Cordilleran slab windows

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ABSTRACT

The geometry and geologic implications of subducted spreading ridges are topics that have bedeviled earth scientists ever since the recognition of plate tectonics. As a consequence of subduction of the Kula-Farallon and East Pacific rises, slab windows formed and migrated beneath the North American Cordillera. The probable shape and extent of these windows, which represent the asthenosphere-filled gaps between two separating, subducting oceanic plates, are depicted from the Late Cretaceous to the present. Possible effects of the existence and migration of slab windows on the Cordillera at various times include cessation of arc volcanism and replacement by rift or plate-edge volcanism; lithospheric uplift, attenuation, and extension; and increased intensity of compressional tectonism. Eocene extensional tectonism and alkaline magmatism in southern British Columbia and the northwestern United States were facilitated by slab-window development.

INTRODUCTION

Within the realm of plate tectonics, the subduction of oceanic spreading ridges is a phenomenon that has created much debate among earth scientists for more than two decades. For example, Palmer (1968) speculated that the East Pacific Rise had been overridden by North America in the Mesozoic, which resulted in the Nevadan and Laramide orogenies. However, McKenzie and Morgan (1969) showed that intersection between the East Pacific Rise and the continental margin actually occurred in middle to late Cenozoic time. In addition, Atwater (1970) argued that upflow of mantle at the East Pacific Rise would have ceased at the time of ridge intersection with the North American trench. Christiansen and Lipman (1972) concurred with Atwater (1970); they preferred the explanation that lithospheric tectonics rather than mantle currents were the cause of elevated asthenosphere, tholeiitic magmatism, and crustal extension in the Great Basin. Other workers, such as Best and Brimhall (1974), Crough and Thompson (1977), Gough (1984, 1986), and Wilson (1988), disagreed, believing instead that mantle upwelling in the region of the subducted ridge was responsible for the attenuated lithosphere of the southwestern United States.

The mystique of ridge subduction probably stems from the incongruity of coincident divergent and convergent plate boundaries. It has persisted largely because of the controversy surrounding the nature of mantle convection and the driving forces of plate tectonics (cf. Chapple and Tullis, 1977; Wilson, 1988). We hope that our discussion of the subduction of ridges and genesis of slab windows beneath North America will stimulate interest in these phenomena and help provide an improved framework for future investigations of lithosphere-asthenosphere interaction.

SLAB WINDOWS

The most insightful report on ridge subduction was made by Dickinson and Snyder (1979) who detailed the evolution of slab geometry beneath the southwestern United States since the mid-Miocene. Their work, augmented by that of Jachens and Griscom (1983), showed that after ridge-trench intersection, the Farallon plate continued to plunge beneath the continent, leaving the Pacific plate at the continental margin. An ever-widening gap—a slab window—thereby developed between the two separating oceanic plates. Synchronously, upflowing asthenospheric mantle filled the window. Earlier authors, such as Uyeda and Miyashiro (1974) and Marshak and Karig (1977), mentioned but did not develop the concept of slab-window generation.

Dickinson and Snyder (1979) used their model to make important suggestions concerning magmatism and tectonics, but perhaps their greatest contribution was simply one of geometry. Prior to their work, cross sections of subducted ridges typically showed a pair of underthrust slabs that met at a rise (e.g., Uyeda and Miyashiro, 1974). Dickinson and Snyder (1979) showed that upon subduction, a ridge would pull apart and progressively widen and form a window. Magma, if it continued to form, would not congeal on the plates' trailing edges because of elevated temperatures in the mantle. More reasonably, the thin, hot, trailing edges of subducted oceanic lithosphere will be thermally eroded, widening the slab window further. As noted by Atwater (1970), once a spreading ridge encounters a trench it "ceases to exist" by losing its linear configuration; the term "ridge subduction" is therefore misleading, but survives (e.g., Armstrong et al., 1985) because of historical usage.

The shape and dimensions of a slab window are primarily functions of relative plate motions, angle of subduction, and presubduction ridge/transform configuration. Oceanic plates whose angle of divergence is large with reference to the overriding lithosphere will tend to produce a wide window. A low angle of subduction will result in a slab window that extends for great distances behind the trench. A highly segmented ridge will produce a window with a zig-zag pattern. A segmented ridge that approaches the trench at a small angle of convergence may produce more than one slab window—one at each locus of intersection.

As illustrated by Engebretson et al. (1985), the Farallon plate may have been the only plate subducting beneath North America from Middle Jurassic to middle Cretaceous time. If this assumption is correct, then the western margin of North America was free from ridge-trench encounters from the Middle Jurassic until about 85 Ma when the Kula plate was born (Woods and Davies, 1982). Slab windows produced by subduction of the Kula-Farallon Rise and later the northern part of the Farallon-Pacific (East Pacific) Rise are the focus of this paper.

KULA-FARALLON-PACIFIC SLAB WINDOWS

Late Cretaceous rifting of the Pacific and Farallon plates to form the Kula plate (Woods and Davies, 1982) has been accepted and used in later reconstructions (Engebretson et al., 1985; Lonsdale, 1988). However, there is little understanding of either the shape of the Kula-Farallon ridge or the position of the Kula–Farallon–North America triple junction. Engebretson et al. (1985) provided a range of possible configurations. In their northernmost option, the Kula-Farallon ridge initially intersected the North American trench adjacent to northern Washington; in the southern option, the intersection was at the latitude of central Mexico. We speculate that the triple junction originated somewhat north of their southern option, at the latitude of northern Mexico (Fig. 1a). This position permits northward transport of British Columbian terranes from that latitude (Irving et al., 1985) on the Kula plate and requires a smaller total length of transform faults between the Kula and Farallon plates than that of more southerly locations. We are not aware of magmatic or structural anomalies in the Late Cretaceous geologic record that could locate more accurately the positions of the ridge-trench intersection and the corresponding slab window.

Figure 1 shows a series of diagrams, based on plate reconstructions by Riddihough (1982), Engebretson et al. (1985), Lonsdale (1988), and

Stock and Molnar (1988), depicting the possible size and position of slab windows beneath the North American Cordillera, from 85 Ma to the present. Assuming a subduction angle of 5°, we have shaded the regions where asthenospheric mantle would have directly underlain 100-km-thick North American lithosphere. Such conditions would have existed either where the upper surface of a downgoing slab reached a depth of 100 km or where descending oceanic lithosphere was absent, at a slab window. With possible exception during the Laramide magmatic gap of the Late Cretaceous and Paleocene (Dickinson and Snyder, 1978), subduction angles were probably steeper than 5°; the Gorda and Juan de Fuca remnants of the Farallon plate are currently descending at about 12° (Jachens and Griscom, 1983; Clowes et al., 1987). Consequently, Figure 1 probably minimizes the actual westward extent of asthenosphere and exaggerates the eastward extent of shallow oceanic lithosphere. The assumption of a 100 km thickness for the continental lithosphere was made for simplicity; actual thicknesses certainly varied, both laterally and temporally. (The present western coastline of North America is shown in all diagrams.)

Figure 1a shows the 85 Ma genesis of the Kula plate; the Kula-Farallon Rise intersects the trench at the latitude of Baja California and continues beneath the continent. Beneath North America, divergence of the two oceanic plates would have, for perhaps a million years, resulted in a discrete linear rift zone (possibly complicated by transform offsets). If magma were produced along this subcontinental part of the rift, it is not likely to have accreted to the edges of the separating plates; a slab window would have gradually formed. During the first few million years of plate separation, the shape of the window would have been governed by the configuration of the initial, subcontinental rift. Gradually, as subduction continued, the window shape would have become controlled by the configuration of the subducting ridge and the angle of divergence between the Kula and Farallon plates with reference to a "fixed" North America (Fig. 1b).

Successive stages in the evolution of this slab window are shown at 70 and 60 Ma in Figure 1, b and c. As determined by plate vectors and our suggested ridge configuration, the Kula–Farallon–North America triple junction, and consequently the slab window, migrated northward. Thickness of the oceanic plate beneath the continent prior to rifting would have been close to 100 km, on the basis of the age of the Farallon plate and the thermal model of Crough (1975). As time passed, sea-floor spreading beneath the Pacific Ocean would have resulted in ever-widening bands of young oceanic lithosphere parallel to the rise. By 60 Ma, the slab window would have been bordered by hundreds of kilometres of thin, buoyant slab.

Starting at about 59 Ma, the Kula plate began to move in a more northerly direction (Atwater, 1970; Lonsdale, 1988), resulting in reorgani-

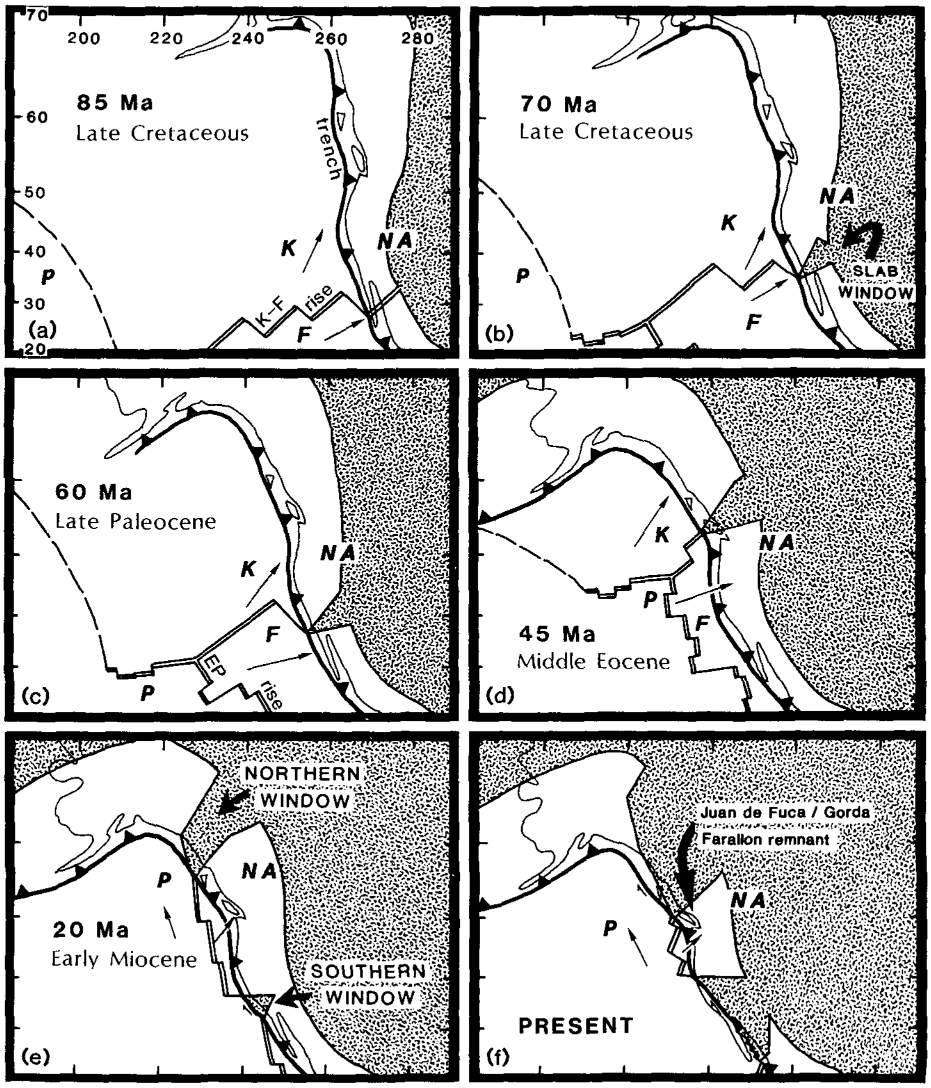

Figure 1. Slab windows beneath North American Cordillera from Late Cretaceous to present, based on plate reconstructions by Riddihough (1982), Engebretson et al. (1985), Lonsdale (1988), and Stock and Molnar (1988). Stippled pattern identifies areas where asthenospheric mantle would have directly underlain North American plate, based on 100 km maximum thickness for continental lithosphere and subduction angle of 5°. Plate motion vectors relative to "fixed" North America, shown for periods of 10 m.y. (Engebretson et al., 1985; Lonsdale, 1988; Stock and Molnar, 1988), were used to construct window shapes. Latitude and longitude, as labeled in a, are same in all diagrams. Southern Pacific–Farallon slab window, shown in e and f, was previously illustrated by Dickinson and Snyder (1979). Plates: F = Farallon; K = Kula; NA = North American; P = Pacific; EP = East Pacific.

zation of the Kula-Farallon Rise and a northward jump in the Kula–Farallon–Pacific triple junction (Lonsdale, 1988). These changes, complete by about 54 Ma, are likely to have caused a northward jump in the Kula–Farallon–North America triple junction and abandonment of the previous slab window. Figure 1d shows a possible configuration of the new ridge and the position of the new slab window at 45 Ma. By this time, the plate edges bounding the old slab window would have descended eastward into the asthenosphere. As implied by ridge-trench intersections shown for 52 and 56 Ma in Engebretson et al. (1985) and 54.5 Ma in Lonsdale (1988), the new window might have originated beneath southern British Columbia or the northwestern United States.

The foregoing hypothesis of Eocene slab windows is inconsistent with recent plate reconstructions by Stock and Molnar (1988), who suggested that Kula-Farallon spreading stopped at about 55 Ma. Their model, however, apparently did not incorporate the conclusions of Lonsdale (1988), which indicate that Kula-Pacific spreading continued until about 43 Ma. Furthermore, during early Eocene plate reorganizations, Kula motion vectors rotated counterclockwise (Lonsdale, 1988), whereas Farallon vectors rotated clockwise (Stock and Molnar, 1988). This information implies that Kula-Farallon spreading not only continued after 55 Ma, but became more divergent with respect to North America, resulting in a wider slab window.

At about 43 Ma, changes in plate motions facilitated capture of the Kula plate by the Pacific plate (Engebretson et al., 1985; Lonsdale, 1988), which resulted in northward extension of the East Pacific Rise. The slab window, once again, could have been abandoned. However, because the new Farallon–Pacific–North America triple junction may have been located near the earlier ridge-trench intersection, we suggest that continuity of the slab window was maintained.

Figure 1e shows a probable position of the triple junction (Riddihough, 1982) and the shape of the slab window at 20 Ma. Highly divergent motion vectors for the Farallon and Pacific plates caused the window to widen, and subducted slab was apparently absent below most of northern British Columbia. Also shown is the newly formed, more southerly Farallon-Pacific slab window of Dickinson and Snyder (1979).

The predicted shape and position of the present-day slab windows are given in Figure 1f. Both windows have grown in size, the northern one having expanded both northward, under much of the Yukon, and southward, beneath central British Columbia. Because motion vectors of the Pacific plate are nearly parallel to the North American coastline, the slab windows will continue to expand as Farallon remnants disappear beneath the continent. In 20 m.y. the windows will have merged and virtually all of the intervening Farallon remnant will have descended into the asthenosphere.

IMPLICATIONS FOR THE CORDILLERA

The Late Cretaceous to Paleocene Laramide orogeny and magmatic null (Dickinson and Snyder, 1978) were followed by voluminous Eocene magmatism extending from Wyoming to Oregon and northward to the Yukon (Armstrong, 1978, 1988; Ewing, 1980). Igneous activity was calc-alkaline, except for certain centers in southern British Columbia and central Montana where it was moderately to strongly alkaline (Ewing, 1980, 1981). In southern British Columbia, lavas of the Marron Formation (Church, 1973; A. Charland, 1989, personal commun.), Penticton Group (Church, 1988), and Kamloops Group (Thorkelson, 1989), and a suite of plutons known as Coryell syenite (Church, 1973) bear a predominantly rift geochemical signature. Genesis of this alkaline province was broadly coeval with large-scale crustal extension and formation of core complexes in the Pacific Northwest, especially in northern Washington and Idaho and southern British Columbia (Ewing, 1980; Coney and Harms, 1984; Church, 1985; Tempelman-Kluit and Parkinson, 1986; Parrish et al., 1988; O'Neill and Pavlis, 1988).

The change from Paleocene magmatic quiescence to widespread Eocene arc magmatism was probably caused by steepening of subduction angles (Coney and Reynolds, 1977; Dickinson and Snyder, 1978). Such downward tilting of the slabs would have been balanced volumetrically by westward and upward transfer of asthenospheric mantle. As previously noted, a slab window is likely to have been positioned below Washington or southern British Columbia in Eocene time. That gap would have provided a direct pathway for the upward flux of mantle from beneath to above the slabs. We suggest that small degrees of decompressive partial melting of mantle rising adiabatically (Presnall et al., 1979; Basaltic Volcanism Study Project, 1981, chapters 1.2.4 and 3.3) through the window produced the alkaline component of Eocene magmatism in southern British Columbia. Furthermore, upflow of magma and hot mantle may have thinned the overlying continental lithospheric mantle, increasing crustal elevation and contributing to tectonic denudation.

Stacey (1973, 1974) and Riddihough (1977) showed that subducted parts of the Juan de Fuca plate did not extend beneath northern British Columbia in Neogene and Quaternary time. Souther (1977) concurred, indicating that arc volcanism was restricted to the Pemberton belt of southwestern British Columbia. These findings are consistent with the existence of the northern slab window as depicted in Figure 1, e and f. In addition, Armstrong et al. (1985) showed that the late Miocene and Pliocene Alert Bay volcanics of northern Vancouver Island were a likely product of "plate-edge" magmatism along the northern edge of the subducting Juan de Fuca plate; i.e., the southern margin of the window. In the northern Queen Charlotte Islands, Miocene-age volcanism of the Masset Formation, showing mixed arc and abyssal tholeiite affinity, may also be a plate-edge manifestation (Souther, 1990). In south-central British Columbia, concomitant basaltic volcanism of the Chilcotin Group has been attributed to a back-arc origin (Bevier, 1983). Because of spatial coincidence with the southward-migrating window margin, we suggest that these lavas are also products of plate-edge volcanism. Mantle diapirism, a probable cause of basaltic plate-edge volcanism, could be produced by a steepening of slab dip or a component of lateral movement of a slab edge through the asthenosphere, either process facilitating upward mantle flow.

Possible consequences for the North American plate, imposed by the late Cenozoic southern Farallon-Pacific slab window (Fig. 1, e and f), were explored by many, including Dickinson and Snyder (1979), Engebretson et al. (1985), Gough (1984, 1986), and Wilson (1988). The most convincing argument is that upwelling of nonmetasomatized mantle during window development caused progressive replacement of andesitic arc volcanism by that of extension-related bimodal tholeiites. Shallow levels of asthenosphere beneath much of the southwestern United States are also attributable to mantle upflow and displacement of the Farallon plate. Whether mantle currents are responsible for extension in the Basin and Range province and the Rio Grande rift and the present high elevations of the Colorado Plateau and Wasatch uplift is less certain. Changes in stress regime caused by development of transcurrent motion between the Pacific and North American plates may be largely responsible for the crustal attenuation (Atwater, 1970).

Another consequence of ridge subduction was indicated by Engebretson et al. (1985), who showed that the age of oceanic lithosphere converging with the continent became significantly younger after spreading began at the Kula-Farallon Rise. They, and several others such as Lipman et al. (1972) and Dickinson and Snyder (1978), recognized that extremely shallow underthrusting of such young, buoyant lithosphere could have contributed to the Laramide orogeny and magmatic null. In support, we note that the margins of the slab window (Fig. 1, b and c) would have been among the youngest parts of the subducted slabs and may have helped to buoy adjacent older sections. Apparently, window development during this period was not associated with localized crustal extension or anomalous magmatism in the North American plate.

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