PLATE TECTONICS: Lecture 5

SUBDUCTION ZONES and ISLAND ARCS

Subduction Zones are where cool lithospheric plates sink back into the mantle. It takes about 50 my for the ocean lithosphere that formed in the hot (>1000°C) environment at mid-ocean ridges to cool to an equilibrium state and sink to its maximum depth below sea-level. Although there is no universal agreement on the balance of forces that drives plate tectonics, the "slab-pull" force is thought to be an important one. For instance the Pacific Plate is the fastest moving plate (ca. 10 cm/yr), and this is the plate that supplies most of the Earth’s subducting lithosphere, and thus where the overall slab-pull force will be the larger. The normal argument is that the cool ocean crust will more easily convert to dense eclogite which, as we have seen in Lecture 1, is much more dense than pyrolite.

What is most surprising is the great variation in geological features associated with subduction. There is a huge difference between the East Pacific and the West Pacific. Not only that, but there are differences along the Andean margin, and also quite major differences as we go back in time. But it is important to understand subduction because this is where the continental crust grew progressively with time.

Subduction is where tectonics, structural geology, sedimentation, igneous petrology, metamorphism, geochemistry, geophysics and applied geology all interact. Typical "textbook" features of a mature continental margin subduction zone are shown below. The cartoon shows sediment being scraped off the downgoing plate to form an accretionary wedge, and that a forearc basin is forming on top of the wedge as it is dragged down (and is presumably fed by volcanic debris from the arc). However, the cartoon avoids the issue of how and where the volcanic magmas come from. To what extent does the basaltic subducted slab contribute to arc magmas? Is it just the fluids carried down in altered oceanic crust that migrate into the mantle wedge overlying the subduction zone and cause melting? Or what extent do sediments carried down the subduction zone then contribute to arc magmas? Why are arc volcanoes nearly always situated about 110 km above the Benioff Zone? What happens to material taken down the subduction zone?

MARGINAL BASINS & BACK ARC SPREADING

Marginal basins are a common feature of the Western Pacific. Examples (north to south) are the Sea of Japan, the West Philippine Basin, the Parace Vela & Shikoku Basins, the Mariana Trough, the Woodlark Basin, the Fiji and Lau Basins. By contrast marginal basins are rarer in the Eastern Pacific. The two examples in the Atlantic are the Caribbean and the Scotia Sea.

Margar basins are small oceanic basins, usually adjacent or "marginal" to a continent, which are separated from larger oceans by an island arc. Some marginal basins at continental margins may be imperfectly developed and represented by thinned crust, often associated with basic volcanism. Karig (1971, 1974) divided marginal basins into:

1. Active marginal basins with high heat flow.
2. Inactive marginal basins with high heat flow.
3. Inactive marginal basins with normal heat flow.

The first two are thought to have formed by back-arc spreading, either still active (1), or recently active (2). The third may represent basins formed by even older back-arc spreading, or normal ocean crust that has been "trapped" behind a recently developed oceanic island arc.

FRAMEWORK OF AN ISLAND ARC SYSTEM

The commonly held model of an arc - back-arc system has the following components:

1. Subduction Zone
2. Fore-arc region with accretionary sedimentary prism
3. Frontal Arc
4. Active Arc
5. Marginal Basin with spreading centre
6. Remnant Arc
7. Inactive Marginal Basin

Although the extensive fore-arc region of many island arcs was thought to be composed of off-scraped sediments, drilling has not substantiated this. It appears that - at least at intraoceanic arcs - abyssal sediments on the downgoing plate are largely subducted.

That the back-arc region is a zone of asthenospheric upwelling is supported by seismic evidence which suggests a low-Q (seismic attenuation) zone behind the arc, compatible with a small amount of melt in the back-arc region.

Magnetic anomalies in back-arc basins are not so well developed, nor have such symmetrical linear patterns, as those in the normal ocean basins. There have been difficulties in identifying the anomalies. It has been suggested by Lawver & Hawkins (1978) that
spreading may be more diffuse and not constrained to one central well-defined spreading centre. Good dateable magnetic anomaly patterns were first described from the Scotia Sea back-arc basin (IA Hill). Spreading in some basins may be asymmetric, with accretion favoured on the active arc side.

**Models for Back-arc Spreading** (see Karig, 1974)

**Active Diapirism:** One of the earliest models, based on the Mariana Arc System, is that of an uprising diapir splitting the arc. The diapir is initiated either as a result of frictional heating at the subduction zone, or more likely through fluids released from the dehydrating subducting slab. The rising diapir then splits the arc in two and the two halves are progressively separated by seafloor spreading:

**Passive Diapirism:** This results from regional extensional stresses in the the lithosphere across the arc system. In effect the downgoing slab, although acting like a conveyor belt, also has a vertical component that causes “roll-back”. The arc and forearc then stays with the subduction zone, as a result of a supposed trench suction force:

**Stepwise Migration:** Here it is assumed that the subducting slab is snapped off near the hinge, presumably because something on the downgoing slab is too light to go down, and so a new subduction is initiated oceanwards. The arc stays near the hinge and the asthenosphere wells up behind it:

**Convection-driven:** This model proposed by Toksoz & Bird (1978), and requires that subsidiary convection cells are driven by the downward drag of the downgoing slab. Calculations suggest that spreading would occur about 10 my after the start of subduction. This might explain why back-arc spreading is more common in oceanic regions™ the lithosphere is thinner and thus more easily disrupted than under continents:

**Uprising Harzburgite Diapir:** This model (Oxburgh & Parmentier 1978) depends on the fact that refractory lithosphere (which has lost its basalt component at mid-ocean ridges) is less dense and inherently more buoyant than normal fertile mantle. Thus it would rise if heated to same temperature as surrounding mantle. Such diapirs could in theory be derived from subducting lithosphere, although it is doubtful that subducting lithosphere could be heated within 10 my; more likely it takes 1000 - 2000 my according to megalith concepts of Ringwood (1982):

**Old and Young Lithosphere:** Molnar & Atwater (1978) have argued that it depends on the dip of the subducting slab whether extension occurs in the back arc region. In the W. Pacific it is old (Jurassic), cold and dense lithosphere that is subducting - with very steep dip and strong vertical component. Thus extensional conditions in back-arc region. In the E. Pacific, on the other hand, the lithosphere subducting beneath the Andes is young (Tertiary), warm and less dense, and subducts at a shallow angle. Thus convergence is more compressive than extensional. Uyeda & Kanamori (1979) have characterised these two extreme types of subduction as Mariana and Chilean type respectively. See also Dewey (1981)
**Other models:** Various researchers have since commented on the possible causes of back-arc spreading, including assessments of dependence on absolute and relative plate motions. Consult some of the references listed below. Experimental laboratory studies have been carried out by Kincaid & Olsen (1987), observing the effects of continued subduction where the subducting slab ‘hits’ the 650 km discontinuity. The results show that steep subduction does produce a significant roll-back effect on the hinge, which will generate extensional conditions in the back-arc region. Note that with subduction rates of about 7 cm/yr it would take about 10 my before newly subducted ocean lithosphere would ‘hit’ the 650 km discontinuity and begin to initiate ‘roll-back’ of the hinge, and thus extensional conditions.

**EVOLUTION OF MARIANA ARC SYSTEM**

The Mariana Arc is perhaps the type intra-oceanic arc system, and the most extensively studied through marine geophysical studies, dredging and drilling (particularly Legs 58, 59 and 60 of DSDP in late 1970’s). From west to east it consists of the following features:

1. **West Philippine Basin**: This may be ‘trapped’ in origin and not strictly formed by back-arc spreading. It appears to pre-date the Kyushu-Palau Ridge. Magnetic anomalies suggest active spreading in the early Tertiary (62-40 Ma) with the NW-SE trending Central Basin Fault as the spreading centre. The Oki-Daito Ridge in the northern West Philippine Sea is aligned parallel to this feature and has been regarded as an old remnant arc; however drilled samples from the Oki-Daito Ridge are alkali basalts, not island arc basalts.

2. **Mariana Trough**: This is 1500 km long, 250 km wide. Rough topography, high heat flow. Magnetic lineations poorly developed, but suggest back arc spreading from about 6 my ago - i.e. when activity on West Mariana Ridge ceased. Near the West Mariana Ridge metabasalts, gabbros and anorthositic cumulates were drilled - deeper part of a rifted-apart arc? Basalts in Mariana Trough are MORB-like, but have some arc characteristics. Vesicular. Spreading still in progress. Further north, on Iwo-Jima Ridge, there is an incipient back-arc basin just beginning to form - the Bonin Trough.

3. **Mariana Active Arc**: This consists of numerous small islands and seamounts, on the eastern edge of the extensive Fore-arc region. Lavas are mainly basalts, basaltic andesites and andesites.

4. **West Mariana Ridge**: Shallower and younger than the Kyushu-Palau Ridge. Drilling penetrated about 1000 m of volcaniclastic material composed of basalts, basaltic andesites, rare andesites and plagioclase phenocrysts. Their character is calc-alkaline, with much higher contents of Ba and Sr than those of K-P Ridge. Arc was active 17-8 my ago. So now a Remnant Arc. Arc built up when spreading in P-V / Shikoku Basins ceased.

5. **Mariana Fore-arc**: The forearc region shows a history of continual subsidence. The basement is Eocene in age (similar to Kyushu-Palau Ridge) and consists of two distinct lava types:

   1. **Island Arc Tholeiites** (very similar in character to those of Kyushu-Palau Ridge). These magmas can normally be easily distinguished from calc-alkaline basalts from more mature arc systems.

   2. **Boninites**, or high-magnesian andesites. These are unusual lavas, combining high Si with high Mg, Ni and Cr. They are thought to have formed by wet-melting of rather refractory lithosphere.

6. **Dacites** also occur on Guam.

Drilling and dredging in the trench area of the fore-arc has recovered mainly volcanic materials. No scraped-off sediments from the oceanic plate - with the implication that all sediment is being subducted, and that the fore-arc itself is suffering tectonic erosion as a result of the rasping action of the downgoing slab.

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TECTONIC EVOLUTION OF MARIANA ARC SYSTEM

Combining evidence from magnetic anomalies, drilling, dredging and geochronology, the geologic history of the arc system can be pieced together. In the period immediately preceding the development of the arc, the plate configuration in the eastern Indian Ocean and western Pacific was dominated by the rapid movement of India northward. There were some major N-S oriented transform faults at this time, so about 60 Ma ago the plate tectonic configuration probably looked like this:

India was just about to collide into Asia to form the Himalayas, Australia had just begun to separate from Antarctica, and note the very large ridge offsets on the N-S transforms. The critical point at this time was that slab-pull associated with the rapidly-moving Indian Plate will stop as soon as India collides. Similarly, the spreading ridge in the NE Pacific is going to push itself under the Aleutians, when upon the slab-pull will also stop. This leaves the northerly pull forces on the Pacific plate very weak, and very vulnerable to change in plate motion direction. So about 40 my ago the Pacific Plate changed motion from northwards to westward (c.f. kink in Hawaiian-Emperor seamount chain). The sequence of events can be tracked as follows:

1. The Kyushu-Palau Ridge is thought to mark the position of one of these major transform faults, with younger, warmer and thinner ocean ocean lithosphere to the west, and older, cooler and denser lithosphere to east. Drawn to scale, the position immediately before the change in plate motion probably looked like this:

   ![Map](image1)

   It can easily be envisaged how the eastern side would easily subduct under the new young warm lithosphere to the west that had recently formed at a spreading ridge. After the change in plate motion direction, the map then looked like:

   ![Map](image2)

A new volcanic arc forms at the site of the easternmost transform, and many complications develop in SE Asia (Philippines, etc.)
because of transforms turning into arcs, and various subduction-flips as thick (plateau-type) ocean crust refuses to subduct. A new subduction zone develops north of Australia.

(2) Rapid build-up of Kyushu-Palau Arc in late Eocene – Oligocene through voluminous eruption of island arc tholeiites and high-Mg boninites. Activity continued for ca 10 my. So what happened to bring about such a rapid rate of magma production. It is possible that the earliest stages of subduction looked as follows:

- **Magma Compositions**

  **Arc Magmatism**

  The magmas erupted at the Mariana Arc show a gradual evolution in composition with time. Note that the whole arc system has evolved entirely within the oceanic regime (no continental crust or subcontinental lithosphere involved).

  The earliest lavas erupted (now seen on Kyushu-Palau Ridge and Mariana Fore-arc) are island arc tholeiites (IAT) and boninites. These are characteristic of very primitive oceanic island arcs, and are not usually erupted on continents or in the later stages of arc development. IAT have similarities with mid-ocean ridge basalts (MORB), in having depleted rare-earth element (REE) patterns, but are usually more Fe-rich and with low Cr and Ni contents, very low Nb and Ta, higher K contents and high K/Rb ratios. Boninites are high-Mg lavas, but have high silica contents more typical of andesites; they have high Cr and Ni contents, but have lower Ti contents and higher K, Rb, Ba and Sr contents than would normally be expected of high-Mg rocks.

  Boninites are thought to result from wet melting of the rather refractory Mg-rich mantle wedge beneath the developing arc - with the wedge being contaminated with elements such as K, Rb, Ba, Sr transported from the subduction zone during dehydration of the hydrous ocean crust.

  IAT could be melts of the more fertile asthenosphere, the magmas then undergoing extensive crustal fractionation en route to the surface. Or they could represent melts of subducted ocean basalt crust (only possible at the very start of subduction when the ocean lithosphere is pushed down into hot mantle).

  After opening of the Parece Vela basin by back-arc spreading, arc volcanic activity was transferred 17 my ago to the what is now the West Mariana Ridge, and continued building up that arc for ca. 9 my. The lavas erupted however were mainly calc-alkaline basalts (CAB) and basaltic andesites, with higher Al contents, much higher Sr and Ba contents and light rare-earth enriched rather than depleted REE patterns. These lavas are more similar to calc-alkaline lavas erupted at continental margins (though the latter are usually dominated by andesite rather than basaltic andesites).

  These CAB magmas may have been derived from the mantle wedge. But if so there is an implication that the wedge may have been enriched in Ba, Sr, light REE, etc., perhaps as a result of continued fluid transport of these elements into the wedge from the dehydrating subducting slab.

  Modern lavas erupted at the active Mariana Arc tend to be mainly andesites and basaltic andesites having characteristics in between those of IAT and CAB. There is some evidence that a small component (ca. 0.5%) of subducted abyssal sediment is involved in their source regions.

  Perhaps the most interesting aspect of the Mariana arc is that at least three distinct magma types appear to have been generated from the one subduction zone. Yet the whole arc system evolved entirely within the oceanic environment.

  **Back-arc Basalts**

  In many respects marginal basin basalts (MBB) are similar to normal mid-ocean ridge basalts (N-type MORB). However during the early stages of back-arc spreading, when the uprising mantle diapir splits the volcanic arc, the basalt magmas are derived from the sub-arc mantle. These basalts tend to have an arc-like geochemical signature. Thus their REE patterns may be slightly light REE enriched, they have higher Ba, Sr, K and Rb, but low Nb and Ta.
Moreover they tend to have higher water contents and be vesicular - a consequence of fluids distilled from the subducting slab. These features are useful discriminants in trying to characterise ophiolites as being derived from either obducted ocean floor or marginal basin crust. See Saunders & Tarney (1984; 1991) for summary.

Addition: Schematic cross-section across the Mariana Arc showing the components involved in magma generation. Fluids are released from the sub-ducting slab as "wet" amphibolite recrystallises at ca. 100km depth to dry dense eclogite. These fluids migrate upwards into the mantle wedge and induce melting of the sub-arc lithosphere. (The more water, the more melting, and higher the magma production?). However, this mantle varies in its fertility because of previous metasomatic events affecting the deeper lithosphere. More active mantle diapirism occurs in the back-arc region, and this results in much more melting and active spreading. Hydrous fluids are still involved in these magmas, but to a lesser extent than in the arc rocks.

WHAT CAUSED THE CHANGE IN PACIFIC PLATE MOTION THAT PRODUCED THE MARIANA ARC?

If we bear in mind that plate motions are dominantly controlled by 'slab pull', then anything which reduces the slab-pull force will encourage changes in the direction and speed of plate motion. It is notable that in the southeastern Pacific the Aluk Ridge (spreading centre) began to progressively subduct along the Antarctic Peninsula; at the same time, the northwestern Pacific the Kula Ridge began to subduct beneath the Aleutians - Kamchatka. A result was a marked reduction in the N™S slab-pull, because recently formed hot lithosphere is not very dense and not keen to subduct. In combination with other plate re-configuring events worldwide, this may have been enough to cause switch in Pacific Plate motion from N – S to E – W. But see Richards et al. (1996)

REFERENCES: Arcs and Marginal Basins

The references below lead to most aspects of interest to island arcs, even if you just look at the abstracts & diagrams!


MARSH, B.D. 1979. Island arc development: some observations, experiments and speculations. Journal of Geology 87, 687-713.


TECTONICS OF SUBDUCTION ZONES

Uyeda & Kanamori (1979) emphasised that there were two contrasting types of subduction zone: Mariana Type and Chilean Type - with of course many intermediate types. The Mariana Type is characterised by a very steeply dipping slab; the Chilean Type by a shallow-dipping slab. These differences were further amplified by Dewey (1981).

Mariana Type has:
1. Deep open trench (up to 11 km deep) that subducts old cold Jurassic crust.
2. A very steep Benioff Zone
3. Extensive faulting, subsidence and tectonic erosion of the outer trench wall.
4. Widespread intra-arc extension and back-arc spreading.
5. More earthquakes in the under-riding than in the over-riding plate.
7. Extensive volcanism; mainly basaltic with only minor andesites.
8. Little or no sedimentary accretion at the trench.
9. Subdued morphological expression.
10. Lavas have quiet eruptive style.
11. Volcanoes are mainly submerged cones with fringing reefs.
12. Poorly developed volcaniclastic dispersal fans.

Chilean Type has:
1. Shallower trench (up to 6 km) that subducts younger, warmer, Eocene age oceanic crust.
2. Thrust faulting common on outer trench wall.
3. Major thrust faulting in the under-riding Nazca Plate up to 200 km west of the trench.
4. A Benioff Zone with a very shallow dip down to about 200 km, and then a steeper deeper portion below a seismic gap.
5. Widespread intra-arc compression and back-arc thrusting over a foreland trough.
6. More, and higher energy, earthquakes in the over-riding than in the under-riding plate.
7. Plutonism is dominant over volcanism.
8. Volcanism is dominantly of andesite-dacite-rhyolite type; basalts being much rarer.
9. Thick (ca 70 km) continental crust gradually tapering trenchward to less than 10 km.
10. Because of dominant compression, continental arc has high uplift rates.
12. Spectacular geomorphological expression.

Difference in seismic characteristics: The steep dip of the Benioff Zone in the Mariana type means that the contact interface between the subducting slab and the mantle wedge lithosphere is less than 100 km, hence not much frictional drag. In any case tectonic conditions are extensional. In Chilean type however, the shallow slab dip and greater thickness of continental lithosphere means that the contact interface can be as much as 400 km. Hence considerable resistance and friction and much greater seismic activity.

Tectonic Erosion and Accretion: In the Mariana Arc there is no accretion of abyssal sediments at the trench. Yet considerable volumes of sediment are entering the trench: sediments are 0.5 km thick on Pacific Plate entering the trench, subduction rate 10 cm/yr for ca. 40 m.y. (work out how many cubic km per unit length of arc!). Instead forearc is undergoing tectonic erosion ("subcretion"). Most of the sediment is being subducted - only a small proportion of it is re-cycled into arc volcanics. Along Chilean margin the sediment supply varies: very little in north where desert conditions, but much more in south where rainfall is high. It has been suggested that the continental basement may be eroding by subcretion in Northern Chile, but growing by sediment accretion in Southern Chile. Where sediment supply is high, sediments may fill the trench and flood over on to the oceanic plate; thus depressing it so that it approaches subduction zone at a shallow angle.

Explanation for differences between East and West Pacific Margins

Contrast cannot be explained simply by differences in convergence rate, since Chilean, Mariana, Japanese and Tonga arcs all have head-on convergence rate of about 10 cm/yr. Contrast must be related to balance between "roll-back" of hinge and convergence rate. If roll-back is faster than convergence rate then back-arc extension results; if slower, then back-arc compression.

Roll-back may be determined by age of subducting lithosphere (Molnar & Atwater 1978). Old cold lithosphere is denser and subducts at steeper angle . . presumably takes less time to reach 650 km discontinuity. If it cannot penetrate discontinuity then splays back (see experiments of Kinkaid & Olsen (1987)) and induces roll-back of hinge at subduction zone, giving extensional tectonics. However, with shallower angle subduction of younger warmer lithosphere the slab will take longer to reach 650 km discontinuity, and will warm up more and become less coherent and less able to induce roll-back effect. So no extension. An additional factor is that in the Eastern Pacific the American Plate is over-riding the Pacific (Nazca) Plate due to the opening of the Atlantic . . although the rate is quite small.

Wider implications: If the balance between compression and extension at convergent plate margins is related to dip of slab (and
hence age of lithosphere subducting), then it may explain why
intraoceanic island arcs are essentially a Phanerozoic phenomenon,
and become rare or absent in the middle to early Precambrian.
Higher thermal gradients in Precambrian would mean greater ridge
length and smaller plates (see Hargraves 1986), so subducting plates
would be younger and warmer, and less likely to subduct at steep
angle. Hence much less likely to induce extensional conditions at
convergent plate boundaries. Is it only when there is extension that
island arcs are produced?

References

DEWEY, J.F. 1981. Episodicity, sequence and style at convergent
Deposits*. Geological Association of Canada, Special Paper 20,
553-572.