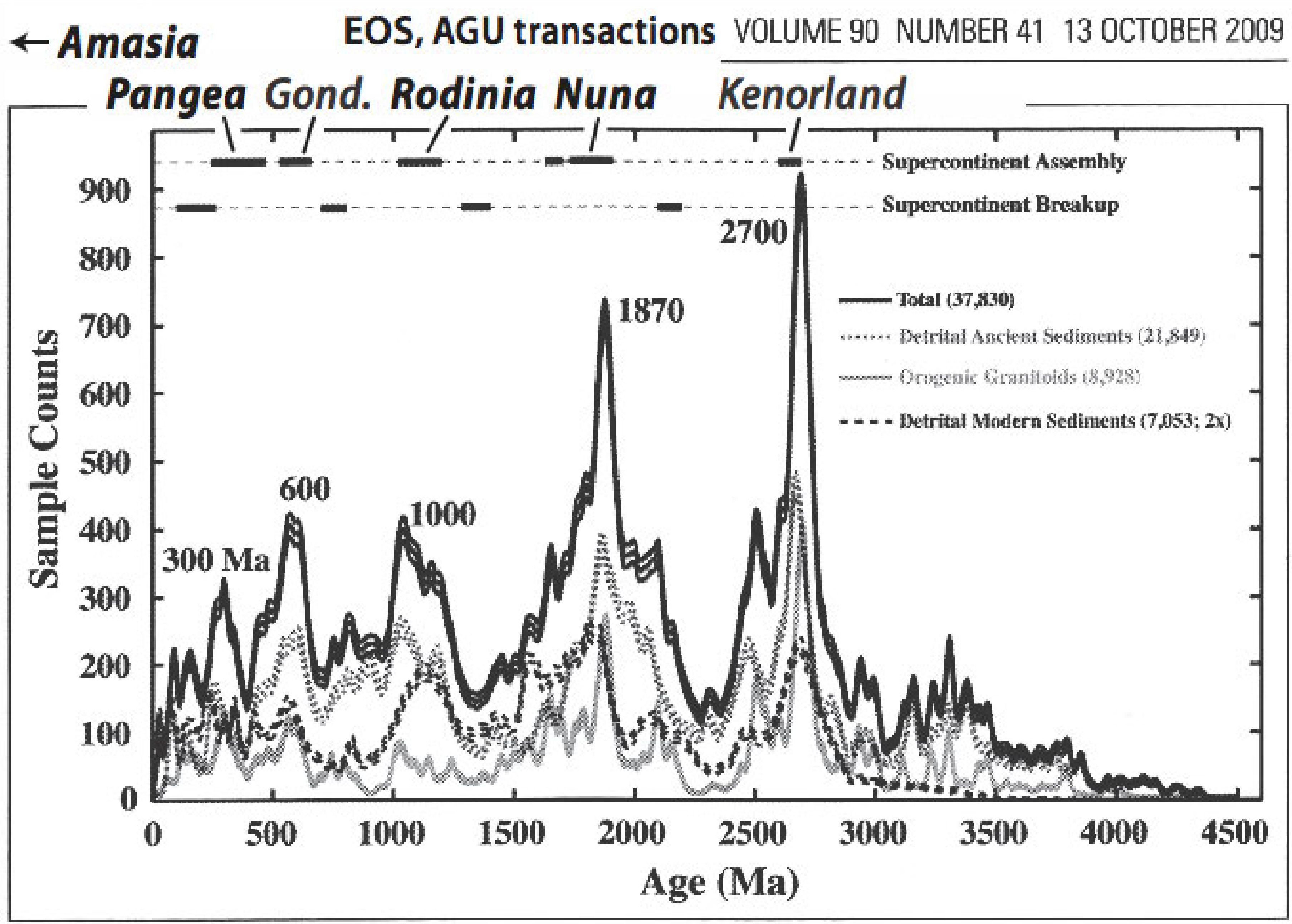
The United Plates of America:



The United Plates of America:

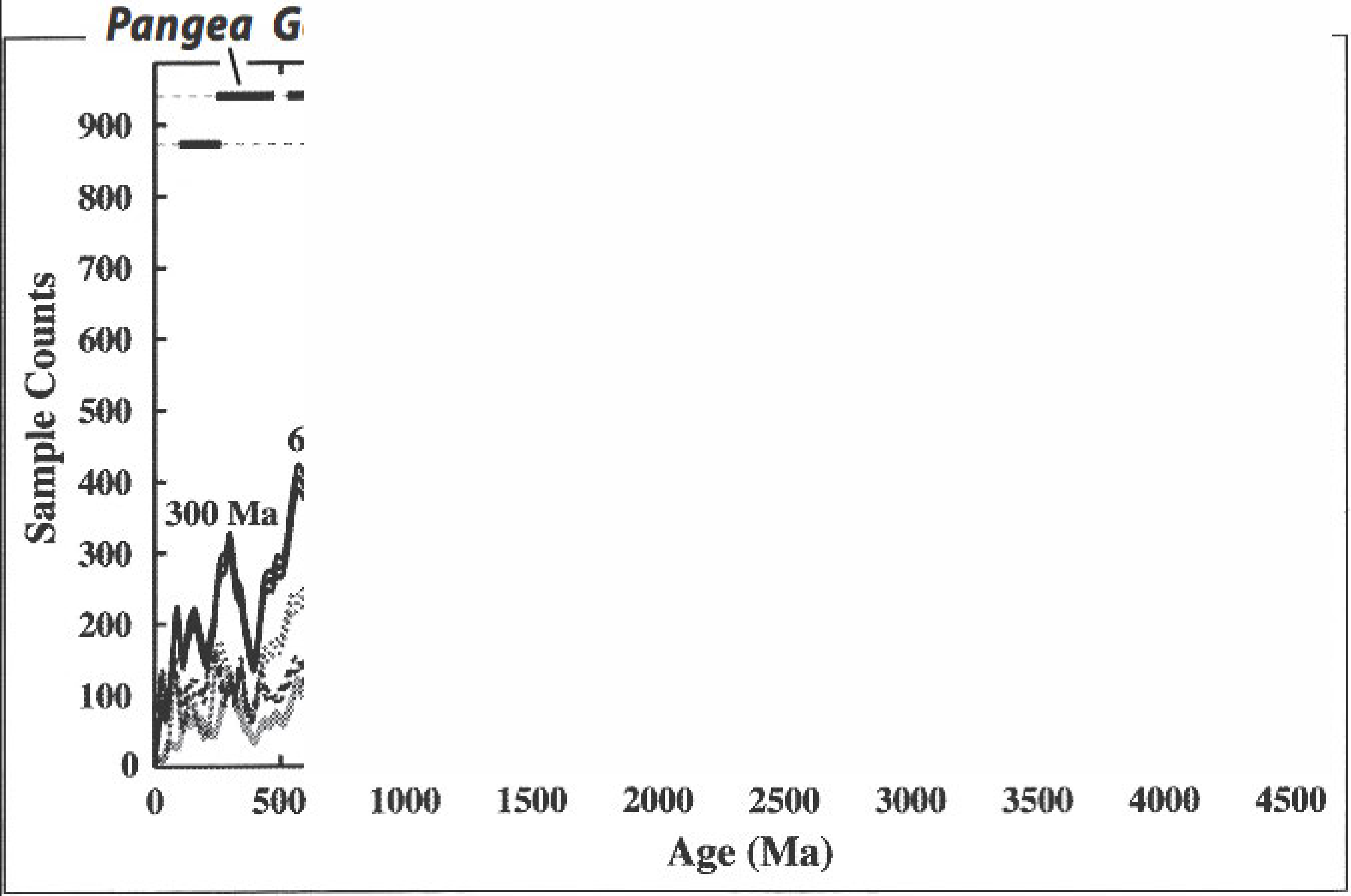


Condie, K.T. & Aster, R.C. Zircon age episodicity and growth of continental crust.

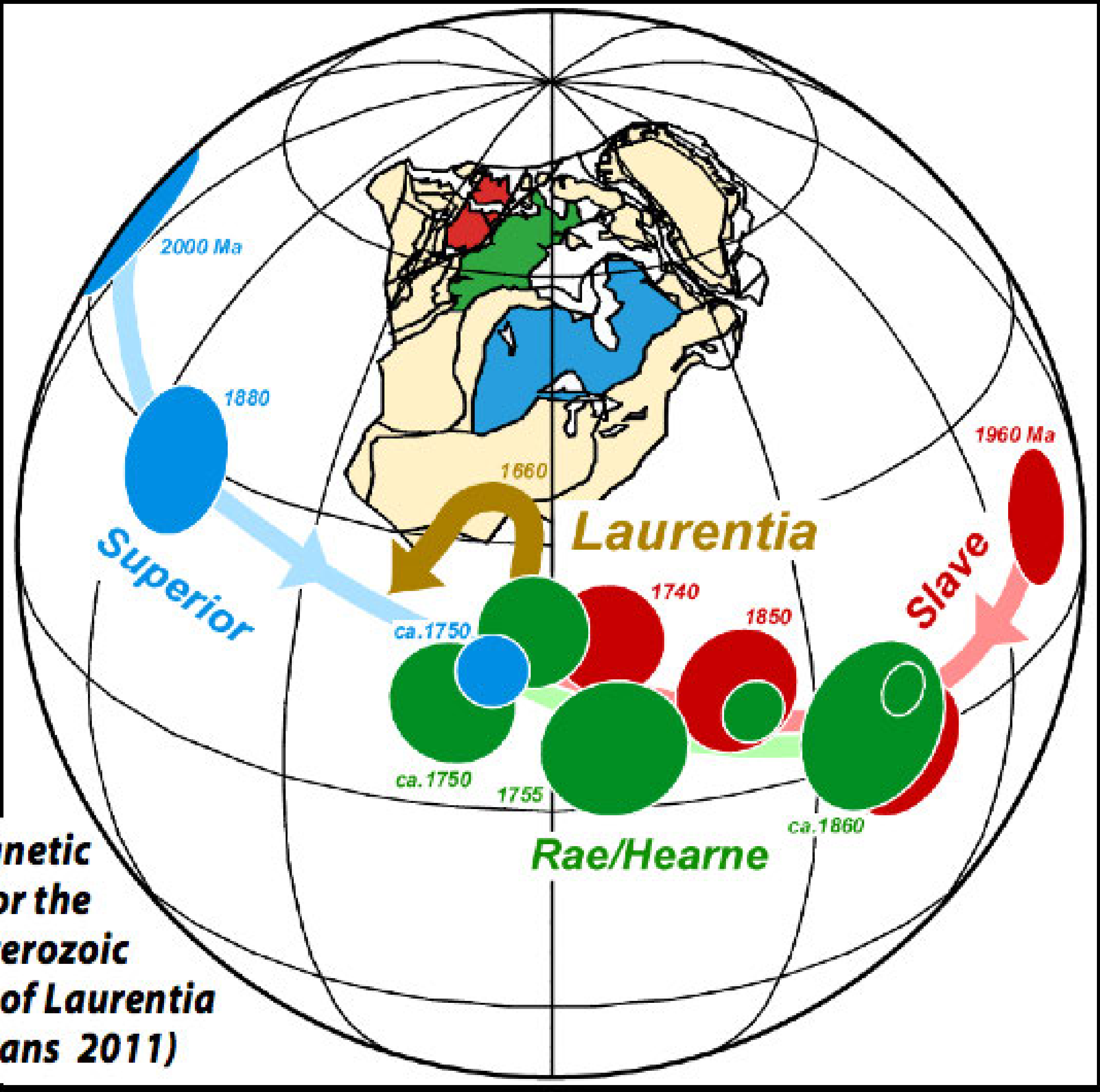


Condie, K.T. & Aster, R.C. Zircon age episodicity and growth of continental crust.

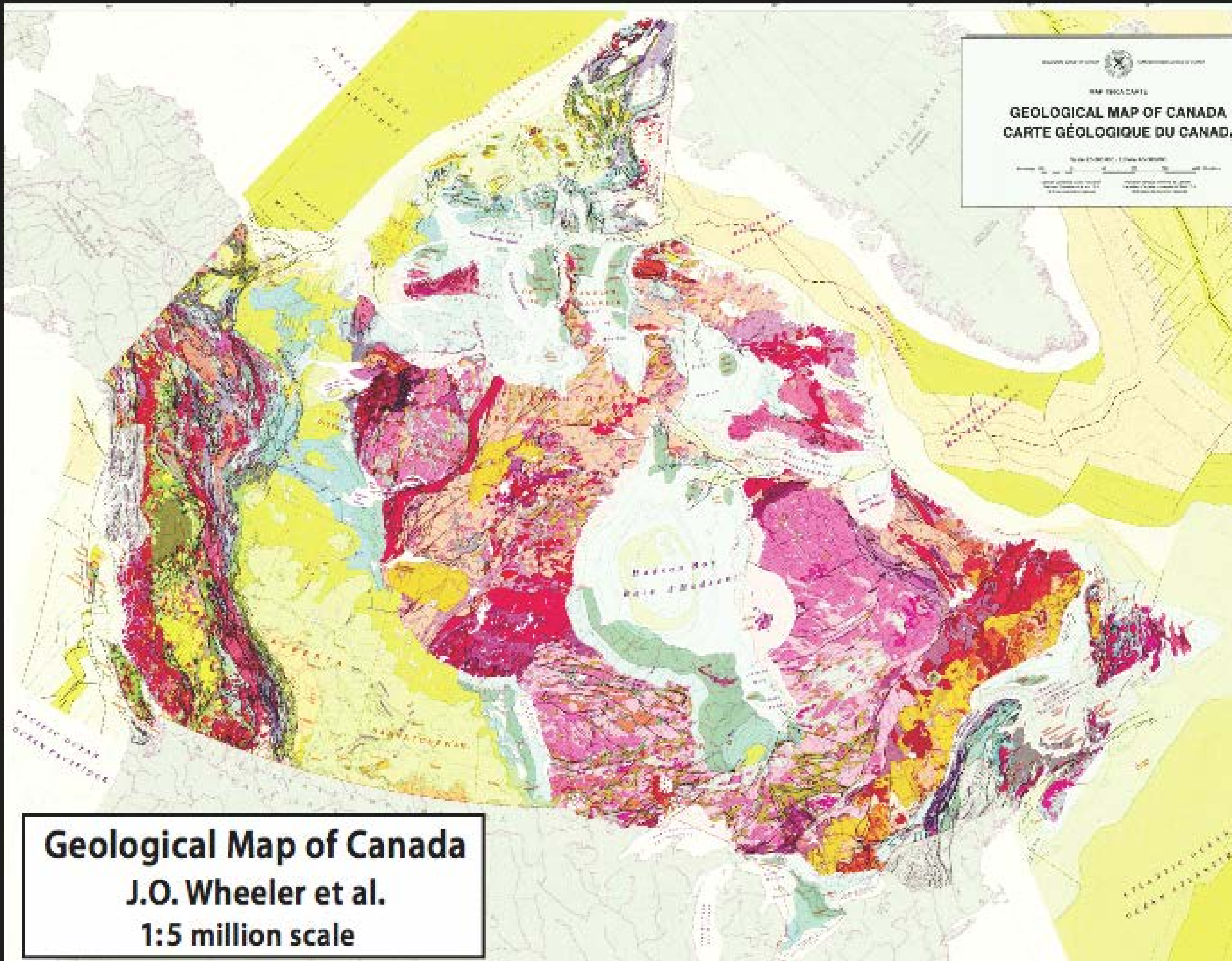
EOS, AGU transactions VOLUME 90 NUMBER 41 13 OCTOBER 2009



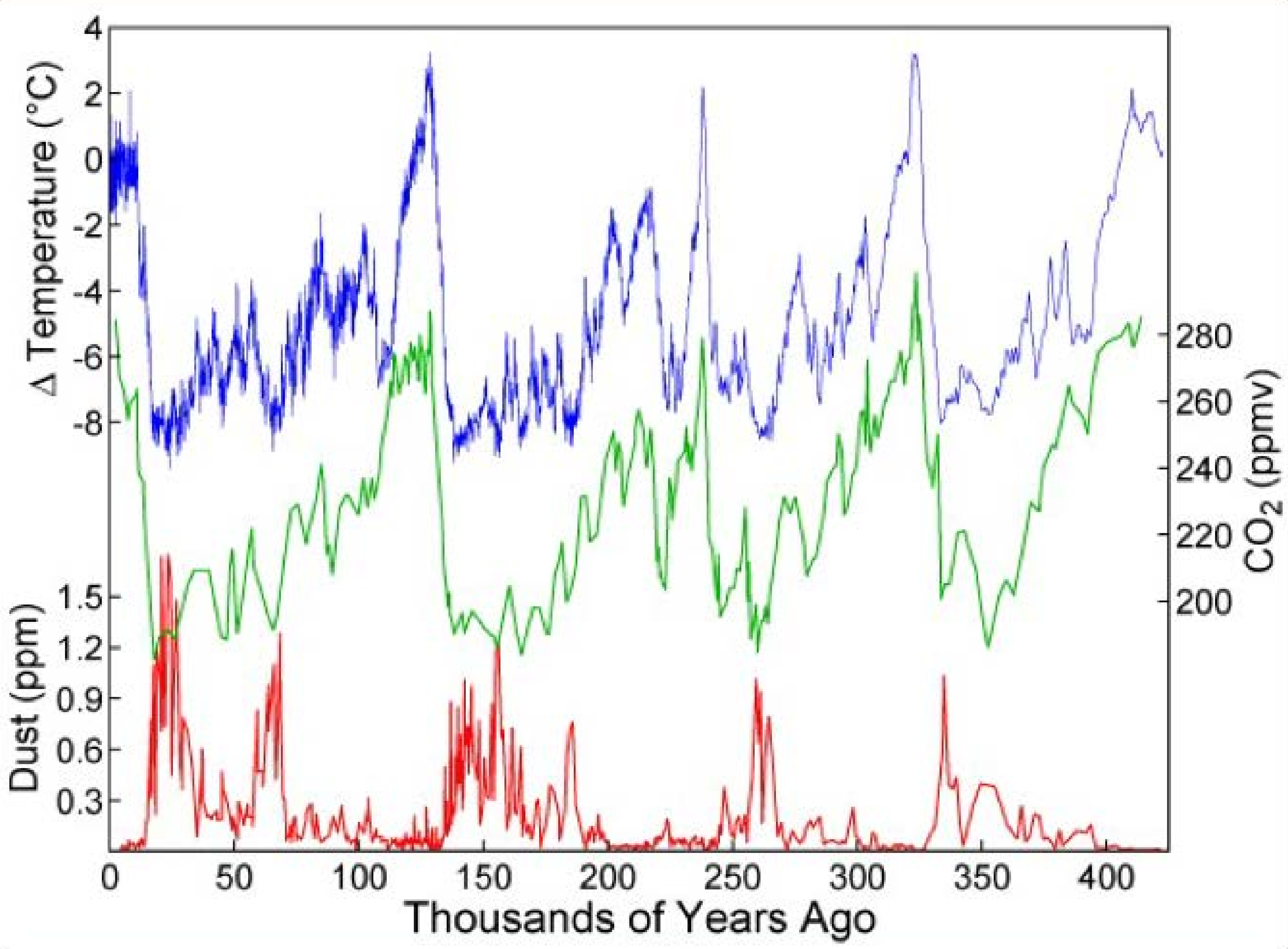
Mackenzie (1.27 Ga) and Franklin (0.72 Ga) dikes, looking north toward their respective flood basalts (Coppermine and Natkusiak)



Paleomagnetic support for the Paleoproterozoic assembly of Laurentia (D.A.D. Evans 2011)

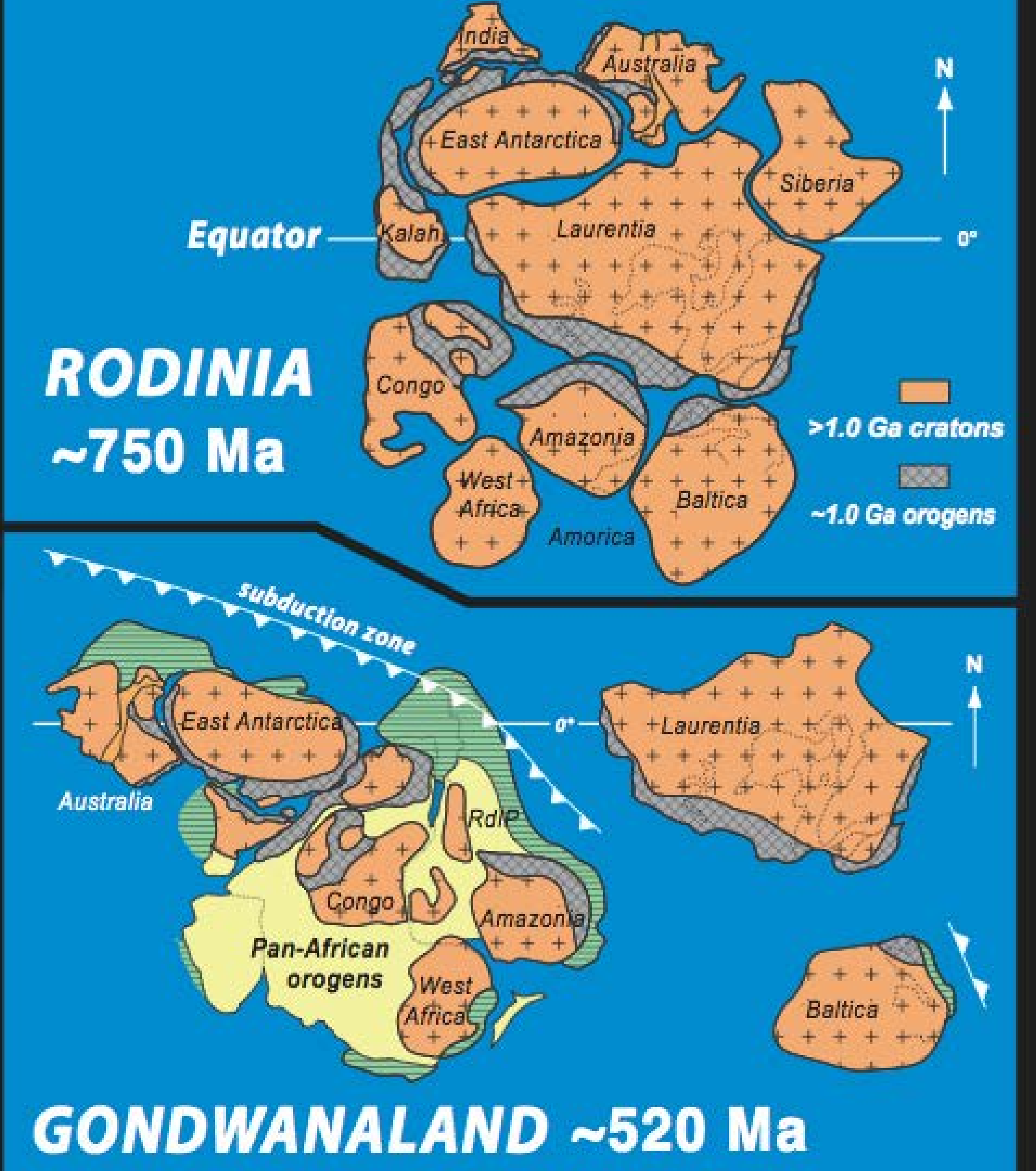


Geological Map of Canada
J.O. Wheeler et al.
1:5 million scale

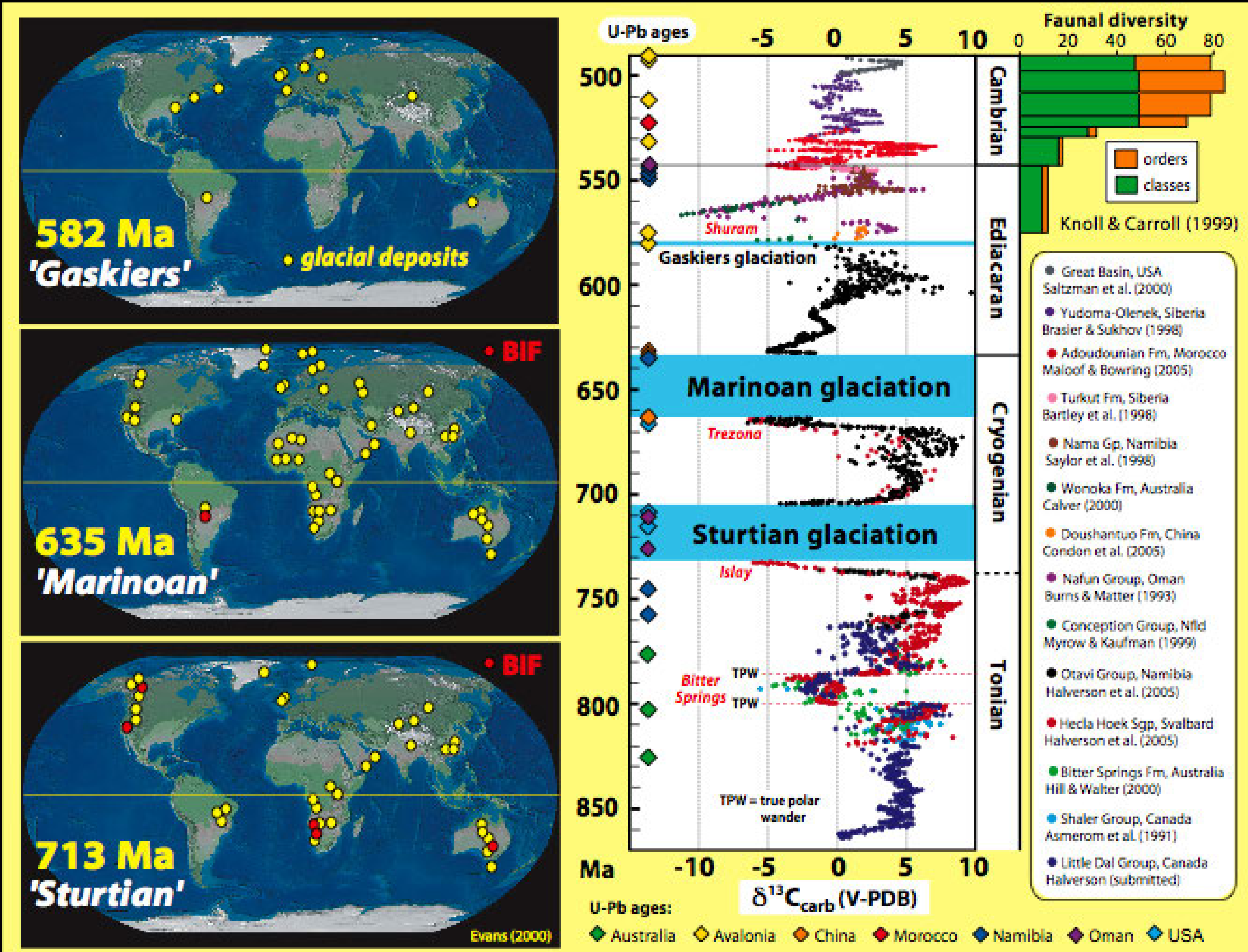


4
2
0
-2
-4
-6
-8
Δ Temperature (°C)
280
260
240
220
200
CO2 (ppmv)
1.5
1.2
0.9
0.6
0.3
Dust (ppm)
0
50
100
150
200
250
300
350
400
Thousands of Years Ago

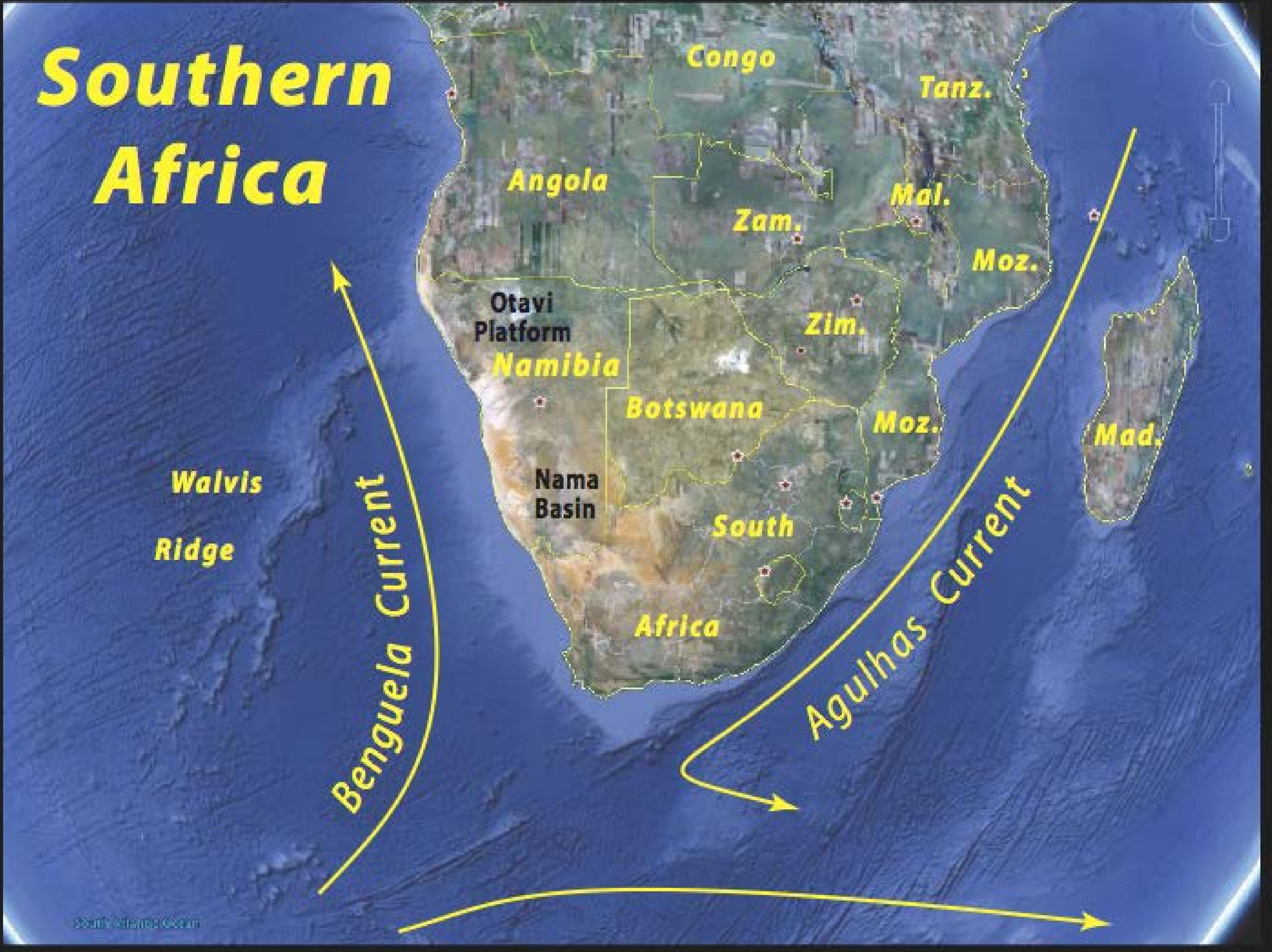
Did the breakout of Laurentia turn Gondwanaland inside-out?

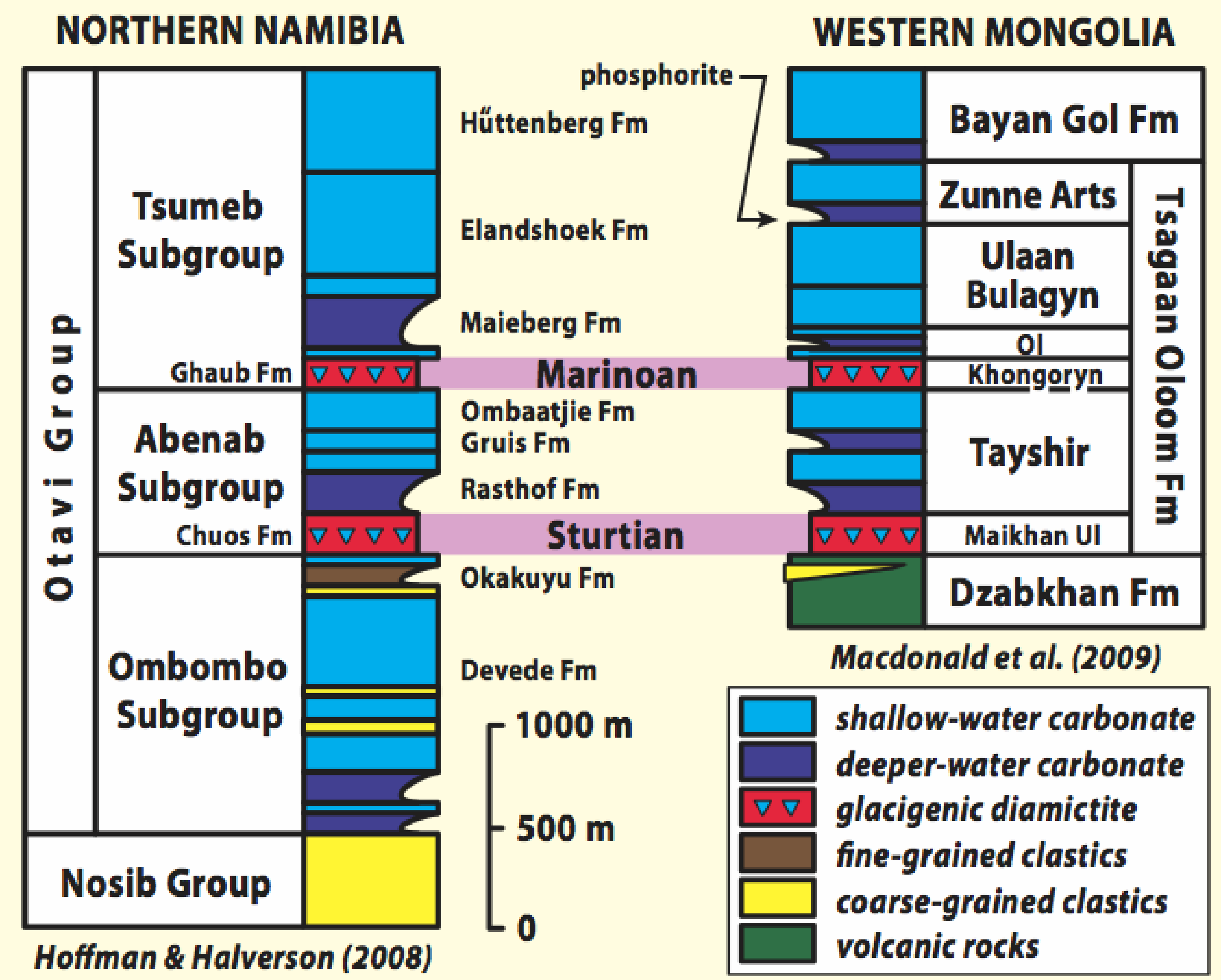


Hoffman (1991) Science 252, 1409-1312.



582 Ma
'Gaskiers'
glacial deposits
BIF
635 Ma
'Marinoan'
BIF
713 Ma
'Sturtian'
Evans (2000)
U-Pb ages
Ma
500
550
600
650
700
750
800
850
-10
-5
0
5
10
$\delta^{13}C_{carb}$ (V-PDB)
Shuram
Gaskiers glaciation
Marinoan glaciation
Trezona
Sturtian glaciation
Islay
Bitter Springs
TPW
TPW
TPW = true polar wander
Cambrian
Ediacaran
Cryogenian
Tonian
Faunal diversity
0
20
40
60
80
orders
classes
Knoll & Carroll (1999)
Great Basin, USA
Saltzman et al. (2000)
Yudoma-Olenek, Siberia
Brasier & Sukhov (1998)
Adoudounian Fm, Morocco
Maloof & Bowring (2005)
Turkut Fm, Siberia
Bartley et al. (1998)
Nama Gp, Namibia
Saylor et al. (1998)
Wonoka Fm, Australia
Calver (2000)
Doushantuo Fm, China
Condon et al. (2005)
Nafun Group, Oman
Burns & Matter (1993)
Conception Group, Nfld
Myrow & Kaufman (1999)
Otavi Group, Namibia
Halverson et al. (2005)
Hecla Hoek Sgp, Svalbard
Halverson et al. (2005)
Bitter Springs Fm, Australia
Hill & Walter (2000)
Shaler Group, Canada
Asmerom et al. (1991)
Little Dal Group, Canada
Halverson (submitted)
U-Pb ages:
Australia
Avalonia
China
Morocco
Namibia
Oman
USA


Southern Africa
Congo
Tanz.
Angola
Mal.
Zam.
Moz.
Otavi Platform
Zim.
Namibia
Botswana
Moz.
Mad.
Walvis Ridge
Nama Basin
South Africa
Benguela Current
Agulhas Current

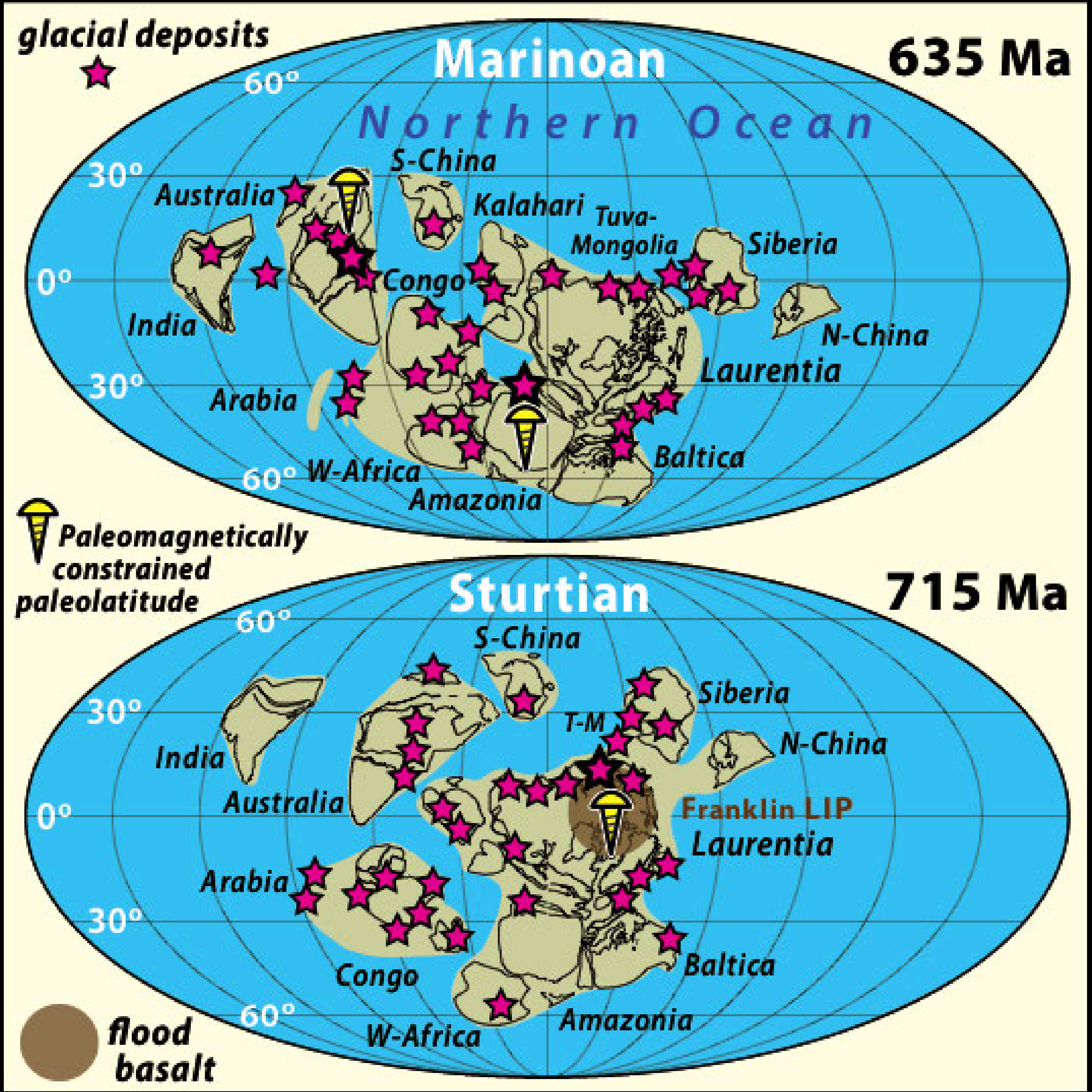


NORTHERN NAMIBIA
WESTERN MONGOLIA
Otavi Group
Tsumeb Subgroup
Abenab Subgroup
Ombombo Subgroup
Nosib Group
Hűttenberg Fm
Elandshoek Fm
Maieberg Fm
Ghaub Fm
Marinoan
Ombaatjie Fm
Gruis Fm
Rasthof Fm
Chuos Fm
Sturtian
Okakuyu Fm
Devede Fm
1000 m
500 m
0
Hoffman & Halverson (2008)
phosphorite
Bayan Gol Fm
Zunne Arts
Ulaan Bulagyn
Ol
Khongoryn
Tayshir
Maikhan Ul
Tsagaan Oloom Fm
Dzabkhan Fm
Macdonald et al. (2009)
shallow-water carbonate
deeper-water carbonate
glacigenic diamictite
fine-grained clastics
coarse-grained clastics
volcanic rocks

Paleogeographic distribution of Cryogenian glacial deposits (red stars)

Hoffman & Li Z-X Paleo.Paleo.Paleo., 277, 158-172 (2009)

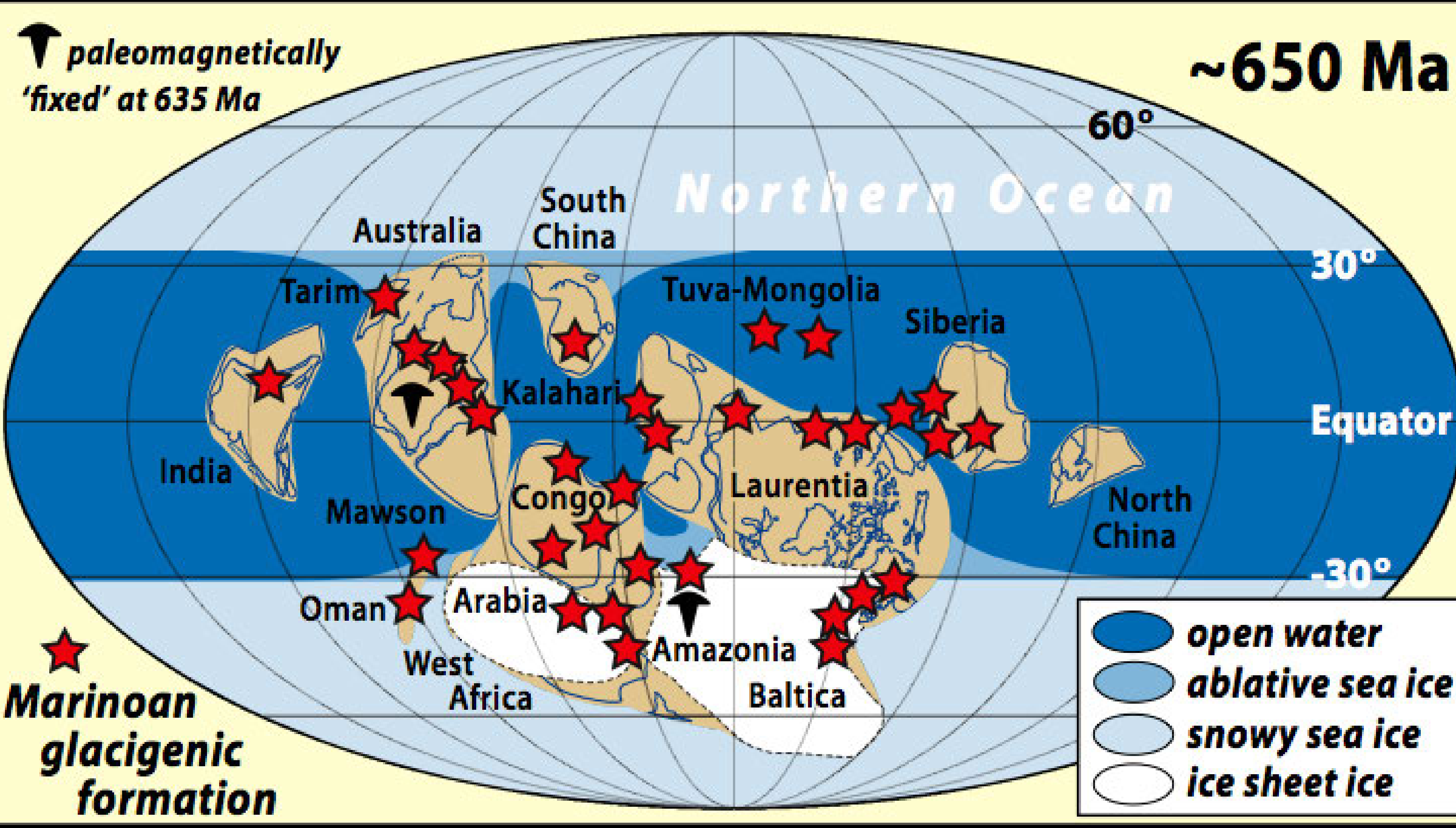
Paleogeography after Li Z-X et al. Precambrian Res., 160, 179-210 (2008)



Global paleogeography at the Cryogenian-Ediacaran boundary
Hoffman and Zhang-Xiang Li (2009) Palaeo. x3, 277, 158-172.

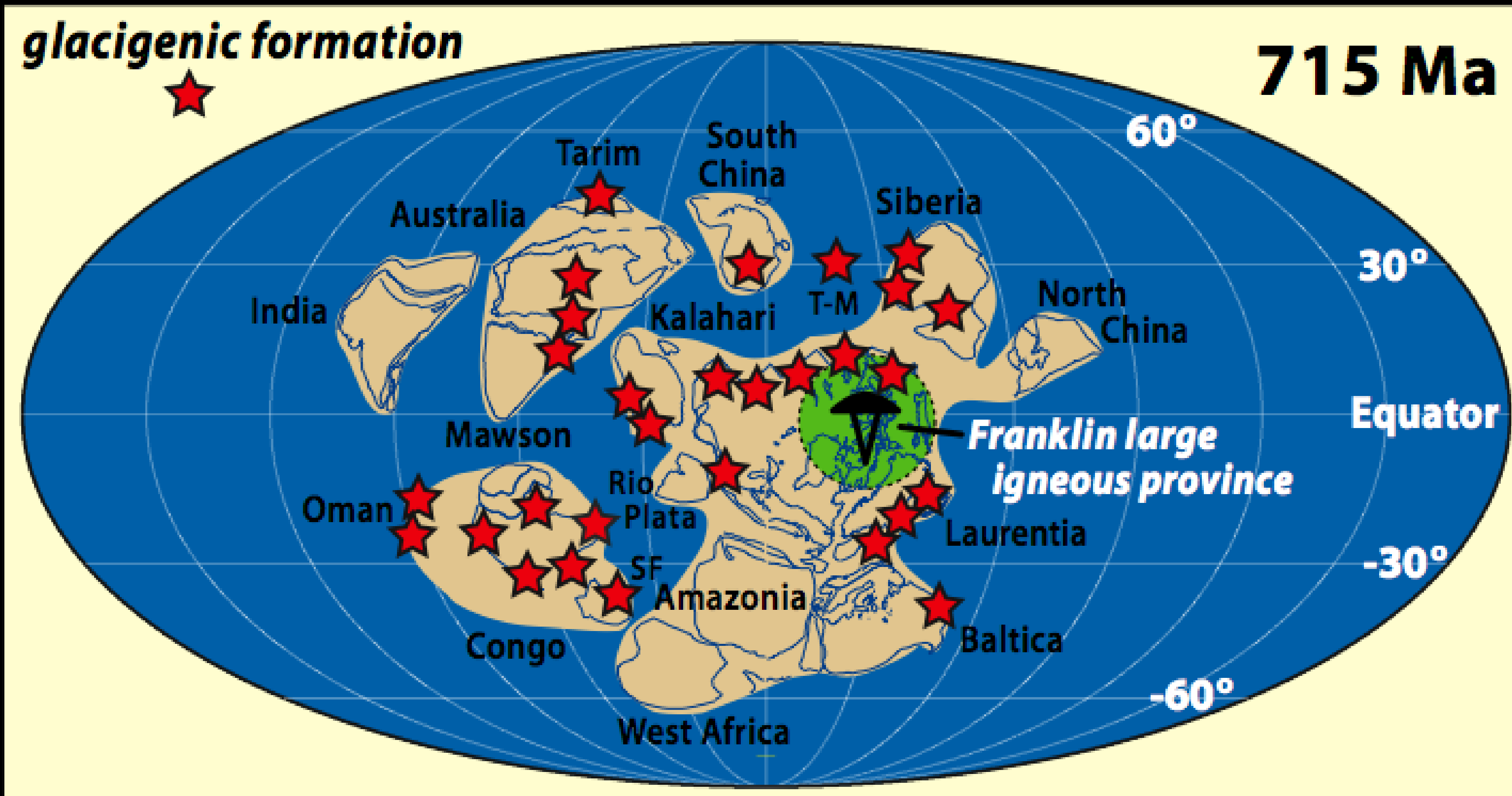
Global paleogeography on the verge of the Marinoan glaciation

Voigt et al. (2011) Climate of the Past - ECHAM5 O-A GCM

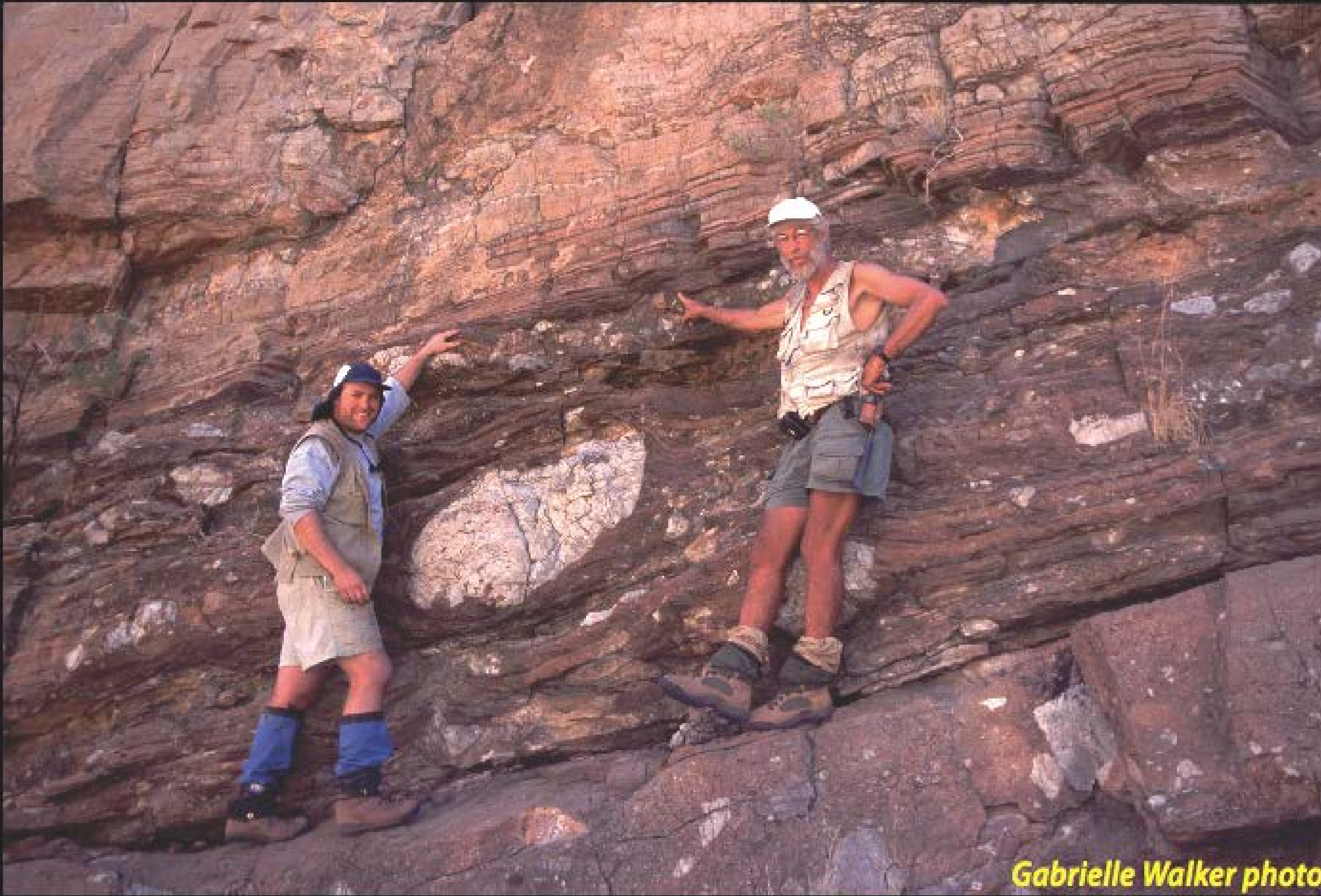


Sturtian glacial-periglacial formations (red stars) on a paleocontinental reconstruction for 715 Ma

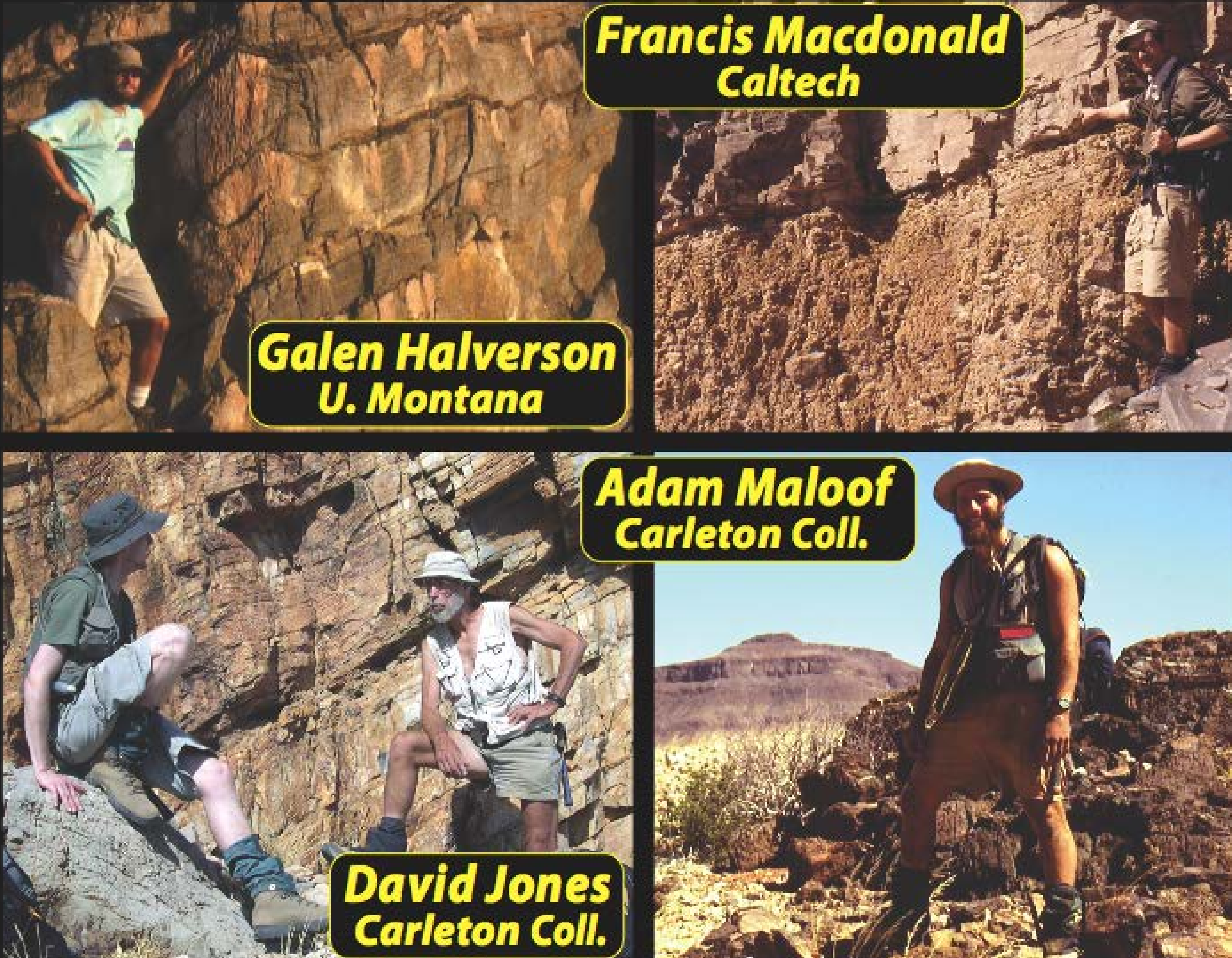
Hoffman & Zheng-Xiang Li (2009) Palaeo-cubed, 227, 158-172.

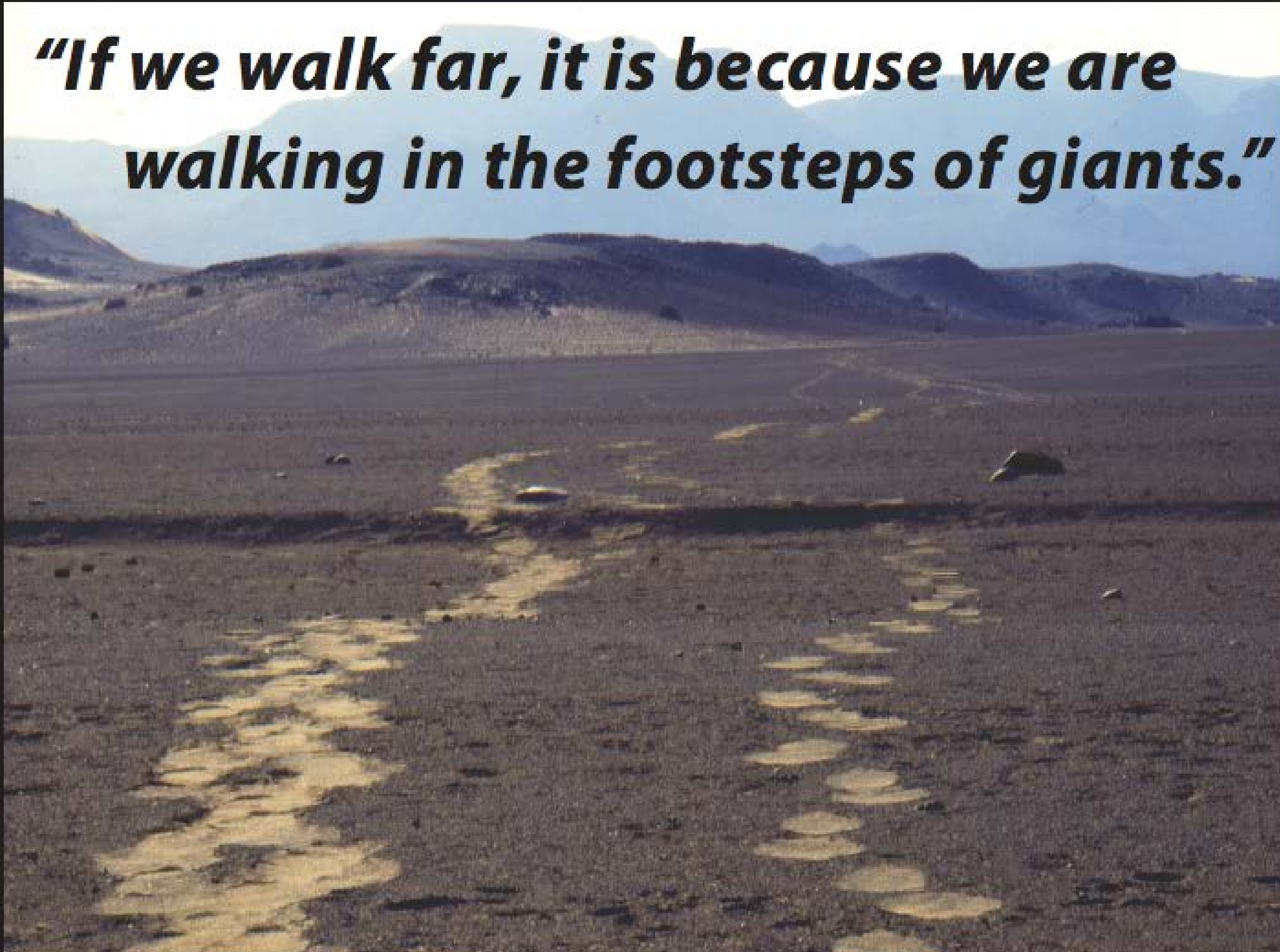


Dan Schrag and Paul Hoffman in Namibia, 2000
Marinoan glacial termination - 635 Ma



Gabrielle Walker photo


Francis Macdonald
Caltech
Galen Halverson
U. Montana
Adam Maloof
Carleton Coll.
David Jones
Carleton Coll.


"If we walk far, it is because we are
walking in the footsteps of giants."