Eastbound sublithosphere mantle flow through the Caribbean gap and its relevance to the continental undertow hypothesis

Walter Alvarez*

Department of Earth and Planetary Science, University of California, Berkeley, CA 94720-4767, USA, and Osservatorio Geologico di Coldigioco, 62020 Frontale di Apiro (MC), Italy

ABSTRACT

Recent evidence indicates that beneath the Caribbean a tongue of sublithosphere mantle is flowing from the Pacific to the Atlantic, dragging the overlying lithosphere eastward: (i) Shear-wave splitting results from beneath the Andean subduction zone and Venezuela suggest mantle flow eastward through the Caribbean. (ii) Volcanic chemistry in Central America indicates a slab source beneath Nicaragua, but a different source in Costa Rica, above the proposed Pacific outflow. (iii) An extinct volcanic arc accreted to the margins of the Caribbean swept eastward through the Caribbean gap between North & South America. The 1982 'continental undertow' model requires shallow-mantle flow through the Caribbean gap from the Pacific to the Atlantic, if continents have deep roots and if shallow-mantle flow beneath oceans is decoupled from convection at deeper levels. The new evidence from the Caribbean is thus compatible with the continental undertow model, and perhaps with other models involving decoupled shallow flow.

Terra Nova, 13, 333–337, 2001

Introduction

Despite advances in understanding the dynamics and depth range of mantle flow and its relation to plate tectonic motions (Richards *et al.*, 2000), the geographical pattern of this flow is not yet well known. Almost two decades ago, I presented a technique for mapping the geography of mantle flow if two conditions hold true (Alvarez, 1982). The first condition is that flow patterns in the shallow mantle be decoupled from those deeper in the mantle. The second condition is that the old, stable parts of continents have roots that extend well below the conventional base of the lithosphere at about 100 km. If these conditions hold, shallow-mantle material driven out of the shrinking Pacific must be channelled through three gaps in the ring of continents that surround the Pacific Ocean. Sublithosphere outflow will pass eastward from the Pacific to the Atlantic through the Caribbean and Scotia gaps (Fig. 1), and will converge south of Australia with flow starting at the Java–Sumatra subduction zone.

The 1982 paper envisioned continental roots extending down into con-

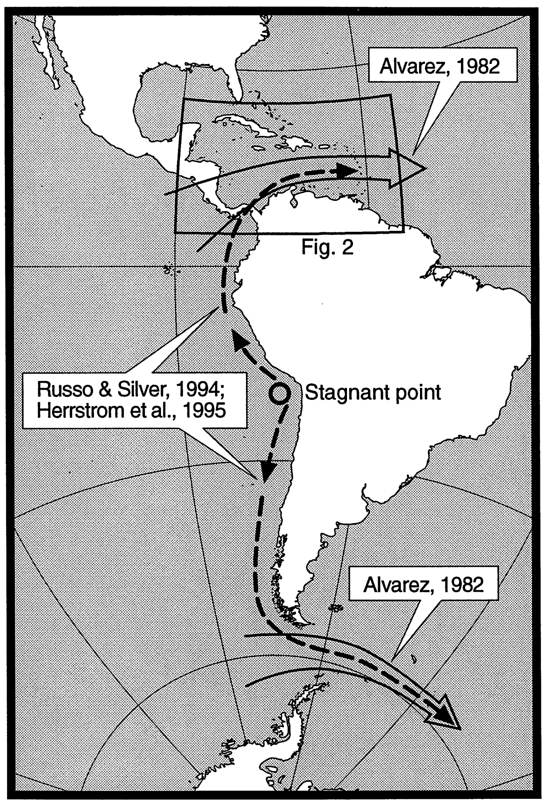

Fig. 1 Routes of sublithospheric mantle flow from the Pacific to the Atlantic proposed by Alvarez (1982) in the continental undertow model, by Russo and Silver (1994) on the basis of evidence from shear-wave splitting that subslab upper mantle west of South America flows parallel to the trench, and by Herrstrom *et al.* (1995) to explain geochemical changes in young volcanic rocks in Central America. The present paper reviews evidence supporting eastward flow beneath the Caribbean.

*Correspondence: Walter Alvarez, Department of Earth and Planetary Science, University of California, Berkeley, CA 94720-4767, USA. E-mail: platetec@socrates.berkeley.edu

tact with the lower mantle, but this now seems too deep. However, as long as there are roots instead of asthenosphere beneath at least the Precambrian nuclei of the continents, which is evident from studies of seismic anisotropy (Silver, 1996), it is difficult to avoid the conclusion that asthenosphere will flow out of the Pacific through the gaps between continental roots. In 1982, there was no way of determining directly whether the two conditions were correct, but the shallow-mantle flow pattern they predict appeared to be reflected in surface tectonics, with the Caribbean and Scotia regions characterized by eastward transport, and with the bathymetrically low and tectonically complex Australia–Antarctic Discordance at the predicted convergence point. The match between surface tectonics and predicted shallow-mantle flow suggested that the Caribbean and Scotia lithosphere was being dragged along by rapidly flowing mantle in the gaps, and this provided indirect support for the two assumptions.

Subducting slabs would also block shallow Pacific outflow, and shrinking of the Pacific by slab rollback might explain the eastward motions in the Caribbean and Scotia regions, without calling on continental roots. Blockage by slabs alone is less restrictive, because outflow could then occur beneath Antarctica and Australia. For the moment, the relative importance of continental roots and slabs as barriers to outflow is not clear, so the present paper stresses the evidence that outflow does take place beneath the Caribbean. Eastbound sublithosphere flow from the Pacific to the Atlantic (Fig. 1) had previously been proposed for the Scotia Sea by Hamilton (1963) and for the Caribbean by Meyerhoff and Meyerhoff (1977), updated by Morris *et al*. (1990).

In the 1982 paper, the evidence for Pacific outflow, combined with the assumption of deep continental roots, led to the hypothesis that the continents are dragged along by roots anchored in the top of the convecting lower mantle. Therefore, it was suggested that continental motions track the top of lower-mantle convection, indicating a simple pattern of four large lower-mantle cells. Nineteen years on, accepting that continental roots do not extend down to the lower mantle, I would revise this slightly and infer a simple pattern of four major cells at the top of the mantle beneath the asthenosphere.

A follow-up paper (Alvarez, 1990), introduced the term ‘continental undertow’ to designate this entire hypothesis and presented isotopic arguments (Klein *et al*., 1988) supporting the convergence of upper-mantle flow south of Australia. Subsequently an alternative explanation for the situation south of Australia was proposed by Gurnis *et al*. (1998). The present paper considers new information bearing on eastward flow beneath the Caribbean. This outflow is predicted by the continental undertow hypothesis, but may be compatible with other explanations, such as slab rollback, as well.

Pacific-to-Atlantic mantle outflow beneath the Caribbean

The Atlantic Ocean basin is currently growing at about 0.45 $km^2\ yr^{-1}$, and if this increase in upper mantle is supplied by sublithosphere flow through the Caribbean and Scotia gaps, each about 600 km wide, then the outflow rate is about 38 $cm\ yr^{-1}$ (Alvarez, 1982; p. 6701). The 1982 paper argued that this outflow should drag the Caribbean plate eastward by viscous coupling, but it could not be determined whether return flow extended several hundred km down through the entire upper mantle or was confined to the asthenosphere. Current interpretations of seismic tomography results suggest that below the asthenosphere the mantle is complex in structure and convection pattern. The low seismic velocity and low viscosity of the asthenosphere and its apparently broad distribution beneath oceanic crust make it a relevant layer in which to consider an independent return flow pattern. For the asthenosphere flow pattern, it is useful to distinguish between ‘return flow’, which transports material from subduction zones to ridges, and ‘escape flow’, driven out of the shrinking Pacific Ocean.

Seismological evidence for sublithosphere outflow

The seismological study of shear-wave splitting provides a technique for detecting crystalline anisotropy in the olivine of the sublithospheric upper mantle (Silver, 1996). The anisotropy is imparted by long-term, solid-state flow in the mantle, so the orientation and magnitude of shear-wave splitting reflect the pattern of accumulated mantle strain. This technique has given two results bearing on the predicted upper mantle flow toward the east beneath the Caribbean lithosphere.

Russo and Silver (1994) studied shear-wave splitting beneath the Andean subduction zone. Instead of flow lines at right angles to the trench, as expected from the usual view that the upper mantle descends coherently with the subducting slab, they found flow lines parallel to the trench (Fig. 1). They concluded that the upper mantle beneath the slab moves north and south, away from a stagnation point midway along the Andean trench, and flows eastward beneath the Caribbean and Scotia regions.

Russo *et al*. (1996) measured shear-wave splitting near the north and south ends of the Lesser Antilles island arc, in eastern Venezuela and Trinidad, and in Puerto Rico (Fig. 2). Fast polarization directions are aligned E–W in both areas, arguing for sub-Caribbean mantle flow in that direction in both areas.

Geochemical evidence for outflow

Additional evidence compatible with sublithospheric flow eastward through the Caribbean gap between North and South America comes from study of the trace-element and isotope geochemistry of volcanoes in Nicaragua and Costa Rica (Carr *et al*., 1990; Herrstrom *et al*., 1995). The lavas from these volcanoes show a systematic change in chemistry from NW to SE (Fig. 2), across the northern boundary of the outflow tongue inferred by Alvarez (1982) and by Russo and Silver (1994).

The Nicaraguan lavas have the geochemical character of mid-ocean ridge basalt (MORB), whereas the Costa Rican lavas have the character of ocean island basalt (OIB). This suggests that Costa Rica and Nicaragua ‘are underlain by mantles with different compositions and that these mantles also have different histories of interaction with the subducting slab’,

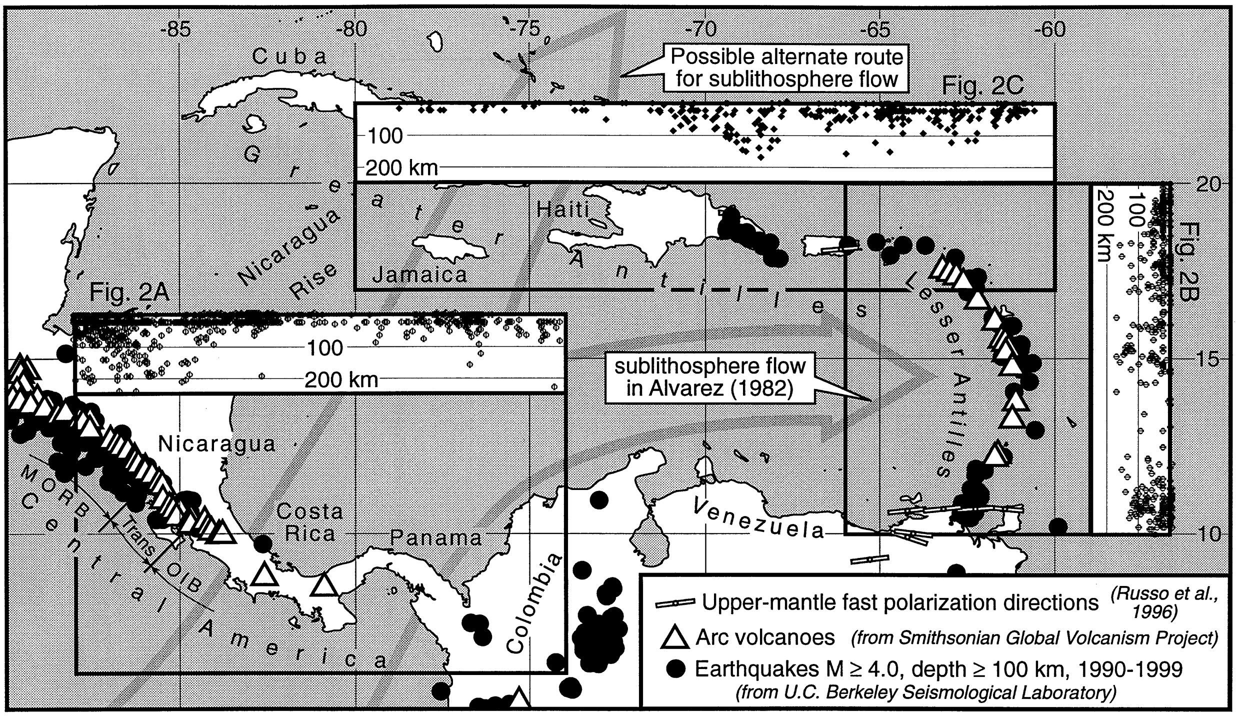

Fig. 2 Active volcanism and seismicity in the Caribbean. MORB (mid-ocean ridge basalt), Trans (transitional) and OIB (ocean-island basalt) show the character of the sources of the Central American volcanoes (Herrstrom *et al.*, 1995). Map shows seismic events $M \geqslant 4$ and deeper than 100 km. Profiles are northward or eastward projections of events inside the heavy boxes, showing all events $M \geqslant 4$. Regions with no evident barriers to asthenospheric flow are evident at the centre of profile (A) and in the left half of (C); the Lesser Antilles slab (B) presents a barrier to asthenosphere flow down to 200 km. Two possible routes for asthenospheric flow are indicated; the southeastern one would probably be restricted to the rate of eastward advance of the Lesser Antilles arc.

and that the Nicaraguan lavas are derived mainly from the subducting Cocos Plate, whereas the Costa Rican lavas are derived from a different source, which has not had much interaction with the Cocos slab (Herrstrom *et al.*, 1995).

Noting similar conclusions made in the previous year by Russo and Silver (1994), Herrstrom *et al.* (1995) argued that the source of the Costa Rican lavas is a stream of mantle which is flowing around the north-western corner of South America and through the Caribbean gap (Fig. 1).

Long-term eastward motion of the Caribbean plate

Because of the presence of E–W strike-slip faults bounding the Caribbean Plate on the north and south, it has long been clear that this small plate is moving eastward (Hess and Maxwell, 1953), with a present velocity of about 2 cm yr^{-1} relative to the Americas Plates (Minster and Jordan, 1978). This motion provided support for the original 1982 undertow hypothesis.

Since then, a more detailed understanding of the motion history of the Caribbean has been developed (Burke *et al.*, 1984; Duncan and Hargraves, 1984; Dewey and Pindell, 1985; Pindell *et al.*, 1988; Ross and Scotese, 1988; Pindell and Barrett, 1990; Pindell, 1994). A key component of this history is the interpretation of Cretaceous–Eocene arc rocks in the Greater Antilles, along the margin of South America, and in the Aves Ridge. For Pindell and Barrett (1990) and Pindell (1994), these are extinct fragments of a volcanic arc that lay near the present site of Central America in the Cretaceous, and has subsequently moved 2500–3000 km eastward through the Caribbean gap (Fig. 3). As the arc moved through this narrow passage, its ends were bent back and accreted onto the bounding continental crust of Florida–Bahamas and South America, thus becoming extinct. The central part of the arc was left behind to form the Aves Ridge, and the present Lesser Antilles arc is the successor to the central part of this far-travelled, extinct arc. Support for this view comes from the timing of orogeny dated by foredeep basins along the north and south margins of the Caribbean. These basins range from Late Cretaceous in the Yucatán, to early Tertiary in Cuba and northernmost Colombia, to late Tertiary in NE Venezuela (Pindell, 1994). This age progression seems to record the travel of the arc through the Caribbean gap at a rate of a few centimetres each year. In addition, the crust of the Caribbean has been interpreted as an oceanic plateau originally formed in the eastern Pacific, possibly over the Galápagos hotspot, and carried eastward through the gap between North and South America (Duncan and Hargraves, 1984; White *et al.*, 1999).

Although not yet fully confirmed, this interpretation of Caribbean history provides a dramatic picture of an

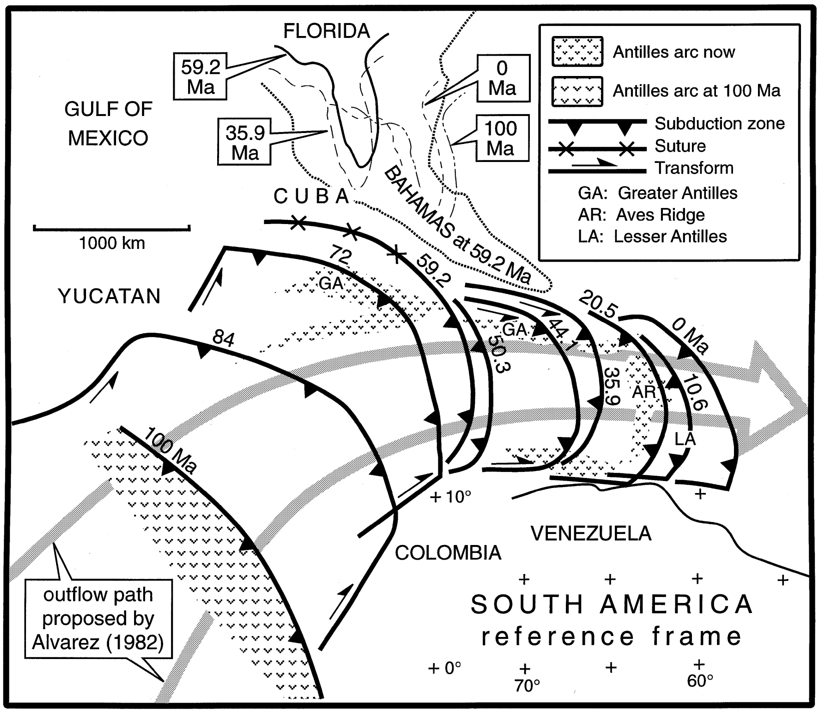

Fig. 3 Inferred eastward travel of the Antilles island arc through the Caribbean gap. The locations of the subduction zone associated with the arc through time are based on the maps of Ross and Scotese (1988), which quantify the reconstructions of Pindell and Barrett (1990). The present position of arc rocks has resulted from bending back and tearing apart of the north and south ends of the arc as they were dragged past the bounding areas of continental crust. Positions of Florida at four times show that the motion of North America relative to South America has been much less than the transport of the Antilles arc through the Caribbean gap. Ages shown are model ages from Ross and Scotese (1988); the accuracy of the dates is 2–5 Myr, and the positions of the arc are estimates, not determinations. Measurements on this map indicate that the arc has had a velocity of 3–6 cm yr^{-1} relative to South America since 100 Ma.

arc swept eastward through a narrow passageway between continents, with the oceanic crust of the Caribbean Plate following along in its wake.

Shallow-mantle outflow – barriers and pathways

The undertow hypothesis predicts shallow-mantle outflow rapid enough to drag the overlying Caribbean plate eastward. If there were recognizable barriers to this flow such as seismic slabs, they would falsify the hypothesis. A plot of earthquake foci in Central America (Fig. 2a) shows that although the seismically active slab extends to more than 200 km beneath Nicaragua and Honduras, it shallows progressively beneath Costa Rica, and there is essentially no earthquake activity deeper than 100 km beneath Panama. Johnston and Thorkelson (1997) treat this aseismic zone as a slab window allowing asthenosphere to escape from the shrinking Pacific.

There is no such shallowing of seismicity under the Lesser Antilles (Fig. 2b), where seismic activity everywhere reaches nearly 200 km, indicating a slab which would block at least the upper part of asthenospheric outflow. This slab should be moving eastward relative to South America at about the same rate as the Caribbean plate, roughly 1.5–2.5 cm yr^{-1} (Jordan, 1975; Minster and Jordan, 1978), so it is moving too slowly to be fully entrained in the 38 cm yr^{-1} outflow predicted by Alvarez (1982). This may falsify the path for outflow shown by Alvarez (1982), Russo and Silver (1994) and Herrstrom *et al.* (1995), or it may be the consequence of complicating factors: (i) lower asthenosphere outflow may be passing beneath the slab; (ii) asthenosphere volume need not be conserved, and outflow need not be evenly proportioned among the three Pacific-rim gaps, so the 38 cm yr^{-1} figure may be too high; (iii) the slab may at times have been shallower; (iv) another outflow route is possible, passing northeastward beneath Cuba, Jamaica, and Haiti (Fig. 2c). Although there would be no deep continental roots beneath these islands to block this path, the rapid outflow might be expected to exert some drag on this part of the Caribbean. It is not yet clear whether this velocity mismatch falsifies the undertow model or just complicates it.

Discussion

In developing the undertow hypothesis in 1982, I found it difficult to formulate specific or inherent predictions suitable for testing. Subsequent observations by others have given unexpected support to the model, although the agreement is not unique to the undertow model. Richards *et al.* (1988; Fig. 4) found that the residual geoid, lower mantle P-wave velocities, and hotspot density all show a dominantly degree-two spherical–harmonic pattern, and in each case this pattern agrees with the four-cell arrangement of lower-mantle flow inferred from the undertow model (Alvarez, 1982). However, the association of this pattern with old subducted slabs (Richards and Engebretson, 1992) was not foreseen in the 1982 paper. Klein *et al.* (1988) discovered that MORBs with isotopic signatures characteristic of the Indian and Pacific Oceans meet at a boundary in the middle of the Australia–Antarctic gap, exactly where the undertow hypothesis suggests that upper-mantle flow from these two reservoirs should converge (Alvarez, 1990), although this was explained in another way by Gurnis *et al.* (1998). A global review of shear-wave anisotropy (Silver, 1996) found '[n]o evidence… for a continental asthenospheric decoupling zone, suggesting that continents are coupled to general mantle circulation'. The present paper has documented three more lines of unanticipated evidence – shear-wave splitting, volcanic geochemistry, and timing of tectonism – that support eastward flow beneath the Caribbean Plate. This is a key prediction of the undertow model; and may also be compatible with other models involving decoupled shallow mantle flow.

Acknowledgements

I appreciate the availability of on-line data on seismicity from the U.C. Berkeley Seismological Laboratory, and on the location of arc volcanoes from the Smithsonian Global Volcanism Project. This paper benefited from useful comments by a number of students and colleagues: Nancy Bramble, Blair Bridges, Shannon Couch, Ben Crosby, Tony Donoghue, Joshua Feinberg, Peter Geerdts, Mark Jellinek, Wade Johnson, Daniel Karner, Shawn Lawrence, Derek Lerch, James Lin, Richard Muller, Diane OíConnor, Ryan Petterson, Mark Richards, David Shimabukuro, Erick Staley, Jason Williams, Max Wilmarth, and Stephen Zatman. I thank Don Anderson and an anonymous journal reviewer for helpful suggestions.

References

Alvarez, W., 1982. Geological evidence for the geographical pattern of mantle return flow and the driving mechanism of plate tectonics. *J. Geophys. Res.*, **87**, 6697–6710.

Alvarez, W., 1990. Geologic evidence for the plate-driving mechanism: The continental undertow hypothesis and the Australian-Antarctic Discordance. *Tectonics*, **9**, 1213–1220.

Burke, K., Cooper, C., Dewey, J.F., Mann, J.P. and Pindell, J., 1984. Caribbean tectonics and relative plate motions. *Mem. Geol. Soc. Am.*, **162**, 31–64.

Carr, M.J., Feigenson, M.D. and Bennett, E.A., 1990. Incompatible element and isotopic evidence for tectonic control of source mixing and melt extraction along the Central American arc. *Contr. Miner. Petrol.*, **105**, 369–380.

Dewey, J.F. and Pindell, J.L., 1985. Neogene block tectonics of Turkey and northern South America: continental applications of the finite difference method. *Tectonics*, **4**, 71–83.

Duncan, R.A. and Hargraves, R.B., 1984. Plate tectonic evolution of the Caribbean region in the mantle reference frame. *Mem. Geol Soc. Am.*, **162**, 81–93.

Gurnis, M., Mueller, R.D. and Moresi, L., 1998. Cretaceous vertical motion of Australia and the Australian-Antarctic discordance. *Science*, **279**, 1499–1504.

Hamilton, W., 1963. Tectonics of Antarctica. *Mem. Am. Ass. Petrol. Geol.*, **2**, 4–15.

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

Hess, H.H. and Maxwell, J.C., 1953. Caribbean research project. *Bull. Geol. Soc. Am.*, **64**, 1–6.

Johnston, S.T. and Thorkelson, D.J., 1997. Cocos-Nazca slab window beneath Central America. *Earth Planet. Sci. Lett*, **146**, 465–474.

Jordan, T.H., 1975. The present-day motions of the Caribbean plate. *J. Geophys. Res.*, **80**, 4433–4439.

Klein, E.M., Langmuir, C.H., Zindler, A., Staudigel, H. and Hamelin, B., 1988. Isotope evidence of a mantle convection boundary at the Australian-Antarctic Discordance. *Nature*, **333**, 623–629.

Meyerhoff, H.A. and Meyerhoff, A.A., 1977. Genesis of island arcs. In: *Gèodynamique Du Sud-Ouest Pacifique, Symposium International, Noumea, Nouvelle-Calèdonie*, pp. 357–370. Éditions Technip, Paris.

Minster, J.B. and Jordan, T.H., 1978. Present-day plate motions. *J. Geophys. Res.*, **83**, 5331–5354.

Morris, A.E.L., Taner, I., Meyerhoff, H.A. and Meyerhoff, A.A., 1990. Tectonic evolution of the Caribbean; alternative hypothesis. In: *The Caribbean Region* (G. Dengo and J.E. Case, eds), The Geology of North America vol. H, pp. 433–457. Geological Society of America, Boulder, CO.

Pindell, J.L., 1994. Evolution of the Gulf of Mexico and the Caribbean. In: *Caribbean Geology: an Introduction* (S.K. Donovan and T.A. Jackson, eds), pp. 13–39. University of the West Indies/Publishers' Association, Kingston, Jamaica.

Pindell, J.L. and Barrett, S.F., 1990. Geological evolution of the Caribbean region: a plate-tectonic perspective. In: *The Caribbean Region* (G. Dengo and J.E. Case, eds), The Geology of North America vol. H, pp. 405–432. Geological Society of America, Boulder, CO.

Pindell, J.L., Cande, S.C., Pitman, W.C. *et al.*, 1988. A plate-kinematic framework for models of Caribbean evolution. *Tectonophysics*, **155**, 121–138.

Richards, M.A. and Engebretson, D.C., 1992. Large-scale mantle convection and the history of subduction. *Nature*, **355**, 437–440.

Richards, M.A., Hager, B.H. and Sleep, N.H., 1988. Dynamically supported geoid highs over hotspots: observation and theory. *J. Geophys. Res.*, **93**, 7690–7708.

Richards, M.A., Gordon, R.G. and van der Hilst, R.D. (eds), 2000. *The History and Dynamics of Global Plate Motions.* American Geophysical Union, Washington, D.C.

Ross, M.I. and Scotese, C.R., 1988. A hierarchical tectonic model of the Gulf of Mexico and Caribbean region. *Tectonophysics*, **155**, 139–168.

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

Russo, R.M., Silver, P.G., Franke, M., Ambeh, W.B. and James, D.E., 1996. Shear-wave splitting in northeast Venezuela, Trinidad, and the eastern Caribbean. *Phys. Earth Planet. Int.*, **95**, 251–275.

Silver, P.G., 1996. Seismic anisotropy beneath the continents: Probing the depths of geology. *Ann. Rev. Earth Planet. Sci.*, **24**, 385–432.

White, R.V., Tarney, J., Kerr, A.C. *et al.*, 1999. Modification of an oceanic plateau, Aruba, Dutch Caribbean: Implications for the generation of continental crust. *Lithos*, **46**, 43–68.

Received 30 August 2000; revised version accepted 13 July 2001

