PLATE TECTONICS: Lecture 6

THERMAL ASPECTS OF SUBDUCTION ZONES

For the last 2 decades, geologists, geophysicists and geochemists have argued about the physical and chemical conditions which allow melting to occur in subduction zones. Whereas it is easy to explain magmatism at ocean ridges where hot mantle is rising, it is not at first easy to explain why magmas appear in abundance when a cold slab is pushed into the mantle at subduction zones. It used to be thought that friction between the overriding and under-riding plates was responsible, but calculations have showed that friction is most unlikely: there is probably too much hydrous fluid and soft oozey subducted sediment that act as a lubricant. It is important to try to understand the thermal structure of subduction zones.

In a classic review paper, Ringwood (1974) suggested that the most primitive island arc lavas (IAT), which are basaltic, could be related to dehydration of the hydrated ocean crust (amphibolite) as it transforms to dense eclogite at depths of ca. 100km. The hydrous fluids rise up into the peridotite mantle wedge, promoting melting (magmas form at much lower temperatures in the presence of water). These magmas then rise slowly up to the arc volcanoes above, and crystallise Mg-rich olivines and pyroxenes as they ascend, so the magmas become more iron-rich. The eruption of basalt (tholeiite) is non-violent. This is shown in cartoon form:

For the calc-alkaline, more silicic and dacitic magmas or more mature arcs, Ringwood suggested a slightly different mechanism based on his experimental work on eclogite. Hydrous melting of eclogite (if Si-poor garnet stays in the residue produces silica-rich dactitic magmas. These then react with the mantle wedge and rise up as diapirs and erupt as much more violent hydrous magmas, of which Mt. St. Helens is a good example.

How can subduction zones give rise to the following range of magmas? Surely this must imply a range of P-T conditions that involve both slab and wedge melting?

Boninites (High-Mg andesites): usually formed at early stage of island arcs
Island Arc Tholeiites (IAT): normally restricted to primitive island arcs
Calc-alkaline basalts & andesites: found in mature island arcs and continental margins
Bajaites (Adakites): High-Mg andesites (but different from boninites) where ridge subduction occurs or mafic rocks have been underplated.
Shoshonites: Often late-subduction or post-subduction: high-Ba, Sr magmas
Archaean TTG suite: Distinctive, and thought to be derived from subducted ocean crust (they resemble adakites).

The critical points of issue are:
(a) under what conditions does the slab melt?
(b) what is the difference between subducting old ocean crust and young ocean crust?
(c) do magmas originate instead in the mantle wedge?
(d) what is the mineralogy of the wedge. Are minerals like hornblende, phlogopite & K-richerite stable in subduction zones?
(e) how can the difference between primitive island arcs (e.g. Marianas) that tend to erupt basalts, and mature arcs (e.g. Andean margin) that tend to erupt andesite, be explained?

Anderson et al. (1978; 1980) were the first to consider the thermal structure of subduction zones seriously. Wyllie & co-workers, in a series of papers (e.g. Wyllie, 1988), used experimental petrology to try to constrain what will melt under hydrous conditions, and what the magma compositions would be. He produced some useful cartoon models, one of which is shown below:

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However, there are a number of problems with these simple models, and it is now accepted that they only account for a minor number of features of subduction zone magmas. For instance, the primitive Mariana arc tholeiites are really a result of fore-arc diapirism connected with the initiation of a new subduction zone, following a change in plate motion, as outlined in the last lecture.
The important points to note are that the ocean crust reaching a subduction zone will be relatively "cold" and "wet". Just how cold it will be will depend on just how many hundreds or thousands of km it has travelled from the spreading ridge. It will be wet as a result of hydrothermal alteration near the ridge axis. As the plate subducts the basaltic crust will undergo a progressive increase in metamorphic grade – Greenshist > Amphibolite > Eclogite facies – which is also a series of dehydration reactions to about 100km depth.

More recently, Peacock (1991) and Bickle & Davies (1991) have produced much better thermal models. For instance, Peacock (1991) has produced useful thermal numerical models. He explores the thermal effect of:

(a) Age of the oceanic crust being subducted. Clearly young warm ocean crust will be more likely to melt if subducted than old cold lithosphere. The diagram below shows the increase in temperature at 1 my intervals (dots) as ocean crust ranging in age from 5 my [A] to 200 my [D] is subducted to 200 km. The surprising result is that only when quite young crust is being subducted is there a possibility of melting (i.e. temperatures reach >900°C beneath the arc). So as subduction continues and older and older crust begins to be subducted, it is less easily melted:

(b) Amount of previously subducted lithosphere. Clearly the more you stuff cool oceanic lithosphere into the upper mantle, the more it will cool it (the iced drink analogy!). With subduction rates of 10 cm/yr it is possible to subduct 100 km of ocean crust per m.y. [the diagrams are drawn for a much slower subduction rate of 3 cm/yr]

The implication from the diagram below is that the cooling effect of continued subduction is quite severe. So after less than 600 km (= 6 m.y.) of ocean crust subduction, temperatures are below those at which the slab melts. But what about the mantle wedge?

The diagram also shows how the top and base of oceanic crust heats up. The base is initially hotter, but the top eventually gets hotter because of heat conducted from the mantle wedge.

(c) Magma from the mantle wedge? Curves E and F show the temperatures of the mantle wedge (straddling the depths at which magmas are generated below arc volcanoes) at 10 m.y. and 20 m.y. after the start of subduction, but without allowing any convection in the mantle wedge. The cooling effect of the slab is very important, quickly taking the wedge below temperatures at which magmas would be generated.

However, Curve G shows the effect of allowing induced convection in the mantle wedge (a similar curve linked with E would be even higher temperature . . . ). In this case the temperatures stay above 950 °C as the wedge material is dragged down, and so hydrous melting would be possible. An important implication from this
Diagram is that it is much more likely that arc magmas are derived from the mantle wedge: conditions for slab melting are very restricted.

(d) Effect of induced convection on slab. Briefly, the modelling shows that induced convection can enhance the meltability of older slab, but the effect on young ocean crust is not important.

(e) Temperature or pressure control on magma generation?

The diagram above shows effect of water on the melting behaviour of basaltic oceanic crust. Under dry conditions melting increases with pressure (red dashed line). However, under water-saturated conditions (red full line) melting temperatures plummet by almost 400°C at depths of 50 km. Importantly, the blue curve shows how hornblende becomes an important mineral under hydrous conditions; however, note that the curve turns over at ~70-80 km to become pressure-sensitive – hornblende in mantle breaks down at ~100+ km. This means that a lot of fluid will be released from hornblende at these depths, which could promote melting. Is this why most arc volcanoes lie ~100 km above the Benioff Zone?

(f) Upward and Downward flow in mantle wedge

There is increasing interest in subduction-induced flow in the mantle wedge. At shallow levels (25-50km) the massive amounts of water entering the subduction zone may hydrate the mantle wedge to give serpentinite: this rock contains >12% water and is significantly less dense than normal mantle, and so can rise diapirically and "intrude" (solid state flow) the fore-arc regions, whether formed of arc volcanics or accreted sediment. Further down, cooling of the wedge by the subduction zone itself may make it negatively buoyant (i.e. denser) and help drag the wedge down, promoting hornblende breakdown and fluid release. This will enhance induced convection effects. The amount of coupling between slab and mantle wedge would however be reduced by soft sediment at the interface between the two. Upward flow further back in the mantle wedge would compensate these effects, particularly if enhanced by low-density fluid and magmas. (to be continued . . . )

REFERENCES


THE FATE OF SEDIMENTS AT SUBDUCTION ZONES

The floors of the world’s oceans are covered by sediment up to 1 km thick (age dependent) as a result of slow accumulation of calcareous and siliceous biogenic oozes capped by fine clays that have been carried in suspension to the middle of oceans. Additionally, nearer continents there may be much thicker accumulations of clastic sediments brought in by deltas and turbidity currents, and further redistributed by strong bottom water currents. Sooner or later this sediment must finish up at a subduction zone. What happens to it? Does it get scraped-off, or does it get dragged down the subduction zone? If the latter, does it just disappear into the deep mantle, or does it get recycled into island arc magmas? The balance is shown as follows:

Effectively, subduction at active margins can be likened to a conveyor belt carrying a lot of loose rubbish moving against a buttress: some material is going to get scraped-off:

There are many variables in the whole process. So it is important to look at a number at different tectonic situations.

(1) Primitive Island Arcs: no sediment accretion

At intraoceanic island arcs, such as the Marianas, there is no sediment supply from the continent (this is trapped by the back-arc basin), and the arc itself produces only a minor amount of volcanic ash (the eruptions are basaltic and not violent). Most of the sediment arriving at the subduction zone is abyssal oozes and clay...
carried on the subducting plate (on old ocean crust, at least 0.5 km thick). It used to be thought that this abyssal sediment was scraped off to form an accretionary wedge in the fore-arc. However, dredging and drilling in the Mariana forearc and trench has shown that there is little to no sediment in the Mariana trench. Yet during the 40 my since the arc system has been in existence, up to 40 km³ of sediments / km length of arc should have been scraped off the subducting plate (which is subducting at 10 cm/year).

The sediment must be subducted - but how? The answer seems to be that, as the subducting plate bends over to become vertical, the flexure causes horsts and graben to develop. Sediments are scraped off from the horsts into the graben and thus encased as the ocean lithosphere deforms (for this reason it was thought this would be a good place to dispose of nuclear waste!) In fact the ocean crust acts as a gigantic rasp on the arc too - the forearc is gradually, but slowly, eroded:

However geochemical studies have shown that very little of the sediment is actually incorporated into the arc volcanics, so most of it must be cycled into the deeper mantle. Presumably, as the slab at the Marianas is avalanching into the lower mantle, the sediments may be taken down also.

(2) Northern Chile: no sediment to subduct

Here the sediment supply is also very limited because of the arid climate. Many of the rivers from the high Andes never quite make it to the ocean, and in any case there few floods (which produce the turbidity currents that carry the sediment out into the ocean proper). Also, major faults parallel to the coast tend to obstruct the rivers, forming saline lakes (were common in N. Chile).

So the situation is similar to that in the Marianas, although the dip of the subducting slab is not so great. Some geologists have suggested that the rasping action of the subducting slab has actually eroded back the continental margin of N. Chile and Peru. Is this why the locus of volcanic activity continually moves eastwards with time in the N. Andes? And why Palaeozoic batholiths are exposed right at the coast, close to the trench? (Although difficult to prove it was there when it has gone!).

Where sediment supply is a little higher, trench gets partly filled with sediment. Some of this sediment may get scraped off. But drilling in the Middle America Trench suggests that the abyssal ocean floor sediments are still subducted (soft oozes act as a lubricant)

(3) S. Chile and Alaska: high sediment input

Here the climate is temperate and wet. Abundant rivers, some deriving from glaciers. Floods common. High rate of sediment supply to the ocean. Sediment supply was even higher during the Pleistocene (and there has not been time yet to subduct them).

Result is that large amount of sediment is carried into the trench. Trench quickly gets filled, and sediment then carried out onto subducting plate. As this continues the weight of sediment actually depresses the plate as it approaches the trench so that angle of dip is smaller (dip increases under the continental margin proper).

With a shallower dip, no horsts & graben form, and sediment is scraped off. This can readily be seen from reflection profiles. Layering of sediments disappears as continent is approached. Low angle thrusts appear. Younger sediments are progressively underplated. If sedimentation rates are high (as they are in high northern/southern latitudes) this can give rise to lateral growth of continents. The process is called subduction-accretion and the structures are called Accretionary Prisms. The general features are shown below:

(4) Characteristics of Accretionary Wedges/Prisms

Lateral continental growth by subduction-accretion is dependent on (a) the supply of material from the ocean, and (b) the sediment supply from the continent. These two might vary over a large range.

(a) Material accreted from oceans

The ocean floor is not smooth. Study of the Pacific map shows that the pre-Tertiary ocean floor is considerably rougher than that generated in the Tertiary. There are more oceanic plateaus, aseismic ridges, ocean island chains and arcs – in large part this results from the spate of mantle plumes which punched through the Pacific ocean plate in the late Cretaceous (120 - 80 Ma). Many of these upstanding structures are capped by carbonate banks, because they stayed above the carbonate compensation depth (CCD) much longer than normal ocean floor.

Ocean floor that is rough and upstanding is more likely to be scraped off when it reaches subduction zones at active margins. So this scraped-off material will be a mixture of mafic rocks (metamorphosed to amphibolite) associated with thick limestone (marble) sequences, as well as siliceous and carbonate oozes (= “cypoline schists”) and lithified clays. Large oceanic structures such as plateaus and arcs may “choke” the subduction zone, causing back-stepping of the subduction zone, the arcs being left as an ophiolite
(e.g. the classic Troodos complex on Cyprus). However, normal ocean floor, which is smooth and cold, may not be scraped off at all (it is this that converts to eclogite to provide the slab-pull force), so the soft carbonate-siliceous oozes and clay may not be scraped off quite so readily.

(b) Material supplied from the continents

This is largely material supplied by river systems feeding active continental margins. Of course at the present day there are not many rivers feeding active continental margins -- they are mostly still feeding the passive margins of the Atlantic, the Indian ocean and around Antarctica/Australia.

It is important to note that in the Upper Palaeozoic and early Mesozoic, the southern continents formed part of Gondwanaland - a very large continental landmass. Moreover much of Gondwanaland was rimmed by active margins. The margin had low relief (the present high Andes is not typical, and results from Miocene deformation and uplift). So it is possible that very large rivers were dumping sediment onto the subducting plate, and the sediment was then accreted back on to the continental margin . . . now exhumed and exposed, particularly in southern Chile, where they are of late Palaeozoic age (before the Andean magmatic cycle), and South Island, New Zealand. But they can also be seen in Alaska, and of course occur in older mountain belts (commonly termed Flysch). Compared with the partly-lithified material scraped off from the oceanic plate, the material coming from the continent is un lithified clastic sediment. The two get tectonically intermixed and intensely deformed (the subduction interface allows thousands of km of relative movement in just a few tens of Ma™ far more than with continental collision), so most rocks from this environment have strong penetrative foliations and linear fabrics (see New Harbour Group on Anglesey) and finish up as tectonic melanges -- lenses of oceanic rocks in deformed soft sediment.

As soft wet sediment (greywacke-shale) is continually underplated beneath the accretionary wedge, it heats up slowly. Water is progressively driven off. Hot water dissolves silica from sandy beds, and deposits it at higher levels as abundant cross-cutting quartz veins. However, because underplating is continuous process, sediments and quartz veins become progressively and very strongly deformed. Can be almost mylonite-like fabric. No bedding remains. Cross-cutting quartz veins are stretched out to become sub-parallel to foliation. Very characteristic rock type. Many tens or even hundreds of km of 'new' crust can accrete laterally onto continental margins in just a few tens of Ma. Continental accretion: from oceanic plateaus to allochthonous terranes.

Erosion of upper part of accretionary wedge may occur, and younger sediments deposited on top in fore-arc basins. These may also become deformed, but less so (could the South Stack Series on Anglesey represent such fore-arc basin sediments?).

References


TERRANES

"Terrane" concepts are now quite widely used in interpreting geological relationships in many parts of the world, and in rocks of many ages. Basically plate tectonics can move segments of continental crust or oceanic crust (e.g. ocean plateaus) many thousands of km in just a few tens of m.y., and as plates can change their direction of motion (c.f. kink in Hawaiian chain), this can lead to the juxtaposition of segments of crust that have a completely different geological histories. So it is not just collision of major continents (e.g. India and Asia to form Himalayas) but also on a much smaller scale. In particular, major transform faults can transport different crustal segments laterally for many 1000's of km (e.g. San Andreas Fault). Of course terranes are usually fault- or thrust-bounded.

Terrane Terminology (Jargon)

"A fault-bounded package of strata that has a geological history distinct from the adjoining geologic units"

Howell (1989) divided terranes as follows:

- Stratigraphic fragments of continents (1)
- of continental margin (2)
- volcanic arc (3)
- ocean basins (4)

However, a genetic terminology is also prevalent:

- Exotic, Suspect, Displaced or Accreted terranes: this implies that the terrane has been transported some distance to its current position.

- Pericratonic: Contains cratonic detritus and formed on attenuated continental crust.

Terranes are sometimes described in terms of tectonic assemblages, which are rock-stratigraphic units formed in actualistic tectonic settings, such as island arcs or ocean floors. A terrane may consist of one or more tectonic assemblages

Domain: A volume of rock, bounded by compositional or structural discontinuities, within which there is structural homogeneity; these may contain minor stratigraphic distinctions as well and can be viewed as subterranes.

Superterranes: A composite terrane, consisting of two or more compound terranes, that were amalgamated prior to subsequent orogenesis.

REFERENCES (General)


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References On Alaskan Terranes


References On Caledonian Terranes


References On Andean Terranes


Baltic Shield Proterozoic Terranes


References On Archaean Terranes

(to be continued)