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How was the Iapetus Ocean infected with subduction?
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Abstract:	Because subduction in the Iapetus Ocean began only ~35 Myr after the end of rifting, spontaneous foundering of mature passive margins is an unlikely subduction-initiation mechanism. Subduction is more likely to have entered the Iapetus from the boundary with the external paleo-Pacific, similar to the incursion of the Scotia, Caribbean, and Gibraltar arcs into the modern Atlantic. The subduction zone probably became sinuous, entraining fragments of the Gondwanan margin along its complex sinistral southern boundary where oblique collision caused Monian/Penobscottian deformation. Following Taconian/Grampian collision of part of the subduction system with Laurentia, remaining parts of the Iapetus were progressively infected with subduction, leading to Silurian closure.
Response to Reviewers:	In revising the paper I have addressed the comments of reviewer 1 (Chew) as follows. I have included a short discussion of the South American Andean margin at lines 51-56, referencing the Chew et al (2007) paper. The relationship of the Ordovician rocks to the Amazonian craton is not at all well constrained; for all we know they could be another allochthonous arc from the margins of our Sea of Exploits. There is not space for an extended discussion of South America, but I have added one more reference (Rapelini) to paleomagnetic work that indicates the level of uncertainty there. To address Chew's second point, I have adjusted Fig 2, and added phrasing (lines 96-98), to indicate that the arc that invaded the Iapetus could have been initially narrow, like the Caribbean. I have kept both of these discussions succinct, as we are pressed for space, particularly because the reference list, already long, was lengthened by the addition of doi numbers. The addition of two more references to address Chew's comment increases this pressure. Because referee 2 was particularly complimentary on the literature cited, I have hesitated to remove any of the references to Paleozoic Iapetan geology. However, I have saved some space by removing one reference on early

	rifting between Amazonia and Laurentia, relying instead on "Hibbard et al. (2007) and references therein". I also felt that a statement about long fracture zones in modern oceans was general enough knowledge not to need reference support, enabling me to remove one other reference. I have not added the Piper reference (rather tentatively suggested by referee 2), as it is cited in Vizan et al, to which I added "and references therein" which uses less space. I have improved the labeling of Gondwanan elements in Fig. 2, as suggested by referee Chew, and adjusted the extent of Avalonia in England as suggested by referee 2. To save a bit more space, I have also increased the overlap between the globes in Fig. 2, and shaved a little off the top and bottom of both figures. This made it difficult to accommodate the chronostratigraphic names requested by reviewer 2, but I have incorporated these in the captions. As it stands, I calculate the revised manuscript to be 4.0 pages.

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How was the Iapetus Ocean infected with subduction?

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ABSTRACT

Because subduction in the Iapetus Ocean began only ~35 Myr after the end of rifting, spontaneous foundering of mature passive margins is an unlikely subduction-initiation mechanism. Subduction is more likely to have entered the Iapetus from the boundary with the external paleo-Pacific, similar to the incursion of the Scotia, Caribbean, and Gibraltar arcs into the modern Atlantic. The subduction zone probably became sinuous, entraining fragments of the Gondwanan margin along its complex sinistral southern boundary where oblique collision caused Monian/Penobscottian deformation. Following Taconian/Grampian collision of part of the subduction system with Laurentia, remaining parts of the Iapetus were progressively infected with subduction, leading to Silurian closure.

INTRODUCTION

Subduction initiation remains a poorly understood part of the plate tectonic cycle (Gudmundsson, 2013). The early Paleozoic Iapetus Ocean provides insight by virtue of its short lifespan, apparent simultaneous subduction on opposing margins (e.g., van Staal et al., 1998; Chew et al. 2007), and the final assembly of surrounding continents in an arrangement broadly similar to their initial configuration, matching the “introverted” model of Murphy and Nance (2003). Most models for the resulting Appalachian – Caledonide orogen (Fig. 1) assume subduction initiation along both the Laurentian and Gondwanan margins. We propose instead that deformation early in the history of the orogen resulted from a single sinuous subduction system analogous to the Scotia and Caribbean arcs in the modern Atlantic.

RIFT HISTORY

Most previous workers (e.g., Cawood et al., 2001; van Staal et al., 2012) agree that the Iapetus Ocean originated by 3-way rifting of Laurentia, Baltica, and Amazonia / West Africa (AWA). Based on ages of mafic dikes and lavas, rifting ranged from ~615–550 Ma, but there are indications of earlier rifting in some areas (summarized by Hibbard et al., 2007; Leslie et al., 2008). Nonetheless, trace fossils from syn-rift rocks (Simpson and Sundberg, 1987; Williams et al., 1995) indicate rifting into at least the Terreneuvian. Smith and Rasmussen (2008) found consistent initiation of drift-phase subsidence from Newfoundland (NL) to Greenland at ~525 Ma. Earliest drift-phase strata in Virginia (Simpson and Sundberg, 1987) are equated with the *Fallotaspis* biozone, ~518–520 Ma (timescale of Peng et al., 2012) and in west NL (Williams and Hiscott, 1987) with the *Bonnia-Olenellus* biozone, ~511–516 Ma. The drift phase of Iapetus expansion must have involved mid-ocean ridges that generated an initial ocean floor, none of which is preserved; ophiolitic rocks in the orogen represent supra-subduction environments (Swinden et al., 1997).

Subsidence of the Laurentian passive margin continued until Taconian/Grampian deformation ~470 Ma. However, the Greenland segment was passive until Scandian deformation

~430 Ma (Smith and Rasmussen, 2008). Other margins of the Iapetus are less well known. The onset of drift in Baltica is placed at 608 Ma by Svenningsen (2001); contrasting portions of the margin succession are preserved in thrust sheets of the Scandinavian Caledonides, where the complex history of later convergence suggests the presence of offshore microcontinents (Roberts, 2003). On the western margin of Amazonia, Chew et al. (2007, and references therein) interpret an extended volcanic arc from Early Ordovician onward, preserved in inliers surrounded by younger rocks. However, the Andean margin of S. America has been strongly overprinted by late Paleozoic, Mesozoic and Cenozoic events, in some cases involving significant along-margin translation and rotation (e.g. Rapelini, 2005). Thus the original location of the early Paleozoic arc is poorly constrained.

SUBDUCTION INITIATION

The timing of subduction initiation is constrained by the oldest arc-related rocks. In NL, these include the peri-Laurentian Little Port Complex (505 +3/-2 Ma Jenner et al., 1991), and the ~507 Ma Twillingate / Lush’s Bight succession, which were deformed and thrust over a continental fragment prior to dike intrusion at ~501–488 Ma (Swinden et al., 1997). Farther SE in NL, arc volcanic rocks (e.g., Tally Pond Group, 509 +/–1 Ma; Rogers et al., 2006) are interpreted as peri-Gondwanan (Zagorevski et al., 2010). These arcs are at most ~35 Myr younger than the end of rifting. Thus the initial phase of drift, during which the Iapetus contained only extensional plate boundaries, was short-lived.

Subduction has often been considered to initiate by spontaneous foundering of old oceanic lithosphere adjacent to a passive margin. Several lines of evidence suggest this is unlikely. First, although development of the Iapetus has been compared with the Atlantic since Wilson (1966), no passive margin formed since Pangea breakup has been converted to subduction despite protracted cooling and local compressive stress (Heidbach et al., 2007). Second, subduction of Iapetus began soon after rifting, though passive margin conditions persisted much later locally. Third, early deformation of the Laurentian margin (e.g., Waldron and van Staal, 2001) resulted from collision with a pre-existing east-dipping subduction zone. Thus foundering of mature passive margins cannot explain subduction initiation in the Iapetus.

Mueller and Phillips (1991) and Stern and Bloomer (1992) proposed an alternative explanation for subduction initiation, at fracture zones juxtaposing lithosphere of contrasting ages. However, the oceans formed in the breakup of Pangea contain several long fracture zones, none of which has been converted to subduction. This is therefore an unlikely explanation for spontaneous early subduction within the Iapetus.

Nonetheless, conversion of an active transform fault between Pacific and Atlantic lithosphere is a proposed mechanism for subduction initiation in the Caribbean region (Pindell and Kennan, 2009). Alternatively, Caribbean subduction initiation may have involved encroachment of an oceanic plateau from the Pacific (e.g., Kerr and Tarney, 2005). Regardless of the cause, the development of the Caribbean Sea led to transfer of a substantial fragment of Pacific lithosphere into the Atlantic. Similar processes may have operated in the evolution of the Scotia plate (reviewed by Dalziel et al., 2013), and may be currently starting at the SW Iberian margin (Duarte et al., 2013). Plate motion of this type has also been invoked in the Canadian arctic by Colpron and Nelson (2009). Application of this model is also supported by geochemical data (Murphy et al., 2014) suggesting derivation of Iapetan ophiolites from mantle that underwent Proterozoic melt extraction, implying encroachment of old lithosphere into the young ocean.

We therefore propose that subduction in the Iapetus was initiated at a boundary between new and old oceanic lithosphere, between Baltica and AWA (shown schematically in Fig. 2), possibly inherited from a Neoproterozoic strike-slip system that bounded AWA (e.g., Murphy et al., 2009). The subduction zone is represented by the Notre Dame – Lough Nafooey Arc system in Canada and NW Europe (van Staal et al., 1998; Chew et al., 2010). Initially narrow, like the Caribbean Arc, it became more arcuate as rapid trench roll-back caused it to migrate into the young Iapetus (Fig. 2B, C). We propose that it progressively "infected" (Mueller and Phillips, 1991) the Iapetus with subduction, eventually leading to ocean closure (Fig. 2E). Similar to the modern Caribbean, the plate boundary system caused transpression and transtension on adjacent continental margins, and incorporated fragments of these as a mosaic of terranes, while margins elsewhere in the ocean remained passive.

IMPLICATIONS FOR CONVERGENCE AND COLLISION

Paleogeographic Reconstructions

In detail, models for Iapetus closure depend on the fate of microcontinental and arc fragments in the Appalachian-Caledonide orogen, where paleogeography has typically been interpreted from 2D cross-sections, and paleogeographic zones have been assumed to be generally continuous: i.e., cylindrical *sensu* Martínez-Catalán (1990). A cylindrical interpretation requires two subduction zones, simultaneously active, to explain coeval tectonism on opposing margins. Our proposed mechanism of subduction initiation implies a *non-cylindrical* evolution, in which convergent deformation developed from a single proliferating subduction system.

Events on the Gondwanan Margin

Terrane classifications (e.g., Hibbard et al., 2007) typically distinguish peri-Laurentian from peri-Gondwanan terranes, the latter including Ganderia and Avalonia (Fig. 1). Both these domains are heterogeneous, but are believed to have originated along the northern margin of Neoproterozoic AWA (e.g., Murphy et al., 2004) although Barr et al. (2014) place them nearer Baltica. These terranes must have undergone westward translation, to bring them to their present positions. Carolinia (Fig. 1) may have had a similar history but is of uncertain provenance; in Fig. 2 we consider only northern Appalachian and Caledonide terranes.

Late Cambrian to Early Ordovician deformation attributed to the Monian and Penobscottian orogenies (e.g., Neuman and Max, 1989) affected Avalonia and Ganderia. During this interval, E. and W. Avalonia show major changes in detrital zircon provenance (Pollock et al., 2009; Pothier, 2013), suggesting plate reorganization prior to their dispersal in the Iapetus. Subsequent arc and back-arc systems in Wales record intermittent subduction until early Katian (e.g., Thorpe et al., 1993).

Ganderia displays more profound Monian/Penobscottian deformation. In NL, ophiolites were emplaced onto quartzose metaclastic successions interpreted as a Cambrian margin of Amazonia, in a “soft” collision between ~486 and ~474 Ma (Colman-Sadd et al., 1992). The Exploits back-arc basin opened during subsequent arc activity (Zagorevski et al., 2010). In New Brunswick (van Staal et al., 1991) and Maine (Neuman and Max, 1989) unconformities separate quartzose metasedimentary rocks from later arc successions. Comparable Cambrian metaclastic rocks in SE Ireland and NW Wales (Tietzsch-Tyler and Phillips, 1989) were deformed prior to Floian sedimentary cover, and juxtaposed with unmetamorphosed Cambrian successions along a pre-Floian boundary interpreted by Gibbons (1990) as sinistral and transpressional.

We interpret all these events to have occurred along the north margin of AWA (Fig. 2C), at the southern transpressional boundary of the advancing Caribbean-style plate, analogous to Cenozoic deformation along the northern boundary of S. America.

Events on the Laurentian Margin

Leading parts of the Notre Dame – Lough Nafooey arc collided with peri-Laurentian continental fragments early in the Taconian/Grampian orogeny, starting ~490 Ma (e.g., Waldron and van Staal, 2001; Chew et al., 2010). Macdonald et al. (2014) have recently identified a Gondwanan fragment in New England involved in this collision by ~475 Ma; its presence is much more easily explained by a scenario such as Figure 2D-E than by a cylindrical model. The arc-trench system, incorporating these deformed fragments, then collided with the main Laurentian margin from Scotland to NL starting ~470 Ma, whereas collision in New England was ~10 Myr later (Bradley, 1989). Subduction reversal probably progressed diachronously (van Staal et al., 1998) following arc collision, leading to westward subduction (Fig. 2E) beneath Laurentia from Late Ordovician onward (Zagorevski et al., 2009; Stone et al., 2012).

Late Ordovician – Silurian Closing of the Iapetus Ocean

East of the arc system was a complex region of back-arc basins and continental fragments similar to the modern Caribbean Sea, here termed the Sea of Exploits (Reusch et al., 2014). Peri-Gondwanan fragments arrived at the Laurentian margin from Katian (Wilson et al., 2004; Waldron et al., 2012) to Wenlock (Waldron et al., 2014 and references therein). Their present-day distribution requires clockwise rotation (Fig. 2C-E) relative to the likely arrangement on the AWA margin (Pothier, 2013), possibly due to eastward drift of Laurentia; Vizan et al. (2003, and references therein) noted that paleomagnetic data from Britain are compatible with large vertical-axis rotations.

The complex transpressional zones bounding the Sea of Exploits to the N. and S. were probably progressively converted to subduction; roll-back allowed them to extend into the remaining parts of the Iapetus, "infecting" it with subduction, and enlarging the Sea of Exploits at the expense of original Iapetan ocean floor (Fig. 2E). At the N. boundary, Avalonia collided with Baltica in dextral transpression during the Late Ordovician along the “Tornquist” line (e.g., Torsvik and Rehnstrom, 2003)

Peri-Laurentian fragments in the Uppermost Allochthon of the Scandinavian Caledonides show Ordovician thrusting and arc development (e.g., Roberts et al., 2007), comparable to the Canadian Appalachians, but contrast with the Greenland Caledonides, where a passive margin survived into the Silurian (Smith and Rasmussen, 2008). We infer that these fragments were transported northward following arc collision, to be emplaced onto Baltica in the Silurian.

CONCLUSIONS

Most models for the evolution of the Iapetus assume subduction initiation by foundering of passive margins on opposite sides of the ocean. In contrast, we suggest incursion of a single highly curved plate boundary system, analogous to the Caribbean, Scotia and Gibraltar arcs in the Atlantic. Behind the advancing arcs, a mosaic of back-arc basins and continental fragments was translated westward. The “infection” of the Iapetus with subduction may explain: early transition from opening to closing; simultaneous deformation on the Laurentian and Gondwanan margins; and the complex collage of terranes in the central Appalachian-Caledonide orogen, many of which were deformed well before Silurian closure. By analogy, the future of the Atlantic may involve subduction propagating from invading arcs, leading to eventual collision and orogenesis.

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Figure 1. Map of the Appalachian-Caledonide orogen modified from Hibbard et al. (2007) and van Staal et al. (1998)

Figure 2. Schematic model for the incursion of a Caribbean-style plate into the Iapetus, showing possible terrane locations and collisions at five time intervals. Colours as Fig. 1. Cambrian positions of main continents based on Murphy et al. (2004); later history based on Domeier and Torsvik (2014). Dotted lines conjectural. (a) Conclusion of rifting (Terreneuvian); (b) Cambrian (Epoch 3) incursion of subduction into the Iapetan realm; (c) Latest Cambrian to Early Ordovician Monian/Penobscottian and early Taconian collisions involving peri-Laurentian and peri-Gondwanan terranes; (d) Floian-Dapingian Taconian/Grampian collision; (e) Katian; dashed lines schematically represent future migration of subduction zones.

Figure 1
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Fig. 1

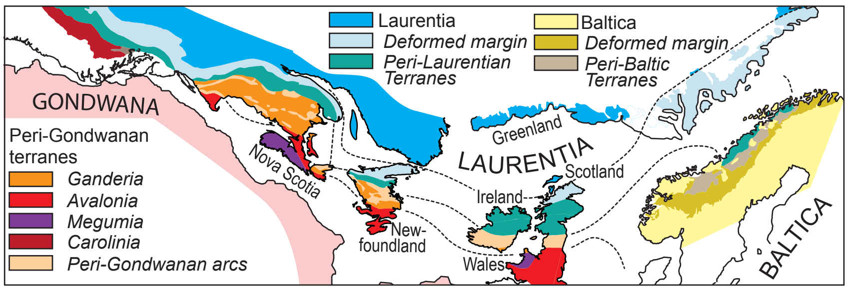

Figure 2
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Fig. 2