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Stranding continental crustal fragments during continent breakup: Mantle suture reactivation in the Nain Province of Eastern Canada

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ABSTRACT

Earth's continental crust has evolved through a series of supercontinent cycles, resulting in a patchwork of Archean cores surrounded by terranes, fragments, and slivers of younger crustal additions. However, the dispersal (and/or stranding) of continental fragments during breakup is not well understood. Inherited structures from previous tectonic activity may explain the generation of continental terranes by controlling first-order deformation during rifting. Here, we explored the influence of lithospheric deformation related to ancient orogenesis, focusing on the impact of the Torngat orogen in the genesis of the Nain Province continental fragment in Eastern Canada. We present three-dimensional continental extension models in the presence of an inherited lithospheric structure and show that a narrow continental terrane could be separated and stranded by deep lithospheric scarring. The results show that continental terranes formed by this method would be limited to a width of 100–150 km, imposed by tectonic conditions during continental suturing. The findings have broad implications, demonstrating an original theory on the fundamental geologic problem of terrane generation and continent breakup.

INTRODUCTION

A continental fragment (or terrane) is an entity that becomes isolated or stranded from its principal domain during plate-tectonic movements (Irwin, 1972; Vink et al., 1984). Although there exists a variety of isolated continents worldwide (Mortimer, 2004), the processes involved in the generation and structure of these fragments during continent breakup are unclear (Dewey and Burke, 1974). Previous work on terranes mainly focused on the provenance from (or accretion to) a continental body (e.g., Coney et al., 1980) or drift mechanics (Gün et al., 2021, 2022), rather than the mechanisms by which the isolation occurs.

Reactivation of inherited structures has been shown to control regional tectonics (e.g., Holdsworth et al., 2001; Schiffer et al., 2020), with orogenesis through continent-continent collisions producing long-lasting lithospheric deformation (Vauchez et al., 1997). Here, we propose that the Paleoproterozoic Torngat orogeny in Eastern Canada, involving oblique collision between the North Atlantic craton and Churchill Province, would have produced lithospheric-scale deformation (Mengel et al., 1991; Connelly and Ryan, 1996; Scott, 1998) that played an important role in the subsequent generation of a continental terrane (i.e., the Nain Province). We present numerical geodynamic experiments to test whether structures inherited from an orogenic event can yield deformation displayed by the observed regional tectonics—in this case, the generation of a continental fragment during extension.

NAIN PROVINCE

The Nain Province is a continental terrane of the North Atlantic craton (Bridgwater et al., 1973; Schiøtte et al., 1990) consisting of Archean gneisses extending for 600 km along the Labrador coast and parts of Quebec in Eastern Canada (Figs. 1A and 1B; Wilton, 1994). However, there are no mechanisms proposed for why the Nain Province would separate from the North Atlantic craton to produce a terrane. In this study, we outlined a process by which a mantle suture can generate a continental fragment that becomes stranded during rifting.

For the origin of the Nain Province, we hypothesized that the Paleoproterozoic collision of the North America craton and the Churchill Province, which produced the Torngat orogen (Scott, 1998), would have generated whole-lithosphere-depth deformation (Fig. 1C; Mengel et al., 1991; Funck et al., 2000). Accretional orogenesis on such a scale would have produced a mantle lithosphere (i.e., the subcrustal lithosphere) suture heterogeneity along a lithospheric contact (Keller and Hatcher, 1999), as discovered in other geologic areas (e.g., Calvert et al., 1995; Schiffer et al., 2014, 2019). Plate motion during Cretaceous rifting of the North Atlantic craton from Eastern Canada (e.g., Abdelmalak et al., 2019) could have reactivated a mantle suture, creating crustal thinning above a focal point at depth and at an offset from the crustal boundary. Previous work in the region has shown that structural inheritance played a substantial role in Mesozoic rifting, but it has not taken into consideration the generation of a continental fragment (Fig. 1) from rifting initiated by a mantle scar (Peace et al., 2018; Heron et al., 2019a; Gouiza and Naliboff, 2021). Our study represents the first study to demonstrate quantitatively the possible role of tectonic inheritance related to accretional orogenesis in the genesis of a continental terrane during subsequent breakup.

MODEL

We investigated the role of a three-dimensional (3-D) mantle lithosphere structure in a continental rifting tectonic setting, similar to that of the North Atlantic craton suture to the Churchill Province (Funck et al., 2000), using

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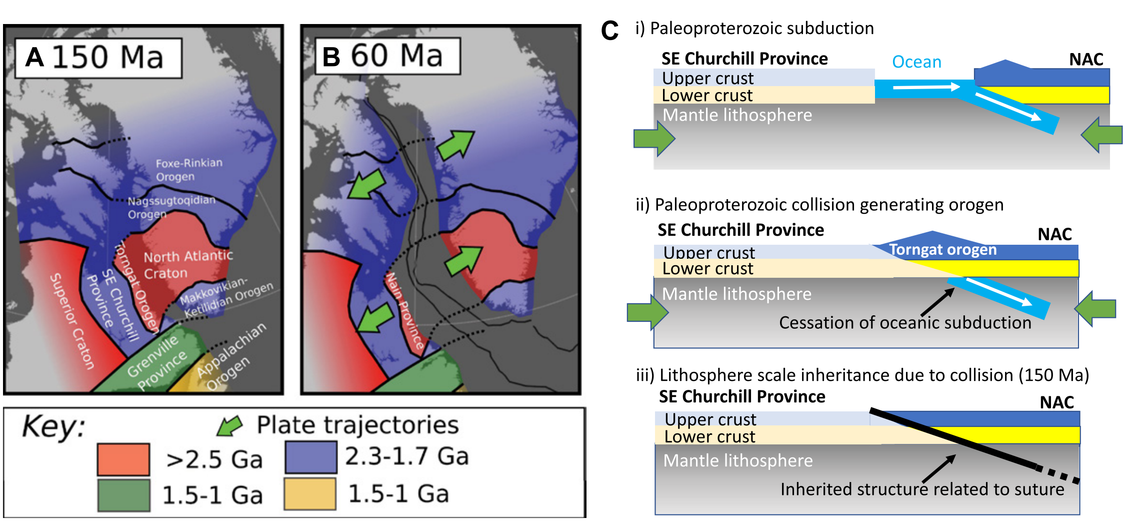

Figure 1. (A,B) Simplified overview of basements that comprise the northwest Atlantic borderlands in a pre-rifting and breakup configurations, modified from Kerr et al. (1997) and St-Onge et al. (2009). (C) Proposed tectonic history of the region (Bridgwater et al., 1973; Schiøtte et al., 1990; Mengel et al., 1991) with the interpretation that the continental collision of southeast Churchill Province and the North Atlantic craton (NAC), which produced the Torngat orogen (Scott, 1998), would also generate a mantle lithosphere suture.

numerical models. The models were implemented in a high-resolution 3-D Cartesian box (Fig. 2A), using the numerical code *ASPECT* (https://aspect.geodynamics.org; Heister et al., 2017). We used a nonlinear viscous flow (dislocation creep) and Drucker-Prager plasticity for the model rheology (e.g., Naliboff et al., 2020). The rheological profile was defined by "normal" lithosphere (e.g., Ranalli and Murphy, 1987) as shown in Table S1 and Figure S1 in the Supplemental Material[1].

The model setup is shown and described in Figure 2C, where the 3-D box underwent extension at 0.5 cm/yr on both sides of the lithosphere (with prescribed sublithospheric return flow below to ensure mass balance; Matthews et al., 2016). All models had ~1.5 km of resolution in the crust and upper mantle lithosphere (Fig. S2). We implemented a scar that was an extrapolation into the mantle lithosphere of the suture between the North Atlantic craton and Churchill Province (Fig. 1A; Fig. S5). There are several mechanisms by which a mantle lithosphere suture could remain weak over time (Heron et al., 2016), for example, through grain-size reduction of peridotite mylonites at ancient plate boundaries (Bercovici and Ricard, 2014). Here, the mantle lithosphere (ML) scar for the reference model EXP-1 was 10 km wide, dipping at an angle of 30° from the horizontal (Fig. 2C), and it was rheologically weak by having a reduced angle of internal friction compared to the surrounding material. The influence of changing the style of such weak scars was explored, and those results are presented in the Supplemental Material (Fig. S9) and in previous studies (e.g., Heron et al., 2016, 2019b). However, our study did not test whether any compositional differences between the crustal layers could produce continental fragments, which may be an avenue for ongoing exploration.

FRAGMENT GENERATION

Extension was applied to continental lithosphere in the presence of a mantle suture in EXP-1 (e.g., iii in Fig. 1C). Figure 3 shows the evolution of tectonic deformation at the surface (Figs. 3A–3E) and in a cross section across the middle of the model (Figs. 3F–3J). After 5 m.y. of extension, the model North Atlantic craton (NAC) is relatively undeformed at the surface (Fig. 3B). However, the cross section shows that the reactivation of the mantle lithosphere scar has created a basin in the upper crust and overall crustal thinning (Fig. 3G). This deformation is close to the western edge of the model NAC but still within the craton (not at the crustal boundary).

After 10 m.y. of extension, the NAC displays significant thinning at the surface (Fig. 3C) with the mantle lithosphere and asthenosphere rising to replace the thinned crust (Fig. 3H). Due to the thinning of the crust directly above the mantle lithosphere structure, the scar reactiva-

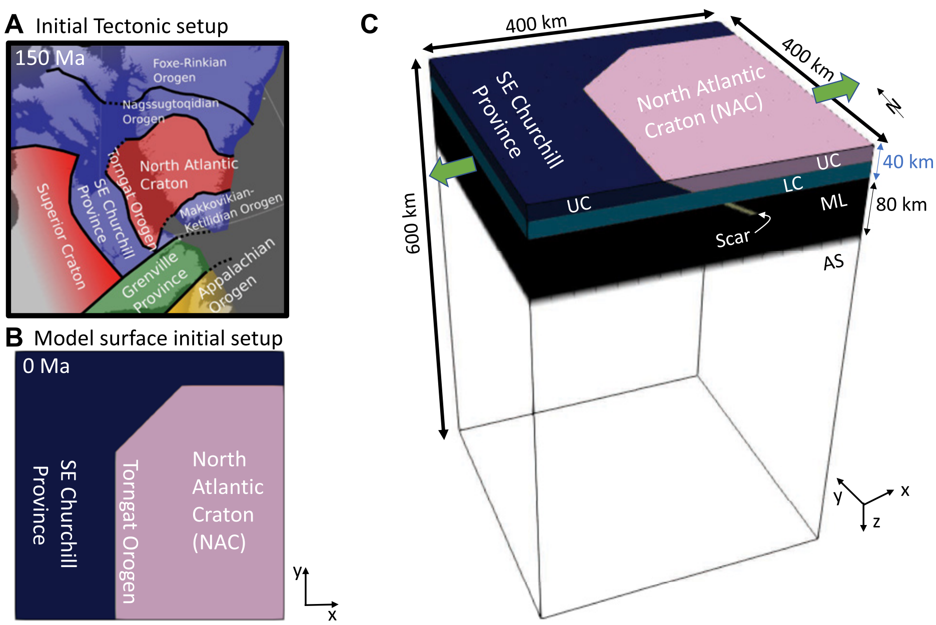

Figure 2. (A) Simplified overview of the basements that comprise the northwest Atlantic borderlands in a pre-rifting configuration, modified from Kerr et al. (1997) and St-Onge et al. (2009). (B) Map view of the initial model setup. (C) Initial setup of the numerical models presented here: a three-dimensional box featuring crust, mantle lithosphere, and a mantle scar with extension applied to the top 120 km (lithosphere) in a left-right direction, and with inflow applied in the mantle below. The mantle scar is a zone of weakness that follows the outline of the crustal contact between the modeled southeast Churchill Province and the North Atlantic craton, at an angle of 30° from horizontal for EXP-1 (45° for EXP-2). UC—upper crust; LC—lower crust; ML—mantle lithosphere; AS—asthenosphere.

[1]Supplemental Material. Methods and supplemental figures. Please visit https://doi.org/10.1130/GEOL.S.21935970 to access the supplemental material and contact editing@geosociety.org with any questions.

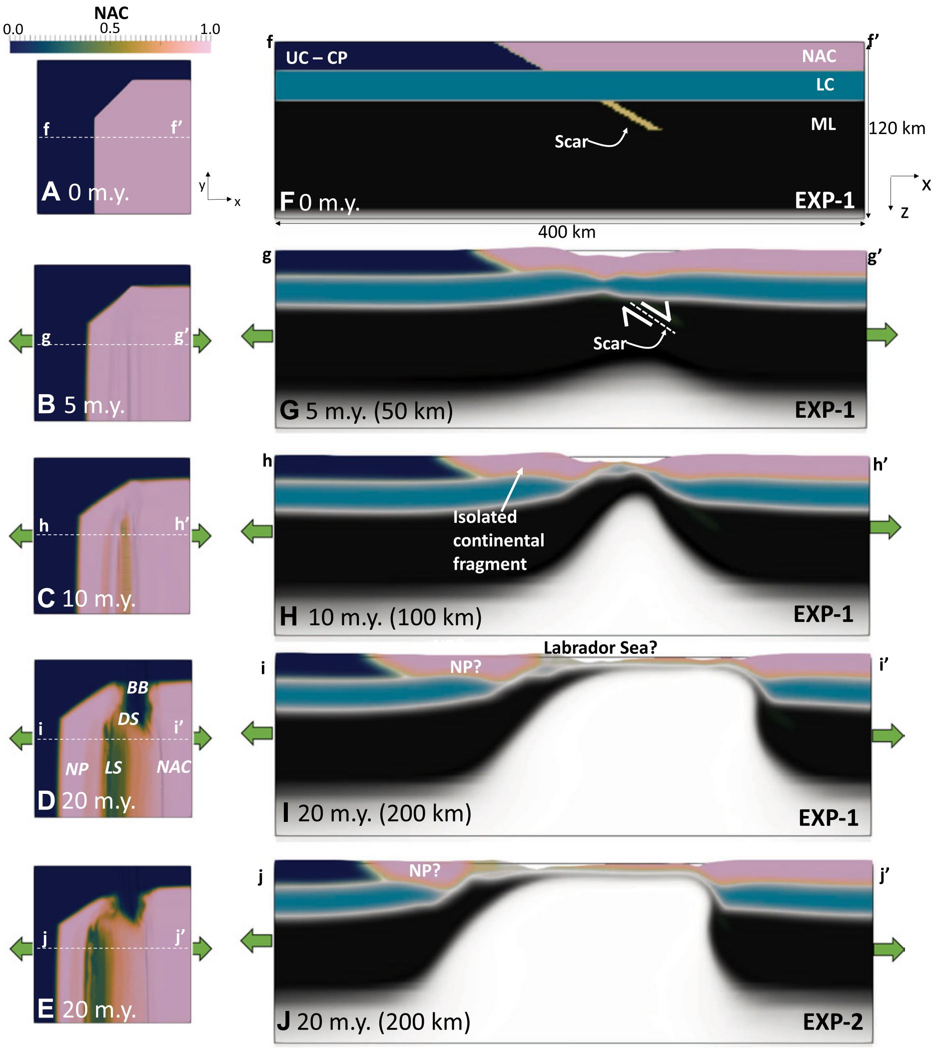

Figure 3. Evolution of rifting from reactivation of mantle lithosphere suture for models EXP-1 (30° angle from horizontal) and EXP-2 (45°), with total extension given in parentheses. (A–E) Map view of the North Atlantic craton (NAC) material field. (F–J) Lithosphere cross sections corresponding to the lines shown in A–E. UC—upper crust; LC—lower crust; ML—mantle lithosphere; AS—asthenosphere; CP—SE Churchill Province; LS—Labrador Sea; NP—Nain Province; DS—Davis Strait; BB—Baffin Bay. Weak mantle lithosphere structure reactivates to generate a basin in the crust above it (G). For a given angle of contact between two lithosphere provinces, crustal thinning occurs at a distance from the crustal boundary (H). This reactivation can generate an isolated terrane (I), where the width is dependent on the lithosphere scar angle (J). The color bar is a compositional field from 0 (no composition) to 1 (where there is material).

tion has produced an isolated continental fragment of the model NAC in the southern area of the model. However, in the northern area of the model, rifting is delayed due to the misalignment of the scar and extension direction. As the extension continues (20 m.y.), mantle material rises to create a proxy Labrador Sea with an isolated continental fragment having a maximum width of approximately ~100 km (Fig. 3H), in keeping with the Nain Province width (Wilton, 1994). The surface deformation shows rifting of the model NAC in both the north (e.g., Baffin Bay) and south (e.g., Labrador Sea) (Fig. 3D), alongside the preservation of the Davis Strait (e.g., Heron et al., 2019a).

The result shown in Figure 3 only features a singular lithospheric inherited structure, but further models showed the findings from EXP-1 to be robust (Figs. S6–S19). Namely, placing crustal scars on the craton contact between the North Atlantic craton and Churchill Province (Fig. S6) still displayed the fragment generation as shown in Figure 3.

The mechanism by which a continental fragment is generated is related to the position of the deep suture in relation to the surface contact between the two crustal domains (e.g., North Atlantic craton and Churchill Province). Fundamentally, the position of the mantle scar determines the breakup of the continent as the weakness in the strong mantle lithosphere propagates strain into the crustal layers above the structure. That is, owing to the nonlinear viscous and plastic-yielding rheology of the crust and mantle in the models, strain progressively localizes, and tectonic deformation in the crust develops directly above the mantle scar (Fig. 3; Figs. S6–S8; Heron et al., 2016). If the mantle scar is offset from the edge of the continent, which would occur during continent collision following the cessation of subduction, then the continent would break directly above the scar and create a fragment.

SUTURE ANALYSIS

In EXP-2, we applied a 45° angle from the horizontal that produced a continental fragment with a width of ~70 km, highlighting the relationship between an increased scar angle and decreased fragment width (Figs. 3E and 3J; Fig. S8).

Dip angles of mantle heterogeneities related to a suture commonly range between 10° and 30° (Cook et al., 2004). Given this shallow nature of mantle lithosphere scarring and the relationship between angle and fragment width outlined by our proposed mechanism, an approximate width for continental terranes could be between 100 and 150 km (Fig. S8). Indeed, both the Nain Province of Labrador and the Lewisian terrane of NW Scotland, another fragment of the North Atlantic craton that became stranded when the Atlantic Ocean opened, have a width of 100 km (with variability of 50 km; Kinny et al., 2005; St-Onge et al., 2009). The shallow dip of mantle lithosphere structures means that a terrane having a width <70 km would be unlikely to be generated through this mechanism, as this would require a steeply dipping structure (>45°), of which there are few examples (e.g., Cook et al., 2004).

CONCLUSIONS

Through 3-D numerical experiments that modeled the opening of the Labrador Sea, we present a new mechanism for terrane generation during continent breakup that originates from inherited structures related to deep plate-tectonic sutures. Our 3-D numerical simulations modeled the breakup of the North Atlantic craton, an Archean-age block, from which the Nain Province terrane rifted (Fig. 1). By implementing a mantle lithosphere scar created by the closing of an ocean between the North Atlantic craton and Churchill Province (Fig. 2), extensional plate-tectonic forces reactivated this inherited structure to focus thinning inboard from the crustal boundary (Fig. 3) and ultimately produced an isolated terrane. The angle of the lithospheric inheritance related to a suture is a key factor in controlling the resulting terrane width, with 100–150 km being a characteristic range for this mechanism. The results here are an important contribution to understanding the processes involved in the generation of terranes, with previous work mainly focusing on their provenance rather than the mechanisms by which they originated.

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