Oblique collision and tectonic wedging of the South American continent and Caribbean terranes

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ABSTRACT

Our studies of the surface structures, seismicity, and gravity anomalies of the Caribbean–South American plate-boundary zone of northeast Venezuela and Trinidad show that the crustal and upper lithospheric structure and kinematics of this zone are complex and differ markedly along strike. We propose a model of the zone's lateral transition from near Trinidad west to Caracas, emphasizing three concepts: (1) the steepening, detachment, and then sinking away of Atlantic oceanic lithosphere that is (was) attached to the northern edge of continental South America; (2) the wedging seaward and imbricate thickening of the northern margin of the continent in the region of the detaching Atlantic slab; the continental wedge overrides the slab and is overridden by terranes attached to the Caribbean plate; and (3) that the structural and kinematic transitions are a consequence of the progressive oblique collision between continental South America and the overriding Caribbean terranes.

INTRODUCTION

It has been postulated that the northern boundary of the South American continent between about long 60° and 65°W (Fig. 1a) has undergone diachronous right-oblique collision with the overriding Lesser Antilles arc system, which surmounts the leading edge of the Caribbean plate (Speed, 1985). In this model, the collision began at about 35–40 Ma at 65°W and progressively drove Caribbean terranes above the continental toe from west to east, to the point north of Trinidad where initial collision is presumably occurring today. Suturing occurs when the terranes reach a critical distance up the continental slope. We retain but update this general concept and relate new findings concerning the South American–Caribbean plate-boundary zone.

The Caribbean plate, manifested as the oceanic Venezuela Basin in Figure 1a, moves generally east-southeast at 1 to 1.5 cm/yr relative to South America (Jordan, 1975; DeMets et al., 1990), and probably moved similarly well back into the Cenozoic, according to North America–South America and North America–Caribbean motion histories (Pindell et al., 1988). The southern Lesser Antilles arc system (Fig. 1a) comprising an arc platform, fore-arc basin, accretionary prism, backarc basin, and remnant arc, has probably moved mainly with the Caribbean plate at its leading edge (Speed, 1985). Three terranes currently identified between the arc system and the continent (Speed and Walker, 1991) have less certain kinematic affiliation to the Caribbean plate. The Tobago terrane (Fig. 1a) probably consists of Mesozoic oceanic crust plus suprajacent Mesozoic arc magmatic (Snoke et al., 1990) and basinal (Pereira et al., 1986) strata. The Tobago terrane may be continuous with Caribbean lithosphere below the Lesser Antilles arc system, or it may be unrelated to the Caribbean and may have been transported with only partial coupling to the Caribbean plate. The Paria-Trinidad terrane (Fig. 1a) contains mainly metasedimentary quartzose schists whose age of maximum metamorphism is thought to be about 25 Ma ($^{40}Ar/^{39}Ar$ dating; Speed and Foland, 1992). The schists are interpreted to have been exhumed by thrust imbrication of strata that composed a precollisional passive margin wedge along northern South America. The imbrication may have been due to accretion at the front of and/or below the Tobago terrane. The Araya-Margarita terrane contains generally higher grade and older metamorphic rocks than the Paria-Trinidad terrane (Avé Lallement and Guth, 1990; Speed and Foland, 1992). The tectonic history of the Araya-Margarita terrane is unclear.

Northern South America in Figure 1a comprises three regional elements: (1) the Guyana shield, bounded eastward by a passive margin beyond which is Atlantic lithosphere of probable Jurassic age (Speed et al., 1984); (2) a Neogene foreland thrust belt of Mesozoic and Paleogene strata and Paleozoic crystalline slices (R. C. Speed, 1991, unpublished data) in which southeasterly shortening in the past 30–35 m.y. totaled at least 40 km (Rossi et al., 1987); and (3) a Neogene foreland basin that has recorded large asymmetric subsidence, thickening northward in the past 30 m.y. (Hedberg, 1950). Prior to collision and overriding, the continent's northern edge was almost certainly a passive margin and was fronted by Mesozoic oceanic lithosphere that was continuous with that of today's Altantic. This is indicated by the northward thickening of Mesozoic shelf strata and the occurrence of basalt and evaporite in grabens below such strata (Moticska, 1987; Feo-Codecido et al., 1984).

Structural relations among these tectonic units observed or inferred from exposures and reflection profiles along 63°W through the Paria Peninsula are shown in Figure 1b. The Paria-Trinidad terrane is thrust above imbricated Mesozoic shelf strata and, locally, Miocene strata (Alvarez et al., 1985), which we interpret as piggybacked foreland basin strata (R. C. Speed and R. M. Russo, 1991, unpublished field data). The Tobago terrane is likewise thrust south above the Paria-Trinidad terrane, as determined in exposures on the Paria coast (Bladier, 1979; R. C. Speed, 1990, unpublished data).

Continental crust, unexposed north of the foreland basin, almost certainly extends northward in the subsurface beyond the southern edge of the Tobago terrane. This is necessary to balance the minimum of 40 km southward displacement of imbricated shelf strata. The northward extent of the Tobago terrane (Fig. 1a) is uncertain. We assume that it continues below the arc platform, but this is not pivotal to the interpretations that follow.

REGIONAL SEISMICITY

Seismicity in the southeastern Caribbean region is irregularly distributed (Fig. 1c). A high concentration of earthquakes occurs in a northeast-trending cluster across the Paria Peninsula, whereas to the west of the cluster in Venezuela (as far as 68°W), and to the east of it around Trinidad, seismicity is markedly lower. Moreover, the Paria cluster includes intermediate-depth earthquakes (70–200 km) that are absent to the west and east. Projection of the Paria cluster hypocenters onto a vertical section (Fig. 1d) indicates a seismic zone dipping ~60°NW. Focal mechanisms of five large-magnitude (5.0–6.2 m_b) earthquakes in the dipping zone are thrusts with nodal planes that strike approximately parallel to the long axis of the Paria cluster (Russo et al., 1992). The configuration and depth of the dipping zone imply that the events occur in an oceanic slab that subducts below terranes moving with the Caribbean plate.

The number of events in the Paria cluster diminishes to the northeast, and from east of Grenada (Fig. 1c) to St. Lucia, seismicity is low. From St. Lucia north, however, a west-dipping slab of Atlantic lithosphere is well defined by high seismicity (Dorel, 1981; Stein et al., 1982; Wadge and Shepherd, 1984). In spite of the Grenada–St. Lucia seismic low, we believe that the Atlantic slab is continuous from St. Lucia to

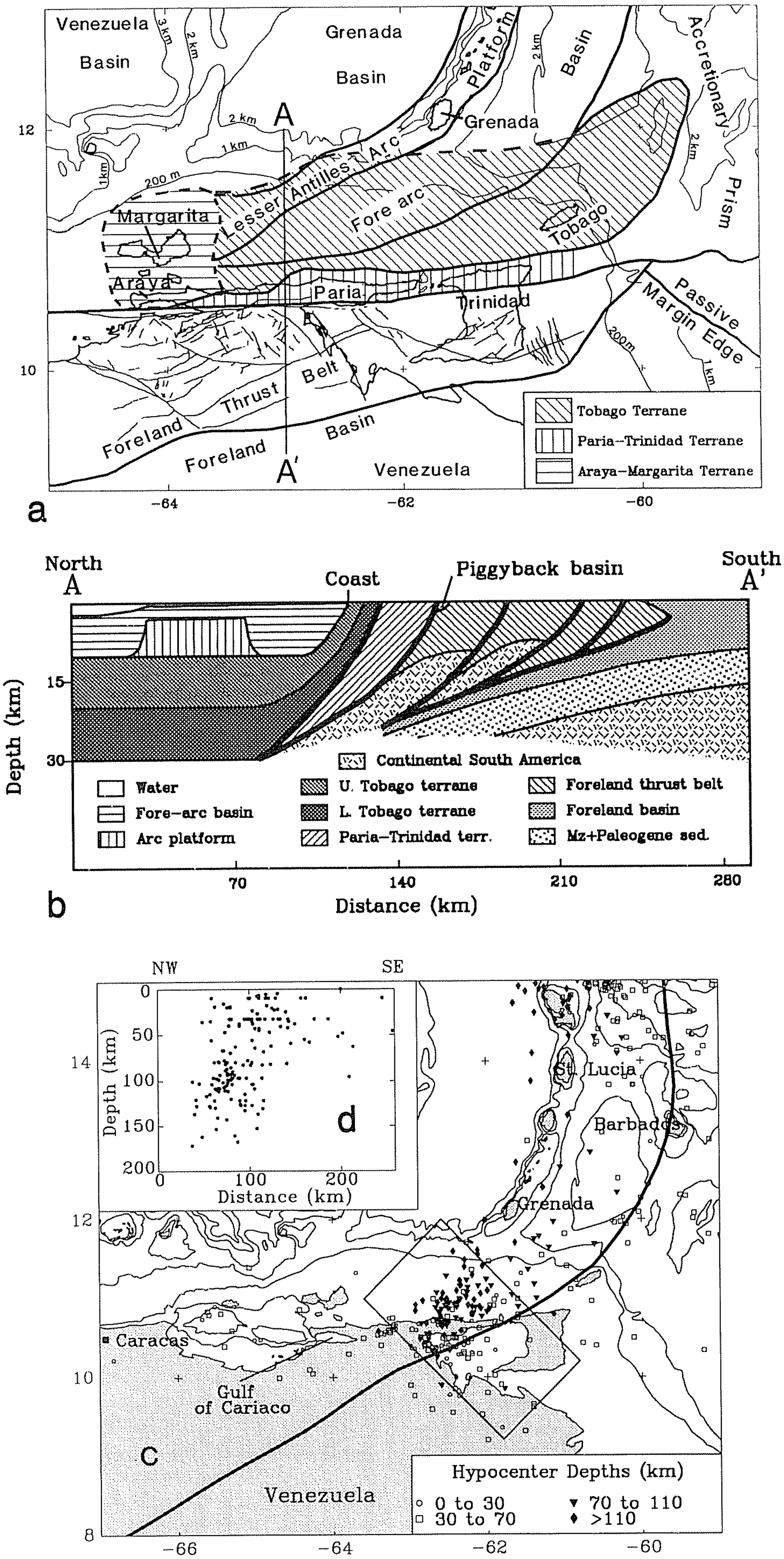

Figure 1. a: Terranes and tectonic elements of southeast Caribbean–South American plate-boundary zone. Terranes (patterns) in places underlie Neogene structures (bounded by heavy lines). Guyana shield (not shown) lies south of foreland basin. A-A′ is section line for part b and Figure 2; however, area of Figure 2 extends south of A′ to lat 8°N, long 63°W. b: Geologic cross section along A-A′. Heavy lines are thrust faults. Note piggyback foreland basin overridden by Paria-Trinidad terrane (U = upper; L = lower). c: Map of National Earthquake Information Center hypocenters (1963–1988). Hypocenters within box are projected vertically in part d. Heavy line is our estimate of top of subducting oceanic slab; note its extension southwest of Paria. Absence of intermediate-depth earthquakes west of Paria cluster is evidence that slab is detached from continental South America. d: vertical section of Paria cluster hypocenters. Earthquakes within box shown in part c are plotted to show approximately 60°NW dip of subducting slab beneath Paria.

Paria because of the active volcanism as far south as Grenada, the occurrence of a few deep earthquakes below the arc between Grenada and St. Lucia (Fig. 1c), and other geophysical evidence near Barbados (Torrini and Speed, 1989). Our estimate of the locus of the top of the dipping Atlantic slab is shown in Figure 1c. Northeast of Paria, the slab is attached to the South American continent and is part of the South American plate.

An evident difficulty arises because the deep seismicity of the Paria cluster extends well south of the exposed northern edge of the continent and below inferred continental crust (Fig. 1, a and b), implying that the dipping slab is below the continent. This is counter to the expected distribution of subduction earthquakes: if the slab were attached to the overridden northern edge of the continent, the earthquakes would lie considerably to the north of the continental edge, *below* the overriding terranes. We resolve this anomaly with the proposition that below Paria, the continent has detached from the slab and has been translated north above the slab, wedging between the overriding terranes and the underriding slab. Where the dipping seismic zone is north of the continental edge, well northeast of the Paria Peninsula, the slab and continent are probably still attached. We propose that to the west of Paria, the slab is completely separated from and has sunk below the continent, thus explaining the absence of intermediate-depth earthquakes west of the Araya-Paria isthmus (see below).

GRAVITY ANOMALIES AND TOPOGRAPHY

Northeastern Venezuela is the site of the world's continental minimum of near-sea-level Bouguer gravity (Bowin, 1976; Bonini, 1978;

Speed et al., 1984), which is less than −190 mgal at the southwest coast of the Gulf of Paria (Fig. 2). It is clear from the magnitude of the negative anomaly and the low topography that the region is not in isostatic equilibrium. Elevations increase west from the Gulf of Paria and reach 1 km or more at 63°W, but calculation shows that elevations of 3 km are expected for isostatic balance and Airy compensation.

We have calculated the gravity anomalies of a crustal model (Fig. 2) on the basis of tectonic units and seismicity discussed above. The model includes as density units the Guyana shield, the Paria slab of oceanic crust formed during Mesozoic drifting of the South American plate, foreland basin, foreland thrust belt, collided terranes, and elements of the Cenozoic Lesser Antilles arc system. Two important inferences drawn from this model are that the Paria slab and a wedge of transitional crust have been overridden by the continent, and that transitional crust exists in the foreland thrust belt. The crustal model employs substantial thickening of continental crust in the collision zone to account for a part of the mass deficiency, because this cannot be achieved by foreland basin parameters alone without totally unreasonable basin thicknesses (>15 km) and density-depth functions (Bonini, 1978; R. M. Russo and R. C. Speed, unpublished). The crustal thickening is accomplished by faulting the crust into three generalized stacked blocks (Fig. 2): an upper sheet in the foreland thrust belt, a lower sheet attached to the Paria slab, and the continental midcrust wedged north between the two sheets. This stacking caused depression of the crust-mantle interface.

The tectonic wedging model, in addition to providing a mechanism for thickening the crust, also provides a rationale for depression of the mantle: both surface and subsurface loads act on South American lithosphere. The overriding terranes and upper transitional crust sheet provide a surface load, and the subducting and detaching Paria slab induces a considerable subsurface load. The loads account for the lack of significant topography coincident with the gravity low. The increase of elevations to the west is also commensurate with the model. The interaction between Caribbean terranes and continental South America has proceeded diachronously from west to east; therefore, detachment of the subducting slab has progressed farther in the western parts of the collided zone. The subducting slab may be completely detached and sinking, and the continent may be rebounding rapidly, leading to uplift and erosion of the overthrust terranes. Detachment also accounts for the absence of deeper earthquakes west of Paria, because tensile stresses can no longer propagate to the buoyant, unsubducted continent, and bending moments are released upon detachment.

Through a combination of forward gravity calculation (Talwani et al., 1959) and least-squares linear inversion (Jupp and Vozoff, 1975), we fit the theoretical gravity anomaly of the model to the observed Bouguer gravity anomaly. Figure 2 shows the good match between the calculated and observed anomalies and the tectonic wedging crustal model.

TOMOGRAPHY

Additional indications of the distribution of tectonic elements with depth can be gleaned from recent work involving delay-time tomography (Van der Hilst, 1990). *P*-wave velocity anomalies along three north-south–trending sections at long 63°, 65°, and 67°W indicate the existence of a high-velocity slab that dips north or northwest. At 63°W this high-velocity slab is at very shallow depths and is apparently in contact with South American lithosphere. At 67°W the top of the slab is at 400 km and lat 7°N. The tomography implies that a slab continues with southwest strike from Paria, the depth to the top of this slab increases southwestward, and the distance between the northern limit of exposed continent and the top of the slab increases westward. If the top of the slab was once attached to the ancient passive margin at the northern edge of South America, then it must now be detached from and overridden progressively from west to east by the continent. An important corollary of this interpretation is that if this slab is laterally fixed relative to the mantle, then absolute motion of continental South America with respect to the mantle is occurring. Given the apparent southwest strike of the slab, this motion may be largely west directed (as in Gripp and Gordon, 1990), but it may also have a northward component and/or clockwise rotation about a vertical axis within northern South America.

TECTONIC WEDGING MODEL

Our synthesis of the regional geology, seismicity, gravity anomalies, topography, and tomography of the Caribbean–South American plate boundary zone is shown in Figure 3. The model includes Atlantic oceanic lithosphere that is continuous through the area of Figure 3 and whose history varies markedly on strike. At 14°N it subducts beneath the Caribbean plate along the Lesser Antilles subduction zone (Fig. 3b), dipping about 50°W (Wadge and Shepherd, 1984). This lithosphere continues south (Fig. 3c) and is attached to continental South America at its eastern passive margin and to a now-buried north-facing passive margin along the Trinidad and Paria coast of the continent. Beneath Paria, the dip of the slab increases to 60°NW, and near the coastline, the slab is being overridden and is detaching from the continent (Fig. 3d). Southwest of Paria, the oceanic slab, because of its negative buoyancy, has detached and progressively sunk below the continent (Fig. 3e), at least as far south as 7°N, at 67°W. Overridden transi-

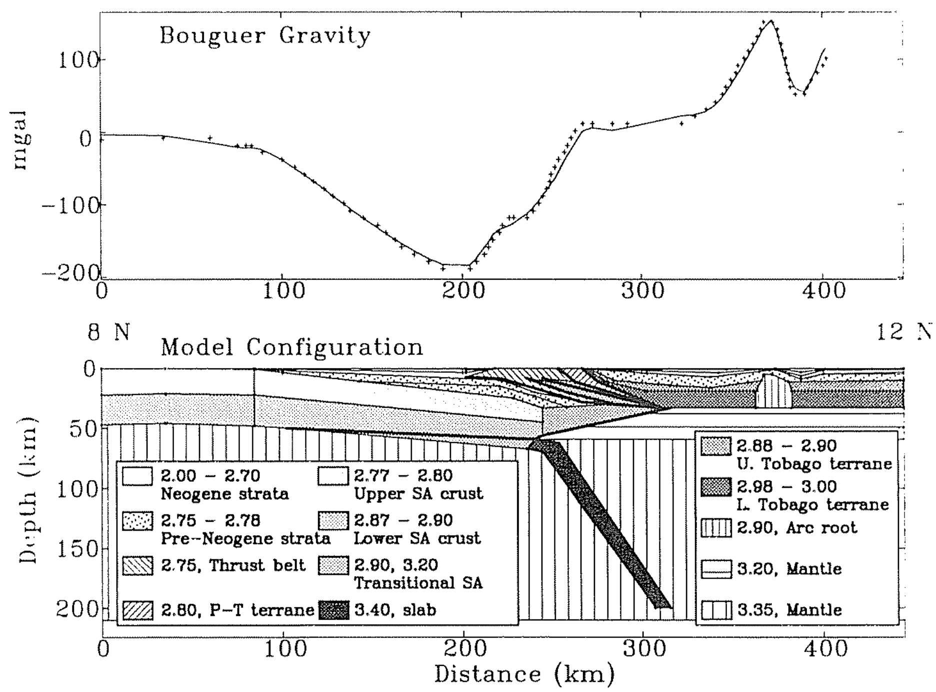

Figure 2. Gravity model (bottom) and comparison of calculated (solid line) and observed (crosses) Bouguer gravity anomalies (top). Section line coincides with A-A′ of Figure 1a, but extends south of A′ to 8°N. Note thin sliver of Neogene foreland basin sediments below thrust belt and above Paleogene and Mesozoic strata. Numbers in key are densities (g/cm^3). Transitional South American (SA) crust attached to slab has density of 3.20 g/cm^3; other transitional crust density is 2.90 g/cm^3. P-T = Paria-Trinidad; U = upper; L = lower.

tional crust is probably too buoyant to subduct and has accreted to the lower continental crust.

In the vicinity of the Paria Peninsula, detachment and overriding of subducting oceanic lithosphere are accomplished by the wedging of South American transitional or continental crust between overriding terranes and above the detaching slab (Fig. 3d). This configuration is commensurate with regional surface geology, the observed distribution of earthquakes, and delay-time tomography; it explains regional gravity anomalies and topography. Kinematically, the tectonic wedging model involves progressive west-to-east oblique collision of continental South America and Caribbean terranes and suturing of the overriding terranes to the continent.

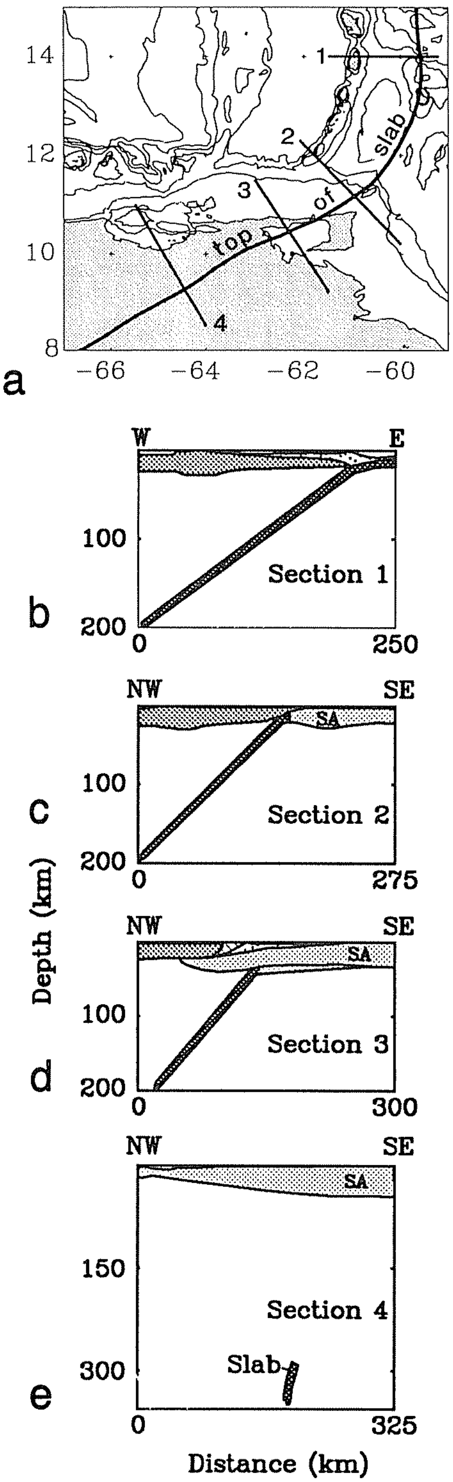

Figure 3. Map (a) and cross sections of along-strike variation of subduction and plate-boundary architecture. Note that each section is 1:1, but horizontal scale varies. b: Subduction of Atlantic oceanic lithosphere (dark, dipping layer) beneath Lesser Antilles fore arc. c: Atlantic oceanic lithosphere attached to South America (SA) subducts beneath Caribbean Tobago terrane. Tobago terrane is just beginning to override continent. d: Tectonic wedging of continental SA beneath Tobago and Paria-Trinidad terranes (patterned area at upper left) and above detaching oceanic slab and transitional lithosphere. Foreland thrust belt (lined) and basin (dots) are also shown. e: Detached and sinking slab below isostatically rebounded SA continent. Overridden transitional crust is accreted to base of continent.

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