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The return of sialic material to the mantle indicated by terrigeneous material subducted at convergent margins

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ABSTRACT

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At convergent margins where oceanic crust is subducted beneath continental or island-arc crust, sediment on the igneous oceanic crust divides into an accreted and a subducted fraction. Although the subducted fraction is larger, it is obscured in many seismic reflection records because of its depth and the effects of the overlying complex structure. Volumes of accreted and underthrust sediment were quantified at individual margins and global estimates were made of the terrigeneous debris subducted. Also included were debris from subduction erosion. The estimated volume of terrigeneous material subducted beneath continental and island-arc crust is sufficiently large to significantly affect processes along the plate boundary. The possible volume reaching the mantle could have considerable affect on mantle evolution.

Introduction

Convergent margins have generally been considered regions of extensive continental growth. In fact, remnants of accretionary masses along ancient continental margins make up many interior continental areas. A simple progressive accretionary growth model, however, must be augmented in accord with contemporary geophysical and geological data. Sediment underthrusting accretionary prisms (see appendix for definitions of terms) has been clearly resolved through improvement of seismic reflection images and drilling across convergent margins (cf. Aoki et al., 1982; Westbrook et al., 1988; von Huene and Culotta, 1989; Shipley et al., 1992). Underthrusting sediment can be subcrustally subducted beneath continents and collect along the plate boundary by underplating. The low density of sediment relative to oceanic basalt would favor underplating at high structural levels in subduction zones. However, it appears from mass balance calculations that some sediment is retained with the subducting slab and passes into the mantle. Once it passes beneath the crust, this terrigeneous (continent-derived) material is subtracted from the continental crustal mass, whereas underplating of terrigeneous sediment effectively repositions it from high to low crustal levels. The volume of subducted sediment that bypasses the accretionary and underplating process affects the net rate of continental growth and mantle evolutionary processes.

The possible accretionary and subduction paths of terrigeneous sediment in convergent margins (Fig. 1) can be recognized by structure in seismic reflection records only within about 15 km of the earths' surface. Sediment carried into a trench is partitioned by a decollement into a frontally ac-

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creted and an underthrust fraction, a complex partitioning that can be resolved only in seismic records that are well processed with modern techniques. Commonly, the greater part of ocean basin sediment arriving at convergent margins is underthrust and deeply subducted. Deep or subcrustally subducted sediment could be incorporated in plutonic and volcanic rocks of the magmatic arc, stored as underplated material attached to the base of the continental crust, or returned to the mantle with the subducting slab. Because the trace-element and isotope geochemistry of many magmas of volcanic arcs indicates only minor addition of subducted terrigeneous material, it is possible that much of the subcrustally subducted sediment may be stored through underplating beneath the margin. But the quantity of material that could potentially underplate (i.e. that which is not accreted or recycled by volcanism) seems much larger than that which could be accommodated by underplating of the upper plate (Armstrong, 1981; Karig and Kay, 1981). The inadequacy of storage by underplating suggests that significant quantities of subcrustally subducted sediment returns to the mantle.

In this paper we emphasize that the volume of sediment subducted at convergent margins has not been fully appreciated, and summarize the global volumes of oceanic sediment subduction described in our review paper (von Huene and Scholl, 1991). We explore some consequences of our estimated volumes of subducted material as they pertain to crustal growth rates, to the fate of subducted terrigeneous debris, and to coupling along the plate boundary.

Recognition of underthrust sediment

Sediment bypassing the accretionary wedge went unrecognized for many years because seismic techniques were insufficient to image clearly below the accretionary complex. Sediment thrust beneath an accretionary wedge is difficult to image because of the three-dimensionality of structure and varying velocity fields in the wedge, as well as great water depth. Dipping reflectors in the accretionary wedge scatter seismic rays and reduce the strength of the returning reflection. Conversely, reflectors at certain dips return signals from the side of the plane of section which overprint and obscure the primary seismic image. Therefore, until the availability of seismic systems sufficiently powerful to insonify the wedge, and particularly the availability of better processing facilities, underthrust sediment remained for the most part unrecognized in poor images. However, the growing number of greatly unbalanced accretionary sediment budgets along convergent margins, the paucity of oceanic pelagic sediment in

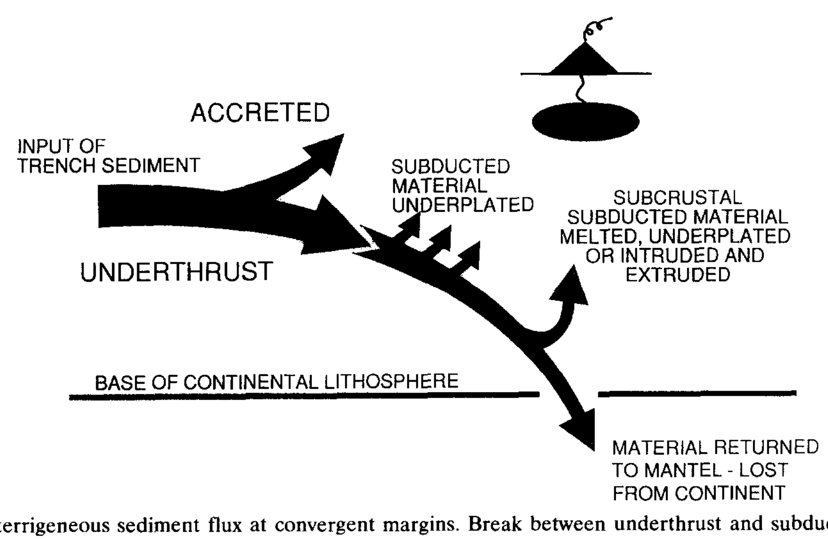

Fig. 1. Diagram of terrigeneous sediment flux at convergent margins. Break between underthrust and subducted material in flow line represents end of regime where structure is imaged in seismic reflection records.

exposed subduction complexes, and the virtual absence of accretionary wedges along some margins required that only part of the trench sediment section was accreted. Histories of these concerns have been presented by Scholl (1987).

Despite the clear imaging of subducting sediment a decade ago (Aoki et al., 1982), a skepticism prevailed because of the seemingly unlikely underthrusting of soft trench sediment. Mechanisms to underthrust soft sediment beneath a continental margin, which locally consisted of ophiolitic rock, seemed inconceivable. Soon, improved seismic images revealed several thick underthrust sections along convergent margins (Bally, 1983; von Huene, 1986), indicating a general convergent margin condition in which the overthrust between plates was within the sediment section. In addition, evidence for a reduction of friction along the decollement from elevated pore fluid pressure, a well known mechanism proposed by Hubbert and Rubey (1959) to explain foreland thrusting, began to accumulate. Some of the first observations indicating elevated pore pressure were from the Japan Trench (Carson et al., 1987) and a survey of academic and industry data (Moore and von Huene, 1980) provided further observations to foster a widening acceptance of this mechanism. The examination of fluid flow has since become one of the most concentrated areas of investigation in the studies of convergent margin mechanical and chemical behavior.

Improved images of underthrust sediment are derived principally from modern seismic processing which resolves the decollement or detachment surface below which sediment is underthrust and eventually underplated or subducted. When presented as a section with its vertical axis in depth rather than time, the underthrust and underplated sections, which have higher seismic velocities, are commonly revealed to be as thick as the overlying accreted mass (cf. Shipley and Moore, 1986). Many studies of convergent margins prior to the 1980's lacked high-quality data and thus the importance of underthrust terrigeneous material went unappreciated. Only exceptional seismic sections indicated the thickness of underthrust and subducted sediment (cf. Aoki et al., 1982; selected sections in Bally, 1983; von Huene, 1986). Few well-migrated seismic sections acquired with a large seismic source at 25- to 50-m maximum shotpoint spacing are without

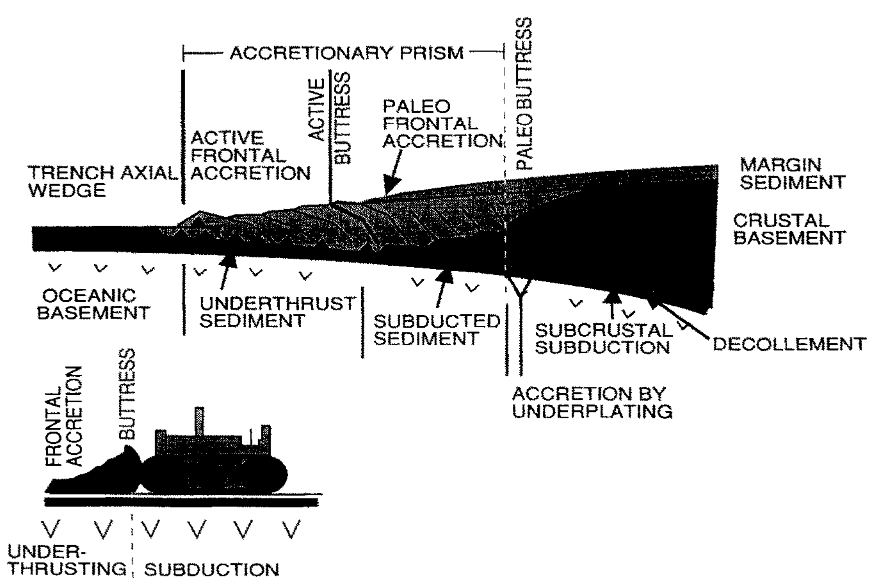

Fig. 2. Tectonic domains defined by von Huene and Scholl (1991) to facilitate estimates of subducted sediment.

some indication of sediment along the convergent margin plate boundary.

Definitions

Sediment underthrusting, sediment subduction, and sediment accretion are defined following the "bulldozer model" (Fig. 2). *Frontal accretion* occurs in front of the blade or *buttress* (Appendix). The sediment passing below the actively accreting frontal mass is considered *underthrust*. Sediment passing farther landward beneath the *active buttress* (Fig. 2) is considered *subducted*. The *active buttress* is not always a sharp boundary nor is it always clearly defined in seismic records but it occurs in association with *underplating*. When *underplating* becomes a principal mode of accretion along the plate boundary, the frontally accreted sediment becomes decoupled from interplate stress. Therefore contractional tectonism in the frontal mass diminishes substantially behind the *active buttress*. At the *active buttress* the underthrusting sediment can be called subducted sediment because it can no longer be frontally accreted.

Although subducted sediment is unavailable for frontal accretion, it accretes by underplating to the base of the accretionary prism and core buttress (Fig. 2). Such underplating is required in accord with the principal of critical taper (Davis et al., 1983) to continue crustal thickening at convergent margins in the absence of major out-of-sequence thrusting. Seismic images of underplating beneath accretionary prisms (cf. Aoki et al., 1982; Moore et al., 1988; Westbrook et al., 1988) and beneath the core buttress (Ladd et al., 1982; von Huene and Miller, 1988; Moore et al., 1991) are observational support for the principal of critical taper. Underplating may accrete subducted material in locations far landward of the prism and well isolated from it (Fig. 1). This underplating (subcrustal underplating) can not be considered part of the accretionary prism. To quantify subducted and accreted materials we first established volumes of underthrust and frontally accreted materials. Because of the difficulty of imaging the structure of this region clearly, and the small number of high-quality

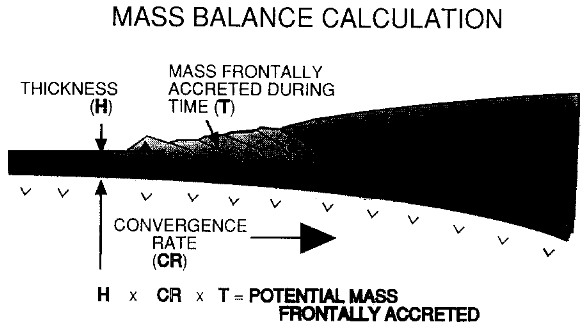

Fig. 3. Principles of mass-balance (volumetric-balance) calculations. Fluids expelled during deformation are taken into account using depth versus average porosity curves.

seismic images across this zone, we relied mostly on volumetric mass balance calculations to quantify subducted sediment. We then made less certain estimates of sediment volumes that bypass the accretionary prism to subduct beneath the crust or subcrustally subduct the margin's rock framework.

To make mass balance calculations, the amount of sediment that could have been accreted during a certain time is reconstructed and compared to that observed to have been accreted (Fig. 3). The volume of sediment accreted during a time period is established from the age of structures in seismic sections across the accretionary prism which are commonly tied to dated samples. * Reconstruction of the amount of sediment that could have been accreted was established from the thickness of contemporary trench fill and underlying oceanic sediment and the rate of plate convergence (Fig. 3). Mass balance estimates of frontally accreted and underthrust sediment were commonly made after drilling of convergent margins during the programs of scientific drilling in the worlds oceans (see preliminary results of DSDP and ODP Legs 57, 60, 66, 67, 78, 84, 110, 112). We used the same principal assumptions in

* The reconstruction was solely volumetric because the internal structure of the frontally accreted mass was only partially resolved in seismic records. Therefore, some unresolved underplated sediment could have been included in the accreted mass which biases the calculation toward less subducted sediment and more frontally accreted sediment.

our analysis of seismic sections to make global estimates of accreted and subducted sediment volumes. The difference between observed and reconstructed volumes is assumed to be the volume of sediment subducted landward of the active buttress. Fluid losses during accretion and underthrusting were accounted for using depth versus average porosity relations derived from drill and seismic data (von Huene and Scholl, 1991). If the data were sufficiently complete to provide relatively good constraints, the calculations were within about $\pm 20\%$.

Estimates of global sediment subduction, contemporary and long-term

We estimated that the contemporary total solid-volume mass of ocean floor sediment, including trench fill, that annually enters subduction zones is 1.9 km^3. In front of the active buttress, about 20% of this global input is frontally accreted and 80% is underthrust (Fig. 2). In front of the core buttress about 50% is in the accreted fraction which here includes accretion by underplating. To make these estimates, convergent margins were divided into 3 types (Figs. 4 and 5). Non-accreting margins, where little net frontal accretion occurs, account for nearly half (21,000 km length) of the worlds convergent margins (Fig. 5A). Although the contemporary margins of this type may have local small accreted masses, long-term net frontal accretion is insignificant. These margins consist principally of a buttress beneath which all sediment entering the generally sediment-starved trench is subducted (Fig. 5A). Sources of terrigeneous sediment are small because the associated landmass is commonly an island arc of small subaerial extent. At these margins about 0.4 km^3/yr of mainly pelagic sediment is subducted. The certainties of these estimates are relatively high and the estimates compare well with the volume of subducted ocean basin sediment estimated by other authors (cf. Hay et al., 1988). The differences with other estimates of subducted sediment (Southam and Hay, 1981; Sloan, 1985) is that we included the

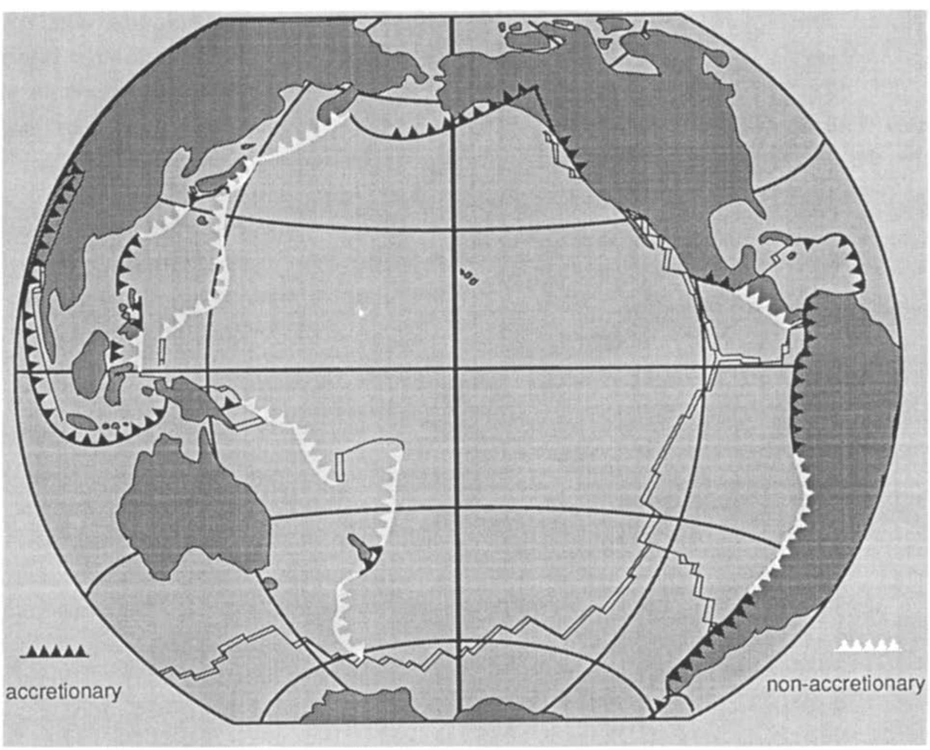

Fig. 4. Map of the Pacific Ocean hemisphere showing the distribution of accretionary and non-accretionary convergent margins.

trench sediment in our estimates, whereas other investigators included only those from the ocean basin.

Margins with small- to moderate-size accretionary prisms (5 to 40 km wide) extend over a length of 16,300 km (Fig. 5B). Contemporary accretionary prisms are commonly nourished by sediment-flooded trenches connected with sediment sources in moderate to extensive land areas. For these prisms, the quality of seismic imaging is important to providing satisfactory constraints on partitioning of the trench sediment into underthrust and frontally accreted fractions. Along four well-studied margins (4,000 km long) with sufficient geophysical and drilling control, we estimated from mass balance calculations that an average 80% of the incoming sediment is underthrust. We applied this proportion to the remaining margins (about 12,000 km) where the data are insufficient to make well-constrained mass balance calculations. At the margins with small to moderate accretionary prisms, about 0.7 km^3/yr of solid-volume sediment is subducted. The greatest uncertainty in this estimate is the unknown lateral variation of accretionary masses along the little or unexplored parts of the small to moderate size prisms.

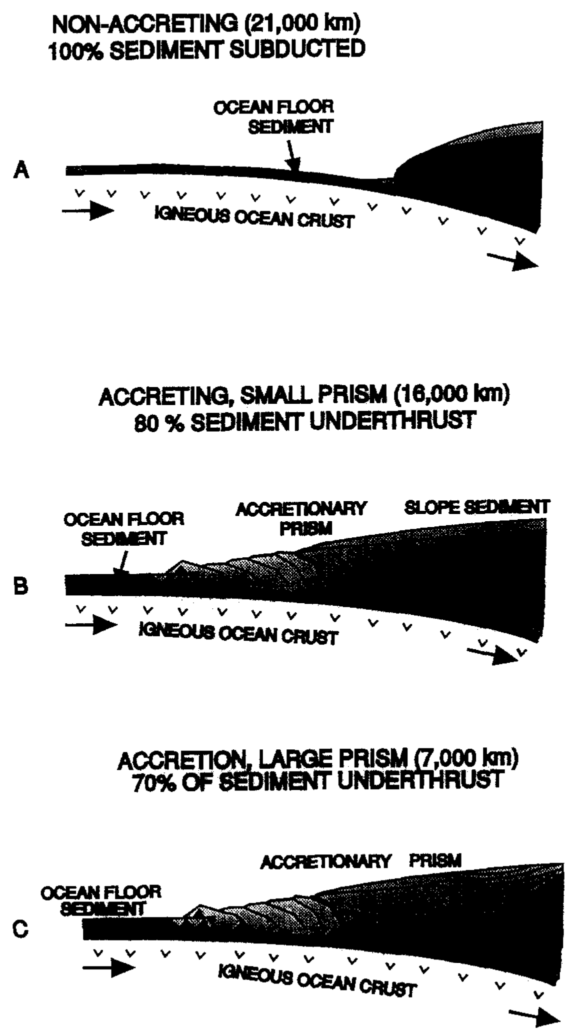

Fig. 5. A division of convergent margins to facilitate estimates of subducted and accreted sediment volumes.

Large accretionary masses border the remaining 6,700 km of prism-fronted margins (Fig. 5C). At these margins the lower part of the active buttress is rarely well imaged. We inferred that the 70% volume that is underthrust, is also subcrustally subducted. The great depth at which the core buttress is buried along these margins, is a principal cause for uncertainty, but unless we have grossly overestimated the subcrustally subducted fraction, the estimate applies to only 0.1 km^3/yr (approximately 8%) of the global sediment subcrustally subducted.

The total amount of contemporary global sediment subducted beneath the margin rock framework is estimated at about 1.0 km^3/yr (Fig. 6). We evaluate the range of uncertainty in the contemporary global estimate at about $\pm 25\%$, the greatest contribution being from margins with small- to moderate-size accretionary prisms.

These calculations for contemporary margins yield rates that are probably not applicable prior to 2.5 Ma, because during the late Cenozoic, glaciation greatly increased trench–floor sedimentation. To estimate a long-term rate of subduction we assumed that glacial rates of sedimentation in the worlds trenches were twice the pre-2.5 m.y. rate. This estimate is guided by the measured increase of terrigeneous sedimentation in the late Cenozoic ocean basins (Southam and Hay, 1981; Sloan, 1985; Hay et al., 1988). Applying a pre-Pleistocene reduction decreases our estimate of subcrustal sediment subduction to 0.7 km^3/yr (Fig. 6). Recognizing the uncertainties in our estimate we avoided overestimating the long-term rate of subcrustal sediment subduction. In accord with the principal of critical taper (Davis et al., 1983), the rate of accretion should remain constant provided that the trench sediment supply is above the minimum level required to supply the prism. In the event the pre-glacial sediment supply was insufficient to nourish the prism adequately, our estimated rates of long-term subcrustal subduction are reduced too severely.

Subduction erosion

Terrigeneous material is also introduced into the subduction channel from subduction erosion. Subduction erosion tectonically removes material that formerly was part of the upper plate. The effects of subduction erosion have been observed at many margins, but only along the northern Japan, central Peru (von Huene and Lallemand, 1990), and northern Chile margins (Mpodozis and Ramos, 1990) have the rates of erosion been estimated within meaningful constraints. Rates of erosion at these margins are constrained by comparing an earlier configuration of the margin with its present one. Drill cores show that regional unconformities, although now deep below the continental slope, were eroded near sea level prior to subsidence by as much as 4–6 km. Restoring the unconformity surfaces to their original depths and reconstructing the former continental slope, provides a cross section of the material missing since the surface subsided and began to receive sediment (von Huene and Lallemand, 1990).

Along the eroded margins of northern Japan and central Peru, a small modern accretionary prism is observed at the front of the margin but subsidence of the same age is observed in the mid-slope area. The occurrence of a small frontal prism along a margin, where the average subsidence of the middle and upper slope area is locally greater than 0.5 km/m.y., during the past 3–5 m.y. indicates that erosion can occur intermittently or simultaneously landward of a region of frontal accretion. If margins with contemporary small- to moderate-sized prisms can also have erosional areas, then erosion is likely to be active along the non-accretionary margins that have no prisms as, for example, the margin of northern Chile where rocks of the volcanic arc have migrated inland some 200 km (Andriessen and Reutter, 1993, in press). In the absence of local constraints, we used the average rate of measured erosion along Japan, Peru and Chile and estimate that along the length of the non-accretionary margins a plausible global erosional rate is 0.63 km^3/yr. This rate, and the long-term subcrustally subducted sediment quantities, result in a total rate of 1.3 km^3/yr, or a rate of subduction at 85% of the rate at which magmatic material is inferred to be added to the continental crust (Reymer and Schubert, 1986). These two volumes are of the same order of magnitude

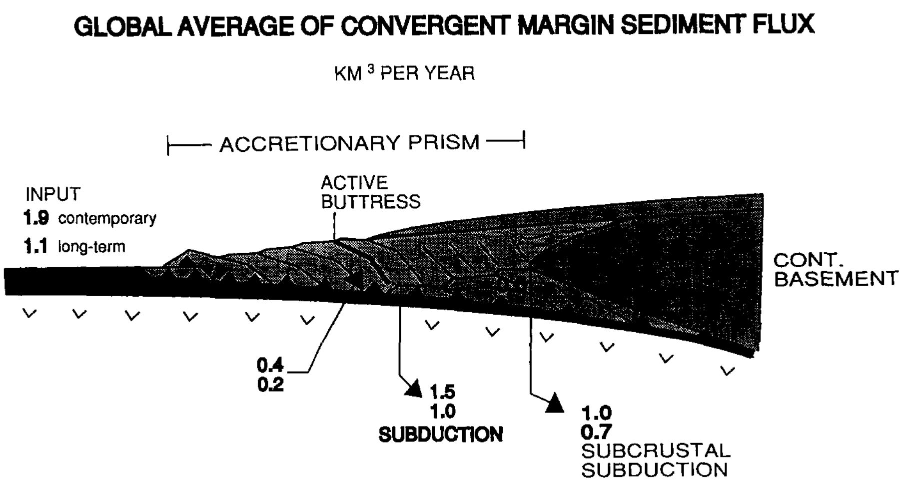

Fig. 6. Diagram summarizing contemporary (upper number) and long-term global (lower number) rates of sediment accretion and subduction.

considering the uncertainties in both estimates (Fig. 7). Particularly significant to constrain with greater precision is the amount of material eroded from the base of the upper plate that provides from 40% to 60% of the total material subcrustally subducted. This is sufficient to make the subducted fraction and the volume of magmatic material added to the crust nearly equivalent.

Consequences of subducting large volumes of continental material

Our estimate of the volume of subcrustally subducted material is at the high end of the range of such estimates which raises questions regarding the consequences of introducing large masses of terrigeneous materials into the plate boundary or transporting them until they reach the mantle wedge. Where are subducted materials stored in the upper plate and in what quantity?

Direct observation of subducted terrestrial material is possible only in the upper part of subduction zones where considerable sediment subduction and underplating has been observed. Rarely is a thick layer of underthrusting sediment on the subducting slab (igneous oceanic crust and lithosphere) imaged seismically at depths greater than 15 km. The next deeper region where the effects of the subducting sediment can be observed, is in products of the volcanic arc that contain trace elements and isotopic material from the subduction zone that have returned to the surface. A radiogenic nuclide that documents clearly the presence of ocean floor sediment about 200 km landward of the trench and from about 100 km depth is ^{10}Be (Brown et al., 1982; Tera et al., 1986; Morris et al., 1990). Preliminary investigations indicate that the concentration of ^{10}Be in young arc volcanic rocks is quantitatively consistent with our estimates of subcrustally subducted terrestrial material, for example along the Aleutian arc (J. Morris, pers. commun., 1991). Despite the evidence from ^{10}Be of sediment subduction to great depth, the trace-element and isotope composition of arc volcanic rocks indicates that arc magmas are principally sourced from mantle rock and that only a few percent of their constituents are contributed by subducted terrestrial material (cf. Kay, 1980; Gill, 1981; Rogers and Hawksworth, 1989). This conclusion is contested by Stern (1991) on the basis of the difficulty to distinguish between contamination by a crustal component subducted into the mantle source region, and contamination of mantle-derived basalts ascending through the continental crust. Counter arguments based on Sr- and O-isotope compositions (cf. Davidson, 1991) are beyond this discussion, but the Andean case may be more confusing than that for some island arcs. It seems that some island-arc rocks have a trace-element and isotope geochemistry that requires relatively small amounts of terrigeneous components.

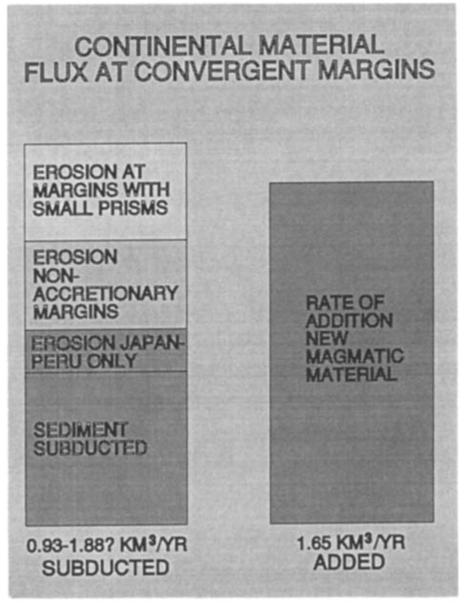

Fig. 7. Rate of material subducted globally is compared graphically with an estimate of material added to the continents to show why it is important to constrain the volume of material eroded. The volumes of eroded material that may be subducted are ranked according to certainty.

Two consequences attending subduction of large volumes of terrigeneous material for discussion here are: (1) the physical (temperature) conditions in subduction zones that affect the release of seismic energy; and (2) the possible process influencing continental growth.

Subducted terrigeneous material and large earthquakes

Significant thicknesses (1 km and more) of sediment with relatively low velocity have been observed on a few subducting plates at 10–15 km depth (for instance, Aleutian – Moore et al., 1991; Japan – von Huene and Culotta, 1989). These low velocities are inferred to indicate relatively high porosities from volumes of original pore fluids in sediment subducted subcrustally. In addition to pore fluids are the fluids derived from mineral dehydration at elevated temperature that replenish fluid drained from the subducted sediment.

The large volumetric estimates of subducted material suggest that significant amounts of sediment may pass into the seismogenic zone at some convergent margins. The volume of fluid entrained in the subducting sediment that later drains from depths greater than 15 km could be consequential. These fluids tend to migrate up the subduction zone similar to the fluids flowing up the plate boundary of the Barbados subduction zone (Moore et al., 1991). Thermogenic hydrocarbons in those fluids indicated a deep source region far landward of the zone where they were recovered during scientific drilling. The fluids of contemporary margins are difficult to follow much deeper than the zone of thermogenic hydrocarbon generation because few distinctive chemical tracers exist to indicate the location of deeper source areas. However, the geochemistry of vein material filling fractures in ancient underplated deposits suggest active fluid circulation prior to cementation when the sediment was at pressures encountered in 10 to 12 km depths (Vrolijk et al., 1987). If the flow of fluids draining from subducting and underplated rocks is sufficiently large, the temperature of the subduction zone will be depressed by advective processes. A physical condition that controls seismicity in subduction zones is temperature, and therefore, the relation of fluid advection to seismicity is important to understand.

A possible relation between seismicity and fluids in subduction zones may involve rates of convergence and subducted sediment volumes. The level of seismic energy released along subduction zones can be divided into three depth regions (Fig. 8). From the trench axis down-dip to 10–20 km depths the energy released from earthquakes is relatively low (cf. Byrne et al., 1988). Low interplate friction in this zone could be linked to excess pore fluid pressure in the sedimentary and in the porous layers of igneous rock comprising the upper part of the subducting plate. The principal seismogenic zone extends from 15 to 50 km

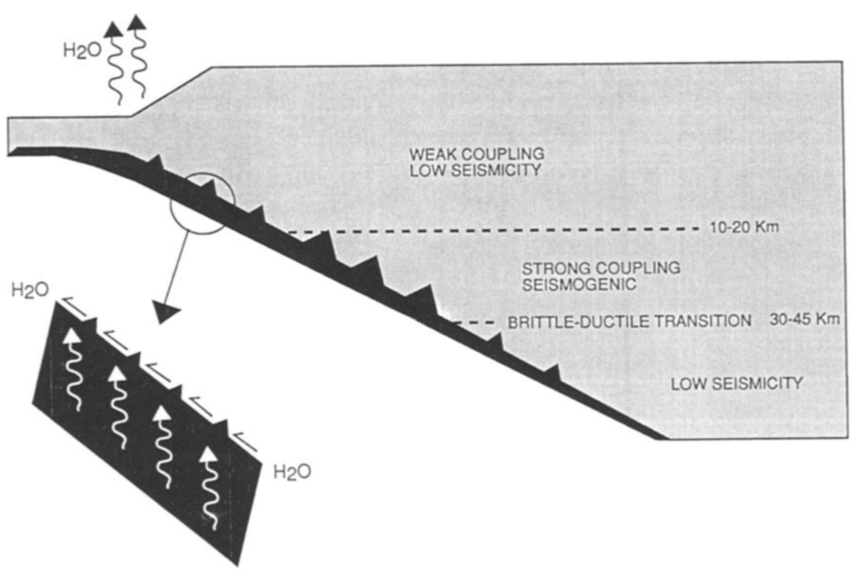

Fig. 8. Diagram of seismicity in a subduction zone related to inferred fluid advection.

depth (Zhang and Schwartz, 1992). Here the plate interface is sufficiently coupled to cause high stress concentrations. Below the seismogenic zone is a lower region of reduced energy release from earthquakes. The depth of the lower boundary of the seismogenic zone is probably controled by rheology of the lithosphere (Meissner and Strehlau, 1982) and is principally a function of pressure and temperature. Increasing pressure increases interplate friction, whereas increasing temperature decreases interplate friction. Thus, if the temperature in the subduction zone is lowered, the seismogenic zone should extend deeper; the greater the depth, the more friction should be encountered across the plate boundary. It can be argued that the volumes of pore fluids, even those derived from mineral dehydration, are likely to be small at great depth and that advective heat transfer is more likely to be effective above the 10–20 km depth region where seismicity is low. Despite the possible absence of much fluid advection from the seismogenic zone, a temperature reduction in a plate segment at shallower depth will be quickly transported deeper in the subduction zone considering that in a million years the subducting plate along many convergent margins can travel 100 km landward.

This possible mechanism is consistent with the observations of Ruff (1989) who noted that areas of large earthquakes are commonly associated with thick contemporary sediment masses in the trench axis. The second observation is the correlation between the depth of maximum seismic energy release and the rate of plate convergence as well as the thickness of sediment in the trench axis (Zhang and Schwartz, 1992). Notwithstanding a less than one-to-one correlation between the depth of the seismogenic zone and the rate of plate convergence (Zhang and Schwartz, 1992) the volumes of fluid entrained in subducting sediment and the thermal history of the subducting plate will also affect this relation. The apparent relation between trench sediment volume and earthquakes is strong enough to warrant consideration of rapid plate convergence and fluid advection as major controls on temperature in the seismogenic zone of convergent margins.

Subducted terrigeneous material and continental growth

Continents grow to a large extent by addition of mantle-derived igneous material to convergent margins. If the rate of subcrustal sediment subduction approaches the rate at which juvenile igneous rock is added to the continents, then the fate of the deeply subducted material becomes an essential factor in establishing rates of continental growth. Subducted material that is stored in the crust as plutons, as volcanic masses, or as underplated masses, has been repositioned from higher to lower crustal levels. If, on the other hand, significant quantities of the subducted material are carried below the base of the crust, they are lost to the continents and thus affect net continental growth rates (Fig. 1).

The lack of much storage of subducted terrigeneous products in igneous bodies as previously discussed, leaves crustal underplating as a potential process whereby subducted terrigeneous material is attached to the base of the upper plate before the subducting slab reaches the mantle. Because the subduction of low-density material into the mantle is counterintuitive, it is appealing to store subcrustally subducted masses above the mantle by underplating. But if most of the subducted matter is underplated to the base of the continents and island arcs, then a massive repositioning of surface rock to the base of the crust should dominate the subsurface geological process along convergent margins. Eventually, the convergent continental margins would be composed largely of rocks metamorphosed at great depths.

To illustrate this problem further (Fig. 9), if most of the subducted material we estimate were underplated, then the worlds' convergent margins, seaward of the arc, would be filled with deeply underplated rock masses in as little as 185 m.y. In fact, the areas of Mesozoic rocks returned from very deep crustal regions to outcrop levels are relatively small. Many seismic images showing layering and energy bands in the lower crust (cf. Mooney and Meissner, 1991) might suggest that perhaps underplated rocks are confined to great

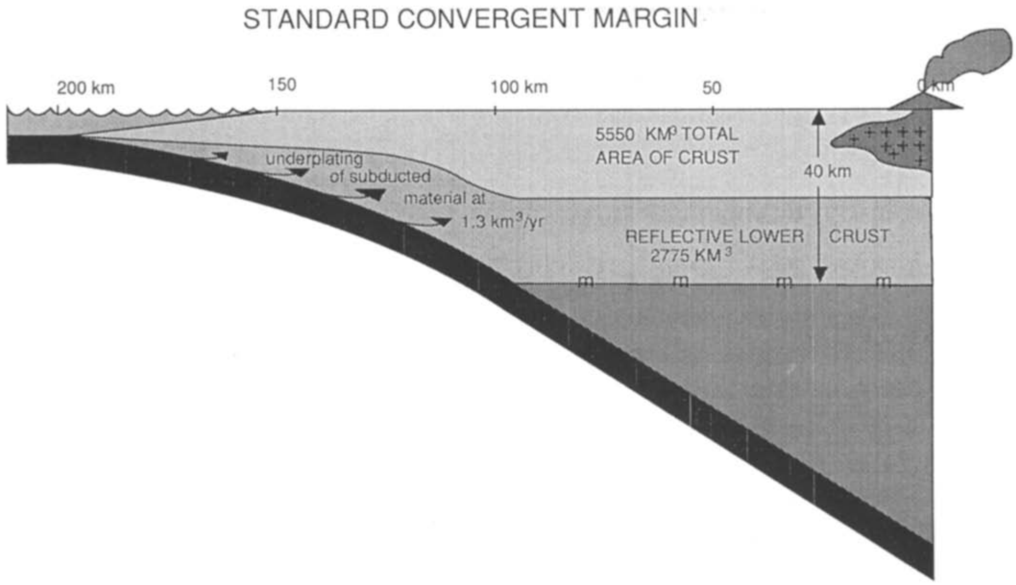

Fig. 9. Consequences of underplating all subducted materials to the base of the upper plate are shown using a standard convergent margin section. If all subducted material is underplated, it fills the forearc area in 185 m.y.; if it fills only the area of lower reflective crust this time is halved.

depths and that only small amounts reach the surface. Assuming the highly unlikely possibility that the reflective lower and middle crust is composed primarily of underplated material of Mesozoic and younger age accounts for only about half of the material subcrustally subducted during that time, the remaining half entering the mantle. Thus, it appears that large amounts of terrigeneous material could be lost from the continental crust by entering the mantle. The degree to which this counterbalances the amount of juvenile igneous rock added establishes a net contemporary rate of continental growth. Despite the lack of understanding a tectonic mechanism, it seems inescapable that significant volumes of terrigeneous materials remain on the subducting slab and enter the mantle.

Concluding statement

We have summarized globally the average rates of subduction of terrigeneous material based on a study of seismic records and mass balance information. Individually, contemporary convergent margins grow in a non-linear fashion or more specifically, tectonic rates remain constant only for tens of millions of years. A variable sediment layer entering convergent margin systems adds to this non-linearity. In some instances the single seismic records of good quality used in our estimates may not represent all of a specific area. Already we have made refinements in the rates of underthrusting and accretion at single margins shown in our summary (von Huene and Scholl, 1991). However, these and further refinements fall within the limits of uncertainty and will probably not greatly alter the magnitude of the global estimate of subducted terrigeneous material that reaches the core buttress and passes landward. The purpose of our study was to demonstrate a global magnitude and thereby emphasize the significance of the fate of subcrustally subducted material in-so-far as it affects the physical character of subduction zones and mantle evolution.

The volume of terrigeneous material subcrustally subducted is of the same order of magnitude as the igneous material added to the continental crust. It seems inescapable that a significant fraction of these materials reach the mantle wedge. The advection of fluids returning from depth could significantly add to the depression of temperatures along the plate boundary which in turn affect coupling across it.

Appendix

Underthrusting: any sedimentary or eroded debris moving landward beneath a decollement – whether beneath an accretionary prism or the margins' core buttress of older rock framework – in conjunction with the subducting oceanic slab.

Frontal accretion: at the front of an accretionary pile, the tectonic skimming of a layer of ocean sediment above a decollement or detachment surface and the addition of this sediment seaward of the margin's active buttress.

Frontal accretionary body: the entire body of sediment added to the prism by the process of frontal accretion.

Active Buttress: the landward edge of the volumetrically growing and tectonically thickening frontal accretionary body.

Underplating: the tectonic process of accreting underthrusting sediment to the base of the upper plate.

Core buttress: the outer edge of the margin's older rock framework seaward of which a growing accretionary prism has formed, or could form, by frontal and underplating accretionary processes.

Accretionary pile or prism: a definable body of oceanic sediment that has been tectonically added to a core buttress by frontal and underplating accretion.

Sediment subduction: underthrusting oceanic sediment that has passed landward of the position of either the active or core buttress, which ever comes first.

Subcrustal subduction: or *sediment by-passing*: subducted oceanic sediment that has by-passed the entire width of the accretionary prism and travelled landward and beneath the seaward edge of the core buttress.

Subduction erosion: the removal of any rock and sedimentary masses from the ocean margin caused by the landward underthrusting or subduction of the lower plate.

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