# A Model of Arc Development, with Doubts and Questions: an Editorial offering*

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This slight offering, in part both speculative and provocative, is also my reward for much agonized editing, or at least it will be if my fellow contributors in particular, or readers in general, enter into discussion and argument on the doubts and questions offered at the end. It is a set of editorial musings, a modified version of part of an earlier preview on island arcs together with a newly conceived cartoon which featured as a lantern slide during the proceedings of our workshop/seminar.

For model purposes a fully developed arc system can be considered as made up of certain intrinsic and associated elements, labelled on the last of the accompanying profiles: continent (C) – marginal sea (MS) – remnant arc (RA) – interarc basin (IAB) – arc orogen (AO) – fore-arc or frontal arc (FA) – accretionary prism (AP) with trench slope break (TSB) – trench (Tr) – trench outer slope (OS).

The growth of the system, an arc with normal polarity, can be summarised in a set of arbitrary stages.

*1. The inception stage*

By some means or other subduction begins. The cartoon suggests a sort of hot linear roll-front which heats the oceanic lithosphere and which is associated (by chance ?) with a deep fracture system, what Russian geologists term an 'abyssal' fracture, possibly an old transform. A degree of asymmetry, of skewness, is envisaged so that the lithosphere to the right of the fracture, that below B, is relatively unaffected. As the heated lithosphere grows hotter, it arches, cracks and produces whaleback swells of the first arc lavas. The colder lithosphere alongside begins to droop into the less dense hotter material; once it bends sufficiently then the snout starts subducting (it must move because it is still part of a driving plate). The real problem is to get the snout to drop sufficiently to clear all or most of the opposed slab. It helps here to invoke strong strike-slip motion along the fracture system, together with Menard's bobbing action of the lithosphere over a bumpy asthenosphere. If this is done in the early stages it is not so difficult to slide or part-slide a corner of the to-be-subducted slab beneath what will be the superposed slab. Under this scheme, the Alpine Fault is a 'failed' part of the Kermadec subduction zone, failed because the continental New Zealand Plateau could not be subducted.

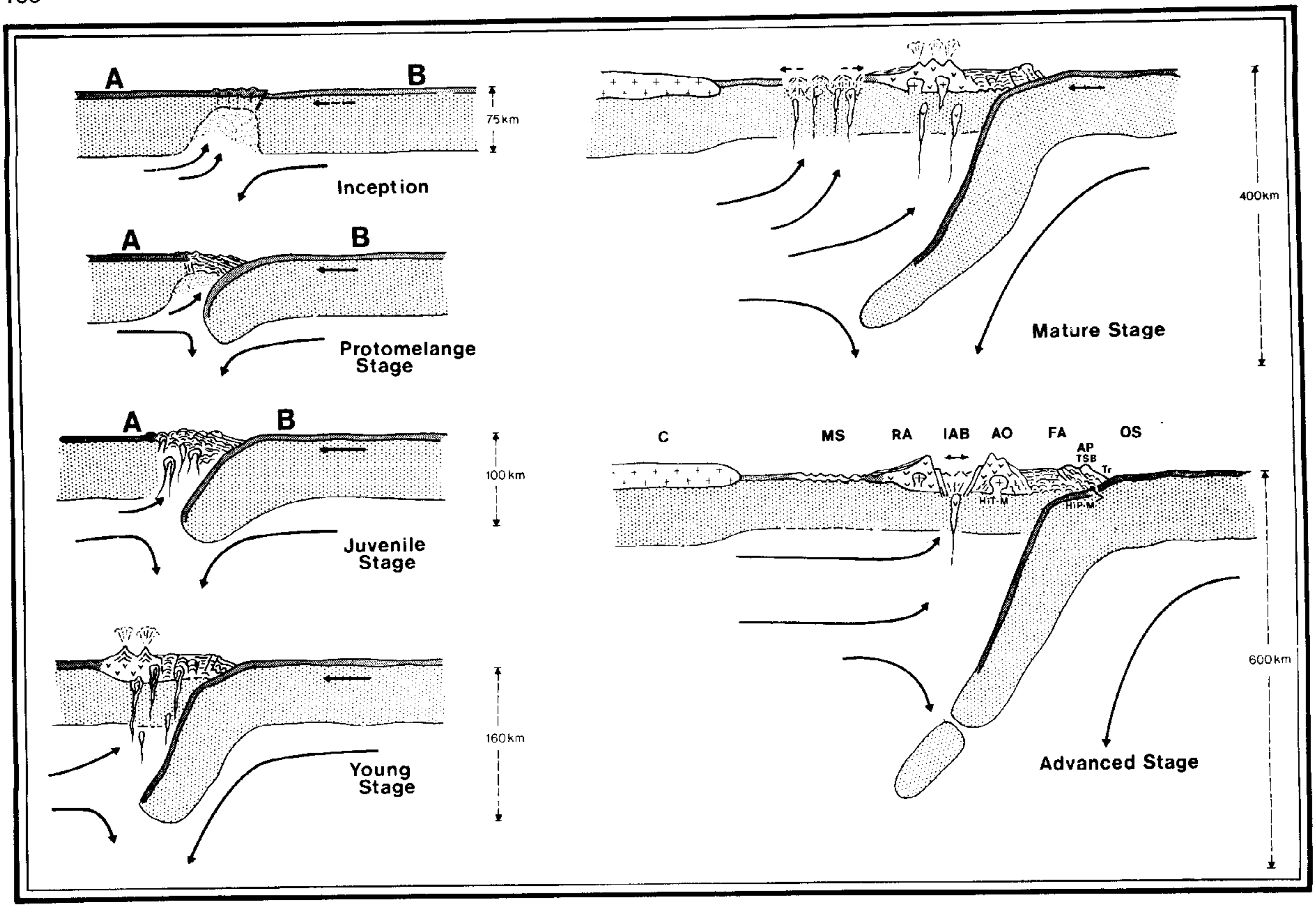
*2. Protomelange stage*

With subduction initiated the trench is formed and the slab reaches depths (greater than 10 km) where metamorphism primarily of high pressure-low temperature type produces a large component of the arc melange, hi-pressure metamorphics. These form a mixture with seafloor sediments and slices of oceanic crust, and are plastered against the face of the superposed slab in the early stages of subduction; they are the first rocks of the accretionary prism. Melts from the major causative agent, the high heat regime, continue to be produced at the surface. They are added to as the slab reaches greater depths (60-90 km) by diapiric intrusions, and extrusions, which result from the action of frictional heat and the heat of the mantle on the surface of the slab and the mantle immediately above. The lava base, intruded by dykes and subplutons, is now established. Deepsea oozes (pelagites) may be trapped in small quantities and metamorphosed within the growing lava pile. The arc tholeiites compose much of this pile and, it is suggested, begin soon after the onset of subduction.

*3. Juvenile or accretionary-prism stage*

Fissure extrusion and intrusion of magmas continue and shield-type volcanism shifts gradually to the rear of the lava pile. Granted occasional speeding-up of lava production, consequent upon change in spreading rates, then some lava ridges may at times become subaerial so that minor amounts of wackes and peperites are added to the developing strati-

*The form of this editorial is unusual, even eccentric, so enhancing the chances of it being read.




graphic column. Nearer the trench, underthrusting, imbrication and normal faulting goes on, the accretionary prism grows in volume and may include significant amount of ultramafites with the potential for remobilisation. The arc is now represented by rocks that at a later stage will be portion of the arc trench gap. In particular, the fore-arc zone, between the volcanic axis and the accretionary prism is now set to act as a trap for sediment derived from the volcanic arc orogen, by now mountainous enough, at the end of this stage, to be subaerial and to form an island chain.

*4. Young stage*

As the slab passes through the amphibolite-eclogite transition the conditions are set for calcalkaline magmatism. Andesitic volcanism begins when the tongue of the slab is at about 100 km depth and results in a rear-sited chain of explosive volcanoes with a tendency to regular linear spacing. Sedimentation, both terrigenous and organogenic, proceeds vigorously. The accretionary prism reaches a volume such that it begins to rise isostatically, the trench becomes markedly asymmetric, the frontal arc and the rear slopes of the accretionary prism (together comprising the arc trench gap) collect large volumes of sediment over a horsts and graben terrain.

*5. Mature stage*

Andesites now form the bulk of the extruded rocks, although basalts may be still added to the frontal area, over the shallower interval between slab and surface. The arc is now a thickened rim of the crustal edge of the superposed plate and responds isostatically. Taphrogenesis intensifies over the whole arc and creates a system of jostling horsts and deep graben which fill even as they form; filled graben are raised as horsts and their sediment caps are recycled into new graben. Diorite plutons may be emplaced near the surface adjacent to the volcanic chain. The arc trench gap widens; the accretionary prism continues to rise and to advance over the subducting slab. At this stage, all the architectural elements of the system are present: trench, accretionary prism (with inner trench wall, trench slope break), frontal arc and arc orogen (main volcanic arc). The TSB may stand above sea levels to form an outer non-volcanic arc. High temperature metamorphics (greenschists, amphibolites, migmatites, gneisses) are produced in the upper parts of the main arc, all rocks of the column being affected. During this stage the slab may retreat, possibly as a result of direct interference with mantle flow, and the arc system follows (Why?). Diversion of mantle material results in diapiric upwelling to floor the gap which will eventually result in a marginal sea or basin.

*6. Advanced stage*

As the slab plunges deeper (and more steeply) to depths of 400 km or more, magmatism becomes increasingly complex; crustal thickness approaches the continental and rhyolitic lavas may be extruded and granitoid plutons, e.g. tonalites, be emplaced within the main arc. When the marginal sea crust reaches oceanic thickness or greater, the mantle diapirs are further accommodated by splitting of the arc so that the rear of the main arc is detached as a remnant arc, with interarc basin in between; the remnant arc may remain volcanic.

Migration of the arc and its splitting results in accelerated mixing and fractionation of magmas at depth and the extrusion of exotic lavas which do not fit the normal arc series.

7. *Old* or *Accretion stage.*

The arc system is now old, perhaps 70 m.y. or more. Given acceptable rates of seafloor spreading, a radical interruption of the subduction process is now overdue. Choking or partial stifling of subduction can be brought about by the incursion of a thick, relatively light and buoyant mass which cannot be subducted, such as a continental edge or another island arc. Should this occur, and the chances are high that it will by now, then flipping of the subduction zone may follow with a reversion, or rejuvenation, of the arc to a younger stage. It will reverse its polarity. Retracking migration will consume the old marginal sea, ending with collision, perhaps final, against a continental margin. The details are not indicated because so little is known about the actual mechanisms of accretion. For the special case of a continent which is carried on a moving plate against the arc-lipped edge of the superposed plate, it is easy to envisage outright collision and the welding of the arc to the continent. In the case of marginal and oceanic arcs which backtrack, with marginal sea and interarc basin being consumed in the process, a final accretion is a theoretical possibility. Given the fact of subduction-flipping, however, then with marginal sea consumed and the arc brought up against a continent, it is open to suggest a further flip and so launch the arc seawards again!

## Doubts and questions

In the general business of island arcs there are many, many doubts, problems and questions to be asked. I select some that appeal to me. What causes subduction? In the scheme, I suggest a very hot linear front but this is really a condition; what causes it, or could cause it, I do not know. Why should subduction take place at one place rather than another? If a feature from some previous regime (an old transform) is a governing feature then the cause must be free-moving and must move with the plate, since subduction is not instantaneous. At the very beginning of subduction, how does the new leading edge clear the opposing edge? This is the problem of drooping, of bending the slab, for which I give only a poor answer. There is the problem of the varying degree of curvature of arcs. The Kuriles reflect the trace of a plane (the top surface of the slab) cutting into a sphere but not all arcuate arcs can be so easily explained; perhaps crimping, along the lines of a bottle crown seal, is part of the answer but the severity of the angle of abuttment between adjacent arcs is difficult to accept given lithospheric rigidity. Within the arc suite of lavas, why the *successive* progression of lava types? As the slab descends tholeiites give way to calcalkaline rocks but why do tholeiites actually cease to be produced? Within the available models the basic conditions for continued production of tholeiites seem to be present. Again, do arc tholeiites follow the extrusion of great volumes of ocean-floor basalts? It is difficult to accept the inception of subduction without the extrusion of floods of basalt. Why don't some arcs, oceanic ones such as Tonga, produce greater volumes of andesitic lavas? What is the effect of the sinking slab, a hanging screen of great size, even at a natural scale, on the heat regime of the upper mantle in general, and on convection currents and movement of mantle material in particular? Why do slabs sink so deeply rather than level out at about the level of the second order discontinuity at 350-400 km? This query is linked to the next: do slabs retreat? How can they retreat if the tongue is already at great depth e.g. Tonga slab? If the slab does not retreat then how is the room provided for the fairly rapid creation of marginal sea and interarc basin? Why should the arc body follow the retreating slab? These are all linked questions and the answers have strong relevance to the evolution of arc systems. Is it valid to talk about evolutionary arc development for relatively short periods of geological time? Are my stages, to about 70 m.y., imposed fictions? Progression and stages are fine until the slab is deep but does this herald the death of the arc from sheer old age at even 100 m.y. (putting aside the choking of subduction)? At even slow half-rates, say 1 cm/yr, a subduction zone 100 m.y. old has consumed 1000 km of slab, which puts it very deep indeed. And yet we know that around the Pacific some thousand of kilometres of ocean surface has been lost, linearly, over the last 100 m.y. Then there is the notion of subduction flipping. Why should the overall economy of plates' interaction (the governing principle) dictate a flip to the reverse side of an arc, facing the existing, old subduction zone, rather than the formation of a new zone in an entirely new location? Given the presence of deep hot zones below some arcs, e.g., below the Lau-Tonga interarc basin, then the answer to this query may be related to the first one: what causes subduction? Having come full circle I will stop at that.