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Cocos–Nazca slab window beneath Central America

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Abstract

Integration of petrologic and tectonic data favours a model of slab window formation beneath Central America in the Pliocene–Pleistocene. Central America has been the site of voluminous Cenozoic arc volcanism. The Cocos and Nazca plates, which are subducting beneath Central America, are diverging along the east-trending Cocos–Nazca spreading ridge. Since 25 Ma the Americas have advanced about 1800 km west over the ridge–transform system. Since at least 8 Ma, plate integrity and the ridge–transform configuration have been preserved during convergence, resulting in subduction of the spreading ridge and development of a slab window. The Panama fracture zone, an active transform fault, is the part of the ridge–transform system currently being subducted. The ridge–transform system formerly adjoining the northern end of the Panama fracture zone is likely to have been left-stepping. We use present-day plate motions to design a slab window to fit known variations in igneous composition, hypocentre distribution, and mantle anisotropy. The modeling demonstrates that subduction of ridge segments and resultant slab window development began between 6 and 10 Ma. Cessation of ridge subduction occurred between 1 and 3 Ma, when subduction of the Panama fracture zone is considered to have begun. The slab window is continuing to expand and migrate northeastward below the Central American volcanic arc.

The absence of a Wadati–Benioff zone from southeastern Costa Rica through Panama corresponds to the position of the slab window. Within this region, dacitic and rhyolitic volcanic rocks have "adakitic" compositions, and are thought to result from anatexis of the young, buoyant crust which forms the trailing edges of the slabs bounding the window. Basalts in this area were derived from an enriched ocean-island type mantle source, whereas basalts from the rest of the arc, in Nicaragua, El Salvador and Guatemala, are mainly derived from slab-modified depleted mantle, characteristic of volcanic arcs. The presence of ocean-island type mantle beneath southern Costa Rica and Panama is explained by eastward flow of enriched asthenosphere from the Galapagos plume-head through the slab window and into the volcano source region. Eastward transfer of asthenosphere is consistent with global plate motion studies and seismic anisotropy in the asthenosphere beneath the Nazca and Caribbean plates. The flow of peridotite is a consequence of progressive shrinkage of the Pacific mantle reservoir and concurrent expansion of the Atlantic mantle reservoir.

Keywords: subduction zones; spreading centers; transform faults; island arcs; slabs; mantle plumes; lithosphere; asthenosphere; geochemistry

1. Introduction

Subduction of oceanic lithosphere beneath the Cordillera has resulted in six situations of ridge–trench intersection from British Columbia to the

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Antarctic Peninsula since the Late Cretaceous [1–4]. All of these intersections are known to correlate with magmatic, and in some cases tectonic, anomalies in the overriding plate. In four of the five cases, these anomalies have been explained with models of slab window development. In the remaining case, where the Cocos–Nazca plate boundary intersects the Middle American trench, the anomalous magmatic and tectonic features have not been placed in a slab window context. Importantly, a convincing physical explanation for the pronounced along-arc geochemical trends in the Central American arc [5–7] has yet to be established. This paper provides a model of slab window formation beneath Central America, demonstrates how window development can explain the magmatic and tectonic anomalies, and speculates on the nature of lithosphere–asthenosphere interactions in the Cocos–Nazca–Caribbean plate region.

A slab window is a slab-free region beneath the convergent margin of an overriding plate [1–4,8]. The window develops during "ridge subduction", in which two oceanic plates are diverging, and the trailing edge of one or both plates is concurrently subducting. Prior to subduction, the divergent boundary is the site of sea-floor spreading, where the plates grow as rising magma cools and accretes onto their trailing edges. At a ridge–trench encounter, one or both of the trailing plate edges descend into the asthenosphere. Once engulfed by asthenosphere, a trailing edge becomes too hot to serve as a site of magma solidification, and growth of the slab ceases. Divergence without growth produces a slab window. First-order estimates of window shape can be made from plate kinematic data. Modeling of thermal conditions [9,10] and strain [11,12] in the slabs is required for more comprehensive depictions.

Ridge–trench intersections produce systematic changes in the overriding plate, as expressed by the previously recognized Cordilleran slab windows below British Columbia and Alaska [2,13,14], the southwestern United States [1], southern Chile [3], and the Antarctic Peninsula [4]. Above a slab window, volcanism of arc character ceases and may be replaced by eruptions of alkalic to tholeiitic magmas with intraplate affinity [3,15,16]. Forearc volcanism may become locally abundant [13,14,17,18]. Above the margins of a slab window, volcanoes may erupt geochemically unusual dacites, termed adakites or bajaites, regarded as possible anatectic melts of young subducted slab [19–21]. In some cases, high heat flow, uplift and extension accompanies the magmatic effects [1,2,22].

2. Postulated Central American slab window

2.1. Prediction of a slab window from regional plate interactions

Five plates, the North American, Caribbean, South American, Cocos, and Nazca plates, interact in the Central American region (Fig. 1). The Caribbean plate separates the North and South American plates and extends from the sinistral Motagua–Cayman Trough fault zone south to a diffuse boundary between the South Caribbean deformed zone and the Bocono–East Andean fault zone in the northern Andes [23–25]. Along the Middle America trench, the oceanic Cocos and Nazca plates are subducting eastward beneath the "American" plates, producing arc volcanism from Mexico to Columbia [5,26]. Divergence between the Cocos and Nazca plates is accommodated by the east-trending Cocos–Nazca ridge–transform system which became active at about 25 Ma [27]. The easternmost part of the Cocos–Nazca plate boundary is the Panama fracture zone, a long, active transform fault which intersects the Middle America trench near the Costa Rica/Panama border. The Cocos ridge, an aseismic ridge on the Cocos plate that formed from interaction between the Galapagos hot-spot and the Cocos–Nazca spreading ridge [27], intersects the trench at about the same point as the fracture zone. Pliocene to recent subduction of the Cocos ridge has locally deformed the forearc and uplifted the volcanic arc in southern Costa Rica [28,29].

Present-day plate motion studies [30,31] indicate that the Cocos plate is subducting rapidly northeastward beneath most of Central America (Fig. 1). Convergence rates for the Cocos plate range from about 6 cm/a along the coast of Mexico to nearly 10 cm/a in southern Costa Rica. The Nazca plate is converging eastward with northern South America at about 7 cm/a. The northernmost part of the Nazca plate, which is subducting beneath Panama at a highly oblique angle, may be separated from the main part of the Nazca plate by a postulated but unidentified transform or spreading boundary [31,32]. Depending on the relative velocities along this postulated boundary, motion of the so-called "North Nazca" plate relative to Panama may range from about 3.5 to 6.5 cm/a [31].

Paleogeographic reconstructions imply that approximately 1800 km of the Cocos–Nazca spreading ridge has been subducted since its inception at 25 Ma [27]. In detail, however, the orientation and behavior of the missing ridge–transform boundary is uncertain. Fossil spreading centres ranging in age from 8 to 22 Ma are located in the North Nazca plate region [7], suggesting that the Cocos–Nazca plate boundary previously extended into this area, and that the near-ridge parts of these plates became fragmented as spreading centres stalled near the trench. However, no fossil spreading centres younger than about 8 Ma have been identified. These observations imply that plate fragmentation related to ridge–trench encounters was limited to the Miocene. Thus, from the Pliocene to the present, subduction of the ridge–transform boundary appears to have been uniform, and uninterrupted by changes in the location or orientation of spreading segments. The plate regime of Central America thereby satisfies the two general conditions necessary for the existence of a present-day slab window: (1) convergence of a spreading ridge with a subduction zone for the past several Ma; and (2) sufficient conservation of plate integrity dur-

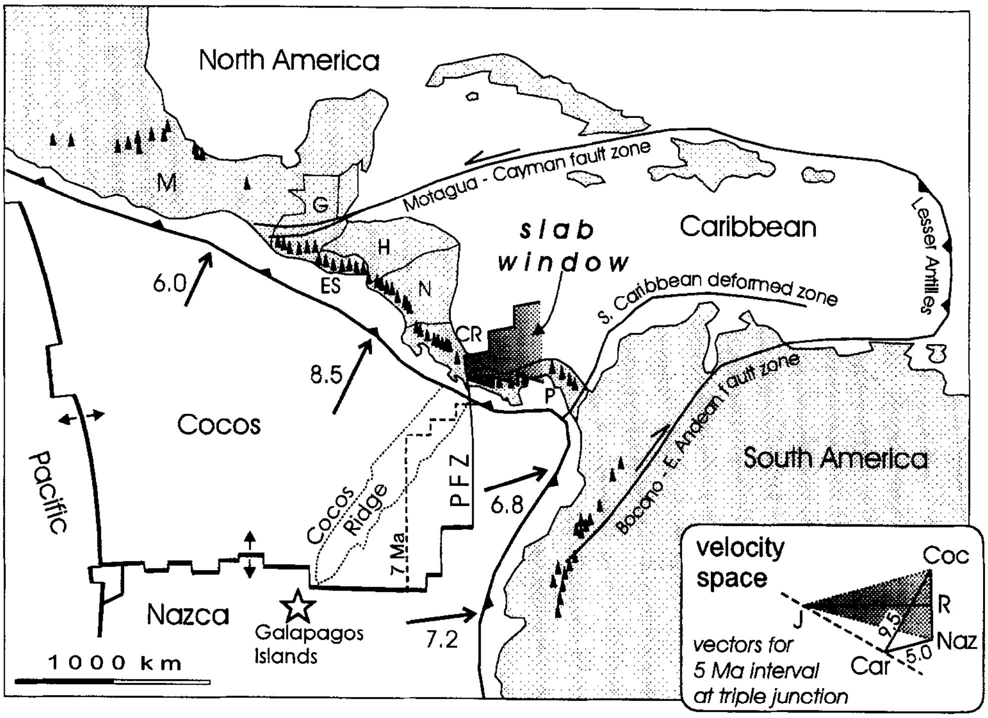

Fig. 1. Simplified tectonic setting of Central America [5,7,42] showing surface projection of postulated slab window between Cocos and Nazca plates beneath southeastern Costa Rica and northwestern Panama. Vectors on Cocos and Nazca plates indicate plate velocites in centimeters/year with reference to fixed Caribbean or South American plates, based on Nuvel-1 plate motion model [30]. Slab window geometry is based on subduction of a left-stepping ridge–transform boundary from 7 to 2 Ma, followed by subduction of the Panama fracture zone (PFZ) from 2 Ma to the present. The position of the PFZ and postulated ridge–transform segments at 7 Ma are shown by a dashed line to the west of the modern PFZ. Dip angles of the Nazca and Cocos slabs used in window construction are 0° and 25°, respectively. ▲ = Volcanoes. Inset map indicates relative plate motions in velocity space at the Caribbean–Cocos–Nazca triple junction. Vector lengths correspond to motion during a 5 Ma interval. Shaded triangle is predicted shape of slab window surface projection under conditions of subhorizontal subduction. *Car* = Caribbean; *Coc* = Cocos; *Naz* = Nazca; *J* = triple junction; *R* = Cocos–Nazca spreading ridge.

ing ridge subduction for the subducted parts of the slabs to diverge from one another.

Subduction of a spreading segment in the Pliocene or Pleistocene seems likely from analysis of the present plate situation. Currently, the Panama fracture zone is the part of the Cocos–Nazca plate boundary which is being subducted. Although the configuration of the plate boundary which lay north of the Panama fracture zone is unconstrained, it is likely that the northern end of the fault originally connected with a spreading ridge, or a ridge–transform fault boundary, which has since been subducted (Fig. 1). As this northern spreading segment was overridden by the Caribbean plate, a slab window would have formed between the trailing edges of the subducted Cocos and Nazca slabs. As subduction of this spreading segment ended, and subduction of the Panama fracture zone began, the slab window would have ceased to form at the trench. With continued subduction of the Panama fracture zone, the window would have widened and moved northeastward.

2.2. Evidence for a slab window

The absence of a Wadati–Benioff zone from southeastern Costa Rica through Panama supports the possibility of a slab window flanked by buoyant, subhorizontal trailing plate edges (Fig. 2). Compilation of earthquake hypocentres beneath Central America reveals that the Cocos plate shallows from about 60° below Guatemala to less than 30° beneath central Costa Rica [12]. Farther southeast, toward the triple junction, the Cocos slab is not seismically evident below about 70 km. Deep seismic reflection studies west of southern Costa Rica indicate that the Cocos slab is sliding at a low angle along the base of the Caribbean plate forearc [29]. Southeast of the Panama fracture zone, the absence of sublithospheric hypocentres indicates that the Nazca plate is either absent or subducting subhorizontally beneath Panama [12].

Previous interpretations of the seismic data have focused on subduction of the Cocos ridge [5,7,29], which intersects the trench at about the same point as the Panama fracture zone (Figs. 1 and 2). Subduction of the thick, relatively buoyant Cocos ridge can explain a variety of phenomena, including shallow subduction of the Cocos plate beneath Costa Rica

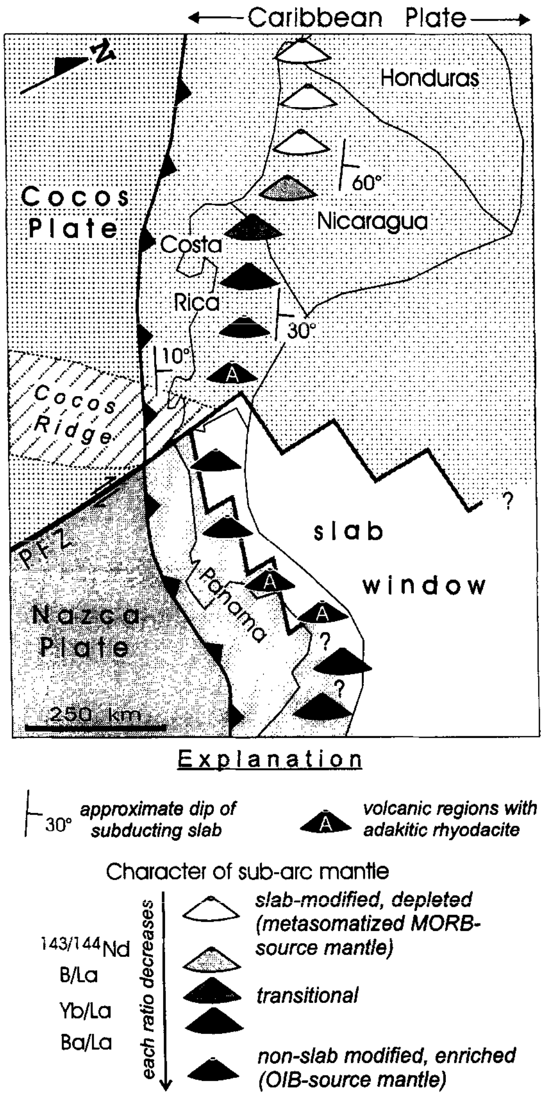

Fig. 2. Tectonic map of Central America showing postulated geometry of subducted Cocos and Nazca slabs, and the slab window, beneath the Caribbean plate. The shape of the slab window to the south and east of central Panama (older than 7 Ma) is unconstrained. Variation in the geochemical character of the mantle underlying the volcanic arc is shown by progressive shading of schematically located volcanoes. Dip angles are indicated for three locations on the Cocos plate. *PFZ* = Panama fracture zone.

and related uplift of forearc and arc. However, subduction of the Cocos ridge cannot explain either the absence of seisimicity in the Nazca slab beneath Panama, or the regional variations in arc geochemistry (discussed below).

Geochemical information from Quaternary volcanoes infers that mantle characteristics beneath Central America vary profoundly from northwest to southeast [5,7,6] (Fig. 2). In the northern part of the Central American arc (Guatemala to Nicaragua), isotopic and geochemical parameters indicate magma derivation mainly from slab-metasomatized, mid-ocean ridge basalt (MORB)–source mantle, typical of most arcs. To the southeast, in Costa Rica and Panama, basalts indicate derivation from ocean-island basalt (OIB)-type enriched mantle affected little by subduction metasomatism [5,6]. The southward increase in OIB character is evident from trends in trace element concentrations and radiogenic isotope ratios. The change from Nicaragua to Panama is particularly well defined by B/La, which decreases from about 5 to about 0.1 [5], and by $^{143}Nd/^{144}Nd$, which decreases from about 0.5131 to 0.5129 [6]. The transition from arc to OIB composition is so pronounced that it has been described as a conundrum [5].

Aluminum-rich, Y-poor dacites and rhyolites occur in the segment of the arc extending from southeastern Costa Rica through central Panama [7,20]. Rocks of this type, termed *adakite*, have been interpreted as products of slab anatexis in this region and in parts of convergent margins elsewhere [20,21]. Thermal modeling indicates that melting of young subducted crust is a viable process, and is most likely where the subducting slab is youngest [9,10]. The youngest and hottest lithosphere subducting beneath the Central American arc lies in the region of the Cocos–Nazca spreading ridge, directly offshore from the sites of adakite magmatism, thus supporting the idea of slab anatexis.

The increase in OIB-like chemical characteristics toward the triple junction infers that the mantle wedge beneath the arc volcanoes has been progressively contaminated or displaced by mantle of enriched plume origin. Contamination is envisaged by the flow of mantle from beneath (and west) of the slabs to above them. Under normal arc conditions, the downgoing slab divides the asthenosphere into sub- and supra-slab reservoirs, each with distinctive geochemical and thermal attributes. Flow of mantle from one reservoir to the other is blocked by the descending plate. However, under conditions of ridge subduction and subsequent slab window development, the slab barrier is locally absent and the sub- and supra-slab reservoirs are brought into contact [1,8]. Flow of mantle from one reservoir into the other may occur according to pressure gradients related to differences in mantle composition and temperature, and motions of the subducting slabs [33].

The OIB characteristics are likely to have been derived from sub-slab asthenosphere belonging to, or affected by, the Galapagos plume head. The Galapagos plume has formed an axial to near-axial hot-spot for at least the last 25 Ma [27], and its plume head is likely to extend under large areas of the Cocos and Nazca plates. A Galapagos plume source is supported by similarities in chemical characteristics between the OIB-like parts of the arc and the Galapagos hot-spot track [5,27]. We contend that a slab window between the Cocos and Nazca plates provides a plausible, suitably located pathway for voluminous influx of enriched sub-slab peridotite into the arc source region. The locations of the adakitic volcanic rocks in Panama and southeastern Costa Rica, possibly generated by slab anatexis, are consistent with melting of the thin, young, trailing edges of the subducted lithosphere bounding the slab window (Figs. 2 and 3).

2.3. Previous explanations

Previous attempts to reconcile the geochemical transitions in the arc have not considered the possibility of divergence between the subducted parts of the Cocos and Nazca plates; that is, the formation of a slab window. In one model [6], the geochemical trend is explained by transfer of "plum pudding" asthenosphere containing OIB-like peridotite from beneath the Nazca plate to the mantle wedge beneath southern Costa Rica and Panama. This model implied that "flattening and breakup of the subducting plate below eastern Costa Rica and Panama" provided the mechanism for OIB-like asthenosphere from beneath the Nazca plate reaching the arc source region. The apparent contradiction of a deforming slab in an area of seismic inactivity was not addressed. In another model [5], the southerly increase in OIB-type characteristics was explained by gentler subduction angles, leading to shallower depths of slab dehydration, and consequent melting of

Caribbean plate lithosphere, parts of which were postulated to be enriched. The aseismic region beneath southern Costa Rica and Panama was rationalized in terms of the high heat flow and buoyancy of the subducting oceanic lithosphere.

Although both of these models [5,6] appealed to sources of enriched mantle, they differ considerably from the interpretation presented here. In the first model [6], the sub-slab region was identified as the source of enrichment, but the pathway for mantle flow was a postulated break in the Cocos slab beneath northern Costa Rica. This explanation may not be viable because, in a recent review of seismic data, the suggestion of a tear in the Cocos slab was rejected in favour of a sharp flexure [12]. Even if the slab in this area is torn, the resultant pathway would lie hundreds of kilometres too far to the northwest to account for the OIB-like compositions in southeastern Costa Rica and Panama. In the second model [5], a sub-slab origin for the enriched mantle source was not considered, and the slab barrier to mantle flow was assumed to be intact. In contrast to these models [5,6], our interpretation explains the anomalous geochemical characteristics of the Central American arc by: (1) considering the region in a tectonic framework of ridge-trench convergence; (2) fully accounting for the gap in slab seismicity; (3) demonstrating the likelihood of a slab window with appropriate location and age; and (4) appealing to a known source of asthenospheric enrichment.

2.4. Mantle currents

The eastward flow of asthenosphere through the Cocos–Nazca slab window (Fig. 3), involving displacement of arc-type mantle by OIB-type mantle from the Galapagos plume, is consistent with global plate motion studies, and with seismic anisotropy of asthenosphere beneath the Nazca and Caribbean plates. The opening of the Atlantic Ocean, together with the roll-back of subduction zones bounding the west margin of the Pacific, has, since the early Mesozoic, resulted in continuous shrinkage of the basin and its underlying sub-lithospheric mantle reservoir [34]. Coherent westward drift of the lithosphere [35–37] implies that shrinkage of the Pacific mantle reservoir has been largely accommodated by the eastward transfer of Pacific asthenosphere into

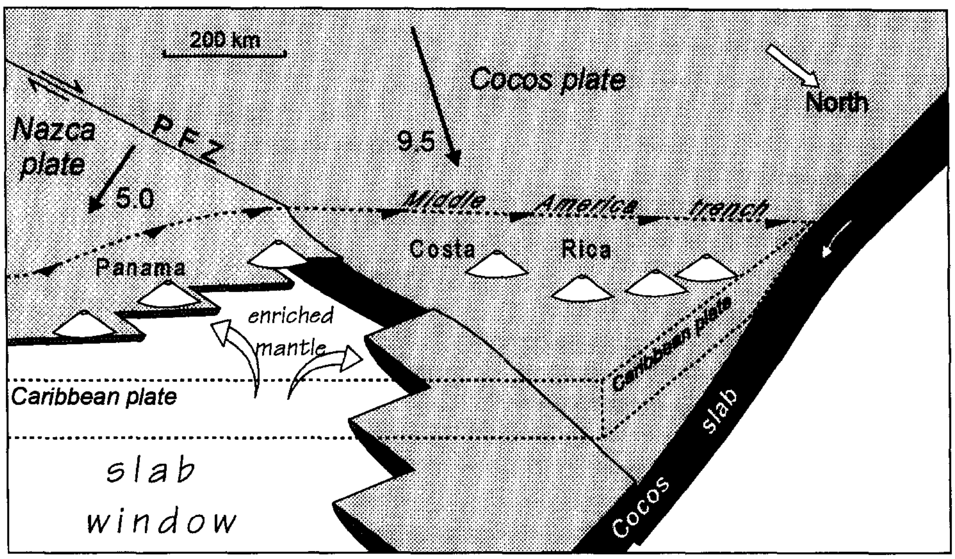

Fig. 3. Block diagram of slab window illustrated in Fig. 1Fig. 2. View is to the southwest. Vectors show Cocos and Nazca plate motions relative to the Caribbean plate in centimeters/year. Enriched asthenosphere is considered to flow from beneath the Cocos and Nazca plates into the arc source region beneath the Caribbean plate (arrows). Anatexis of the trailing slab edges is likely, although window shape has not been modified to reflect thermal erosion. Areas of Pliocene–Recent volcanism on the Caribbean plate are shown schematically. *PFZ* = Panama fracture zone.

the expanding Atlantic mantle reservoir. However, slabs subducting eastward beneath the Americas form a barrier to Pacific–Atlantic asthenospheric transfer. Eastward outflow of asthenosphere is thereby restricted to slab windows, tears within slabs, or regions of very low-angle subduction [12,38]. In the case of shallow subduction, the supra-slab mantle wedge beneath the Cordilleran volcanic arcs remains shielded from the sub-slab asthenosphere. Only in the case of a slab window or a large slab tear can voluminous sub-slab peridotite gain direct access to the roots of the arcs. Beneath Central America, the only plausible pathway for exotic mantle to enter the volcano source region is a slab window located in the seismically quiet zone of southern Costa Rica and Panama.

Shear-wave splitting in the asthenosphere beneath the Nazca plate has been attributed to north-directed mantle flow around the north end of the Andean subduction zone [39]. Similar seismic anisotropy beneath the southern margin of the Caribbean plate indicates rapid eastward asthenospheric flow [39]. These observations are consistent with channelling of asthenosphere northward around South America and into the Caribbean region [6,39]. Apparently, the Nazca slab and the South American craton act as a barrier to eastward mantle flow, causing the sub-slab asthenosphere to flow subparallel to the trench until it reaches Central America where it vents eastward [39]. The Cocos–Nazca slab window forms the principal conduit for this seismically observed asthenospheric outflow.

2.5. Geometrical modeling of the slab window

The geometry of a slab window beneath Central America is dependent on three main factors: (1) motions of the Nazca and Cocos plates relative to the Caribbean plate; (2) presubduction ridge–transform configuration of the Cocos–Nazca plate boundary; and (3) angles of slab dip [1]. If these factors can be quantified, window morphology may be constructed on the assumptions that plate motions were constant, and thermal erosion and spherical shell strain are negligible [8]. Plate kinematics and slab dip angles in the western Caribbean are sufficiently understood for first-order geometrical calculations. However, the configuration of the divergent plate boundary prior to subduction is poorly constrained because both the Nazca and Cocos plates have been subducting along with their record of sea-floor magnetic anomalies.

In the absence of geomagnetic stripes, clues to the location and morphology of a postulated slab window are provided by patterns of volcanism, trends in chemical and isotopic composition, and variations in seismic activity (Fig. 2). When all available data are considered, the window is most favourably located beneath southeastern Costa Rica and northwestern Panama, where Quaternary volcanic activity is minimal, magma sources are anomalous, and slabs are not seismically evident. In this position, the window is flanked by volcanoes containing adakitic rhyodacite whose origin is consistent with anatexis of thin trailing edges of subducted Nazca and Cocos lithosphere. Northwest of the window, mafic igneous compositions change from OIB- to arc-type, consistent with a progression toward normal conditions of subduction. Slab dip angles increase away from the window on both sides, as predicted for subducted lithosphere flanking a slab window [8,40].

Our model of the Cocos–Nazca slab window (Figs. 1–3) was constructed according to geometrical principles of formation [8] using present-day plate motions together with the aforementioned constraints on window location. The angle of subduction is considered to be subhorizontal for the Nazca plate, and 25° for the Cocos plate. Under these conditions, the subducting ridge segments widen into slab window margins, which closely approximate the shaded triangle in the velocity space diagram (Fig. 1). The subducting transform faults maintain their orientations within a few degrees and produce north–south steps in the window margins. The pre-subduction ridge–transform boundary which formerly adjoined the northern end of the Panama fracture zone was considered to be left-stepping (Fig. 1), as it is at the southern end of the fracture zone. Divergent boundaries with this configuration, in which ridge segments consistently step "away" from the trench, are more likely to subduct uniformly than those which step "back" toward the trench [4,41]. The steps in the window margin of the Cocos plate are larger than those of the Nazca plate because the Cocos plate occupies the acute angle between the spreading ridge and the trench [8]. Modifications from thermal erosion and spherical shell strain have not been modeled.

The window illustrated (Figs. 1–3) has been designed to best fit the regional geophysical and geochemical data. Its formation would have occurred from subduction of a left-stepping ridge–transform boundary beginning at 7 Ma beneath western Panama (Fig. 1). In this model, subduction of ridge and trench segments alternated from 7 to 2 Ma, in 1 Ma intervals, followed by subduction of the Panama fracture zone beginning at 2 Ma. During subduction of the ridge segments, the window underwent new growth at the ridge–trench intersection, which was migrating northwestward (Fig. 1, inset). During subduction of the transform faults, new growth from the triple junction was suspended and the existing window widened and shifted northeastward. The interplay between northwestward growth and northeastward translation constrained the location of the slab window to near its original position for the past 7 Ma. Currently, the window terminates against the northern end of the Panama fracture zone. As the fracture zone continues to subduct, the window will expand in a north–south direction, and shift to the northeast. Geometry of the subducted slabs older than 7 Ma has not been modeled (Fig. 2).

The parameters used in this model are not exclusive in the construction of a suitable slab window model. Other adequate models can be generated by invoking subduction of ridge segments (mainly left-stepping) starting between 6 and 10 Ma, and ending between 1 and 3 Ma with inception of subduction of the Panama fracture zone. Thermal modeling may provide additional constraints on the "best fit" configuration of the former ridge–transform boundary.

Plate velocities were obtained from the Nuvel-1 [30] plate calculator of K. Tamaki at the University of Tokyo. The plate velocities used in estimating slab window shape were calculated for the current Cocos–Nazca–Caribbean triple junction. At that location, the Nazca plate has a calculated velocity of 5.0 cm/a toward 75°, in contrast to a nearby global positioning system (GPS) measurement of 3.5 cm/a toward about 80° [31]. If the GPS value is substituted for those of Nuvel-1, the estimated slab window becomes slightly wider but is not appreciably different in orientation.

3. Conclusions

Subduction of Cocos–Nazca spreading ridge segments from about 7 to 2 Ma led to the Pliocene–Pleistocene development of a slab window beneath Central America. The slab window is delineated by a local absence of a Wadati–Benioff zone in southern Costa Rica and northwestern Panama. The window is flanked by the gently dipping Cocos and Nazca slabs which steepen away from the aseismic zone. This inter-slab gap is currently widening and migrating northeastward beneath the Caribbean plate. OIB-type sub-slab mantle, belonging to or affected by the Galapagos plume head, has flowed eastward through the slab window, displacing the slab-metasomatized MORB-type mantle and contaminating the source region of the Central American volcanic arc. This transfer of exotic mantle, together with anatexis of the trailing edges of the slabs bounding the window, explains the pronounced along-arc variations in igneous geochemistry.

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References

[1] W.R. Dickinson and W.S. Snyder, Geometry of subducted slabs related to San Andreas transform, J. Geol. 87, 609–627, 1979.

[2] D.J. Thorkelson and R.P. Taylor, Cordilleran slab windows, Geology 17, 833–836, 1989.

[3] R.D. Forsythe and E.P. Nelson, Geological manifestations of ridge collision: evidence from the Golfo de Penas–Taitao Basin, southern Chile, Tectonics 4, 477–495, 1985.

[4] M.J. Hole, Post-subduction alkaline volcanism along the Antarctic Peninsula, J. Geol. Soc. London 145, 985–998, 1988.

[5] W.P. Leeman and M.J. Carr, Geochemical constraints in subduction processes in the Central American Volcanic Arc: Implications of boron chemistry, in: Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America, P. Mann, ed., GSA Spec. Pap. 295, 57–74, 1995.

[6] E.A. Herrstrom, M.K. Reagan and J.D. Morris, Variations in lava composition associated with flow of asthenosphere beneath southern Central America, Geology 23, 617–620, 1995.

[7] J.A. deBoer, M.S. Drummond, M.J. Bordelon, M.J. Defant, H. Bellon and R.C. Maury, Cenozoic magmatic phases of the Costa Rican Island Arc (Cordillera de Talamanca), in: Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America, P. Mann, ed., GSA Spec. Pap. 295, 35–56, 1995.
[8] D.J. Thorkelson, Subduction of diverging plates and the principles of slab window formation, Tectonophysics 255, 47–63, 1996.
[9] J. Severinghaus and T. Atwater, Cenozoic geometry and thermal state of the subducting slabs beneath western North America, in: Basin and Range Extensional Tectonics near the Latitude of las Vegas, Nevada, B.P. Wernicke, ed., GSA Mem. 176, 1–22, 1990.
[10] S.M. Peacock, Numerical simulation of subduction zone pressure–temperature–time paths: constraints on fluid production and arc magmatism. Philos. Trans. R. Soc. London A. 335, 341–353, 1991.
[11] K. Yamaoka and Y. Fukao, Spherical shell tectonics. Rev. Geophys. 24, 27–53, 1986.
[12] M. Protti, F. Guendel and K. McNally, Correlation between the age of the subducting Cocos plate and the geometry of the Wadati–Benioff zone under Nicaragua and Costa Rica, in: Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America, P. Mann, ed., GSA Spec. Pap. 295, 309–326, 1995.
[13] P.J. Haeussler, D. Bradley, R. Goldfarb, L. Snee and C. Taylor, Link between ridge subduction and gold mineralization in southern Alaska, Geology 23, 995–998, 1995.
[14] T.L. Pavlis and V.B. Sisson, Structural history of the Chugach metamorphic complex in the Tanana River region, eastern Alaska: a record of Eocene ridge subduction, GSA Bull. 107, 1333–1355, 1995.
[15] C.M. Johnson and J.R. O'Neil, Triple junction magmatism: a geochemical study of Neogene volcanic rocks in western California, Earth Planet. Sci. Lett. 71, 241–262, 1984.
[16] M.J. Hole, G. Rogers, A.D. Saunders and M. Storey, Relation between alkalic volcanism and slab window formation, Geology 19, 657–660, 1991.
[17] R.S. Marshak and D.E. Karig, Triple junctions as a cause for anomalously near-trench igneous activity between the trench and volcanic arc, Geology 5, 233–236, 1977.
[18] R.W. Johnson, A.L. Jaques, C.H. Langmuir, M.R. Perfit, M.T. McColloch, H. Staudigel, B.W. Chapell and S.R. Taylor, Ridge subduction and fore-arc volcanism: petrology, and geochemistry of rocks dredged from the western Solomon arc and Woodlark Basin, in: Marine Geology, Geophysics and Geochemistry of the Woodlark Basin–Solomon Islands, B. Taylor and N. Exon, eds., Earth Sci. Ser. 7, pp. 113–154, Circum-Pac. Counc. Energy Miner. Resour., Houston, TX, 1987.
[19] G. Rogers and A.D. Saunders, Magnesian andesites from Mexico, Chile and the Aleutian Islands: Implications for magmatism associated with ridge–trench collisions, in: Boninites and Related Rocks, A.J. Crawford, ed., pp. 416–445, Unwin Hyman, London, 1989.
[20] M.J. Defant and M.S. Drummond, Derivation of some modern arc magmas by melting of young subducted lithosphere, Nature 347, 662–665, 1990.
[21] S.M. Kay, V.A. Ramos and M. Marquez, Evidence in Cerro Pampa volcanic rocks for slab-melting prior to ridge–trench collision in southern South America, J. Geol. 101, 703–714, 1993.
[22] B.P. Luyendyk, Hypothesis for Cretaceous rifting of east Gondwana caused by slab capture, Geology 23, 373–376, 1995.
[23] J.L. Pindell and S.F. Barrett, Geological evolution of the Caribbean region: A plate tectonic perspective, in: G. Dengo and J.E. Case, eds., The Caribbean Region, Decade of North American Geology H., pp. 405–432, GSA, Boulder, CO, 1990.
[24] J.T. Freymueller, J.N. Kellogg and V. Vega, Plate motions in the North Andean region, J. Geophys. Res. 98, 21,853–21,863, 1993.
[25] P. Mann and R.A. Kolarsky, East Panama deformed belt: Structure, age and neotectonic significance, in: Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America, P. Mann, ed., GSA Spec. Pap. 295, 111–131, 1995.
[26] J.Z. deBoer, M.J. Defant, R.H. Stewart and H. Bellon, Evidence for active subduction below western Panama, Geology 19, 649–652, 1991.
[27] R. Hey, Tectonic evolution of the Cocos–Nazca spreading center, GSA Bull. 88, 1404–1420, 1977.
[28] J. Corrigan, P. Mann and J.C. Ingle, Jr., Forearc response to subduction of the Cocos Ridge, Panama–Costa Rica, GSA Bull. 102, 628–652, 1990.
[29] R.A. Kolarsky, P. Mann and W. Montero, Island arc response to shallow subduction of the Cocos Ridge, Costa Rica, in: Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America, P. Mann, ed., GSA Spec. Pap. 295, 235–262, 1995.
[30] C. DeMets, R.G. Gordon, D.F. Argus and S. Stein, Current plate motions, Geophys. J. Int. 101, 425–478, 1990.
[31] J.N. Kellogg and V. Vega, Tectonic development of Panama, Costa Rica, and the Columbian Andes: Constraints from global positioning system geodetic studies and gravity, in: Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America, P. Mann, ed., GSA Spec. Pap. 295, 75–86, 1995.
[32] G.K. Westbrook, N.C. Hardy and R.P. Heath, Structure and Tectonics of the Panama–Nazca plate boundary, in: Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America, P. Mann, ed., GSA Spec. Pap. 295, 91–110, 1995.
[33] D.J. Thorkelson, Ridge subduction: kinematics and implications for the nature of mantle upwelling: Discussion, Can. J. Earth Sci. 31, 1486–1489, 1994.
[34] W. Alvarez, Geological evidence for the geographical pattern of mantle return flow and the driving mechanism of plate tectonics, J. Geophys. Res. 87, 6697–6710, 1982.
[35] X. LePichon, Sea floor spreading and continental drift, J. Geophys. Res. 73, 3661–3697, 1968.
[36] Y. Ricard, C. Doglioni and R. Sabadini, Differential rotation

between lithosphere and mantle: A consequence of lateral mantle viscosity variations, J. Geophys. Res. 96, 8407–8415, 1991.

[37] S.T. Johnston, Asthenospheric forcing and the origin of horseshoe arcs, Geol. Assoc. Can./Min. Assoc. Can., Progr. Abstr. 20, A-50, 1995.

[38] B.L. Isacks and M. Barazangi, Geometry of Benioff zones: Lateral segmentation and downwards bending of the subducted lithosphere, in: Island Arcs, Deep Sea Trenches and Back-arc Basins, M. Talwani and W.C. Pitman, III, eds., Maurice Ewing Ser. 1, pp. 99–114, 1977.

[39] R.M. Russo and P.G. Silver, Trench-parallel flow beneath the Nazca Plate from seismic anisotropy, Science 263, 1105–1111, 1994.

[40] T.A. Cross and R.H. Pilger, Controls of subduction geometry, location of magmatic arcs, and tectonics of arc and back-arc regions, GSA Bull. 93, 545–562, 1982.

[41] S.C. Cande, R.B. Leslie, J.C. Parra and M. Hobart, Interaction between the Chile ridge and Chile trench: Geophysical and geothermal evidence, J. Geophys. Res. 92, 495–520, 1987.

[42] G. Dengo, Geodynamics of Central America, in: Geodynamics of the Eastern Pacific Region, Caribbean and Scotia Arcs, R. Cabré, ed., AGU Geodyn. Ser. 9, 33–40, 1983.