Can back-arc processes in a simplified model explain much of the complexity of the northern Appalachian orogen?

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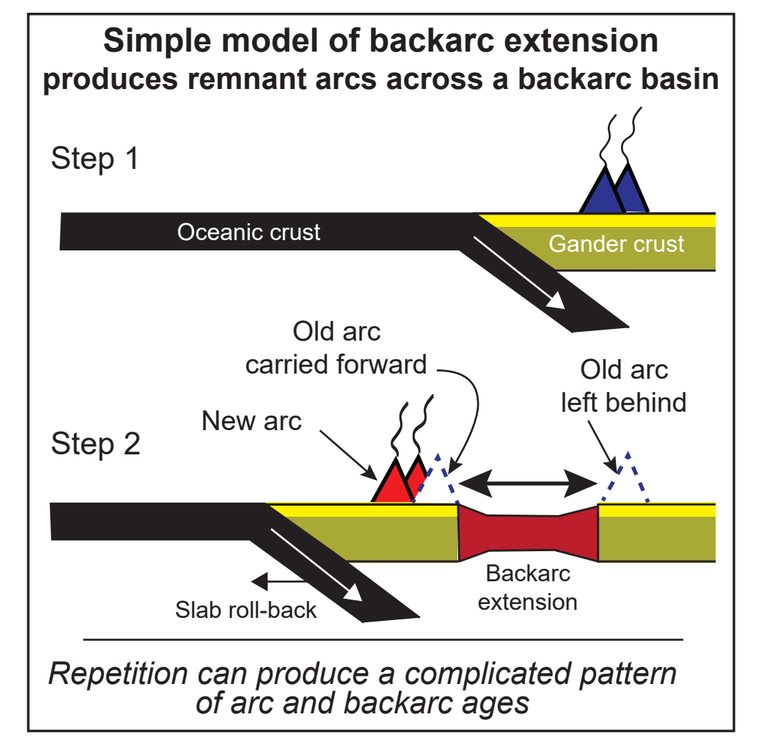
Introduction

In the Early Paleozoic, there is abundant evidence for west-facing arcs related to east-dipping subduction beneath Gondwana. Post-Taconic collision, there is similarly abundant evidence for east-facing arcs related to west-dipping subduction beneath Laurentia. The Laurentian passive margin was now an active Andean-style accretionary margin.

Is it possible that most if not all of northern Appalachian geology can be explained by this essentially two-stage scenario? In particular, can arc features of similar age but widely distributed in space be explained, rather than by separate subduction zones, by "upper plate" dispersal processes including arc migration (slab roll-back, changing dip angle) and most significantly, arc splitting (backarc extension potentially resulting in widespread separation).

Here, we test this concept by constructing a series of scale maps and comparing these model results with the known distribution of arc ages. This tests the hemisphere-scale model proposed by Waldron et al. (2014). The exercise yields quite good agreement and potentially a far simpler scenario to explain the notoriously challenging tectonic puzzle of the northern Appalachian orogen.



Key Data

1) Ganderian vs. Laurentian provenance based on detrital zircon (DZ) ages

Ganderian (peri-Gondwanan) DZ age populations are distinguished by 650-520 Ma grains sourced from a Neoproterozoic arc system. Ganderian cover rock is shown on the basemaps in yellow, including the Albee and Dead River Fms in NH and ME (Karabinos et al., 2017), Cape Elizabeth Fm. and Cookson Gp. in coastal ME (Schultz et al., 2008; Hussey et al., 2010), Cookson and Woodstock Gps. of NB (Fyffe et al., 2009; van Staal et al., 2016) and the Quinebaug Fm in eastern MA (Walsh et al., 2019). The largely volcanic Ellsworth Schist is contemporaneous with the Cookson Gp. in coastal ME (Osberg et al., 1995) and has sediments with Ganderian DZ ages (Reusch et al., 2004).

A significant addition to this list is the Moretown Fm. (MacDonald et al., 2014; Karabinos et al., 2017) which is the farthest-west Ganderian rock and thus a key model constraint (see basemap).

Laurentian DZ populations have ca. 1050 and 1200 Ma grains from Grenvillian crust, e.g. the Rowe Schist, west of the Moretown Fm across the Brompton-Baie Verte Line (BBVL), has Laurentian DZ signature (Karabinos et al., 2017). **East of Moretown Fm, the Chain Lakes Massif (CLM) has Laurentian DZ ages (Gerbi et al., 2006a), another key constraint.**

The Cram Hill Fm. of VT overlies the Moretown Fm, has mixed Laurentian and Gondwanan DZ ages, and is considered part of the Shelburne Falls Arc (SFA, Karabinos et al., 2017). The northern part of Cram Hill Fm. correlates with the St-Daniel of Quebec, interpreted as forearc with input from Laurentia and an arc (Tremblay et al., 2011). In order to reconicle this, we distinguish "northern Cram Hill Fm." (interptreted as forearc) vs. "southern Cram Hill Fm." (interpreted as arc). A zone of thin- to absent Cram Hill Fm. separates northern and southern parts.

2) Ganderian vs. Laurentian provenance of basement and igneous rock

Laurentian vs. Ganderian igneous rock can be distinguished based Nd and Pb isotope ratios (Tomascak et al. 2005). Ammonoosuc Volcanics (with backarc geochemical character, Dorais et al., 2012) have Ganderian Nd-Pb ratios, similar to the Tetagouche backarc rocks of the MIramichi HIghland in NB. Ammonoosuc Volcanics crop out along the Bronson Hill Anticlinorium (BHA), which also hosts the Oliverian Domes. Aleinikoff et al. (2007) found a mix of Laurentian and Ganderia isotopic ratios in the Oliverian Domes, which are arc-related plutons formed ca. 450 Ma (post-Taconic).

The SFA of VT, MA and CT is an arc on Gondwanan terrane (Karabinos and Williamson, 1994; Macdonald et al., 2014). The Cambrian to Ordovician arc and backarc related rocks in the SE part of the study area (Miramichi Highlands, Casco Bay, Penobscot arc including Nashoba, New River and Annidale Terranes) have Ganderian provenance (c.f., Kay et al., 2017; Hussey et al., 2010, van Staal et al., 2016; Fyffe et al., 2011). Tetagouche Gp. of NB is geochemically similar to the Ammonoosuc Volcanics (Dorais et al., 2012) and represents the Tetagouche-Exploits backarc perhaps 800 km wide (van Staal et al., 2012; van Staal and Barr, 2015). The Ascot Cplx (Notre Dame Arc) of QE is arc with Laurentian Nd character, either from underlying crust or subducted sediment (Tremblay et al., 1994).

The Neoproterozoic arc rocks of the Massabesic Gneiss Complex (MGC) of southern NH and MA have Ganderian isotopic ratios (Dorais et al., 2012). The Pelham Dome (MA) is either Avalonian or Ganderian basement (Aleinikoff et al., 1979; MacDonald et al., 2014)

3) Radiometric ages of arc and backarc rocks

Ages represented on the basemap and histogram are U-Pb ages of zircons taken from publications that are listed on a separate sheet (110 data points). The 492 Ma age in the Ellsworth Terrane is pers. comm. G. Dunning.

Devonian plutonism that may be arc-related include the syntectonic NH Plutonic Series that are drawn into nappes (ca 413- 393 Ma; summarized in Dorais (2003) and the Emsian plutons (413.5-401 Ma) and related Piscataquis Volcanic Belt (Bradley et al., 1999). "Syntectonic NHPS" refers to the Bethlehem, Kinsman and Spaulding Fms, which have a tectonic fabric.

4) Key Faults

The Baie Verte-Brompton Line (BVBL) and Cameron' Line are initially a west-vergent thrust fault separating the Rowe Schist from Moretown Fm., interpreted as a suture between Ganderia and Laurentia (MacDonald et al., 2014; Waldron et al., 2018). In Quebec the BBVL is offest by St-Joseph normal fault due to extension in the CT Valley - Gaspe Trough (CVGT; Tremblay and Castonguay, 2002).

The Dog Bay - Liberty Line is an east-vergent thrust fault separating Ganderian rocks with contrasting character, interpreted as the Salinic suture (Reusch and van Staal, 2012; Dokken et al., 2018).

The Norumbega Fault shows Devonian dextral offset of perhaps 125-140 km (Ludman and West, 1999).

The Bloody Bluff Fault and equivalent in Canada are interpreted as the Acadian suture beween Ganderia and Avalonia (Hibbard et al., 2006).

5) Polarity of subduction

Penobscot (ME and NB), Nashoba (MA), Popelogan (ME), Shelburne Falls (VT, MA and CT), and Notre Dame (QE) arcs are widely interpreted to overlie east-dipping subduction (van Staal et al., 1996; van Staal and Barr, 2012; Kay et al., 2017; Karabinos et al., 1998; Moench and Aleinikoff, 2003; DeSouza et al., 2012; Perrot et al., 2017) spanning Cambrian through Ordovician time.

The Oliverian Domes and Quimby Volcanics of the BHA (ME, NH, MA and CT) represent arc rocks above west-dipping subduction, intruding through Laurentian crust (Karabinos et al., 1998; Moench and Aleinikoff (2003). West-dipping subduction closed the ocean between Avalonia and composite Laurentia, leading to the Acadian Orogeny (van Staal et al., 2012)

6) Paleolatitude based on magnetic data

Paleomagnetic data and plate reconstructions place the Laurentian margin at ~20° S latitude in the Cambrian, drifting north to about 10° S in Ordovician (Torvsik et al., 2012; Swanson-Hysell and MacDonald, 2017), aligned east-west facing south. Across the Iapetus Ocean, Ganderia (in Nova Scotia) was at roughly 50°S latitude at 500 Ma (Johnson and Van der Voo, 1985), aligned ~20° to the southeast relative to the Laurentian margin (van Staal et al, 1998). Van Staal et al. (2012) calculated a convergence rate of 9 cm/year for the leading edge of Ganderia during closure of the Iapetus, and 5 cm/yr for the trailing edge, with the difference due to backarc spreading. Magnetic data from the ca. 465 Ma Tetagouche Gp. in Miramichi Highlands indicate formation at 53°S latitude (Liss et al., 1996); this implies Ganderian northj motion of 15-30 cm/yr to close the Iapetus (assuming an 800 km-wide backarac remains and 10-20 m.y duration).

Methods

Database assembly

U-Pb age datapoints were placed graphically on the basemap in ArcGIS. Map outlines of rock units were drawn from state and provincial geologic maps.

Tectonic map reconstruction

We undertook an iterative process of drawing a series of to-scale maps for key geologic ages and comparing the final reconstruction with the basemap arc ages and outcrop patterns. Where the final reconstruction differed from the basemap, we judged the cause and adjusted the map reconstructions to decrease the variance. The arcs and terranes were treated as rigid blocks during the process of backarc spreading. During the orogenic events, shortening was allowed on the leading edge of the terranes.

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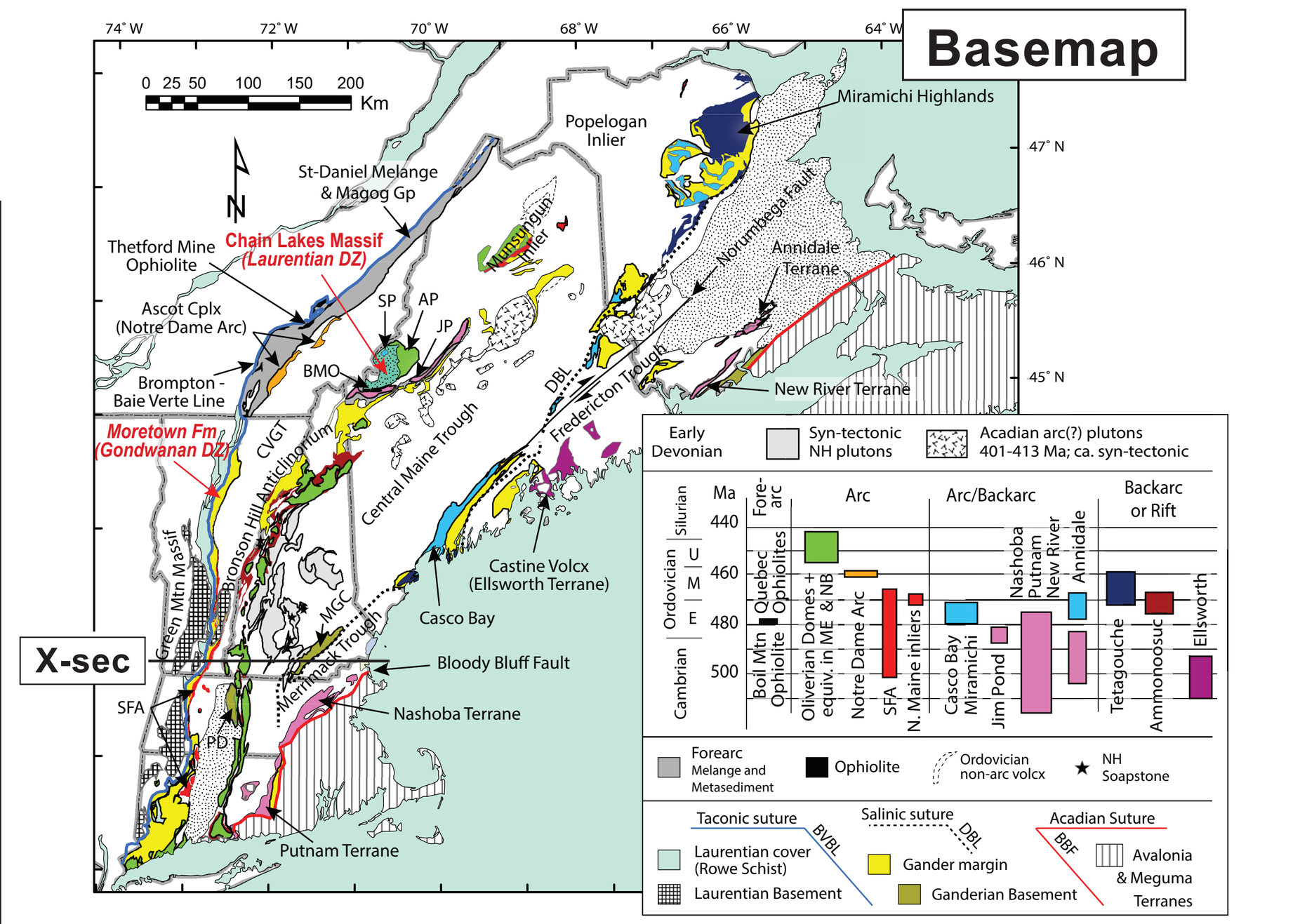
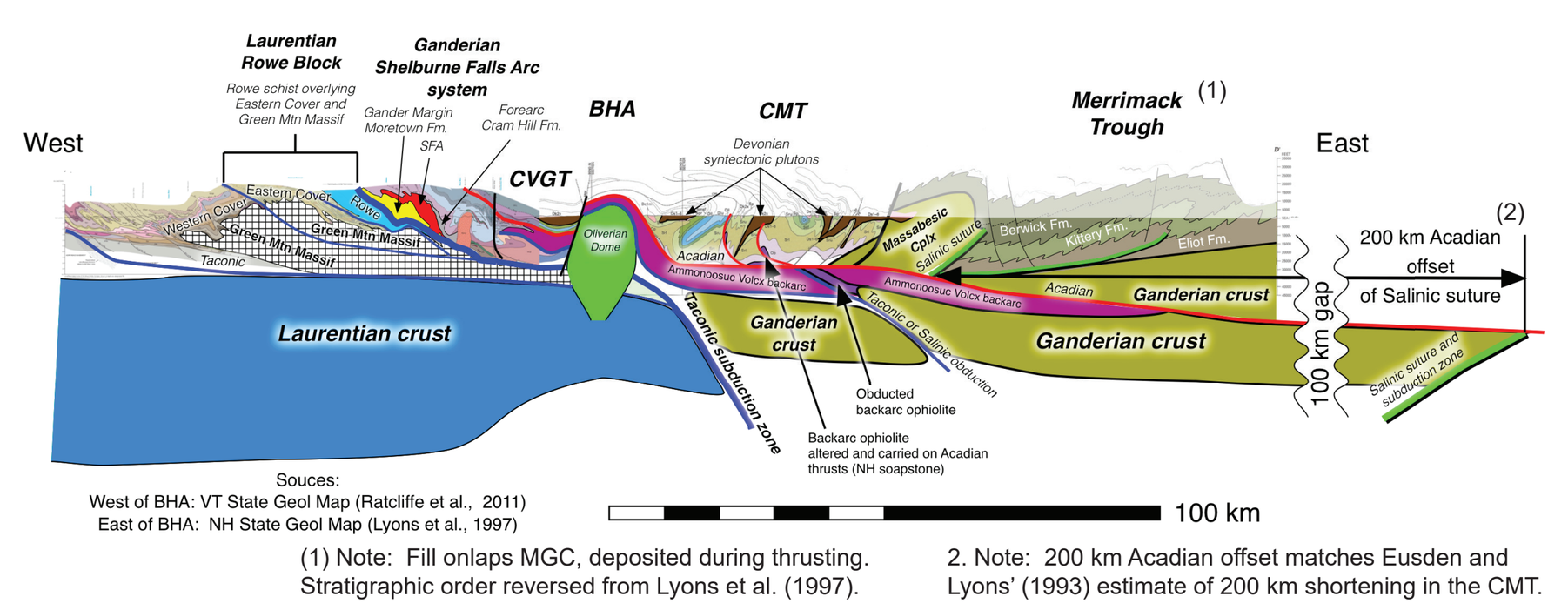
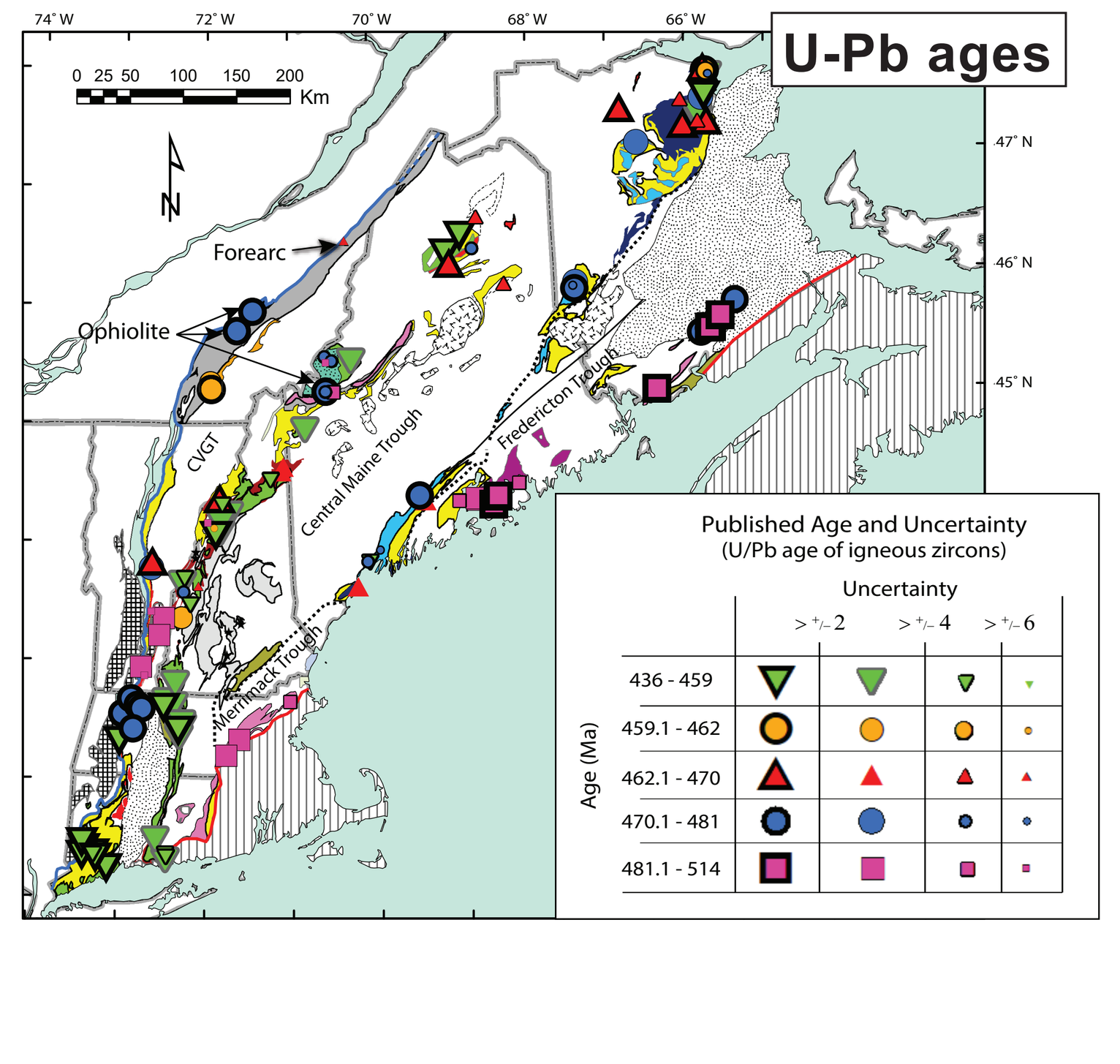
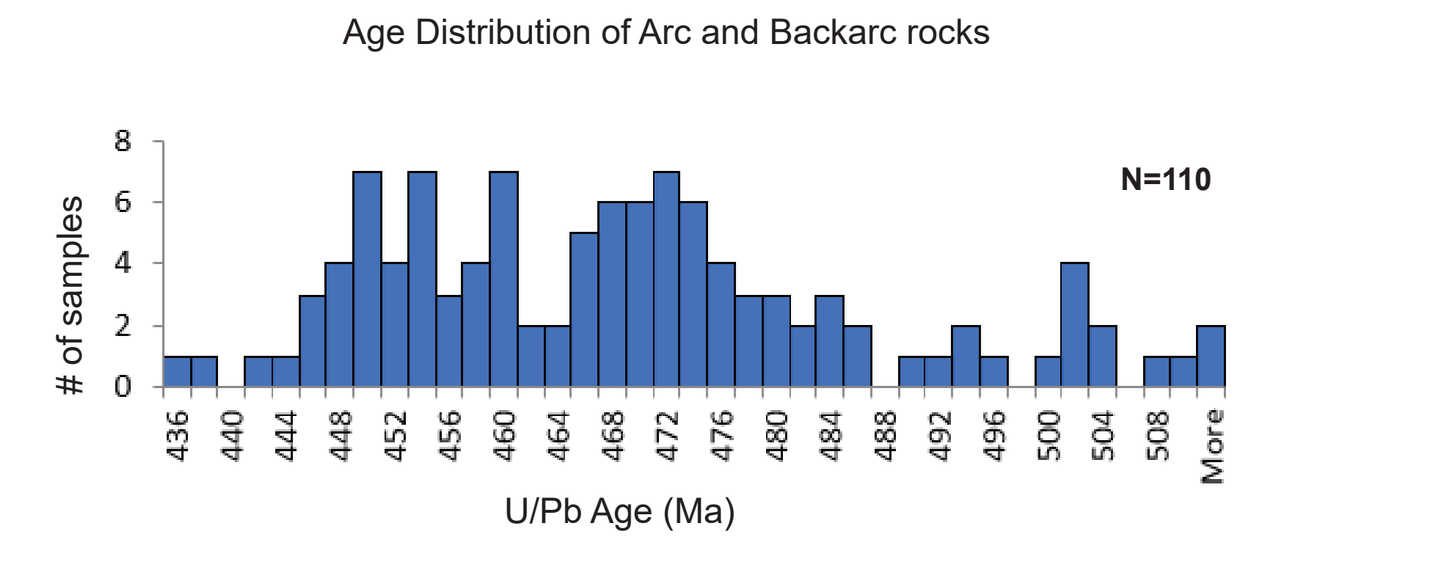
Basemaps and Cross Section



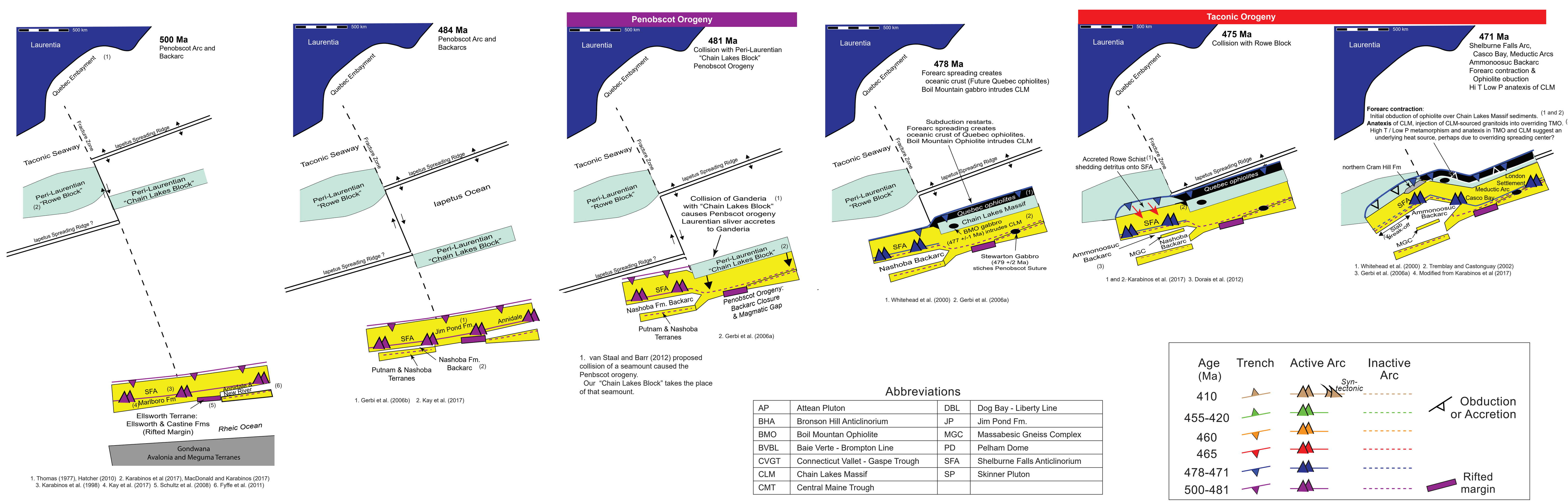






Tectonic Reconstructions

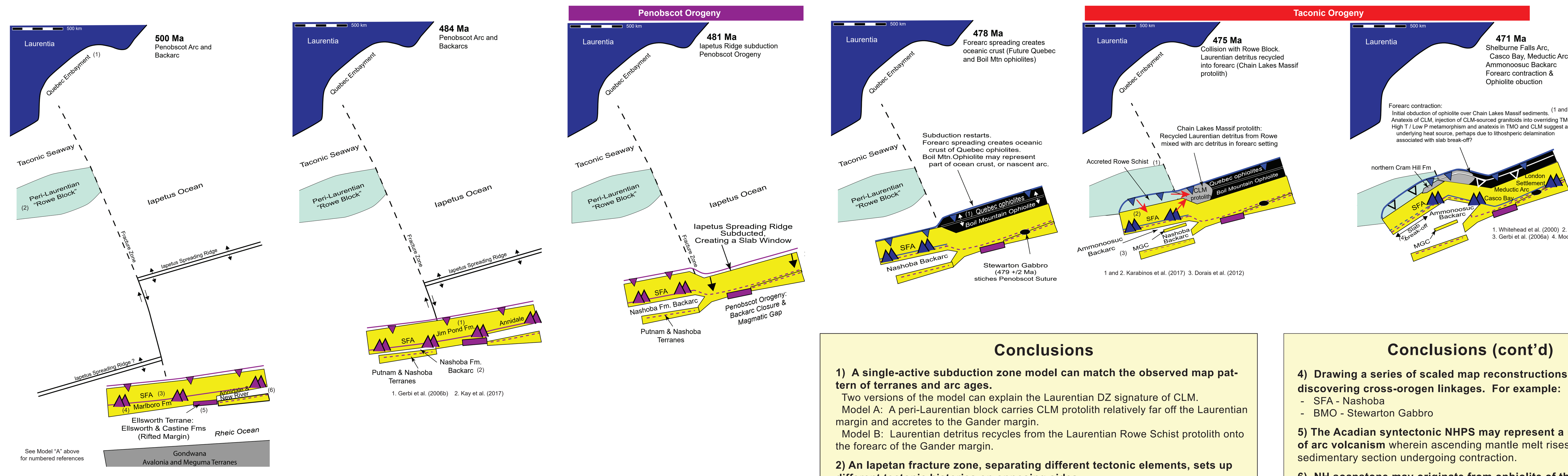
Model A: Penobscot Orogeny due to Ganderia collision with a Sliver of Laurentian crust



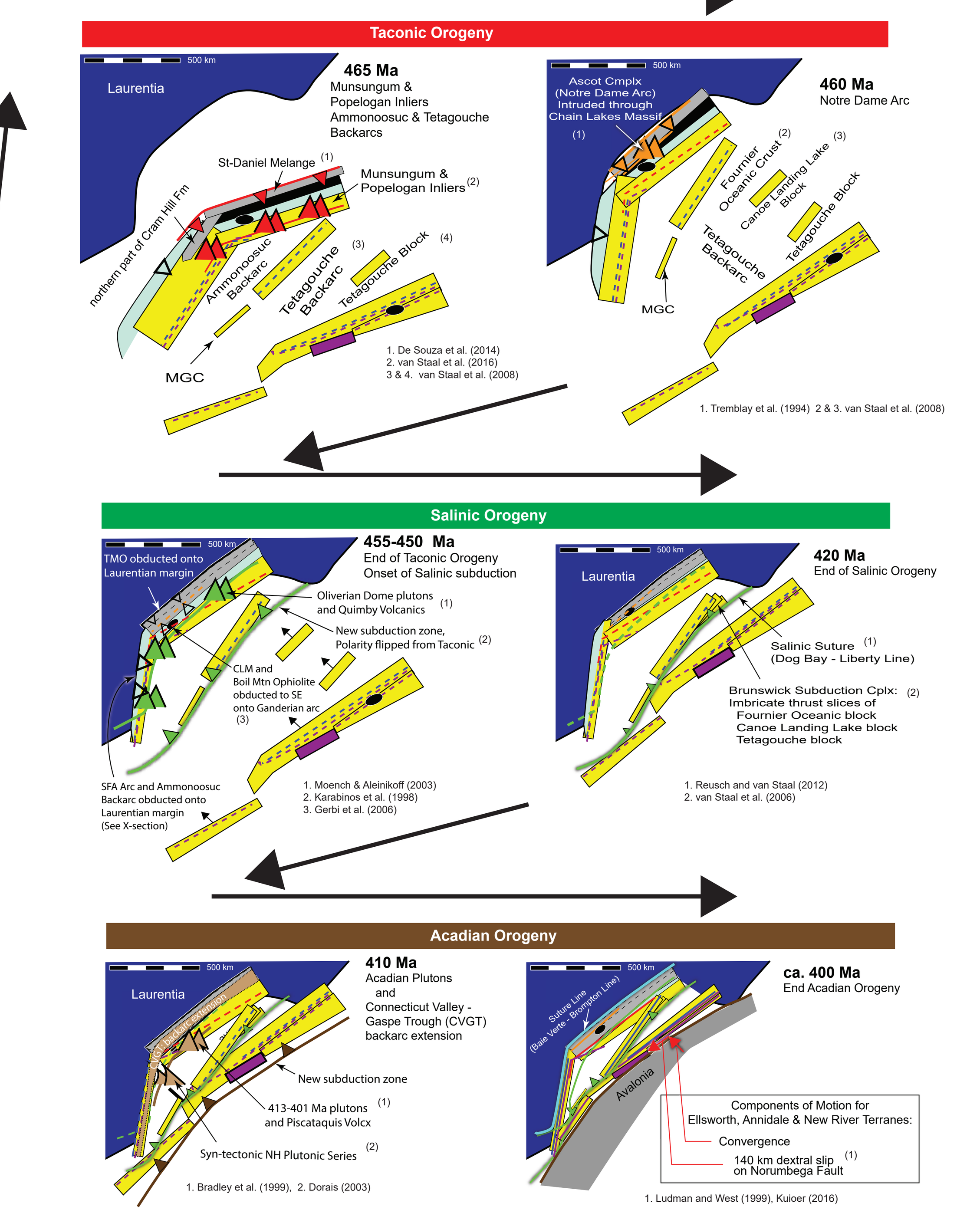
Abbreviations

AP	Attean Pluton	DBL	Dog Bay - Liberty Line
BHA	Bronson Hill Anticlinorium	JP	Jim Pond Fm.
BMO	Boil Mountan Ophiolite	MGC	Massabesic Gneiss Complex
BVBL	Baie Verte - Brompton Line	PD	Pelham Dome
CVGT	Connecticut Vallet - Gaspe Trough	SFA	Shelburne Falls Anticlinorium
CLM	Chain Lakes Massif	SP	Skinner Pluton
CMT	Central Maine Trough		

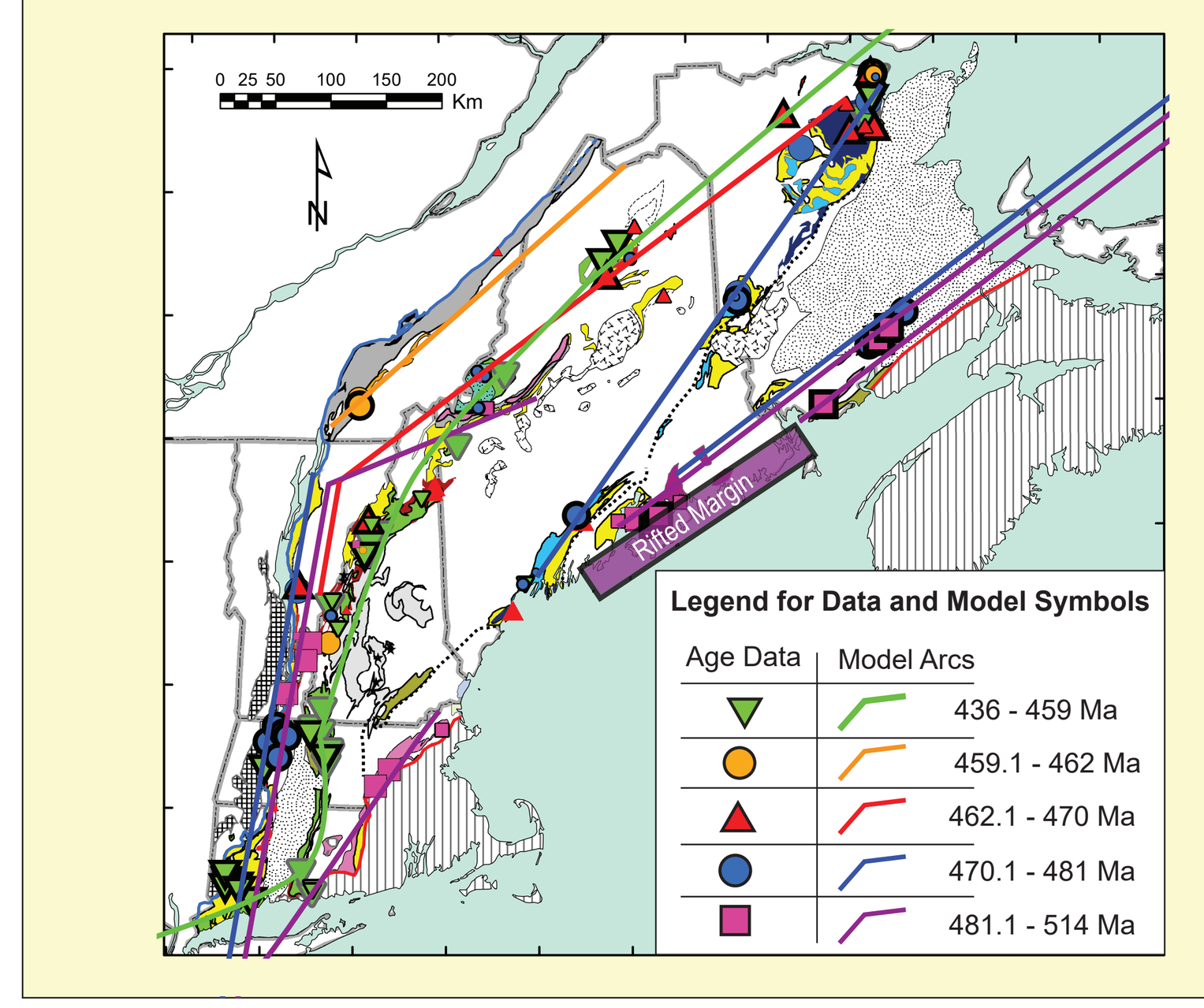
Model B: Penobscot Orogeny due to Ganderia collision with Iapetus spreading ridge



Both models similar (Model "A" shown)



Comparison of Modeled Arcs to Age Data



Good Fit between Modeled Arcs and Age data

Laurentian and Gondwanan Provenance also fit well

Conclusions

1) A single-active subduction zone model can match the observed map pattern of terranes and arc ages.
Two versions of the model can explain the Laurentian DZ signature of CLM.
Model A: A peri-Laurentian block carries CLM protolith relatively far off the Laurentian margin and accretes to the Gander margin.
Model B: Laurentian detritus recycles from the Laurentian Rowe Schist protolith onto the forearc of the Gander margin.

2) An Iapetan fracture zone, separating different tectonic elements, sets up different tectonic histories on opposing sides.
- **The Penobscot Orogeny is limited to the NE side** due to Gander collision with (A) the "CLM Block" or (B) the Iapetus spreading center.
- **The early Taconic Orogeny is limited to the SW side** due to collision with the Laurentian "Rowe Block".

3) The Nashoba backarc is related to the early part of the SFA, and the Ammonoosuc backarc is related to the late part of the SFA

Conclusions (cont'd)

4) Drawing a series of scaled map reconstructions aids in discovering cross-orogen linkages. For example:
- SFA - Nashoba
- BMO - Stewarton Gabbro

5) The Acadian syntectonic NHPS may represent a rare version of arc volcanism wherein ascending mantle melt rises into a thick sedimentary section undergoing contraction.

6) NH soapstone may originate from ophiolite of the Ammonoosuc backarc basin, brought to the surface during Acadian orogeny.

Acknowledgements

We received very helpful advice from Dyk Eusden, Chris Gerbi and Justin Strauss. Roger got early encouragement from Lisa Hjelm.

Areas for further study:

1) Paleomagnetic analysis by Liss et al. (1993) indicates Tetagouche basalts formed at 53 °S latitude, but our model places that at 35° S.
- Fitting 53° S may require a model with an offset subduction zone with the Tetagouche side lagging behind the SFA side.

Evidence of an offset subduction zone might be found in the complex structure along the BVBL at the VT-QE border.

2) The model implies that the age-range minimum of the northern part of the Cram Hill Fm. (correlative to St-Daniel Melange) is younger than that of the southern Cram Hill. Age data may test this.