SCIENCE OPPORTUNITIES IN OCEAN DRILLING TO INVESTIGATE RECYCLING PROCESSES AND MATERIAL FLUXES AT SUBDUCTION ZONES

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Crustal Fluxes at Subduction Zones

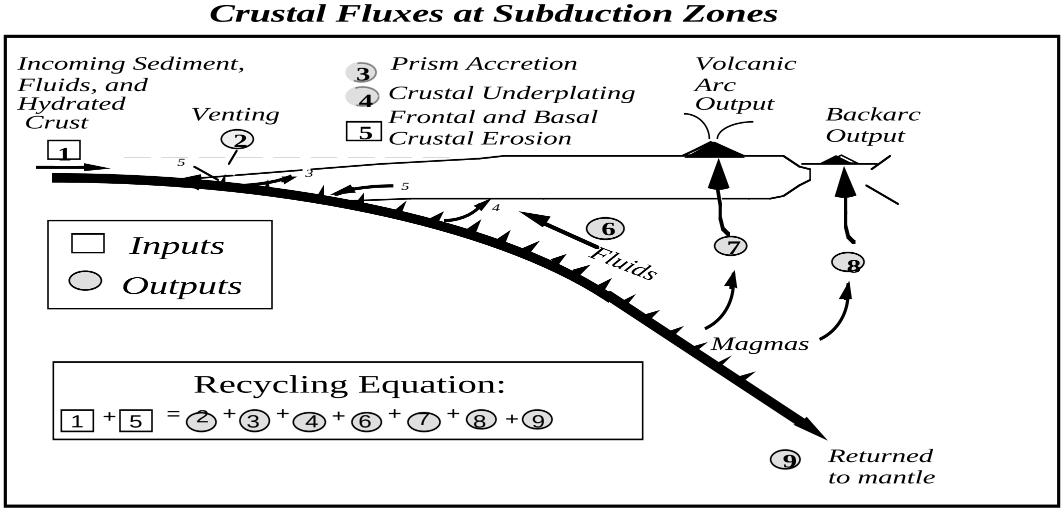


TABLE OF CONTENTS

EXECUTIVE SUMMARY

At subduction zones the return flow of igneous ocean crust to the mantle recycles components of accrued sediment, fluids, alteration products, and entrained sialic rock debris. Recycling is to the terrasphere, atmosphere, and hydrosphere from which materials in these components were initially derived, or to the deeper underlying mantle from which each of these surficial realms of the Earth were themselves largely extracted. Investigations of subduction zone recycling are concerned equally with the mass fluxes involved and the processes, behavior, and effects of material and elements moving through the entire subduction cycle from trench floor to deep mantle.

Recycling studies have broad scientific appeal and merit because they address the effects and consequences of the vertical movement and exchange of crustal and mantle materials. But recycling research has near-term societal relevance as well because the involved processes and mechanisms influence the geo-environmental and geohazards settings of nearly 45,000 linear km of our ocean margins. The impact on the world's populace of subduction zone earthquakes, tsunamis, and arc volcanism, all manifestations of subduction zone recycling, has been immense. Recycling also produces and releases large volumes of global-change gases to the hydrosphere and atmosphere, thus directly affecting climatic patterns an Earth scale.

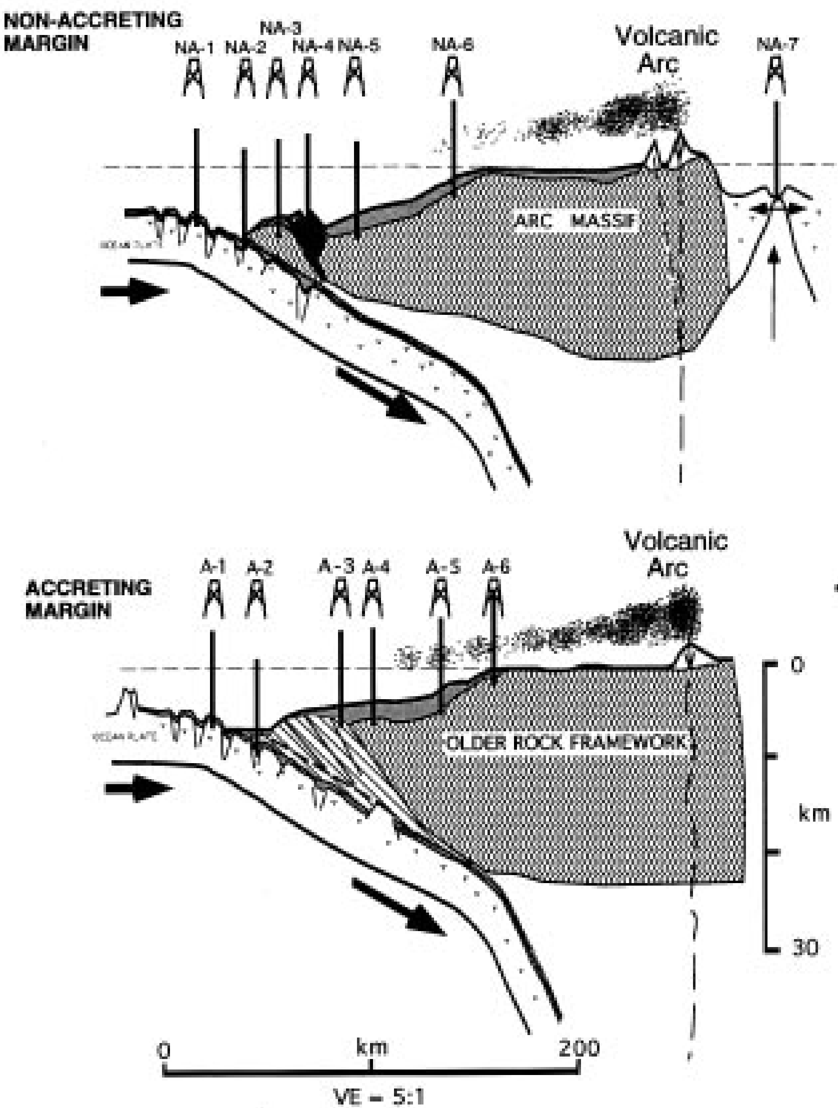
Although the scope of recycling studies involves many different approaches, scientific ocean drilling provides the only way to obtain much of the data needed for those conducted at modern subduction zones. This is absolutely clear, because if the measured effects of recycling processes are to be linked to mass fluxes, and mass fluxes are to be quantified, then the

- age, stratigraphy, and composition of material stored in the forearc,
- history of vertical tectonism in the forearc,
- and the fluid and volcanic output and geochemical components from the forearc, arc, and backarc regions,

must be related to inputs inventories of material ingested by the subduction zone. The Ocean Drilling Program, and a suitable drilling strategy, can uniquely provide the data needed to constrain these processes (Figure EXS-1).

During the past decade the combination of advanced seismic imaging, ODP drilling, and trace element and isotopic studies of deep sea sediment, ocean crust, arc magmas, and deeply subducted rock, has established that the physical machinery of recycling involves the subduction of altered and fluid-bearing ocean crust, the subduction of ocean floor sediment, and the tectonic erosion of the upper plate. The later two processes mainly recycle continental crustal material and associated fluids and hydration products, which trace element and isotopic geochemistry unequivocally establish can reach mantle depths of at least 100-125 km.

The JOI/USSAC workshop recognized that, beyond investigating the physical and chemical processes of recycling, a desirable scientific goal for ODP drilling is to contribute to a major improvement in the global estimate of the mass and composition of the terrestrial material and fluids moving through the subduction zone. In particular with respect to material moved to the base of the upper plate, or transferred to the mantle overlying the descending slab potentially for recycling upward to the lithosphere of the overlying plate. Mass flux investigations address questions about how the Earth evolved; key among them are:



NA-1: Complete ocean-floor section and upper part of igneous crust [*Input reference, stratigraphy, petrology, and geochemistry*]

NA-2: Complete trench-floor section and upper part of igneous crust [*Input reference stratigraphy, petrology, and geochemistry*]

NA-3: Lower part of outer forearc, sedimentary section and upper part of basement rock [*fluids, basement type, history of vertical tectonism, ash geochemistry*]

NA-4: Outer forearc, serpentinite diapirs [*inclusions, fluid flux, geochemistry*]

NA-5: Outer forearc, complete sedimentary section and upper part of basement rock [*fluid flux, basement type, history of vertical tectonism, ash geochemistry*]

NA-6: Upper forearc, complete sedimentary section and upper part of basement rock [*fluid flux, basement type, history of vertical tectonism, ash geochemistry*]

Vol. Arc: Geochemistry well know, and eruptive rocks exhibit strong slab signature

NA-7: Backarc upper crustal rocks [*geochemistry and fluid flux*]

A-1: Complete ocean-floor section and upper part of igneous crust [*Input reference stratigraphy, petrology, and geochemistry*]

A-2: Complete ocean-floor section and upper part of igneous crust [*Input reference stratigraphy, petrology, and geochemistry*]

A-3: Older part of accretionary prism and complete section of overlying slope deposits [*Age of prism, fluid flux, history of vertical tectonism, ash geochemistry*]

A-4: Complete section of overlying slope deposits and upper part of basement [*origin of basement, history of vertical tectonism, fluid flux, ash geochemistry*]

A-5: Complete section of overlying slope deposits and upper part of basement [*origin of basement, history of vertical tectonism, fluid flux, ash geochemistry*]

A-6: Complete section of overlying slope deposits and upper part of basement [*origin of basement, history of vertical tectonism, fluid flux, ash geochemistry*]

Vol. Arc: Geochemistry well know, and eruptive rocks exhibit strong slab signature

FIGURE EXS-1: Idealize drilling transects to investigate recycling processes, mass fluxes, and movement of upper plate crustal materials and subduction components through the subduction cycle. Drilling strategies for geophysical- and geochemical-imaging approaches are shown combined. Not shown is the requirement for parallel transects across targeted margins to identify the effects of lateral changes in input parameters of sediment mass, physical properties, stratigraphy, solid matter and fluid geochemistry, and bathymetric relief.

• How does subduction affect the chemical budgets of the ocean and at what time scale?

• At what rate is old continental crust returned to the mantle through sediment subduction and subduction erosion?

• What is the rate of continental growth over time?

• What fraction of new continental crust is derived from old continental crust via subduction recycling?

• What fraction is derived directly from the mantle?

• What fraction of subducted crustal material contributes to crustal thickening through underplating?

• What is the effect of crustal extraction and subduction recycling on the dynamic thermal, mineralogical and chemical behavior of the mantle?

Mass flux investigations requiring estimates of input and output of subduction components along the downdip-length of the subducted plate can be approached in two different but mutually complementary ways:

(1) scientific drilling combined with geophysical imaging, and

(2) scientific drilling combined with geochemical imaging (Figure EXS-1).

The geophysical approach compares the present or past-predicted input volume of material against the mass of accreted material geophysically imaged beneath the landward trench slope, and the volume of upper plate material required to explain warped paleobathymetric surfaces traced geophysically along and across the margin. Geophysical imaging sets constraints at the front of the recycling system, and, at depths of 20-30 km, is the last direct flow monitor for following subduction zone mass throughput. Imaging deeper, the geochemical approach employs a variety of elemental and isotopic tracers that indirectly image the slab and material flow, and can monitor and constrain fluxes of subduction components to depth of 100-125 km and deeper. The success of both approaches depends upon age and stratigraphic information, chemical and physical measurements, and logging results gathered at across-margin and along-margin drilling sites positioned at targeted subduction zones.

Different but complementary drilling strategies are needed to support geophysical and geochemical imaging approaches to recycling investigations. For example, to geochemically image recycling processes and fluxes, it is crucial to realize that, at most subduction zones, it takes 2-3 my years for subducted material to reach sub-arc depths and return via arc magmatism. It is thus important to simplify interpretations of results and tests for diagnostic effects by eliminating as much as possible changes in input parameters during this time period. Equally important, opportunities for wall-rock contamination of returning fluids and melts must be kept at a minimum. These circumstances require drilling where near steady-state input conditions have existed over much of latest Cenozoic time, and where the ascent of fluids and melts travel least through reactive continental crust or accretionary piles. Advantages must also be taken of subduction zones laterally along which the input parameters change geographically but not temporally. These circumstances lead to the recognition that certain drilling areas and settings are important to successful geochemical imaging of recycling fluxes and processes.

Complementing this need to eliminate variables, geophysical imaging approaches seek to identify background rates of mass material movement and storage under “steady-state” conditions, but also where changes in plate-boundary conditions cause rates to increase or decrease dramatically, for example, as the consequence of the subduction of a seamount or oceanic ridges. It is equally important to compare mass flux rates, whether effected by sediment subduction or subduction erosion, at both non-accreting and accreting margins (Figure EXS-1). Because geophysical imaging techniques can analyze the effects of recycling processes and fluxes operating over tens of millions of years, advantages can be taken of space-time changes in plate boundary conditions at one locality or that progress laterally along the margin. This circumstance can vary from a migrating collision zone or the progressive along-axis flooding of a trench floor with thick turbidite deposits.

Drilling strategies for geochemical and geophysical approaches require across-margin and along margin site selection of targeted subduction zones. And both require the recovery of trench-floor or oceanic reference sections to gather site-specific input information, including from the upper part of the underthrusting igneous crust. Idealized drilling transects of targeted margins are shown on Figure EXS-1. In general, recycling drilling can be most profitably targeted where:

- The late Neogene history and geochemistry of arc volcanism, both along and across strike, is well known,
- Arc magmatic rocks posses a strong slab signal (e.g., ^{10}Be, B, Ba) that can be tracked cross-arc with increasing slab depth,
- Contamination of ascending melts through older crustal rocks and accretionary prisms is minimal,
- The composition of the input material has not changed much in late Neogene time
- A prominent, steady-state but lateral change occurs in input components that can also be tracked laterally by forearc, arc, and backarc fluid and eruptive products
- Seismic imaging of the forearc region is adequate to define the geometry and solid mass of an accretionary prism and its structural setting with respect to a backstop or buttress of older rocks,
- Seismic imaging is adequate to define details of slope-mantling deposits, in particular to trace laterally and across the width of the margin paleobathymetric surfaces or key unconformities that bury the backstop and older part of the prism,
- Slope-mantling sediment is known to be datable, fossiliferous, and thus capable of reconstructing a history of Neogene and early Cenozoic vertical tectonism, or retains a record of paleodip changes that can track forearc tilting and tectonism.
- A prominent bathymetric feature has underthrust the landward trench slope, in particular where the collision point of a chain of seamounts or ridge has migrated laterally along the margin.

Clearly the greatest scientific gains will be achieved if many or all of these strategies can be executed along single margin sectors. Drilling sediment inputs and stored masses provides limited gains in terms of recycling studies if the margin's subsurface rock and sediment architecture is unknown, or if the history of coastal tectonism is unknown, or if a volcanic arc is absent, or if the geochemistry of arc volcanic rocks are unknown or substantially overprinted by upper crustal contamination. The problem of mass material flux and crustal recycling is best tackled with an integrated drilling transect to recover samples of crustal inputs, accreted ocean floor material, slope deposits that record margin tectonism, forearc fluids, and products of arc and backarc volcanism. But the full problem of recycling requires an even broader set of tools than those provided by the drilling program, and includes on-land, experimental, and theoretical modeling studies as important components, issues that are also stressed in the defining documents of the MARGINS Initiative.

The approach that we encourage with this Recycling Report is to try to focus on the whole system at margins where significant progress can be made on many fronts through an integrated drilling effort.

PART I

INTRODUCTION AND BACKGROUND INFORMATION

Large quantities of ocean-floor terrigenous and biogenic sediment, together with associated fluid, and hydration and alteration products, are annually added to the upper layer of igneous ocean crust and carried into subduction zones around the world (Figure 1). Although some of these materials are derived from atmospheric and hydrospheric sources, the great bulk are contributed to the ocean basin from continental or terrestrial areas. When drawn within the embrace of a subduction zone, the host igneous crust and its freight of additives begin a process of recycling (see "definitions" below) or the transfer of material to the fluid reservoir of the ocean basin, the crustal mass of continents and island arcs, and to the underlying mantle from which the Earth's terrestrial and fluid realms were derived (Figure 2). Recycling at ocean margins also includes large volumes of mostly sialic material tectonically eroded from the upper plate by the underthrusting action of the downgoing ocean plate.

Challenging scientific questions, including many that are relevant to societally important concerns, arise regarding the processes, solid-volume and geochemical mass fluxes, pathways, and fates of recycling materials. These wonderments in particular focus on the effects, consequences, and destinies of subducted continental components. To explore these issues and practical strategies to address them through ocean-floor drilling a JOI/USSAC-sponsored Recycling Workshop was convened during the week of June 12, 1994. Driving this event was the notion that scientific ocean drilling can uniquely provide quantitative information on the composition and quantities of recycling components entering the subduction zone, refluxed to the ocean basin, accreted in the forearc, returned to the upper plate via magmatic or diapiric processes, or restored to the mantle with the subducting slab (Figure 2; see also, Plank et al., 1993).

The Recycling Workshop was organized within a larger meeting of approximately 120 scientists gathered at Avalon, Catalina Island, California, to participate in a cross-disciplinary, top-to-bottom-examination of the subduction process of ocean crust. The subduction conference—SUBCON—was partly sponsored by JOI/USSAC. SUBCON's 5-day program of thematic papers, poster displays, and a field trip to examine a deeply underplated (15-45 km) body of subducted sediment and igneous ocean crust (The Catalina Schist), provided a unique opportunity to attract the attention and inputs of a large sector of subduction-interested earth scientists to scientific opportunities in deep sea drilling and subduction zone recycling investigations.

(I-1) THE RECYCLING WORKSHOP

The JOI/USSAC Recycling Workshop was convened in two formal sessions and one multi-day informal session. The first gathering, open to all SUBCON participants, was an introductory assembly on Monday, June 13, 1994, at which extremely diverse global geochemical and geophysical perspectives of recycling processes and effects were presented. The second session was carried out informally during the remainder of the week through the all-conference presentation of about 120 papers and posters that brought forward the results of 35 field, laboratory, and modeling investigations directly relevant to recycling science and drilling. The final gathering, an all-conference session held on Friday afternoon,

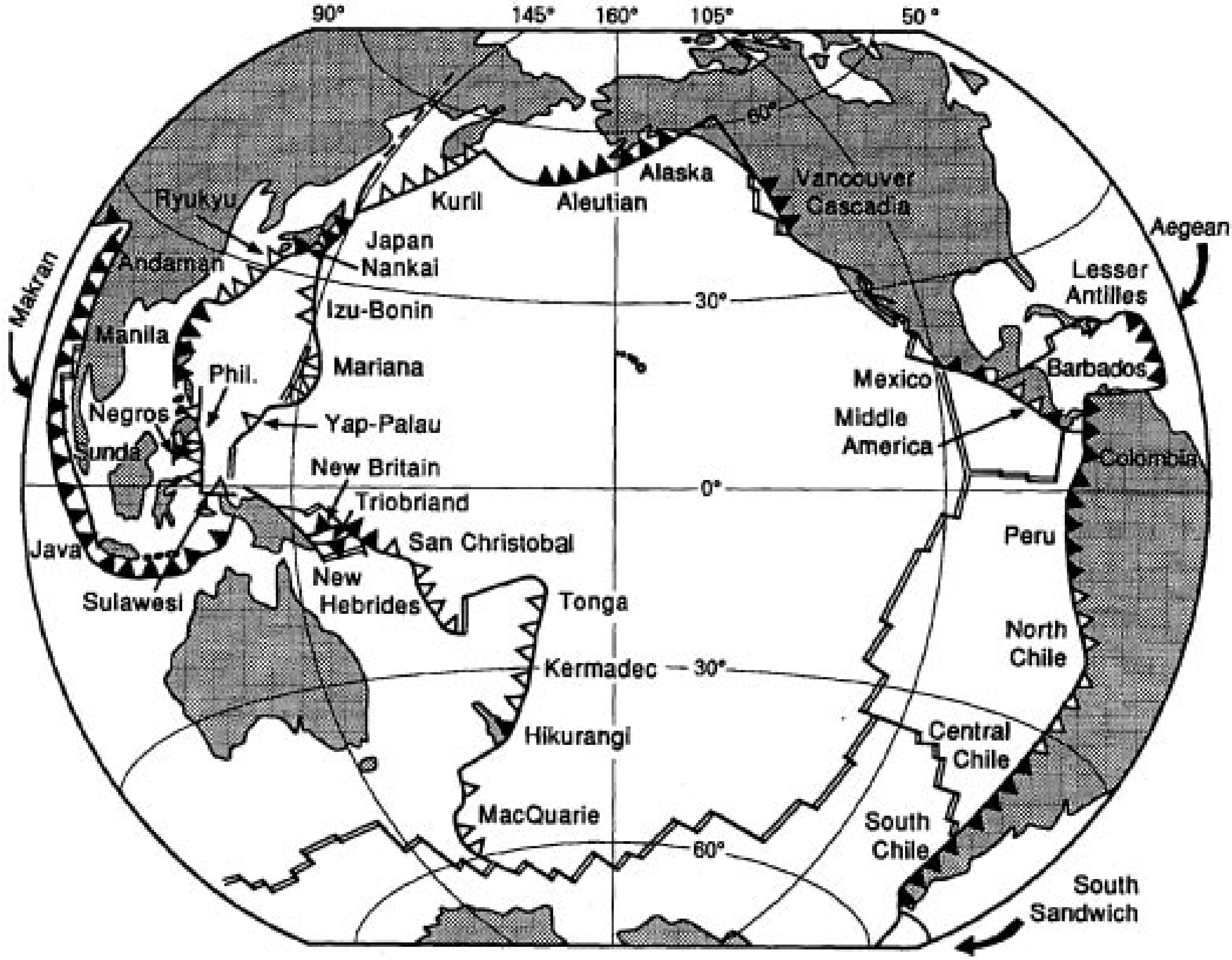


FIGURE 1: Trenches (barbed lines) bordering convergent margins of the Pacific, Caribbean, and eastern Indian Ocean regions at which recycling of crustal material occurs. Not shown, but indicated, are the short trench segments of the Makran region of the Gulf of Oman, northwestern Indian Ocean, the South Sandwich Trench connecting South America and Antarctica, and the Aegean region of the eastern Mediterranean. Filled barbs identify **accreting margins** along which small to intermediate size (5-40 km in length) and large (40-100+ km) prisms are actively growing, mainly in response to the offscraping of trench-floor deposits (Figure 4). Open barbs identify trenches bordered by **non-accreting margins** along the base of which effectively no sedimentary prisms are forming (Figures 4, 6 and 8)).

The global length of subduction zones where recycling occurs is approximately 43,000 km (non-accretionary =19,000 , accretionary =, 24,000). Qualitative information implies that the annual solid-volume mass of upper plate material currently being recycled to mantle depths is about 1.0 km3; over geologically long periods of time the rate is proably closer to 0.7 km3/yr.

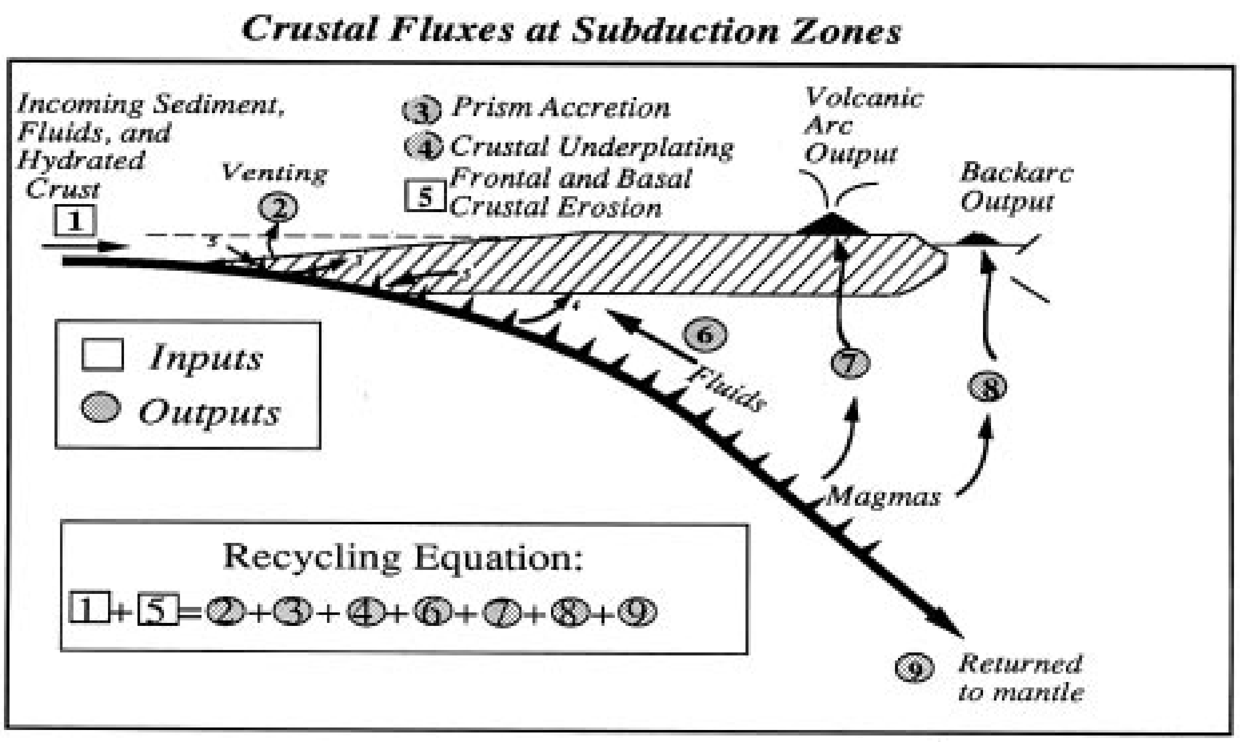


FIGURE 2: The flux of crustal material and subduction components, the bulk of which is terrestrial or upper plate material, through a subduction zone. Arrows indicate schematic flow, not detail flow patterns. The complete recycling or flux of subduction components to the mantle depends on many other fluxes: the partitioning and loss and gain of bulk sediment in the shallow part of the subduction zone (by accretion, underplating, and erosion), chemical and fluid fluxes due to sediment dehydration and melting, and chemical fluxes to the volcanic arc and backarc. Scientific ocean drilling can successfully, and in certain areas, uniquely address each of these fluxes

June 17, focused on clarifying fundamental goals, exploring outstanding problems and concerns, and discussing basic drilling strategies to maximize results and minimize known or perceived data-interpretion difficulties.

This report brings forward the main points of the deliberations of SUBCON's Recycling Workshop and related background information. A conference proceedings volume of extended abstracts, many of which address recycling issues and observations, was provided all participant and potentially will be published as a U.S. Geological Survey Open File Report (reorganizational and downsizing issues in 1994 through much of 1996 USGS continues to delayed this plan). However, a volume of expanded thematic papers has been assembled and will be published, probably late in 1996, as a Monograph of the American Geophysical Union Monograph (Bebout et al, 1996).

SUBCON attendees specifically invited to participate in the Recycling Workshop are listed in Appendix I. All SUBCON attendees, many of whom participated at various times in both formal and informal sessions and discussions, are listed in Appendix II.

(I-2) RECYCLING STUDIES—SCIENTIFIC AND SOCIETAL INTERESTS

Two rationales for conducting recycling studies at subduction zones were emphasized at the Workshop:

(1) To garner basic scientific knowledge of material fluxes and recycling processes at convergent margins, and

(2) To understand the societally important consequences of the subduction of ocean crusts and recycling components, both solids and fluids (see definitions below), as they affect global-change and geohazard settings and processes.

Scientific interests voiced at the Recycling Workshop also grouped themselves into two general thematic areas:

1) Recycling Processes—i.e., the physical, thermal, mineralogic, and geochemical processes involved in the movement of rock, sediment, and fluids through the subduction zones, and

2) Recycling Fluxes—i.e., the quantitative movement (flux) and pathways of solid, fluid, elements, and dissolved materials moving through the subduction zone.

With respect to fluxes, mass or bulk material flux refers to the transport of material from one spot to another (i.e., metric tons, cubic meters, etc., of sediment, rock, fluids) . "Element or chemical flux" refers to the transport of chemical elements from one spot to another. The relation between element and mass flux is often model dependent and must be specified.

These interests and interest in addressing them through ocean drilling have been around for more than a decade. For example the Mantle/Crustal Working group of COSOD-II (1987 (p. 64)) recognized that a proper strategy of ODP drilling is:

*"**urgently needed to advance studies of convergent margin chemical fluxes and to better understand processes of crustal recycling.**"*

In keeping with this recommendation, a strategy and scientific rationale for geochemical reference drilling to determine the geochemical and isotopic characteristics of old ocean crust entering the subduction zones of the western Pacific was proposed by Langmuir and Natland (1986). Although a drilling leg was scheduled for this investigation, the leg was subsequently canceled. Drawing on the implications of newer observations (see, for example, Morris et al., 1990; Plank and Langmuir, 1993), and the high rankings assigned to recycling drilling by the JOIDES Lithosphere (1994) and Sedimentary and Geochemical Processes Panels (1994), and the Tectonic Panel (1995), drilling proposals to address recycling science have again being submitted (Plank et al., 1993).

Although the recommendations of COSOD-II focus on addressing flux questions through the techniques and approaches of geochemical imaging, it has become increasingly understood that geophysical imaging and drilling can provide complementary and similarly indispensable information bearing on recycling processes and bulk-material fluxes. In a gross sense, physical imaging of present input volumes with respect to the stored volumes of accretionary prisms sets mass storage and by-pass constraints at the front of the recycling system. Geochemical imaging traces material transfer landward and to depths beyond the capabilities of modern seismic techniques. Both investigative approaches combine sampling, physical measurements, and logging results gathered by offshore drilling with onshore studies of vertical tectonism, patterns and styles of faulting, and arc magmatism. The major scientific objectives of these two complementary approaches, and drilling strategies to provide information on recycling fluxes and processes, are, respectively, amplified in Parts II and III of this report.

The scientific relevance of recycling investigations thus lies in addressing questions concerning the amounts, effects, and changes (alteration) of component materials moving through the subduction zone. A major scientific objective of recycling investigations is also to learn about the fate of component materials. At high structural levels, component material can be recycled to ocean basin waters or stored along the ocean edges as accretionary piles. At deeper levels, component material can take up temporary or long-term residence at the base of the crust, or descend deeper still and either return upward to the crust of the upper plate via magmatic and diapiric processes or mix downward into the globally circulating mantle (Figure 2). Determining the net growth of continental crust over relatively long periods of geologic time, and the companion geochemical evolution of the underlying mantle and arc magmatism, are also important objectives of recycling studies. Special workshop attention was thus focused on how scientific ocean drilling can contribute to determining the flux of continental and fluid components to mantle depths and the important processes involved.

Recycling processes and mechanisms also have societal relevance as they influence the geoenvironmental and geohazard settings of subduction zones and their impact on the world's populace. Under recycling topics is the role of subducted sediment and water in affecting subduction zone seismicity and tsunami hazards, in supplying elements and fluids involved in ore formation, in removing CO_2 and affecting the carbon dioxide balance of the Earth's atmosphere, in fluxing hydrocarbons, including methane, to the ocean basins, in contributing to explosive arc volcanism and longer term effects on climate modification and in the "volcanogenic pollution" of the atmosphere.

To sum up, processes as different as deformation in accretionary prisms, hydrocarbon and ore formation, hazardous seismicity and volcanism, the building of continents via arc volcanism, their removal by subduction processes, climate modification, injection of toxic trace metals into the hydrosphere and atmosphere, and chemical change of the Earth's deep mantle are all linked to the recycling of sediment, crustal rock, and sea water at subduction zones. To understand the array of socially and scientifically important consequences of subduction recycling, we must be able to characterize the compositions and quantify the masses of subducted materials, and to identify the processes by which they are either returned to the surface or carried to depth. The focus of this Workshop Report is thus to pinpoint the contributions that ocean drilling can make to advancing our understanding of the processes, consequences, and effects of crustal component recycling, some of which are charted on Figure 3.

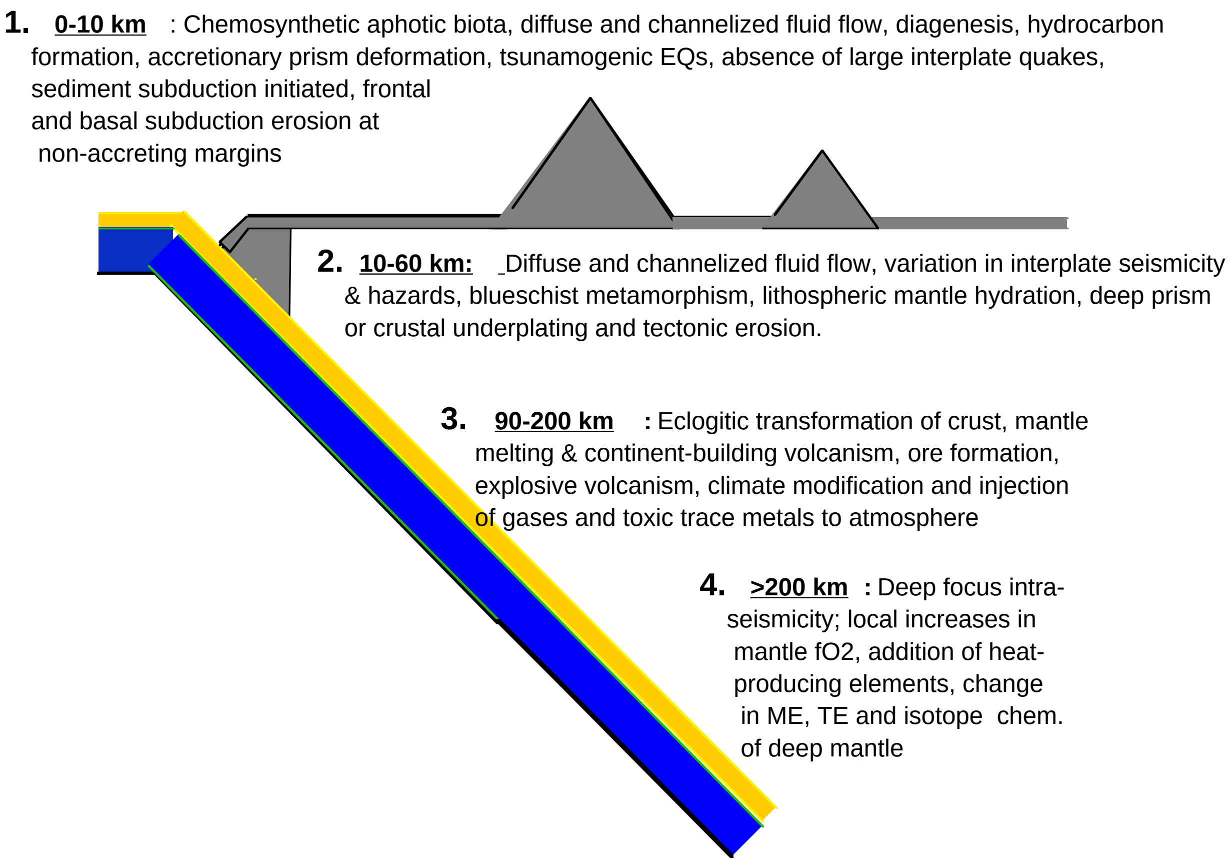


FIGURE 3; A summary of major processes, effects, and consequences, at increasing depth, of the subduction of sediment, seawater, basalt alteration products, and upper plate debris.

(I-3) THE SORT OF SOLID MATERIAL THAT GETS RECYCLED

An important question concerns the general or bulk lithologic composition of component materials recycling through subduction zones. With respect to subducted continental components, Rea and Ruff (in press) extracted from DSDP and ODP data that the globally-averged composition of oceanic sediment (i.e., that deposited seaward of the trench area, see definitions below) drawn into subduction zones is, by solid-volume mass:

	Oceanic Sediment
Terrigenous (including ash)	76 percent
Biogenic carbonate	15 percent
Biogenic opal	09 percent

Adding to these figures the thickness of turbidite beds deposited by trench-axial sedimentation processes, including an estimate of the pile of non-fluidized mass-wasting debris that accumulates at the based of the landward trench slope, the globally-averaged composition of ingested sediment changes to:

	Oceanic + Trench-axis Sediment
Terrigenous (including ash)	93 percent
Biogenic carbonate	04 percent
Biogenic opal	03 percent

Subduction also erodes continental and island arc matter from the upper plate. The solid-volume of this terrigenous material annually stripped from ocean margins is probably at least 1.0 km^3/yr (von Huene and Scholl, 1991), and potentially much greater (Lallemand et al., 1992a; Lallemand, 1995). Within the subduction zone, the globally-averaged mixture of recycling continental material is thus:

	Processed at Subduction Zones
Terrigenous (including ash)	95 percent
Biogenic carbonate	03 percent
Biogenic opal	02 percent

Exclusive of igneous ocean crust, the great bulk of recycling material is thus sialic or continental in origin. It is derived either tectonically by subduction-induced erosion of the upper plate, or depositionally by accumulation of volcanic ash, terrigenous sediment, biogenic debris, and rock-alteration products, all largely of upper plate origin.

With respect to the solid-volume mass of the material involved, over long periods of geologic time the through-put volume of continental material that reaches subcrustal or mantle depths is potentially large. During most of late Cenozoic time, it is estimated that roughly 2.0 km^3 of solid-volume sediment, and at least this volume (2.6 km^3) of fluids, annually enter the global length (~43,000 km) of subduction zones (von Huene and Scholl, 1991; Moore and Vrolijk,1992). A large but poorly quantified fraction of this ingested continental material may well reach the mantle.

(I-4) DEFINITIONS

A number of terms and expression used in this report describe recycling concepts, processes, mechanisms, and component materials. To provide consistency in their meaning and use, these term and expressions are defined below, and some of them are diagrammatically shown on Figures 1, 2, 3, and 4

(I-4-1) GENERAL TERMS AND CONCEPTS

(I-4-1-1) Subduction zone recycling (also subduction recycling, recycling, and crustal recycling):

Means, at subduction zones, the return flow of igneous ocean crust to the mantle, including its components of accrued sediment, fluids, alteration products, and entrained sialic rock debris, either recycled relatively directly to the terrestrial, atmospheric, and hydrospheric realms that contributed them, or to the deeper underlying mantle that originally formed these near-surface materials or reservoirs by igneous and outgassing processes. Subduction recycling thus refers to the behavior of material and elements in the downgoing slab throughout the entire subduction cycle (Figures 1, 2, 3 and 4).

(I-4-1-2) Recycling components/constituents (materials):

Means the solid and fluid materials (components) entering the subduction zone that have been added to the subducting layer of igneous ocean crust by deposition, entrapment, chemical alteration, and attachment or inclusion processes. To many geochemists a component is a geochemically defined end member observed in mixing diagrams, which may or may not correspond exactly to a physical entity. Hence the expression Recycling constituent refers to a physical, and therefore drillable and recoverable component or entity.

(I-4-1-3) Continental (or sialic) components:

Means any recycling component derived by arc-volcanic processes or the mechanical and chemical erosion of terrestrial (arc and continental rocks) or sialic crust, including both detrital and dissolved materials. Includes virtually all ocean-floor terrigenous and biogenic sediment and interbedded ash debris and material tectonically eroded from the upper plate.

(I-4-1-4 Fluid component:

Means any recycling aqueous or gaseous component, including gas hydrates, derived ultimately from the atmosphere, hydrosphere and biosphere.

(I-4-1-5) Accreted material:

Means any recycling component material or oceanic igneous rocks that is tectonically transferred from the underthrusting crust of the lower plate to the front (frontal accretion) or base (basal accretion or underplating) of the crust of the upper plate.

(I-4-1-6) Subducted material:

Means any ocean crustal or recycling component material underthrusting the ocean margin that is transported to mantle depths (i.e., to depths >~30-40 km). This definition is equivalent to subcrustally subducted material as used by von Huene and Scholl (1991).

(I-4-1-7) <u>Accreting Margin:</u>

Means any convergent ocean margin along which an observable (i.e., > 5-10 km in width) accretionary wedge or prism of offscraped ocean-floor deposits has formed (Figure 4).

(I-4-1-8) <u>Accretionary prism (wedge or complex)</u>: Means a mass of rock and sediment underlying the landward trench slope composed of igneous crustal material and recycling components of sediment and fluids tectonically scraped off the subducting plate and added or accreted to the frontal or seaward edge of the bedrock framework of the upper plate. Rock and sediment masses of the lower plate that underplate the older rock framework of the upper plate are not considered to be part of an accretionary prism (see Subduction Accretion elsewhere below).

(I-4-1-9) <u>Non-Accreting Margin:</u>

Means any convergent ocean margin along which effectively no accretionary prism has formed, or where small (typically < ~ 5 km in width) masses of offscraped ocean-floor sediment have accumulated that are many times—at least an order of magnitude—smaller than the potential mass of the accretionary pile (Figure 4).

(I-4-1-10) <u>Oceanic sediment (deposits)</u>:

Means sediment of any composition or origin that accumulates in the ocean basin seaward of subduction zones and ocean-margin rimming deep sea trenches.

(I-4-1-11) <u>Ocean-floor sediment (deposits)</u>:

Means sediment or mass-wasting debris of any composition or origin that accumulates anywhere over igneous oceanic crust, i.e., trench axis and more seaward areas of the ocean basins.

(I-4-1-12) <u>Trench-axes sediment (deposits)</u>:

Means sediment of any composition or origin that accumulates along the axial regions of deep sea trenches, commonly as a landward thickening or wedge-shaped body of terrigenous turbidity beds, but also as piles of mass wasting debris from the landward trench slope. (Figure 4).

(I-4-1-13) <u>Trench-floor section</u>:

Means the complete section of oceanic sediment and trench-axis sediment that is ingested at subduction zones. The ocean-floor deposits of the trench region are therefore equivalent to the trench-floor section.

(I-4-2) TECTONIC PROCESSES

(I-4-2-1) <u>Underthrusting</u>:

Means the process of the landward and downward movement (underthrusting) of the igneous crust and included continental and fluid components of the lower plate beneath the sediment and rock framework of the upper plate. Subsurface transport takes place below a detachment or decollement surface, or within and below a thicker zone of distributed interplate shearing (i.e., the subduction channel; see Cloos and Shreve, 1988ab) that constitutes the interplate boundary.

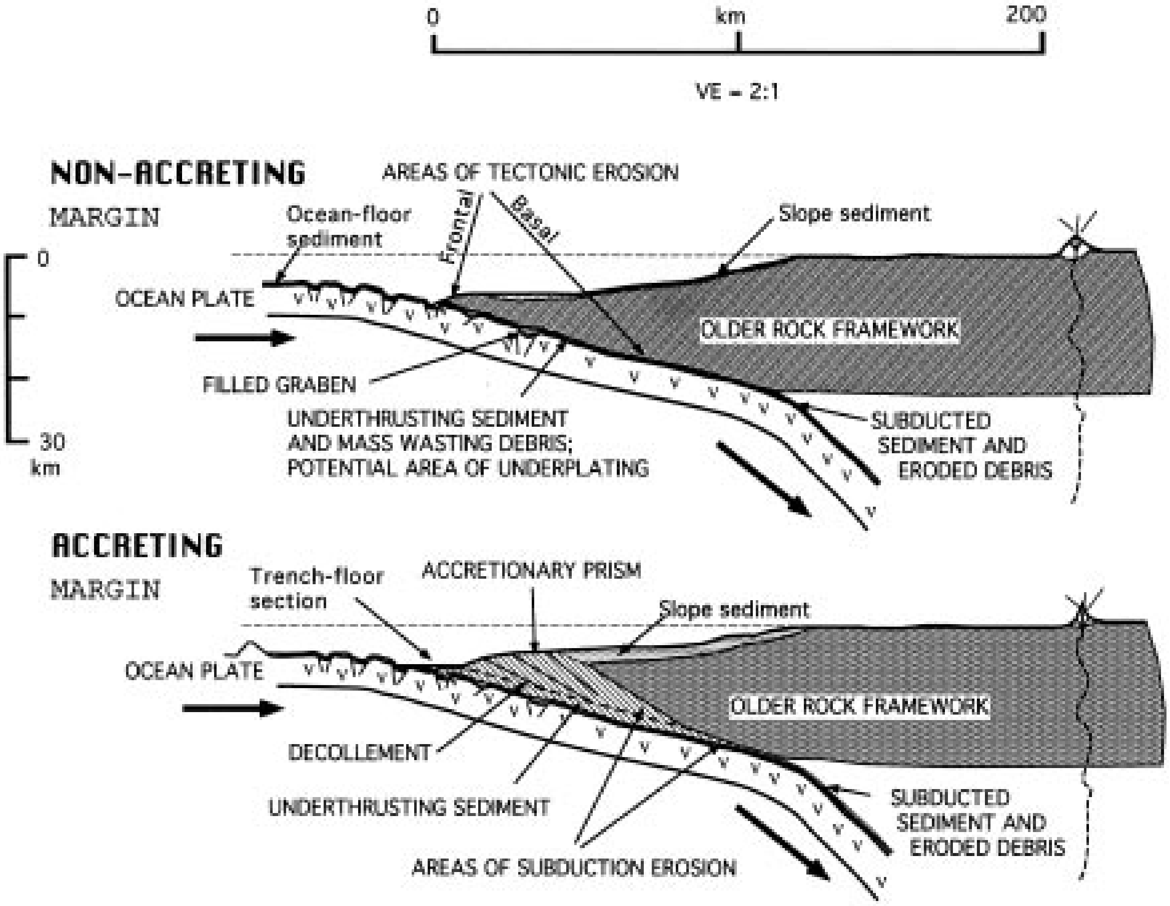


FIGURE 4: Cartoon models of mass flux processes operating at non-accreting (upper) and accreting margins (lower). At non-accreting margins most of the deposits of the trench floor section, including mass wasting debris filling underthrusting grabens, is most probably subducted to mantle depths. At accreting margins, a small to large fraction of the trench-floor section is offscraped above a decollement to form an accretionary prisms.Tectonic erosion--subduction erosion--is thought to occur at both the front and along the base of the margin. Frontal erosion at accreting margins may require the underthrusting of a large seamount or aseismic ridge (Lallamand et al., 1992b).

Efficiency of offscraping is mass of accretionary body (MAB) divided by thickness of trench-floor section (Th) **X** convergence rate (CR) **X** time of prism growth (Tm)--: MAB / (Th)(CR)(Tm) **X** 100. Commonly, over several million years, at accretionary prisms less than 40 km in width the efficiency of offscraping or prism-making is 20 percent or less of the sedimentary mass ingested by the subduction zone .

(I-4-2-2) Subduction accretion (accretion):

Means the tectonic process at subduction zones that transfers solid and fluid recycling components and igneous crustal rocks of the underthrusting lower plate to either the structural front (frontal accretion) or subsurface base (basal accretion or underplating) of the crustal layer of the upper plate. Seaward of the upper plate's older rock framework, frontal and underplating processes combine to build accretionary prisms (wedges). Underplating beneath the older crustal framework rock generally landward of the lower trench slope, i.e., beneath the mid-slope area of the forearc, is not considered part of the prism-growing processes (see Accretionary prism, above; Figure 4).

(I-4-2-3) Subduction underplating:

Means the subsurface process of attaching sediment and rock masses underthrusting the margin to either the base of an accretionary prism or the margin's inboard framework of older, crustal rocks.

(I-4-2-3) Sediment subduction:

Means, at ocean margins, the process of the underthrusting of ocean-floor sediment to reach mantle depths, i.e., depths > 40-60 km. Subducted sediment thus totally by-passes frontal and underplating accretionary processes. This definition is equivalent to subcrustal sediment subduction of von Huene and Scholl (1991)].

(I-4-2-4) Subduction erosion:

Means, at ocean margins, the process of removal and transport of upper plate material toward subcrustal and mantle depths.[erosion can be effected at the front of the margin (frontal erosion) or along it's base (basal erosion)]

(I-4-3) GEOCHEMICAL PROCESSES

(I-4-3-1) Fluids:

Refer to fluids that are largely aqueous (hydrous) C-O-H-S-N fluids, generated in the slab during dehydration reactions, as opposed to silicate melts, generated by partial melting of silicate material.

(I-4-3-2) Geochemical Imaging:

Means measuring elemental concentrations or ratios, or isotopic ratios (collectively called "tracers") that are distinctive in sediment, fluids, altered basaltic crust or mantle and can be used to show the contribution from these materials to vented fluids or erupted magmas or serpentinite diapirs.

(I-4-3-3) Source Materials:

Means materials whose dewatering, dehydration or melting contributes to the fluids or melts that are sampled at the surface. "Component" or "end-member" may be used in lieu of "source materials", particularly when defined by chemical relationship.

(I-4-3-4) Source Region:

Means the location from whence fluids and melts originate. For non-accretionary margins, the source region for fluids is thought to be the slab; for arc magmas the source region is thought to be the sub-arc mantle wedge which has been modified by addition of a subduction component.

(I-4-3-5) Subduction component or end-member:

Means material transported from the slab to the mantle. May sometimes be subdivided into sediment component or basaltic component where the source can be inferred chemically. Transport may be in a fluid or a partial melt, but does not generally involve wholesale transfer of bulk sediment or altered basalt.

(I-5) SKETCH-PAD HISTORY OF RECYCLING WONDERMENTS AND RE-LATED EVIDENCE

The broad scientific importance of the subcrustal subduction and mantle recycling of sialic or continental material attained wide recognition only during the past 5-10 years, But the modern history of recycling interest extends back at least 40 years. As alluded to earlier, attention arose from observations about apparently missing volumes (mass-balance deficits) of sediment and basement rock at ocean margins, and the melting and source-region implications of the trace-element and isotopic geochemistry of eruptive rocks. For example, Bob Coats' studies of Aleutian arc volcanism in the 1950's led him to propose that the underlying cause of arc volcanism generally was the injection of sediment and fluids down the Wadati-Benioff zone to mantle depths (Coats, 1962). Coats' seminal idea was reached by his cross-disciplinary mating of global-scale geochemical and seismic observances, which combined to both satisfy the nutrient-feeding mechanism required by arc eruptive rocks and resolve the paradox of that time about which way the thrust plane dipped beneath ocean margins—it was landward, not seaward (Figure 5A, panel 1).

Awareness that recycling was occurring at ocean margins thus arrived separately from two fields of inquiry, one drawing upon the techniques of geophysical imagery, and the other on geochemical methods of imaging subsurface process. As a background for contemporary research directions in subduction zone recycling, and in particular as potentially advanced by scientific ocean drilling, thumb-nail sketches of the history of these contrasting but complementary approaches to recycling investiga-tions are provided here.

(I-5-1) GEOPHYSICAL IMAGING AND MISSING MASSES OF SEDIMENT AND ROCK AT UNDERTHRUST MARGINS

Geophysical imaging of the rock and sedimentary fabric of ocean margins is principally carried out by seismic reflection and refraction methodologies. Both techniques make it possible to resolve the geometry, internal structure, massiveness, and areal extent of the lithologic sequences of ocean margins. Although the resolving power of seismic imaging decreases with subsurface depth (i.e., > 20-30 km), and with approach to the coast, the technique is nonetheless a powerful way to compared the rock and sedimentary make up of ocean margins with that predicted by the plate tectonic paradigm. Offshore geophysical investigations in combination with scientific drilling and onshore mapping failed to locate the expected rock and sedimentary sequences of lengthy sectors of underthrust margin, a circumstance that set off searches for both missing sedimentary bodies and crustal framework rocks.

(I-5-1-1) <u>Subduction of Ocean-floor Sediment</u>.

In 1963, nearly 15-years before the notion of sediment subduction was seriously entertained by many earth scientists, Jim Gilluly linked his notice of missing masses of ocean-floor sediment to a concept of subduction. Restating his views in 1969, Gilluly observed that—

"***The volume of sediment off the Atlantic coast of the United States is at least 6 times as great as that off the Pacific Coast. This disparity is readily accounted for if the continent is drifting westward and has overrun large volumes of sediment on a former Benioff zone.***"

In the early 1970s, in concert with the wide acceptance of the general plate tectonic paradigm, research efforts focused on identifying and examining accretionary piles of the trench-floor section predicted to have been offscraped at long-established underthrust margins—for example the Franciscan complex of western California. But companion coastal and offshore seismic reflection studies at some underthrust margins failed to turn up subaerial or subaqueous accretionary prisms of discernible size. Onshore mapping also identified a major mass-balance problem, specifically the paucity of oceanic pelagic deposits in ocean-rimming mountains belts of accretionary deposits, for example the Franciscan Complex, which was constructed of less than 1 percent pelagic beds but should have displayed a volume at least 20-50 times greater. Thousands of kilometers of lower plate underthrusting predicted millions of km^3 of offscraped pelagic deposits around much of the Pacific rim, but only a fraction of this volume was accounted for (Scholl et. al., 1977, Scholl and Vallier, 1981). Somehow, pelagic deposits were being subducted to great, potentially subcrustal, depths (Moore, 1975), despite the intuitive observation that low-strength sedimentary material could not be stuffed beneath ocean margins of higher-strength rocks as could igneous ocean crust. To roughly quote an intrigued but skeptical observer, “you can’t stuff a marshmallow beneath a safe door” Instructively, the fact that ocean-bordering mountain belts were virtually bereft of offscraped oceanic deposits had earlier prompted Kuenen (1950, p. 399) to deduce that continental drift could not have occurred, and that ocean basins as presently existing were thus long-lived if not permanent features of the earth’s surface relief.

As a consequence of DSDP drilling at the Japan, Mariana, and Middle American margins, ‘seriously’ considered evidence for many earth scientists that deficiencies of sedimentary masses at convergent margins could be tied to a concept of sediment subduction first became noticeable in the late 1970s (Scientific Party, 1980; von Huene et al., 1982; Hussong and Uyeda, 1981, Moore et al., 1982, and von Huene and Aubouin et. al., 1980). Drilling transects across these margins were targeted to investigate the effects of subduction zone processes on their tectonic evolution. But a fundamental outcome at each margin was the discovery that both the mass and age of seismically imaged accreted sediment were woefully under representative of the sediment that must have entered these subduction zones during Cenozoic time. Paradoxically, drilling at the toe of the massive Barbados accretionary wedge blundered into evidence of pore-fluid overpressures within the body of underthrusting sediment (Biju-Duval, Moore, et al., 1984). The ability of pore-fluids to bear a lithostatic load, which Hubbert and Ruby (1959) had decades before identified as the physical explanation of why overthrusting of continental crustal rocks occurred, also accounted for the deep underthrusting of trench-floor sedimentary sections (Moore and Vrolijk, 1992). In the 1980s and early 1990s, ODP drilling at the Peru (Suess and von Huene et al., 1990, and south Chile margins (Lewis, Behrmann, and Musgrave et al., 1995) provided additional verification of the efficacy of subcrustal sediment subduction.

(I-5-1-2) <u>Ripping Off Upper Plate Rock</u>.

More than two decades ago an additional subduction process that removed rather than stored rock and sediment at convergent margin was identified. Murauchi (1971), for example, interpreted regional geophysical data to mean that the seaward basement framework rock of the Japan margin had been truncated—tectonically removed—by the underthrusting action of the lower oceanic plate (Figure 5A, panel 3). Concluding similarly, but based on geologic evidence of regional structural terminations, Miller (1970a,b) ascribed the removal of a wide track of basement rocks from the outer Chile margin to a subduction-linked process of tectonic erosion; and so did Rutland (1971) explaining the landward migration of the Chilean arc-volcanic front during Mesozoic and Cenozoic time (Figure 5A, panel 2).

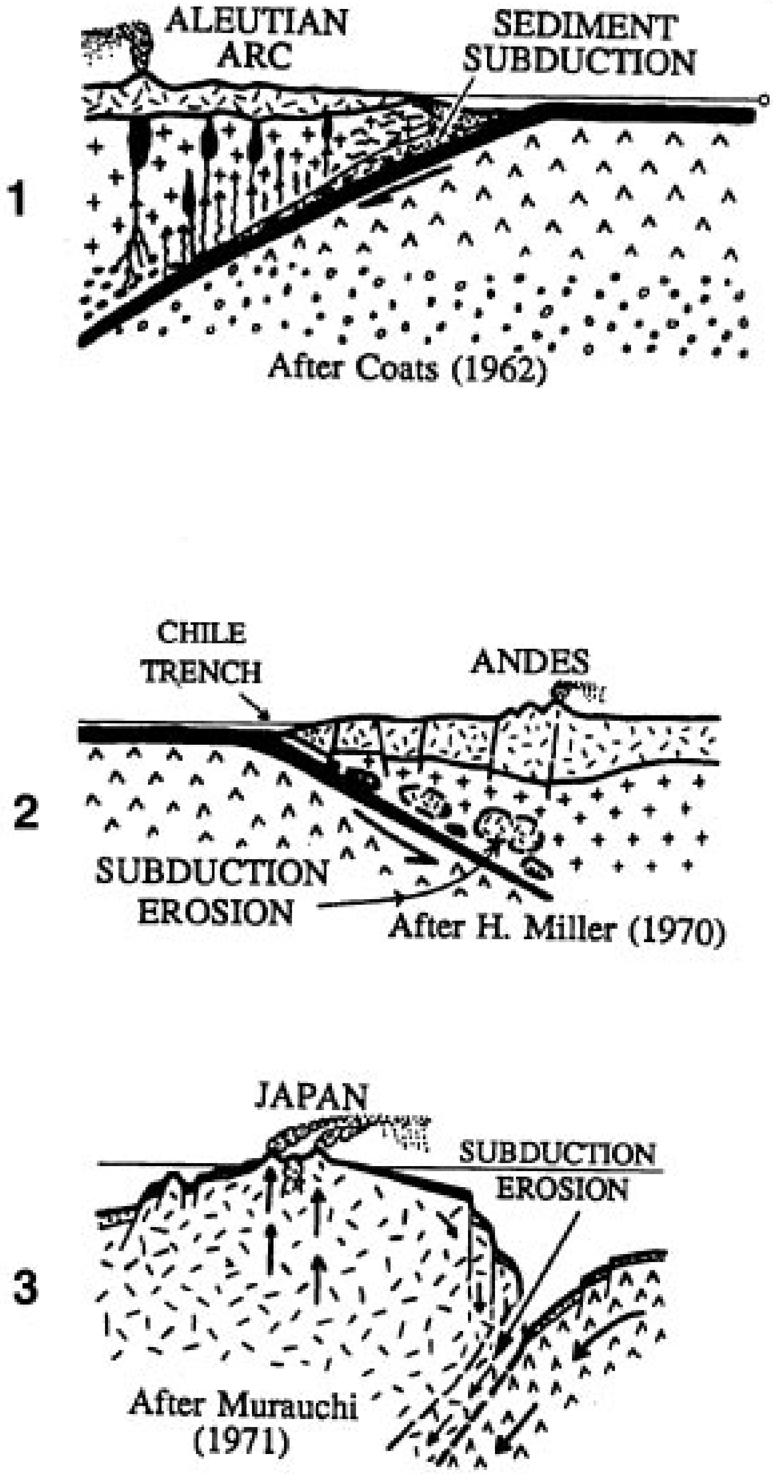
Other stratigraphic and structural observations along the western South American margin were similarly ascribed to the consequences of tectonic erosion (see, for example, Katz, 1971 and Plafker, 1972). Page (1970) argued that tectonic processes truncated lengthy sectors of the early and middle Tertiary margin of California, then underthrust by the eastward subducting Farallon plate. Opposing this rather bizarre consumptive interpretation, which called for the vertical or down-dip removal of crustal material, was the countering argument that the structural truncations reflected regional-scale scars along which lengthy slivers of crustal rock had been detached and moved laterally away from a sector of ocean margin (Karig, 1974). This explanation was particularly appealing as it met the predictions of the growing popularity of the concept of tectonostratigraphic terranes, which called for the distant transport of exotic slivers and slices of continental margin rocks, e.g., Baja California.

In 1977 and 1978, an unexpected scientific bonus of drilling at the Japan and Mariana margins was the documentation of massive (3-5 km) Cenozoic subsidence of the submerged forearc region (Scientific Party, 1980; von Huene et al., 1982; Hussong and Uyeda, et al., 1981). Subsidence at this magnitude, during a few tens of millions of years, was attributed to crustal thinning effected by erosion of the base of the forearc's rock framework. The process was soon dubbed subduction erosion (Scholl et al., 1980). Subsequent drilling along the Peru (Suess and von Huene et al., 1990), Mariana (Fryer, Pearce, Stokking, et. ,al., 1992), Tonga (Hawkins, Parsons, Allan, et al., 1994) and south Chile (Lewis, Behrmann, and Musgrave, et al., 1995) margins enlarged the storehouse of observations attesting to the effects of subduction erosion, in particular as manifested by forearc subsidence and the shoreward advance of the trench axis.

Seaward-increasing rates of subsidence was established by the drilling-intersection and dating of a deeply-submerged, smoothly descending surfaces of subaerial erosion or nearshore deposition, or, on seismic reflection records, the seaward tracing of surfaces of known or suspected shallow-water paleobathymetry to outer slope depths. Although subsidence alone did not prove the efficacy of subduction erosion, when other factors were eliminated, for example evidence for crustal thinning caused by regional-scale extension or seaward sliding of the margin, which would have been manifested by down-to-basin rotation of the forearc basement, or the underthrusting of the forearc by dramatically older (colder) oceanic lithosphere, the magnitude and history of subsidence identified the ravages of subduction erosion. The notion that subduction erosion is a volumetrically important process of recycling continental crust was bolstered by evidence that rates of forearc subsidence and landward trench-axis advance were accelerated by the subduction of prominent bathymetric features, perhaps most solidly documented along the Peru margin (Suess and von Huene et al., 1990) and Tonga Trenches (Lonsdale 1986; Ballance et al, 1989; Hawkins, Parsons, Allan, et al., 1994) (see, also Lallemand et al., 1994).

Unlike processes of sediment subduction, drilling, sampling, and geophysical imaging at convergent margins did not recover evidence directly identifying the processes causing subduction erosion. Circumstantial evidence and regional relations implied that over-pressured pore and fracture-filling fluids and related subsurface hydrofracturing processes were the underlying cause of erosion of the base of the upper plate—i.e., basal erosion. Frontal erosion, which effected the landward advance of the trench axis, was tied on similar inferential grounds to the consequence of the mass wasting of thinned and seaward tilted landward trench slopes, and also where seamounts and ridges collided with and penetrated the slope, to the consequence of the "sediment subduction" of debris-filled grabens underthrusting the base of the inner trench wall (see Figure 6). Lallemand et al., 1990; von Huene and Scholl (1991), LePichon et al (1993), and Lallemand et al (1994) review much of the presumptive and conceptual thinking about the key processes causing frontal and basal subduction erosion.

FIGURE 5A: Examples of the first published depictions of the mechanical mechanisms involved in the mass recycling of crustal material and components via processes of sediment subduction and subduction erosion.



(I-5-1-3) Summary

During the past three decades geological and in particular geophysical data gathered both offshore and onshore at convergent ocean margins, and the results of DSDP and ODP drilling, established that large masses of ocean-floor sediment and upper plate crustal rocks are missing from them. Along each kilometer of subduction zone, the estimated solid-volume of ocean-floor sedimentary deposits subducted to subcrustal depth, and potentially to the mantle, is estimated to be 20-25 km^3/my. Conservative estimates place the volume of upper crustal rock removed via subduction erosion at approximately 30 km^3/my/km of trench. But, based on perhaps more realistic modeling, the global average rate may be at least 60 km^3/my/km trench (Lallemand, 1995). Processes linked to the subsurface lithostatic lifting effects of pore-fluid overpressure and rock hydrofracturing are widely presumed to effect both sediment subduction and subduction erosion. But other processes, for example, phase-change induced contraction of young, geothermally warm slab underthrusting the forearc my add upper plate material to the downgoing plate, thus causing crustal thinning (Engebretson and Kirby, 1995).

Notwithstanding the gaining of these general understandings, consequential questions to be addressed with respect to mass flux issues focus on the volume rates of sediment subduction and subduction erosion at specific types of subduction zones, margin-specific sectors, and at specific tectonic settings. Quantitative information is desired regarding both background and accelerated rates of sediment subduction and upper-plate erosion and the circumstances and conditions that determine them. Equally important, information is needed about the composition and major lithologic fabric of the stratigraphic sequences cycling through specific types of subduction zones. Mass flux investigations must also go beyond globally averaged approaches and seek to balance fluxes at individual margins and track the bulk movement, temporary or long-term storage, or permanent loss of material recycled landward and downward at them. Drilling in combination with geophysical imaging can provide the mass-flux data sought. Strategies to achieve them are discussed below in Part II.

I-5-2 GEOCHEMICAL EVIDENCE FOR CRUSTAL RECYCLING IN ARC VOLCANIC ROCKS AND FOREARC FLUIDS

Along with the geophysical and mass balance arguments for crustal recycling, has come independent geochemical evidence from arc volcanic rocks. Different element and isotope compositions have long distinguished arc volcanics from their cousins at mid-ocean ridges and ocean islands. The logical source of the distinctive arc geochemical signatures is the subduction zone: from subducted sources (continental and basaltic) and from subduction zone processes (dehydration, melting, chemical scavenging, water-rock reactions). At depths greater than ~ 20-30 km in subduction zones, our abilities to image or geophysically detect subducted material are greatly compromised. Thus, we become dependent on geochemical tracers recycled to surface rocks and fluids to “see” the subducted material and the processes that occur at increasingly greater depths in the subduction zone (Figure 5B). Attempts to invert the chemical composition of arc volcanics to reveal their sources in the subduction zone have constituted a fertile area of geochemical research for over 20 years. Below is a brief over-view of the different lines of geochemical evidence preserved in arc volcanics for the recycling of various crustal components at convergent margins.

(I-5-2-1) Evidence for Fluid Recycling to the Forearc and Volcanic Arc

Drilling into the forearc regions of subduction zones has found evidence that volatile species are driven off the downgoing slab well before it reaches the depth of arc magma genesis. Beginning with DSDP Leg 57 and continuing through ODP, about a dozen forearc regions have been drilled to date. Nearly all of them collected sediment cores with an unusual feature for the deep sea: some of their pore waters were considerably depleted in chloride relative to sea water, typically by up to 25 to 50%. A variety of explanations were offered for this large freshening of the pore water. Most of these explanations called on processes which could occur only within the thick sedimentary pile of an accretionary prism. Prior to ODP Leg 125, all of the forearcs drilled had such prisms, so it was difficult to discern the cause of the freshening. Leg 125 targeted the Mariana and Izu-Bonin forearcs, the first drilled which lack accretionary prisms and are instead characterized by tectonic erosion. Serpentinite seamounts are common in these two forearcs and had been hypothesized to form by hydration of forearc mantle by water driven off the downgoing plate. One such seamount drilled in the Mariana forearc was found to have greatly freshened pore water upwelling through it. The unusual composition of this water, which was highly enriched in S and C in both reduced and oxidized forms, Rb, and B relative to sea water, strongly suggested that it had originated by dehydration of the subducting lithosphere. The flux of H_2O was sufficient not only to serpentinize a large mass of forearc mantle, but also to form springs which precipitated carbonate and silicate chimneys at the sea floor. Serpentinization accompanying slab dehydration may be a common process in subduction zones, by which H_2O, S, C, and other volatile elements are returned to the oceans. In many of them, however, the products of this process would be hidden beneath accretionary prisms.

Arc magmas attest to even deeper recycling of subducted fluids. The explosivity of arc volcanoes, the presence of hydrous phenocrysts such as amphibole, as well as characteristic crystallization sequences and mineral compositions (Yoder, 1969; Eggler, 1972; Sekine et al., 1979; Rutherford and Devine, 1988; and discussions in Gill, 1981 and Johnson et al., 1994) testify to initial high water contents of arc magmas. Recent advances in analytical techniques as well as laboratory experiments have led to some of the first direct measurements of initial water contents, typically on the order of 1-4 wt H_2O, but as high as 6% in some basaltic andesite (Bacon et al., 1992; Gaetani et al., 1993; Sisson and Grove, 1993; Sisson and Layne, 1993). In order to explain the selective enrichments of some trace elements in arc basalt, geochemists have long pointed to a water-rich fluid phase as the culprit for transporting certain element and isotope tracers from the dehydrating subducting slab to the sub-arc mantle, and then triggering mantle melting beneath the arc (Kay, 1980; Gill, 1981; Tatsumi, 1986). Thus water at once becomes an agent of recycling as well as an agent of melting in subduction zones. Subduction provides the obvious source of arc water via the continuous injection of seafloor materials, rich in pore water and hydrous minerals, into the mantle beneath arc volcanoes. The metamorphism and dehydration of the subducting crust provides the driving force that releases water from its downward subducting path to an upward path toward the surface of the earth.

The clear crustal inputs, volcanic and forearc outputs, and linking processes of metamorphism, migration and melting, provide strong evidence for an important deep water cycle at convergent margins.

(I-5-2-2) Evidence for Sediment Recycling

Perhaps as dramatic as the recycling of some fraction of the oceans through the solid earth and arc volcanoes, is the realization that seafloor sediment also participates in this cycle. In a paper remarkable for its time, Coats (1962) presented a fairly modern picture of subduction and arc volcanism which included the underthrusting of seafloor sediment along a megathrust that extended beneath the Aleutian arc (Figure 5A). Moreover, Coats suggested that sediment was recycled to the arc, in order to explain the presence of andesite in crust otherwise devoid of sialic material.

The first compelling geochemical evidence for sediment subduction and recycling to the arc came from Pb isotopes. Several studies in the 1970’s presented Pb isotopic data for arc volcanic rocks that formed apparent mixing lines between mantle and sediment isotopic compositions (Figure 5B, panel 1; Armstrong, 1968; Armstrong and Cooper, 1971; Church, 1976; Kay, et al., 1978). This evidence was muddied, however, by the recognition of enriched mantle domains as well upper crustal contamination of magmas during their passage to the surface (Morris and Hart, 1983; Tilton and Barreiro, 1980). Thus it became possible to explain the Pb isotopic composition of arc volcanics with enriched mantle or upper plate interaction, and sediment subduction and incorporation in the arc source was no longer always required. However, Pb isotope studies of incoming sediment together with the arc volcanic material sometimes found sympathetic co-variation of sediment and volcanic Pb isotope compositions along the length of an arc (White et al, 1985; Woodhead, 1989), arguing for a sedimentary source for much of the lead. Thus the isotopic arguments for sediment recycling became stronger by actually drilling and analyzing the deep sea sediment feeding individual trenches.

Evidence that finally tipped the scales of sediment subduction came from the discovery of measurable ^{10}Be in arc magmas (e.g., Brown et al, 1982; Tera et al., 1986). ^{10}Be was just the sort of isotopic tracer needed to distinguish recently subducted sediment from ancient enriched mantle and upper plate sources. ^{10}Be is a relatively short-lived isotope (half life = 1.5 my) that is formed in the atmosphere by cosmic ray spallation reactions on oxygen and nitrogen and then rains down on the surface of the earth where it is strongly adsorbed onto sediment and soils. After roughly 10 my, the ^{10}Be concentrations are too low to measure, and so it is a clear tracer of young surface materials. A series of studies throughout the 1980’s found increasingly compelling evidence that ^{10}Be enrichments were a characteristic feature of arc basalt, not found in basalt from other tectonic settings (Figure 5B, panel 2; Tera et al., 1986; Morris and Tera, 1989; Morris et al., 1990). The lack of ^{10}Be in some arc systems was also anticipated and found. Arc volcanic rocks contained little measurable ^{10}Be where incoming sediment was predominantly older than Miocene (e.g., the Marianas), and so barren of ^{10}Be, or where plate convergence rates were so slow that ^{10}Be would decay substantially on transit from trench to arc source (e.g., Antilles). So in addition to providing smoking-gun evidence for sediment subduction in some arc systems, its absence from others also fulfilled important predictions of the sediment subduction model.

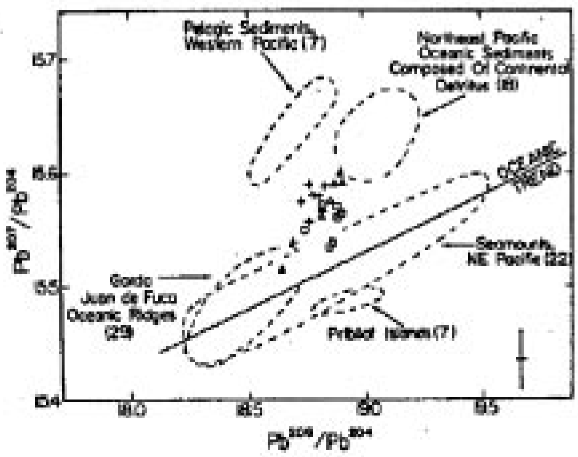
Finally, like White et al. (1985), more recent work by Plank and Langmuir (1993) showed sympathetic variations between subducted sediment and associated arc eruptive material, although this time on a global scale, and using elemental instead of isotopic tracers (Figure 5B, panel 3). From DSDP and ODP drill core samples and data, the mass flux of elements being carried into the mantle in sediment columns was shown to vary by over an order of magnitude for eight different subduction zones. These variations in the sediment input flux are reflected in the chemical enrichments observed in the associated arc volcanic rocks, in several arcs explaining the odd trace element signatures characteristic of individual arcs by the sedimentation processes unique to the subducting section of seafloor. This study demonstrates that many tracers are potentially available to track the sediment recycling process, and to ultimately try to constrain the mass balances.

(I-5-2-3) Recycling of oceanic crust

The cycling of oceanic crust from ridge crest to subduction zone is a fundamental consequence

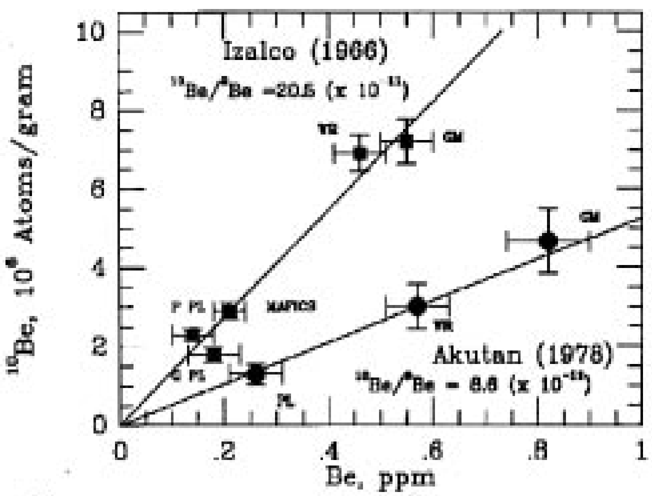
FIGURE 5B:
Some of the initial geochemical evidence for sediment recycling to arc volcanoes.

1



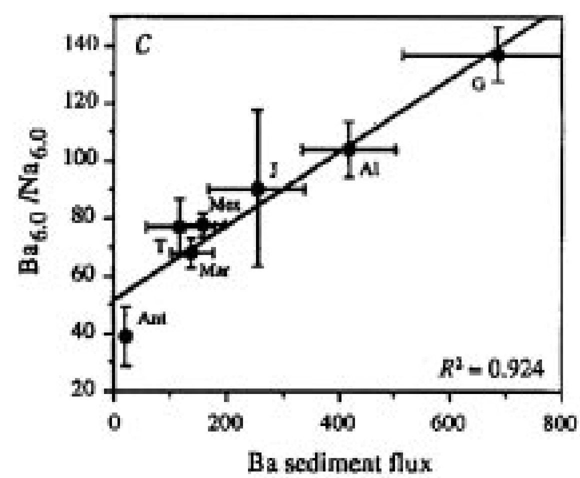
Mantle-sediment mixing trends observed in arc basalt Pb isotopes (from Kay et al., 1978).

2



^{10}Be in Izalco and Akutan lavas. Rocks and phenocrysts from each volcano define a characteristic $^{10}Be/^{9}Be$ (from Morris and Tera, 1989).

3



Correlation between sediment flux into trenches and trace element enrichment in associated arc volcanics (from Plank and Langmuir, 1993).

of plate tectonics. Geochemically, however, recycling of the oceanic crust can be viewed as little net gain: the basaltic crust forms from mantle melting at mid-ocean ridges, and then gets returned to the mantle at subduction zones. If that is all that happens, then no net changes occur in mass or composition, just an unmixing process at the ridge , followed by remixing during subduction. This simple scenario is not correct in detail, however, because the oceanic crust reacts with sea water and takes up various oceanic components, including H_2O and CO_2 (Hart and Staudigel, 1989; Ito et al., 1983; Staudigel et al., 1995). Thus, if nothing else, the oceanic crust serves as a conveyor belt that carries continental components into the mantle. Indeed, many models of arc magmagenesis point to the oceanic crust as a dominant source of recycled components to the arc, such as Sr (Sun, 1980; Ellam and Hawkesworth, 1988), Ba (Kay et al., 1978), B (Morris et al., 1990; Ishikawa and Nakamura, 1994), Pb (Miller et al., 1994), As (Noll et al., 1995), and H_2O (Peacock, 1990; Plank et al., 1994). Thus, although potentially difficult to resolve from sedimentary recycling, oceanic crust recycling may be just as important, if not more so, for some element and volatile budgets.

The oceanic crust may play different roles for different element tracers. It may be simply a non-reactive conveyor belt, delivering all or some of it's continental load to the arc source, and the rest to the deeper mantle. It could also be reactive, and lose its own intrinsic budget of elements to the arc. Recent evidence from Pb isotopes suggests this is the case (Miller et al., 1994; Puecker-Ehrenbrink, et al., 1994; Chauvel et al., 1995; Noll et al., 1995). The oceanic crust may continuously lose its Pb in subduction zones, and this irreversible process may be responsible for the separate evolutions of Pb in the mantle and continental crust. The net contribution of the oceanic crust to other element cycles is mostly unexplored, and will require better estimates of the bulk compositional effects of seafloor alteration, as well as quantitative modeling.

(I-5-2-4) Summary

Although the evidence for crustal recycling in arc volcanic rocks is very strong, two principle questions still remain — How and How Much? What reactions occur in sediment and basalt layers in the subducted plate beneath arc volcanoes? Do the reactions involve dehydration or melting? How do reactions change with increasing depth in the slab? Are the losses to the sediment and basaltic layers linked and modulated? How do fluids migrate into the mantle wedge and promote melting? These questions are essential to understanding the nature of the recycling agents themselves. The issue of How Much requires that inputs and outputs be quantified, and that rates be measured on the different parts of the cycle. We address these different issues, and how we may approach them with drilling, below in Part III of this workshop report.

PART II

RECYCLING PROCESSES AND MASS MATERIAL FLUXES—APPROACHES VIA SEISMIC IMAGING AND OCEAN FLOOR DRILLING

(II-1) INTRODUCTION

Preliminary mass balance calculations that combine the results of ocean drilling and the seismically imaged structure of underthrust margins imply that a solid-volume mass of ocean-floor sediment of at least 1.0 km^3/yr presently and globally by-passes prism forming processes and reaches deep subcrustal depth. This mass is roughly half of the estimated volume of ocean-floor deposits (trench-floor section) presently entering subduction zones. Ocean-floor sediment that by-passes prism formation is potentially subducted—recycled—to the mantle

Geophysical imagery and ocean drilling results also establish that thinning of sialic framework rock occurs at some underthrust ocean margins. At these margins, progressively larger amounts of thinning toward the trench are presumably effected by processes of subduction erosion. Estimates of the volume removed, and potentially transported to mantle depths (subducted), are presently model dependent and globally amounts to at least 1.0 km^3 of solid-volume upper plate material (Figures 1 and 4). If the modelling approach taken by Lallemand et al. (1992a) and Lallemand (1995) is correct, then the global wastage of terrestrial crust is potentially twice this volume, an amount that has important implications for the rate of ocean-basin closure.

Reported volumes of subducted sediment, although thought to be conservative estimates, are nonetheless based substantially on seismic and drilling results from 6 localities along sectors of only 5 accretionary margins (Aleutian, Alaska, Middle America, Peru, and northern Japan; von Huene and Scholl, 1991; 1993). Hence the margin-to margin variability in rates of bulk recycling, both for sediment subduction and subduction erosion, is factually poorly known, in particular for the major margin types. Variability in crustal recycling caused by subduction erosion is perhaps least constrained, both with respect to background rates and rates accelerated by collisional processes. These issues are first order problems in mass flux investigations—they are explored more fully below.

(II-2) SEDIMENT SUBDUCTION—ISSUES AND QUESTIONS

From the interest perspective of bulk sediment recycling, major questions concern the percent of incoming ocean-floor sediment, i.e., the trench-floor section (see definitions), that is subducted, its major lithologic composition, changes in these parameters with time and location, and the processes that effect sediment underthrusting from trench floor to the mantle. On a regional scale, getting accurate estimates of global sediment ingestion and composition, and the fraction of this input that reached subcrustal depths, are essential inputs to issues of ocean margin and coastal vertical tectonism, seismicity, and rates of arc volcanism. More globally, mass flux rates are essential inputs determining the geochemical evolution of the Earth's mantle and the growth history of its overlying continental crust of consolidated arc magmatic bodies (see, for example, Reymer and Schubert, 1984; Ben Ottoman et al., 1989; Armstrong, 1991; Weaver, 1991).

To provide the information needed, the time-averaged input of ocean-floor sediment must be determined for sectors of underthrust margins where seismic imaging and drilling can be combined to accurately calculate or constrain the fraction of sediment that by-passes prism formation and potentially reaches the mantle (Figure 4). Sediment flux to the mantle is thought to occur at both non-accreting margins and accreting margins, which are those bordered by accretionary prisms a few kilometers to more than 100 km in width. At margins bordered by prisms, the longer the prism has been forming, the greater its width and volumetric mass and therefore the more difficult it is to reconstruct the time-average input volume—i.e., the product of average convergence rate and trench-floor sediment thickness (Figure 4).

The global sediment input rate is calculated by summing the separate inputs for each major sector of the roughly 43,000 linear km of globally active subduction zones, 19,000 km non-accretionary, 24,000 km accretionary (Figure 1). Active subduction zones are those bordered by erupting magmatic arcs, although some of them, e.g., the Nanki margin of southwestern Japan, lack eruptive arc magmatism. A Wadati-Benioff seismic zone also indicates an active subduction zone, but some subduction zones, for example that of the Cascadia margin of northwestern United States and western Canada, virtually lack interplate seismicity (Heaton and Kanamori, 1984). The ingestion volume is calculated as the product of the rate of plate convergence measured orthogonal to the strike of the trench and the solid-volume thickness (i.e., the sediment pile reduced to its zero-porosity thickness) of the trench-floor section at the base of the landward trench slope (Figure 4).

Presently, the solid-volume rate at which the trench-floor section is swept into the global length of non-accreting and accreting subduction zones is close to 2 km^3/yr. But this rate may be more typical of the past 2-3 my than of the Cenozoic and possibly the Mesozoic more generally. Since the early Oligocene, the compounded effects of ocean margin tectonism and climatic cooling have steadily increased the flow of terrigenous sediment to the ocean basins (Hay et. al, 1988), and, presumably, also to the mantle. Accelerated glacial-age erosion of the continents and lowered sea levels combined to flush large volumes of terrigenous debris directly to trench axes, in particular to high-latitude trenches, e.g., Aleutian, Alaska, Cascadia, Southern Chile. As a consequence, along these trenches sectors the rate of terrigenous sediment subduction during late Cenozoic time has been elevated.

A conservative view can be taken that the pre-glacial age thickness of the trench-floor section nourishing accretionary margins was half that typical of modern trenches (von Huene and Scholl, 1991). Adopting this figure reduces the global rate at which sediment entered subduction zones during most of Tertiary time to perhaps just over 1.0 km^3/yr, which assumes that the global length of trenches and the average underthrusting rate normal to their trends have remained generally the same. Contrastingly, some geochemical imaging approaches are less sensitive to the issue of changing rates of ocean-floor sedimentation through time. For example, recycling studies based on the geochemistry of historic or Holocene arc eruptive rocks, can, except where underthrusting is slow (20-40 km-my) and magma ascent is much delayed, reflect the imprint of sediment that entered the subduction zone about 2-3 my years ago, and thus in concert with the major switch to accelerated glacial-age sedimentation (see elsewhere below). Along non-accreting margins, changes in the rate of late Cenozoic terrigenous sedimentation ought not to be a factor, i.e., in absence of the special effects of seamounts and ridge subduction, what's entering the subduction zone now is probably similar to that underthrusting the margin since at least middle Cenozoic time.

It was noted earlier that the composition of the ocean floor or pelagic section entering subduction zones is approximately 76 % terrigenous, 15 percent biogenic carbonate, and 9 percent biogenic opal (Rea and Ruff, in press). However, with specific respect to the composition of ocean-floor sediment entering the subduction zones of the northern and northwestern Pacific margin, ODP and DSDP drilling results establish that the ingestion rate of biogenic silica, chiefly diatomaceous deposits, greatly increased in the middle Miocene after about 14 Ma, and in particular after 6 Ma, near the top of the late Miocene (Rea et al, 1995). Turn-on of the north Pacific diatom productivity switch is linked to early Neogene changes in the global pattern of thermohaline circulation. Hence, in late Cenozoic time, the flux of siliceous sediment to the mantle underlying the north Pacific rim in particular has been substantially higher here than at most other subduction zones (Rea and Ruff, in press). Increased sediment subduction, in particular that of porous and water-rich diatomaceous debris, conceivably could boost productivity of arc magmas (Rea, personal communication, 1996; Dadisman and Scholl, 1995). Determining time and trench-parallel variability in the volume and composition of the trench-floor section input to subduction zones are thus important factors involved in assessing the long-term effects and consequences of subduction component recycling.

From the specific perspective of a seismic imaging-ocean drilling approach to sediment subduction, answers are needed to the overarching questions and issues elaborated on below:

(1) At non-accreting margins (where the prisms is about 5 km wide or less) presently 19,000 linear km in global length), what fraction of the underthrusting trench-floor section escapes underplating the base of the forearc crust to reach mantle depths—i.e., what is the sediment by-passing efficiency at margins where effectively no or only minimal accretionary prisms have formed (Figures 1 and 4)?

(2) At accreting margins where intermediate-size prisms (~5-40 km in width, ~5-10 my in age, 16,000 liner km) form in response to frontal and underplating accretionary processes, what fraction of the incoming trench-floor section reaches mantle depths—i.e., what is the sediment by-passing efficiency at margins were processes of subduction accretion have formed typical-size accretionary prisms**.**

(3) At accreting margins where large and relatively old prisms have formed (> ~40 km in width, 30-50 my in age, presently 8, 000 km in linear length, Figure 1), what proportion of the trench-floor section nourishing their growth escapes subduction accretionary processes and mixes into the mantle—i.e., what is the long-term sediment by-passing efficiency at margins bordered by large accretionary prisms?

(4) At both accreting and non-accreting margins, how are local rates of sediment subduction changed by the subduction of seamounts and ridges and other forms of ocean floor relief—i.e., to what extent does the underthrusting of physiographic features, positive and negative, increase or reduce ,the efficiency of subduction of ocean-floor sediment to mantle depths?.

(II-2-1) BACKGROUND RATES AND PROCESSES AT NON-ACCRETING MARGINS

Sectors of trenches generally starved of sediment input (i.e., less than about 500 m of depositional section) lack geophysically definable prisms of more than a few km in width. Hence the bulk of the sediment underlying the trench floor is presumed to efficiently underthrust the margin's rock framework. (Figures 4 and 6)**.** These trenches in particular include those bordering the ocean arcs of the western Pacific (e.g., Kuril, Izu-Bonin, Mariana, Tonga, Kermadec, and Scotia arcs), arid continental areas (e.g., central and northern Chile), those with limited sediment supply (e.g. Nicaraguan and Guatamalan sectors of the Middle America Trench, and those with efficient sediment-trapping basins located up-slope of the trench (e.g., Kamchatka, Ryukyu, and possibly the eastern Java, arcs; Figure 1)

Orthogonal convergent rates at non-accreting margins tend to be fast (70-170 km/ my), so even though the solid-volume of the trench-floor section entering the subduction zone is typically thin, 200-500 m, the volume underthrusting rate can be high. During much of Cenozoic time, non-accreting margins (presently 19,000 km) globally consumed about 0.4 km^3/yr of trench-floor sedimentary section, which converts to about 20 km^3/my (solid volume mass) for each running km of trench floor.

Although DSDP and ODP drilling have provided some notion of the nature of the ocean-floor section underthrusting non-accretionary margins (Rea and Ruff, in press), with the exception of one site (DSDP 499) in the Guatemalan sector of the Middle America Trench (von Huene, Aubouin et al., 1980), virtually no direct observations are available about the lithology and chemistry of the trench fills ingested at non-accreting margins. This circumstance is particularly true of the mostly non-accretionary trenches that border virtually the length of the western Pacific, from the Kamchatka Trench southward to the southern end of the Kermadec margin. At non-accreting trenches, terrigenous clastic sediment and potentially large volumes of slope-wasting debris add thickness and lithologic composition to the underthrusting section of oceanic-floor deposits. Gravity sliding of the landward trench slope, a major process effecting frontal subduction erosion, piles debris on the ocean-floor section and tops-off and overfills underthrusting grabens, (Figures 4 and 6; see, for example, Ballance et al., 1989; von Huene and Scholl, 1991; Lallemand et al., 1990, 1994). Based on forearc drilling and dredging, this material could include large amounts of redeposited serpentinite detritus (Fryer, 1992) and, if ODP site 841 along the outer Tonga forearc is a guide, detritus from subaerially erupted nascent arc material and overlying shallow-water limestone deposits (Hawkins, Parson, Allan, et al., 1994). At the collision zones of large seamount chains, regionally unusual sections (200-500 m) of pelagic carbonate and siliceous beds are also introduced into the subduction process as resedimented detritus (Kulm et al., 1974; Ballance et al., 1989).

Little information presently exits about the physical characteristics and conditions of the decollement or interplate boundary that allow oceanic and axial trench sediment and slide debris to efficiently underthrust non-accretionary margins. Over long periods of time (5-10 my) it seems likely that the bulk of the underthrust material is not subcrustally stored by underplated processes, but probably reaches the mantle. This judgment is drawn from observations that, except at major collision or obduction zones, the coastal regions of non-accreting margins typically lack belts of exposed high P-T metamorphic rock nor exhibit histories of sustained uplift, both regional relations that might attest to crustal thickening by underplating processes. Prism formation and subcrustal underplating can occur for short periods of geologic time along sectors of non-accreting margins, which, for example, may be a contributory circumstance explaining the ^{10}Be and related geochemical anomalies recorded in late Cenozoic arc volcanic rocks of the Nicaragua-Costa Rica margin of the Middle America Trench (see for example, Tera et al, 1986; Shipley and Moore, 1986; Plank et al, 1993, Leeman et al., 1994; von Huene and Flueh, 1994; Leeman and Carr, 1995; Hinz et al, 1996). Factually, however, little is understood about the passage process of sediment and eroded debris beneath the upper plate and their potential storage there for periods of time.

Excluding debris piles supplied by frontal subduction erosion and mass wasting, if the bulk of oceanic and axially deposited trench sediment is flushed to the mantle at non-accreting margins, then the long-term rate at which sediment subduction proceeds (see definitions above) is globally about 0.4 km^3/

my (solid volume). This mass is about half of the total amount of ocean floor sediment estimated to be subducted at all ocean margins. If the present relative proportion of sediment-starved and sediment-nourished trenches is characteristic of the past, then a somewhat greater fraction of continental material may be recycled at non-accreting margins than at those better supplied with sediment and along which accretionary prisms form. But the issues remain that little factual information is available about:

(1) the lithology, stratigraphy, and physical properties of the trench-floor sedimentary column underthrusting the great length of non-accretionary margins, and

(2) the physical conditions that allow efficient sediment and debris-pile underthrusting and potential subcrustal underplating and subduction and non-accreting margins.

(II-2-2) BACKGROUND RATES AND PROCESSES AT ACCRETING MARGINS

Accurate estimates of accretionary rates require excellent seismic images and microfossil-rich drill samples of accreted sediment. Constraining the mass of accreted material requires an image of the structural backstop or rock buttress against which an age-defined volume of sediment has accumulated, and precise velocity information about this body so that its average porosity can be calculated and thus it solid-volume defined accretionary volumes in the +/- 10% range, an improvement over older published estimated of +/- 25%. However, accurate mass balance calculations are only possible for accretionary masses of Pliocene and Quaternary age for which the average input thickness of trench-floor sediment can be reconstructed. Longer-term fluxes, in particular for high-latitude trenches, are less accurate because of input-rate uncertainties. Far longer-term (i.e., 20-50 my) mass balance calculations can, theoretically, be provided by long-lived and much larger prisms, e.g., the Vancouver, Aegean, Makran, Barbados masses. But acoustic images of both the sedimentary mass involved, the geometry of the backstop, and the average sediment input thickness over long periods of geologic time make mass balance calculations extremely unreliable and subject to large errors.

Trenches that are underlain by sedimentary sections thicker than about 500 m are commonly flanked by actively growing accretionary prisms. These prisms are typically only a few tens of km in width and their nourishment is provided along many margins by a landward-thickening body of trench-axis turbidite beds—the so-called trench turbidite wedge. The turbidite wedge typically accumulates over a landward dipping section of oceanic deposits of pelagic and terrigenous beds (Figure 4). Prisms also form in the absence of a turbidite wedge where the oceanic section is unusually thick, for example along the northern Barbados Ridge of the Lesser Antilles margin (Westbrook et al., 1988) and off northern Kamchatka where the 1.5-2.0 km thick Meiji sediment drift of pelagic and hemipelagic deposits enters the trench (Geist and Scholl, 1994; Dadisman and Scholl, 1995), the eastern Aleutian Trench where deposits of the Surveyor Fan enter the subduction zone, and, problematically, the sector of the Middle America Trench adjacent to Costa Rica (Shipley and Moore, 1986; Hinze et al, 1996).

Exceptionally massive accretionary prisms (> 40 km in width and as much as 25-30 km in thickness) presently only form where the incoming sedimentary pile, whether constructed of trench-axis deposits, oceanic sediment, or a combination of these depositional sequences, is more than 1-2 km thick and where the supply of sediment has been sustained over a long period of geologic time (> 20-50 my). Contemporary large prisms only exits where orthogonal underthrusting is relatively slow (20-30 km/my). Examples of large prisms include those off the Makran margin of western Pakistan, the Sunda margin of Indonesia, and adjacent to the Manila, Lesser Antilles, northernmost Cascadia, and Aegean margins (Figure 1).

Although it can be assumed that at non-accretionary margins, with time, 100 percent of the incoming sediment is underthrust and most likely subducted, a fundamental question concerns the efficiency of prism-forming processes at accretionary margins. That is, with respect to the volume rate of sediment supplied to the subduction zone (trench floor thickness X orthogonal convergence rate, see Figure 4), over a relatively long period of time (~5-10 my), what fraction is offscraped to form a prism and what fraction continues landward to underthrust the width of the margin's rock framework and potentially reach the mantle? Linked to this question is the factor of selective subduction of the older beds and offscraping of the younger units (Moore, 1975). This circumstance influences the isotopic and trace element geochemistry of subducted sediment. Although most commonly oceanic pelagic beds are selectively underthrust or subducted at convergent margins, DSDP and ODP drilling have established that the opposite is true for the northern Barbados margin (Moore et al., 1990).

As noted above, prism-forming efficiency can be addressed through seismic imaging and deep-sea drilling. The process involves seismically mapping the volume of a prism and comparing this mass with that predicted to have accumulated if all of the incoming sedimentary section had been accreted over the growth life of the whole prism or a defined part of it. The width and thickness of the prism are measured seaward of a buttress of older accretionary material or igneous rock of an arc massif, either of which can serve as the accumulation backstop for accretionary growth (Figure 4). Critically needed lithologic, growth history, and age information about the prism <u>can only</u> be determined by drilling. Seismic reflection and drilling data are combined to measure subsurface porosity values and to convert the prism's seismic dimensions to a solid-volume mass. If a defined prism mass formed during the past 3-5 my, a good approximation can be made of the minimum average thickness of the sedimentary section entering the subduction zone.

By combining seismic and drilling data along 5 sectors of convergent margins bordered by intermediate size prisms that formed during the past 3-5 my, the maximum efficiency of offscraping has been estimated to be only about 35 percent, i.e., at least 65 percent of the incoming section by-passes prism-forming accretionary processes and potentially reaches the mantle (von Huene and Scholl, 1991). But the correctness of an offscraping efficiency of roughly one-third that can be widely or even regionally applied is troubled by several factors:

(1) at the margins studied, age information about the oldest beds involved in frontal accretion—information that can only be obtained through drilling—involved inferences,

(2) at the margins studied, seismic resolution of the deeper geometry of the prism, in particular the volume-mass of prism-underplated sediment, and imaging of the geometry of the backstopping or core buttress against which the prism began to accumulate, was commonly inadequate, only constrained between broad limits, and lacked control on variability along strike,

(3) at the margins studied, estimates of the thickening of trench-axis deposits that occurred in response to the onset of Northern and Southern Hemisphere continental glaciation at roughly 2.7 my ago was poorly constrained. A trench-axes thickening of about two over the pre-glacial thickness was estimated by von Huene and Scholl (1991).

(4) the need for additional as well as greatly improved by-passing measurements at margins bordered by intermediate size prism, e.g., northern Kamchatka, central and eastern Aleutians, south-central Alaska, central and southern Cascadia (Washington-Oregon), central Mexico, Nicaragua and Costa Rica sectors of the Middle American Trench, southcentral and southern Chile, northern Hikurangi (New Zealand), central Java (?), and Nankai and northern Japan.

Where large prisms have formed (50-100+ km in width), great uncertainty attends estimating the proportion of ocean-floor sediment that by-passes them to either underplate the framework crust of the upper plate or reach the mantle. Efficient offscraping may be characteristic of large prisms (Davis and Hyndman, 1989), which are all located in settings of slow orthogonal convergence and rapid ocean-floor sedimentation. As noted, most of the uncertainty about offscraping efficiency at massive prisms is linked to difficulties in accurately determining their geometry and bulk density and the long-term or average rates of convergence and sediment input that built them. In contemplating the long-term average thickness of ingested trench-floor section, the application of a large glacial-age correction factor is probably unjustified for many large prisms because the thick trench sections that supported their growth over tens of millions of years were nourished more by mountain-building processes than the effects of continental- or alpine-scale glaciation during the past 2-4 my alone (e.g., the Makran, Aegean, Sunda, Manila, Barbados-Lesser Antilles, Vancouver-Cascadia prisms).

For margins bordered by large accretionary prisms, it is unclear how deep-sea drilling can improve the present estimate of 10 percent by-passing (range of 0-20 %, von Huene and Scholl, 1991). However, important strides can be made by drilling to determine the lithology and age of some of the middle-age rocks of large size prisms. The purpose is to better resolve their growth rate over shorter periods of time, which could provide invaluable information about the volume of underthrusting sediment that passes at least to deep and more arcward areas. Clearly, the availability of deep, high-quality seismic reflection data is paramount

(II-2-3) MASS FLUX WHERE LARGE BATHYMETRIC FEATURES ARE SUBDUCTED

Subduction of most large ridges and seamounts, or their collision with the landward trench slope (i.e., Aleutian, Louisville, Cocos Ridge, Nazca, and Juan Fernandez Ridges, and the South Chile Rise) is accompanied by accelerated erosion and subduction of terrigenous material and a wide range of related phenomena that includes migration of the arc magmatic front, upper plate faulting and folding, coastal uplift, coastal underplating, and creation or obliteration of forearc basins (see Lallemand et al., 1990, Geist et al., 1993, Tagudin and Scholl, 1994, and Kolarsky and others, 1995, for discussions). Geophysical investigations and drilling along the sector of the Peruvian margin affected by the underthrusting of the Nazca Ridge turned up evidence that during ridge subduction the rate at which material was removed from the margin was accelerated. In the wake of ridge subduction, sediment subduction appears to first wane and then accelerate (von Huene et al., 1996). Sandbox experiments demonstrate enhanced rates of sediment subduction in the wake of a subducting physiographic prominence (Lallemand et. al., 1994). Perhaps a manifestation of enhanced sediment subduction is the significant enrichment of ^{10}Be in arc eruptive rocks of Japanese volcanoes overlying the subducted trend of the Erimo seamount chain. Other Japanese volcanoes have no ^{10}Be at all.

(II-3) SUBDUCTION EROSION—ISSUES AND QUESTIONS

The proportion of the total amount of recycling continental or sialic components contributed by processes of subduction erosion at non-accreting margins and also those bordered by intermediate size prism, is thought to be large—at least 45-60 percent. The amount is larger if significant erosion also occurs at margins bordered by large accretionary prisms, and larger still (~factor of 2) if the model-dependent calculations of Lallemand (1995) are correct. With respect to the volume recycling of crustal material to mantle depths, it is importance to separate long-term rates, which include the contribution of background rates of upper-plate removal, and short-term rates that reflect perturbations above and below background caused by the passage of major ocean-floor bathymetric features beneath the inner trench wall or perhaps flooding of the trench floor with sediment. Quantifying rates of subduction erosion at various types of convergent margins is therefore a first-order earth science problem. Related questions of an overarching nature are noted below:

1) At non-accreting margins, what are the long-term and background (i.e., in absence of events that accelerate or greatly reduce upper plate recycling) rates of removal of upper plate material effected by frontal and basal erosion—i.e., in absence of collisional events, does subduction erosion take place in the background, and, if true, at what rates?

2) At accreting margins, what are the long-term and background rates of removal of upper plate material, in particular that caused by basal erosion—i.e., does subduction erosion of the margin's rock framework take place beneath the inner forearc area of margins along which prism accretion occurs, and, if true, at what background rates?

3) What rates of subduction erosion, both frontal and basal, are associated with the underthrusting of large bathymetric features (i.e., seamount, ridges, ocean plateaus)—i.e., how are local and background rates of erosion changed, and over what range, by the subduction of physiographic prominences?

4) Over relatively long periods of geologic time (5-10 my), what fraction of material removed from the upper plate, including the basal parts of long-growing or fossil accretionary prisms, underthrusts the width of the forearc—i.e., what fraction of the mass of material removed and transported landward and downward by subduction erosion reaches the mantle?

(II-3-1) BACKGROUND RATES AND PROCESSES AT NON-ACCRETING MARGINS

Along non-accretionary convergent margins, structures caused by processes of subcrustal or basal tectonic erosional are difficult to identify because they occur at depths not well imaged with seismic reflection techniques. In contrast, effects and processes of frontal erosion are easy to observe in high resolution, swathmapping morphology and seismic reflection data of the lower landward trench slope (Figure 7 see, for example, von Huene et al, 1995). Evidence for missing material, however, is much more difficult to quantify than that for material added (accreted), which exists in physical reality. Convincing documentation for eroded or missing material usually requires scientific drilling to establish chronostratigraphic-and paleobathymetric-based records of ocean margin subsidence. This record can either be of net regional forearc subsidence in excess of 2-3 km that accumulates over a relatively long period of geologic time (20-30 my), or a subsidence in excess of 1-2 km that was produced geologically rapidy (1-4 my). Subsidence of these magnitudes and rates are greater than that possible by other mechanisms, for example, upper-plate crustal cooling, progressive increase in age of the underunning slab, and, except where verified by structural evidence and special tectonic settings, extensional collapse (e.g., western Woodlark Basin, Mutter et al, 1992; or collisional (obductive) loading of the margin (e.g., eastern Papua New Guinea, Silver et al, 1991).

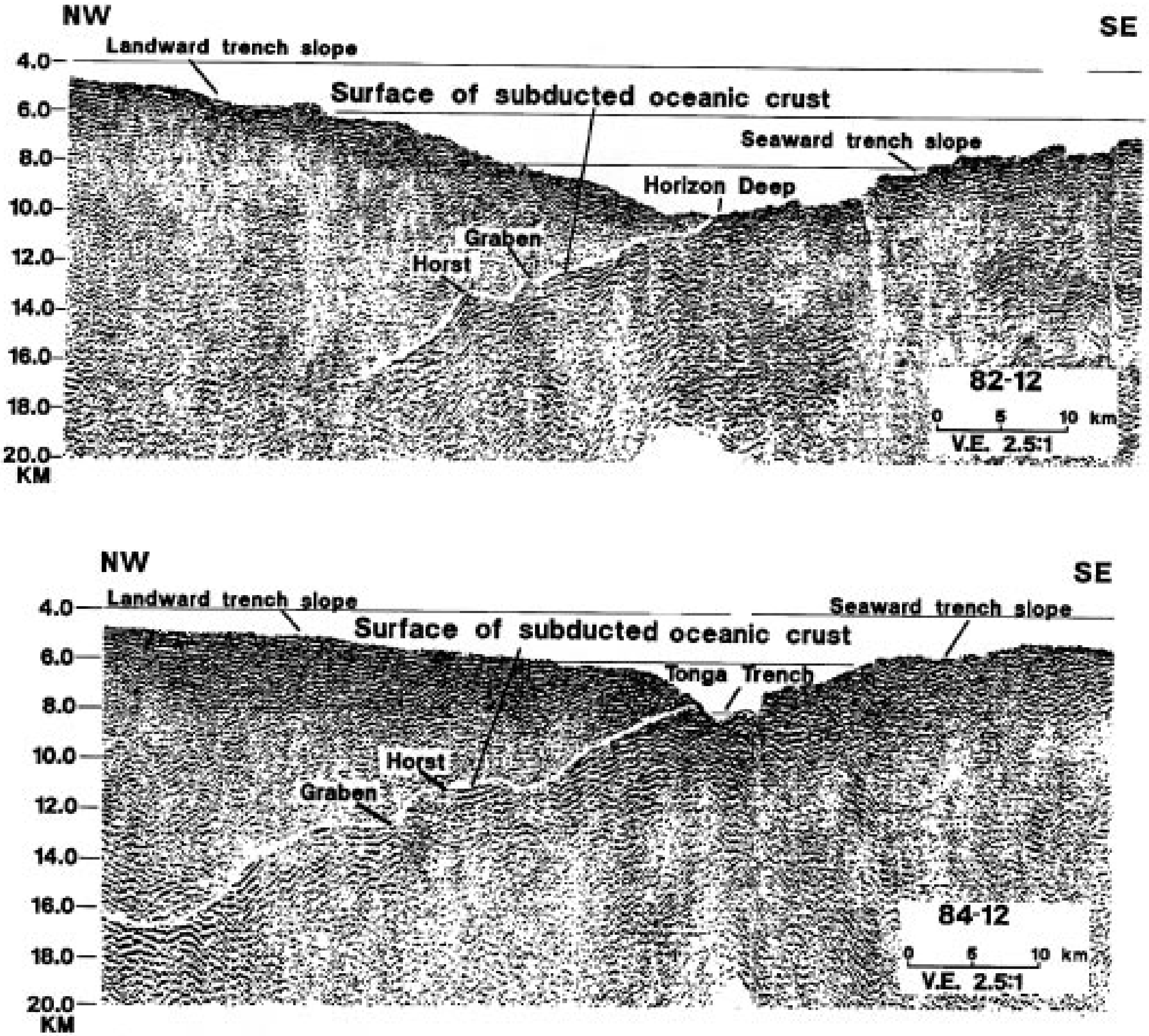


FIGURE 6: Two depth-converted and migrated seismic reflection records that cross the Tonga margin in the vicinity of 26 deg S latitude (see Figure 8 for locations). The Tonga margin is a type example of a non-accretionary subduction zone that consumes rather than offscrapes virtually 100 percent of the incoming trench-floor section (Figure). Deep (500-1,000 m) grabens on the subducting slab of Pacific crust, probably of Jurassic age, fill with mass wasting debris as they underthrust the base of the landward trench slope. Filling is thought to be a major processes of frontal subduction erosion (Ballance et al, 1989). At the only deep-water site on the Tonga forearc, ODP drilling on Leg 135 established both long-term and short-term rates of forearc subsidence (Hawkins, Parons, Allan et al., 1994). Rapid late Cenozoic subsidence of the outer forearc is attributed to crustal thinning caused by the subduction of the Louisville Ridge (Figure 8).

Thus along most underthrust margins large amounts of forearc subsidence documented by paleodepth indicators or structures recovered in DSDP and ODP cores signals the effects of tectonic erosion along the interplate boundary. However, few margins have been drilled sufficiently well to obtain a good record of vertical tectonism, and no detailed paleobathymetric record across the width of a margin has been obtained anywhere. At a number of margins, Japan, Peru, and Tonga in particular, a depositionally buried angular unconformity cut by wave-base erosion can be traced by seismic imagery seaward from the shoreward reaches of the margin to a subsea-level depths of 4-5 km and deeper below the lower landward trench slope (Figure 8**).** This seaward plunging erosional surface records a long-term (30-45 my) net history of removal of upper plate material from the subsurface base of the margin. The long-term rate of net subsidence can be determined if the unconformity is reached and the age of burial beds determined along the lower landward trench slope.

But the long-term history of vertical tectonism is thought to be a blending of background process on which the effects of shorter periods of more rapid rates or erosion, and underplating and accretion that can thicken and uplift the margin, are superimposed. For example, along the Japan margin, the subsidence history based on benthic foraminifera recovered at a few intervals from cores at DSDP Sites 438 and 439 establishes a long-term net sinking since the Oligocene, but the seismic stratigraphy of the forearc basin and structure of the front of the margin suggests a variety of episodes of subsidence and accretionary growth affected the margin during the past ~35 Ma. The accretionary prism at the base of the northern Japan margin is thought to contain sediment of only late Miocene (5-8 Ma) age, reflecting the latest phase of accretionary growth attached to a fossil prism of mostly Mesozoic age. The growth effects of accretion are evidently taking place in the face of background-rate or net subduction erosion of the older prism and consequent subsidence of more landward areas of the trench slope. Along the Peru margin, subsequent to subduction of the Nazca Ridge, accretion of new prism material stabilized during the past 8 my. Thus long-term net effects of erosional thinning and accretionary thickening are measured over periods of time greater than rates associated with late Cenozoic processes. Along the Tonga forearc, subduction of the Louisville Ridge during the past 2-3 my has accelerated erosion of the forearc well above the long-term rate of the past 40-45 my, which may dominantly reflect the consequences of a background processes of erosion caused by the underthrusting of ocean-plate grabens (Figure 6; Ballance et al., 1989; Hawkins, Parson, and Allan et al., 1994).

Minimum rates of frontal subduction erosion induced by the filling of underthrusting grabens can be estimated geometrically. For Japan, the rate is about 16 km^3/my/km of trench; for northern Chile, the rate is roughly 25 km^3/my/km of trench, somewhat lower than the long-term post-Jurassic rate of 35 km^3/my. Seismic images landward of the inner wall of sediment-starved trenches show filled structural grabens and generally an overlying sequence of underthrusting material (see, for example, von Huene and Scholl,1991). Some of the imaged sequence could be underplated rather than material in transport. Off northern Chile, the plate-boundary sequence is about 0.8 km thick. Assuming that the entire thickness of the graben fill and overlying sequence is attached to the lower plate, than a maximum of perhaps 70 km^3/my/km of trench of eroded material, probably mostly by frontal processes, is presently underthrusting the margin and potentially to mantle depths.

Another measure of the long-term rate of erosion can be based on the landward migration of volcanic arcs, for example in central and northern Chile (Rutland, 1972). The migration of the volcanic front has been about 3 km/my during the past 70 my. If the distance between the trench and volcanic arc remained constant during this time, then arc migration corresponds to an equivalent long-term rate of trench slope retreat toward the east. Measured since the age of emplacement of the oldest arc plutonic rocks exposed along the shoreline, Late Jurassic, the long-term rate is much less, about 1 km/my, which was used to estimate the long-term rate of removal of upper plate crust of 35 km^3/my/km of trench (von

Huene and Scholl, 1991). Other estimates along northern Chile are 50 km^3/my (Stern, 1991), who also speculates the rate could be as high as 500 km^3/my. However, rates of erosion and process effecting them prior to accelerated Andean uplift (~25 Ma) and the formation of the Nazca plate could have been very different, and probably lower. Hence, depending upon the history of the margin, late Cenozoic rates of subduction erosion may not be representative of either long-term rates of background rates. However, by deep sea drilling the subsidence history of the margin can be determined across its width and along its length, thus making it possible to distinguish long-term, background, and short-term rates of subduction erosion. An important component of the drilling proposal of MacLeod et al (1996) adopts this drilling strategy to resolve the history and effects of subduction erosion processes along the forearc region of the Tonga Ridge.

(II-3-2) BACKGROUND RATES AND PROCESSES AT ACCRETING MARGINS

The global rate at which upper plate crustal material is recycled is strongly dependent upon rates of subduction erosion at margins bordered by intermediate size accretionary prisms. Their intermediate size may reflect alternating episodes of accretion and erosion, or an imbalance in the joint effects of these process that allows a limited accretionary growth. The global length of these margin is approximately 16,000 km. Evidence that prism accretion at the structural front of the margin occurs simultaneous with background rates of basal subduction erosion of landward areas of the forearc are implied by both observational and modelling results, in particular for Japan and Peru, and also for the central Aleutians (see, for full discussions, Le Pichon and Henry, 1992, Le Pichon et al, 1993, and Lallemend et al. 1994).

A common observation in sandbox experiments is the erosion of accreted material at the back of the accretionary prism (Kukowski et al, 1994). Cycling of material from the accretionary prism into the subduction channel has not been convincingly reported from structures imaged in seismic reflection records, although the processes has been inferred von Huene et al., 1996). It appears to be required where the volume of material stored at the front of a prism greatly exceeds a general mass balance for the prism as a whole. Erosion of older prism material may also help explain why reconstructed or “balanced” cross-sections of intermediate size accretionary prisms can fail to structurally rebuild the packets of accretionary material potentially offscraped by frontal processes (McCarthy and Scholl, 1985).

Seismic images of processes of basal erosion at accreting margins bordered by intermediate and large prisms require more resolution and deeper penetration than presently possible. But deep sea drilling of margins bordered by intermediate prisms can be designed to search for evidence of contemporaneous accretion and rock-framework thinning and subsidence. Theoretical considerations, and perhaps observations of sustained crustal uplift adjacent to large prism (e.g., Vancouver and Nanki prisms), argue that high accretion rates and basal subduction erosion may be incompatible processes at the same margin (Le Pichon et al. 1993). However, little offshore evidence has been brought to bear on addressing the issue of upper plate erosion at margins bordered by large, actively growing prisms.

As discussed immediately below, subduction of large bathymetric features at margins flanked by actively accreting intermediate size prisms causes rapid removal and recycling of older accretionary material and basement rock of the upper plate (see, in particular, Lallemand et al., 1994, Lewis, Behrmann and Musgrave et al., 1995; and von Huene et al., 1966). By inference, prominent physiographic features passing through large accretionary prisms should also cause removal and potentially subduction recycling of older prism material and more landward framework rock of the backstop (Lallemand et al., 1992b). An example of where these processes appear to be underway is the collision

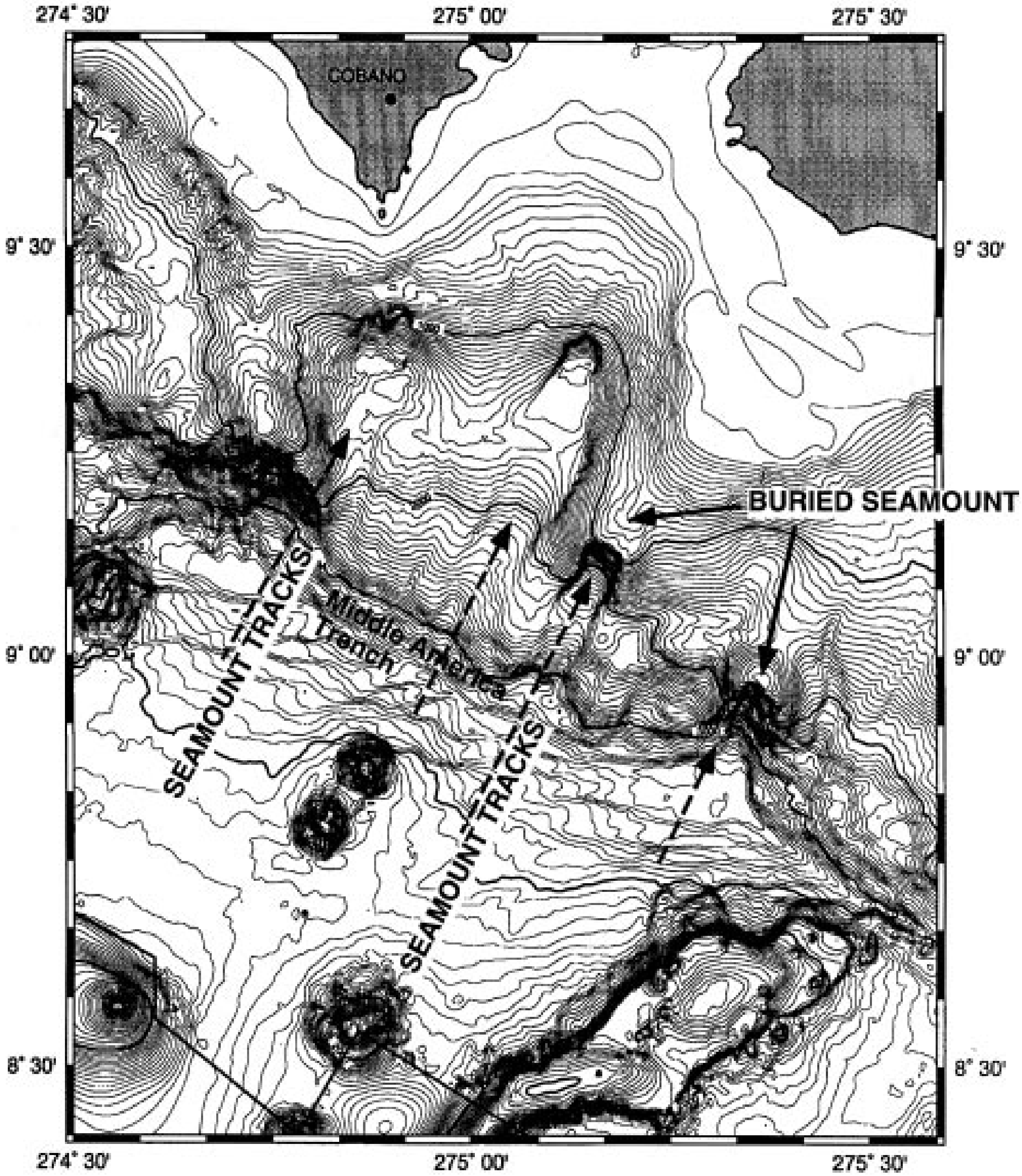


FIGURE 7: Hydrosweep-based (swathmapping) bathymetry of a sector of the Costa Rican margin of the Middle American Trench underthrust by a seamount province bordering the Cocos Ridge. The morphology of the landward trench slope reveals the tracks (dashed arrows) of seamount that have passed through it. The tracks themselves are the relative convergence direction of the Cocos and Caribbean plates. Impact and passage of the seamounts accelerate frontal subduction erosion and the subduction of the debris. At depth beneath the margin, it is likely that basal subduction erosion is enhanced (adapted from von Huene et al., 1995). The margin is elevated over the summits of underthrusting (buried) seamounts.

zone of the Scarborough seamount chain (South China Sea) with the large Manila accretionary prism (Lallemand et al., 1990), possibly also where the Barracuta Ridge underthrusts the Lesser Antilles prism.

(II-3-3) ENHANCED RATES WHERE LARGE BATHYMETRIC FEATURES ARE SUBDUCTED

Geophysical investigations and drilling have shown that a significant impact on mass flux is caused by subduction of large bathymetric features. Subducted seamounts that have penetrated, or are in process of penetrating, the lower landward trench slope leave bathymetric “grooves” of their passage, trails that are prima facies evidence of localized accelerated rates of removal and transport of frontal upper plate material to deeper depths. (Figure 7; von Huene et al., 1995). Sandbox models of subducting physiographic edifices further show a specific seaward taper (angle of descent) of the forearc margin with respect to a basal friction value that either promotes accretion or the erosion as a seamount passes through the inner trench slope. The morphology of a trail varies with the material through which the seamount plows. Depending on the size of the seamount, seamounts passage through the landward trench slope locally changes the quantities of materials accreted and underthrust. Initial increase of underthrust material from frontal erosion is followed by a sharp decrease as healing of the scar by accretion in the wake of the seamount uses most of the sediment input before the prism returns to a stable geometry.

Similar processes, but of greater significance to material flux of crustal material, are associated with the subduction of large aseismic ridges. Perhaps the most defining example of accelerated frontal and basal subduction erosion caused by ridge subduction is that evidenced by the 50-km offset in the Tonga-Kermadec trench-axis coincident with the subduction of the Louisville Ridge (Figure 8; Lonsdale,1986; Scholl, 1987; Ballance et al., 1989, Pelletier and Dupont, 1990).It is likely that accelerated subduction erosion along the front of the Tonga Ridge is accompanied by crustal underplating and consequent elevation of the ridge crest (Lallemand et al., 1990). Along the South American margin material flux from subduction of the Nazca Ridge beneath Peru varies an order of magnitude from its crest to a point 1000 km north of where the ridge enters the trench (von Huene et al., 1996). Results from ODP Leg 112 indicated rapid erosion of the Peruvian convergent margin, consuming older prisms and upper plate basement, was caused by subduction of the Nazca Ridge.

It is important to note that passage of a subducted ridge can be succeeded by renewed accretion against an erosional scar gouged in the landward trench slope. Geophysical work and ODP drilling at the underthrusting zone of the South Chile Ridge documents this processes (see, for example, Lewis, Berhmann, Musgrave et al., 1995). Where the Nazca Ridge collides with Peru, geophysical and drilling data reveal that new prism grew rapidly to 15 km in width. Initially, the wedge taper was low and accretion took about 60 per cent of the sediment supply, but the accreted fraction decreased to less than 30 percent as the taper, with time, steepened and the prism narrowed, despite an increased supply of trench-axis sediment. Underthrusting of sediment changed from about 2 km^3/my/km of trench at the ridge crest to 38 km^3/my/km about 800 km north of the crestal region where sediment accumulated along the trench axis. Ridge subduction affected material flux in this convergent margin system for about 8 my. The range of material flux appears sufficient to affect interplate coupling and, within the seismogenic zone, the ridge crest may become an asperity for great earthquakes. Intraplate coupling and accompanying hydrofracturing during large strain-release earthquakes are thought to be important factor contributing to accelerated basal subduction erosion and rapid forearc subsidence in the wake of ridge subduction.

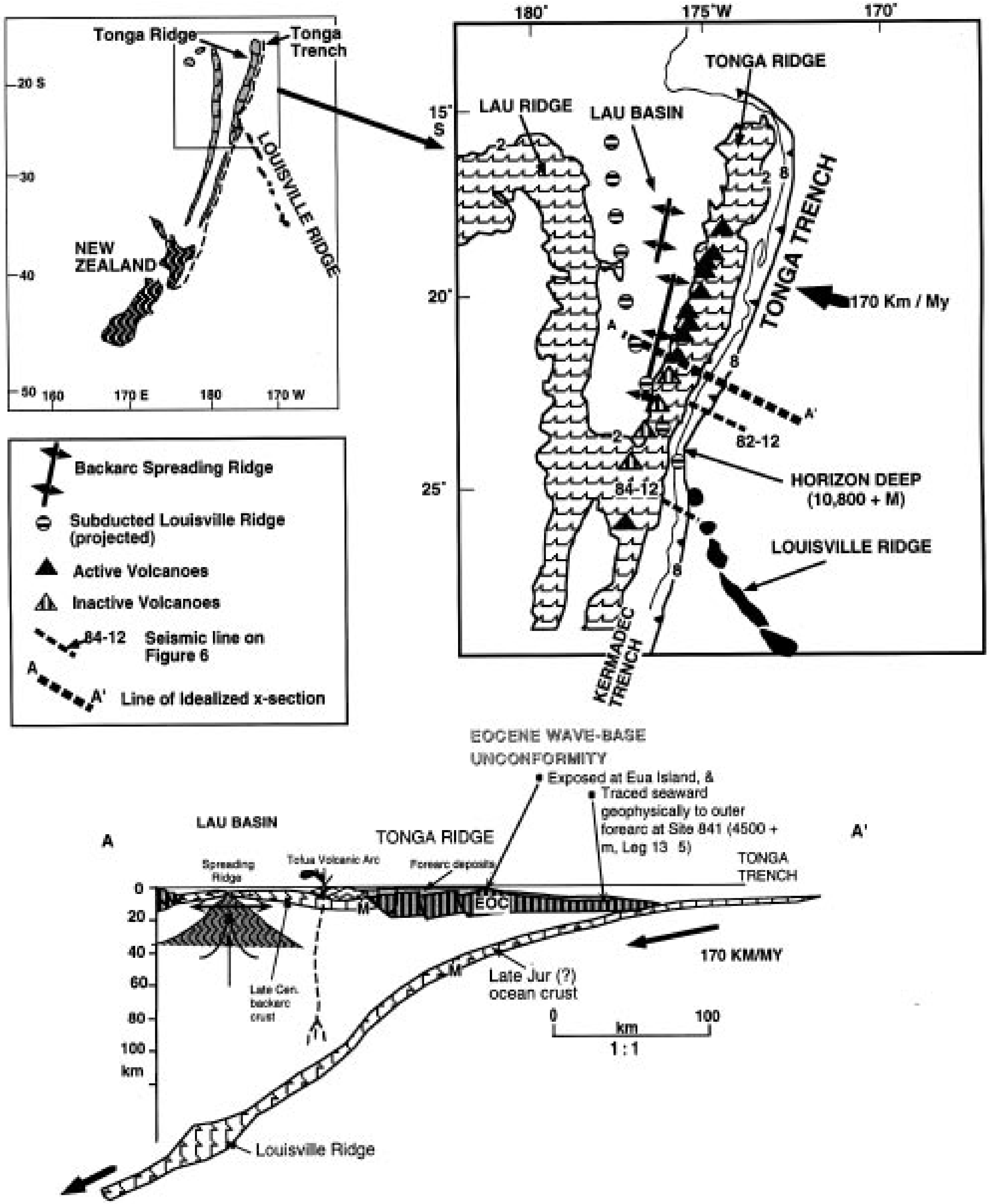


FIGURE 8 : Collision zone area of the Louisville Ridge (hotspot chain of seamounts) and the Tonga Ridge. The collision occurs geologically fast, at 170 km/my, but the collision zone travels even more rapidly southward toward New Zealand. Frontal and basal subduction erosion have combined to gouge a ~ 50-km-wide "cookie bite", the Horizon Deep or Bight, into the lower landward trench slope, thus indenting the axial trends of the Tonga and Kermadex Trenches. A-A' is idealized structural section across Tonga-Lau subduction zone system. Subduction erosion has caused subsidence of the Tonga forearc and seaward tilting of a 40-45 my old wave-base-eroded unconformity to a depth on the outer forearc of 4.5 km. The unconformity is exposed on Eua Island and can be traced geophysically seaward to ODP site 841, where shelfal limestone was drilled overlying subareally erupted arc volcanic rocks (Hawkins, Parson, Allan et al., 1994). Subduction erosion was accelerated in late Cenozoic time by the underthrusting of the Louisville Ridge (see Ballance et al, 1989; Lallemand et al., 1990, Pelletier and Dupont, 1990). Other regional relations coincident with the collision zone are southward opening of the backarc Lau Basin in the wake of the migating collision zone, uplift of the Tonga Ridge north of the collision zone, and extinquishing of active arc volcanism where the subducted ridge passes beneath the trend of the arc (see, for example, Dupont and Herzer, 1985; Lallemand et al., 1990; Geist et al., 1993; Tagudin and Scholl, 1994;

(II-4) DRILLING STRATEGIES FOR MASS FLUX INVESTIGATIONS OF SEDIMENT SUBDUCTION AND SUBDUCTION EROSION

A plan of drilling can be used to measure and track the mass flux of crustal material moving beneath the submerged margin. The basic strategy involves the drilling of a series of holes across the width of a targeted margin to establish :

(1) site-specific age and lithologic information of key sedimentary, mass wasting, and igneous rock sequences and

(2) the site-specific histories of vertical tectonism.

More than one transect is needed to establish along-margin variability and differences in vertical histories and recycling or underplating rates, in particular where the effects of the subduction of large bathymetric structures are sought. To control site locations, high-quality seismic reflection data, both of upper and deep crustal structures, and swathmapping seafloor imagery are critically needed geophysical information. An idealized drilling transect, which is combined with sites needed to support geochemical imaging of recycling processes and mass fluxes, is shown on Figure EXS-1 of the **Executive Summary,** placed at the front of this workshop report.

From the point of view of global rates of crustal recycling and mantle evolution, the mass flux of subduction component material must be addressed at both non-accreting and accreting margins. Because non-accreting margins are characteristically “fast “ subduction zones (i.e., convergence rates > about 80 km/my), and margins bordered by large prisms and thick sequences of trench-floor sediment are “slow” subduction zones (< 50 km/my), just under half of the estimated solid-volume mass of sediment subducted to mantle depths (1.0 km^3/yr in late Cenozoic time) is consumed at non-accreting margins. Subduction erosion at non-accreting margins is estimated to convey to the mantle a little more than half the global rate of solid-volume material stripped from the front and basal areas of the upper plate (~1.3 km^3/yr). These figures are based on extrapolated information gathered at only a handful of convergent margins, a circumstance that underscores the scientific need for flux investigations at both accreting and non-accreting margins and proper drilling strategies to carry them out.

(II-4-1) AT NON-ACCRETING MARGINS

With respect to subduction erosion, quantitative information about the mass flux of crustal material beneath non-accreting margins requires a transect or series of holes to determine the margin-wide history of vertical tectonism. Extrapolation of a margin-wide history of uplift and subsidence from a single hole, as practiced at past drilling legs, can only establish long-term or net processes at one location. Multiple paleobathymetric record are needed at cross-margin (transect) and margin-parallel sites to identify areas of concentrated subsidence and uplift and their lateral shifts with time. Comprehensive, margin-wide (including onshore data were available) histories locate forearc areas of plate-boundary erosional activity and underplating and the linkage of these processes to both background and short-term causes.

Margins with buried wavebase-erosion surfaces that cut across the top of both older (fossil) accretionary prisms and their backstops, or within the slope sediment that bury them, are also excellent targets along which to establish histories of vertical tectonism. These surfaces are usually time-transgressive and thus represent past as well as current tectonic regimes. Determining the nature of this time-transgressive record provides invaluable information to quantify long-term rates and volumes of material removed. To better quantify frontal erosion rates, drill targets intended to date unroofing (collapse events) or retreat of middle slope areas are needed. A comprehensive cross-margin subsidence history, however, allows a reconstruction that identifies rapid episodes of slope retreat caused by frontal erosion events.

Sediment subduction issues tied to non-accreting margins chiefly involve the gaining of accurate knowledge about the age, lithology, and physical properties of trench-floor sedimentary sequences underthrusting the base of the landward trench slope. Information is need about both the material filling underthrusting grabens and the material overlying the surface of the intervening horst blocks (Figure 1 and 6). Drilling transects located across targeted non-accreting margins must therefore at least sample the trench-floor section, and preferably near the base of the landward trench slope. Reaching the decollement just inboard of the trench is an important objective with respect to determining the physical conditions associated with efficient underthrusting of sediment and mass-wasting debris at non-accretionary margins.

A successful drill strategy for investigating subduction erosion processes and rates at non-accreting margins can take advantage of drilling shallowly-submerged margins buried by slope deposits that accumulated in paleodepth zones (middle bathyal and shallower) conducive to carbonate preservation and in a region of good faunal diversity (generally true of low and mid-latitude margins). Despite relatively poor faunal diversity and preservation, other strategies to determining vertical tectonism along more deeply submerged margins can be linked to time-varying tilting rates (i.e., greater trenchward tilting = higher basal and frontal rates of subduction erosion; see, for example, Hawkins, Parson, and Allan, 1994 and MacLeod et al, 1996). An important consideration to keep in mind is that the paleoceanographic settings of modern deeply submerged margins, including those located at high-latitudes, may have been much different with respect to faunal diversity, preservation, and water depth in early and middle Cenozoic time. Accurate long-term paleobathymetric histories can thus be reconstructed for these margin in particular by integrating dip-change and paleobathymetric information.

(II-4-2) MARGINS WITH PRISMS

To quantify rates and volumes of accretionary growth, and thus to calculate missing masses that have potentially been subducted, it is important to site holes along the transect in the middle slope region near the backstop. The point is to establish the maximum age of the accreted material and the time and paleobathymetry of its initial burial. In these upslope areas sharper age control and paleobathymetric histories are possible because shallower-water biozones are most likely to be preserved in slope deposits mantling the older part of the accretionary wedge. Entering and successfully sampling the underlying and deformed sediment of accretionary wedges can encounter hole stability problems. The reputation that convergent margin drilling conditions are difficult stem from sampling and penetration experiences at the front of the accretionary zone, where deformation is youngest, fluid movement most rapid, and cementation least advanced. But holes drilled into the prism higher on the slope are better cemented, least fluid rich, and thus stable, as drilling across the Guatemalan, Mexican, and Peruvian margins has shown.

To constrain material flux, a hole in the trench axis and in the oceanic sediment and igneous basement of the oceanic plate are also required. Logging-while-drilling (LWD) is an expensive and time-consuming tool to use here, but its use allows for an accurate measuring of the in-situ physical conditions of the material input to the subduction zone, which are necessary parameters to model subsurface pore-water pressures. Modelling is the least expensive method to characterize physical conditions in the subduction channel (i.e., material moving downward in the vertical zone between relatively fixed upper plate framework rock and the subducting igneous slab). Modelling is effectively the only approach, other than detailed earthquake seismology, to establish the physical properties of material moving along plate boundary.

Because background rates of subduction erosion affect convergent margins fronted by intermediate and possibly even large accretionary prisms, holes along the transect can be resourcefully sited to determine histories of vertical tectonism in key areas. Besides those sited over the uppermost part of the accretionary prism, critical attention should be paid to sites located on the crestal region of the backstop of older more consolidated rock. Experience has shown that the less permeable rock of the backstop tends to channel ascending fluids from dewatering sediment underthrusting it upward between the front of the backstop and the prism offscraped against it. Hydrofracturing linked to the movement and escape of overpressured pore-waters appears to concentrate the effects of basal subduction erosion in this area.

Where possible, drilling along the top of the backstop bordering large accretionary prisms may successfully determine a history of vertical tectonism. At these upslope sites it is likely that vertical changes by underplating and erosion processes can be identified, in particular if the history can be compared to that of the nearby coastal region and distinguished from the episodic consequences of out-of-sequence thrusting, the subduction of large bathymetric features, and the longer-term effects of crustal and slab temperature change.

(II-4-3) WHERE LARGE BATHYMETRIC FEATURES ARE SUBDUCTED

Scientific ocean drilling can profitably investigate the rates of both enhanced sediment subduction and subduction erosion where larger bathymetric ridges or chains of seamount are subducted. Verification has been provided through the successful combination of geophysical investigation and drilling results off western South America in the vicinity of the collision zones of the Nazca Ridge (von Huene et al, 1996), and the South Chile Ridge (Lewis, Behrmann, and Musgrave et al., 1995), Both of these collision zones migrate laterally along the trench with time, thus providing an opportunity to design a drilling strategy to compare the effects of processes and rates under pre-subduction, collisional, and post-subduction conditions. A drilling strategy of this sort has been devised for the migrating underthrusting zone of the Louisville Ridge beneath the Tonga forearc (MacLeod et al, 1996; Figure 8). Where ridge underthrusting is orthogonal or nearly so to the landward trench slope (e.g., Cocos Ridge, western end of the Aleutian Ridges, d’Entrecasteaux Ridge and satellite seamounts at the New Hebridies Trench), forearc, coastal, arc, and backarc effects can be prominently evident, and rate and process comparisons at the collision zone can be made with distance from it, (see, for example, (Fisher et al., 1986) Geist and Scholl, 1994, and Kolarsky et al., 1995).

An important drilling strategy is therefore to measure and compare lateral time-space changes and differences in rates and total mass flux, whether effected by a migrating collision zone of a ridge or a chain of seamounts, or with respect to a fix location of edifice underthrusting. Cross-margin site positioning for subducting ridges and seamount chains is similar to that outlined for investigating background rates and consequences of sediment subduction and subduction erosion, but differing in that transects of the margin are require at positions tectonically above, in the vicinity of, and, below the collision zone.

With special respect to orthogonal subduction of large bathymetric structures, although the measure of material flux may be beyond the capability of the present drill ship to investigate, an interesting strategy would be to combine ocean floor drilling with that of deep continental drilling. For example, if deep onshore drilling were sited on the Osa Peninsula of Costa Rica, the top of the subducting Cocos Ridge is probably within reach of the KTB land drilling rig. Combined with a series of offshore holes seaward of Costa Rica, an ultra deep hole would be able to compare some of the physical, mineralogic, and fluid conditions deep in the subduction zone with those recorded immediately landward of the inner trench wall. Because the collision point of the Cocos Ridge and Costa Rica sector of the Caribbean plate has not moved laterally since the late Miocene, impressive onshore effects of the collision have evolved (Kolarsky et al., 1995), perhaps even affecting the isotopic and trace-element geochemistry of arc volcanic rocks erupting laterally along the Central American Trench (see elsewhere immediately below and also Plank et al., 1993)

PART III

RECYCLING PROCESSES AND MATERIAL FLUXES—APPROACHES VIA GEOCHEMICAL IMAGING AND OCEAN FLOOR DRILLING

(III-1) INTRODUCTION

Trace element ratios, isotope ratios and elemental fluxes are the tools that geochemists use to trace the movement and metamorphism of crustal material in subduction zones. These various tools have led to the clear recognition of subducted crustal material in the source of arc volcanics, for example as recognized along the Central American arc (Figure 9). Identifying the processes that accommodate subduction recycling, and quantifying the fluxes at various points in the cycle are the ultimate goals. Indeed, without some knowledge of the actual processes going on, it is difficult to link the geochemical budgets (determined on an element by element basis) with the mass budgets. Thus the path of understanding is one that requires bootstrapping knowledge: beginning with element tracers to identify the processes, then quantifying the element fluxes to begin to quantify the reactions that characterize each process, then using the reactions to quantify the macroscopic changes to the system, such as mass and chemical losses during subduction. A hypothetical example might go like this:

1) ^{10}Be may be used as a tracer to identify sediment recycling,

2) the ^{10}Be recycling flux is estimated from input and output rates,

3) the efficiency of the ^{10}Be recycling, combined with experimental data on Be partitioning, points to a specific recycling process, such as sediment melting,

4) a sediment melting model leads to specific predictions for mass and chemical losses attending sediment subduction for each subduction zone, which can be tested against observations.

This example is an ideal, but represents one clear path of inquiry. The state of the science is that a plethora of geochemical tracers of subduction have been identified, while our understanding of the processes, reactions, and mass fluxes is still evolving.

This section explores in some detail first how geochemists trace crustal material through the subduction zone and how the tracers can be used to identify the various processes that attend subduction recycling. The discussion then turns toward how the different recycling processes can be quantified, and element fluxes determined. Although the scope of these problems may require many different approaches (experimental lab studies, non-drilling marine programs, and integrated efforts such as defined by the Margins Initiative), ocean drilling provides the only way to obtain much of the information needed. Thus, a final section focuses on drilling strategies that can help to identify and quantify the subduction processes.

(III-2) GEOCHEMICAL TRACERS

For all the reasons discussed earlier, it is not possible to directly measure the volumes of water, sediment and basalt alteration products delivered to the depths of magma generation at convergent margins and beyond, into the deeper mantle. Neither is it yet possible to directly measure well the flux of water into subduction zones, or its flux out over different depth intervals. Rather, geochemists use a

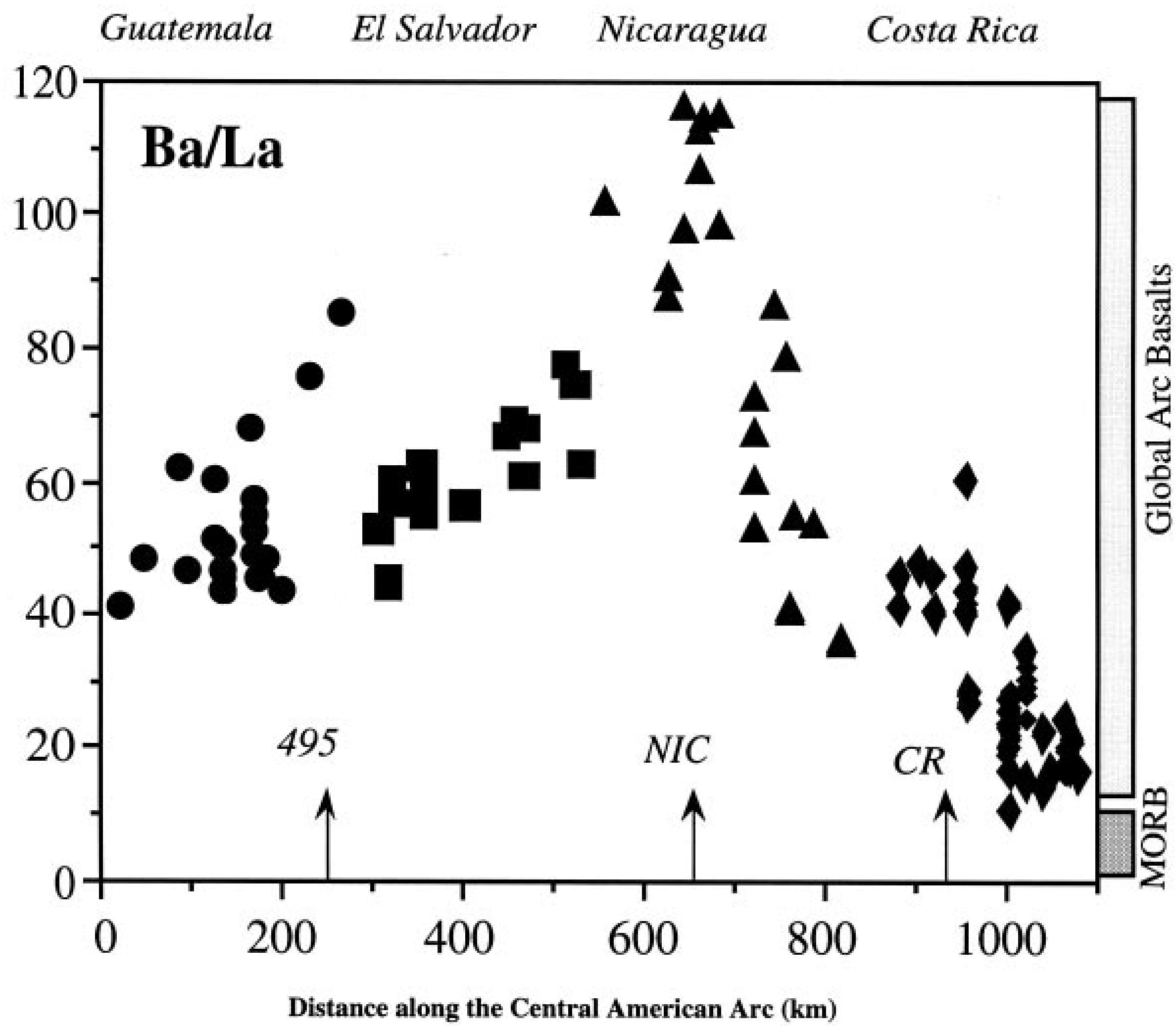


FIGURE 9: Regional variations in the geochemistry of Central American arc volcanics [data from Carr et al., 1990; Carr and Rose, 1987; excluding high-Ti or BVF samples]. Symbols correspond to political boundaries, and arrows indicate the approximate position of the DSDP transect at Guatemala (495), and proposed drilling transects at Costa Rica (CR) and Nicaragua (NIC). Regional gradients along the Central American arc in sediment and slab tracers (such as Ba/La) generally peak in Nicaragua volcanic rocks and decrease dramatically in Costa Rica volcanic units.

carefully selected subset of isotopes and elements as proxies in the effort to track water, sediment and altered basaltic crust, and the processes affecting them during subduction. In order to be effective proxies, the geochemical tracers should satisfy a few criteria. Ideally, they are:

1) elements or isotopes that are enriched in the subducted input (so they provide a large input signal) and in the volcanic or fluid output (so we can detect them through the process),
2) not present in large quantities in the mantle or upper crust (so they are not obscured by other parts of the system), and
3) strongly partitioned into aqueous fluids and silicate melts (so they recycle to the surface efficiently, i.e., are not affected by AFC and fluid-rock processes).

Below we outline briefly some of the geochemical tracers that satisfy some or all of the above criteria, and so are useful in studies of recycling process and fluxes.

(III-2-1) SUBDUCTION TRACERS IN FOREARC FLUIDS

Slab-derived fluids can hydrate and serpentinize the shallow forearc mantle, which ascends diapirically to the surface. Where accretionary prisms are absent, these diapirs can reach the seafloor, forming serpentinite seamounts, as has happened in the Mariana and Bonin forearcs. In these areas, where fluids are actively upwelling, we can sample both the lithospheric mantle and the slab-derived fluids. Such fluids in the Mariana forearc are rich in H_2O, C as both CH_4 and CO_3^{2-}, S as both H_2S and SO_4^{2-}, and have high Na/Cl, K, Rb, and B. They are poor in Li, Mg, Ca, Sr, Ba, Si, Mn, and ^{34}S (Mottl, 1992)]. The hydrated mantle is enriched in B, Sr, and Li (Ryan et al., 1994). While these same processes probably occur in forearcs with accretionary prisms, the additional reactions within these thick sediment piles greatly complicate the resulting fluid flow paths and compositions, making their interpretation much more difficult and ambiguous. Thus, the fluids and serpentines sampled in the Mariana and Bonin forearcs provide the least adulterated samples of slab-derived components. Based simply on the enrichments in these fluids, the most useful tracers in identifying slab-derived fluids in forearcs include C, S, N, B, Cl, and Sr and their isotopes; the alkalies Na, K, Rb, and Cs; As and Sb; and the isotopes of O and H.

(III-2-2) ISOTOPIC TRACERS IN ARC MAGMAS

Radiogenic isotope ratios (Sr, Nd and Pb) make effective tools for tracing mixing processes in subduction zones, as they are unaffected by variations in partial melting or crystal fractionation, and are sensitive to mixing between source materials of different compositions. The distinctive high $^{207}Pb/^{204}Pb$ signature of many arc lavas, deriving from subducted sediment, was discussed earlier. Where homogeneous mantle mixes with a homogeneous subduction component without subsequent crustal contamination, mixing arrays amongst the Sr, Nd and Pb isotopes can be used to pinpoint mantle and subduction components, their compositions and the proportions of each (Figure 10; Barreiro 1983; Whitford and Jezek, 1982; White and Dupre , 1986; Ben Othman et al, 1989; Lin, 1992; Miller et al, 1994). In a number or arcs, however, no systematics or multi-component mixing (i.e. triangles, blobs etc. rather than linear arrays) are observed pointing to mantle heterogeneity, crustal contamination, multiple subduction components or multiple episodes of subduction modification of the mantle (e.g. Hildreth and Moorbath, 1988; Carr et al, 1990; Lin et al, 1990; Edwards et al, 1993; and many others). Such complex relationships provide clues regarding source materials for the magmas and processes involved, but do not provide unique constraints.

Stable isotopes have frequently been used to investigate subduction contributions to arc volcanism. Many arc lavas without evidence of crustal contamination have delta ^{18}O values within ≈1%o of mantle values, characteristics that can be explained by a small subduction component, or by fractionation of olivine and magnetite (Harmon and Hoefs, 1984; Ito and Stern, 1985/6, Bottinga and Javoy, 1975; Kyser et al, 1981). Very high delta ^{18}O values are often observed where lavas erupt through, and assimilate, thick sections of continental crust (e.g. Harmon and Hoefs, 1984; James, 1984; Hildreth and Moorbath, 1988). The use of D/H, C and He isotopes has been hampered by uncertainties regarding the effects of shallow magma degassing and meteoric water circulation on the isotope composition of gases and fumaroles, although recent He studies from the Sunda-Banda arc of E. Indonesia argue for contribution of S, C and He to volcanic gases from subducted sediment (Poorter et al, 1991). Sulfur isotope studies from several arcs (Woodhead et al, 1987; Hochstaedter et al, 1990; Alt et al., 1993) often show a shift from mantle values consistent with sediment addition, but the unquantified effects of degassing and biological reactions in sediment mean that interpretation of S isotope data can be complex.

B and Li stable isotopes provide new approaches to subduction zone studies. The mantle has nearly homogeneous B isotopic compositions (Chaussidon and Jambon 1992), while sediment and altered oceanic basalt have isotopic compositions that are different from each other and also from mantle values (Spivack and Edmond, 1988; Ishikawa and Nakamura, 1992, 1993). Studies of volcanic arc lavas (Leeman, 1987; Spivack and Edmond, 1988; Palmer 1991, Ishikawa and Nakamura, 1994; Ishikawa and Tera, 1994) show simple mixing systematics between mantle and a homogeneous subducted component that has isotopic compositions typical of those measured in altered basaltic crust outboard of the trench. Details of B geochemistry through the subduction cycle need more work, but the presence of simple relations in this system also augers well for tracking masses and deciphering processes. Marine sediment and altered basalt frequently have Li isotopic compositions similar to each other, reflecting interaction with sea water, but different from mantle values (Chan and Edmond, 1988; Chan et al, 1992, 1994), setting the stage for a useful tracer of subduction. As Li is modestly compatible in many mantle minerals (Ryan and Langmuir, 1987), the Li isotopic signature of subduction modification of the mantle wedge may build up through time.

The short-lived radioisotopes of ^{10}Be and the U-series chain are useful in tracking mass fluxes, subduction zone processes**,** and the timescales of transport during subduction recycling. Decaying with a 1.5-my half-life, ^{10}Be does not build up in the mantle over time, so this isotope is insensitive to mantle composition or heterogeneity. Also as a result of its half-life, the ^{10}Be is all in the uppermost part of the subducting sediment column. ^{10}Be enrichments in arc lavas effectively illuminate the slab at depth and image the presence there of the youngest sediment. Simple two component mixing lines between the ^{10}Be/^{9}Be ratio, and other isotopic or elemental ratios point toward the composition of the subduction component that gets into the mantle (Figure 11). Where data for the sediment exist, the subduction component in the mantle may be compared against the column entering the trench, to specify the fraction of the sediment column that must be subducted to depths of magma generation**.** (Morris et al, 1990; Edwards et al, 1993; Reagan et al, 1994). The flux of ^{10}Be into the subduction zone may also be compared with the flux out of the volcanoes to specify the mass flux of subducted sediment necessary to supply the volcanic arc, in a manner analogous to that used for other elements in sediment (Plank and Langmuir, 1993). In other words, the chemical flux of ^{10}Be constrains the mass flux of sediment.

U series disequilibria isotope studies of volcanic arcs show that the Th isotopic compositions of intra-oceanic arc lavas cover a much wider range than observed in the mantle underlying areas away from subduction zones, probably reflecting the addition to the mantle of elements derived from pelagic

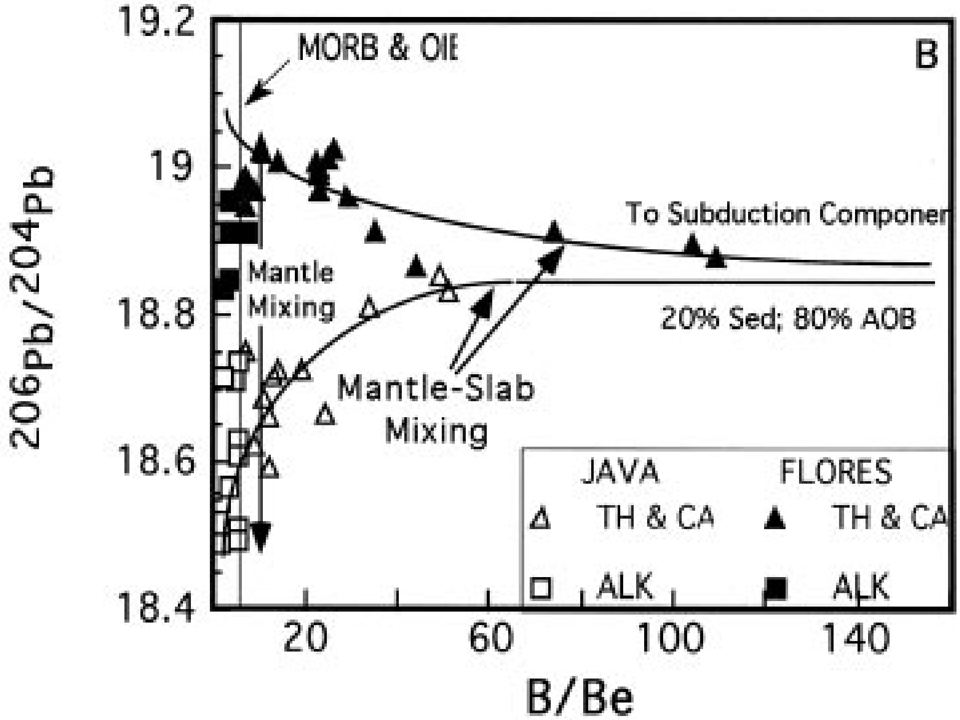


FIGURE 10: B/Be vs $^{206}Pb/^{204}Pb$ relationships for alkaline and calc-alkaline lavas from Indonesia (following Edwards et al, 1993). Isotopic variation in alkaline lavas with low B/Be reflect pre-existing mantle heterogeneity. The convergence of mixing curves for Java and Flores at high B/Be ratios points to a common subduction component. Modelling of B/Be vs Sr, Nd and Pb isotopes indicates a subduction component comprised of 20% Indian Ocean sediment and 80% altered basaltic crust.

(oceanic) sediment in some localities and of altered oceanic crust and/or carbonate at other sites (Newman et al, 1986; Condomines et al, 1988; Williams and Gill, 1990; Sigmarsson et al, 1990; Gill et al, 1993; McDermott and Hawkesworth, 1991; Reagan et al, 1994). Additionally, some 30-40% of subduction zone lavas show excess U, a phenomenon observed only above subduction zones, and indicating the addition within the last 300 ka to the mantle of U in excess of Th (Condomines and Sigmarsson, 1993). Relations between ^{10}Be and U disequilibria isotopes argue that the U disequilibria systematics are imposed by a slab derived component. Timescales required for elements to leave the slab, move into the mantle, become incorporated in mantle melts which then ascend to the surface is often less, and sometimes much less, than 300 ka.

(III-2-3) TRACE ELEMENT TRACERS IN ARC MAGMAS

In looking at a periodic table of the elements, one clearly has a wide range of elements tracers to choose from. Some elements are more useful than others, however, in trying to trace crustal material through the subduction zone. Most major elements in sediment and oceanic crust (Si, Al, Fe, Mg, Mn, Ca) are also major elements in the mantle, so these elements are difficult to trace once they enter the mantle buffer. On the other hand, many trace elements that exist at the part per million or billion level in the mantle may be orders of magnitude more enriched in subducted crustal material. Examples include alkali (K, Rb, Cs) and alkaline earth (Sr, Ba) elements, the light elements (B, Li, Be), the light rare earth elements (LREE: Ce, Pr, Nd, Sm), the halogens (Cl, F, I, Br), volatile compounds (H_2O, CO_2) and U, Th and Pb. All of these elements are variably enriched in arc magmas over what we would expect to come out of the mantle at mid-ocean ridges. Thus their high concentration in crustal input to subduction zones combined with their high content in the arc output makes these elements the potential tracers in recycling studies. The goal is then to trace these elements back down the volcano and into the slab, to reveal the reactions and mass fluxes occurring there.

While it may sound straightforward to compare the concentration of a tracer in a volcanic rock to the subducted inputs, the absolute concentration of element tracers can be influenced by many intervening processes — crystallization, melting, dewatering, dilution by minerals, mass loss from reaction, deeper subduction, etc. For this reason, elements are often ratioed to other elements that exhibit similar behavior through several of these processes. For example, Ce and Pb have very similar behavior during mantle melting and basalt crystallization, and have a virtually contant ratio in all mid-ocean ridge basalt and ocean island basalt (Pb/Ce ~ 0.3) [Hofmann et al., 1986]. However, Ce and Pb are fractionated by hydrothermal processes, and arc volcanic rocks, continental crust and both terrigenous and hydrothermal seafloor sediment have distinctly higher Pb/Ce than the oceanic ratio [Miller et al., 1994; Peucker-Ehrenbrink et al., 1994]. Thus the high Pb/Ce ratio in arc basalt can be used as a tracer of subducted sediment and/or hydrothermal processes.

Many trace element ratios are like Pb/Ce in that they are distinctive in arc basalt relative to basalt from other tectonic settings. For example, the alkalis, alkaline earths, and U, Th, and Pb are typically enriched in arc basalt relative to the LREE (e.g., high Ba/La, K/La, Sr/Nd, Th/La, Pb/Ce) [Kay, 1980; Perfit et al., 1980; Gill, 1981; Arculus and Powell, 1986; Miller et al., 1994]. The LREE, in turn, are often enriched over the high field strength elements (Zr, Hf, Nb, Ta) such that high La/Nb and Sm/Zr distinguishes arc basalt from other oceanic basalt, which have constant or lower ratios. These general geochemical systematics among element groups in arc basalt may also be typical of some types of marine sediment (e.g., marine carbonates have high Sr/Nd, hydrothermal sediment have high Pb/Ce, and barite-infested biogenic oozes have high Ba/La) [Ben Othman et al., 1989; Plank and Langmuir, 1993]. Thus, in some cases, trace element ratios may be used just like isotopes to identify subducted sediment sources. However, trace element ratios are different from all isotope ratios discussed above in that they may be fractionated by processes at high temperatures. For example, high Pb/Ce could also be produced by hydrothermal processes that preferentially strip Pb from basalt or sediment. High La/Nb may be caused by melting with residual rutile (which strongly partitions Nb but not La). Thus trace element ratios may store another level of information about processes not available from radiogenic isotope ratios alone, provided the effect of source composition can be removed.

(III-2-4) COMBINING TRACE ELEMENTS AND ISOTOPES

As one might imagine, using isotope and trace element ratios together provides the best means for separating subducting sources from the subduction process. For example, Miller et al. [1994] used Pb/Ce ratios in conjunction with Pb isotope ratios to determine how much Pb in the Aleutian arc is derived from subducted sediment vs. basalt. By then comparing the proportions with the known inputs to the subduction zone, they could also assess how much of the Pb/Ce enrichment in the arc is due to the subducted material, and how much is caused by the recycling process itself. They conclude that far more Pb is derived from the basaltic crust than can be explained by the subducting basalt's Pb/Ce, and so the subduction process is one that preferentially strips 30% of the Pb from the oceanic crust. This example illustrates how studies that combine trace elements and isotopes may gain additional insights into the processes and fluxes attending subduction.

B and Be also provide great potential for combined trace element-isotope study. Arc basalt is distinguished by enrichment in B over Be (Leeman et al., 1990: Morris et al, 1990 Leeman et al., 1994; Ryan and Langmuir, 1988; 1993). High B/Be may reflect sediment or altered oceanic crust sources, or the preferential partitioning or scavenging of B into aqueous fluids during subduction metamorphism (Morris et al, 1990). Combining the elemental information with Be and B isotopes, however, can help to discern among these models of source vs. process by uniquely distinguishing the subducted sediment contribution (with high ^{10}Be; Tera et al., 1986) from the altered oceanic crust contribution with high d^{11}B Ishikawa and Nakamura, 1992, 1993). Thus, as in Pb/Ce, B/Be can ultimately be used to quantify the fluxes from the subducted crust to the arc, and is an area of active research. Critical to all of these approaches is being able to determine the composition of material (sediment and altered oceanic crust) feeding a given subduction zone.

While clearly useful in identifying sources and processes, trace element and isotope ratios can not be mass balanced without some estimate of the absolute concentration of the elements. This requires making some additional assumptions about the extent of crystallization and melting and arc magma fluxes. Plank and Langmuir (1993) calculated sediment input fluxes for many element tracers. Comparing them to arc output fluxes reveals a deficit in some elements (Sr notably, but also H_2O), which points to important contributions from the altered oceanic crust. By combining elemental fluxes with isotope ratios, the different fluxes from subducted sediment and oceanic crust to the arc can be calculated uniquely (as outlined above for Pb and B). Using element tracers to calculate mass fluxes is a remaining challenge, but indeed necessary for quantifying the recycling process at various levels in the subduction zone.

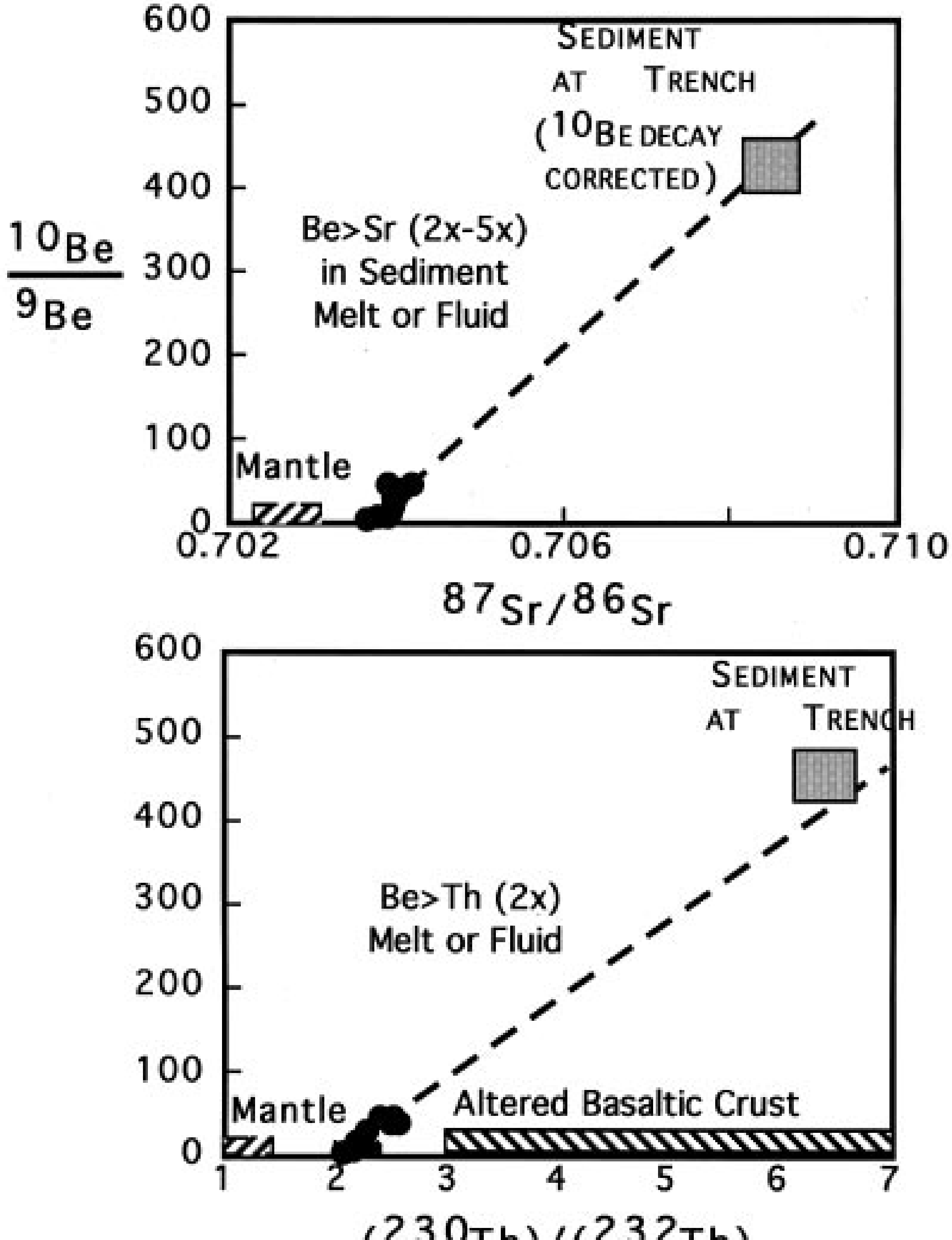


FIGURE 11: Sr-Th -Be isotope relationships for Nicaragua volcanic rocks (following Reagan et al, 1994). The measured isotopic composition for the lithologically weighted sediment column at DSDP 495, outboard of Guatemala, is shown. Mixing between the measured sediment and the mantle can produce the range of volcanic compositions, if and only if the sediment contributing to magma generation is closely similar to that now entering the trench (i.e. steady state sediment subduction for ca 2 my), and if little sediment is offscraped anywhere between the trench and the depths of magma generation. For this arc, a contribution from the altered basaltic crust is not required.

(III-3) RECYCLING PROCESSES

Subduction recycling involves two general paths: a downward one, driven by the negative buoyancy of the subducting slab, and an upward one, driven by the positive buoyancy of fluids released from the subducting slab. Because the downward path is fairly well described by global plate tectonics, we focus here on the upward path. Indeed, fluids (C-O-H-S-N fluids or silicate melts) may be thought of as the agents of recycling to the arc crust, and so understanding their origin and evolution as they move from slab to surface is at the heart of deep recycling studies. The following section explores the process of prograde metamorphism in the slab, which gives rise to fluids (aqueous and/or melts), and how this process is identified in fluids and melts that are sampled in the upper plate. Subsequent sections explore the process of fluid migration through the overlying mantle and crust, and the possible side-effects on fluid composition.

(III-3-1) PROGRADE SUBDUCTION METAMORPHISM

As the slab subducts, increasing pressure and temperature lead to progressive dehydration metamorphism, devolatilization releasing C-O-H-S-N fluids of varying but largely aqueous compositions. At the shallowest levels (0-10 km), the dominant mode of dewatering is simply due to compaction, but at greater depths, dehydration reactions begin to occur in the subducted sediment and basalt. These reactions can include:

(1) diagenetic transformation of opal-A, including expulsion of interlayer water at about 30° to 80°C;

(2) expulsion of interlayer water from smectite and its transformation to illite at about 50° to 150°C;

(3) breakdown of hydrocarbons to methane in organic-rich sediment at about 60° to 150°C;

(4) metamorphic dehydration of sedimentary minerals, mainly clays, beginning at about 250° to 300°C;

(5) metamorphic dehydration of chlorite, amphibole, and other hydrous phases in the basaltic crust, beginning at about 450° to 500°C; and

(6) dehydration melting of sediment during muscovite breakdown at 650 - 750°C.

Fluids generated by these processes will carry with them a host of mobile chemical species, some of them having been isotopically fractionated by the processes by which the fluids were derived.

At least three current approaches are available to identifying the progressive metamorphic reactions in the slab. One is to sample fluid outputs in the upper plate at varying distances from the trench. Changes in the fluid composition across the strike of the arc logically reflect changes in the depth of metamorphism in the slab. Another approach is to study exposed sections of subduction complexes (such as the Catalina Schist) and to determine the compositional changes attending increasing grade (see, for example Bebout et al., 1993 and Bebout 95). The final approach is to simulate subduction in the laboratory, by experimentally metamorphosing crustal lithologies or by measuring relevant partition coefficients. We discuss each of these approaches in turn below.

(III-3-1-1) Cross-Arc Studies

The unique conditions and products of subduction zone metamorphism have long been recognized. Fluids driven off the slab during metamorphism may be sampled directly in sediment starved fore-arcs, and in veins trapped in subduction assemblages such as the Catalina Complex. Fluids may also be sampled indirectly through the concentrations of fluid-mobile elements in arc and back-arc lavas. In all cases, measured or inferred fluid compositions from a range of depths provide constraints on element mobility and mineral stability during progressive metamorphism.

One way to infer processes of devolatilization and fluid transport during prograde metamorphism is to attempt to sample slab-derived fluids both along and across non-accretionary forearcs such as the Mariana. Here a band of probable serpentinite seamounts 70 km wide and 1000 km long provides an opportunity to sample upwelling fluids at various locations above the subducting slab. Transects across this forearc would correspond to varying depths from the seafloor to the top of the downgoing slab, and hence to increasing temperature and pressure at the likely source locality for the fluids. Variation in the concentrations of key chemical species in the upwelling fluids collected on such a transect would provide direct evidence about how devolatilization and element mobility vary with metamorphic grade.

Cross-arc studies may markedly help in identifying mineralogical and chemical variations during progressive slab metamorphism. In another series of cross-arc studies, Tatsumi et al. (1991, 1992) find trace element evidence for specific mineral reactions in the slab: amphibole breakdown below the main volcanic front, and phlogopite breakdown beneath the backarc. Other cross-arc studies show that volcanoes above greater and greater depths in the slab show progressively less enrichment in B, Li, Cs, As and Sb. These elements are considered fluid-mobile, and the gradients are interpreted to reflect early (shallow) mobility out of the slab. Other slab tracers such as K, Ba, Be, and the REEs do not have changing concentrations with increasing metamorphic grade over the 20-70 km depth interval, while they are certainly enriched in arc volcanic rocks (sampling ~ 100 km depths in the slab). This change in behavior of Ba, K and Be from fluid immobile at shallow depths to mobile in regions of magma generation may reflect different mineral stabilities (and hence element solubilities) at depth, enhanced solubility with increasing P and T (i.e. greater carrying capacity of a fluid) or sediment melting rather than fluid extraction as a transport mechanism at depth. Heated debate continues over these points. In the meantime, empirical relationships between elements that are mobile at shallow levels in subduction zones may be used to evaluate dehydration processes, while elements that are apparently not transferred out of the slab at depths shallower than those of magma generation may be useful for calculating deeper mass fluxes.

(III-3-1-2) Exposed Subduction Complexes

Several recent studies have focused on the chemical effects of subduction metamorphism as preserved in exposed metamorphosed rocks (Moran et al, 1992; Bebout et al, 1993). One extensively studied complex is the Catalina Schist, which with increasing pressure and temperature shows decreasing water, silica, nitrogen, B, Li, Cs, As and Sb contents, as well as fractionating N isotopes. These systematics most likely reflect extraction from the sediment of a fluid enriched in those same elements (ibid). The trace elements progressively lost from the Catalina schist are also those that are enriched in lavas erupted over the shallowest part of the slab (Bebout et al., 1993) demonstrating good convergence of these two approaches in identifying the chemical consequences of subduction.

(III-3-1-3) Laboratory Studies

With recent advances in experimental techniques, there have been several new laboratory studies aimed at subduction metamorphism and fluids. One class of studies is directed at determining mineral equilibria of slab lithologies, providing direct information on the mineral reactions that will occur for different slab P-T paths (Wyllie and Wolf, 1993; Nichols et al., 1994; Johnson and Plank, 1993; Pawley and Holloway, 1993). Another class of experiments is focused on measuring solubilities and fluid/solid partition coefficients for important tracer elements (Brenan et al, 1994, 1995; Keppler, 1996; Tatsumi et al., 1986; Tatsumi and Isoyama, 1988). These experimental studies provide a forward approach to studying subduction metamorphism, complementary to the above inverse approaches that infer reactions based on fluids sampled at the Earth's surface.

(III-3-2) FLUID/MELT MIGRATION THROUGH THE MANTLE

The fluids generated by progressive metamorphism of the slab are more buoyant than the surrounding slab or mantle, and so they will rise out of the slab into the overlying mantle (roughly vertically, following pressure gradients induced by mantle flow; Spiegelman and McKenzie, 1987). Depending on the depth, temperature and composition of the mantle, the fluids will react to form other hydrous minerals in the mantle (such as serpentine or amphibole), cause mantle melting, or simply migrate as a fluid phase through the mantle.

At shallow levels, fluids serpentinize the mantle, and the serpentinite itself rises buoyantly as diapirs to intrude the forearc (Fryer et al, 1995). Thus, fluid is transported fairly directly from slab to surface. At greater depths, where the surrounding mantle is hotter, the presence of water and other chemical components will lower the solidus temperature of the mantle and lead to melting. Melting may continue if the mantle is able to rise adiabatically, due to the lowering of density and viscosity by the infiltrating fluids and melts (Plank and Langmuir, 1988). The degree to which the mantle melts adiabatically vs. purely due to the infiltration of water is debated (Davies and Stevenson, 1992; Davies and Bickle, 1991; Baker et al., 1994). Even after melting ceases, melts will continue to percolate upward and eventually erupt out a volcano. Thus the slab-derived fluid is greatly diluted by mantle melts, and arc magmas are mostly mantle-derived by mass. Although subduction components in arc magmas generally constitute a small percentage of the over-all magma mass, they may make up a dominant portion of different element budgets (e.g., for H_2O or Pb).

Regardless of the depth at which a fluid was generated in the slab, some finite interval exists over which the fluid or melt migrates through the mantle, a path that presents an opportunity for further reaction. McKenzie (1984) and Navon and Stolper (1987) show that elements can fractionate as melts or fluids of one composition migrate through mantle of another. During grain boundary migration, elements partition into mantle minerals as a function of melt velocity, grain size and partition and diffusion coefficient. Very incompatible elements remain in the melt while compatible elements partition into the olivines and pyroxenes of the mantle. Detailed application of melt migration models to subduction zone magma generation and melt compositions has yet to emerge, due to the complexities of the setting. Nonetheless, workers are increasingly concerned about the effects of elemental fractionation during transport through the mantle as a means of either producing or modifying subduction signatures (Hawkesworth et al, 1991; Stern et al, 1992; Keleman et al, 1990, Keleman et al., 1990; Stolper and Newman 1994).

Some evidence exists, however, to suggest that many element tracers are mostly unperturbed during migration through the mantle. For example, lavas erupting behind the volcanic front in the Aleutians, Bismark and Kurile arcs, which pass through long mantle columns between the slab and arc crust, have ^{10}Be enrichments that are comparable to those at the volcanic front. This suggests that Be is transmitted efficiently, regardless of the mantle column length below the volcano. Elements more incompatible than Be (B, Cs, Rb, K, Ba, U, Th, Pb) should thus also be transmitted effectively through the mantle column, and ratios of these elements to each other should change little during transport. Indeed, the limited data sets available (Morris et al, 1990; Woodhead and Johnson, 1993; show variation in the opposite sense to that predicted from transport effects. It appears, therefore, that the group of incompatible elements typically used as tracers and discussed thus far are more sensitive to subduction zone processes than to intra-mantle fractionations.

(III-3-3) FLUID/MELT MIGRATION THROUGH THE CRUST

Just as there is always some tendency for melt and fluids to react with the mantle column through which they ascend, there is an even greater tendency for melt reaction within the crust. This is in part because the melting point of sialic material is below the temperature of mantle-derived magma (basalt), so wallrocks will partially melt, and contaminate magmas that pass through them. Continental material is also very enriched in some elements and isotopes, and so even small amounts can make a significant effect on tracer budgets. Thus while mantle columns are refractory and relatively unreactive, continental columns may be highly reactive and contaminating. Indeed, continental contamination has been well documented for several arc volcanoes, particularly those built on thickened continental crust (e.g., Leeman, 1983; Davidson, 1987; Hildreth and Moorbath, 1988). Not only will crust alter the original chemistry of basaltic magma, but the effects are quite similar to those of sediment subduction and incorporation, because sediment is, after all, largely continent-derived. Thus in many cases it is difficult to distinguish upper plate from lower plate continental sources, and clear identification of the subduction component using many tracers becomes a challenge.

Despite the clear problems associated with continental contamination, there are a few ways to minimize the effects. One is to focus only on island arcs built predominantly on basaltic oceanic crust, which is less reactive and less enriched than sialic crust. Another is to consider only the most mafic compositions associated with an arc volcano, as these compositions are by definition the least modified from primary mantle melts. In some cases, assimilation/fractional crystallization trends may be recognized in a magma suite, and compositions extrapolated to the least contaminated end-member. Finally, some tracers (e.g., ^{10}Be) can uniquely distinguish recent sediment material in the subducting plate from ancient continental material in the upper plate. Thus, with a judicious selection of arcs, magma compositions and tracers, the over-printing effects of continental contamination may be avoided.

A similar analogy can be drawn for sampling fluids in forearcs. There will be some tendency for deeply-sourced fluids to react with forearc sediment, or for the deep fluids to be mixed and overwhelmed by fluids derived from accretionary wedge sediment (i.e., chemically evolved sea water). Thus as for arc magmas, certain types of margins may be better suited for identifying subducted components in forearc fluids. These margins clearly include those with little or no accreted sediment to contaminate the deep fluid signal.

(III-4) TOWARD MASS FLUXES

The above sections focused on how geochemical tracers are used to identify processes. Once various processes are identified, the next obvious step is to begin to quantify the processes (e.g., how much sediment is recycled to arc volcanoes?). Mass fluxes provide the means to quantify different paths of subduction recycling, and to answer some fundamental questions about how the Earth evolves. For example, some key questions are:

- How does subduction affect the chemical budgets of the ocean?
- At what rate is old continental crust returned to the mantle through sediment subduction?
- What is the rate of continental growth over time?
- What fraction of new continental crust is derived from old continental crust via subduction recycling,
- What fraction is derived directly from the mantle?
- What is the effect of crustal extraction and subduction recycling on the dynamical, thermal, mineralogical and chemical behavior of the mantle?

Geophysical imaging at depths of 20-30 km is the last direct “flow monitor” for following mass transfer during subduction. In this section, we focus on the ways that the geochemistry of forearc fluids and arc lavas, in combination with geophysics, may be used to “image” the slab at depth and constrain mass transport.

In general, a mass flux approach requires an estimate of the element input fluxes to the subduction zone (composition, volume and subduction rate for sediment and altered basalt) and estimates of the element output fluxes at different levels in the system (fluid fluxes and magma fluxes across the width of the forearc and arc). A mass balance would then use these input and output fluxes to determine the efficiency of the specific recycling process (such as fluid return to the forearc).

(III-4-1) FOREARC FLUXES

In order to balance inputs and outputs from the ocean, the flux of slab-derived fluids out forearc margins must be considered. As discussed above, these fluxes should first be assessed in a non-accretionary forearc, thereby avoiding the complications resulting from reactions in a thick accretionary prism. Once the unique geochemical signature of the slab-derived fluids has been characterized, and its variation with parameters related to subduction geometry understood, this signature can be used to assess the additional fluxes associated with devolatilization and other reactions in accretionary prisms.

Although forearc fluids can be sampled and chemically analyzed, a major challenge is to determine fluid fluxes that reflect some steady-state. Transient flow or three-dimensional flow are two processes that may complicate the measurement of meaningful fluid fluxes. Thus mapping fluid flow in 4 dimensions (including time) is an important long-term goal of study for several forearc margins. Another approach to fluid fluxes includes forward calculations of the rate at which fluids are liberated from the slab. Good estimates of the sediment and basalt input to the subduction zone can help to place upper limits on the fluid output (it can’t exceed the dewatering volumes during metamorphic reactions). This approach takes advantage of known, steady-state convergence rates, but requires estimates of the depths of different mineral dehydration reactions in the slab. Nonetheless, in order to obtain reasonable fluid flux estimates, it may be critical to work from both ends: combining the measured fluid output compositions with the fluid mass fluxes calculated from inputs and metamorphism.

Forearc fluid fluxes are also important to mass balancing the deeper fluxes. That flux which is not returned to the forearc, continues along the subduction path, and becomes the input flux for the deeper parts of the cycle. Thus, at some level, it is necessary to quantify the shallow input and output fluxes before understanding any deeper recycling. However, geochemistry provides a means to get around the serial nature of this problem. Some tracers are largely immobile during shallow dehydration processes beneath the forearc, but are clear tracers during recycling to the arc (such as Th, Be, Ba). By using these tracers, important aspects of the deeper crustal recycling problem can be usefully addressed, without obtaining quantitative estimates of forearc fluid fluxes.

(III-4-2) ARC FLUXES

(III-4-2-1) Sediment Fluxes to the Arc

There are a few recent examples of an element flux approach to quantifying the amount of subducted sediment that is recycled to the volcanic arc. For example, Plank and Langmuir (1993) determined the sediment-hosted flux for various elements (K, Cs, Rb, Ba, Sr, La, U, Th) into several subduction zones around the world. They found that the sediment fluxes, which vary globally by a factor of ten or more for many tracers, correlated with the composition of the associate volcanic arc (Figure 9). This observation alone indicates that the chemistry of arc lavas serves in some way as a “flow monitor” for the supply of subducted material to the depths of magma generation. More detailed modelling of the input and output fluxes using averaged arc data suggests that 20-50% of the sediment inventory of K, Cs, Rb, Ba, Sr, La, U and Th is extracted from the sediment to feed the volcanoes (Plank and Langmuir, in prep), with the remainder available for subduction to the deep mantle.

Zheng et al (1994) compared the flux of ^{10}Be entering trenches with the flux out of arc volcanoes. They also found that the total amount of ^{10}Be supplied to different subduction zones varies by an order of magnitude, and that it could not be inferred from global models, but must be measured from drill cores. Note from Figure 12 that ^{10}Be is concentrated at the top of the sediment column. Thus, Zheng et al (1994) found that in order to supply sufficient ^{10}Be to the Nicaragua arc (and Aleutians), more than 85 % of the incoming sediment must be subducted to the depths of magma generation (Figure 13). This 85% is a lower limit on the fraction of sediment subducted, as it requires that the transfer of ^{10}Be from the slab to the mantle and thence to the surface be 100% efficient and instantaneous. The less efficient the transfer, the larger the subducted sediment fraction must be. Be-Th-Sr isotope relations for Nicaragua sediment and volcanoes confirm that nearly 100% subduction of oceanic sediment is required along this sector of the Central American arc (Figure 11 Reagan et al, 1994).

In some cases, then, the fluxes from the slab to the depths of magma generation can be well constrained. These element flux models compare the input at the trench to the output at the arc, and thus make no assumptions as to the intervening losses to the forearc. As noted above, some of the elements modeled are not found in appreciable quantities in forearc fluids (^{10}Be, Th) and so may be used to infer deeper fluxes into the mantle.

(III-4-2-2) Basalt Slab Fluxes to the Arc.

In general, estimates of fluxes from the basaltic slab to the arc are more difficult to ascertain than sediment fluxes because of fewer useful tracers, and little data on alteration inputs. Nonetheless, Pb, Sr, B, U-series, and Li isotope systems provide promising avenues for quantifying contributions from the

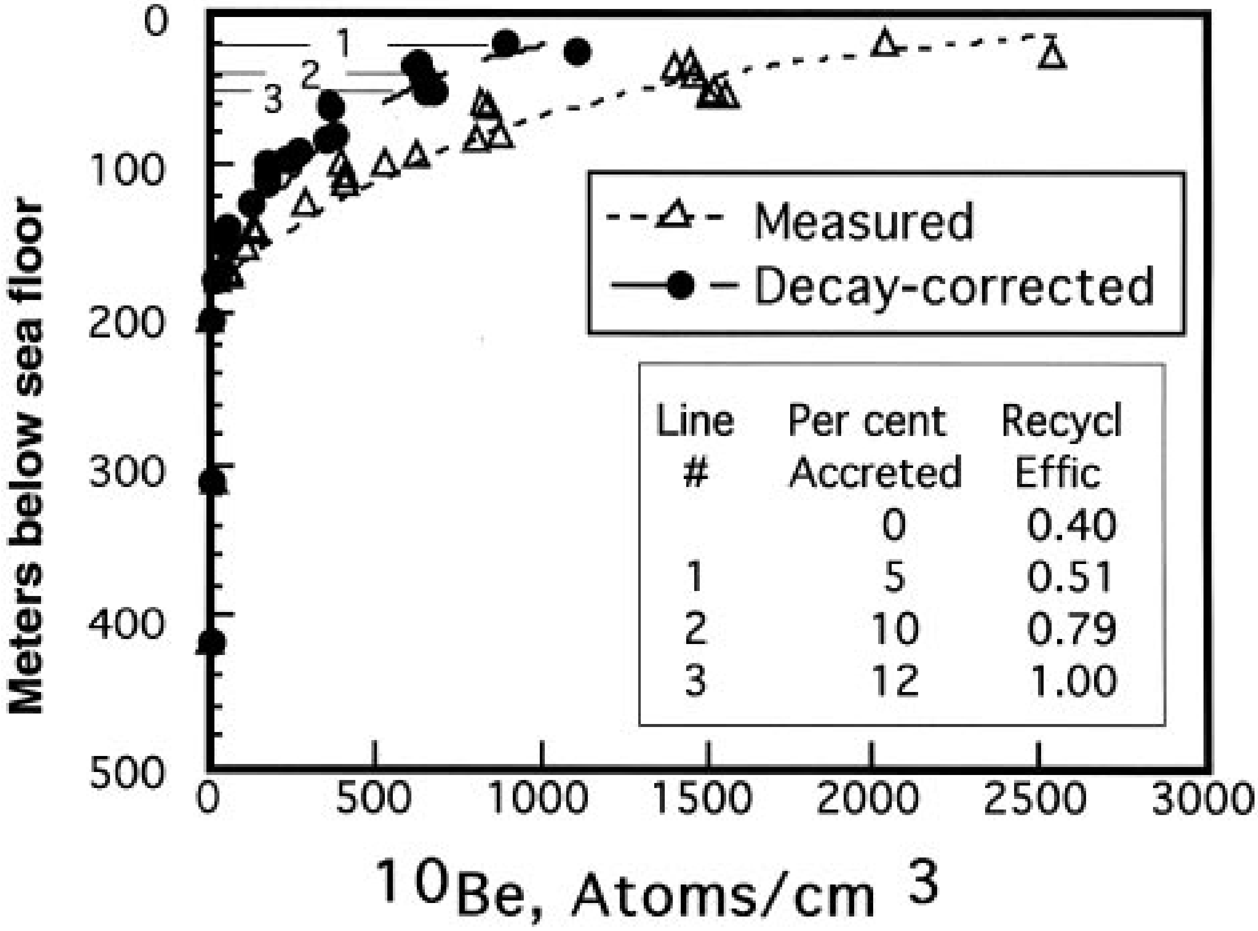


FIGURE 12: The measured profile of ^{10}Be in DSDP 495, outboard of Guatemala, and the values corrected for ^{10}Be decay during subduction from the trench to a point directly beneath the volcanic arc. If the efficiency of ^{10}Be recycling to the arc is 40%, then all sediment must subduct to depth to feed the arc. Horizon 3 corresponds to the required amount of sediment subduction, where the ^{10}Be recycling efficiency is unrealistically high at 100%. Subduction of all sediment below horizon 3 is insufficient to supply the arc with ^{10}Be.

altered basaltic crust. For example, Miller et al. (1994) used Pb mass fluxes and isotopes to calculate that the basaltic crust lost 30% of it's Pb budget to the Aleutian arc. Much more detailed work on different isotope systems and on alteration inputs are needed to obtain further estimates of basaltic recycling fluxes.

(III-4-2-3) Arc Magmatic Output Rates.

As for forearc fluid output fluxes, the most difficult part of the volcanic output flux to determine is the mass flux. Time-averaged growth rates may be obtained from Reymer and Schubert (1984), who estimated arc volumes and ages. But are these time-averaged growth rates pertinent to recent growth and subduction rates? Are arc growth rates in steady-state or are there growth spurts and lulls? These are big questions that are difficult to answer, largely because of the lack of temporal studies (on the scale of a few my) of arc growth rates, and because intrusive magmatic additions are difficult to size or date. Geologic or remote sensing mapping of volcanic units would be a useful first step in this problem, as would continental drilling (such as for Hawaii, DePaolo and Stolper, 1994). Backarc magmatic rates are more clearly linked to observable seafloor spreading rates and oceanic crustal thickness.

(III-4-3) DEEP MANTLE FLUXES

Fluxes of subducted material past and below the arc into the deep mantle depend on knowing the process whereby elements are transferred out of the slab, and its effect on the composition of the residual slab. Still hotly debated (after all these years), experimental studies, geochemical studies of cross-arc trends, and further investigation of ratios such as Ce/Pb and U/Nb in oceanic basalt are addressing the issue.

In the meantime, fluxes of continental components to the deep mantle are probably best studied using those tracers which are least affected by the shallower processes. For example, detailed mass balances of elements like Th and Ba, which are mostly lost at the depths of magmagenesis, can be used to infer the "leftover" fluxes into the deep mantle. This requires good control on inputs and cross-arc outputs for a number of margins.

Other elements may pass largely undisturbed through the entire metamorphic history of the slab, and simply stick to the slab (e.g., Nb and Ta; see Patchett et al, 1984). The Sm-Nd isotope system is another example of a geochemical system that is minimally fractionated by the low and high temperature part of the subduction cycle (Allegre et al, 1983; DePaolo 1983, 1989; Hart, 1988; Jacobsen 1988, Hofmann, 1988). The input fluxes for these elements at the trench then simply becomes the deep mantle flux as well.

Although we can address deep mantle fluxes by a judicious selection of tracers, and by detailed input-output studies, the end-result is an element-specific flux (e.g., the flux of Th or Ba into the deep mantle). In order to move from element specific fluxes to total mass fluxes, we again need to understand the process of mass transfer. Is it slab melting? Is it dehydration? What phases and/or compositions control the percent of melting or dehydration? A combined attack based on both element flux studies and process-oriented studies is thus essential to determining the final material flux recycled into the deep mantle.

(III-5) DRILLING STRATEGIES

Drilling may be used effectively on both the input and output side of the flux balance. The large variation in chemistry noted for sediment entering trenches (Plank and Langmuir, 1993; Zheng et al, 1994) preclude the use of a generic sediment column for a specific recycling calculation. Similarly, the high and low temperature alteration characteristics of the basaltic crust may depend on spreading rate, spreading fabric, stress regime at the ridge, plate age, and basement topography, as well as sediment thickness, composition and deposition rate. Sedimentation and alteration characteristics will affect the water and CO_2 content of the subducting plate as well as its mineralogy, thereby potentially affecting the fluid balance in site-specific ways.

It is absolutely clear, therefore, that if the effects of processes are to be disentangled from mass fluxes and the mass fluxes quantified, then fluid and volcanic output from the forearc-arc-backarc must be compared against the specific subducted input to the associated trench. This work can only be done through the Ocean Drilling Program.

In the remainder of this section, we discuss general characteristics of convergent margins that would make them particularly useful for recycling studies, along with some specific examples. Wherever possible, potential new drilling sites should be combined with data from existing holes to minimize cost and maximize scientific return. Because geophysical imaging and geochemical imaging look at different depth stages of the same cycle, sites chosen must be suitable from both vantage points. An idealized drilling transect, which is combined with sites needed for geophysical imaging approaches to recycling processes and mass fluxes, is shown on Figure EXS-1 of the **Executive Summary,** placed at the front of this workshop report.

A number of strategies can be identified to target the margins ideal for geochemical recycling studies. These strategies are grouped below in terms of sampling crustal inputs, and fluid and volcanic outputs.

(III-5-1) STRATEGIES IN DRILLING CRUSTAL INPUTS

• **Complete Penetration of the Entire Sedimentary Column Should Be Feasible.** It is necessary to drill through the entire sedimentary section approaching a trench, because it is always the lowermost sediment that is most likely to be subducted to the greatest depth with the downgoing plate. Thus, sedimentary sections should be targeted as those penetratable by the drill string (presently, feasible thicknesses might be < few kms).

• **The Composition of Input Material Should Be Relatively Constant Over the Past Few My.** Volcanoes tap material that subducted a few million years ago (depending on the rate and dip of subduction), while in most circumstances, drilling can sample only that material entering the subduction zone today. These input fluxes are most relevant, therefore, at places where the input is as close as possible to steady-state, or at least has not varied appreciably in the past few my. Seismic stratigraphy and plate models can give some indication of how the crustal section at the trench varies from that currently beneath the volcano.

• At Least the Upper, Oxidative Alteration Zone of the Basalt Basement Must Be Sampled. The budget for many element tracers (notably the alkalis and CO_2) resides largely in the upper, oxidative zone of alteration of the oceanic crust (upper 200-300 m). Water content, however, at least at ODP Hole 504B continues to be high (> 1 wt) through the upper 2000 m of basaltic crust (Alt et al., 1996). There are currently few predictive models for the temporal and spatial variations in the alteration budget of the oceanic crust. Thus, at this point in time, a great need exists for drilled sections through the oceanic crust. Ideally, drilling should take place in crust of varying ages and spreading rates, to test for systematics effects on alteration style.

(III-5-2) STRATEGIES IN DRILLING FLUID OUTPUTS IN FOREARCS

• Drill Non-Accretionary Forearcs. The key drilling strategy to assess fluxes in forearcs is to drill additional serpentinite seamounts in non-accretionary forearcs, in order to avoid the complicating influence of fluids derived from accretionary sediment. Non-accretionary margins with known abundant serpentine include the Marianas, Izu-Bonin and Guatemala sectors of the Pacific rim.

• Drill Across the Width of the Forearc. Drilling the forearc at varying distances between the trench and the arc can provide samples of fluids generated at different temperature and pressure conditions at the top of the subducting slab. For the Marianas margin, for example, a band of likely serpentinite seamounts stretches 70 km wide and 1000 km long, allowing for more than one trench-to-arc transect to be drilled. Much more site work will have to be done first to verify that these seamounts are, in fact, serpentinite, and to identify which ones are actively venting fluids, as, for example, were sampled at Conical Seamount on ODP Leg 125.

• Long-Term Monitoring of Sites. One major distinction between now and the previous round of margins drilling is the technological capability to deal with fluids through CORKed holes. CORKing provides a means to monitor fluid flow and composition within a hole through time, which means the effects of drilling disturbances may be lessened, and real temporal variations may be revealed.

(III-5-3) STRATEGIES WITH RESPECT TO VOLCANIC OUTPUTS

• **The Volcanic Arc Should Contain a Strong Slab Component.**

Clearly the identification of subducted crustal sources and processes is easier if the signal is large in the resultant arc volcanic rocks.

• **Upper Crustal Contamination of Magmas Should Be Minimal.** Upper crustal contamination processes may obscure the identification of subducted crustal components. Thus study of oceanic arcs is preferable to continental ones, because the tendency for contamination is minimized by a few factors (see Sect. III-3-2).

• **The Late Neogene History and Geochemistry of Volcanic Rocks Should Be Known.** Although there are few temporal studies of arc magmas over the scale of a few my, such studies are desirable to address the issue of steady-state. If the arc volcanoes are in near steady-state over the past few my, then this would indicate that either the crustal input fluxes were also in steady-state, or some moderating process is active. If there are clear temporal variations, then this can be used as an additional signal with which to test modeled changes in the rate or lithological stratigraphy of subducting crustal material. Drilling may provide such temporal information by sampling sequences of buried submarine lavas or volcaniclastic sediment.

• **Cross-Arc Trends in Volcanic Outputs Should Be Identified.** Similar to forearc fluid studies, sampling across the strike of the arc and into the backarc provides a view of the fluids and/or melts generated at different temperature and pressure conditions at the top of the subducting slab. Cross-arc trends in slab tracers can thus identify the effects of progressive metamorphism of the slab, as well as help quantify deep outputs from the slab.

• **Along-Arc Trends Should Be Identified.** Geochemical variations in slab tracers along a volcanic arc can be used to test whether these variations are an effect of the subducted input. For example, smooth variations in slab tracers along the Central American arc may reflect systematic variations in either the mass or composition of the sediment input, the extent of offscraping, or the efficiency of the deep recycling process along the margin (Figure 9). These various hypotheses can be tested with drilling. Many arcs display along-strike trends, and taking advantage of this natural signal of variability is one promising approach to conduct recycling experiments with the drill ship.

(III-5-4) THE NEED FOR FOCUSED EFFORTS AND INTEGRATED APPROACHES BEYOND DRILLING

Although the above strategies were presented as separate items, clearly the greatest scientific gains will be achieved if all of these strategies are realized at a single margin. Drilling sediment inputs provides limited gains in terms of recycling studies if a volcanic arc is not present (such as for the Nankai trough), or if erupted rocks are substantially overprinted by upper crustal contamination (as has been argued for the southern Lesser Antilles/Barbados). The problem of crustal recycling is best tackled with an integrated drilling transect, to recover crustal inputs, forearc fluids, and products of arc and backarc volcanism.

As should be clear from the preceding sections, the full problem of geochemical recycling will require an even broader set of tools than those provided by the drilling program, and would include on-land, experimental, and theoretical modeling studies as important components, which are also stressed in the defining documents of the MARGINS Initiative.

The current approach to recycling studies is a piecemeal one, where various parts of the problem are investigated at various margins. This approach has evolved because certain margins are better suited to certain parts of the problem (e.g., accretionary processes are well understood, accompanying arc volcanic products show a large sediment signal, sites of fluid egress have been identified, etc.). Although this is a good way to understand individual processes, it is not a good way to determine the behavior of the whole subduction zone system. Uncertainties are necessarily large if one compares sediment input at one margin, with fluid output at another, with volcanic output at yet another.

The approach that we encourage with this Recycling Report is to try to focus on the whole system at a few margins where significant progress can be made on many fronts through an integrated drilling effort.

SUMMARY

(See Executive Summary at the front of this Workshop Report)

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APPENDIX I

Invited Recycling Workshop Attendees
(Addresses are in Appendix II)

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