The Tectonic Context of Neoproterozoic and Early Paleozoic Environmental Change

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My work has only been possible with the help of great students, great post docs, great collaborators, and great advisors….

Collaborators

Arctic Alaska & Canada: Charlie Roots (GSC); Mo Colpron (YGS); Mark Schmitz & Jim Crowley (BSU); Galen Halverson (McGill); Erik Sperling (Harvard); Guy Narbonne (Queens); Bill McClelland (Iowa); ***Mongolia:*** Davey Jones (Amherst); Tanja Bosak (MIT); Oyungerel Sambuu (MUST); ***Namibia:*** Sara Pruss (Smith); Catherine Rose (Trinity); ***Appalachians:*** Paul Karabinos (Williams); Jim Crowley (BSU); ***Death Valley:*** Tony Prave (St. Andrews), Ryan Petterson; ***China:*** Dan Condon (BGS): Maoyan Zhu (NIGPAS); ***Geochemistry:*** Dave Johnston, Dan Schrag & Greg Eischied (Harvard); Frank Dudas (MIT); Nick Tosca; ***Geochronology:*** Jim Crowley & Mark Schmitz (BSU); Al Brandon (Houston); Dan Condon (BGS); Robert Buchwaldt & Sam Bowring (MIT); Alan Rooney (Harvard); ***Paleontology:*** Phoebe Cohen (Williams), Tanja Bosak (MIT), Sara Pruss (Smith)

Advisors

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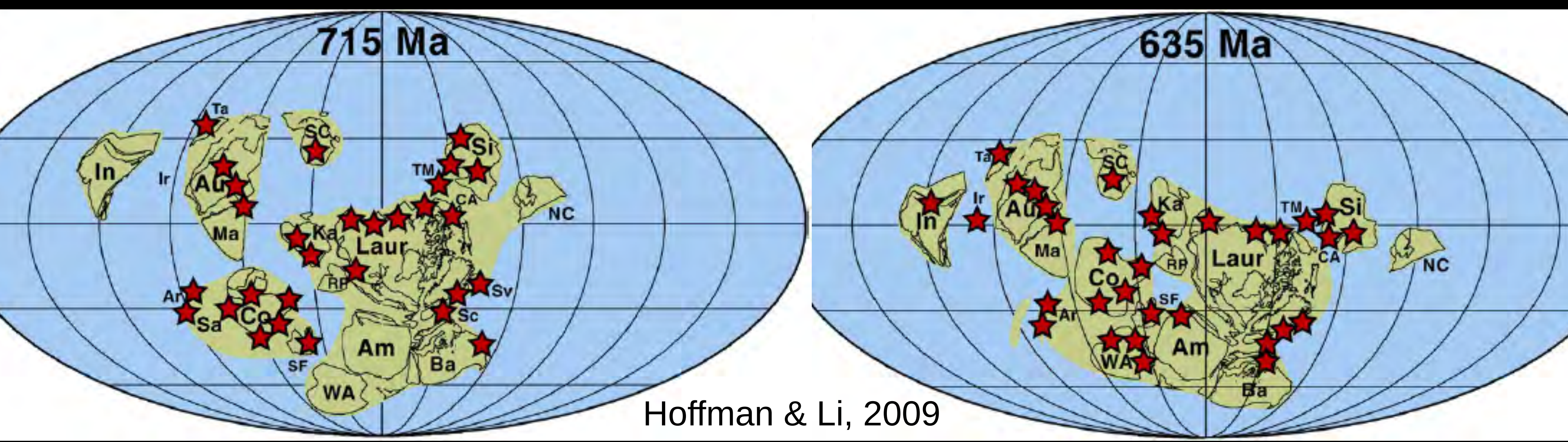
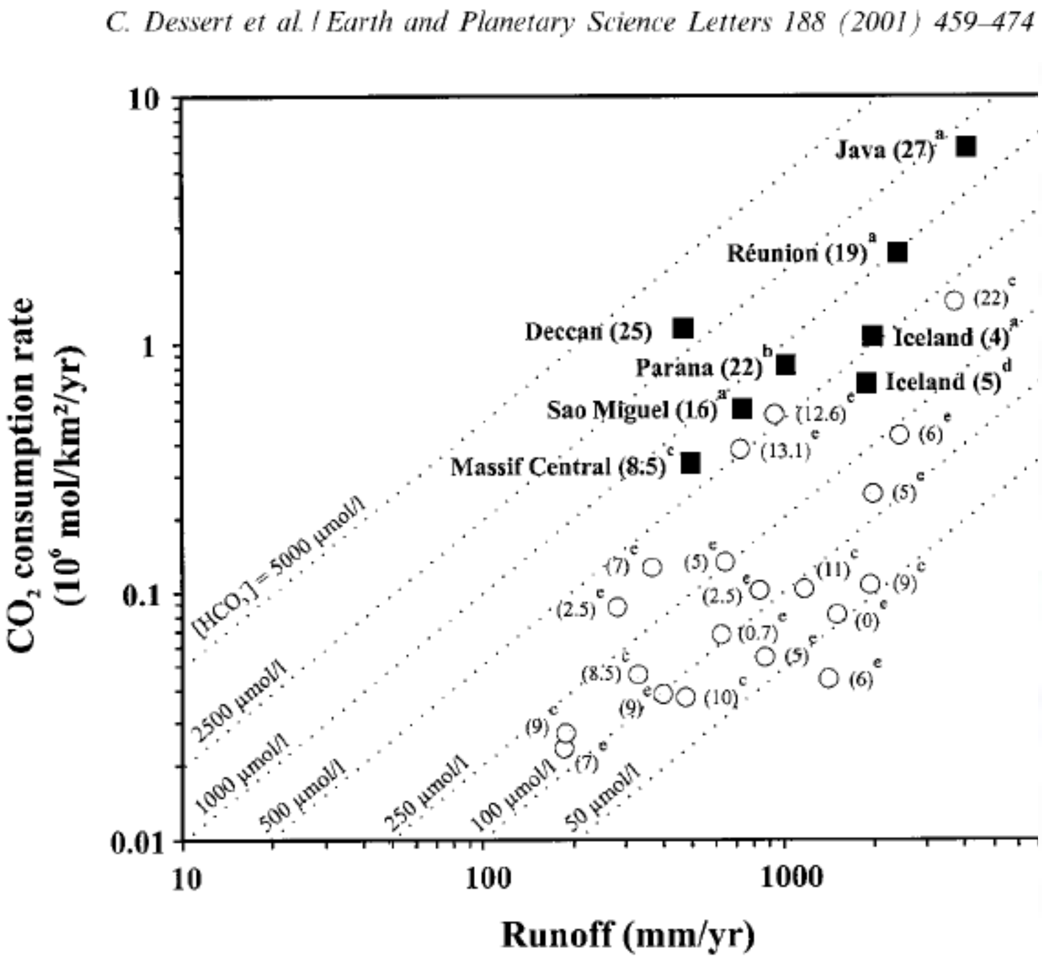
A Brief History of Neoproterozoic Snowball Earth

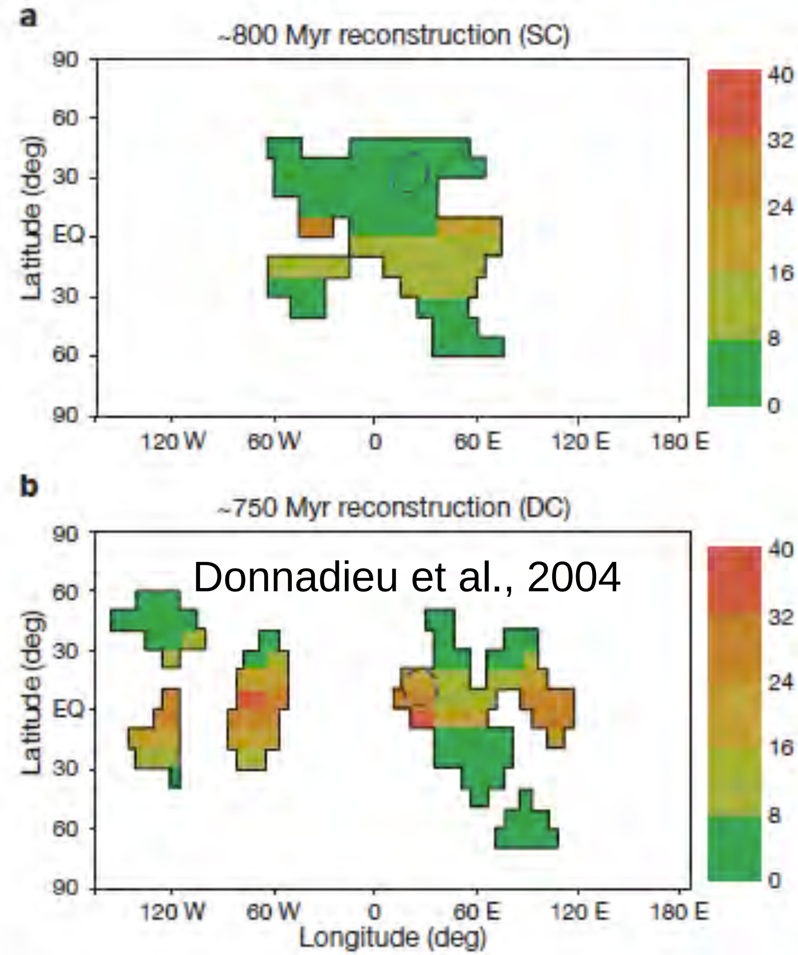
- Neoproterozoic glacial deposits are ubiquitous and occur in carbonate successions (Harland, 1964)
- Energy balance models predict runaway ice albedo event if ice extends <35; never occurred because no way out (Budyko, 1969)
- Paleomag confirms low latitude glaciation; decline of silicate weathering and continued outgassing provides a solution out of terminal glaciation (Kirschvink, 1992)
- Cap carbonates record the high CO_2 glacial aftermath (Hoffman et al., 1998; Bao et al., 2008)



Hoffman & Li, 2009

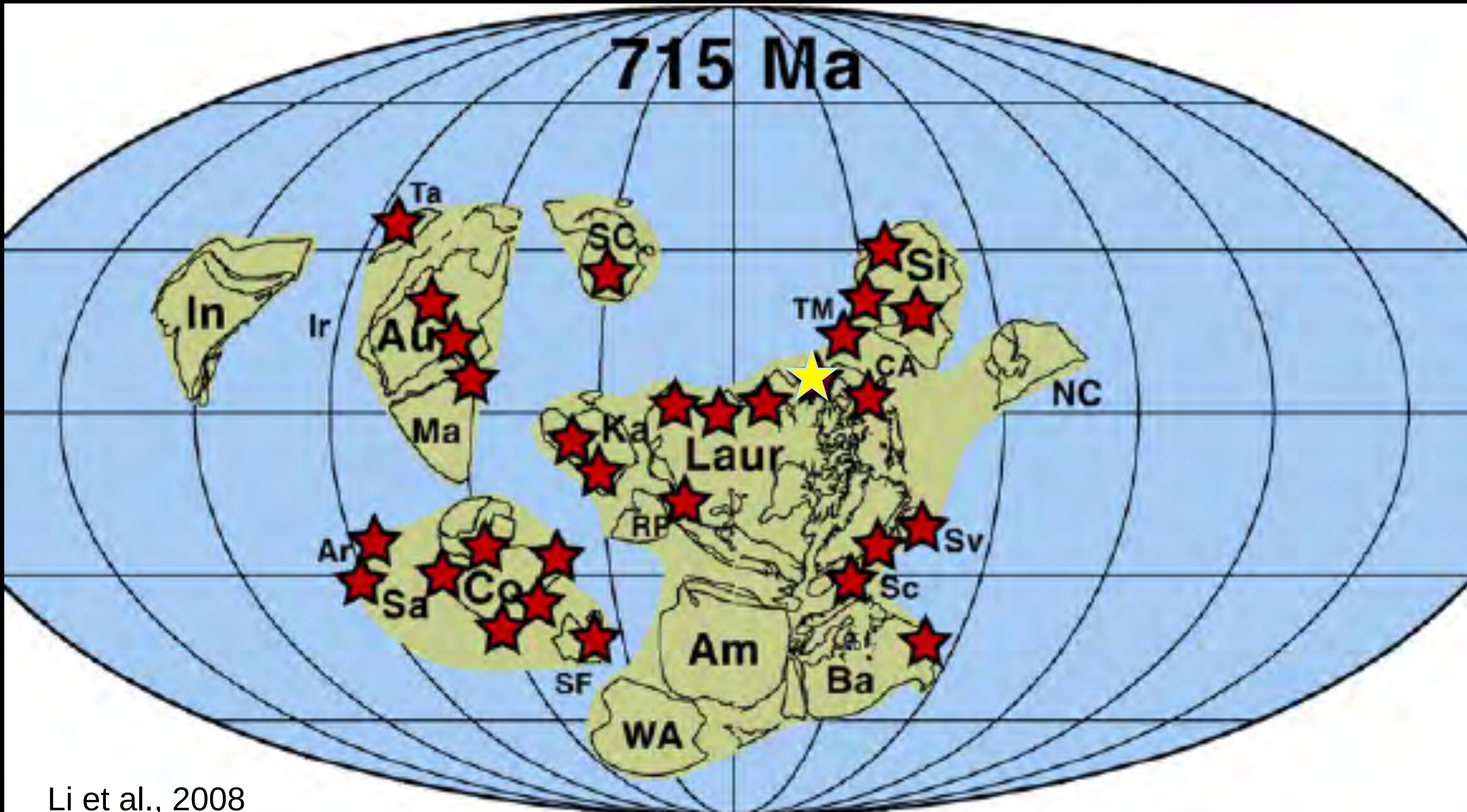
What initiated the 1st glaciation in ~1 billion years?





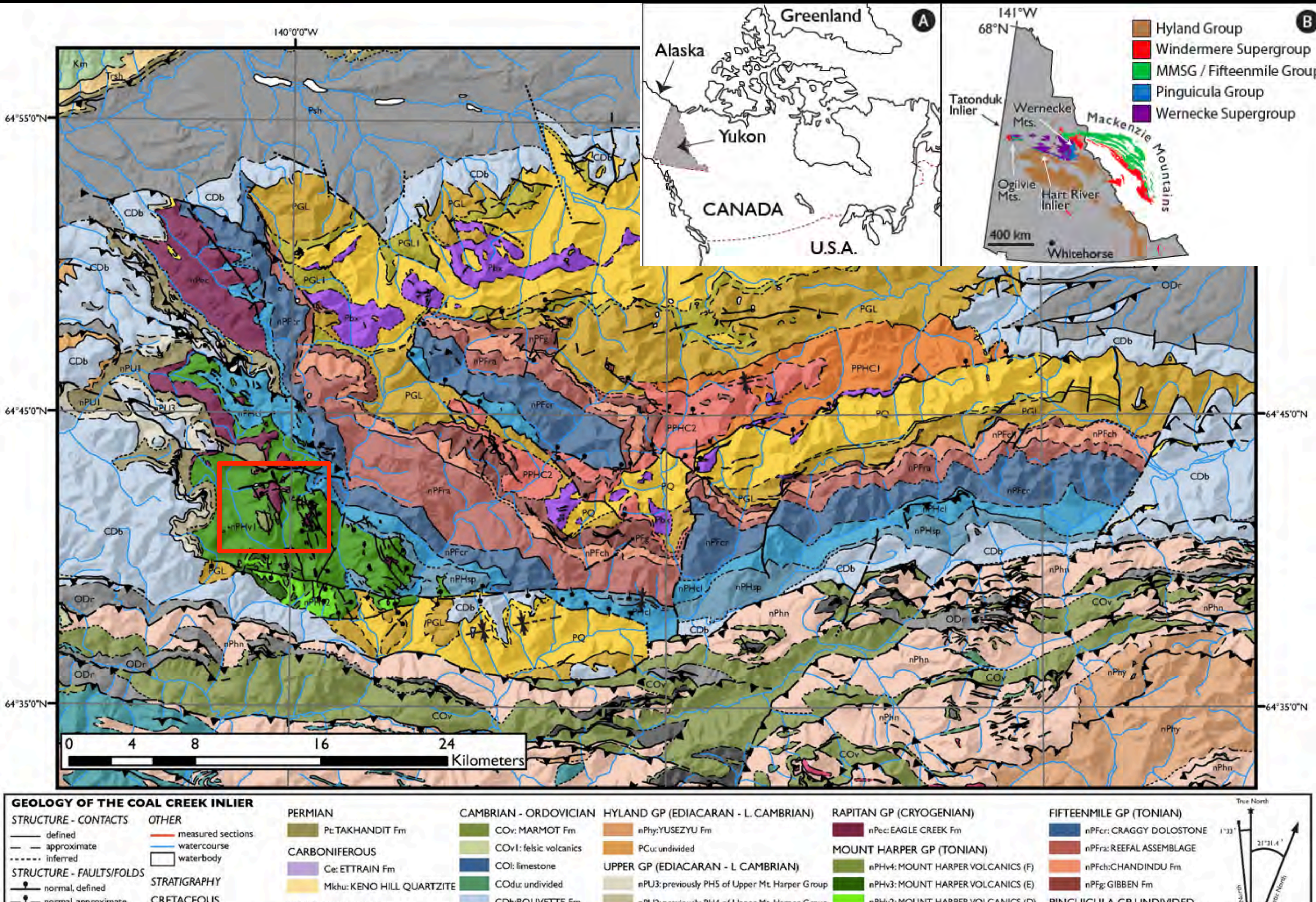
- Null hypothesis: CO_2 outgassing has not appreciably changed (Rowley, 2002) and sink controls long term climate change
- Low latitude rifting and increased runoff on highly weatherable LIPs initiated glaciation (Godderis et al., 2003; Kent & Muttoni, 2009 for Cenozoic)
- What is the timing of rifting, LIP emplacement, and glaciation?

Cryogenian Paleogeography

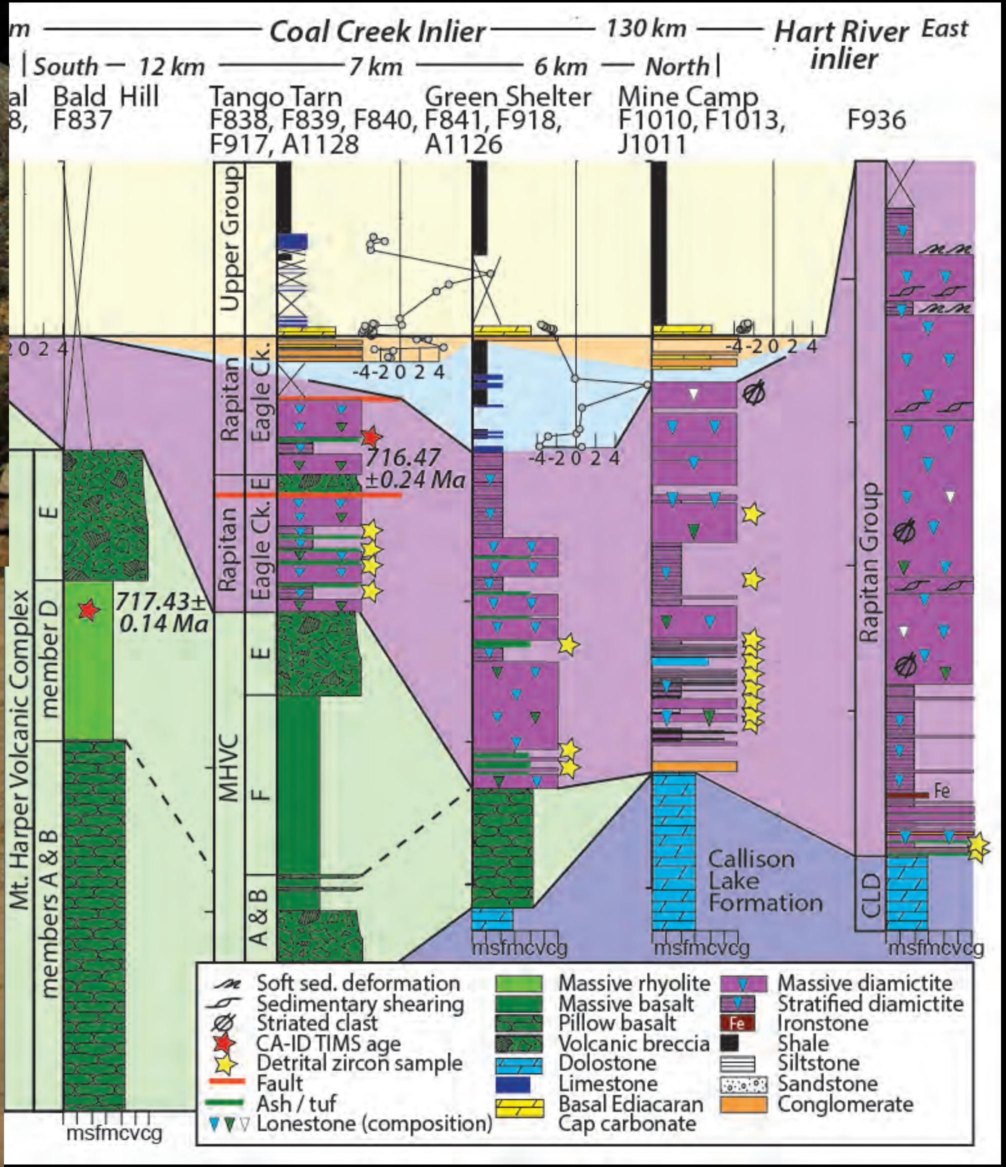


Red stars mark Sturtian glacial deposits.
Yellow star marks approximate position of NW Canada at ca. 715 Ma

Strauss et al., in prep., YGS, Geology of the Coal Creek Inlier, Yukon

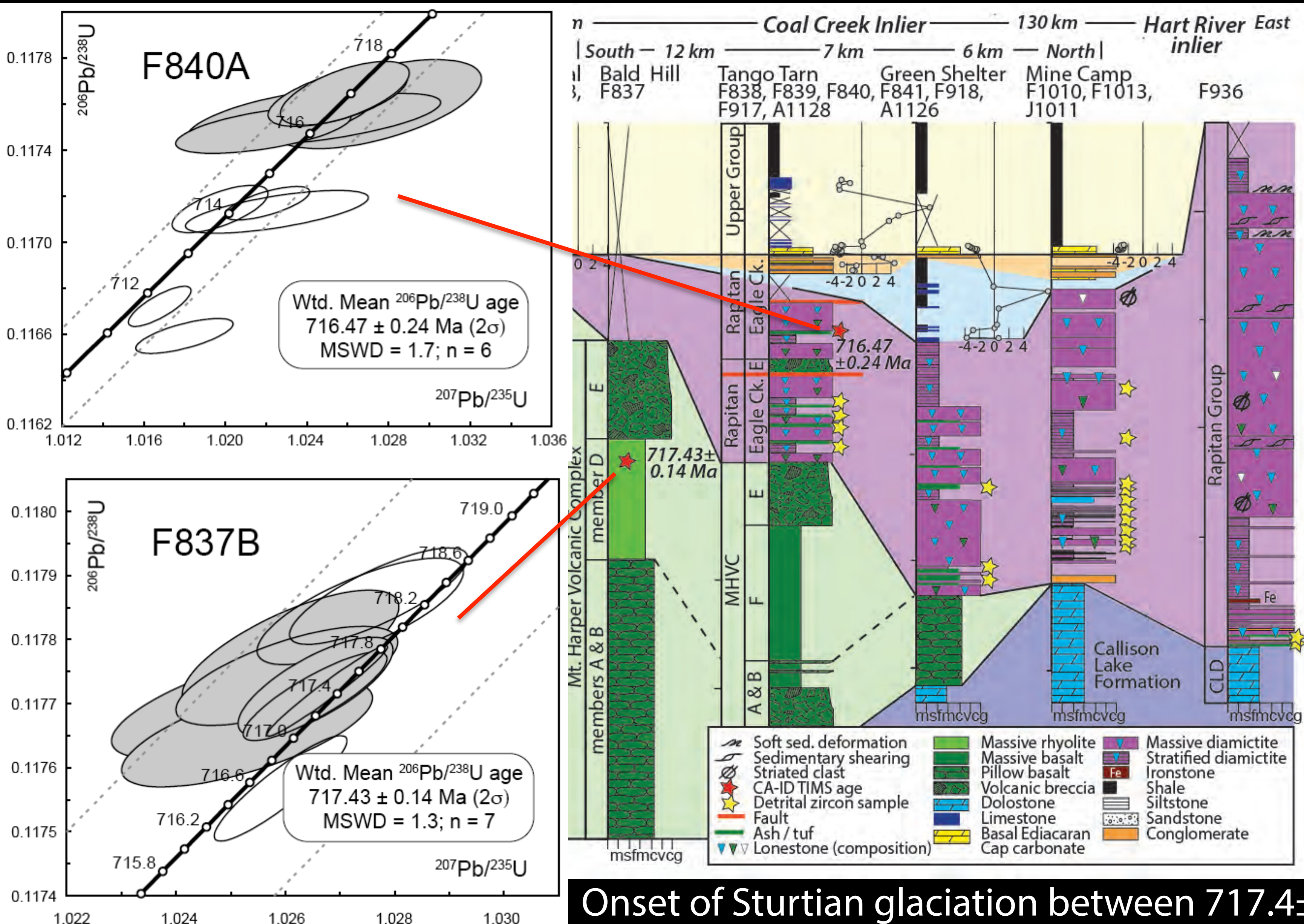


Stratigraphy of Rapitan Group in the Ogilvie Mountains



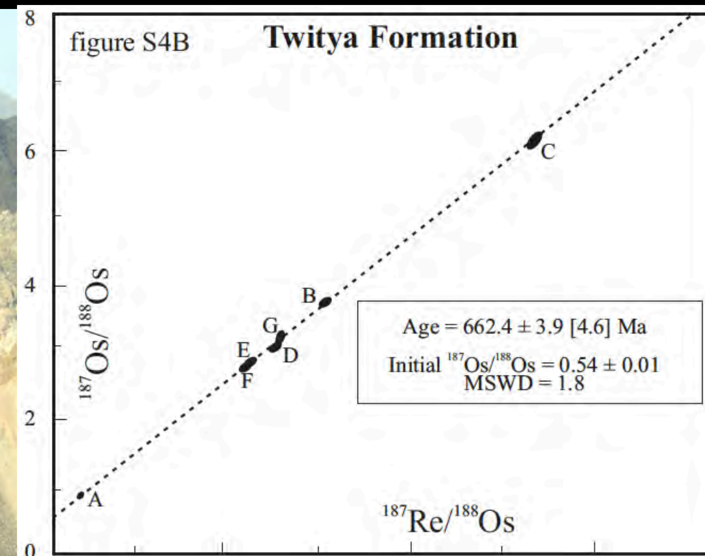
Dropstones and striated clasts are common within Rapitan Gp. In the Yukon

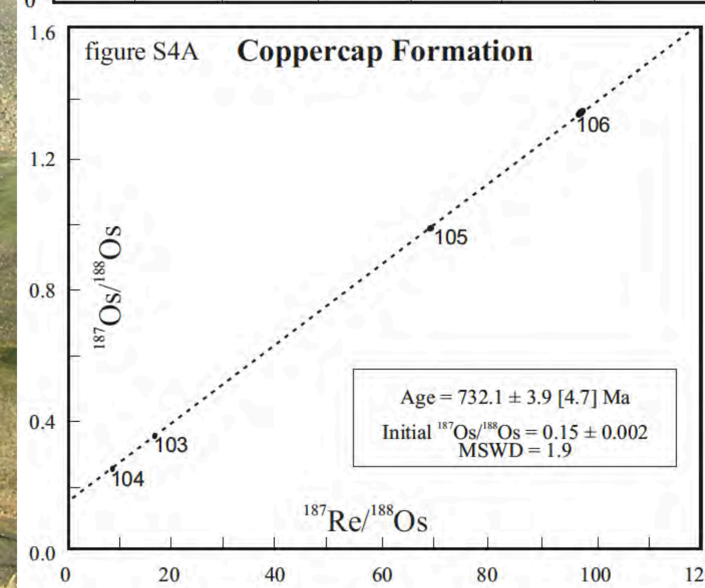
U/Pb geochron of Rapitan Group in the Ogilvie Mountains



Onset of Sturtian glaciation between 717.4±0.1 & 716.5±0.2 Ma (Macdonald et al., 2010)

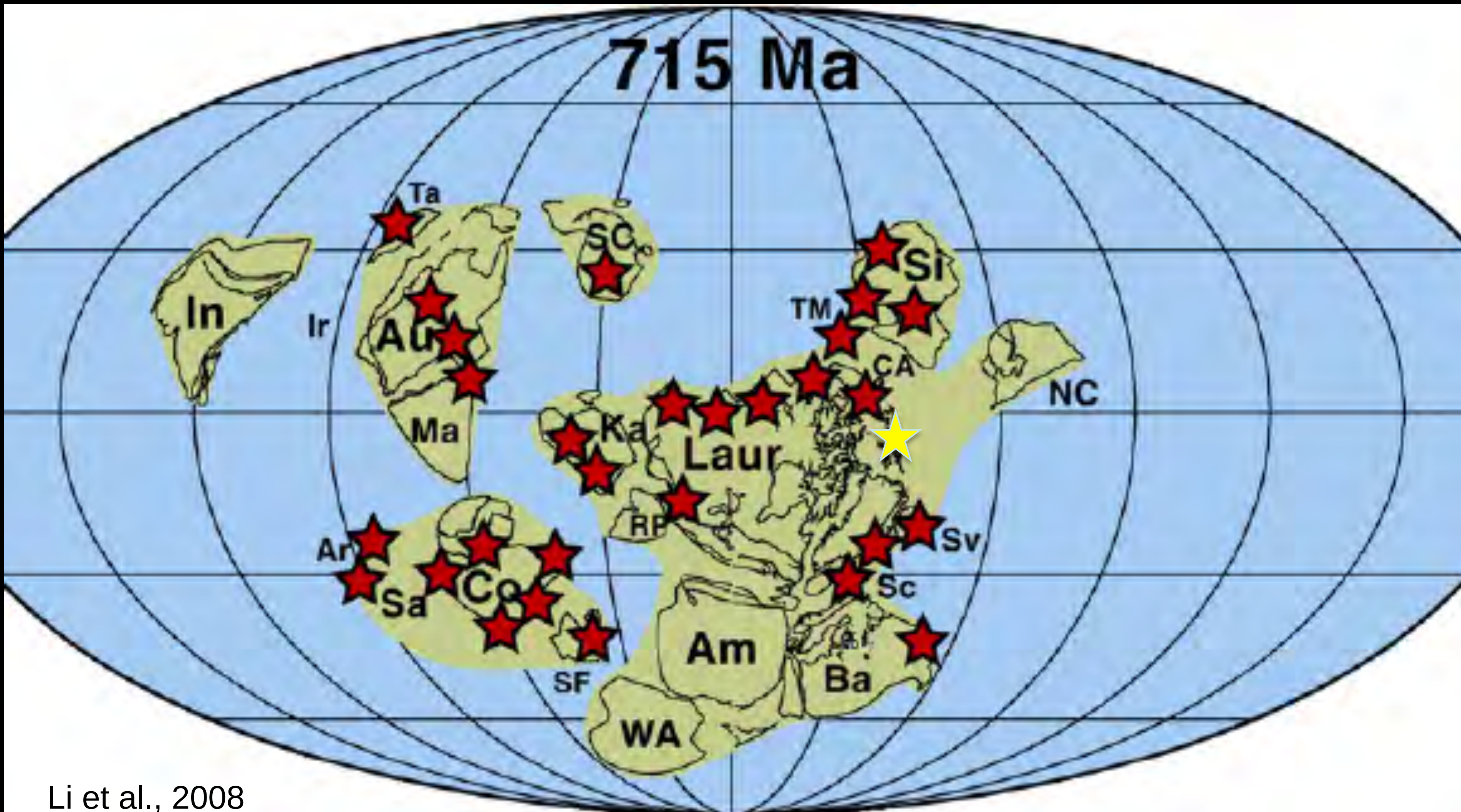
Re/Os geochronology of bracketing the Rapitan Group





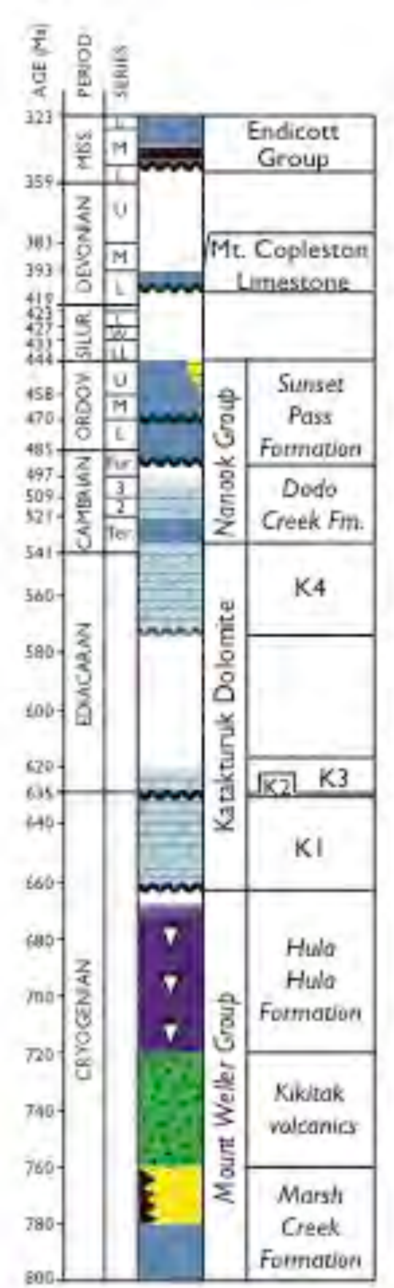
Sturtian glacial strata deposited during active extension but can be mapped through the Yukon to the Mackenzie Mnts. with 732±4 Ma ~100 m below and 662 ±4 Ma ~1 m above Rapitan Group (Rooney et al., 2014, PNAS)

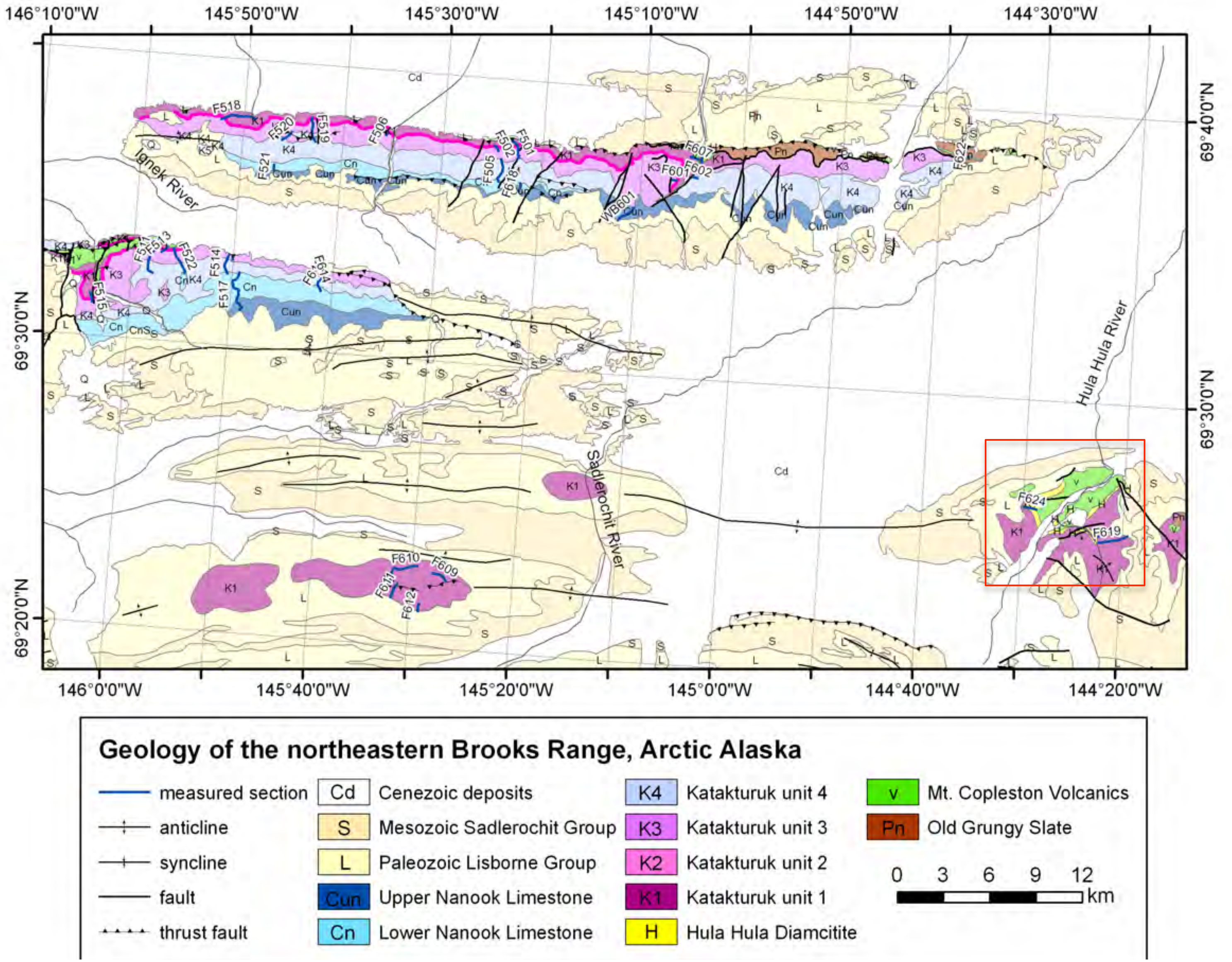
Cryogenian Paleogeography



Red stars mark Sturtian glacial deposits.
Yellow star marks approximate position of Arctic Alaska at ca. 715 Ma

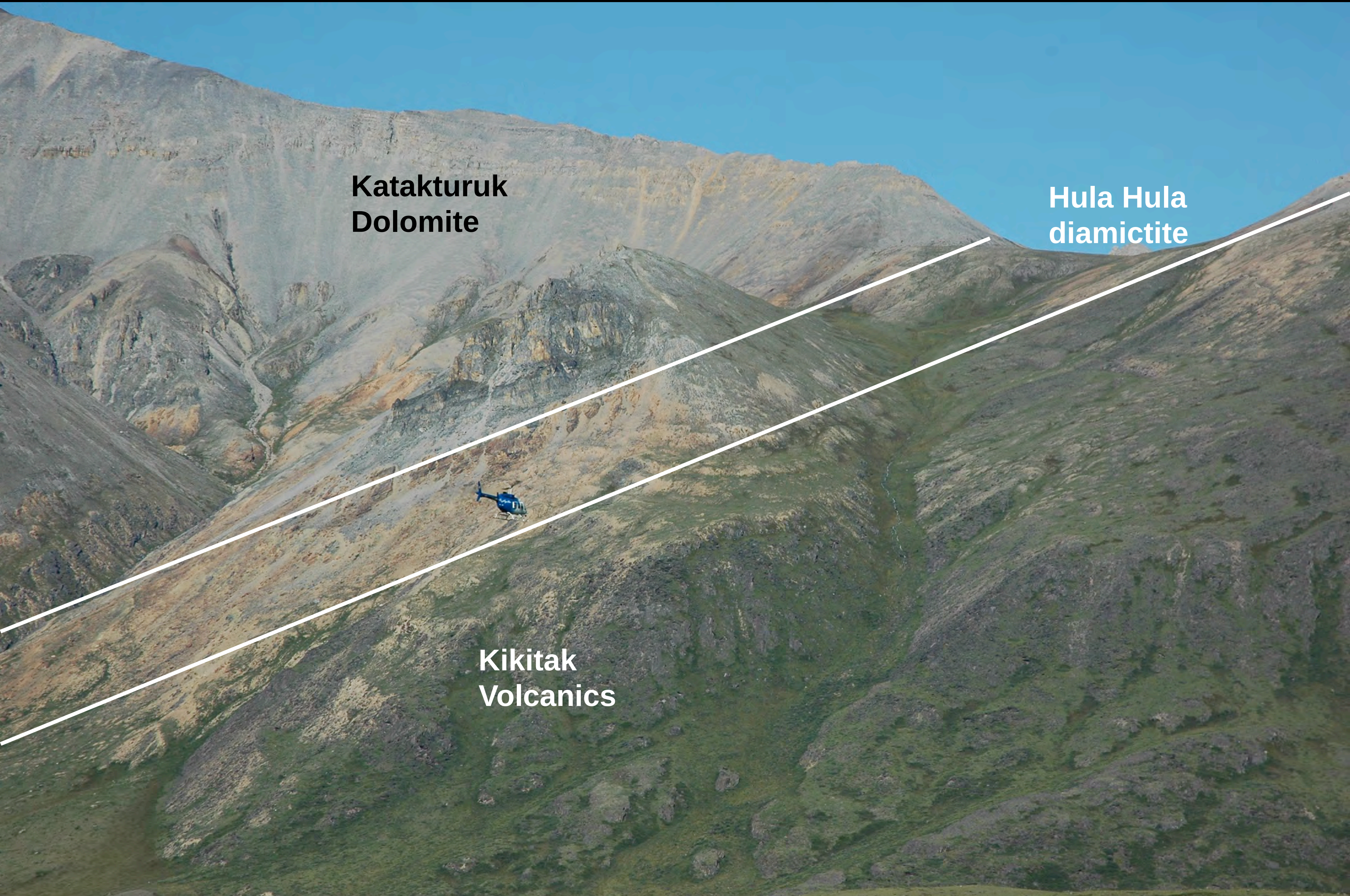
Geology of the NE Brooks Range, Arctic Alaska





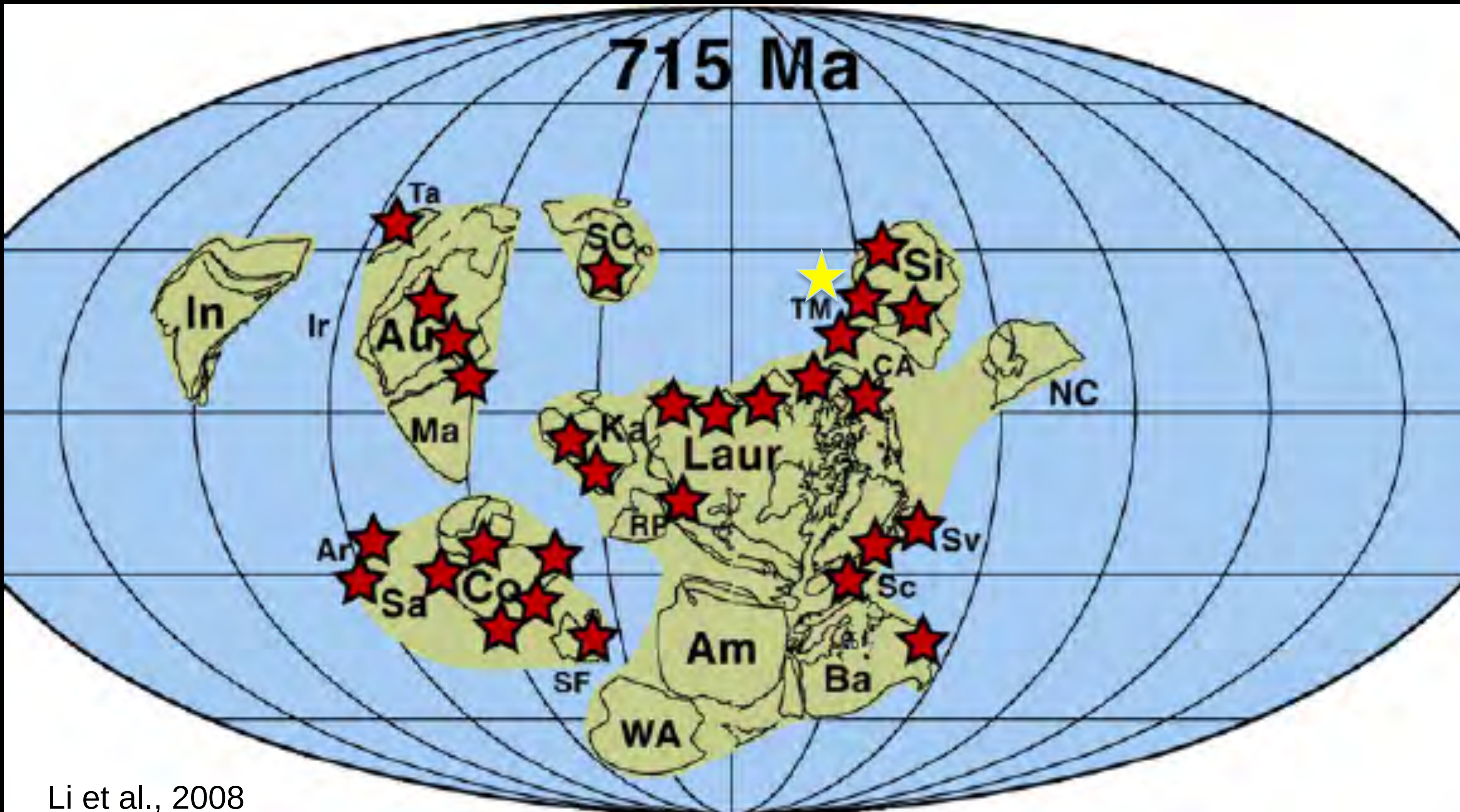
Macdonald et al., GSAB, 2008; Strauss et al., Lithosphere, 2013

Sturtian glacial deposits on mafic volcanics in Arctic Alaska



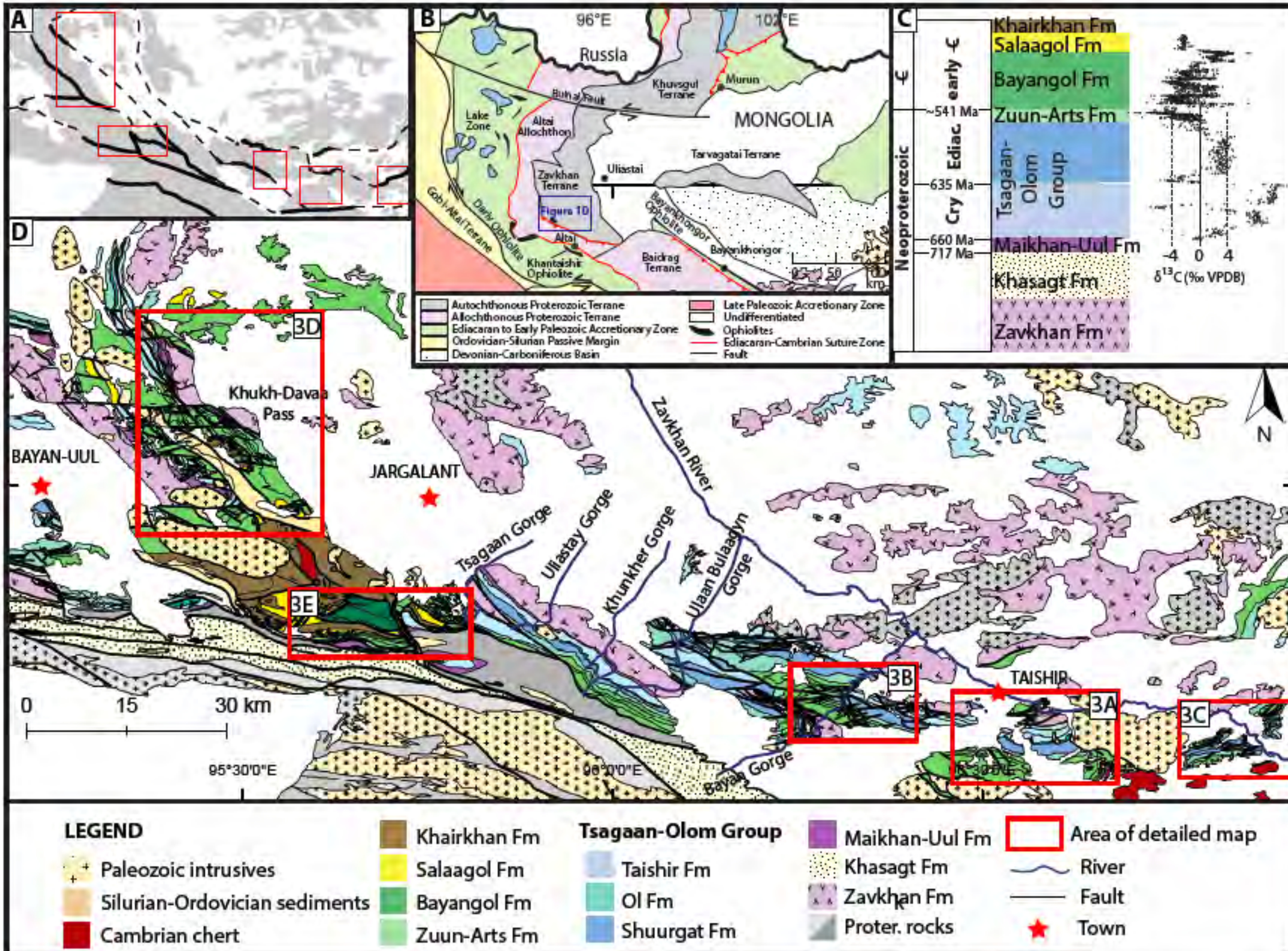
719.5 Ma zircons (CA-ID-TIMS) below Hula Hula diamictite

Cryogenian Paleogeography

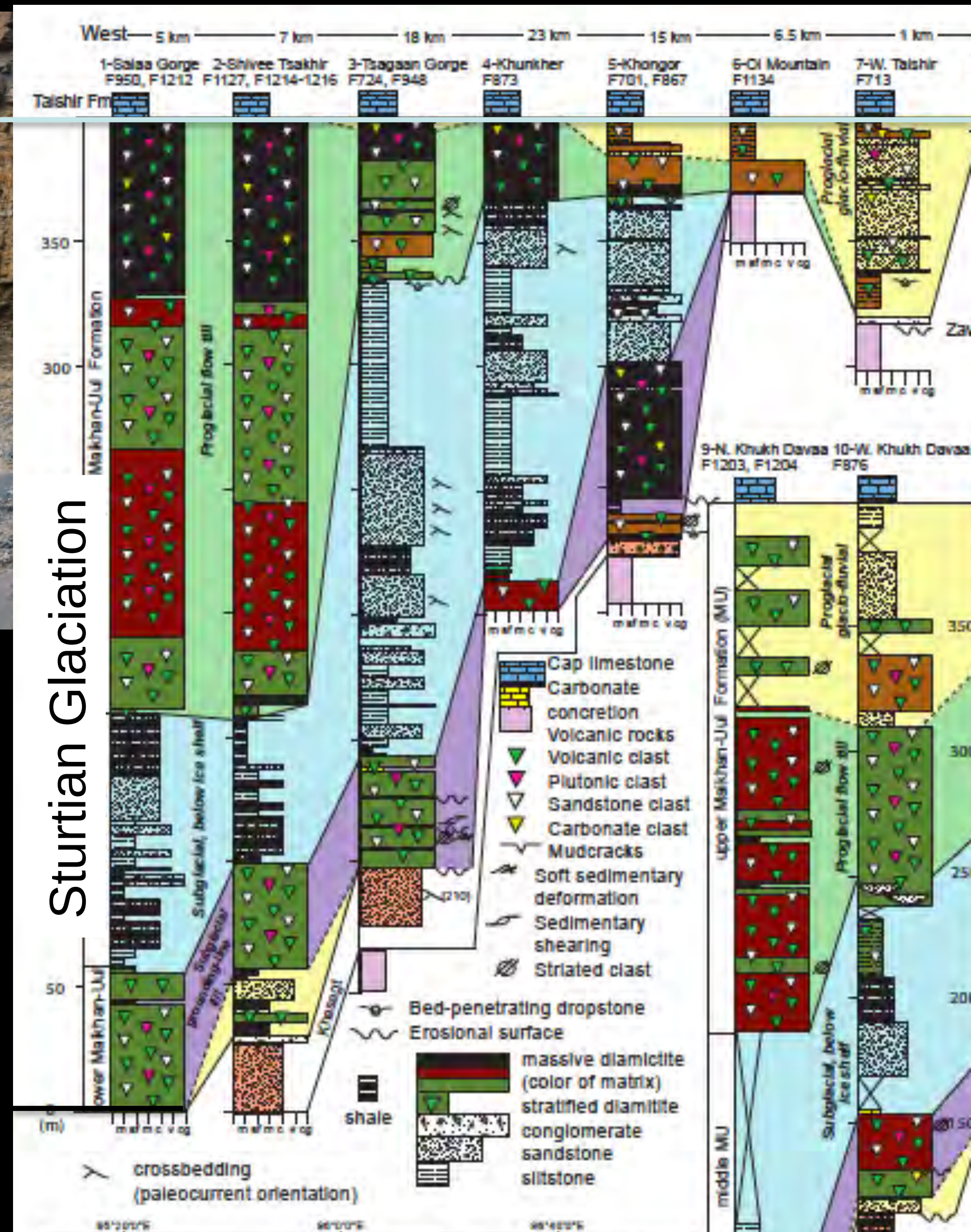


Red stars mark Sturtian glacial deposits. Yellow star marks approximate position of Mongolia at ca. 715 Ma (rifted continental arc with Siberian basement….)

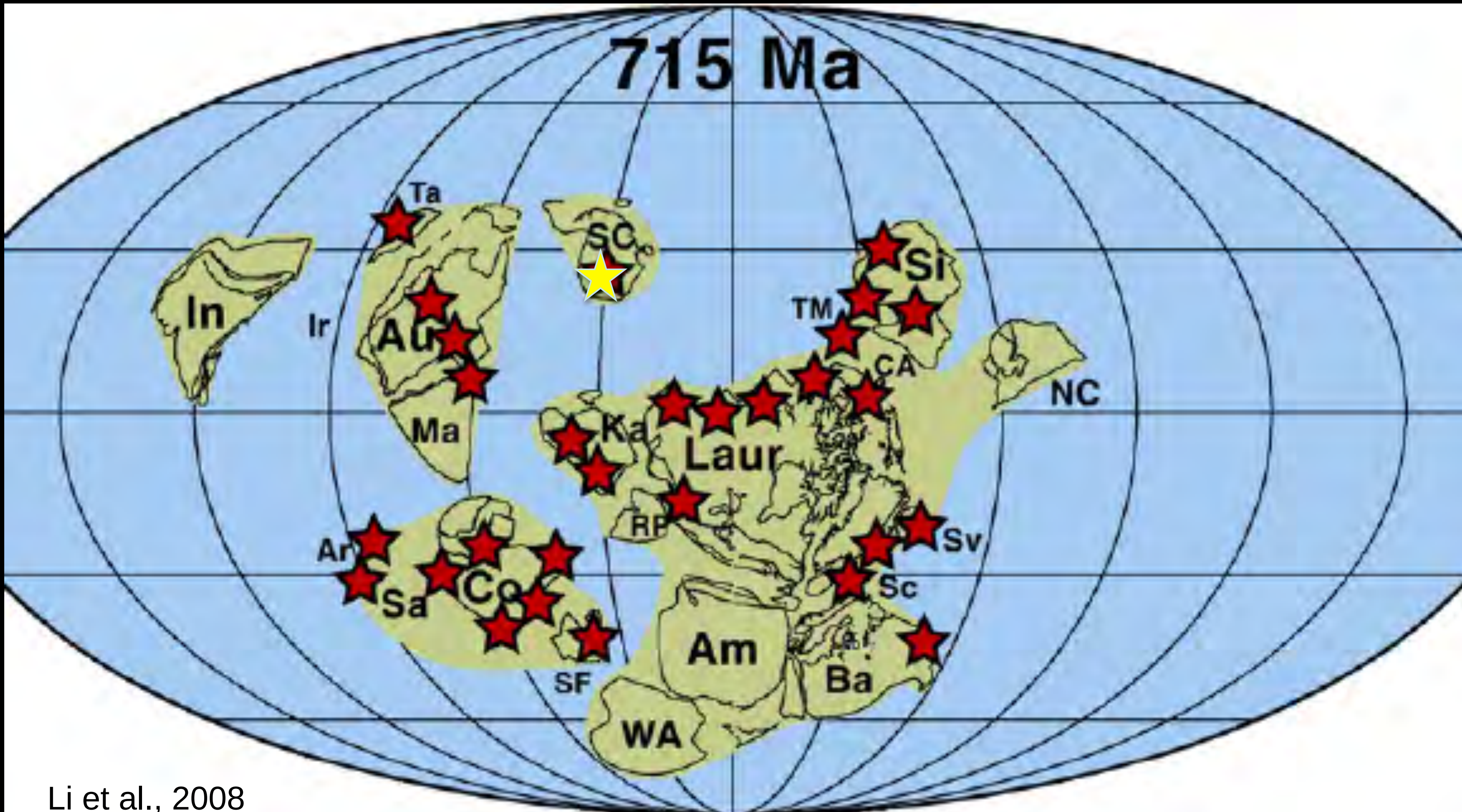
Smith et al., in prep., Geology of Zavkhan Basin Mongolia



659±4 Ma Re/Os age on the basal Taishir Fm=> Sturtian glaciation in Mongolia bracketed between <731-659 Ma (Rooney et al., in prep.; Bold et al., in prep.)

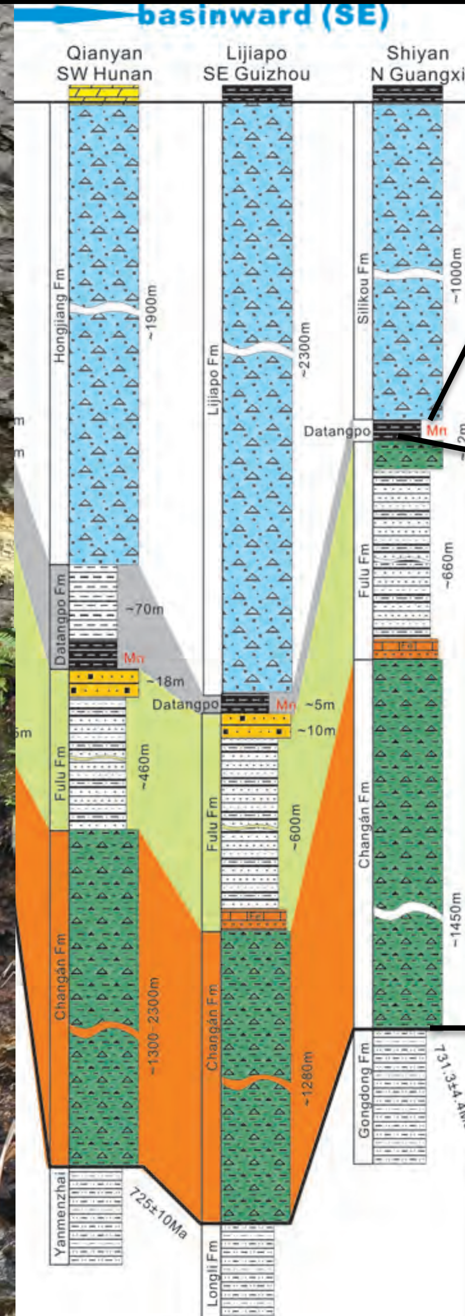


Cryogenian Paleogeography



Red stars mark Sturtian glacial deposits. Yellow star marks approximate position of South China at ca. 715 Ma (although could be on west side of Australia)

718-659 Ma (TIMS U/Pb zircon) Sturtian Glaciation in (green) S. China



- 635 Ma

-659 Ma

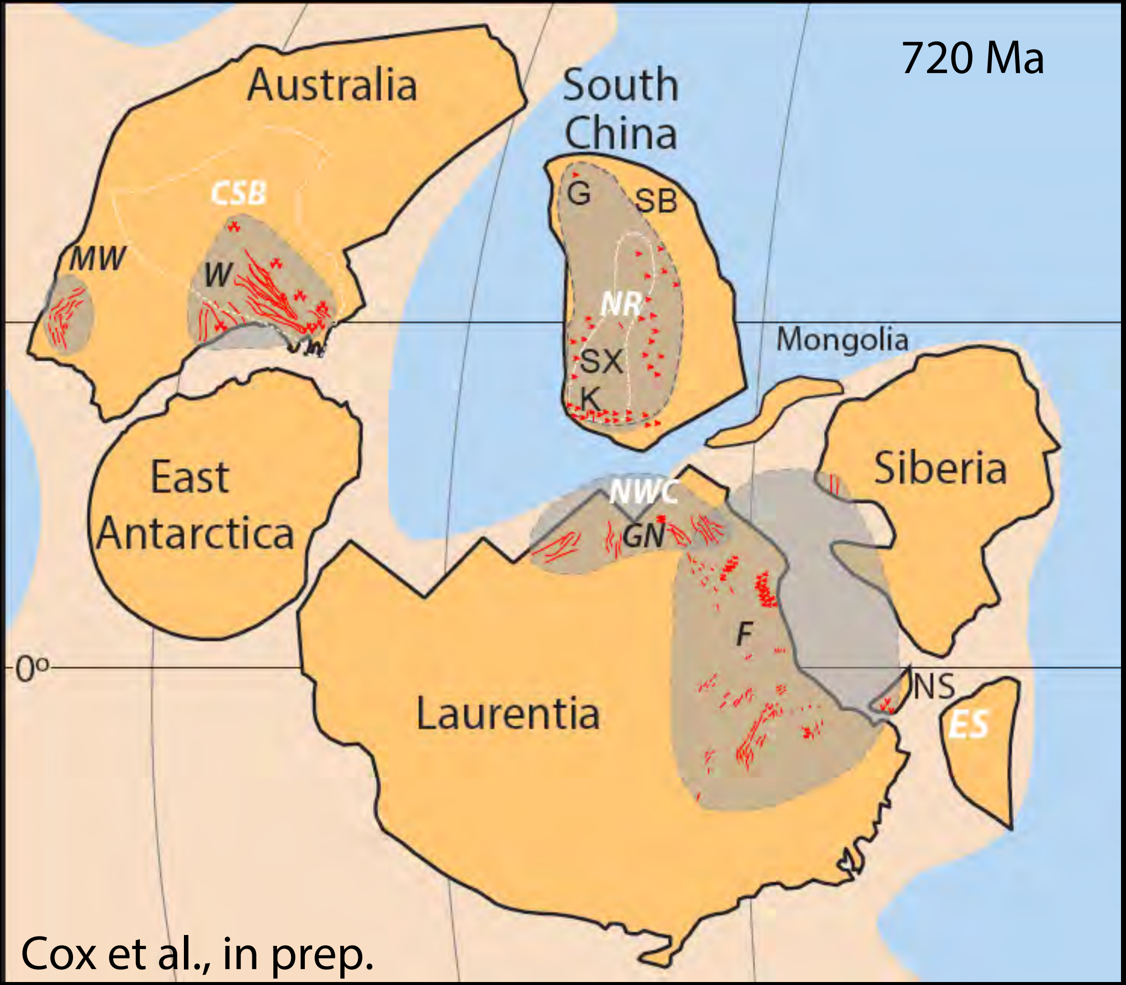
Tiesi'ao

Fulu Fm.
(clast poor
graded beds)

Chang'an

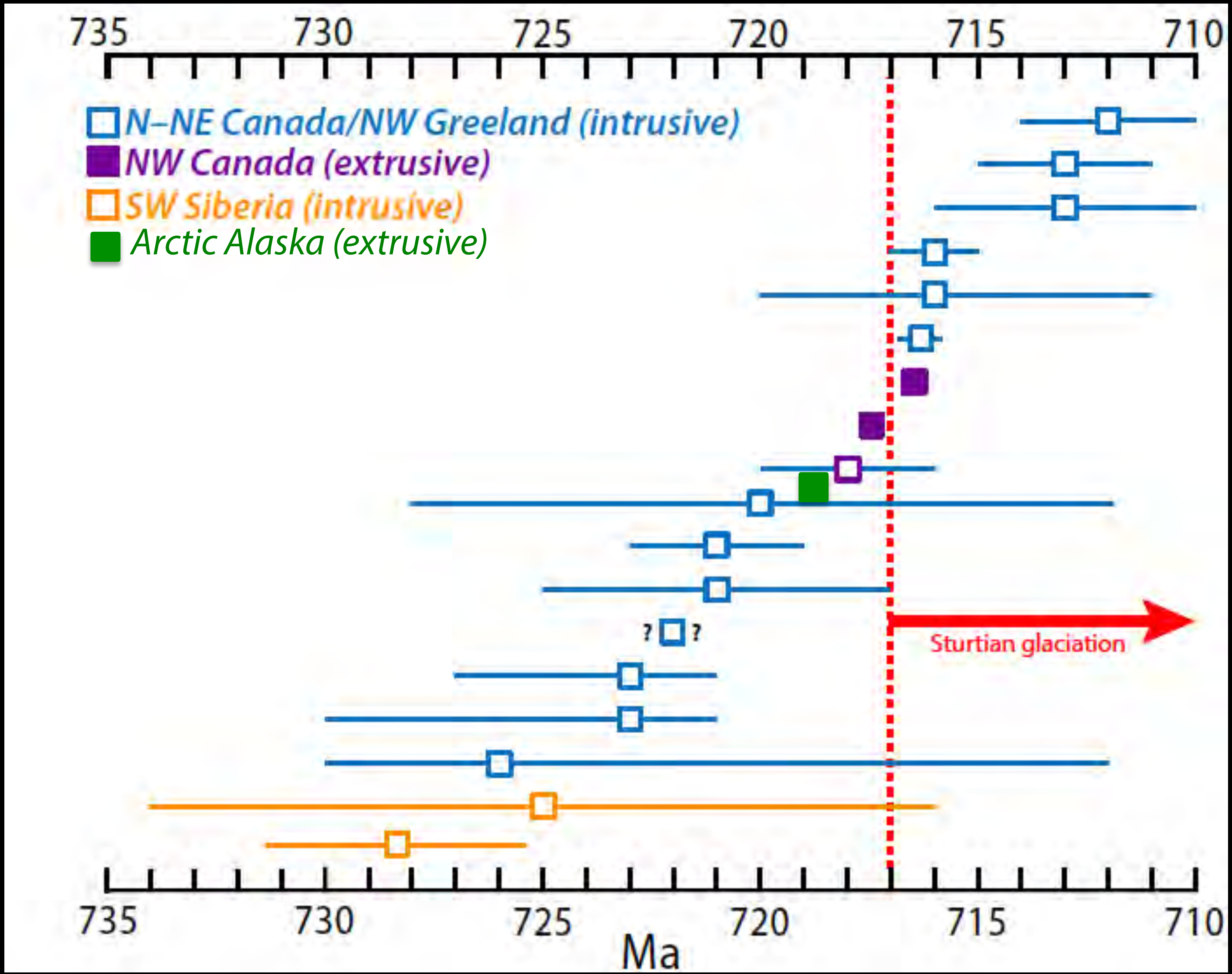
- 716 Ma

Rifting of Rodinia begins by 810 Ma with emplacement of multiple large igneous provinces at low latitude



- Sturtian initiated between 717.4±0.1 & 716.5±0.2 Ma and there is no evidence for earlier Neoproterozoic glaciation (Macdonald et al., 2010 a, b)
- Paleomag suggests low latitude continent distribution (already prone to cooler climate through with high albedo) & Franklin LIP in the tropics

Geochronological constraints on the Franklin LIP & onset of the Sturtian glaciation—does coincidence = causation?



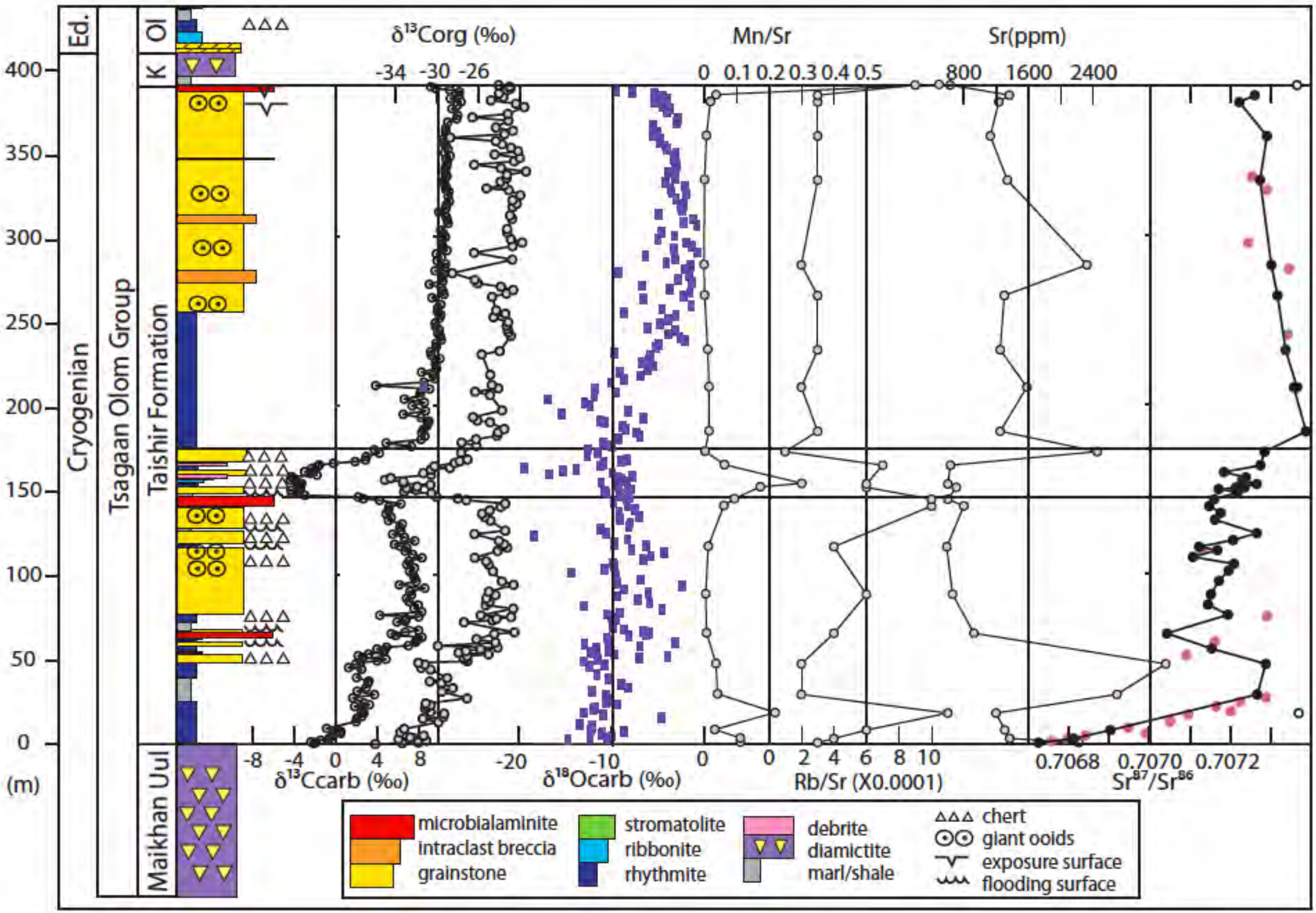
Summary of Age Constraints on Cryogenian Glaciations

- Sturtian glaciation started globally by 716 Ma & ended at 660 Ma—termination has been dated in Mongolia, South China, & NW Canada (Macdonald et al., 2010a; Rooney et al., 2014; Rooney et al., in prep.) —1st glaciation in ~a billion years
- Marinoan glaciation ended synchronously at 635 Ma—termination has been dated in S. China, NW Canada, Australia, Kalahari & Namibia (Hoffmann et al., 2005; Condon et al., 2006, Calver et al., 2014; Rooney et al., in prep.)
- Onset of Sturtian glaciation indistinguishable from main eruption phase of Franklin LIP

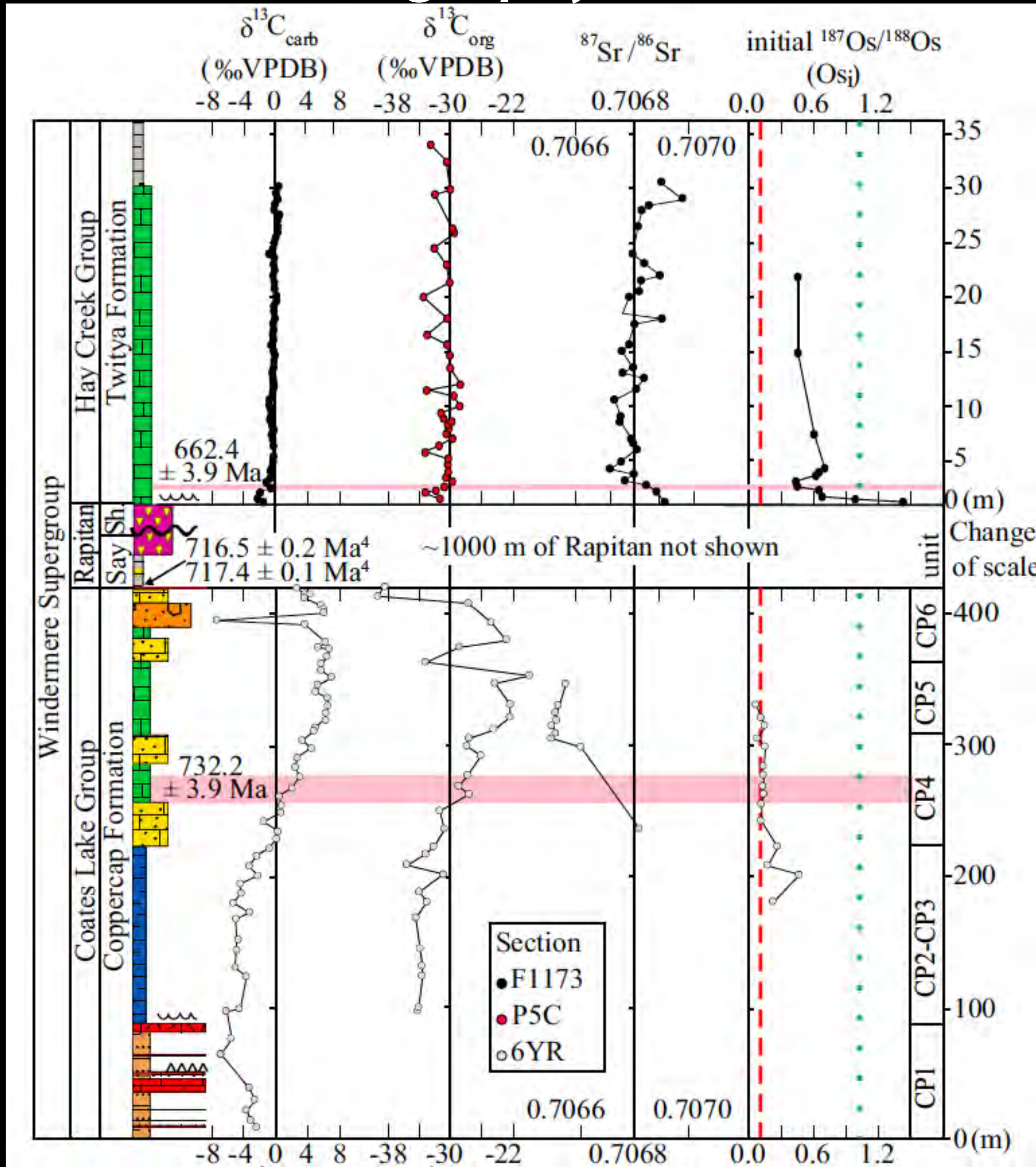
Big questions:

- What did a 57 Myr low-latitude glaciation look like and what did it do to geochemical cycles and life?
- What is the mechanistic relationship between the Franklin LIP on onset? Weathering? Productivity? Aerosols?

Bold et al., in prep., chemostratigraphy from Mongolia

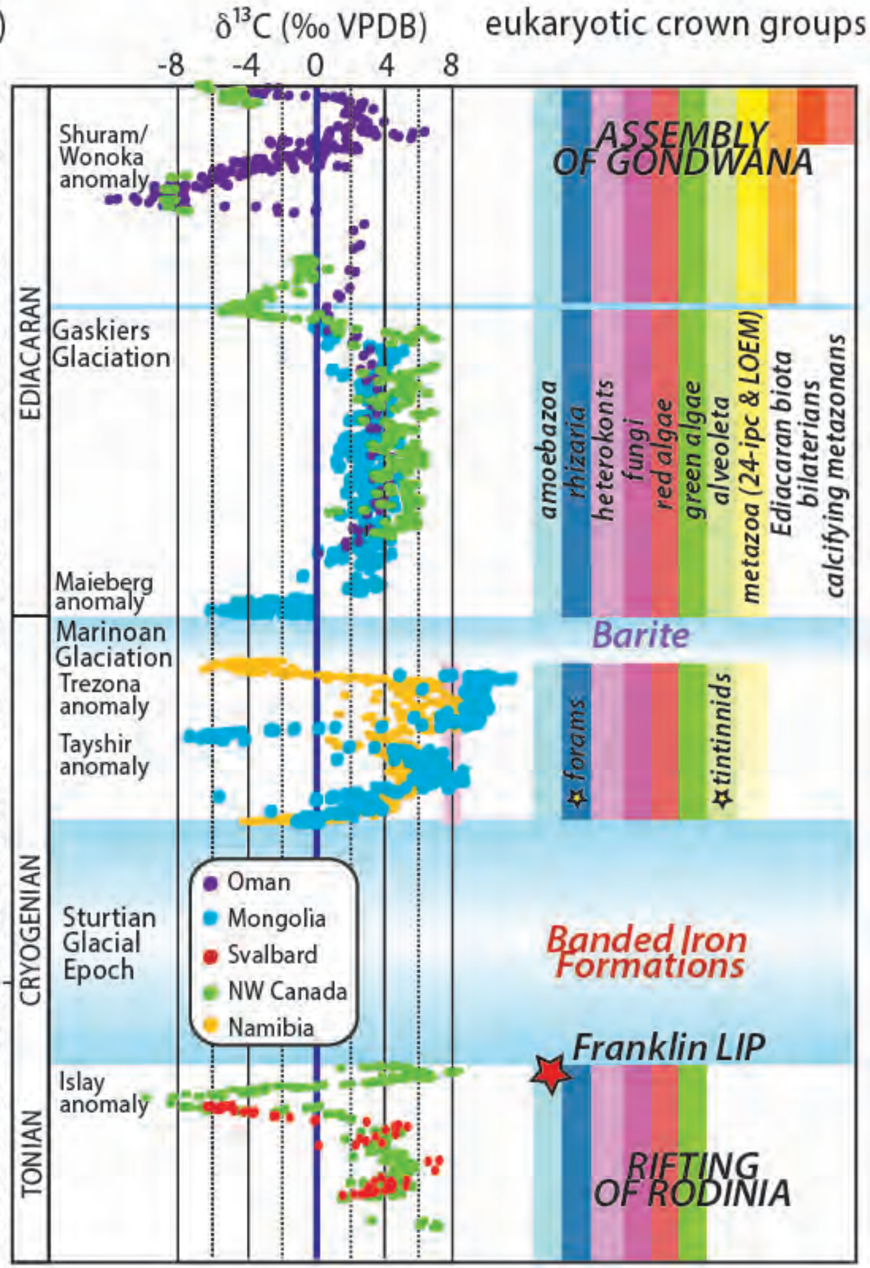


Chemostratigraphy from NW Canada



Sturtian

Rooney et al. (2014)

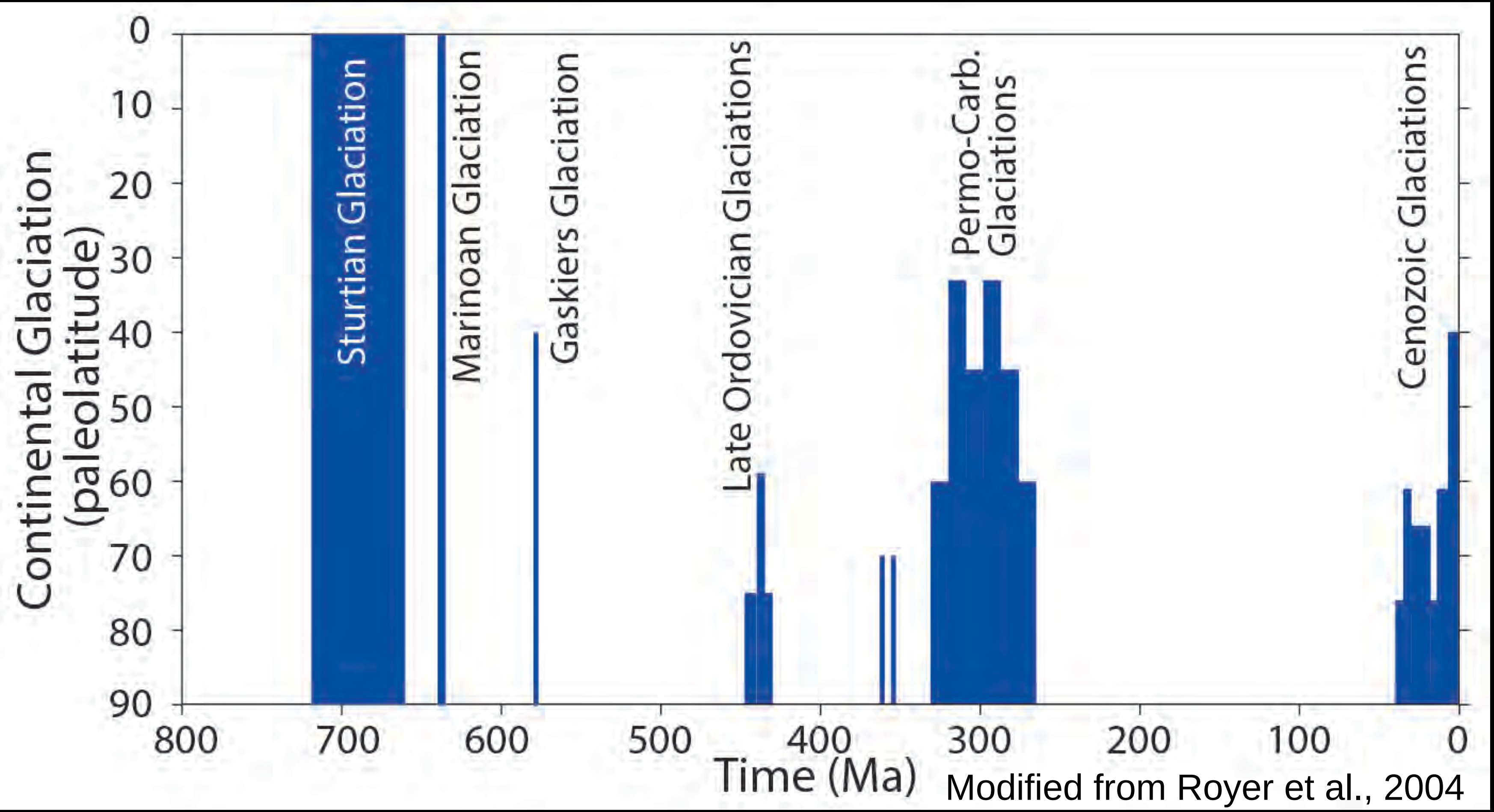


Modified from Macdonald et al., 2010

Calibrating the Cryogenian

- Os, Sr, and Nd isotopes indicate enhanced weathering of basalt before onset of glaciation
- High albedo with low latitude paleogeography + increased weatherablity with tropical LIP = cool climate
- Was there an additional proximal trigger?
- Flood basalts also have >Fe and P than average continental crust => fertilization and increased burial? Carbon isotope record?
- Sulfur aerosols? Need multiple extended eruptions or increased residence time in anoxic atm.
- These hypothesis can be tested with sub-million year resolution CA-ID-TIMS geochronology

Natural Long-Term Climate Change Experiments

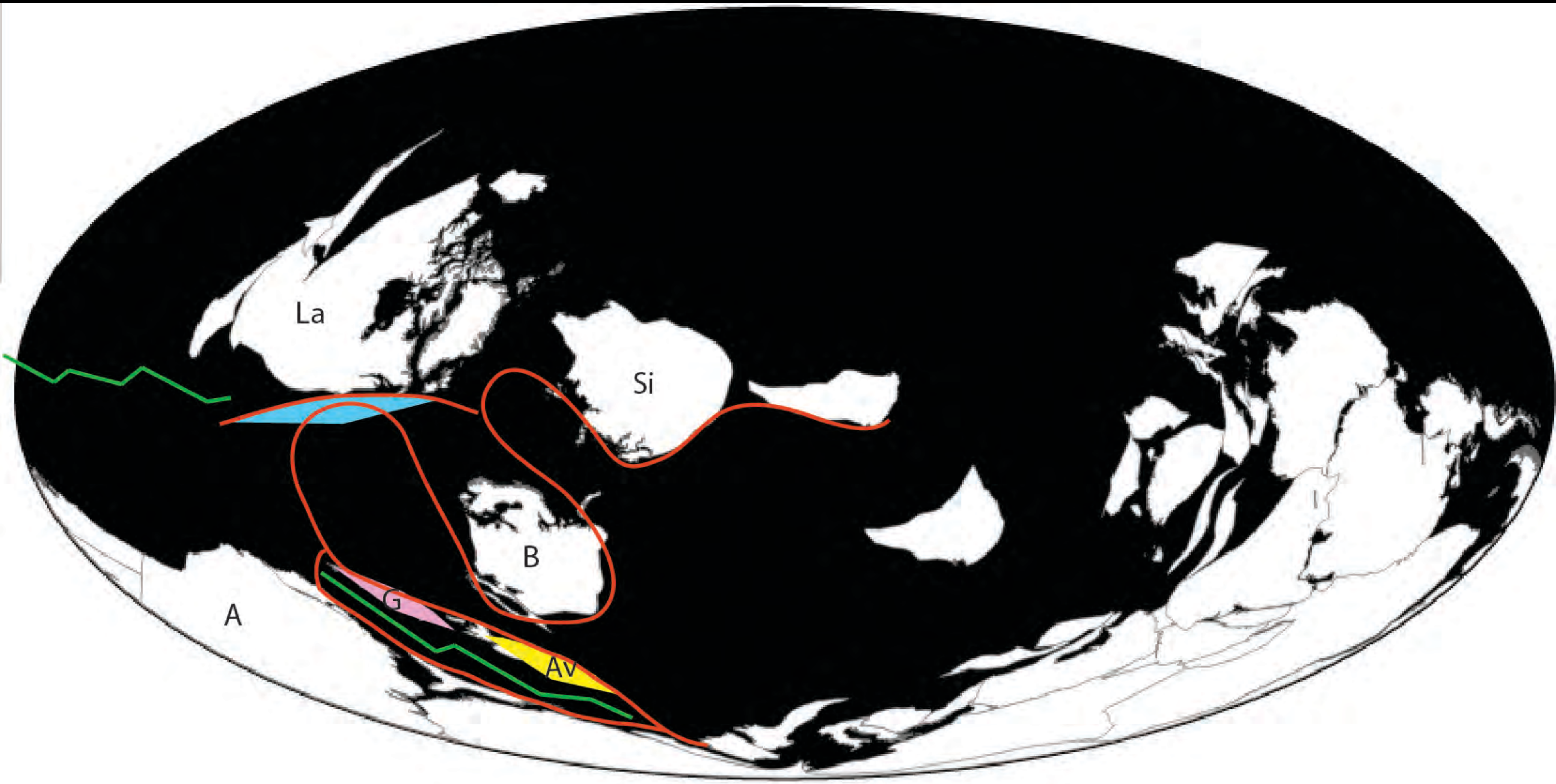


Future directions: Tectonic context of Neoproterozoic-Paleozoic climate change

-Why did the silicate weathering feedback fail in the Neoproterozoic? Sensitivity of silicate weathering feedback through time (e.g. Maher & Chamberlain, 2014)?

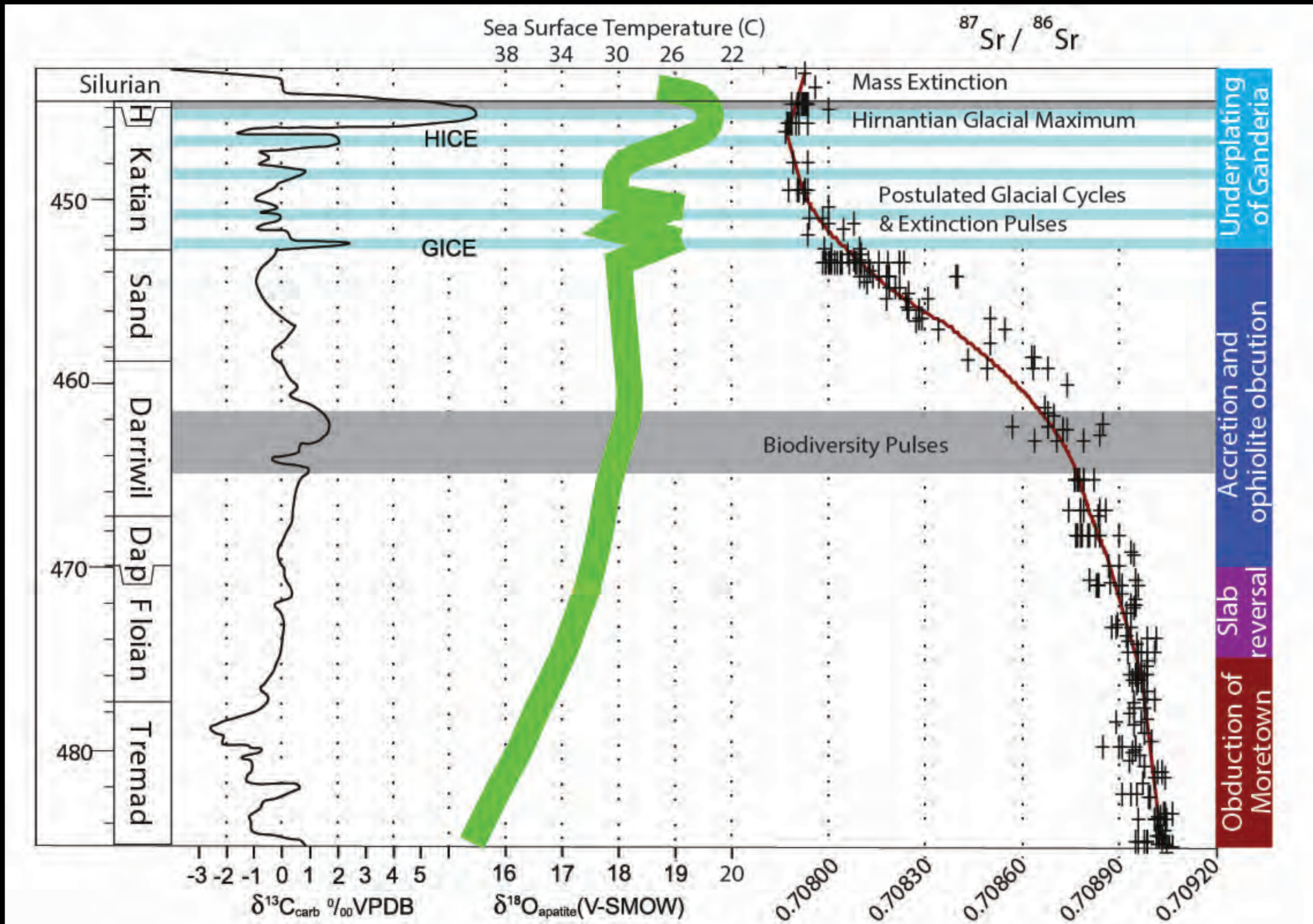
-What initiated the Late Ordovician glaciation and why did the silicate weathering feedback stablize?

Arc obduction in Appalachian-Caledonian Orogenic Belt



First Gondwanan fragment, Moretown terrane, arrived on Laurentian margin at 475 Ma (Macdonald et al., 2014) with massive ca. 465 Ma ophiolite obduction.

Ordovician strontium isotope drawdown



Sr contrasts with Cenozoic because there is not an analogous Himilayan-style basement uplift until later, different paleogeography than Neoproterozoic….
Towards a general model of paleogeography, tectonics and long term climate?


Thank You GSA!