Crustal recycling by slab failure

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ABSTRACT

Models for crustal recycling are based upon estimates of the amount of material being returned to the mantle today; thus, a better understanding of those processes will help to constrain the models. We suggest—through the use of an Early Proterozoic example in the Wopmay orogen—that failure of the subducting slab during collision leads to large quantities of crustal material being recycled into the mantle, that this process has been active since the Early Proterozoic, and that it may explain the paucity of rift deposits in other orogens.

INTRODUCTION

The origin of continents and the differentiation of Earth are contentious issues among geoscientists. Some argue that a volume of continental crust comparable to that of today formed early in Earth's evolution and that it is constantly recycled through the mantle (Armstrong, 1968, 1981, 1991; Fyfe, 1978; Bowring and Housh, 1995), whereas others argue that continents have grown incrementally over time (Moorbath, 1977; Jacobsen and Wasserburg, 1981; Jacobsen, 1988; McCulloch and Bennett, 1994). Because isotopic arguments cannot uniquely constrain either model (Amstrong, 1991; Patchett and Chauvel, 1984), it falls upon geologists to document methods by which each end member can be tested.

Inasmuch as new crust is constantly being formed at plate margins today, the notion that a similar amount of continental crust is regularly recycled into the mantle is implicit in models that invoke early formation of crust. If the various mechanisms for crustal recycling and their rates are unknown, then it is impossible to perform the necessary mass-balance calculations to evaluate the importance of recycling; hence the model remains unverified. Several mechanisms are proposed for the recycling of continental crust, foremost of which is subduction of sediments in trenches (Armstrong, 1986; von Huene and Scholl, 1991; Kay, 1980). Other mechanisms involve convective removal of continental lithosphere during collision (England, 1993; Kay and Kay, 1988), subduction of altered oceanic crust (Albarede and Michard, 1986), delamination of lower crust related to Andean-type compressional thickening (Kay et al., 1994; Kay and Kay, 1993), and the foundering of restite (Arndt and Goldstein, 1989). In this paper we propose that failure of the subducting slab during collision may be another way in which substantial quantities of continental material are recycled into the mantle.

Slab failure involves the tearing of oceanic lithosphere from its continent during collision when the strength of the system is overcome by the competing forces generated by dense oceanic lithosphere and buoyant continental crust (Sacks and Secor, 1990; Davies and von Blanckenburg, 1995). Because continents are buoyant, they are difficult to subduct, and because old oceanic lithosphere is so dense that it cannot be stopped from sinking, the two separate and the dense oceanic lithosphere sinks into the mantle. Conceptually, it is a process that is likely to occur in all collisional orogens except those in which the subducting slab is young and hot. Failure of the subducting slab has recently gained popularity to explain a wide variety of features of collisional orogens. Slab failure may be responsible for rapid uplift (Chatelain et al., 1992), syncollisional magmatism (Davies and von Blanckenburg, 1995), tomographic gaps in the descending slab (Wortel and Spakman, 1992), and seismic discontinuities (Wortel and Spakman, 1992). Here we present evidence that during continent-arc collision in the Wopmay orogen, substantial amounts of continental material were likely torn from the subducting continent and transported into the mantle along with the detached oceanic lithosphere.

WOPMAY OROGEN

The Wopmay orogen (Fig. 1) is a 1.88 Ga orogenic belt located in the northwestern Canadian Shield (Hoffman, 1989). The orogen formed during the Calderian orogeny when the Hottah terrane, interpreted as an arc-bearing microcontinent, collided with the western margin of the Archean Slave craton. During the collision, 2.02–1.9 Ga rift and shelf-rise sedimentary rocks that formed a west-facing package atop the Slave craton, as well as overlying foredeep rocks, were tectonically shortened and transported eastward in thin-skinned fashion along a basal decollement in response to attempted westward subduction of the Slave craton beneath the Hottah terrane. The collision culminated in emplacement of an extensive allochthon of Hottah terrane over rocks of Slave craton and thick-skinned deformation of the collision zone. By 1.870 Ga, a new subduction zone of opposite polarity had developed to the west of the Hottah terrane and that subduction led to continental arc magmatism of the Great Bear magmatic zone during the period 1.87–1.84 Ga (Hildebrand et al., 1987). Shutdown of arc magmatism was followed by oblique folding of the arc rocks, intrusion of granitic plutons, and east-west compression resulting in an orogen-wide swarm of conjugate transcurrent faults.

MOREL SILLS

A 200-km-long, 10-km-wide, orogen-parallel swarm of gabbroic sills within the orogen (Fig. 1) provides evidence for extension orthogonal to the plate boundary during the collision. Referred to as the Morel sills, the intrusive rocks were originally interpreted as foredeep magmatism because they intrude orogenic flysch of the foredeep and rocks of the passive margin (Hoffman, 1987). They are concentrated at the shelf-slope break, which—when the 45% shortening on thrusts and folds in the foreland is palinspastically restored (Tirrul, 1983)—sits close to the abrupt western margin of Slave craton (Fig. 1) as defined by outcrop and isotopic studies of younger granitoid plutons (Bowring and Podosek, 1989; Housh et al., 1989; Hildebrand and Bowring, 1988). The sills have chilled marginal zones and generated narrow metamorphic aureoles in their wall rocks, yet are metamorphosed and transported by thrust faults (Hoffman, 1987). Because they intrude orogenic deposits but are also deformed, they must be syncollisional. No feeder dikes for the intrusions were found in the field despite the proclivity for mafic rocks to be resistant relative to surrounding foredeep sedimentary rocks; however, because the sills form a northward-trending swarm and are deformed by northward-striking folds and thrusts, the feeder dikes likely have the same strike as the sills and folds or they would probably have been spotted. If correct—and this conclusion is supported by the overall orogen parallel trend of the swarm—then the sills reflect east-west extension in the lower plate orthogonal to the plate boundary during their emplacement.

PAUCITY OF RIFT DEPOSITS

There is only one thin northward-striking band of rift deposits preserved (Fig. 1) within the orogen (Hoffman and Pelletier, 1982; Hildebrand et al., 1991; Bowring and Grotzinger, 1992). Because the outcrops are excellent and the region has been mapped in considerable detail, the lack of preserved rift deposits is real and demands an explanation. We hypothesize that the lack of such deposits is not because they never existed; rather, they and their attenuated continental basement were torn from the Slave craton during slab failure.

The western margin of the Slave craton appears abrupt, not only at the surface but also at depth. The primary evidence for the abrupt margin is the lack of any Pb or Nd isotopic signature for Archean crust in slightly younger rocks of the Great Bear magmatic zone (Bowring and Podosek, 1989; Housh et al., 1989). If there were Archean crust beneath the Great Bear magmatic zone, it should be obvious isotopically, because where it crops out just to the east, it is mostly ancient, in the age range 3–4 Ga (Bowring et al., 1989). A few plutons of the Great Bear magmatic zone are present east of the edge of the Slave craton and clearly show the effects of interaction with ancient crust (Bowring and Podosek, 1989).

Overall, the data indicate that the sharp western edge of the Slave craton marks the eastern limit of stretched upper crust during rifting. Four lines of evidence support this conclusion: (1) when shortening on thrusts and folds in the foreland is restored (Tirrul, 1983), the passive-margin shelf edge coincides with the western limit of the Slave craton; (2) despite nearly continuous cross-strike outcrops and complete mapping of the unconformity between crystalline basement and passive-margin shelf strata, there are no normal faults of Early Proterozoic age that cut the interface; (3) there is no evidence for major strike-slip displacement; and (4) on younger continental margins the shelf edge typically coincides with the transition from stretched to nonstretched upper crust (Klitgord et al., 1988; Bassi et al., 1993). Accordingly, we infer that the rift deposits and their underlying continental crust—rocks formerly west of the abrupt edge—are missing because they were torn from the Slave craton and subducted along with the oceanic slab.

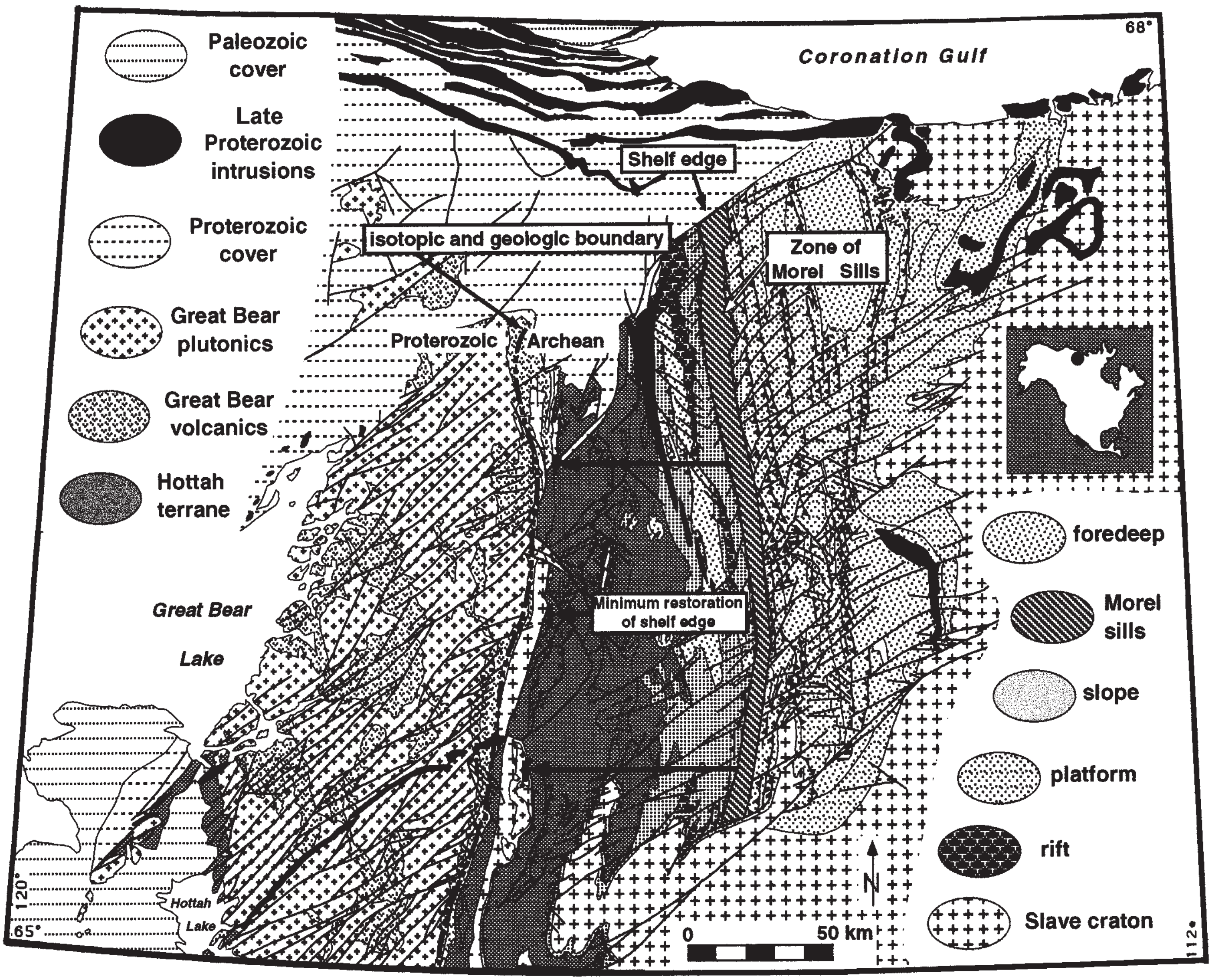

Figure 1. Geologic sketch map of northern half of Wopmay orogen showing present location of Rocknest shelf edge, western limit of Slave craton based on outcrop and isotopic studies, and minimum restoration of Rocknest shelf edge based on conservative bed-length restoration in thrust belt (after Tirrul, 1983). Morel sills, too small to show individually at this scale, intrude shelf edge, and their zone of intrusion is shown by heavy line pattern. Location shown in inset map. Map based on Hoffman (1989); Hildebrand and Bowring (1988); Hildebrand et al. (1991).

The simplest mechanism to generate extension and mafic magmatism above what should be a cold, amagmatic plate is slab delamination or break-off (Sacks and Secor, 1990; Davies and von Blanckenburg, 1995). This mechanism explains the lack of rift deposits, the abrupt continental edge of the Slave craton, and the syncollisional lower plate magmatism that produced the Morel sills (Fig. 2). Accordingly, we interpret these features to be the direct consequence of slab failure.

Although the limit of stretched crust is a mechanically favorable location for the lithosphere to fail, it is probably not the only control on where the lithosphere fails. In rift settings, normal faulting is confined to the brittle upper crust, whereas the lower crust is thinned by ductile flow due in part to the impingement of upwelling asthenosphere and lateral flow (e.g., Wernicke, 1989). Furthermore, new oceanic lithosphere probably grows beneath rifted margins as they move away from the spreading center, and this process should help bond the oceanic-continent interface. A possible control on the site of slab failure along a rifted margin of an Archean craton may be the transition between thick, depleted, Archean lithosphere beneath the foreland and the same lithosphere thinned earlier during rifting (Jordan, 1988). The sharp geological and geophysical discontinuities that coincide with the isotopic expression of the boundary between the two different-age lithospheres support this idea for the western edge of the Slave craton.

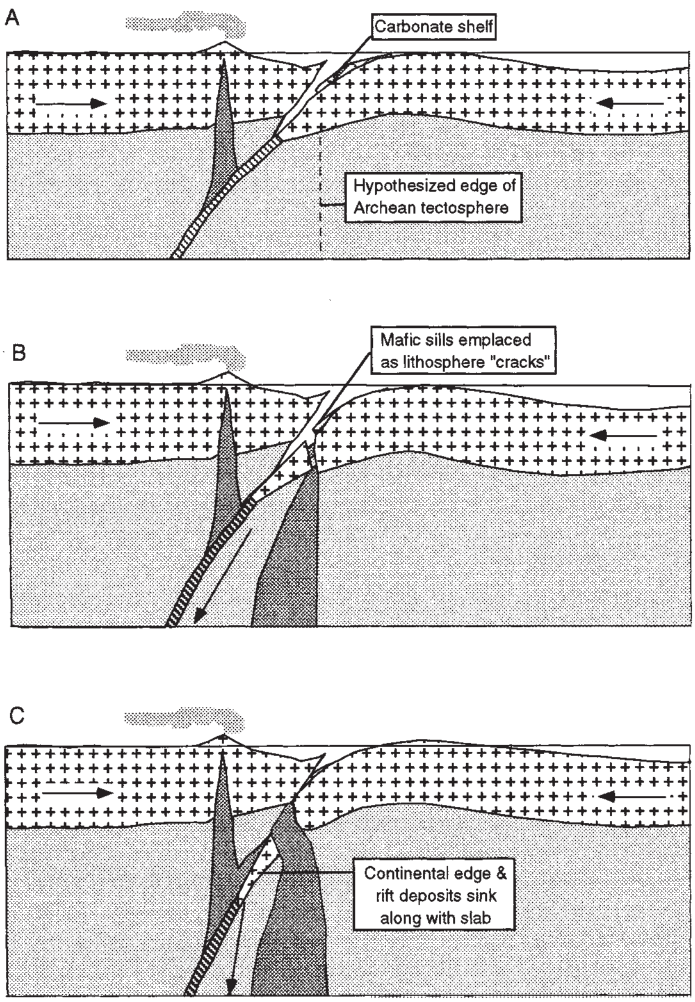

Figure 2. Model for recycling of continental crust by slab failure. We have purposely left off accretionary-prism rocks and other details for simplicity. A: Subduction of passive continental margin beneath arc brings into play competing forces generated by buoyant continental crust with thick tectosphere and cold, dense oceanic lithosphere near continental edge. B: As plate motion continues, descending slab begins to tear, which allows upwelling of mantle. This may produce syncollisional mafic magmatism in lower plate. In Wopmay orogen, magmatism was expressed as linear, margin-parallel swarm of mafic sills emplaced into shelf edge region during collision. C: Descending slab tears off at edge of subcontinental tectosphere and sinks into mantle. Large volumes of extended continental crust, rift deposits, and orogenic sediments are subducted by this process.

IMPLICATIONS

If modern rifted margins are any measure of the width of Early Proterozoic margins, then substantial quantities of continental material were subducted along with the slab. Consider that modern margins have a rifted zone ranging from 200 to 400 km across (Klitgord et al., 1988; Bassi et al., 1993; Keen and Dehler, 1997) and an average thickness of 15 km if 100% extension is assumed. These dimensions mean that for every kilometer of subduction margin, there are roughly 3×10^3 to 6×10^3 km^3 of material recycled into the mantle if the entire margin is consumed. Given that the total volume of continental crust today is about 7×10^9 km^3 and collisional belts are 1×10^3 to 2×10^4 km long, 1%–2% of the total volume of the continents can be subducted in one collisional event involving a passive margin. When integrated over 4.5 b.y., the volume of subducted material is large, and this process is potentially an important mechanism for crustal recycling.

We conclude by pointing out that the major orogens of North America are characterized by relatively small amounts of volcanic rocks preserved from prior rifting (Rankin et al., 1989; Gabrielse and Campbell, 1991; Poole et al., 1992) and in some cases the missing deposits may have undergone the same fate as rift deposits in the Wopmay orogen. Furthermore, we believe that this process, active in the Early Proterozoic, is still taking place today (Chatelain et al., 1992; Wortel and Spakman, 1992), which suggests that crustal recycling by slab failure has been a major process on Earth for at least 2 b.y. and perhaps for all of Earth history.

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