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Speculations on the origins and fate of backarc basins

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Abstract
The 20 or so known backarc basins (BABs) vary so much in age, duration and spreading width, rate of opening, and geological settings, that no single unifying model has been able to explain their origin, rapid opening, and diversity of configurations. We propose that the key to understanding BABs is the finite width of the slab under BABs. We show that when a normal and wide subducting slab (which is held up by hydrodynamic forces at the slab corner) is breached by lateral tears, the lifting force is lost, and the resulting slab fragment quickly sinks under its own weight. This sinking leads to the rapid opening of a backarc basin and the fast migration of the slab hinge, and the associated arc. We speculate that slab tears may be most easily caused by the docking, in subduction zones, of oceanic rises, plateaus, or seamount chains. The model implies also that backarc basin opening ceases when its associated arc approaches a spreading ridge, continental lithosphere, or another arc. The arc may then disappear, or remain as a fossil arc: such fossil arcs may give rise to great geological complexity, especially when several backarc basins have been active simultaneously, as is the case in present-day Southeast Asia, and may have been the process which formed the Alaska collage in Mesozoic times.

1. Introduction

The origin of backarc basins remains an outstanding problem of plate tectonics (Karig, 1971; Uyeda, 1977; Taylor and Karner, 1983; Jarrard, 1986). These basins are a few hundred to a few thousand kilometers wide. As the trenches associated with active basins typically migrate rapidly, at rates of several cm/y, backarc basins open up quickly, and often episodically, and remain active for short periods only. The 20 or so known backarc basins vary so much in age, duration of spreading, width, rate of opening, and geological settings, that no single unifying model to date has been able to explain their origin (Taylor and Karner, 1983). We propose that the key to understanding the opening of the backarc basins is that the underlying slabs have finite widths, and often are quite narrow. It is this aspect that controls the hydrodynamic suction acting as the corner between the subducting slab and the overriding plate. This suction keeps a wide slab from sinking straight down into the asthenosphere.

Many two-dimensional models (Elsasser, 1971; McKenzie, 1969; Sleep and Toksoz, 1971; Jischke, 1975; Stevenson and Turner, 1977; Tovish *et al.*, 1978; Yokokura, 1981; Willeman and Davies, 1982; Carlson and Melia, 1984; Hsui and Tang, 1988; Wdowinski *et al.*, 1989; Carlson and Mortera-Gutierrez, 1990; and Hsui *et al.*, 1990) share one common aspect of the subduction process – the hydrodynamic resistance at the slab corner which prevents the slab from rapid vertical sinking under its own weight (although slow motion relative to the asthenosphere does apparently occur even when suction is effective) (Garfunkel *et al.*, 1986).

The novel aspect of the model we consider here for the opening of backarc basins is based on the loss of the hydrodynamic lifting force at the slab corner, and loss of the associated lift it imparts to the plate, when the slab is laterally broken. The flow into the resulting narrow corner region is made much easier than in the very wide unbroken slab case. However, this approach implies that the narrow slab fragment, backarc basin, and the associated corner flow must be treated as a three- dimensional, not two-dimensional, problem.

Here we attempt to address four questions: 1) how and why are backarc basins initiated? 2) why do they open rapidly? 3) when and how does the opening stop? and 4) what is the cause for their diversity, as reflected by the three main types (fig. 1) – the Mariana type, with subduction under the arc in the same direction as under the neighboring plate boundaries; the Scotia type, with subduction direction under the arc opposite to the neighboring plate boundaries; and the Tyrrhenian type, with subduction restricted to the arc itself.

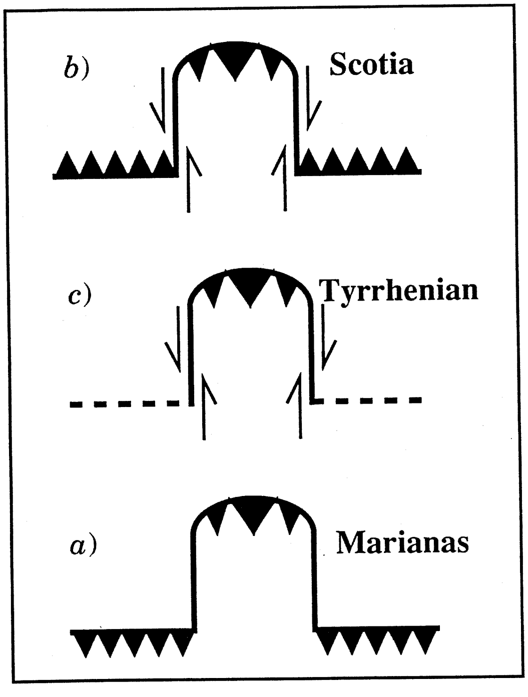

Fig. 1. Three basic types of backarc basins (BAB): a) Mariana type, with subduction under the BAB in the same direction as the entire plate; b) Scotia arc type, with subduction under the BAB opposite to the general subduction direction; c) Tyrrhenian type with subduction limited to the BAB itself.

2. The proposed model

As shown by Willeman and Davies (1982) the shape and stability of an infinitely wide, subducting slab moving with velocity V are governed by the balance between the gravitational downward pull due to a density excess $\Delta\rho$ over the asthenosphere, and the hydrodynamic lifting force at the slab corner region (fig. 2). It is this lifting force that prevents the infinitely wide slab from sinking vertically under the force of gravity into the asthenosphere.

What happens when an infinitely wide slab is breached so that a slab fragment of finite width is created? The most obvious consequence is that sideways asthenospheric flow through the tears can develop (fig. 3). This flow greatly reduces the lifting moment which holds the infinitely wide slab up.

Using the Hele Shaw approximation (Lamb, 1932) we have compared the behavior of finite and infinite width slabs. Taking a slab dip of 40°, slab thickness of 70 km, slab length of 700 km, asthenospheric viscosity of 10^{21} Pa·s, plate velocity of 8 cm/y, slab's Poisson's ratio of 0.3, and slab average Young's modulus of 2.10^{11} Pa, we find that an infinitely wide slab can be supported in its dipping configuration by the corner suction. (In this example we took a corner width of 10 km from Jischke, 1975.)

As shown in fig. 4, the viscous suction for a narrow slab fragment is significantly decreased by the sideways asthenospheric flow, causing the lifting force to decrease and consequently increasing the downward bending moment on the slab.

The slab will behave elastically under downward bending moments provided they do not exceed the slab's plastic limit. If the yield stress of the slab material is 10^8 to 10^9 Pa, the limit moment of a 70 km thick slab is about 10^{17} to 10^{18} N m/m (Rabotnov, 1979).

Whith the above parameters the distribution of bending moments along slabs of different widths are shown in fig. 4. Bending moments significantly exceed the plastic limit when slabs are 1400 km or narrower. It is therefore most likely that the resulting plastic yielding causes the instability of narrow slabs and their rapid sinking.

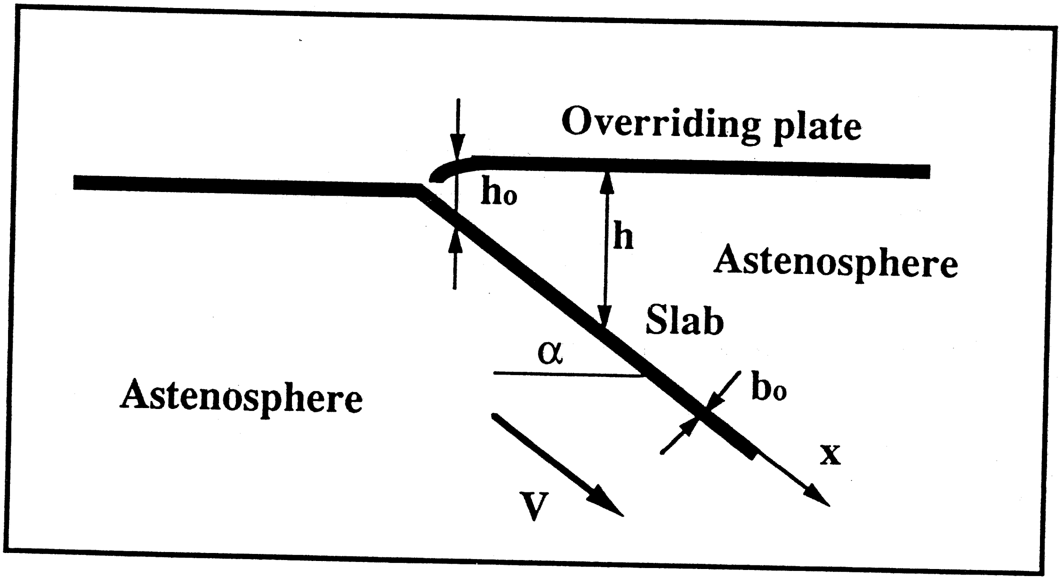

Fig. 2. Two-dimensional geometry of the corner region between the descending slab and overriding plate: relative slab velocity V, slab dip, slab thickness b_0, and corner width h_0.

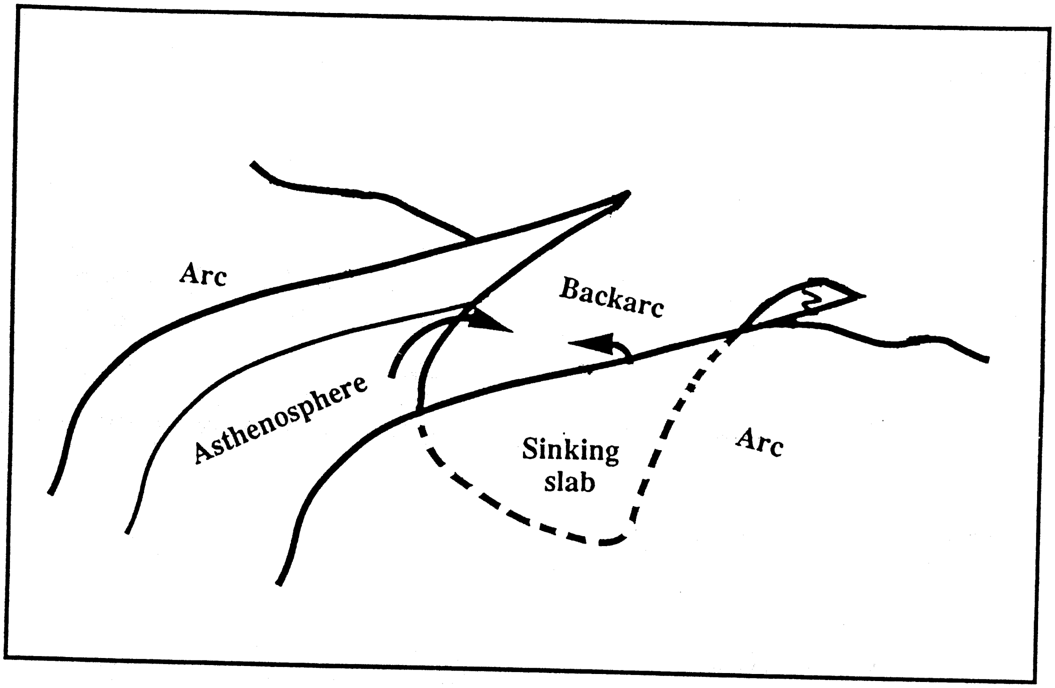

Fig. 3. Relation between slab fragment and slab from which it separated. Arrows indicate direction of asthenospheric side flow through the corner gaps.

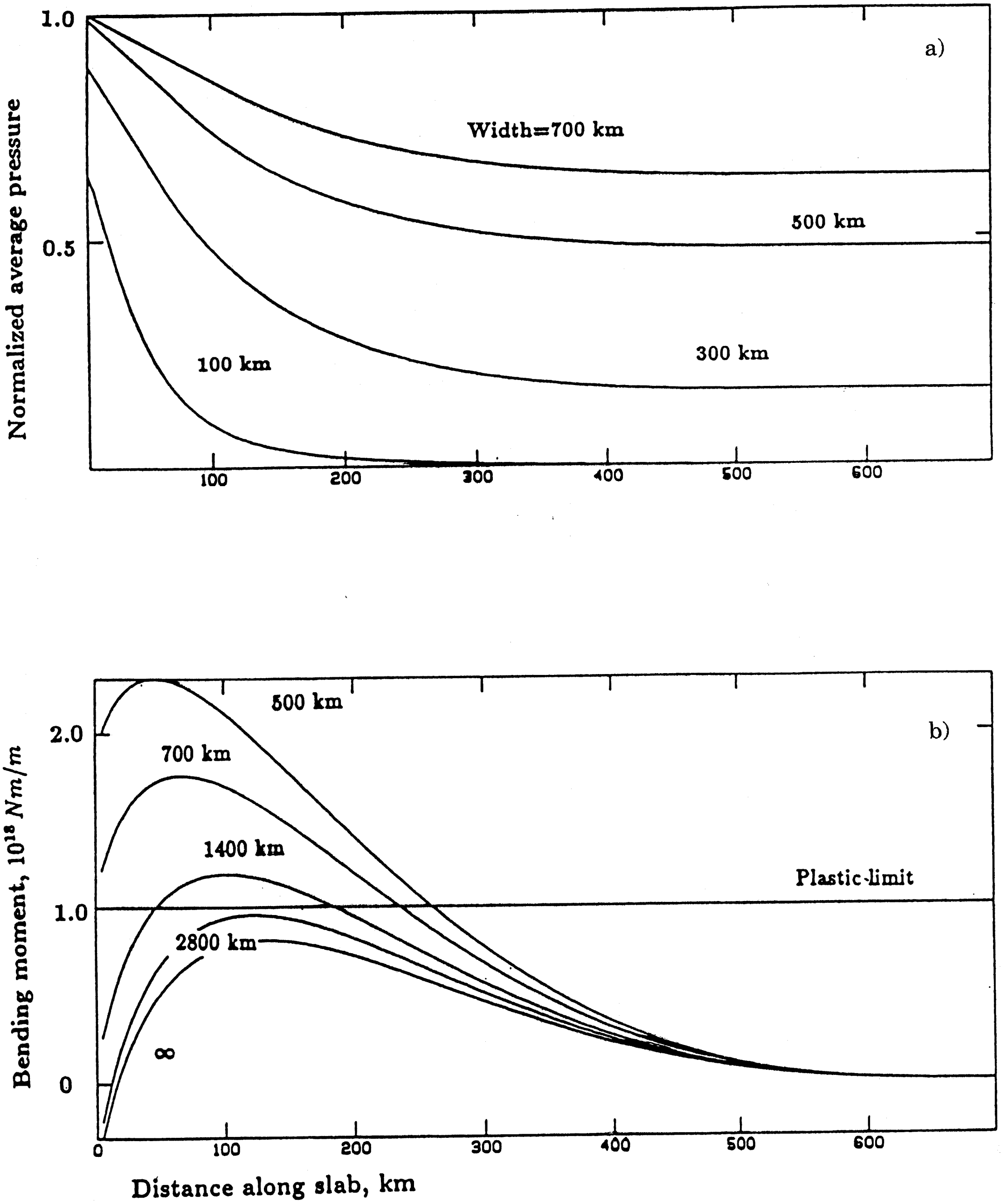

Fig. 4. a) Distribution of (normalized) average pressure along a dipping slab fragment *vs.* slab width: the average pressure is normalized by pressure distribution along an infinitely wide slab. b) Bending moment along the dipped slab *vs.* width *S* of slab fragment. Narrow slabs (S<1500 km) have bending moments which exceed their plastic yield moment.

3. Migration of the slab hinge

One consequence of this slab fragment sinking is the migration of the hinge where the slab fragment bends into the asthenosphere. This hinge migration in turn causes a backarc basin to open up, at a rate related to the fragment's sinking rate.

To relate the fragment's sinking rate to the velocity at which the hinge migrates, we assume that the difference in bending moments created by the downward gravitational force and the hydrodynamic resistance to the sinking fragment is balanced at the hinge by the plastic limit moment developed by the internal stresses in the hinge region. Estimating the hydrodynamic resistance from the steady translation of an ellipsoid in a viscous liquid (Lamb, 1932) and using the values listed above, we find that a slab 500 km wide and 500 km long can induce a hinge migration velocity between a few to 25 cm/y in reasonable agreement with the geologically determined backarc opening rates. This result suggests that hinge velocities of sufficiently narrow slabs (1500 km or so) may be on the order of tens to a few hundred km per million years. This is in reasonable agreement with geologically determined backarc opening rates.

4. Speculations on the initiation of backarc basins

What could create tears in slabs? One speculation is that the cause may be the docking of oceanic rises, plateaus, or seamount chains in regular subduction systems (Nur and Ben-Avraham, 1982; Ben-Avraham *et al.*, 1981). Such docking may disrupt otherwise «normal» oceanic slabs, and thus explain some of the diversity of types of backarc spreading behavior.

1) In the «Japan Sea» type of case (*) (fig. 5 I)) we envision that the collision and accretion of an old rise or rises with Asia-induced tears in the subducting Pacific plate. To accommodate future plate motion, the trench jumped seaward giving rise to tears at the boundaries of the accreted domain.

As a result, a slab fragment developed and began to sink rapidly underneath the collision zone, side flow was established, and the trench began to migrate backward. Similarly, in the Marianas (fig. 5 II)) the Magellan Seamount chain and the Ogadawara plateau to the north, and the Caroline ridge to the south may have caused tears in the subducting plate. The sinking of the resulting slab fragment was then presumably responsible for the rapid eastward migration of the Marianas trench.

2) In the Scotia Arc case (fig. 5III)) the slab fragment dip is opposite to the slab under South and Central America. Presumably here too, as in Japan, a rise clogged a segment of an existing trench, and caused a slab fragment to develop, and as in Japan, the trench was forced to jump. But unlike Japan the subduction direction of the new slab fragment was opposite to the original dip perhaps because the overriding oceanic plate involved was older and heavier than the subducted plate.

3) In the Tyrrhenian Sea case (Lavecchia, 1988) the encroachment of the African and the Balkan continental blocks eliminated subduction north and south of Calabrian leaving only a narrow strip of oceanic crust (fig. 6). As tears developed, the resulting slab fragment underneath today's Tyrrhenian Sea began to sink, and the trench of the Calabrian arc began to recede rapidly.

5. Cessation of backarc spreading

In our model, the cessation of backarc spreading requires the disappearance of the slab fragment. This can happen when 1) the arc approaches a spreading ridge, *i.e.* the future merger of the Scotia arc with the mid-Atlantic ridge. At current rates, this will happen in about 2.10^7a; 2) the arc collides with a continent, *i.e.* the Hellenic and Calabrian arcs (fig. 7) both of which are presently approaching collisions with Africa. At current convergence rates, these arcs will become inactive in 5.10^6 a to 10.10^6a; and 3) an arc collides with another arc, *i.e.* in Southest Asia's Sulu, Makasar, and Celebes basins (Rangin, 1989). As a pair of arcs collide subduction will cease, leaving behind closed extinct basin sutures, with the geological signature of past arc accretion.

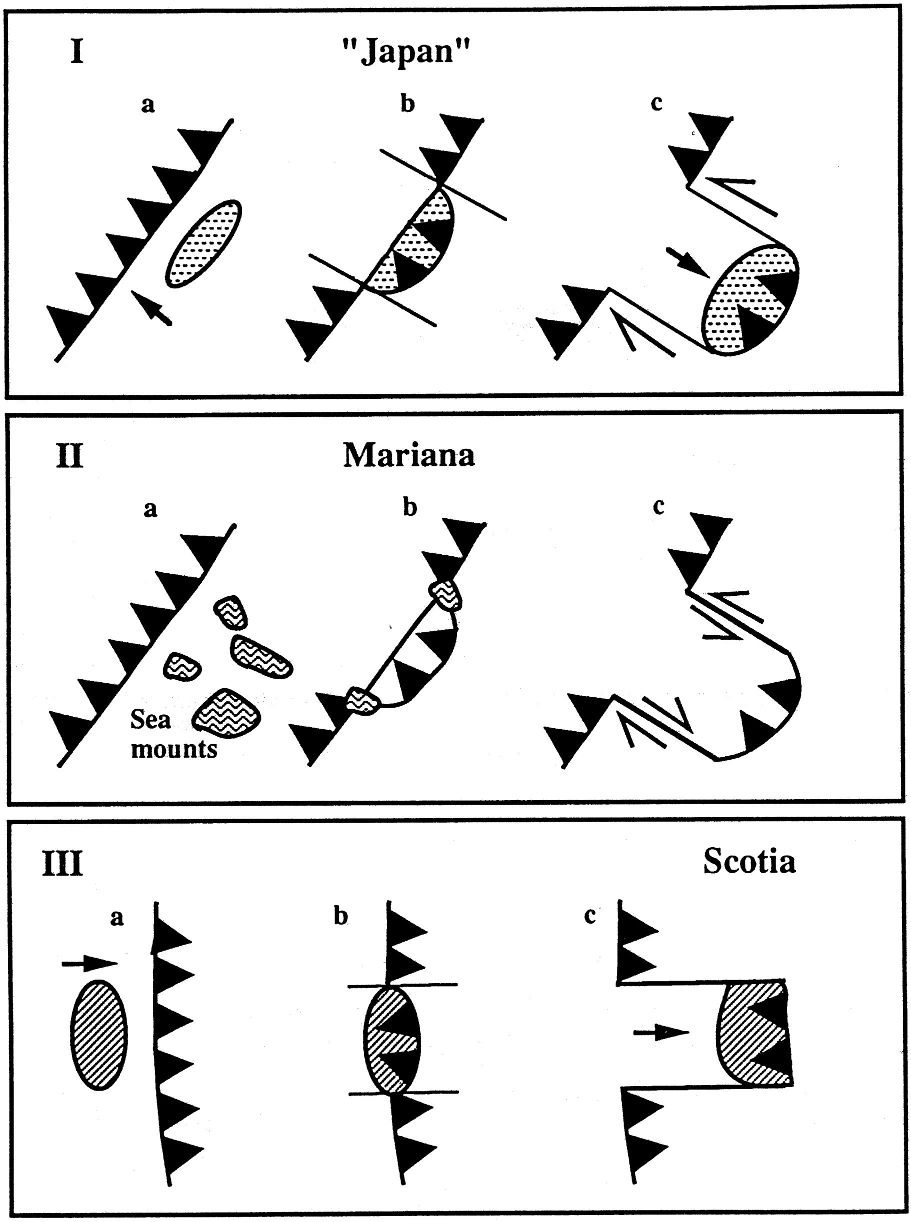

Fig. 5. I) The origin of a «Japan Sea»-type backarc basin. a) Approaching oceanic rise; b) subduction jump following the consumption of the rise, and formation of slab tears; c) opening of a backarc basin due to the sinking of the slab fragment formed between the tears. II) The origin of Mariana-type backarc basin. a) Approaching sea mount chains; b) breaching of slab by the consumption of the sea mounts; c) opening of the backarc basin. III) The origin of a Scotia-type backarc basin. a) Approaching oceanic rise; b) subduction direction flip following the consumption of the rise, and formation of slab tears; c) opening of a backarc basin, with slab fragment dip opposite to that of the slab from which it was separated.

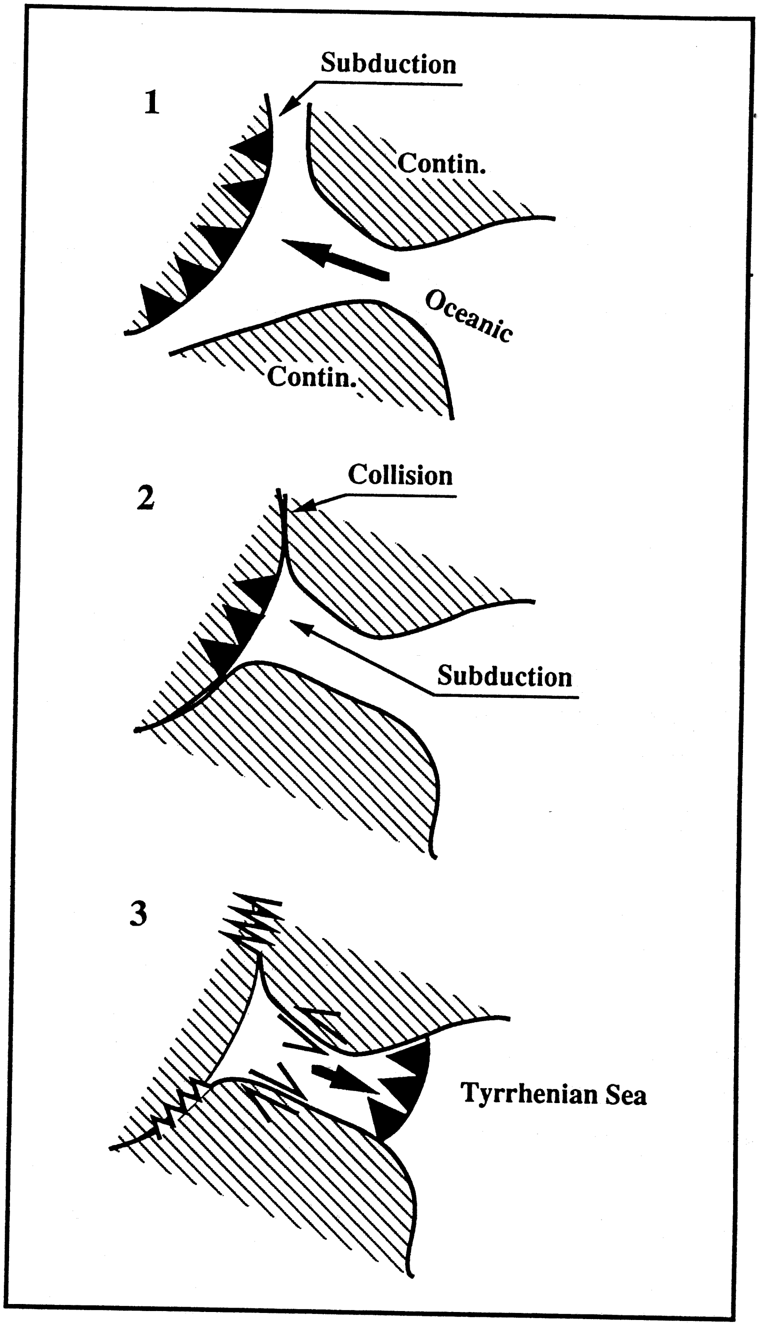

Fig. 6. Origin of the Tyrrhenian Sea. 1) Approaching continental blocks; 2) creation of a narrow subduction zone and iniziation of a slab fragment; 3) opening of backarc basin due to sinking fragment and migration of the slab hinge.

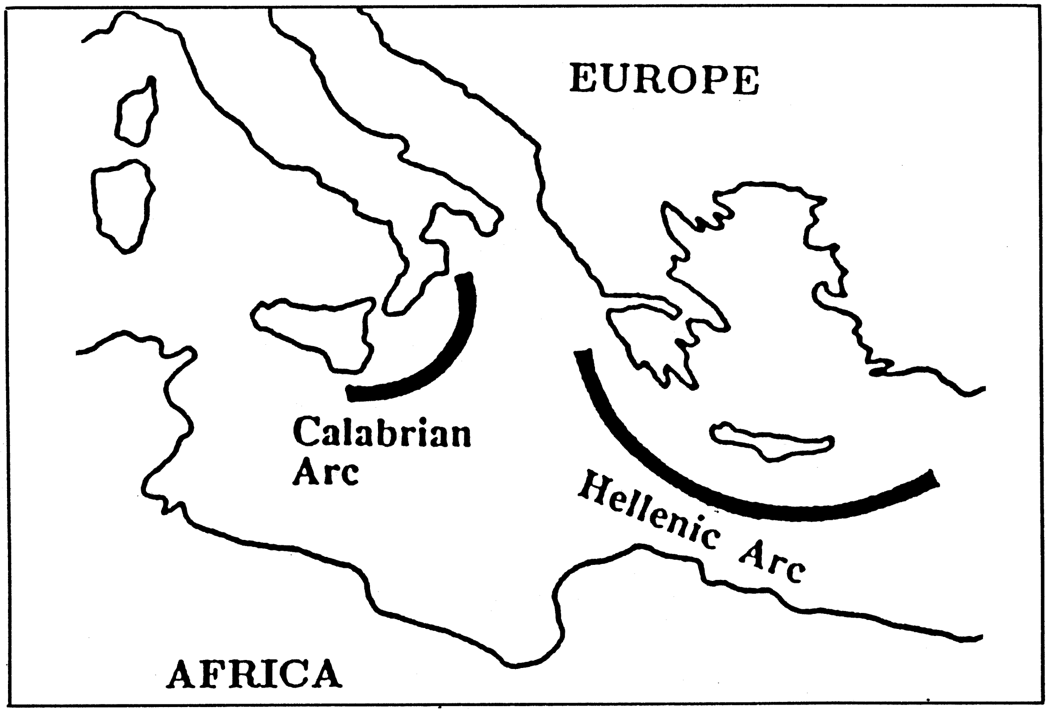

Fig. 7. The active Calabrian and Hellenic arcs are fated to collide with Africa in a few million years.

6. Orogeny and accreted terrane

The great mobility of arcs and the ease with which backarc basins can start and stop may provide also an explanation to the formation of complex collage like orogenic systems in which pile-ups of arcs, terranes and plateaus are presumably involved (Coney, 1972; Ben-Avraham *et al.*, 1981). A good example is the Southeast Asia archipelago with its multitude of falling slab fragments, active and mobile arcs, moving continental fragments, and active lithospheric tears – all presently in the process of convergence and coalescence. Because of the «freedom of motion» of the slab fragments this archipelago could, given enough time, be transformed into an Alaska-like collage consisting of a complex orogenic system of accreted terrains, and a bewildering mix of continental and oceanic rocks. Consequently, one can imagine that at coalescence rates of a few cm/y, this 1500 km wide region will become an Alaska-like collage in only a few tens of millions of years.

The orogenic complex that results from this kind of arc pile-up may be distinct from the two traditional and distinct types of orogeny: the Andean ocean-continent type and the Himalaya continent-continent collision type (*e.g.*, Wilson and Burke, 1972). The pile-up collage may represent a third, totally different kind of orogeny, which may well be responsible for the formation of some of earth's most complex orogenic belts. This process provides a possible resolution also of the stubborn debate about the origin of accreted terranes (*e.g.*, Nur, 1983): some investigators have suggested that many terranes, for example in Western North America, are far travelled, whereas others (*e.g.*, Ernst, 1984) strongly argue that they are mostly arcs that separated from and returned to North American following only a short episode of opening and closing of a backarc basin. If our model is correct, these two seemingly opposing processes may in fact be closely interlinked: the arrival and docking of anomalous oceanic rise or plateau – presumably far travelled – is the requirement for the opening of a backarc basin in the first place, so that both local backarc opening and far-travelled rises are involved.

7. Summary

Tears in subducting plates are the most likely cause for the loss of lifting force at the corner between slabs and their overriding plates. Tears give rise to slab fragments that can rapidly sink under gravity vertically into the asthenosphere. This sinking leads to the fast migration of the slab hinge and the rapid opening of a backarc basin. The narrower the fragment the easier it is for it to sink, and for the backarc basin to open up. We speculate that the tears which create the slab fragment may be caused by the arrival in subduction zones of oceanic rises, plateaus, or seamount chains.

According to the model proposed here backarc basin openings cease when their arcs approach spreading ridges, continental lithosphere, or other arcs. They then may disappear, or else leave behind fossil arcs consisting of oceanic, continental, or mixed rocks. Such fossil arcs may lead to great geological complexity, especially when several backarc basins have been active simultaneously, as is the case in present-day Southeast Asia, and was the case in Alaska in Mesozoic times.

(*) It was pointed out by several reviewers that the Japan Sea itself may actually not fit our model. Because the evidence is not in as yet, we use the «Japan Sea» only as a name of the kind of processes we envision here.

REFERENCES

BEN-AVRAHAM, Z., A. NUR, D. JONES and A. COX (1981): Continental accretion: from Oceanic plateaus to allochthonous terranes, *Science*, **213**, 47-54.

CARLSON, R.L. and P.J. MELIA (1984): Subduction hinge migration, *Tectonophysics*, **102**, 399-411.

CARLSON, R.L. and C.A. MORTERA-GUTIERREZ (1990): Subduction hinge migration along the Izu-Bonin-Marinara Arc, *Tectonophysics*, **181**, 331-344.

CONEY, P.J. (1972): Cordilleran tectonics and North America plate motion, *Am. J. Sci.*, **272**, 603-628.

ELSASSER, W.M. (1971): Sea floor spreading gas thermal convection, *J. Geophys. Res.*, **76**, 1101-1112.

ERNST, W.G. (1984): California blueschists, subduction and the significance of tectonostratisgraphic terranes, *Geology*, **12**, 436-440.

GARFUNKEL, Z., C.A. ANDERSON and G. SCHUBERT (1986): Mantle circulation and the lateral migration of subducted slabs, *J. Geophys. Res.*, **91**, 7205-7223.

HSUI, A. T. and X. TANG (1988): A note on the weight and the gravitational torque of a subducting slab, *J. Geodyn.*, **10**, 1-8.

HSUI, A.T., X.M. TANG and M.N. TOKSOZ (1990): On the dip angle of subduction plates, *Tectonophysics*, **179**, 163-175.

JARRARD, R.D. (1986): Relations among subduction parameters, *J. Rev. Geophys.*, **24**, 217-284.

JISCHKE, M.C. (1975): On the dynamics of descending lithospheric plates and slip zones, *J. Geophys. Res.*, **80**, 4809-4813.

KARIG, D.E. (1971): Origin and development of marginal basins in the Western Pacific, *J. Geophys. Res.*, **76**, 2542-2561.

LAMB, H. (1932): *Hydrodynamics* (Cambridge Press).

LAVECCHIA, G. (1988): The Tyrrhenian-Apennines system: Structural setting seismotectogenesis, *Tectonophysics*, **147**, 263-296.

MCKENZIE, D.P. (1969): Speculations on the consequences and causes of plate motions, *Geophys. J. R. Astron. Sci.* **18**, 1-32.

NUR, A. (1983): Accreted terranes, *J. Res. Geophys.*, **21**, 1779-1785.

NUR, A. and Z. BEN-AVRAHAM (1982): Oceanic plateaus, the fragmentation of continents, and mountain building, *J. Geophys. Res.*, **87**, 3644-3661.

RABOTNOV, U.N. (1979): *Mechanics of deformable solids* (Moscow).

RANGIN, C. (1989): The Sulu Sea, a backarc basin setting with a Neogene collision zone, *Tectonophysics*, **161**, 119-141.

SLEEP, N. and M.N. TOKSOZ (1971): Evolution of marginal basins, *Nature*, **23**, 548-550.

STEVENSON, D.J. and J.S. TURNER (1977): Angle of subduction, *Nature*, **270**, 334-336.

TAYLOR, B. and G.D. KARNER (1983): On the evolution of marginal basins, *J. Res. Geophys.*, **21**, 1727-1741.

TOVISH, A., G. SCHUBERT and B.P. LUYENDYK (1978): Mantle flow pressure and the angle of subduction: Non-Newtonian corner flows, *J. Geophys. Res.*, **83**, 5892-5898.

UYEDA, S. (1977): Some basic problems in the trench-arc-back-arc systems, in «Deep Sea Trenches and Back-Arc Basins», edited by M. TALWANI and W.C. PITMAN III, Island Arcs, *Maurice Ewing Series, A.G.U.*, **1**, 1-14.

WDOWINSKI, S., R.J. O'CONNEL and P. ENGLAND (1989): A continuum model of continental deformation above subduction zones: Application to the Andes and the Aegean, *J. Geophys. Res.*, **94**, 10 331-10 346.

WILLEMAN, R. and G. F. DAVIES (1982): Bending stresses in subducted lithosphere, *Geophys. J.R. Astron Soc.*, **71**, 215-224.

WILSON, J.T. and K. BURKE (1972): Two types of mountain building, *Nature*, **239**, 448-449.

YOKOKURA, T. (1981): On subduction dip angles, *Tectonophysics*, **77**, 63-77.