Ridge subduction: kinematics and implications for the nature of mantle upwelling:[1] Discussion

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Introduction

The authors, E. Farrar and J.M. Dixon, in a recent paper on "ridge subduction," discuss the magmatic and tectonic effects of overridden sea-floor spreading centres. Their paper provides a useful compilation of information on several ridge–trench encounters, and elucidates a certain type of plate interaction called "eduction." However, much of their analysis is flawed because they (1) do not consider the geometry of subducted slabs and intervening slab windows; (2) misrepresent the importance of slab windows to magmatism and tectonism in the overriding plate, and to mantle currents; and (3) incorrectly link the concept of slab window formation to a model of "passive" mantle upflow. Consequently, their paper overlooks the controlling influence that slab windows have on asthenosphere–lithosphere interactions when diverging plates are subducted. Since the authors present their material in the style of a comprehensive review, their omissions and misrepresentations warrant critical response.

Numerous authors have established that ridge–trench encounters tend to affect the overriding plate in three main ways: (1) tectonic erosion of forearc, and related uplift of forearc and arc; (2) change in magmatic regime from arc-type volcanism to rift- or plume-type volcanism, extending from forearc to retroarc; and (3) broad, thermally supported uplift, high heat flow, and extension (Stacey 1974; Fox et al. 1985; Merritts and Vincent 1989; Thorkelson and Taylor 1989; Hole 1990; Hole et al. 1991; Babcock et al. 1992; Hole and Larter 1993; references cited in the authors' paper). The authors concur, and appeal to "active" asthenospheric upwelling (e.g., Hess 1962; Gough 1984; Wilson 1988) beneath the overriding plate as a principal cause. Although the authors' depiction of active mantle dynamics is plausible, the geological context of their arguments is unacceptable. Specifically, they appeal to "ridge subduction" and mantle upwelling without providing a framework of subducted slab geometry. Without full appreciation of slab geometry and the constraints imposed by slab windows, their arguments are limited to a vague precept of mantle convection.

Development of slab windows

Before a sea-floor spreading ridge enters a trench, it is an axial zone of plate growth. Basaltic magma produced by decompression melting of upwelling asthenosphere cools onto the trailing edges of the diverging plates. At a ridge–trench encounter, one or both of the plates descends into the asthenosphere. As the subducted part of an oceanic plate diverges from the other oceanic plate, basaltic magma may continue to be produced between them. However, the trailing edge of the subducting oceanic lithosphere becomes progressively immersed in hot asthenosphere and ceases to act as a cold barrier to magma uprise. Consequently, as a trailing plate edge subducts it stops growing. Without plate growth, plate divergence results in an ever-widening gap (Uyeda and Miyashiro 1974) called a slab window (Dickinson and Snyder 1979).

Figure 1 is a simplified block diagram of a slab window produced by subduction of two oceanic plates that are diverging along a mid-ocean ridge segmented by alternately right and left stepping transform faults (Thorkelson 1990). The interlocking pattern between plates B and C on the sea floor is reflected in the zigzag edges of the slabs bordering the slab window. Active volcanism on the overriding plate is manifest by calc-alkaline volcanoes (grey) in a volcanic arc, and alkalic to tholeiitic volcanoes (black) in the general region above the slab window (Dickinson and Snyder 1979; Hole et al. 1991).

At a convergence rate of 10 cm/a (100 km/Ma), the configuration in Fig. 1 could have developed after about 10 Ma of subduction. This style of slab–mantle interaction, in which slab continuity is maintained and the mesosphere is impervious to descending slabs, is permissive according to studies of seismic tomography and mantle rheology (Thompson et al. 1984; Zhou 1990; van der Hilst et al. 1991; Irifune and Ringwood 1993). Although this model is simplified, it illustrates how diverging plates will become separated by an asthenosphere-filled gap as they subduct. It also shows that the slab window may permit asthenospheric mantle to flow from beneath the descending oceanic plates to beneath the overriding plate. Even if the slabs do not remain intact all the way to the base of the asthenosphere, they are likely to act as fundamental barriers to flow, leaving the slab window as the principal pathway for transfer of asthenospheric mantle.

Importance of slab windows

Determining the correct geometry of the slab window(s) in an area of ridge–trench intersection is critical to the understanding of magmatism and tectonics in the overriding plate. Dickinson and Snyder (1979), Forsythe and Nelson (1985), Thorkelson and Taylor (1989), Hole (1990), Thorkelson (1990), and Babcock et al. (1992) developed models of slab window formation to help understand on-land geology. In contrast, the authors do not consider window geometry in their review of ridge–trench interactions. In their Figs. 2, 7, and 9, they show diagrams of sea-floor spreading ridges extending beneath the

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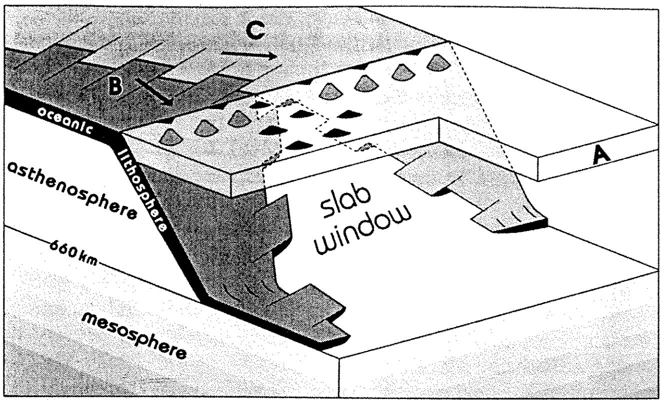

FIG. 1. Schematic diagram of a slab window between two subducting oceanic plates (modified from Thorkelson 1990). The sea-floor spreading ridge, segmented by alternately right and left stepping transform faults, is converging at a 75° angle with the trench. Both slabs are descending at 45° through the asthenosphere. Oceanic plate B is converging with the overriding plate at about 75°, while oceanic plate C is converging at about 50° (arrows). Plate C has just reached the mesosphere (highly viscous mantle beneath the 660 km seismic discontinuity; Irifune and Ringwood 1993), whereas plate B, with its higher angle of convergence and rate of subduction, had reached the base of the asthenosphere much earlier, and has moved horizontally along the top of the mesosphere. On overriding plate A, calc-alkaline volcanoes (grey) form a volcanic arc, while tholeiitic to alkalic volcanoes (black) are active above the general region of the slab window. Diagram is drawn in orthographic space, and neglects the effects of spherical shell strain (Yamaoka and Fukao 1986), thermal erosion of the window margins (McKenzie 1969; Dickinson and Snyder 1979), and variable slab dip angles (Cross and Pilger 1982).

overriding plate, implying that the oceanic plates continued to grow along their trailing edges after subduction. Referring to a linear extension of a sea-floor spreading ridge, the caption for their Fig. 7 reads, "The ridge is shown by double solid line at sea and by double broken line where subducted." In each of these figures, a slab window, not a linear continuation of a spreading ridge, should have been illustrated.

In the authors' Fig. 1, a set of four diagrams, in which ridge and trench are parallel, is used to illustrate four cases of plate kinematics. The authors argue that divergence between the second oceanic plate and the overriding plate is the most likely consequence of ridge subduction, but neglect to indicate that the likelihood of this phenomenon decreases with increasing angle between ridge and trench, becoming nil when ridge and trench are perpendicular. Clearly, this regime of "eduction" is a special case requiring near-parallelism between ridge and trench.

In their discussion of magmatism in the overriding plate, the authors do not consider the basic lithosphere – asthenosphere architecture imposed by the downgoing slabs and intervening window. In their analysis of late Cenozoic plateau volcanism behind the arc in the southern Andes, they ignore the controlling influence of the slab window, which formed from the overridden Nazca Rise, as illustrated by Forsythe et al. (1986) and Kaeding et al. (1990). In their discussion of alkalic volcanism and "ridge subduction" beneath the Antarctic Peninsula during the Cenozoic, the authors disregard the comprehensive petrologic and tectonic information provided by Hole (1988, and subsequent papers), who studied the relationship between ridge collision, slab window formation, and volcanic evolution. In a context of slab geometry, Hole (1990) and Hole and Larter (1993) considered models of mantle convection related to sea-floor spreading, and alkalic melts derived from subducted transform faults. The authors also relate overriding of the Pacific – Juan de Fuca ridge to selected late Cenozoic volcanic belts in British Columbia. They ascribe eastward-progressing volcanism in the east-trending Anahim Volcanic Belt to subduction of a north-trending ridge. Their analysis is questionable for two reasons: First, they fail to explain why a narrow east-trending volcanic belt should develop from subduction of a north-trending ridge. Second, their analysis considers only a few of the abundant Miocene to Recent nonarc volcanic centres in British Columbia, Yukon, and southeastern Alaska, all of which were erupted above the northern Pacific – Farallon slab window of Stacey (1974) and Thorkelson and Taylor (1989). The timing and composition of all of these volcanic fields (Bevier et al. 1979; Armstrong et al. 1985; Souther and Yorath 1991) are broadly related to trailing-edge subduction of the Farallon Plate, opening of a slab window, and replacement of hydrated mantle with less metasomatized asthenosphere.

The authors suggest that subduction of a fossil spreading ridge, which has been inactive for 15 – 20 Ma, can lead to mantle upwelling beneath the overriding plate. This suggestion is dubious because a downgoing slab containing an old, inactive ridge will subduct as a single plate. The fossil spreading ridge, inactive for at least 15 Ma, would have cooled to form a "thin" 40 km thick zone within the 50 – 100 km thick oceanic plate (cf. Crough 1975). Without *concurrent* divergence and subduction, a slab window will not form. Without a slab window, mantle beneath the oceanic plate remains trapped, and cannot upwell beneath the overriding plate. After 15 Ma of subduction, hundreds of kilometres of slab would have been subducted, possibly reaching the asthenosphere – mesosphere boundary (Fig. 1). Thus, the downgoing slab will have acted as a barrier, effectively blocking the rise of suboceanic mantle. The convection of mantle, which the authors postulate lingered for over 15 Ma after cessation of sea-floor spreading, would not have affected the overriding plate.

Style of mantle upflow

The authors equate the concept of slab window formation to a model of "passive" mantle flow. This misunderstanding of slab window tectonics apparently stems from the phrase "broad and diffuse upwelling" used by Dickinson and Snyder (1979) in their depiction of mantle dynamics during formation of the late Cenozoic slab window beneath the southwestern United States. Significantly, Dickinson and Snyder (1979, p. 623) entertained the possibility of "mantle diapirism . . . [affecting] a larger area at the surface than is represented by the slab window at depth," implying both upward and lateral asthenospheric flow in an active mantle environment. Thorkelson and Taylor (1989) described how active mantle convection could be emulated by passive asthenospheric uprise through the slab window and lateral flow beneath the overriding plate, in response to steepening of subduction angles. Other authors have discussed the effects of slab window formation without committing to either model of mantle flow (e.g., DeLong et al. 1978; Forsythe et al. 1986; Hole et al. 1991; Babcock et al. 1992; Hole and Larter 1993).

The issue of whether Dickinson and Snyder (1979) or the other authors favoured active or passive mantle dynamics is secondary to the recognition of window development and migration. If mantle upflow of any sort follows ridge subduction, it must occur within the spatial constraints imposed by slab geometry. The preference of the authors to invoke active mantle uprise does not reduce the importance of subducted slab geometry. On the contrary, if a model of active mantle flow is to be sensibly articulated it must be integrated with knowledge of window shape, size, location, and migration.

In the authors' Fig. 8, a narrow zone of mantle upwelling, labelled "overridden East Pacific Rise," is shown beneath the Rio Grande Rift of the southwestern United States. They use this diagram to illustrate their contention of active mantle convection. However, the position of the postulated axial plume head is inconsistent with the principle of symmetrical sea-floor spreading and the tenet that mantle convection is focussed beneath the ridge. The conflict exists because the Rio Grande Rift is located along the projected trailing edge of the descending Juan de Fuca Plate (Dickinson and Snyder 1979), not the hypothetical extension of a "subducted ridge." If a narrow axis of upwelling beneath North America exists as a continuation of the East Pacific Rise, then the axial plume would be located halfway between the trailing edge of the subducting Farallon Plate and the formerly adjacent part of the Pacific Plate, that is, near the centre of the slab window, which extends from the west coast of California to the Rio Grande Rift (Dickinson and Snyder 1979). Mantle currents may have been accentuated along the trailing Farallon slab edge as mantle rose through the slab window, but this is an "edge effect" whereby mantle is physically and chemically disrupted by migration of a window margin (Bevier et al. 1979; Dickinson and Snyder 1979; Armstrong et al. 1985; Thorkelson and Taylor 1989), a process distinct from the more deeply sourced axial plume of convection that the authors postulate. Significantly, the authors provide no evidence to indicate that mantle uprise has not occurred as broad diffuse upwelling, as envisaged by Dickinson and Snyder (1979), a style of upflow consistent with either active or passive upflow.

Conclusion

The authors suggest that a "slab window model" is unable to account for the widespread volcanism and extension that they attribute to mantle upwelling following "ridge subduction." Their position misconstrues the efficacy of slab window tectonics, because models of slab window development are principally geometrical in nature. As noted by Atwater (1970), Uyeda and Miyashiro (1974), and subsequent authors, "ridge subduction" exists only at the trench; beyond that, the ridge is transformed into an ever-widening window. For most of the cases cited by the authors, the term "slab window formation" should be substituted for "ridge subduction." Developing a slab window model is prerequisite to any meaningful analysis of mantle flow related to ridge–trench interaction.

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