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COLUMN

The Tooth of Time: How do passive margins become active?

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Orogenic belts should be studied from the outside inwards: that was drummed into me at McMaster University by Vint Gwinn, a young American sedimentary and structural geologist with oil industry experience. It was 1963 and he was putting the finishing touches on a paper, still cited today, proving that thin-skinned thrusts underlie the Central Appalachian Plateau and northwestern Valley and Ridge, where no fault breaks the surface (Gwinn 1964). Gwinn was informal yet passionate, invoking sedimentary successions in orogenic forelands as the best records of subsidence and sedimentation related to orogenesis, as controls on the trajectories of faults and related folds, and as horizons for tracking deformation. Gwinn's course primed me to appreciate graduate school in the Central Appalachians.

At Johns Hopkins University, structural geologist Ernst Cloos and sedimentologist Francis Pettijohn led field trips every weekend during the Fall and Spring semesters. The field trips were obligatory for incoming graduate students and they offered an Appalachian cross-section from the inner edge of the Allegheny Plateau to the Atlantic coastal plain, encompassing the Valley and Ridge fold-and-thrust belt, the basement-cored Blue Ridge anticlinorium, the metamorphic Piedmont, and the post-orogenic Newark Basin—a Triassic-Jurassic ter-

restrial rift-basin. The Paleozoic 'geosyncline' began with an Eocambrian (Ediacaran) conglomerate-basalt rift assemblage, overstepped by a westward-tapering wedge of lower Cambrian clastics derived from the craton, a middle Cambrian clastic-carbonate transition, and an upper Cambrian through lower Ordovician sequence of shallow-marine carbonate rocks, memorably exposed in cattle pastures in the Great Valley of Virginia. The eastern limit of shallow-water carbonate rocks lay just to the east of the Blue Ridge Anticlinorium. Pettijohn called this Sauk Sequence (Sloss et al. 1949; Sloss 1963) the 'pre-orogenic orthoquartzite-carbonate stage' of the geosyncline, noting that a lithologically similar stage occurs in the middle Precambrian (Paleoproterozoic) geosyncline of Minnesota (Pettijohn 1957, p. 641). Coming from the Devonian of the Niagara Escarpment, nonbioturbated carbonates for me were a revelation.

Then something different occurred: shallow-water carbonate gave way unexpectedly to black sulfidic shale, locally associated with submarine landslides ('olistostromes'). This was overlain by a thick middle Ordovician sequence of greywacke turbidites, followed by upper Ordovician-lower Silurian crossbedded sandstones of easterly derivation. Adopting terminology from a younger orogen, the European Alps, Pettijohn (1957) referred to the 'euxinic' (black shale), 'flysch' (greywacke turbidite) and 'molasse' (crossbedded sandstone) stages of the geosynclinal cycle, and he related them to the Taconic orogeny. The geosynclinal cycle was then repeated with a Silurian-lower Devonian pre-orogenic orthoquartzite-carbonate stage overlain by middle Devonian euxinic shale and flysch, followed by upper Devonian-

Carboniferous molasse, the so-called Catskill Delta. But what were 'geosynclines' (Kay 1951; Aubouin 1965), and why did long-lived carbonate shelves suddenly founder at the beginning of the orogenic stage?

I had heard Harry Hess speak at McMaster on the impermanence of ocean basins (Hess 1962), but all I remember of the lecture was his ability to smoke two cigarettes simultaneously, without tipping an ash, while pacing back and forth, or writing on the blackboard. Bob Dietz, who had conceived of sea-floor spreading independently of Hess (Menard 1986) and who had postulated that North America was overriding the Pacific Ocean floor, based on the truncation of sea-floor magnetic anomalies at the continental margin (Dietz 1961), visited Johns Hopkins in 1965. Appropriately, he presented his actualistic interpretation of geosynclines as Atlantic-type continental shelves ('miogeoclines') and rises ('eugeoclines'), that undergo orogeny when the overburdened oceanic lithosphere spontaneously ruptures and 'slides' (subducts) under the continental margin (Dietz 1963). His talk was not well received, paleocurrent studies having shown that the two Appalachian molassic sequences were derived from the east (Pelletier 1958; Yaekel 1959), implausibly from the offshore in Dietz's (1963) model. Granted, his model worked pretty well for the pre-orogenic stage, with the eastern limit of shallow-water carbonate marking the continental shelf-slope break. But the orogenic scenario was not in fact actualistic because nowhere is subduction being initiated at an Atlantic-type margin at present, not even in the Bay of Bengal where subduction initiation is optimized by the enormous load of sediment and strong in-plane com-

pressive stress, related to subduction at the Java Trench and the topographic head of the Tibetan Plateau.

After teaching at Franklin and Marshall College in southeastern Pennsylvania for a year, I joined GSC in May 1969 in a position vacated by Precambrian paleontologist Hans Hofmann. Ending was the era of military-style reconnaissance operations north of 60°, when 12 or more 1:250,000-scale sheets were mapped in a single sub-Arctic summer. Topical studies logically followed. Within weeks I was standing at the edge of the Wopmay Subprovince (Stockwell 1961), the Paleoproterozoic (then Aphebian) orogenic belt I had invoked in my PhD thesis to account for the paleocurrent reversal in the East Arm of Great Slave Lake (Hoffman 1969), 600 km to the south. Actually, I was standing on 1.5 meters of lake ice, 20 km from the Arctic Ocean, looking at 70% snow cover. If my timing was impetuous, the location was deliberate: under the melting snow was the best-exposed autochthonous sedimentary section at the edge of the orogen. To the west was a broad belt of tightly-folded sedimentary rocks and beyond that was the volcanic, plutonic and metamorphic core of the orogen. Our guides to this place were an 8-mile-to-the-inch reconnaissance map (Fraser 1960), a visionary regional stratigraphy (Fraser and Tremblay 1969) and the Canadian Arctic Expedition (1913-1918) report on the geology along the coast (O'Neill 1924). The next day we dropped down stratigraphically to the Archean basement, finding a depositional unconformity at the base of a transgressive marine quartzite sequence (Odjick Formation), gradationally overlain by 0.8 km of cyclic peritidal dolomite, the Rocknest Formation (Grotzinger 1986a). The 1.6-km-thick ortho-quartzite-carbonate sequence dips to the west and above it we found a duplicate sequence, which rides on a paper-thin thrust fault detached a few meters above the basal unconformity (Tirrul 1982). The snowy slog back to camp was painless, given the prospect of a 140-km-wide foreland thrust-fold belt to work on in the years ahead (Tirrul 1983; Hoffman and Tirrul 1994), conveniently planed off by the Laurentide Ice Sheet. Plunge reversals would

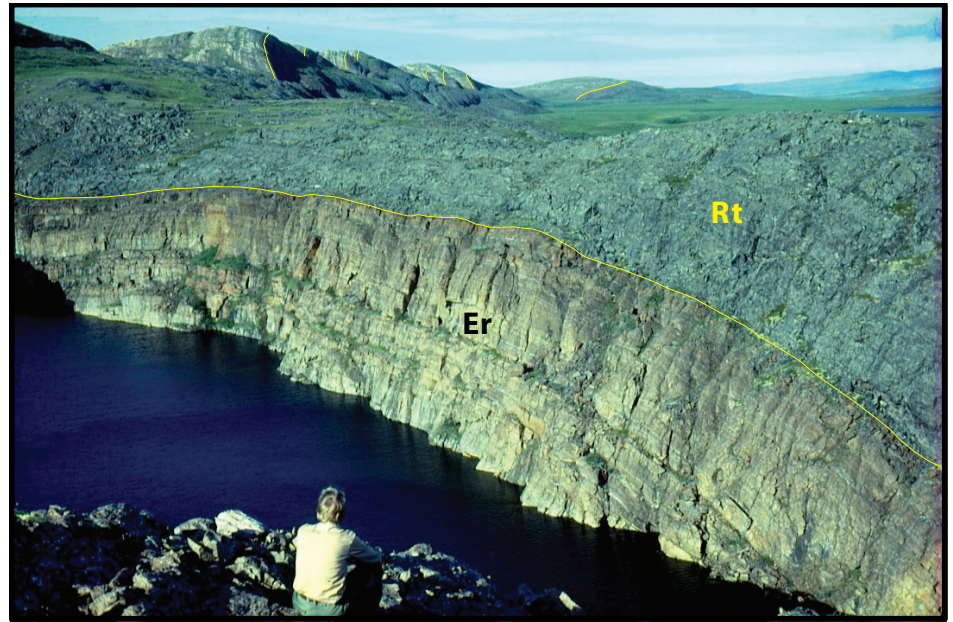


Figure 1. Abrupt drowning of the Rocknest Formation (Er) marks the abortive subduction of the passive-margin carbonate shelf in Wopmay orogen at 1882 Ma (Bowring and Grotzinger 1992). Here, 30 km east of the frontal thrust and 300 km (palinspastic) landward of the ancient shelf-slope break, the basal foredeep deposits consist of craton-derived glauconitic siltstone (Rt), which tapers westward to a few meters of granular ironstone, overlain by graphitic-pyritic slate and felspathic-greywacke flysch. Abortive subduction of the passive margin caused a subduction zone flip, forming an active margin with subduction dipping beneath the continent. S.B. Lucas (foreground) ponders the metamorphic temperature. Tree River fold belt at 67°26'05"N, 112°22'38"E, Nunavut, Canada.

provide us with more structural relief than is exposed on any mountain on Earth (Hoffman et al. 1988).

A day later we returned to the top of the allochthonous dolomite, marked by a long narrow valley and a structurally intact sedimentary sequence. Bioherms of sunlight-seeking columnar stromatolites distinguish the final meters of dolomite (Grotzinger 1986b). They are abruptly overlain by a few meters of glauconitic quartz-siltstone (Tree River Formation), several decameters of sulfidic-graphitic slate (Fontano Formation), and then a kilometer or more of immature, coarse-grained, felspathic-greywacke turbidites (Asiak Formation). The abruptness of the transition and the thickness of greywacke turbidites diminish eastward (Fig. 1), implying that the anomalous subsidence was limited to the outer 300 km (palinspastic) of the carbonate shelf. The abrupt drowning of the Rocknest platform, and its burial by euxinic and flysch-type deposits, anticipated Pettijohn's lower Ordovician geosynclinal

cycle by a factor of four in its age. The parallel tectonic development of geosynclines over the last two billion years was empirically evident, but not yet their interpretation in terms of plate tectonics (Pettijohn 1957; Hoffman et al. 1970).

What caused the carbonate shelves to founder at the beginning of the orogenic stage? The answer would eventually come from the Appalachian-Caledonian orogen, informed by theoretical geophysics and modern examples. In 1964, Hank Williams (1964) recognized the Newfoundland Appalachians as an orogenic system in which two different continental shelves (Dietz's 'miogeoclines') face each other across an early Paleozoic oceanic tract. Tuzo Wilson (1966) extended this interpretation throughout the North Atlantic region, based on a long-known faunal discordance. He inferred that intra-oceanic island arcs got lodged between the collided margins when the Paleozoic ocean closed. On the western margin in Newfoundland, Bob Stevens (1970) recognized two Cam-

bro-Ordovician flysch sequences, the older distinguished by quartzo-feldspathic turbidites shed from Laurentia (Dietz's 'eugeoclinal') and the younger (Arenig-Caradocian) derived from the east and distinguished by detrital chromite and other ultramafic detritus (Stevens and Church 1969). Two months before I first saw the drowned carbonate shelf in Wopmay orogen, John Dewey (1969; see also Bird and Dewey 1970) published a plate tectonic model for the development of the Appalachian-Caledonian orogen. He ascribed the Ordovician (Taconic) orogeny on the Laurentian margin to the effects of west-dipping subduction, initiated spontaneously at the distal edge of a passive continental margin. His model for the Laurentian margin was basically an elaboration of Dietz's (1963) concept of collapsing continental rises. It had the same defects as Dietz's model: it didn't account for abrupt drowning of the miogeoclinal; it predicted arc magmatism on the Laurentian margin where none existed, and it was non-actualistic.

A more satisfactory model (McKenzie 1969) appeared just three months after our slog in the snow in the Wopmay foreland. It was a generic model with no particular regional application and its author was a 27-year-old geophysicist from Cambridge University on a Fairchild Fellowship at Caltech. Two years earlier, Dan McKenzie (McKenzie and Parker 1967)—and independently Jason Morgan (Morgan 1971; Le Pichon 1991)—had conducted the first quantitative test of Tuzo Wilson's (1965) concept of plate tectonics. McKenzie's subsequent 1969 paper is accurately titled, "*Speculations on the consequences and causes of plate motions*", and it deals with dynamic coupling and feedback between plate motions and mantle convection at subduction zones. He views continents as non-subductable due to compositional buoyancy: their arrival at a trench inevitably results in strong crustal deformation and "*a change in the motion or the boundaries of the plates*" (McKenzie 1969). "*If the trench and island arc originally had oceanic crust on both sides, the island arc is likely to flip, and instead of attempting to consume the continent it will consume oceanic crust originally behind the arc.*" McKenzie gives no active or

ancient example of subduction zone flip: it is a speculation. John Dewey, then 32, immediately recognized the generic significance of subduction polarity flip as a consequence of arc-continent collision, but he did not favour its application to the Taconic (or Grampian) orogeny (Dewey and Horsfield 1970; Dewey and Bird 1970, 1971).

To the best of my knowledge, the late Bill Chapple (1973) of Brown University was the first to invoke subduction flip for the Appalachians in a talk at the 1973 GSA Annual Meeting in Dallas. It was a rare foray into regional tectonics for a numerical modeler (Chapple 1968, 1969, 1970), who is remembered for his later insights on the force balance acting on lithospheric plates (Chapple and Tullis 1977) and a ground-breaking approach to the mechanics of thin-skinned thrust-and-fold belts (Chapple 1978). Chapple (1973) proposed that the Taconic orogeny was the result of 'abortive subduction' of the Laurentian passive margin beneath a west-facing island arc. Assuming an average modern rate of plate convergence, he estimated how long different stages of the arc-continent collision including thermal relaxation would last, and compared these estimates with geological constraints. His model explained the abrupt but diachronous foundering of the continental terrace as it entered the trench, and the associated 'staircase' normal faults through plate flexure. It accounted for the subsequent euxinic (trench outer-slope) and flysch (trench axis) deposits, as well as deformation during detachment and accretion onto the upper plate. It conformed with the absence of arc magmatism on the Laurentian margin until shortly after the arc-continent collision. It was never written up as a paper.

Nothing Bill Chapple could have written would have supported Dan McKenzie's (1969) speculation of subduction flip so eloquently as the active arc-continent collision in Taiwan (Fig. 2), described by geologist R.W. Murphy in Kuala Lumpur and published (Murphy 1973; see also Suppe 1981, 1984) the same year as Chapple's GSA talk in Dallas. Convergence between the Philippine Sea and Eurasian plates drives the west-facing

Manila Trench–Luzon arc, at the leading edge of the Philippine Sea plate, against the oblique, southeast-facing, passive continental margin of China. The arc-continent collision is diachronous, progressing southwestward along the continental margin, converting it from a passive to an active margin. Every stage in the process is simultaneously active at different latitudes. South of Taiwan, the Manila Trench consumes ocean crust of the South China Sea and the China margin is unaffected. Taiwan marks the abortive subduction of the China margin eastward under the Luzon arc: causing the South China Sea slab to tear off, arc volcanism to shut down, and the accretionary prism to be engorged with sediment from the China margin. Mountainous topography and heavy precipitation drive exhumation of metamorphic rocks in central Taiwan. North of central Taiwan, the southeast-facing Ryuku Trench and arc mark the subduction of the Philippine Sea plate northward beneath the Eurasian plate. The latest volcano of the Ryuku arc is at the northern tip of Taiwan, and roll-back of the Philippine Sea slab creates a rift basin, the Okinawa Trough, behind the Ryuku arc. The entire process, from the collapse of the passive margin to the establishment of an active continental margin arc above the flipped subduction zone, takes around 4 million years (Suppe 1984). At a given latitude, a collision-induced mountain range rises and falls on the same time-scale. A broadly similar process was shown to have occurred in New Guinea in the late Miocene (Hamilton 1979; van Ufford and Cloos 2005) and to be ongoing in Timor, where the northwest margin of Australia enters the Java Trench (Von der Borch 1979). In 1978, the Rangoon-based economic geologist Andrew Mitchell (1978) interpreted the Taconic-age Grampian orogeny of the Scottish Caledonides as a subduction flip tripped by arc-continent collision. The next year, having completed the northern transect of Wopmay orogen, I followed suite (Hoffman 1979, 1980, 1982).

The subduction flip scenario makes falsifiable predictions about the timing and polarity of arc magmatism, relative to shelf drowning and to subduction-related deformation and meta-

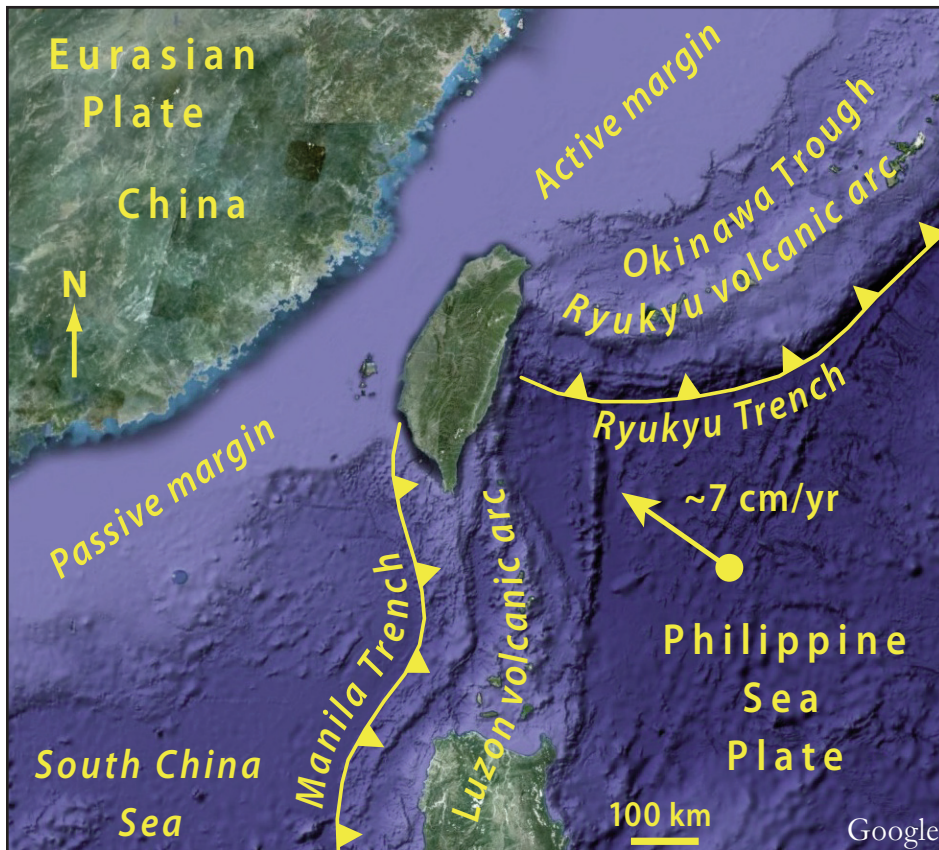


Figure 2. Taiwan island (center) marks the active collision of the Luzon arc with the passive continental margin of southeast China. Continued convergence between the Philippine Sea and Eurasian plates causes subduction to flip during arc-continent collision, resulting in northwest-dipping subduction at the Ryukyu Trench. The conversion of the passive margin into an active margin progresses southwestward at a rate of ~ 95 km per million years (Suppe 1984). Teeth on trench-lines indicate the upper plate.

morphism. Arc magmatism should not touch the passive margin until a few million years after shelf drowning, when it will have the opposite tectonic polarity compared with the collided arc. The model predicts that both arcs will be deformed by subsequent collisions—a subduction flip never involves the terminal collision in an orogen. Tectonism subsequent to arc-continent collision can be protracted, as in the Appalachians, if a large ocean basin existed behind the collided arc. Integration of structural mapping with metamorphic petrology, basalt and granitoid petrochemistry, high-resolution (ID-TIMS) U-Pb geochronology, and isotopic tracers has confirmed the Taconic subduction flip scenario for active margin inception and a complex accretionary history in the Canadian Appalachians (van Staal 1994; van Staal et al. 2007, 2009; van Staal and Barr, in press). The same overall scenario con-

tinues into the New England Appalachians (Karabinos et al. 1998; Dorais et al. 2012) and the Irish Caledonides (Friedrich et al. 1999). In fact, the vast majority of all active margins, both modern and ancient, were the result of subduction flip following arc-continent collision (Bradley 2008). There are good mechanical reasons for this: it is very difficult to initiate subduction at a subsided passive margin because of the strength of the plate (Cloetingh et al. 1989). In the high heat-flow region behind the arc, the plate is more easily ruptured.

Surprisingly, there are two orogens in which there was an active margin whose origin remains unresolved, mainly because the question in the title has not been seriously asked until recently. One is the orogen in which I live, the North and South American Cordillera. The other is the orogen in which I work, the Damara of Namibia.

These are stories for another time.

In Wopmay orogen (Fig. 3) there are two magmatic belts, the older Akaitcho-Hepburn belt to the east and the younger MacTavish-Great Bear belt to the west. The younger belt has all the trappings of a continental magmatic arc and it must have faced to the west because no ocean existed to the east when it was active (Hildebrand et al. 1987, 2010b; Cook 2011). The older belt is the leading edge of an arc (Hotah terrane) that collided with the Slave passive margin, causing the Calderian orogeny and triggering the subduction flip (Hildebrand et al. 2010a). The arc-continent collision is best dated by the collapse of the passive margin (Fig. 1) at 1882 Ma, ~ 132 million years after the rift-to-drift transition (Bowring and Grotzinger 1992; Hoffman et al. 2011). When Marc St-Onge and I, under the tutelage of Dugald Carmichael, mapped the prograde metamorphic sequence related to the Hepburn intrusions, we inferred that the metamorphic isograds to the east cut distal correlatives of the passive continental margin (St-Onge 1981, 1984; St-Onge and King 1987). This should not occur if the Hepburn intrusions were part of an arc that collided with the passive margin. Accordingly, I attributed the Hepburn intrusions to the tearing off of the westerly-dipping slab during arc-continent collision (Hoffman 1980). This implied that the intrusions should be derived from Archean crust of the Slave craton, which was contradicted by isotopic tracers (Bowring and Podosek 1989; Housh et al. 1989).

In a recent synthesis of the Calderian orogeny and northern Wopmay orogen, Robert Hildebrand (Hildebrand et al. 2010a; Hildebrand 2011) affiliates all of the Hepburn intrusions and the high-grade part of the metamorphic sequence with the leading edge of the accreted terrane. Both the integrity of the prograde metamorphic sequence and the post-collisional age of peak metamorphism are questioned in this scenario. For my part, I have more confidence in the integrity of Marc's metamorphic sequence than in my own correlation of the high-grade metamorphic rocks with the passive-margin Odjick Forma-

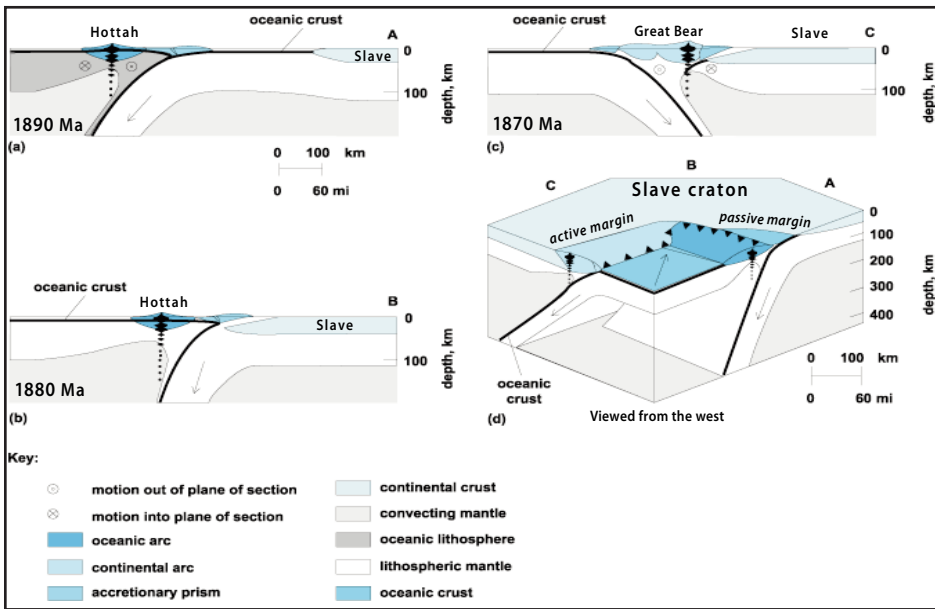


Figure 3. Block diagram of an oblique arc-continent collision with diachronous subduction flip (d). Cross-sections illustrate Wopmay orogen (looking north) at 65°N present latitude at ~1890 Ma (a), 1880 Ma (b) and 1870 Ma (c). Passive continental margin (a) is converted to an active margin (c).

tion. When the metamorphic isograds were mapped, there wasn't a single U-Pb date in the entire orogen; with modern isotopic diagnostics, it should be possible to distinguish accreted (Hottah terrane) from indigenous (Odjick Formation) protoliths in the metamorphic sequence, as well as the metamorphic chronology. Sedimentary protoliths derived from the Archean Slave craton will be easy to distinguish from the more juvenile signature of Hottah terrane (Bowring and Podosek 1989; Housh et al. 1989), given appropriate samples, but if the Odjick Formation was sourced from the contemporaneous Thelon orogen (Hoffman and Grotzinger 1993), isotopic fingerprinting will be more of a challenge. Two months before writing this column, I got an unexpected email from GSC in Ottawa. Did I still possess my old field notes and annotated air photos from Wopmay orogen? They were needed to select samples from the GSC collections. Three boxes of field notes and air photos were soon taking the fourth transcontinental trip of their 20-year diaspora, this time by air.

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