CONTROLS ON TECTONIC ACCRETION VERSUS EROSION IN SUBDUCTION ZONES: IMPLICATIONS FOR THE ORIGIN AND RECYCLING OF THE CONTINENTAL CRUST

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[1] Documenting the mass flux through convergent plate margins is important to the understanding of petrogenesis in arc settings and to the origin of the continental crust, since subduction zones are the only major routes by which material extracted from the mantle can be returned to great depths within the Earth. Despite their significance, there has been a tendency to view subduction zones as areas of net crustal growth. Convergent plate margins are divided into those showing long-term landward retreat of the trench and those dominated by accretion of sediments from the subducting plate. Tectonic erosion is favored in regions where convergence rates exceed 6 ± 0.1 cm yr^{-1} and where the sedimentary cover is <1 km. Accretion preferentially occurs in regions of slow convergence (<7.6 cm yr^{-1}) and/or trench sediment thicknesses >1 km. Large volumes of continental crust are subducted at both erosive and accretionary margins. Average magmatic productivity of arcs must exceed 90 km^3 m.y.$^{-1}$ if the volume of the continental crust is to be maintained. Convergence rate rather than height of the melting column under the arc appears to be the primary control on long-term melt production. Oceanic arcs will not be stable if crustal thicknesses exceed 36 km or trench retreat rates are >6 km m.y.$^{-1}$. Continental arcs undergoing erosion are major sinks of continental crust. This loss requires that oceanic arcs be accreted to the continental margins if the net volume of crust is to be maintained. *INDEX TERMS:* 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 8110 Tectonophysics: Continental tectonics—general (0905); 8125 Tectonophysics: Evolution of the Earth; 3025 Marine Geology and Geophysics: Marine seismics (0935); 1020 Geochemistry: Composition of the crust; *KEYWORDS:* tectonics, subduction, magmatism.

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1. INTRODUCTION

[2] Documenting the origin and fate of the continental crust is a key goal of the earth sciences, central to our comprehension of how the Earth has chemically differentiated over long periods of geological time. Despite this importance our understanding of the crust's history is still vague. Although magmatic productivity at mid-ocean ridges exceeds that in the magmatic arcs that are developed along convergent plate boundaries, understanding how melt is transferred to the crust in convergent plate settings is more important to constraining the origin and evolution of the continental crust. This is because oceanic lithosphere is usually destroyed by subduction, while tectonic and geochemical evidence indicates that active margins are likely the principal source of the continental crust [e.g., *Dewey and Windley*, 1981; *Taylor and McLennan*, 1985; *Rudnick and Fountain*, 1995; *Barth et al.*, 2000]. However, any attempt to mass balance the mass flux in arc systems must also account for the fact that subduction zones represent the only significant pathway by which continental material can be returned to the upper mantle. Because the involvement of subducted sediments in the generation of arc magmas is now widely documented [e.g., *Woodhead and Fraser*, 1985; *Tera et al.*, 1986; *Plank and Langmuir*, 1993], it is important to quantify the degree of this subduction if the proportion of subducted crust recycled through the arcs is to be separated from that returned to the upper mantle. In addition to sediment subduction, evidence is now mounting that tectonic processes may remove significant volumes of continental crust at subduction zones and transport them to great depths in the Earth. Quantifying how much crust is subducted to the roots of volcanic arc systems, and even back into the upper mantle, is important to the general problem of how melt is produced in arc settings, as well as whether large volumes of existing continental crust are ever recycled back into the mantle over long periods of geologic time. If significant volumes of crust are lost at modern

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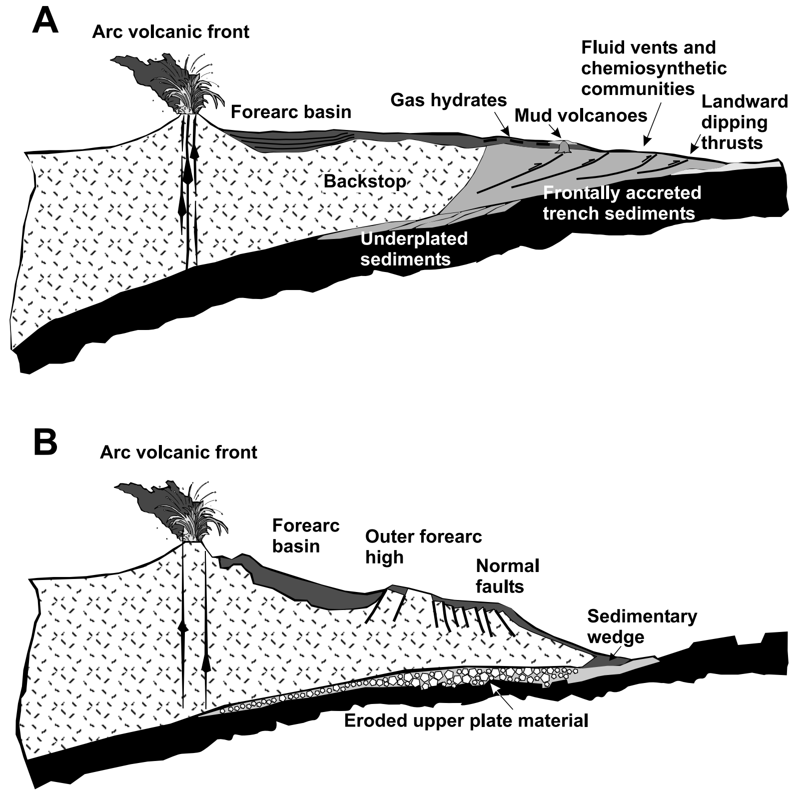

Figure 1. Schematic cartoons showing the features common to the two basic types of active margin: (a) accretionary and (b) erosive. Accretionary margins, such as Cascadia, are characterized by forearc regions composed of thrusted and penetratively deformed trench and oceanic sediments that often develop mud diapirism and volcanism because of sediment overpressuring. Gas hydrate zones are also commonly associated with structures in the wedge; in contrast, erosive plate margins, such as Tonga, are marked by steep trench slopes, composed of volcanic, plutonic, and mantle rocks. Sedimentary rocks are typically limited to the forearc basin, where they may be faulted but are not strongly sheared in the fashion of an accretionary wedge. In the Marianas, serpentinite mud volcanism is recorded.

convergent margins, then new crust must be generated at faster rates if the current volume of the continental crust is to be sustained.

[3] In this contribution we attempt to quantify the mass flux through the major subduction zones of the Earth in order to understand the controls that cause convergent margins to either accrete continental material delivered by the subducting plate or, alternatively, to subduct the trench sediment pile and even erode the basement of the overriding forearc. In practice, this means estimating the composition, rate, and distribution of the sediment and rock input into the major subduction zones and comparing this to the output through the volcanic arc systems in each individual system and on a global basis.

[4] Convergent margins appear to fall into one of two classes, accretionary and erosive (Figure 1). Shortly after the start of the plate tectonic revolution, it was recognized that some active margins were associated with thick sequences of tectonized oceanic and trench sedimentary rocks that were inferred to have been off scraped from the subducting oceanic plate during active convergence [e.g., *Seely et al.*, 1974; *Hamilton*, 1969; *Ernst*, 1970; *Karig and Sharman*, 1975]. Similar sequences were recognized in ancient orogenic belts and inferred, together with ophiolites, to mark the location of former oceanic tracts [e.g., *Dewey and Bird*, 1970; *Mitchell and McKerrow*, 1975]. At the same time it was recognized that at other margins oceanic and trench sediments might be subducted [*Coats*, 1962] along with fragments of crystalline crust tectonically removed from the overriding plate [*Miller*, 1970; *Murauchi*, 1971; *Scholl et al.*, 1977; *Hilde*, 1983]. Nonetheless, a common view of active plate margins continued to depict these as regions of dominant sediment accretion, even in regions where the sediment cover of the oceanic plate was very thin (e.g., Marianas [*Karig*, 1982]).

[5] However, during the late 1980s and 1990s, continued seismic surveying, coupled with drilling by Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) in a variety of forearc settings, began to reveal that sediment accretion was by no means a ubiquitous feature of convergent margins [*Hussong and Uyeda*, 1981; *von Huene et al.*, 1980; *Nasu et al.*, 1980]. Dredging of oceanic volcaniclastic, volcanic, intrusive, and even serpentinized and fresh mantle peridotite rocks from the trenches of the western Pacific [e.g., *Fisher and Engel*, 1969; *Bloomer*, 1983; *Fryer et al.*, 1985; *Bloomer and Fisher*, 1987] demonstrated that no long-term sediment accretion was occurring in these areas (Figure 1). *von Huene and Lallemand*

[1990] showed that such forearcs were not accreting and were even actively losing parts of their crystalline basement. *von Huene and Lallemand* [1990] used forearc subsidence to demonstrate long-term landward retreat of the trench along the Peru and Honshu (Japan) margins, requiring significant tectonic erosion of the underside of the overriding plate. This erosion was presumed to relate to the abrasion of the forearc crust by the basement of the subducting oceanic plate, as suggested by *Hilde* [1983].

[6] In their seminal review, *von Huene and Scholl* [1991] highlighted the importance of nonaccretionary active margins, which they considered to span 19,000 km. These authors also noted that even in accretionary active margins ~70% of the sediment column is likely subducted to great depths below the forearc. This result implied a major degree of continental crustal recycling through arc magmatism in the subduction zones. Although it is largely continentally derived clastic turbidites that are accreted and pelagic sediments that are subducted [e.g., *Moore*, 1989; *Le Pichon et al.*, 1993], it is, nonetheless, true that all the sediments on the oceanic plate are composed of material extracted from the mantle and delivered into the oceans from the continents either by fluvial or eolian transport or in a dissolved form, such as Ca_2CO_3. Thus any sediment not accreted within the forearc represents crustal material subducted to the magmatic roots of the volcanic arc or returned to the mantle.

[7] Although for the purpose of this paper we define margins as being accretionary or erosive, we do so recognizing that in any given system both processes may be occurring, either switching through time or at the same time in different parts of the subduction zone. It is common to find small accretionary complexes in the trench of subduction zones where tectonic erosion is dominating under the forearc (e.g., the Aleutians and Chile [*Scholl et al.*, 1987; *von Huene et al.*, 1999; *Laursen et al.*, 2002]). In these intermediary examples, accretion at the trench axis may result in no net retreat of the trench relative to a fixed point on the overriding plate. Indeed, oceanward growth of the forearc wedge may even occur. Nonetheless, because of tectonic erosion of the underside of the forearc wedge, landward parts of the forearc may be in a state of long-term subsidence due to crustal loss. For the purpose of this paper an erosive margin is defined as one in which a fixed point on the forearc approaches the trench through time, as a result of net crustal loss through tectonic erosion, regardless of whether there is accretion at the trench axis itself.

2. DEFINITION OF AN ACCRETIONARY AND EROSIVE MARGIN

[8] In this study we calculate mass balances for subduction zones over relatively long periods of geological time (>10 m.y.) because of the nature of the geologic record that allows the rates of mass flux to be constrained. We thus define a margin as being accretionary only if it is has experienced net accretion over such periods of time in the recent geologic past, i.e., a margin in which a fixed point on the forearc migrates upward and/or landward over long periods of geological time. Accretion occurs because of the transfer of material from the subducting plate into the overriding plate, either by frontal off scraping at the trench axis or by underplating of the forearc wedge at greater depths. It is important to recognize the long time duration implied by this definition, because even accretionary margins can experience short-term periods of erosion (e.g., Nankai Trough), for example, precipitated by collision of seamounts, which are not typical of the margin's development over periods of 10 m.y. or more. Likewise, erosive margins can experience short-term accretion following collision with seamounts, material that is then removed by the background steady state tectonic erosion [e.g., *Johnson et al.*, 1991]. Tectonized debris aprons, comprising material eroded from and then reincorporated into the overriding plate, such as those recognized offshore Costa Rica [*Shipboard Scientific Party*, 1997], would not constitute an accretionary complex in this study, as this material never formed part of the subducting plate. We also classify as erosive those margins that are characterized by older accretionary complexes but which are now in a state of long-term (>10 m.y.) trench retreat due to the removal of material from the underside of the forearc wedge (e.g., Honshu and Mexico). In this study we use the term accretionary and erosional in reference to the entire forearc region trenchward of the volcanic arc. Thus margins with no clear accretionary wedge at the trench but whose forearcs are experiencing underplating and uplift driven by the net transfer of material from the subducting plate into the overriding plate would be considered accretionary. The key discriminant for this study is whether the net volume of crust in a forearc wedge is growing or decreasing as a result of tectonic activity transferring mass from one plate to another. This difference in net growth or loss is often manifest by a fixed point within the forearc experiencing net landward or trenchward motion over long periods of geologic time. Because this definition emphasizes the evolution of the whole forearc, rather than just the region of the trench, our geometrical analysis of different subduction systems is chosen to examine the forearc over large distances, which should reflect the dominant tectonic process under the forearc. For example, while an erosive margin might develop a small accretionary prism at the trench axis, this will not influence the overall taper of the margin or bathymetric slope over 50–100 km, which is instead controlled by the erosive tectonics under the forearc.

3. TECTONIC EROSION

[9] Since *von Huene and Scholl* [1991] provided a mass balance for the global subduction system, new work on the tectonics of forearc regions has continued to emphasize the importance of subduction erosion in removing material from active plate margins. Subduction erosion is often envisaged as being due to strong coupling between the overriding and subducting plate, although processes other than high friction abrasion, such as high fluid pressure, may drive the subduction erosion process in some regions, such

as northern Chile [*von Huene and Ranero*, 2003]. Material is known to be removed from under the marine and coastal sections of many forearcs, and possibly further inland too, where there is usually no sediment deposited to record the subsidence. This rock may be delivered to the magmatic roots of the volcanic arc and possibly returned back into the upper mantle. *Lallemand* [1995, 1998] argued that strong coupling between the downgoing and overriding plates around the Pacific Rim results in rapid tectonic erosion (4–10 km m.y.$^{-1}$) over long periods of geologic time. While supporting a generally erosive model for Pacific margins, *Clift and MacLeod* [1999] used subsidence and structural data from the Tonga forearc to argue for a slower trench retreat rate than favored by *Lallemand* [1995, 1998] of 1.5 km m.y.$^{-1}$ since the Oligocene, rising to an average long-term rate of 3.8 km m.y.$^{-1}$ after accounting for the indentation caused by collision of the aseismic Louisville Ridge with the Tonga forearc. Slightly higher long-term rates of trench retreat have recently been estimated at 4.7 km m.y.$^{-1}$ for the South Sandwich islands [*Vanneste and Larter*, 2002], another oceanic subduction system.

[10] The rates of tectonic erosion of plate margins in continental arc settings have also undergone revision. *von Huene and Lallemand* [1990] estimated an average trench retreat rate of 2.5–3.5 km m.y.$^{-1}$ since 20 Ma along the Peru margin and 3.0 km m.y.$^{-1}$ for the Japan Trench since 16 Ma. As before, these rates represent the long-term evolution of the margin and not a specific subduction event. Similarly, *Vannucchi et al.* [2001] calculated an average trench retreat rate of 3 km m.y.$^{-1}$ for the Costa Rican forearc since 17 Ma, based on the subsidence history of coastal sediments to great depth within the forearc slope. Further studies demonstrated that much of the subsidence occurred during the last 5.0–6.5 m.y., resulting in the loss of 50–60 km of forearc and giving a recent trench retreat of 8 km m.y.$^{-1}$ [*Vannucchi et al.*, 2003]. *Laursen et al.* [2002] estimated a trench retreat rate of 3 km m.y.$^{-1}$ for central Chile since 10 Ma, which is close to the 3.1 km m.y.$^{-1}$ rate calculated by *Clift et al.* [2003c] for the Lima Basin of the Peruvian forearc since the Eocene (47 Ma). This rate is consistent with the earlier study of Peru by *von Huene and Lallemand* [1990]. However, tectonic erosion in the Lima Basin area appears to have accelerated since 11 Ma when the Nazca Ridge began to collide with the forearc, pushing average rates since that time to 10 km m.y.$^{-1}$. Clearly, ridge collision events have been key in controlling long-term (>10 m.y.) tectonic erosion rates.

[11] Most recently, a reevaluation of the vertical tectonics offshore Guatemala based on DSDP coring data now shows that these regions are also areas of long-term subsidence (Figure 2) [*Vannucchi et al.*, 2004]. The steady subsidence of the forearc basement in each case reflects the migration of the drill site closer to the deep water of the trench through time, driven by the subduction erosion that causes any given part of the forearc to subside because of basal tectonic erosion of the forearc wedge and to approach the trench because of frontal tectonic erosion of the plate margin. In practice, the subsidence history of a drill site represents a fixed point migrating through the eroding trench system. Assuming that trench slopes remained approximately constant during the Neogene, the reconstructed vertical subsidence of these forearcs implies a landward trench retreat rate that averages 0.9 km m.y.$^{-1}$ in Guatemala. This rate is based on the recognition of sediment on the trench slope that was originally deposited in shallower water (i.e., 600–1000 m at DSDP Site 569, middle bathyal zone). Given the age of the sediment (i.e., 23.8 Ma, top Oligocene) and the horizontal distance between the current location and modern day depth equivalent on the forearc slope (~36 km), a long-term rate of trench retreat can be calculated at 0.9 km m.y.$^{-1}$. Offshore southern Mexico, benthic foraminifer assemblages within sediments recovered at DSDP Sites 489 and 493 indicate that they were deposited in 50- to 150-m water depths at 23 Ma (early Miocene [*Shipboard Scientific Party*, 1981]). Although *McMillen and Bachman* [1982] argued for great water depths (>3000 m) on the basis of the lack of carbonate material, the lack of deeper water microfossils mixed with the shallow water fauna, together with a lack of sedimentary evidence for redeposition, argues against a deep water origin. Therefore, because DSDP Sites 489 and 493 now lie in 1268- and 675-m water depth, respectively, the deepening of the water depth implies a loss of ~25 km of forearc since 23 Ma (25 km is the horizontal, trench-perpendicular distance between the 50- and 1200-m isobaths in the region of the drill sites), a long-term rate of trench retreat of ~1 km m.y.$^{-1}$. This figure is somewhat lower than inferred from the ~4 km of water depth increase since 8 Ma reconstructed by *Mercier de Lepinay et al.* [1997], which implies an increase in the rate of trench retreat since that time compared to the 8–23 Ma period. Our calculated long-term trench retreat rates in Mexico and Guatemala are modest compared to those seen in Tonga, South Sandwich, Honshu, Chile, or Peru. Nonetheless, the observation of subsidence and trench retreat is a crucial one because Mexico in particular has for many years been considered a classic accretionary plate margin [e.g., *Karig et al.*, 1978; *Moore et al.*, 1979; *Shipley et al.*, 1980].

4. ALTERNATIVE MECHANISMS FOR FOREARC SUBSIDENCE

[12] Other tectonic processes, apart from basal tectonic erosion of the forearc crust, could explain the subsidence observed in many forearc regions. Extension of a forearc wedge may occur because of gravitational collapse of an unstable steep tapered wedge [*Platt*, 1986]. If the basal friction along the plate interface is reduced, then this will aid gravitational collapse [*Aubouin et al.*, 1984] and could also account for the basement subsidence that is reconstructed by subsidence analysis of drilling data. However, this explanation is hard to propose for large-scale subsidence lasting 20–30 m.y., as there is a limit to how narrow a forearc taper can be sustained. The amount of extension needed to account for the degree of subsidence recorded in those forearcs where data are available would require exten-

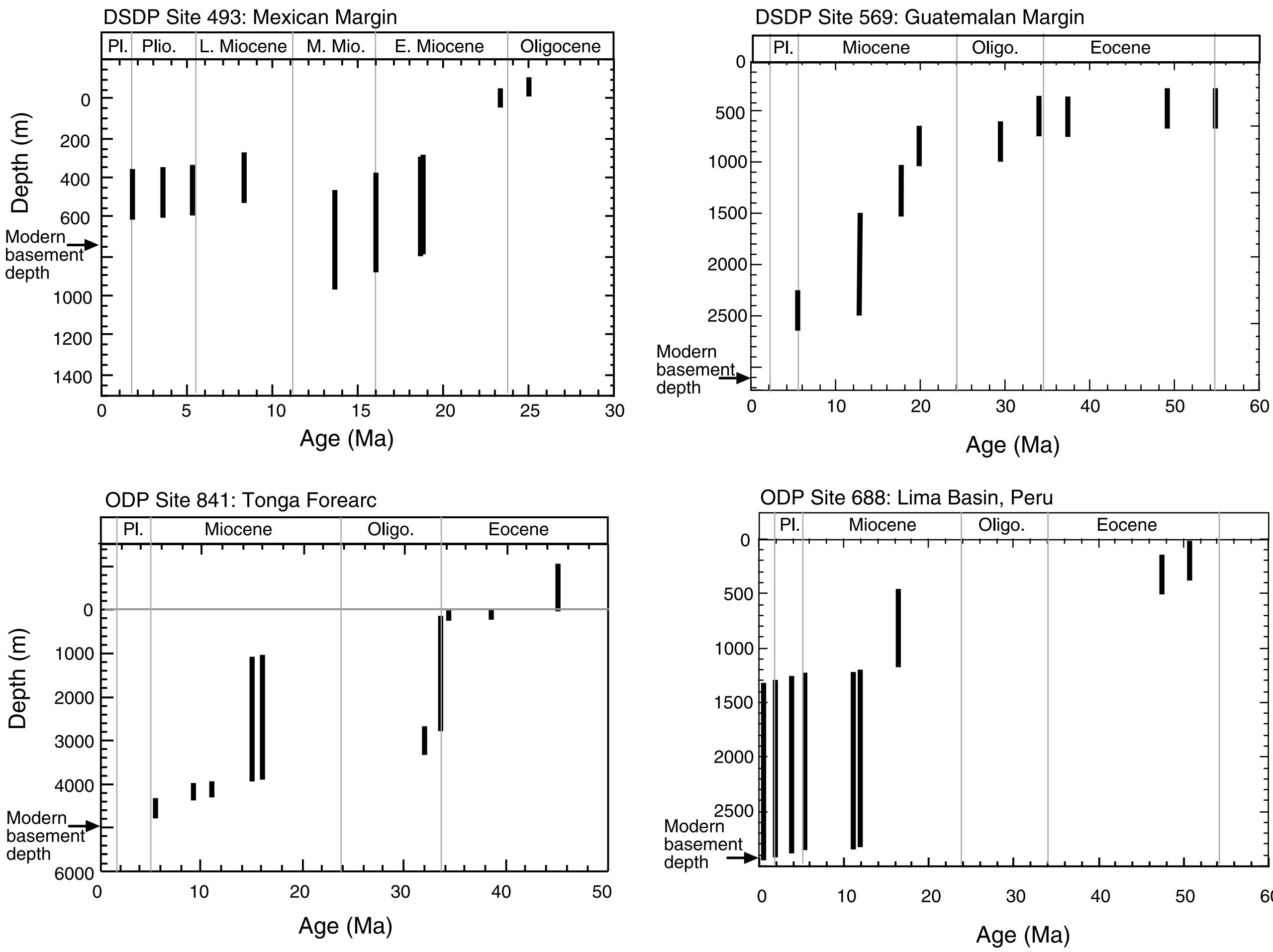

Figure 2. Sediment-unloaded depths to basement at a series of Ocean Drilling Program (ODP) Deep Sea Drilling Project (DSDP) wells in the Guatemalan, Mexican, Tonga, and Peruvian forearcs. Vertical lines show the uncertainty in the water depth estimates derived from benthic foraminifer assemblages [*Vannucchi et al.*, 2004; *Clift and MacLeod*, 1999; *Clift et al.*, 2003c]. The basement depth in each case was calculated after unloading the sedimentary sections using the back-stripping method of *Sclater and Christie* [1980] and accounting for changes in sea level using the reconstruction of *Haq et al.* [1987]. This method effectively isolates the component of the subsidence that is not caused by sediment loading and compaction or by eustatic sea level change and which is thus interpreted as having a tectonic origin.

sion far beyond that recorded by any normal faulting seen in seismic profiles of the margin. For example, seismic profiles across the Costa Rican forearc show only slight normal faulting of the acoustic basement [e.g., *Ranero and von Huene*, 2000], contrasting with the large subsidence measured by *Vannucchi et al.* [2001]. In that case the crustal extension implied by the subsidence can be accounted for by basal erosion of the forearc crust and not horizontal extension. Moreover, any narrowing of the forearc wedge taper by extension would also have to keep pace with and exceed the thickening of the wedge caused by continued accretion in order to produce net subsidence. Because the present bathymetric slope of the Mexican forearc is steep and the wedge taper angle is 13°, compared, for example, to 6° in the classic accretionary margin of Cascadia (Tables 1 and 2), it is difficult to envisage that this wedge and slope were much steeper again in the late Oligocene. The Mexican taper is, however, similar to the 11° measured in the erosive Tonga margin [*Dupont and Herzer*, 1985], although locally the trench slope in Tonga is even steeper, where the margin is in collision with the Louisville Ridge and thus in a state of strong tectonic erosion [e.g., *Lonsdale*, 1986; *Ballance et al.*, 1989]. Another potential mechanism for driving forearc extension and seaward trench migration is slab rollback [*Uyeda and Kanamori*, 1979]. This process would necessarily narrow the taper of the forearc unless subduction accretion kept pace with trench retreat or unless spreading in the back arc as well as in the forearc accommodates the extension. In several western Pacific arc systems, slab rollback and back arc spreading appear to be operating at the same time as active tectonic erosion of the forearc. The fact that basal tectonic erosion, removing material from the front of the plate, is the primary mechanism for driving subsidence is also shown by the migration of volcanic arcs through time. Although variations in slab dip can cause the location of the arc magmatic front to migrate relative to the trench, over long periods of time a landward retreat of the arc is to be expected if tectonic erosion is dominant. In Central

TABLE 1. Compilation of the Geometric, Geologic, and Tectonic Information on the Accretionary Plate Margins Considered in This Study[a]

	Length, km	Convergence Rate, km m.y.$^{-1}$	Orthogonal Convergence Rate, km m.y.$^{-1}$	Age of Margin,[b] Ma	Forearc Slope Angle, deg	Taper Angle, deg	Wedge Width,[c] km	Sediment Thickness, km	Sediment Porosity, %	Crustal Thickness, km
South Chile	2000	20	20	15	2.2	7.6	45	3.2	33	45
Lesser Antilles	850	40	40	50	1.7	6.0	135	4.5	24	38
Oregon-Washington	850	38	34	50	1.8	5.7	100	2.2	37	45
British Columbia	550	42	38	50	1.8	5.7	100	2.5	36	45
Aleutians	1500	75	61	50	2.7	9.2	50	1.5	41	27
Alaska	2050	64	60	24	2.1	7.4	80	2.5	36	45
Taiwan-north Luzon	700	30	30	6	2.3	4.7	60	4.5	30	32
SW Japan-Nankai	900	40	39	140	2.0	9.6	200	2.3	27	40
Sumatra	1800	60	52	50	1.4	5.1	110	2.5	36	45
Java	2100	77	76	50	2.9	7.9	100	1.2	41	45
Burma-Andaman	1800	65	27	25	1.0	3.5	150	5.0	28	40
Makran	1000	38	38	90	1.5	7.5	200	6.0	21	40
Aegean	1200	20	20	35	0.5	3.5	160	8.0	18	35

	Sediment Delivery Rate, km^3 m.y.$^{-1}$	Accretion Rate, km^3 m.y.$^{-1}$	Accretion Efficiency,[d] %	Material Subduction Rate, km^3 m.y.$^{-1}$	Magmatic Production,[e] km^3 m.y.$^{-1}$	Net Crustal Growth Rate,[f] km^3 m.y.$^{-1}$	Age of Oceanic Plate, Ma	Key Sources
South Chile	43	7	16	36	27	34	24–36	*Cande et al.* [1987], *Behrmann and Kopf* [2001]
Lesser Antilles	137	19	14	118	54	73	62–82	*Brown and Westbrook* [1988]
Oregon-Washington	48	10	21	38	47	57	4–8	*Fisher et al.* [1999], *Gerdom et al.* [2000]
British Columbia	61	10	16	51	51	61	0–3	*Fuis* [1998], *Hyndman et al.* [1990]
Aleutians	54	4	7	54	83	87	60–65	*Ryan and Scholl* [1993], *Vallier et al.* [1994]
Alaska	96	17	18	79	81	99	28–60	*Fuis* [1998], *Plafker et al.* [1977]
Taiwan-north Luzon	95	25	26	70	41	65	25–28	*Taylor and Hayes* [1980], *Karig* [1983]
SW Japan-Nankai	65	24	37	41	53	77	20–25	*Moore et al.* [2001]
Sumatra	83	11	13	72	70	81	40–70	*Schlüter et al.* [2002], *Izart et al.* [1994], *Karig et al.* [1979]
Java	54	14	26	40	103	116	70–110	*Kopp et al.* [2001], *Van der Werff* [1995], *Moore et al.* [1982]
Burma-Andaman	99	27	28	71	37	65	68–120	*Moore et al.* [1982]
Makran	179	29	16	150	51	80	180–220	*White and Louden* [1982]
Aegean	131	22	17	109	27	49	180–220	*Chaumillon and Mascle* [1997], *Kopf et al.* [2003]

[a]See Figure 3 for locations.
[b]Margin age is defined as the time at which long-term net accretion started along each margin.
[c]Wedge width is defined as the trench-perpendicular distance between the trench and the backstop, following the definition of *von Huene and Scholl* [1991].
[d]Accretion efficiency represents the volume of rock accreted into the margin since its inception compared to the total volume delivered after accounting for porosity and assuming that the thickness of the trench sediment section has been constant.
[e]Magmatic productivity is calculated by prorating the total global magmatic budget in proportion to the orthogonal convergence rate at each arc.
[f]Net growth rate is calculated by adding the average long-term accretion rate to the magmatic production rate.

TABLE 2. Compilation of the Geometric, Geologic, and Tectonic Information on the Erosive Plate Margins Considered in This Study[a]

	Length, km	Convergence Rate, km m.y.$^{-1}$	Orthogonal Convergence Rate, km m.y.$^{-1}$	Trench Retreat Rate, km m.y.$^{-1}$	Trench Retreat Rate Constrained?[b]	Forearc Slope Angle, deg	Taper Angle, deg	Sediment Thickness, km	Sediment Porosity, deg
North Chile	2000	90	89	3.0	yes	3.7	7.2	0.3	50
Peru	2200	82	77	3.1	yes	3.2	8.0	0.7	46
Ecuador-Colombia	1100	70	63	3.0	no	5.1	10.2	0.6	47
Costa Rica	450	88	80	3.0	yes	3.4	7.6	0.4	48
Nicaragua	275	85	78	2.0	no	5.0	15.0	0.3	48
Guatemala	500	83	74	0.9	yes	5.5	16.4	0.3	48
Mexico	1700	70	68	1.0	yes	6.0	13.4	0.6	47
Kurile	1100	85	85	3.0	no	4.6	10.3	0.5	48
Kamchatka	1100	80	80	3.0	no	2.7	9.2	0.8	44
NE Japan	1000	100	100	3.0	yes	5.9	9.8	0.8	44
Mariana	1600	90	90	1.0	no	3.2	7.1	0.4	48
Izu-Bonin	1300	95	89	2.0	no	6.1	11.0	0.4	48
Ryukyu	1000	70	69	3.0	no	5.2	11.7	0.4	48
South Luzon	400	90	90	1.5	no	4.4	9.0	0.4	48
Philippine	1000	95	40	3.0	no	7.6	17.5	0.6	44
Tonga	1500	110	110	3.8	yes	6.5	11.0	0.4	48
Kermadec	1250	70	68	1.5	no	3.6	6.7	0.4	48
Solomons	2750	110	110	3.8	no	6.6	10.2	0.3	50
South Sandwich	700	77	77	4.7	yes	7.0	17.0	0.4	48

	Crustal Thickness, km	Sediment Delivery Rate, km^3 m.y.$^{-1}$	Sediment of Total Subducted, %	Rate of Material Subduction, km^3 m.y.$^{-1}$	Magmatic Productivity km^3 m.y.$^{-1}$	Net Crustal Growth Rate, km^3 m.y.$^{-1}$	Age of Oceanic Plate, Ma	Key Sources
North Chile	45	13.5	9	149	120	−15	42–46	*von Huene et al.* [1999], *Bohm et al.* [2002]
Peru	45	26.4	16	166	104	−35	10–40	*Hagen and Moberly* [1994], *Flueh* [1995]
Ecuador-Colombia	45	19.7	13	155	86	−49	15–24	*Moberley et al.* [1982], *Gutscher et al.* [1999]
Costa Rica	35	16.9	14	122	108	3	22–24	*Christeson et al.* [1999], *Shipley et al.* [1982]
Nicaragua	32	12.2	16	76	105	41	18–22	*Shipley et al.* [1982]
Guatemala	40	12	17	72	100	66	15–18	*von Huene et al.* [1985]
Mexico	40	19.7	33	60	91	51	0–10	*Mercier de Lépinay et al.* [1997], *Moran et al.* [1996]
Kurile	25	18.4	20	93	115	40	105–115	*Klaeschen et al.* [1994], *Schnuerle et al.* [1995]
Kamchatka	40	28.2	19	148	108	−12	85–105	*Klaeschen et al.* [1994]
NE Japan	40	35.2	23	155	135	15	115–134	*Salisbury et al.* [2002], *Ito et al.* [2000]
Mariana	20	17.3	46	37	121	101	134–180	*Mrozowski et al.* [1982]
Izu-Bonin	20	18.2	31	58	121	81	134–180	*Taylor et al.* [1992]
Ryukyu	30	13.4	13	103	93	3	46–53	*Kodaira et al.* [1996], *Lallemand et al.* [1999]
South Luzon	32	17.3	26	65	121	73	16–25	*Taylor and Hayes* [1980], *Karig* [1983]
Philippine	32	25.1	21	121	54	−42	42–53	*Bloomer and Fisher* [1988], *Schlüter et al.* [2002]
Tonga	20	21.1	22	97	149	73	83–120	*Clift et al.* [1998], *Dupont and Herzer* [1985]
Kermadec	20	13.4	31	43	91	61	83–120	*Ballance et al.* [1999], *Karig* [1970]
Solomons	25	16.5	15	112	149	54	45–54	*Karig and Mammerickx* [1972]
South Sandwich	20	14.8	14	109	104	10	83–120	*Larter et al.* [2001], *Vanneste and Larter* [2002]

[a]See Figure 3 for locations.
[b]Trench retreat rate may be constrained by published studies or inferred by comparison with similar studied margins. Inferred rates are open to revision.

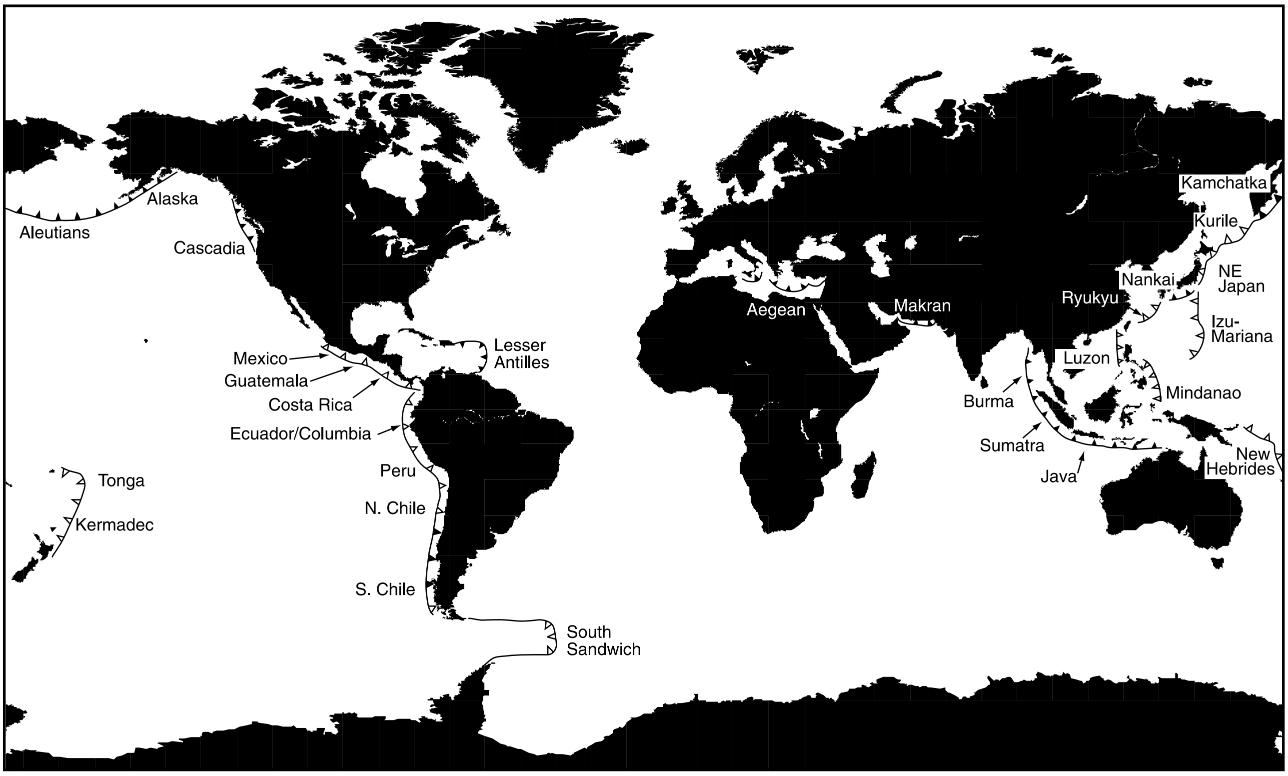

Figure 3. Map showing the distribution of accreting versus eroding subduction zones considered within this study. Accretionary margins are shown with solid barbs on the plate boundary, while open barbs mark erosive margins.

America the common exposure of arc volcanic and plutonic rocks along the coast (e.g., onshore from the DSDP drilling transect in SW Mexico) between the modern arc and the trench is clear evidence for the long-term landward retreat of volcanism in that region. Similarly, the dredging of arc volcanic rocks in western Pacific trenches [e.g., *Bloomer and Fisher*, 1988] supports the hypothesis of major crustal loss due to subduction erosion in those areas. In view of the apparent misidentification of accretionary margins in the past we believe that it is timely to reassess the importance of accretion as a dominant process in active margin setting worldwide.

5. ACCRETIONARY PLATE MARGINS

[13] Despite the apparent dominance of tectonic erosion in areas formerly considered accretionary, there is no doubt that subduction accretion is an important process at many plate margins. Figure 3 shows the general distribution of accretionary plate margins on a global scale. These tend to be in areas of rapid sediment delivery from the continental interior, often from large rivers draining mountainous continental sources. Rapid trench sedimentation is a feature long associated with subduction accretion [*von Huene and Scholl*, 1991]. In this study we have compiled a series of transects across these accretionary margins in order to show their geometry and overall structure, where that data exist (Figure 4). When possible, the transects were chosen to be close to DSDP and ODP well sites in order to provide ground truthing and age control for seismic profiles. The transects in Figure 4 are constructed to show the shape of the accretionary prism in each case, together with the associated continental crust and subducting plate. They do not imply any specific tectonic setting, except net long-term accretion. In Table 1 we show the basic geometric characteristics of each accretionary complex, together with information on the average thickness of sediment on the subducting plate as it reaches the trench axis. Table 1 is meant to be a dynamic compilation, which should be updated as better geological and geophysical data become available. The sediment thickness at the trench axis is the key variable, rather than the thickness of the pelagic section, because it is this total package that is either accreted or subducted when overthrust by the forearc. The average trench bathymetric slope was calculated over a distance of at least 50 km perpendicular to the trench axis along with the total taper of the accretionary complex based on the dip of slab derived from seismic reflection profiles. In all cases this length scale is entirely within the accretionary prism and is set at this scale to eliminate unwanted noise from small-scale structures and to allow comparison with the erosive margins at the same scale. Our scale of analysis is similar to that chosen by *Saffer and Bekins* [2002] and allows comparison of results between different studies. Moreover, because of the long timescale of our analyses, looking at mass fluxes over 10- to 15-m.y. time periods, we also argue that it is appropriate to examine the forearc geometry on a long length scale. The shape of the forearc slope closer to the

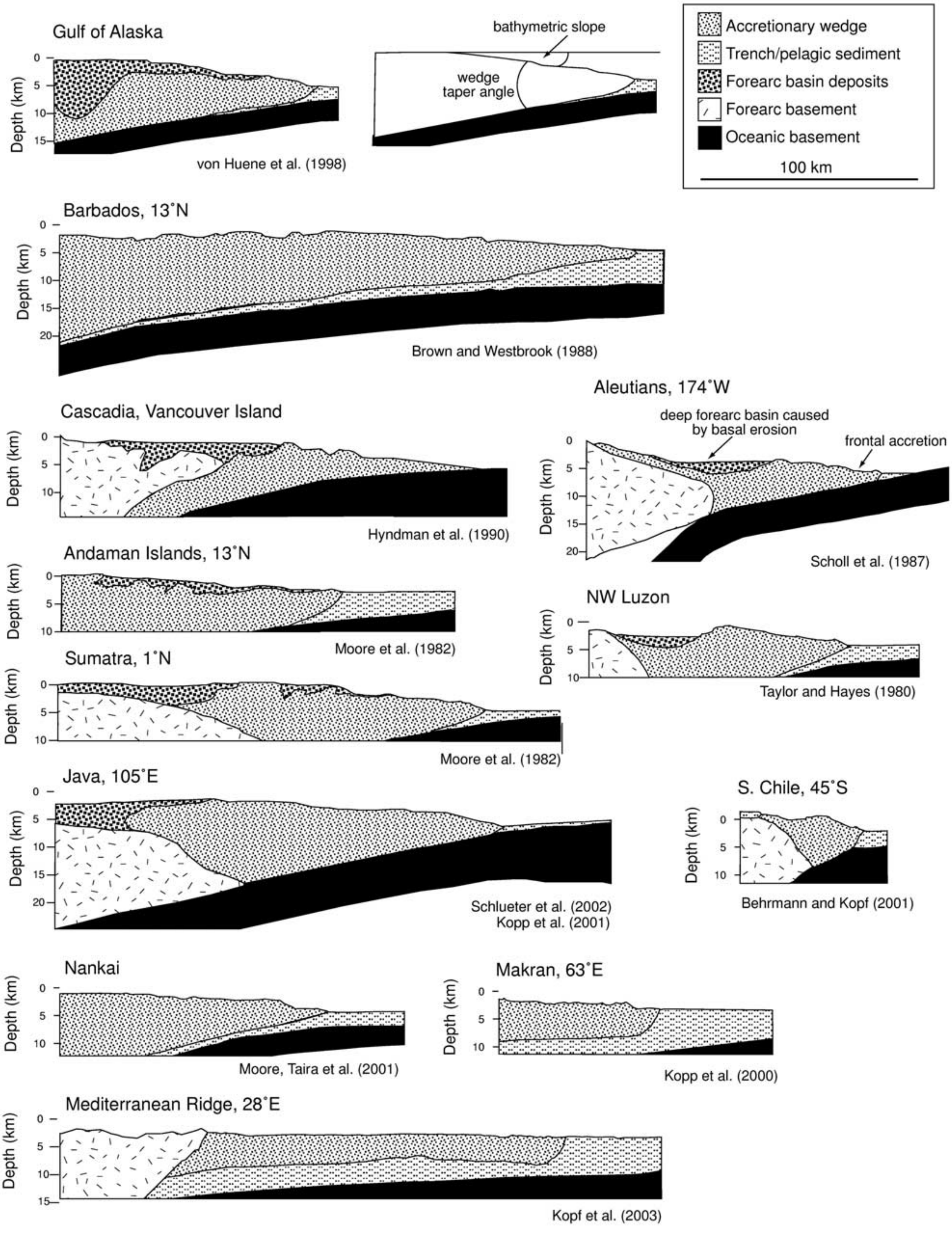

Figure 4. Compilation of profiles across accretionary plate margins considered in this study. Profiles are redrawn and resized to a common scale in order to allow direct comparison of different margins. Sources for the original data are shown next to each profile.

trench may be more susceptible to short-term changes in the trench tectonics, while to alter the trench slope over distances >50 km requires tectonic processes operating continuously over long time periods.

[14] We compare the geometry and accretionary rate of the forearc with the modern convergence rates calculated by *DeMets et al.* [1990] for the point on the margin at which the profile was taken. Specifically, we consider the trench-perpendicular convergence rate, while recognizing that this necessarily changes along strike in arcuate margins, such as the Aleutians, or if the pole of rotation lies close to the active margin. Naturally, when long stretches of active margin are considered, there is significant variability, which cannot be expressed in a single profile. For example, where the sediment source is concentrated at one end of the margin, e.g., in the Lesser Antilles, the Barbados accretionary wedge is much wider (~300 km across) in the south, where it is fed by the Orinoco River, compared to the sediment-starved north (80 km across). In this case we chose the best surveyed profile to represent this margin. By showing the geometrical data with error bars, we attempt to account for some of the along-strike variability, although in margins with strong changes like the Lesser Antilles this is not practical, while on very long poorly surveyed margins, such as Chile or Sumatra, the proposed relationships between margin geometry and geodynamics can only be considered to apply to the regions around the survey itself.

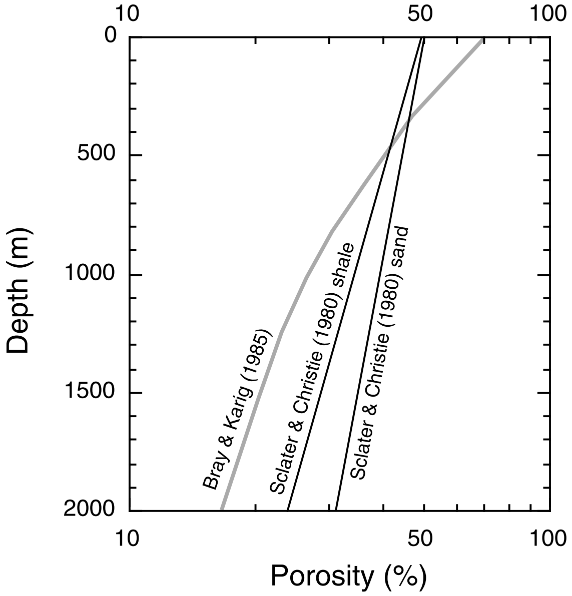

Figure 5. Porosity depth plot for sand and shale from *Sclater and Christie* [1980] compared to the accreted sedimentary values of *Bray and Karig* [1985]. The effect of overthrusting has a major impact on the dewatering characteristics of the sedimentary column. Average values between these two plots were used to calculate the average porosity of the sediment entering the trench for each profile analyzed.

6. SUBDUCTING SEDIMENTARY SECTION

[15] The height of the trench sediment column was recalculated as a volume of equivalent rock after accounting for porosity. In examples where DSDP or ODP drilling provided porosity measurements, then these values were used to correct for porosity. Where no appropriate measurements were available, the porosity-depth model of *Sclater and Christie* [1980] was used, assuming that the trench sediment represented an approximately even mixture between sand and shale (Figure 5). This compaction model has been ground truthed in numerous drilled sedimentary sections from the North Sea and rarely shows deviations >5% unless the section is greatly undercompacted. Figure 5 shows the strong difference between the *Sclater and Christie* [1980] model and the accreted sedimentary model of *Bray and Karig* [1985]; however, in this case we are calculating the volume of rock in the trench before overthrusting. *von Huene and Scholl* [1991] showed the wide variability of porosity-depth relationships in trench sediments, which broadly coincide with the *Sclater and Christie* [1980] model. Because the measurements from trench sediment do not form a well-defined trend that differs significantly from a normal sedimentary sequence, the *Sclater and Christie* [1980] values are used in this study. However, overpressuring, which can cause undercompaction, is associated with the deformation front at accretionary complexes [e.g., *Cochrane et al.*, 1996]. *Screaton et al.* [2002] noted that the pelagic section under the trench sediments may be overpressured immediately before overthrusting as a result of the rapid deposition of trench turbidites. This process is not thought to be a major source of error because the thickness of the pelagic section is generally moderate, usually <500 m, so that while the overpressuring of this section is important to the accretion process, it will not result in large errors in calculating the volume of rock represented in the sedimentary section. Consequently, the conversion of sediment volume to rock volume is not considered to be a highly inaccurate procedure if the lithologies are known.

[16] Uncertainties related to the conversion of seismic sections to depth section are more likely to be a significant source of error. Velocity measurements made on samples recovered by scientific drilling can help define an appropriate velocity-depth model, while in most cases the conversion is made based on the stacking velocities derived during the processing of multichannel seismic reflection profiles. In most of the examples we use the velocity-depth conversion performed by the authors of the specific local study. Errors in the velocity-depth conversion will cause errors in the calculated taper of the accretionary wedge and, in turn, with the volume of accreted sediment. Uncertainties in the seismic velocities are likely no more than 20% (a figure derived from observed lateral variability in seismic velocities within individual stratigraphic units in a number of margins worldwide). Furthermore, because the lithologies involved are known and the compaction histories of sediments do not vary so much, the velocity-depth conversion should not vary by more than this value, affecting large accretionary complexes more than smaller ones. In areas

with little modern drilling or seismic data, appropriate velocities are defined from other, analogous study areas [e.g., *Shipley et al.*, 1998; *Gerdom et al.*, 2000].

[17] Once the overall taper of the accretionary complex has been determined, an estimate can be made of the volume of accreted sediment, given the length of the margin and the width of the accretionary complex. The total accreted rock volume can, in turn, be used to calculate a long-term, average rate of material accretion if the age of the subduction zone, or at least the age of active accretion, is known.

7. EROSIVE PLATE MARGINS

[18] A compilation of erosive margin forearcs was made in a similar fashion to that described in section 3 for the accretionary margins (Table 2). Again the profiles were depth converted when possible and plotted on a common scale (Figure 6). In order to estimate the global flux of material through the subduction zones the rate of trench retreat has to be estimated for margins where independent studies have not yet constrained the rates of erosion. Eight margin segments have been the subject of detailed local studies that provide estimates of trench retreat rate. Rates were assigned to the remaining margins based on similarities in their geotectonic settings and geometries, as well as proximity to well-constrained examples. Because the forearc in these regions tends to be composed of crystalline or volcanic crust the velocity-depth conversion from seismic profiles is less complex than for heterogeneous sedimentary accretionary complexes. The time-depth conversion was typically done by the original studies from which we compiled the data. Where the time-depth conversion was not done by the source reference, we used recent velocity models for erosive margins to constrain reasonable crustal thicknesses [e.g., *Suyehiro et al.*, 1996; *Holbrook et al.*, 1999; *Ranero et al.*, 2000; *Clift et al.*, 2003a].

[19] As noted in section 1, the collision of seamounts or aseismic ridges with active margins is known to have a strong erosive effect on their geometries [e.g., *Ranero and von Huene*, 2000; *Vannucchi et al.*, 2003], and where possible, we chose to examine regions that were representative of the steady state condition of the entire margin rather than only in the vicinity of an aseismic ridge collision. Thus the profile from Tonga forearc is taken at 26°S, just south of the region now being indented and steepened by the Louisville Ridge. The Lima Basin profile is taken from a location where collision of the Nazca Ridge started at 11 Ma, allowing time for equilibrium to be restored after a period of accelerated erosion [*Clift et al.*, 2003a]. This approach allowed minimum estimates for the mass removed to be calculated.

7.1. Crustal Thicknesses

[20] As in the case of the accretionary margins we estimate the rate of long-term loss of crustal material from the plate margin. This was achieved by using the long-term rate of trench retreat and the average crustal thickness close to the arc volcanic front. Because the overall geometry of a margin must be assumed to have remained approximately constant through long periods of geologic time, each kilometer of trench retreat must require removal of material equivalent to a 1-km-wide block of arc crust. The assumption of constant forearc slope is clearly a false simplification, yet in the absence of a transect of well-constrained drill sites that could reconstruct the slope, this must be used as a working model. While tectonic erosion is known to steepen trench slopes [e.g., *Dupont and Herzer*, 1985; *von Huene and Lallemand*, 1990], this steepening cannot continue indefinitely for long periods of geologic time (>10 m.y.) if the trench retreat rate is not very slow. As a result, trench retreat over long periods of time can only be accommodated by loss of the full crustal thickness on which the volcanic arc is built. The crustal thickness under the forearc is often hard to measure with seismic data because serpentinization of the mantle wedge can eliminate or reduce the velocity contrast between crustal and mantle material. Although it can be argued that the subducting plate can only be removing crustal (as opposed to mantle) material from the overriding plate between the trench and the forearc Moho, this distance is only well defined in a few well-surveyed arcs. Moreover, if the forearc retains a fairly constant geometry through time, then for each kilometer of landward advance of the trench a matching kilometer of normal thickness crust, on which the arc is built, must be lost. There is no reason to suspect that thinner crust under forearc regions compared to inland reflects original heterogeneity of the overriding plate; it is, rather, a product of the subduction process. As such, crustal thinning linked to tectonic erosion must extend inland from those regions of the forearc closest to the trench. For example, arc lower crust, which is known to have a low viscosity [e.g., *Kirby and Kronenberg*, 1987; *Hopper and Buck*, 1998], may flow toward the trench, so that the zone of crustal loss would extend farther inland than just under the outer forearc. As a result we opt to use the full crustal thickness on which the arc is built to estimate crustal losses by tectonic erosion. This method is applied whether the arc is continental, built on a basement of continental crust, or oceanic. While it has been argued that oceanic arcs are built of older mid-ocean-ridge-type crust, drilling and dredging evidence, in fact, points to these being located on subducted related, albeit spread, crust dating from the earliest phase of subduction [e.g., *Stern and Bloomer*, 1992]. As such this oceanic arc basement may be considered as part of the arc construct and does not have to be subtracted from the total crust lost when calculating the amount of arc crust lost by tectonic erosion.

[21] Determining the true crustal thickness is not always possible because of a lack of accurate seismic refraction or gravity data. Nonetheless, the crust under the Costa Rican, Nicaraguan, and Guatemalan sections of the Central American Arc has been estimated at 35, 32, and 40 km, respectively [*Carr et al.*, 1990]. Farther south, wide-angle seismic data from central Chile indicate average crustal thicknesses of 45 km in that region [*Beck et al.*, 1996; *Bohm et al.*, 2002]. Northern Honshu, being a mature continental arc, also has significant crustal thickness of 40 km [*Ito et*

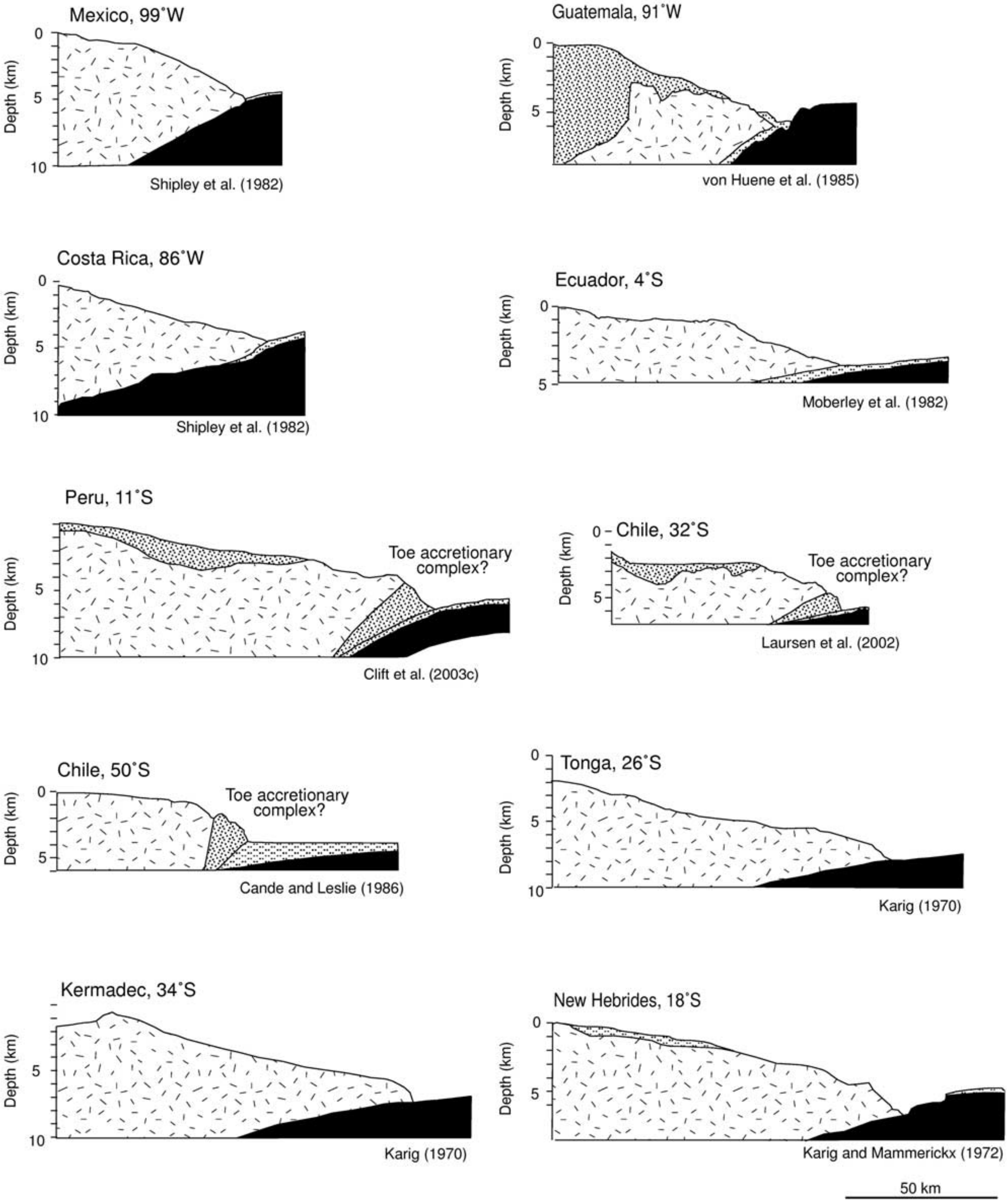

Figure 6. Compilation of profiles across nonaccretionary and erosive plate margins considered in this study. Profiles are redrawn and resized to a common scale in order to allow direct comparison of different margins. Sources for the original data are shown next to each profile.

al., 2000]. In contrast, *Suyehiro et al.* [1996] measured crustal thicknesses of only 20 km under the central Izu Arc, and *Larter et al.* [2001] estimated a crustal thickness of only 16–20 km under the Scotia (South Sandwich) Arc. A range of 25–30 km thickness was recorded by *Holbrook et al.* [1999] in the oceanic Aleutian Arc. Although the latter is an accretionary margin, its magmatic crustal structure may be typical of mature oceanic island arcs, despite the fact that subduction erosion is likely removing crust from under the forearc but landward of the accretionary complex [*Ryan and Scholl*, 1993]. Unlike the western Pacific or Scotia Arcs, the Aleutians have not experienced a recent arc rifting-back arc

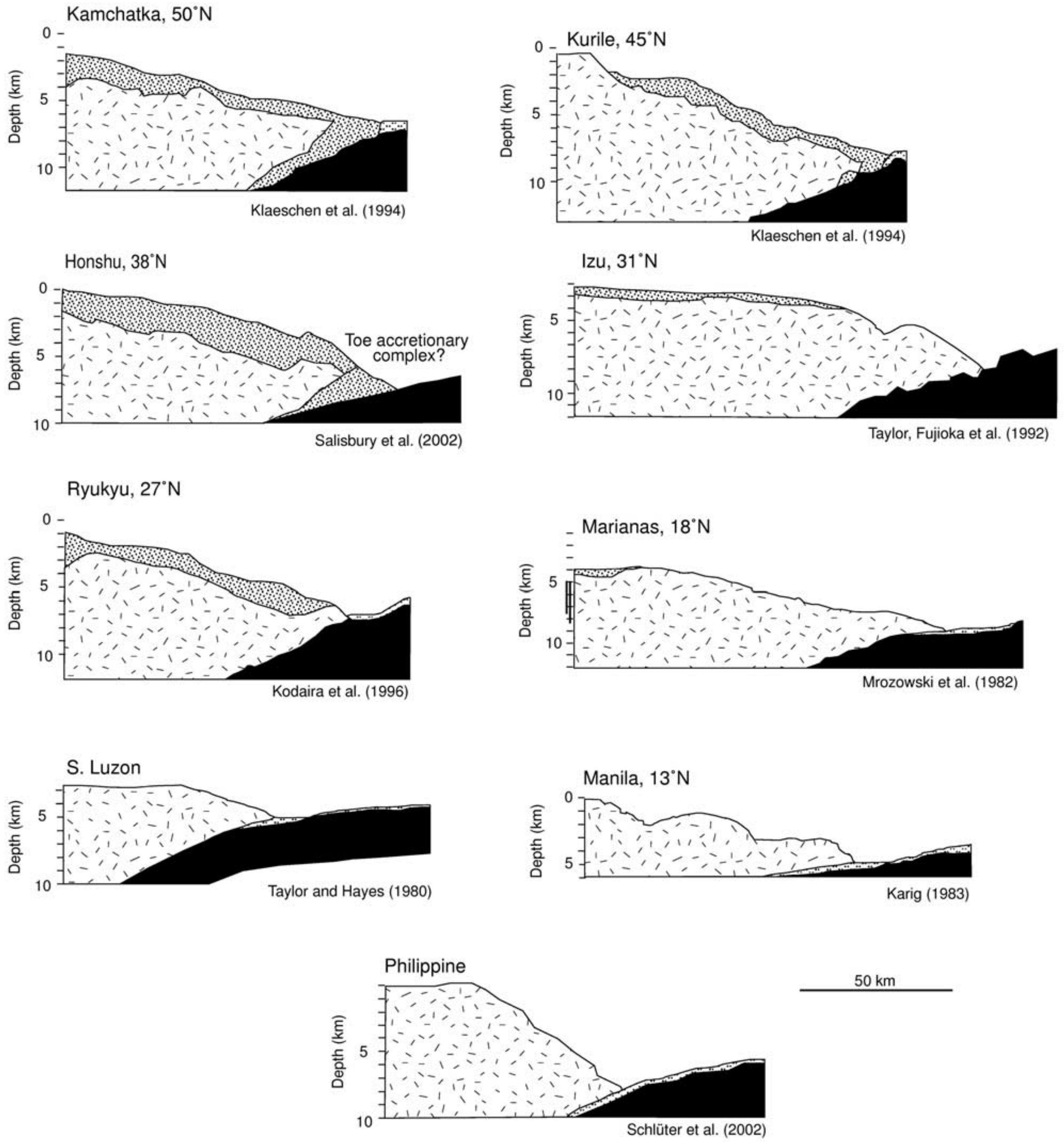

Figure 6. (continued)

basin formation event, which may be the reason that its crust is slightly thicker than either the Scotia or Izu Arcs. For the purpose of this study we define a mature oceanic island arc as one that has experienced several million years of magmatism along an arc volcanic front, following the cessation of the boninitic submarine volcanism in a seafloor-spreading environment that characterizes the evolution of oceanic arcs immediately following subduction initiation [*Crawford*, 1989; *Stern and Bloomer*, 1992].

[22] Using these crustal thickness estimates as representative examples, we assigned crustal thicknesses to arcs with no seismic refraction constraints. The crust underlying the Peruvian and Colombian Arcs is considered to be most similar to Chile in tectonic setting and is thus also assigned a thickness of 45 km. The Kurile and Solomons Arcs have estimated thicknesses of 25 km because, like the Aleutians, they are unrifted oceanic arcs. The Ryukyu Arc is no older than 15 Ma [*Sibuet et al.*, 2002], and its submarine character limits possible crustal thicknesses to ~30 km, since crust of normal density range that is thicker than ~32 km and in local isostatic equilibrium is elevated above sea level. Because the Ryukyu Arc is young, we infer that much of the crustal

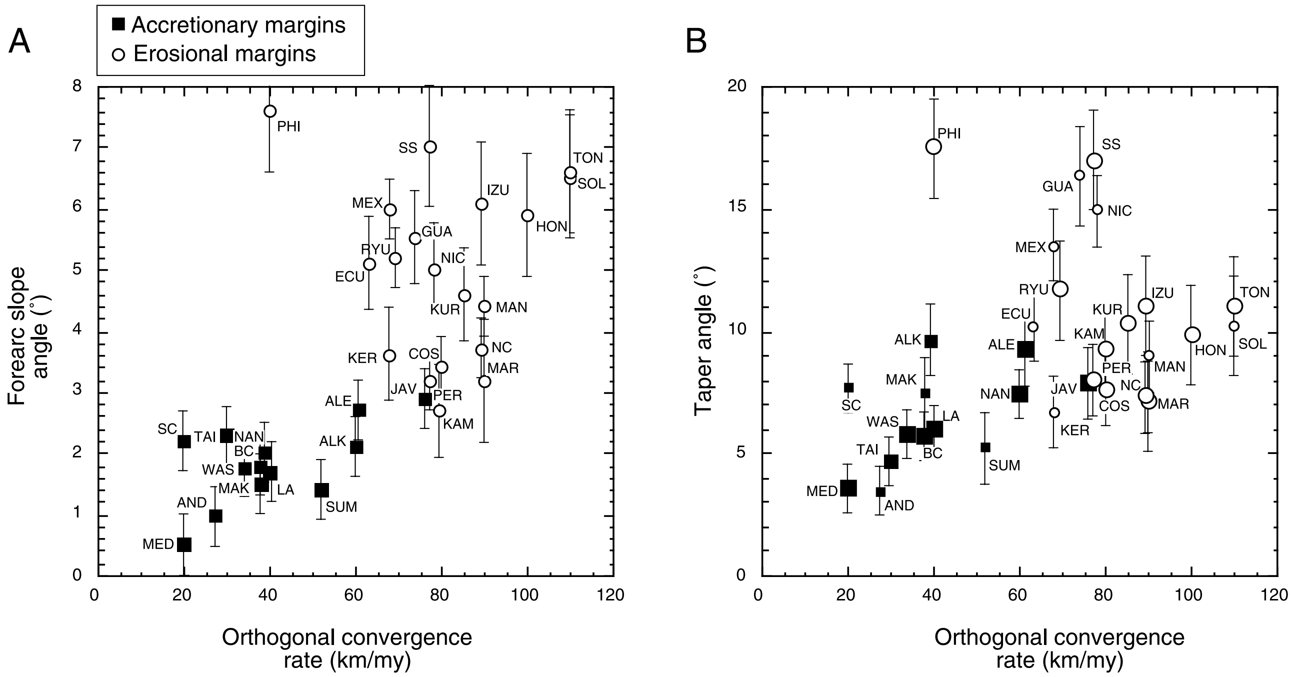

Figure 7. Diagrams showing the relationship between plate convergence rates and the shape of the forearc convergence rate versus (a) topographic slope and (b) forearc taper, both over wavelengths >50 km. Large symbols show margins for which the taper has been quantified by deep penetrating seismic data, while the smaller symbols show margins for which a taper is inferred from slope and shallow seismic data. Abbreviations are as follows: ALE, Aleutians; ALK, Alaska; AND, Andaman; BC, British Columbia; COS, Costa Rica; ECU, Ecuador; GUA, Guatemala; HON, Honshu; JAV, Java; KAM, Kamchatka; KER, Kermadec; KUR, Kurile; LA, Lesser Antilles; MAN, Manila; MAK, Makran; MAR, Marianas; MED, Mediterranean; MEX, Mexico; NAN, Nankai; NC, northern Chile; NIC, Nicaragua; PER, Peru; PHI, Philippines; RYU, Ryukyu; SC, southern Chile; SOL, Solomons; SS, South Sandwich; SUM, Sumatra; TAI, Taiwan; TON, Tonga; and WAS, Washington-Oregon.

thickness under the modern active arc represents rifted fragments of the preexisting East China Shelf. The southern section of the Luzon Arc is also located on continental crust, is slightly elevated above sea level, and is thus assigned a thickness of 32 km. The Tonga and Kermadec Arcs have both experienced recent and/or continuing active extension and consequently are closer to Izu in crustal structure, a fact confirmed by seismic refraction study of the central Tonga Arc, i.e., 20-km-thick crust [*Crawford et al.*, 1996].

7.2. Trench Retreat Rates

[23] Estimating trench retreat rates for the erosive margins is potentially a major source of uncertainty because only a moderate number of margins have been studied in detail, and even in these examples, there are significant uncertainties. Typically, trench retreat rates are estimated by the recognition in the trench slope of rocks that must have formed much farther landward, e.g., in shallow water, so that their modern deep-water location must be caused by tectonic erosion. The long-term rate of trench retreat is then calculated from the age of the rock and the horizontal distance that the location must have advanced toward the trench since its eruption or sedimentation in order to account for the change in paleobathymetry. In the best examples this trenchward advance of a fixed point on the overriding plate can be charted in detail provided the age and paleobathymetric resolution is good (e.g., Figure 2). In several cases, only a long-term average rate can be derived. Nonetheless, because the rate of subduction accretion was averaged over long time periods (>15 m.y.), it is appropriate to use long-term average rates of tectonic erosion if the two are to be directly compared. In practice, this is the only practical approach because of the age of the forearc stratigraphic record that constrains the rate of trench retreat. Trench retreat was estimated at only 0.9 km m.y.$^{-1}$ in Guatemala, based on the modern slope geometry and the rates of subsidence since the Oligocene (25 Ma [*Vannucchi et al.*, 2004]). As discussed in section 2, in Mexico long-term trench retreat rates appear to be even slower at 1 km m.y.$^{-1}$, despite having accelerated since 8 Ma [*Mercier de Lepinay et al.*, 1997]. Farther south, *Vannucchi et al.* [2001] estimated long-term rates of trench retreat at 3 km m.y.$^{-1}$ in Costa Rica. Here we estimate a trench retreat rate of 2 km m.y.$^{-1}$ for Nicaragua, since this is intermediate between Costa Rica and Guatemala in geometry and in convergence rate. Two studies of Peru [*von Huene and Lallemand*, 1990; *Clift et al.*, 2003a] now bracket trench retreat in that area at 1.7–3.5 km m.y.$^{-1}$. We use the average rate since the Eocene of 3.1 km m.y.$^{-1}$ to estimate rates of crustal subduction, a value that lies close to the value of 3.0 km m.y.$^{-1}$ in northern Chile calculated by *Laursen et al.* [2002]. We further assign trench retreat rates of 3.0 km m.y.$^{-1}$ to the Colombia/Ecuador margin by

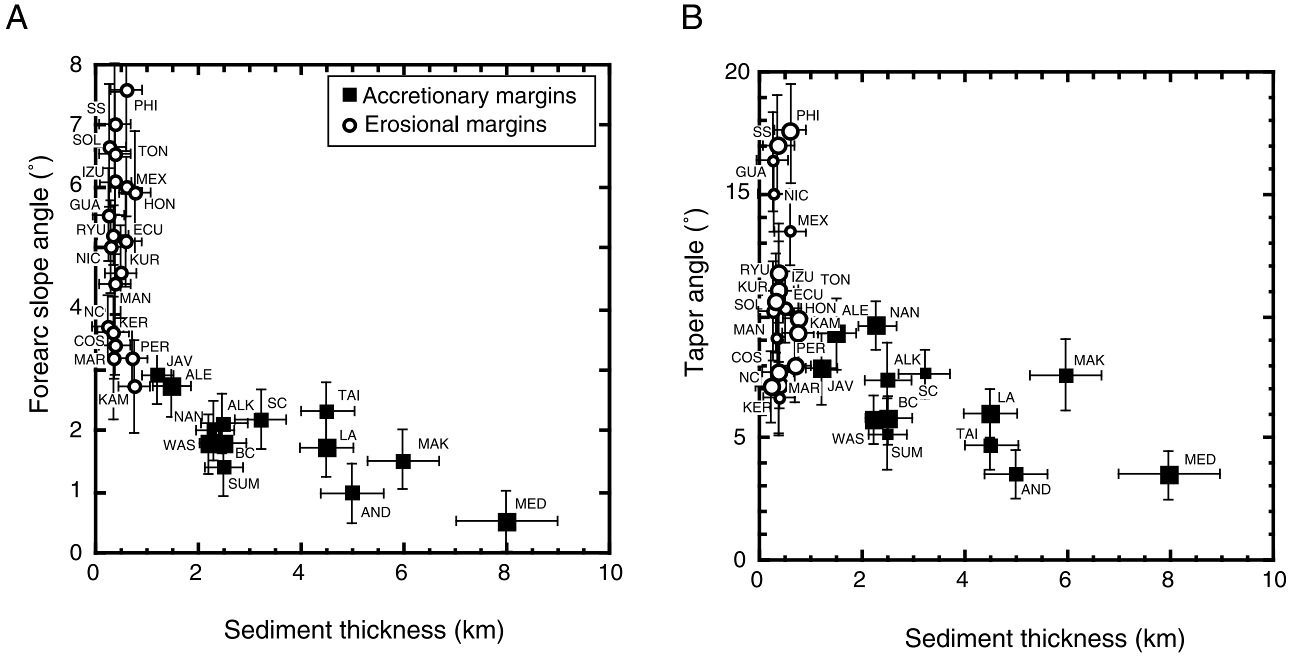

Figure 8. Diagram showing the inverse relationship between the thickness of sediment at the trench on the subducting plate and (a) the long wavelength slope of the forearc and (b) the taper of the forearc wedge.

comparison with Peru, Chile, and Costa Rica. In the western Pacific, *von Huene and Lallemand* [1990] calculated the Honshu Trench to be retreating at 3.0 km m.y.$^{-1}$. We assign the Kurile, Ryukyu, and Manila Trenches a retreat rate of 3.0 km m.y.$^{-1}$ to match that measured in northern Japan, because these arcs have similar tectonic settings and convergence rates to that well-documented margin.

[24] The highest long-term trench retreat rates were recorded in the oceanic arcs, with 3.8 km m.y.$^{-1}$ in Tonga [*Clift and MacLeod*, 1999] and 4.7 km m.y.$^{-1}$ in South Sandwich [*Vanneste and Larter*, 2002]. Similarly, the Solomon Arc is assigned a rate of 3.8 km m.y.$^{-1}$ to match its nearby neighbor, Tonga, given the similar convergence rates in each arc. The Kermadec Arc is assigned a lower value of 3.0 km m.y.$^{-1}$ in recognition that it has yet to collide with the highly erosive Louisville Ridge and because the convergence rate is lower on this part of the margin than it is in Tonga. Tectonic erosion rates in the Izu-Bonin-Mariana Arc are likely lower than that seen in the Tonga region. We infer lower rates for the Marianas because the presence of serpentinite mud volcanoes in the Marianas forearc requires the hydration of the mantle underlying the forearc crust [*Fryer et al.*, 1985]. Rapid tectonic erosion of the underside of the Tonga forearc may be the reason that such features do not form in that area, because the mantle close to the trench is removed too quickly to be altered to serpentinite. Paleowater depth constraints from the Izu-Bonin-Mariana forearc [*Hussong et al.*, 1982; *Fryer et al.*, 1990; *Taylor et al.*, 1992] indicate water depths >2000 m since the Eocene in all drilled locations. At DSDP Sites 458 and 459 in the Mariana forearc the basement is composed of submarine pillow lavas [*Natland*, 1982]. Similarly, the forearc volcanic rocks at ODP Site 786 are pillow lavas and breccias, whose volatile contents indicate submarine eruption, similar to their modern depths [*Newman and van der Laan*, 1992]. Although *Lagabrielle et al.* [1992] argue for shallower, even subaerial water depths in the Eocene, this is based on the occurrence of explosive volcanic products indicating eruption above 500-m water depth (pressure compensation level). These volcaniclastic materials may have been reworked into deeper water and may not indicate the water depth at the site of sedimentation. Furthermore, the recognition that volatile-rich eruptions may occur in much deeper water (>1.8 km [*Gill et al.*, 1990]) suggests that Eocene eruption in the Izu forearc could have been in deep water even if the eruption was explosive. Indeed, the benthic foraminifer assemblages in the sediments at ODP Site 786 are in accord with those from the Marianas in showing deepening from 1.3 to 2.1 km in the Eocene to 3 km in the present day [*Kaiho*, 1992]. This observation is consistent with a slow long-term rate of basal erosion and trench retreat. We assign an arbitrary low trench retreat rate of 1 km m.y.$^{-1}$ for the Mariana section of this margin and 2 km m.y.$^{-1}$ for Izu-Bonin, since that part of the margin has a steeper trench slope and an absence of serpentinite mud volcanoes, suggesting slightly faster rates, perhaps intermediate to the 3 km m.y.$^{-1}$ measured in Honshu just to the north [*von Huene and Lallemand*, 1990].

8. CONTROLS ON FOREARC GEOMETRIES

[25] Using the data compiled from each subduction zone and presented in Table 1, it is now possible to investigate how certain characters of the subduction setting relate to one another. Figures 7a and 7b show plots of convergence rate compared to forearc slope angle and to the overall taper

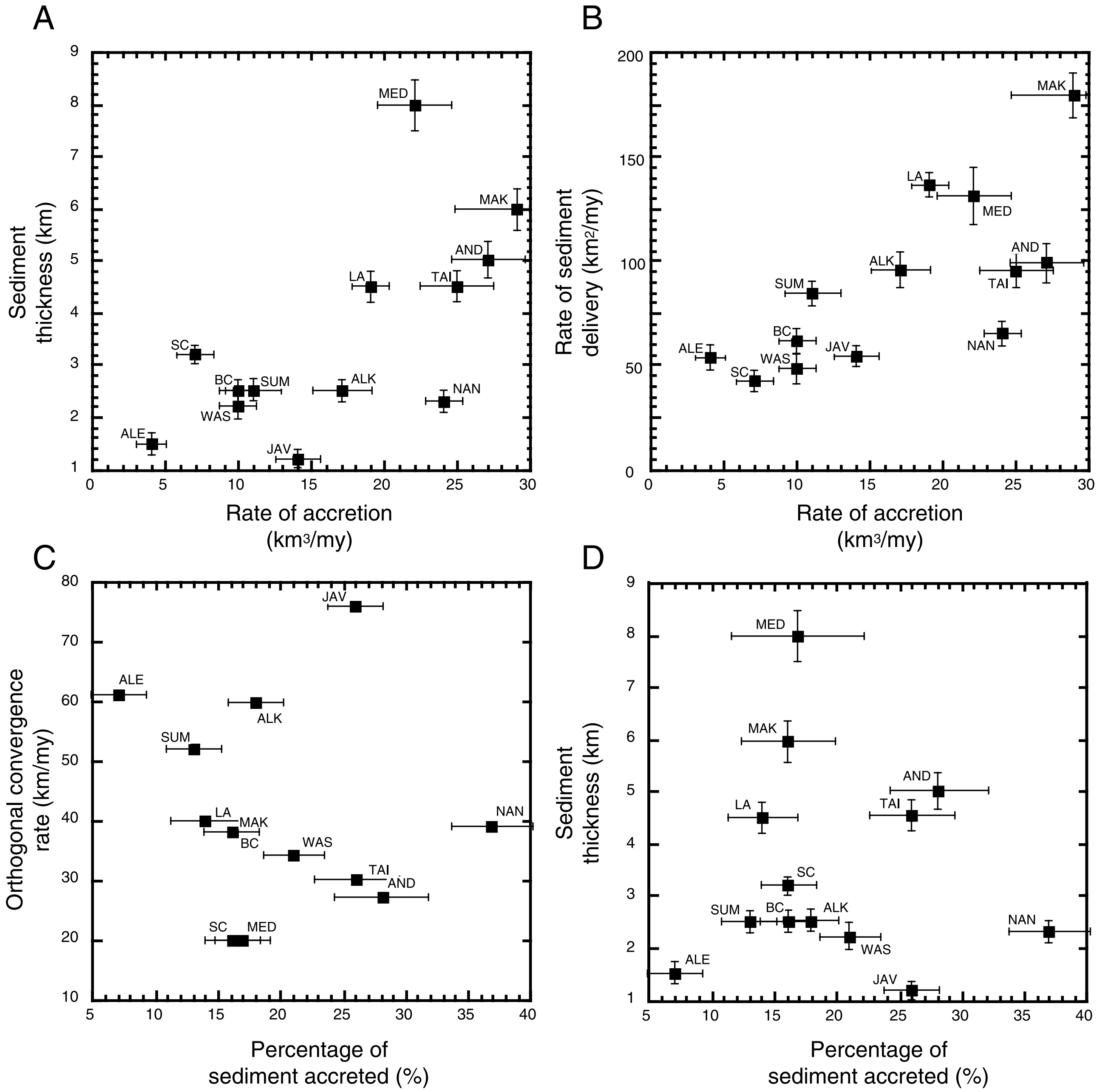

Figure 9. Diagrams exploring the relationship between the rate and efficiency of sediment off scraping in accretionary plate margins. Long-term rate of sediment accretion appears to be related to both (a) the thickness of sediment on the subducting plate and (b) the net rate of sediment delivery to the trench. The proportion of the subducting sediment column accreted shows a little correlation with (c) the orthogonal convergence rate or (d) the thickness of the trench sediment.

of the forearc, respectively. In both cases, there is a positive correlation between slope or taper angle and the convergence rate for accretionary margins, with a less well defined relationship in the erosive margins. It is, however, clear that erosive plate margins do not form forearc wedges with bathymetric slopes less than 3°, slope gradients that are typical in accretionary settings. In addition, erosive plate margins do not appear to form in regions where the orthogonal convergence rate is <6.3 cm yr^{-1}, while accretionary margins do not form in regions where the orthogonal convergence rate exceeds 7.6 cm yr^{-1}. The Philippine Trench is the exception to this rule in being apparently erosive but with a slow orthogonal convergence rate because of the strongly oblique character of the subduction. Relation motion of ~95 mm yr^{-1} along the Philippine Trench is very fast and appears to discourage accretion. The relationship between forearc taper and convergence rate is not quite as well defined as is that with the slope angle, but the same general positive trend is still visible, with some overlap between the accretionary and erosive margins.

[26] The relationship between accretionary wedge geometry and convergence rate suggests a basic first-order control on the forearc imposed by the subducting plate. Wedge models for accretionary margins [e.g., *Davis et al.*,

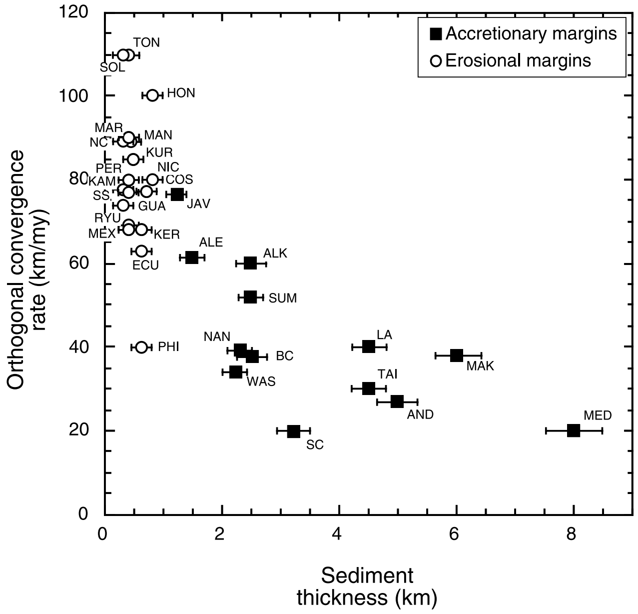

Figure 10. Plot of sediment thickness at the trench related to the velocity of the plate convergence.

1983; *Platt*, 1986; *Gutscher et al.*, 1996] predict that the steepness of an accretionary wedge should be a function of the friction along the base of the wedge, the coefficient of internal friction of the material forming the wedge, and the internal rheology of the wedge. Although the Mediterranean Ridge is unusual in having a very low wedge slope, likely linked to the very low basal friction imposed by Messinian salt on which the major detachments focus [e.g., *Chaumillon and Mascle*, 1997; *Kopf*, 1999], this situation is an exception, and there is an overall tendency of the accretionary margins to correlate in the way that is observed.

[27] *Saffer and Bekins* [2002] proposed that the pore fluid pressure at the base of the wedge controls the taper of the forearc wedge, because this was a dominant control on the basal friction. These authors suggested that muddy impermeable accretionary complexes can maintain lower wedge tapers, especially when convergence rate is high, because the fluids released from the subducting sediments cannot escape to the seafloor. This study was based on four relatively slow convergent margins (including one, Mexico, that we reinterpret as being erosive). This compares with the 13 accretionary margins considered here. Our results show that over the full range of convergence rates the taper of the wedge is positively, not negatively, correlated with the convergence rate. This may imply that, contrary to the findings of *Saffer and Bekins* [2002], it is convergence rate that seems to dominate over lithology and to affect fluid regime as a control of forearc wedge taper.

[28] It is noteworthy that the fastest (and steepest) accretionary convergent margins are often adjacent to mountainous continental interiors that can deliver large volumes of coarse sandy sediment to the trench axis (e.g., Alaskan, Aleutian, Chilean, and Java margins). In comparison, the slower converging (and less steep) Makran, Aegean, and southern Lesser Antilles systems do not have mountainous hinterlands, and thus they have muddier, thicker trench sediments. If this trend of faster convergence with fast eroding mountains producing coarse trench sediments and steep wedge tapers were universal, then the lithological mechanism of wedge taper control proposed by *Saffer and Bekins* [2002] could be consistent with the convergence rate control shown here. However, fast convergence does not always generate high topography, and conversely, some slow accretionary margins lie adjacent to very high topography, e.g., the Andaman Arc and Taiwan; consequently, we favor convergence rate over lithology as being the dominant control to wedge taper.

[29] We do, however, support the hypothesis of *Saffer and Bekins* [2002] that fluid flux can be a key control of forearc geometries in accretionary margin settings. Figure 8 shows that the slope and taper of the forearc wedge in accretionary margins are inversely related to the thickness of sediment on the subducting plate at the trench axis. Because sediment is a much greater reservoir of fluid than igneous basement, at least in the shallower levels of any given subduction zone, margins with thick sediment cover, releasing more fluid into the wedge during the early stages of subduction, might be anticipated to have the shallower slopes and narrower tapers. Clearly, this relationship does not apply to the slope of erosive forearcs.

[30] The volcanic, plutonic, and mantle rocks that make up the forearc basement in erosive settings appear to have more strength than the accretionary wedge sedimentary rocks, allowing them to maintain a steeper trench slope that is not dependent on the dewatering characteristics of the subducting plate. Figure 7a shows that there is a weakly defined relationship between the speed of convergence and the erosive forearc slope (discounting the highly oblique Philippine Trench). The very fastest trench systems in Tonga and the Solomons are also seen to have the steepest slopes. Steep trench slopes may be caused by greater friction along the base of the forearc wedge. None of the erosive margins have significant sediment thicknesses on the subducting plate, so dewatering of these deposits is not considered to be a crucial control for these margins. Instead, the dominant control on basal friction and wedge geometry appears to be convergence rate itself, coupled with the greater strength of erosive forearc crust. This relative strength of the erosive forearc crust may be related to the common igneous, rather than sedimentary, lithologies encountered in these settings. In addition, away from the outer trench slope the igneous crust of an erosive forearc should be faulted in a more discontinuous style and thus retain greater strength between faults than the penetratively deformed sedimentary rocks of an accretionary wedge [e.g., *Cowan*, 1982; *Ogawa*, 1985; *Taira et al.*, 1992; *McCall*, 2002].

9. CONTROLS OF RATES OF ACCRETION

[31] The physical controls on the process of sediment accretion were explored through comparison of the rates of accretion with the nature of the subducting plate and its

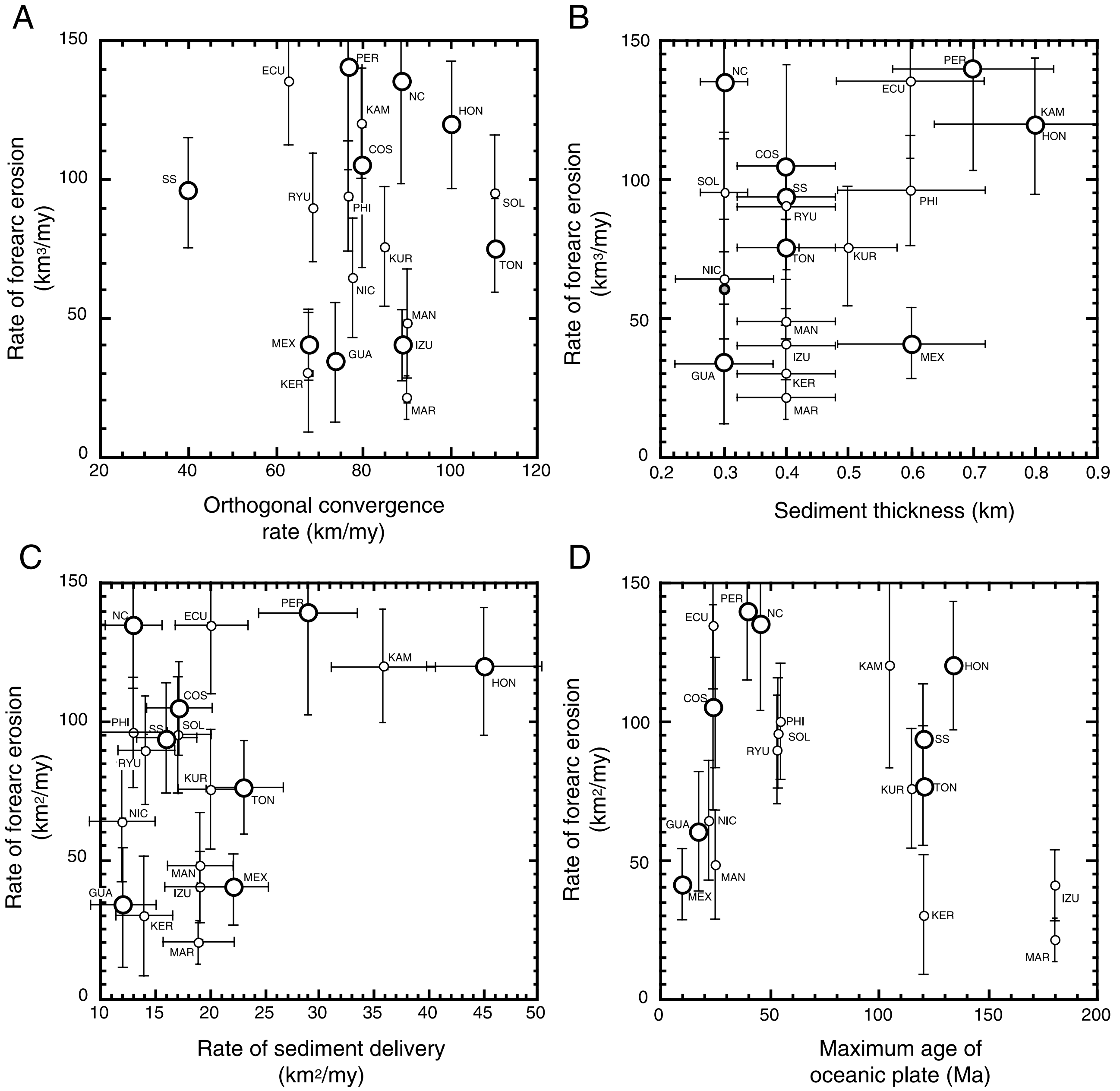

Figure 11. Diagrams showing the interrelationships between the rate of forearc erosion and a variety of tectonic criteria that were significant in controlling the rate of sediment off scraping in accretionary margin settings. In the case of erosive plate margins, no such simple control is recognized. Large circles show margins for which the rate of tectonic erosion has been quantified, while the small circles show margins for which a tectonic erosion rate is inferred by comparison.

sedimentary cover. Figure 9a shows the long-recognized correlation between the thickness of sediment (uncorrected for porosity) on the subducting plate at the trench axis and the rate of accretion in the forearc [e.g., *von Huene and Scholl*, 1991]. When the volume of rock equivalent is calculated for the incoming sedimentary section by removing the sediment porosity from the volume of sediment reaching the trench, there is still a broad correlation between the rate at which sedimentary rock mass is delivered to the trench axis and the long-term rate of accretion (Figure 9b). Because the thickness is strongly linked to the rock volume, this agreement is no surprise. Thicker sections of sediment on more slowly subducting plates are more readily accreted than thinner sections of sediment on faster subducting plates. Indeed, Figure 9c shows that the efficiency with which sediment is stripped from the subducting plate and incorporated into the forearc wedge is roughly inversely related to the rate of convergence, i.e., faster rates of convergence result in lower proportions of the sediment reaching the trench being accreted into the forearc wedge. Java appears to be an exception to the general trend in being more efficient than would be expected for its convergence rate. There appears to be no clear relationship between the thickness of the trench sediment column and the proportion of that column that is eventually incorporated into the forearc wedge (Figure 9d).

[32] The link between the efficiency of sediment accretion and the convergence rate is largely a function of the fact that the thin trench sediment thicknesses correlate with fast rates of convergence (Figure 10). Because rates of clastic sedimentation in the trench are typically much higher than those in the open ocean pelagic setting, the duration which any given vertical section of an oceanic plate spends in the fast deposition zone within the trench axis largely determines the thickness of the sediment pile that is eventually underthrust or accreted, provided there is a flux of sediment from an adjacent continental landmass. At one extreme, great sediment thicknesses are associated with slow convergence where a passive continental margin comes into collision with a trench, resulting in orogeny and the cessation of convergence (e.g., Taiwan and Aegean). The correlation between orthogonal convergence rate and trench sediment thickness makes it difficult to assess which of these two factors may be controlling the geometry of the accretionary forearcs. Are narrow wedge tapers driven by the dewatering of thick sediment sections or by the slow convergence rate? The rough positive link between convergence rate and forearc slope in erosive plate margins suggests that convergence rate may be the dominant control, determining both sediment thickness and basal friction and, in turn, wedge geometry.

[33] Whether the trench sediment is accreted or subducted below the forearc has often been considered to be controlled by lithology. Because of the porosity and strength difference between the fine-grained, muddier pelagic and hemipelagic sediments at the base of the incoming sediment column and the sandier sediments of the trench at the top, it has been suggested that an accretionary prism décollement will preferentially form close to the transition between these sediment types [e.g., *Moore*, 1989; *Le Pichon et al.*, 1993]. Our correlation between accretion efficiency and the convergence rate makes sense in this context, because the convergence rate will largely determine the thickness of the trench clastic section deposited, which, in turn, is sandier and may be accreted to the forearc. Clearly, sediment supply is also important in allowing a thick trench sequence to be deposited [*Helwig and Hall*, 1974], yet the correlation in Figure 10 seems to suggest that either orthogonal convergence rate is dominant or is itself linked to sediment supply. At one extreme the fast, oceanic convergent margins of the western Pacific (e.g., Tonga, Marianas, Mindanao, and Ryukyu) have little or no trench sediment because of the short time available to deposit the trench section and because they have no continental interior from which to derive clastic sediment. These margins show little or no efficiency in off scraping the sedimentary cover to the subducting plate. At the other extreme, more slowly convergent or collisional margins with mountainous continental drainage basins have large trench sediment thicknesses, which are relatively efficiently harvested by the accretionary wedge (e.g., Cascadia, Makran, and Taiwan).

[34] As noted above, accretion appears to be an effective process when convergent rates are <76 mm yr^{-1} and where the sedimentary cover is >1 km thick. Since the rate of convergence itself is controlled by the density and thus thermal age of the subducting slab, the tendency to accrete or erode is partially controlled by the age of subducting oceanic lithosphere. However, the rate of convergence is controlled by the gravitational pull of the entire subducting slab not just a short stretch adjacent to a given margin. Convergence rates may also be disrupted by continental collision events. Consequently, we conclude that there is no simple relationship between the age of the plate, the rate of convergence, and the efficiency of the accretion process.

10. CONTROLS OF RATES OF EROSION

[35] Determining what is controlling the long-term rates of crustal loss in erosional plate settings is not possible from this current study, although it is apparent what are not key controls. Figure 11 shows that the long-term rate of crustal loss from the forearc is not closely correlated to convergence rates, sediment thickness on the subducting plate, the rate of sediment delivery to the trench, or the maximum age of the subducting plate. Apart from noting that slow converging margins with thick sedimentary sections on the subducting plate always develop accretionary complexes and are sites of net forearc growth over long timescales, no clear pattern emerges. We suggest that the reason for this is that the rate of plate erosion is controlled largely by the roughness of the subducting plate. In particular, the collision of large aseismic ridges with convergent margins appears to dominate the erosive history in the best documented examples (e.g., Tonga, southern Chile, Mindanao, Peru, and Costa Rica [*Dupont and Herzer*, 1985; *Cande and Leslie*, 1986; *Ballance et al.*, 1989; *von Huene et al.*, 1996; *Pubellier et al.*, 1999; *Behrmann and Kopf*, 2001; *Laursen et al.*, 2002; *Clift et al.*, 2003a; *Vannucchi et al.*, 2003]). Although the collision events themselves can be very short-lived events at a single point on the margin, the erosional impact of such events is profound on the net long-term subsidence and erosion history of that margin. *Ballance et al.* [1989] in particular showed that ridge collision caused the Tonga forearc to be significantly shortened and tilted toward the trench relative to uncollided forearc within the Kermadec region. This was interpreted to reflect the influence of the Louisville Ridge in removing material from under the forearc, especially close to the trench.

[36] The erosive effect of subducting normal oceanic crust over long periods of geologic time appears to be quite moderate. It is noteworthy that even in margins where the subducting oceanic plate has thin sediment cover at the trench axis and experiences large normal faulting due to

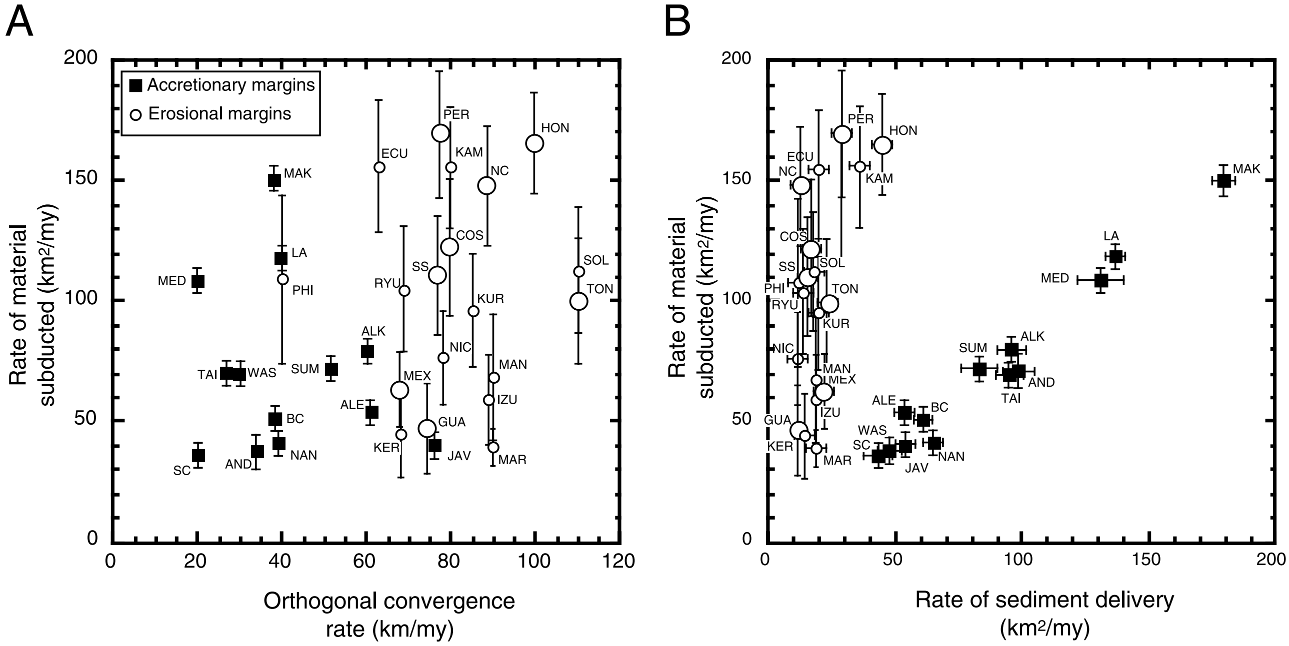

Figure 12. Diagrams showing the relationship between the rate of material subducted below the forearc in both accretionary and erosive plate margins versus (a) the convergence rate and (b) the rate of sediment delivery at the trench from the subducting plate. Large circles show erosive plate margins for which a trench retreat is well defined, compared to the small circles representing margins for which tectonic erosion rates are inferred.

flexure (indicating that the roughness of the basement might be high), the long-term trench retreat rate is modest, e.g., ~1.5 km m.y.$^{-1}$ since 35 Ma in Tonga [*Clift and MacLeod*, 1999] and 1 km m.y.$^{-1}$ in northern Chile [*von Huene et al.*, 1999]. In contrast, the Tonga margin loses ~50 km from its forearc during its short-lived (~1 m.y.) collision with the Louisville Ridge, more than doubling the long-term erosion rate. Trench retreat rates increase eightfold in Peru after the ~4-m.y.-long collision of the Nazca Ridge with that margin at 11 Ma [*Clift et al.*, 2003a]. In Chile, collision of the Juan Fernandez Ridge has increased retreat rates to 3 km m.y.$^{-1}$ since 10 Ma [*Laursen et al.*, 2002], though in this case the orthogonal collision has resulted in the ridge eroding only a short stretch of margin, though over a relatively long period of time. Similarly, we suggest that the trench retreat rate in Costa Rica is much faster (3 km m.y.$^{-1}$) than the rate deduced from the subsidence history in Guatemala and Mexico (~1.0 km m.y.$^{-1}$) because the orthogonal, long-lived subduction of Cocos Ridge is boosting the tectonic erosion in Costa Rica, especially under the Osa Peninsula but also along its flanks to the north and south.

[37] We wish to emphasize that while ridge collision boosts erosion rates, this process is ongoing in noncollisional subduction settings, such as Mexico and Guatemala, where forearc subsidence and thus crustal loss are documented. The Marianas represents a sediment-starved margin in which oceanic crust even older than that in Tonga is being subducted and which might also have a rough, potentially erosive basement. This part of the Pacific Plate is also ornamented with numerous atolls and guyots, yet in this area the trench retreat rate is inferred to be somewhat less than that seen in Tonga, at least in the recent geological past (see discussion section 7.2). The general similarities between the Mariana, Izu, and Tonga Arcs in terms of their ages and dimensions suggest that they likely experienced similar constructional histories and that the present less erosive nature of the Mariana forearc is not typical of the long-term history since the Eocene start of subduction. These observations argue against the ability of even rough, normal oceanic basement to erode forearc crust at a fast rate (i.e., $\geq$3 km m.y.$^{-1}$) during steady state subduction. We conclude that it is the collision of major oceanic ridges that is the most effective mechanism for loss of crust from margins that are otherwise in states of equilibrium or moderate trench retreat. We also recognize the importance of slow, continuous tectonic erosion as an efficient mechanism for removing forearc basement.

11. RATES OF MATERIAL SUBDUCTION TO THE MANTLE

[38] Using the mass budgets constructed for each of the margins, it is now possible to estimate the rate of mass flux through each margin and specifically to estimate how much crustal material is lost to the mantle or volcanic roots of magmatic arc and how much is added to the forearc wedge. In the case of erosive margins the entire sediment package on the underthrusting plate is subducted to depth below the forearc along with any crust removed from the plate margin. In the case of accretionary margins the net rate of deep sediment subduction is represented by the difference be-

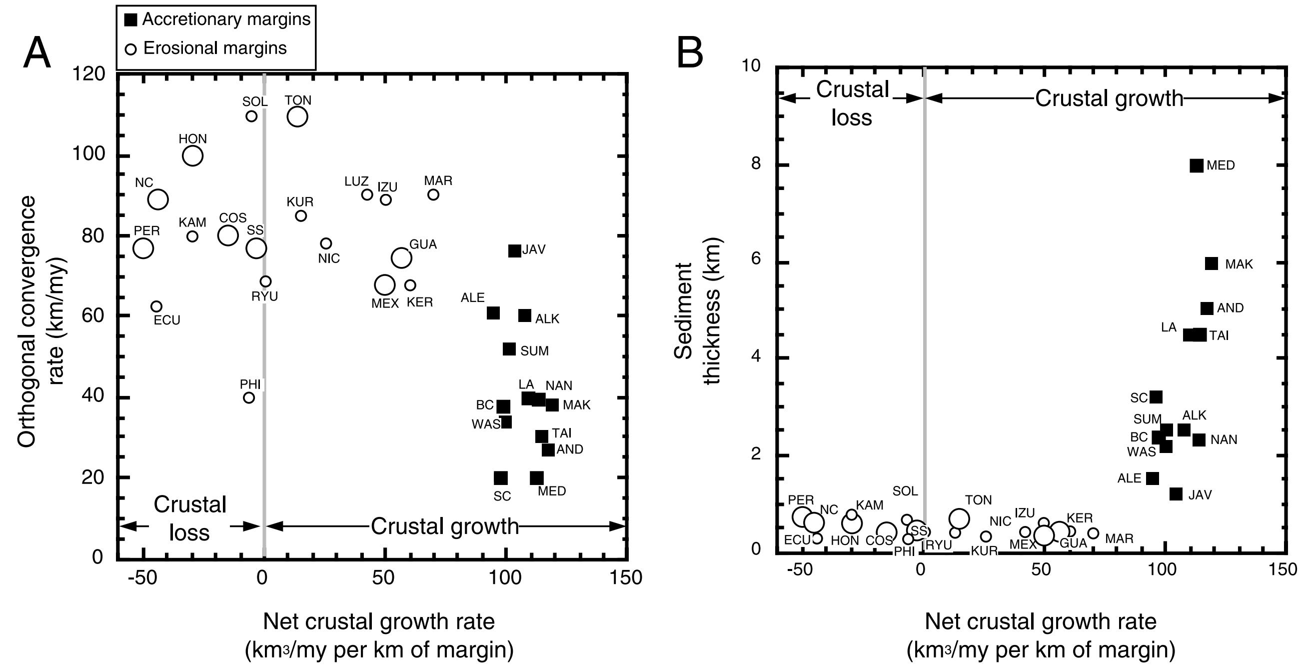

Figure 13. Diagrams showing the relationship of (a) orthogonal convergence rates and (b) trench sediment thicknesses to the net crustal growth or loss along the global active margins, using the uniform magmatic accretion rate of 90 km^3 $m.y.^{-1}$ km^{-1} of margin, required to conserve modern crustal volumes.

tween the rate of sediment delivery and the rate of growth of the accretionary prism. As before, these budgets necessarily average rates over tens of millions of years. Figure 12a shows that there is no correlation between the orthogonal plate convergence rate and the rate of rock subducted below the forearc wedge for all margins. It is noteworthy that the rate of material subduction is not systematically higher in the erosive margins than it is in the accretionary margins. This reflects the inefficiency of the accretionary process and the tectonic erosion that accompanies accretion in some settings (e.g., Aleutians [*Scholl et al.*, 1987]). However, clearer separation between the two styles of margin is apparent in Figure 12b where the rate of material subducted below the forearc is plotted against the rate of sediment delivered to the trench. The separation reflects the fact that in the accretionary margins the rate of material subduction is the same as the rate of sediment subduction, which is linked to the total amount of material delivered to the trench. In contrast, in the erosive margins it is the rate of trench retreat, i.e., erosion of the forearc basement, that dominates the mass subduction budget. We calculate that in the erosive margins only 12–48% (median 22%) of the total material subducted below the forearc is derived from the sediments in the subducting plate, compared to 100% in the accretionary margins.

[39] An important result of our calculation is that subduction accretion is a relatively inefficient process for cleaning sediment off the oceanic basement on which it was deposited. Only 7–37% of the sediment reaching the trenches appears to be added to the accretionary complexes, with the bulk subducted to depth. While the efficiency of the accretionary process does not appear to be linked to the rate of plate convergence and the thickness of the trench sediments, it may be more strongly linked to lithology, being favored in regions of sandy trench sediment. Globally, the median proportion of the rock delivered as sediment to the trench that is accreted from the subducting plate is only 17%, with the remainder being subducted at least ~50 km below the forearc wedge.

12. FATE OF SUBDUCTED CRUSTAL MATERIAL

[40] Whether the subducted sediment and arc basement is returned to the upper mantle or merely reworked through the magmatic roots of the adjacent arc is a key question that has important implications for the fate and origin of the continental crust. Geochemical evidence tells us that sediment involvement in arc petrogenesis is nearly ubiquitous, but whether all the sediment is recycled or subducted is a more difficult question. The answer to this question hinges on the magmatic productivity rates in the arcs. In a global compilation of arc crustal volume, *Reymer and Schubert* [1984] estimated that 20–40 km^3 of new melt were added every one million years per kilometer of active margin, compared to a global average rate of crustal loss of 90 km^3 $m.y.^{-1}$ km^{-1} calculated in this study. At this rate a volume of crust equivalent to the entire modern total volume ($\sim 8.0 \times 10^9$ km^3) could be fluxed through the planet's active margins in a little more than 2.2 b.y. Even assuming the highest rate of crust growth estimated by *Reymer and Schubert* [1984], this would predict a steady decline in the volume of the continental crust. However, *Schubert and*

Reymer [1985] argued that because of the generally constant degree of continental freeboard above mean sea level during the Phanerozoic (<630 Ma), the continental crust must, in fact, be growing slowly during that time period, a model supported by Nd isotopic evidence for continental evolution [*Jacobsen*, 1988]. *Schubert and Reymer* [1985] inferred that because of decreasing total global heat flow from the mantle the ocean basins will tend to deepen with time, lowering sea level unless the continental crust grows at a rate sufficient to keep pace with the larger volumes of the ocean basins, i.e., 0.9 km^3 yr^{-1}. In order to achieve this rate of growth in the context of the revised subduction erosion rates we calculate that the average magmatic productivity of the global volcanic arcs must be $\sim$91 km^3 m.y.$^{-1}$ km^{-1} of margin. A productivity of 90 km^3 m.y.$^{-1}$ km^{-1} is required just to maintain the current crustal volume.

[41] These average rates of magmatic productivity may be compared to recent estimates for productivity based on seismic refraction work. *Holbrook et al.* [1999] estimated long-term magmatic growth rates of 55–82 km^3 m.y.$^{-1}$ km^{-1} of margin for the Aleutians, while *Suyehiro et al.* [1996] indicated long-term average accretion rates of 66 km^3 m.y.$^{-1}$ km^{-1} of margin in the Izu Arc. Both these estimates do not account for the gradual loss of crust by subduction erosion, meaning that the true estimates of magmatic output for these arcs would be higher. Average magmatic productivity would be $\sim$106 km^3 m.y.$^{-1}$ km^{-1} of Izu-Bonin margin if our trench retreat estimate of 2 km m.y.$^{-1}$ is correct. Although we consider the Aleutians to be accretionary in this study on the basis of an accretionary prism on the trench slope, the development of a prominent perched forearc basin [*Scholl et al.*, 1987] indicates subsidence and possible tectonic erosion closer to the arc, suggesting that the rate of *Holbrook et al.* [1999] must also be considered a minimum. These estimates are consistent with our proposed rates. In contrast, for the Peruvian margin, *Atherton and Petford* [1996] estimated only 8.0 km^3 m.y.$^{-1}$ km^{-1} of margin, a figure that if true must be substantially below global averages. In practice, however, determining rates of magmatic accretion in the mid and lower crust of continental arcs is very difficult, even with good seismic refraction data.

[42] The magmatic productivity rate inferred from the slow growth model (i.e., 91 km^3 m.y.$^{-1}$ km^{-1} of margin) is by definition insufficient to account for the present volume of the continental crust if extrapolated over the entire history of the Earth, as it was determined to maintain not to build the present crust. Magmatic productivity rates would have to reach an average of >135 km^3 m.y.$^{-1}$ km^{-1} of margin in order to account for the present crustal volume within the known age of the Earth, assuming modern subduction erosion rates. Because these values appear to be somewhat higher than justified by existing seismic refraction work, we conclude that the crust must have experienced an earlier phase of more rapid growth. This result is consistent with isotopic evidence for fast crustal accretion during the Achaean and Early Proterozoic, with growth slowing into the Phanerozoic and more recycling of existing continental material [*Armstrong*, 1971, 1981; *Allègre and Rousseau*, 1984; *Taylor and McLennan*, 1985; *Goldstein et al.*, 1997; *Elliott et al.*, 1999].

13. ARC MAGMATIC PRODUCTIVITY

[43] Figure 13 graphically demonstrates the difference between the two types of active margin. As might be expected, the accretionary margins all show net growth of the crust in these locations, while many, but not all of the erosive margins, show net loss of material if the average rate of magmatic production assuming no modern continental growth (90 km^3 m.y.$^{-1}$ km^{-1} of margin) is assumed for all arcs. We note that while sediment accretion does allow a single margin to grow, this material is not new continental crust but is merely reworked crust, redistributed to a new location. Our mass budgets predict that the Guatemalan, Mexican, Nicaraguan, Kermadec, Kurile, southern Luzon, Tonga, and Izu-Bonin-Mariana Arcs would be sites of active crustal growth, with other erosive margins in a state of net crustal decline. If this is true, then this begs the question as to when the bulk of the present Costa Rican, South Sandwich, or Solomon Arc volumes were generated if not in the present arc setting. In the case of Tonga and Izu-Bonin-Mariana Arcs, there appears to have been an earlier voluminous phase of magmatism shortly after the start of subduction [e.g., *Bloomer et al.*, 1995]. If this is a common feature to arcs, then this process could conceivably generate a large arc massif that may decline because of the long-term tectonic erosion. There is, however, no geologic evidence that oceanic arc crust grows and shrinks in this fashion. Moreover, the presence of abandoned remnant arc ridges formed after rifting in the Scotia, Tonga, and Izu-Bonin-Mariana back arcs shows that net construction of arc crust continued after the initial subduction volcanism. The geology of these arc systems suggests that they had similar constructional histories since subduction initiation, which is at odds with the predictions shown in Figure 13.

[44] We infer that arc magmatic productivity must vary significantly between arcs, with greater melt production in the oceanic arc systems and less under the continental arcs. This conclusion is consistent with arc petrogenetic models such as that of *Plank and Langmuir* [1988] in which the thicker crustal lid over the decompressing and melting mantle wedge in continental arcs inhibits upwelling and results in less melt production than in the oceanic arcs, whose thinner lids permit higher melt fractions.

[45] Here we approximate the degree of melting in each arc in order to generate more realistic mass balances for each margin. Figure 14 shows the results of the melt redistribution assuming that the degree of partial melting in a single arc is controlled largely by the height of the melting column [*Plank and Langmuir*, 1988]. In making this calculation we assume that the bulk of the fluids are lost from the subducting plate 100 km below the arc volcanic front, so that the height of the melting column is calculated as being 100 km, the crustal thickness. However, this model

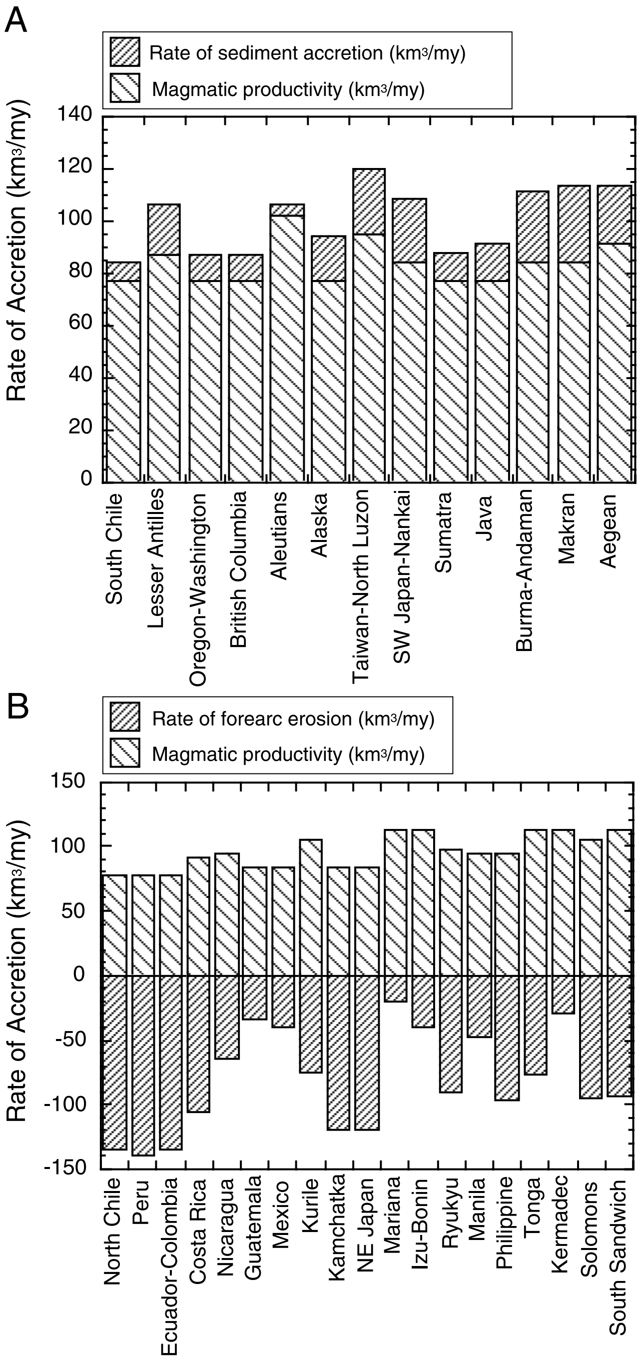

Figure 14. (a) Plot showing the calculated rate of melt production at each accretionary convergent margin based on the height of the melting column [*Plank and Langmuir*, 1988] together with the rate of rock accretion in the forearc accretionary wedge to give the net rate of crustal growth in these settings. (b) Plot showing the calculated rate of melt production at each erosive convergent margin based on the height of the melting column compared to the rate of tectonic erosion of the forearc basement.

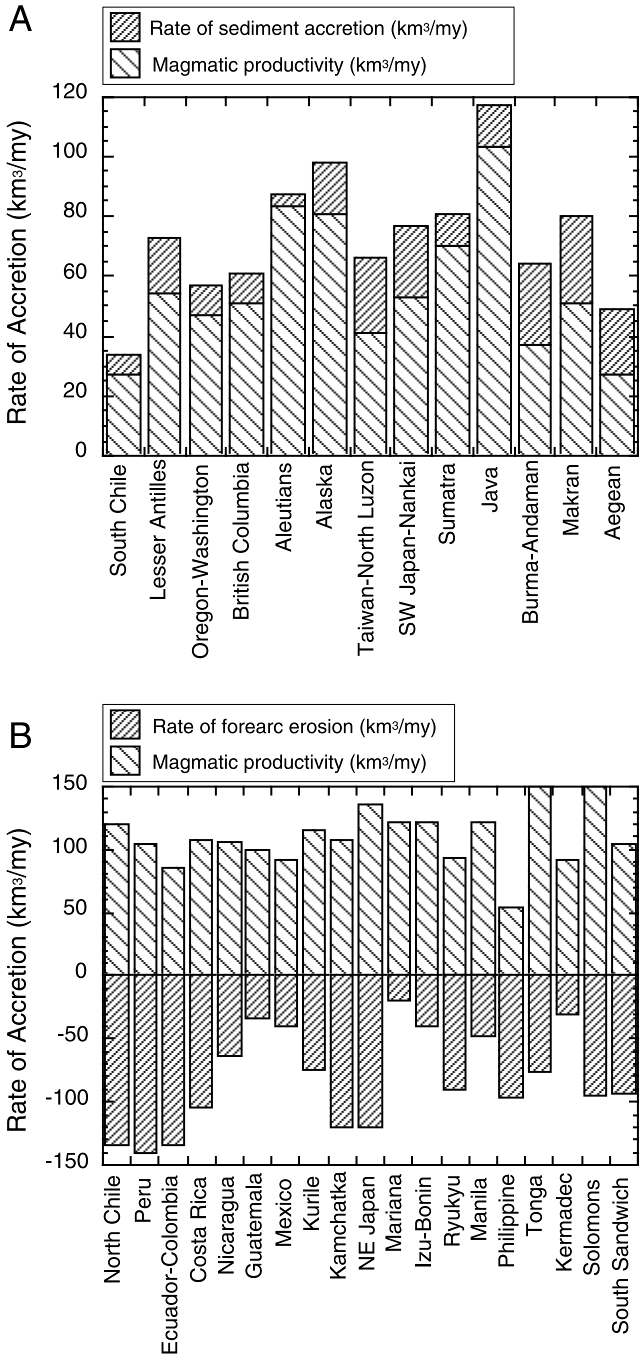

Figure 15. (a) Plot showing the calculated rate of melt production at each accretionary convergent margin based on the rate of convergence together with the rate of rock accretion in the forearc accretionary wedge to give the net rate of crustal growth in these settings. (b) Plot showing the calculated rate of melt production at each erosive convergent margin based on the rate of convergence compared to the rate of tectonic erosion of the forearc basement.

yielded geologically unrealistic estimates, such as excess melting in the Aegean, Taiwan, Makran, and Nankai Arcs (Figure 14a), and not enough melting in Tonga, Solomons, and Kermadec Arcs (Figure 14b). Consequently, we chose to estimate global distribution of melting by scaling this in proportion to the rate of convergence. Petrogenetic models such as that of *Tatsumi et al.* [1983] indicate that the degree of melting in an arc is largely a function of the amount of water added to the mantle wedge, which, in turn, is governed by the rate at which hydrated oceanic crust is

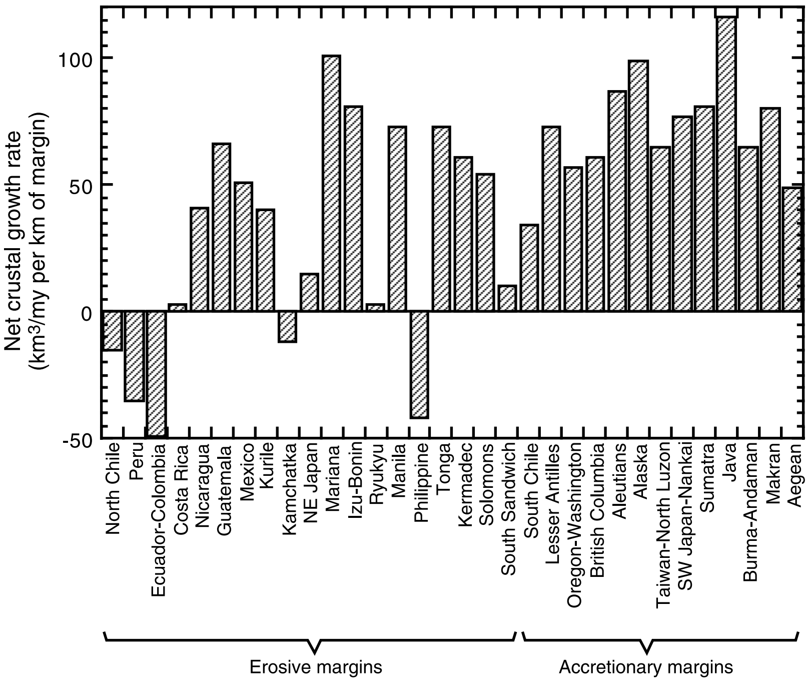

Figure 16. Diagram showing the integrated growth or erosion rate of each active plate margin in relation to the global average growth rate required to maintain the continental freeboard. Note that several erosive plate margins are actively growing crust despite rapid loss at the trench.

delivered to the trench. In making this estimate we recognize that the degree of melting can vary by large amounts through time with changes in the volumes of fluid released from the subducting plate during short-lived periods of slab roll back and arc rifting [e.g., *Clift et al.*, 2001]. As a result we estimate average magmatic productivity rates over long time spans (>10 m.y.). Because our accretionary and erosive mass budgets are also averaged over tens of millions of years, this approximation in the degree of melting is reasonable because the variations induced by tectonic events tend to last for <2–4 m.y.

[46] In redistributing the global melt production to the arcs on the basis of the convergence rates we assume that the degree of melting under any arc is related in a linear fashion to the modern convergence rate of *DeMets et al.* [1990]. Figure 15a shows the net crustal growth budget for the accretionary plate margins broken down into the relative contributions from magmatism and from subduction accretion. The contrast with the melt column-derived budget is large (see Figure 14a). The dominance of magmatism as the engine for crustal growth in these margins is apparent, accounting for 55–95% of the total growth rate. The Aegean, Andaman, Makran, and Taiwan Arcs show the lowest proportions of magmatic crustal growth, which is appropriate given the geology of these regions, their high rates of sediment accretion, and their modest or nonexistence volcanic output. Our calculations support models that favor convergence rates and not melting column height as the dominant control on arc petrogenesis. Unfortunately, because of the small number of robust estimates for arc magmatic productivity it is not feasible to independently determine the relationships between various geodynamic controls and the rates of melting. We can, however, at least conclude that a convergence rate-based model produces geologically sensible results.

[47] Figure 15b shows the rate of magmatic productivity versus the rate of forearc erosion at the erosive plate margins. It is noteworthy that the oceanic arc systems, such as the Tonga, Kermadec and Kurile Arcs, show magmatic accretion rates far in excess of their erosion rates, despite the fact that these have some of fastest trench retreat rates known globally. The net growth in these areas is caused mostly by the fact that convergence rates are fast, driving rapid melting that exceeds the rate of crustal loss. In particular, the Marianas is noteworthy for having not only high melting rates but also lower forearc erosion, implying rapid crustal accretion at least in recent geologic times. Because the arc edifice in the Izu-Bonin-Mariana margin is not significantly larger than that in Tonga and because it was initiated at the same time during the Eocene, we conclude that over long periods of geologic time the two arcs must have had similar rates of trench retreat and net growth. This is probably because tectonic erosion has generally been higher in the Marianas than it has been recently. In contrast, the South Sandwich Arc has a predicted slow growth of crust at the current rate of forearc erosion estimated by *Vanneste and Larter* [2002]. Our model indicates that this rate of erosion must be close to the limit that is stable at the current convergence rate or there would be no arc edifice remaining. In practice, oceanic arcs have only a limited range of possible stable crustal thicknesses and trench retreat rates, given the range of plate motion rates. At one extreme an arc with a 12 cm yr^{-1} convergence rate and a 20-km-thick crust would be unstable

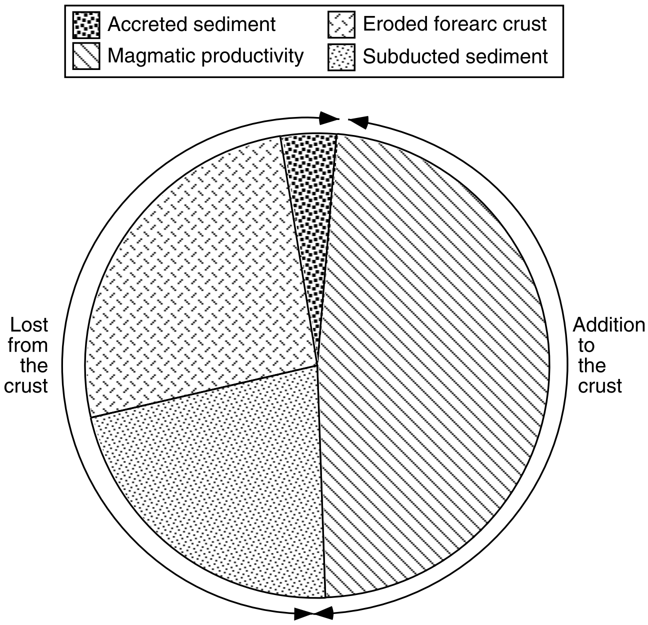

Figure 17. Pie chart showing the relative proportions of the major inputs and outputs from the global subduction systems with respect to the crust. Note the dominance of arc magmatism over subduction accretion as a source of new material.

for sustained trench retreat rates in excess of 6 km m.y.$^{-1}$, which would represent a maximum value.

[48] Our model predicts that oceanic arc systems are only viable entities because of their high melt rate, thin crust, and fast rates of convergence. Each system is a balance between the tectonic erosion removing the arc crust and the magmatism building it up. If convergence rates are slow, then melting may not be able to keep up with rates of tectonic erosion, unless convergence becomes so slow that accretion takes over as the dominant process. Thinner arc crust is more stable than thicker crust because a smaller volume of material is removed for every kilometer of forearc crust removed by tectonic erosion. For example, at an average trench retreat rate of 3 km m.y.$^{-1}$ and a convergence rate of 8 cm yr^{-1} the crust must be less than 36 km thick in order to be in state of net growth. Thicker crusts are only possible if the trench retreat rate is slower (e.g., the Marianas) or if the convergence rate is faster (e.g., Tonga). These controls may explain the general pattern in modern oceanic arc systems for long-term trench retreat rates at ~3.0 km m.y.$^{-1}$ and crustal thicknesses of 20–25 km.

13.1. Net Crustal Production

[49] The net rates of crustal production or loss in all convergent margins are summarized in Figure 16. Not

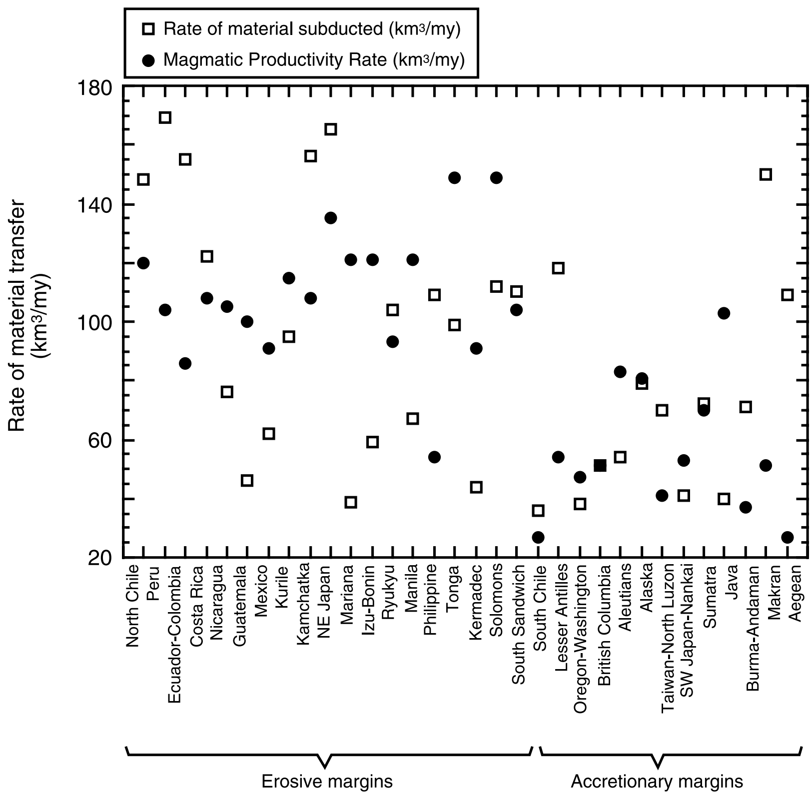

Figure 18. Diagram showing the relative rates of material subduction compared to magmatic productivity in the world's major subduction zones. The arcs of the erosive margins could theoretically be sourced from the recycling of subducted materials, while the accretionary margins require new extraction of crust from the upper mantle.

surprisingly, the accretionary margins show rapid rates of growth. The Marianas Arc is the most productive of the erosive margins, driven by its high melt production and low erosion rate compared to other oceanic systems. Nonetheless, it is noteworthy that all the oceanic arcs, even South Sandwich, are predicted to be in a state of growth despite their typically erosive tectonic character. This prediction is consistent with the geological evidence from these systems. In contrast, we identify several continental convergent margins that are sites of significant net loss of crust (South America, Kamchatka, and the Philippines). In these areas the magmatic productivity is limited by the moderate convergence rates, while the significant crustal thicknesses mean that tectonic erosion has removed large volumes to great depths below the forearc.

[50] The net loss of crust along continental active margins, where convergence is too fast to allow accretion, has significance for the origin of the continental crust. Our calculations imply that the crustal volume can only be maintained by the growth of oceanic arc crust, which must later become accreted to the continental margins through collisional events. If these blocks were subducted, then the continental crust would be in rapid decline, unless magmatic productivity was much higher than we estimate. However, much higher rates do not seem realistic given the present understanding of arc magmatism. The role that oceanic plateaus play in the formation of the continental crust has been much debated in the past [e.g., *Ben-Avraham et al.*, 1981]. While the addition of such crust is well documented in examples such as the Umnak Plateau of the Bering Sea and the Wrangellia Terrane of western North America, these represent relatively small and unusual areas of crust. Chemically, plateau crust is typically mafic and enriched and lacks the relative Nb depletion characteristic of both arcs and average continental crust [e.g., *Rudnick and Fountain*, 1995]. In addition, the seismic velocity of accreted plateau crust is too high in the lower and mid crust [e.g., *Morozov et al.*, 2001] compared to the continental average [e.g., *Christensen and Mooney*, 1995]. Consequently, we consider plateau accretion to be a minor contributor to the overall mass budget of the continents.

[51] The arc accretion process is most clearly displayed in the modern collision of Taiwan with southern China, during which the Luzon Arc is accreted to the edge of Asia [*Teng*, 1990; *Lallemand et al.*, 2001; *Clift et al.*, 2003b]. Prior to collision, oceanic island arcs make unsuitable building blocks for the continental crust because their bulk chemistry is too mafic and light rare earth element depleted compared to average continental crust [*Rudnick and Fountain*, 1995]. However, *Draut et al.* [2002] now demonstrate, using an example from the Paleozoic Caledonides, that the accretion process itself is fundamental in transforming the bulk chemistry of igneous arc crust into a suitable building block for the continental crust. Thus we now envisage the slow growth of the continental crust being driven by the magmatic production at accretionary margins, coupled with the accretion of oceanic arcs outpacing the crustal loss at the continental erosive margins.

13.2. Mass Balancing the Crust

[52] The mass balance in the global subduction zones is shown in Figure 17, which demonstrates the dominance of arc magmatic productivity over sediment accretion as a process for conserving the mass of the continental crust. It is also noteworthy that the tectonic erosion of forearc basement appears to be ~20% greater than sediment subduction as a source of continental material flux either to the magmatic roots of the arc or back into the upper mantle. The rate of material subduction in some erosive margins is sufficient to account for their level of magmatic productivity (i.e., the volume of arc magmatism could simply reflect remelting and recycling of the subducted crust, e.g., Peru, Costa Rica, and NE Japan (Figure 18)). Similarly, because of the inefficiency of accretionary complexes in preventing deep subduction of sediment much of the magmatism in the accretionary margins could be explained by relatively shallow recycling. However, isotopic evidence from oceanic arc systems typically shows that much of the arc volcanic output is derived by melting of the upper mantle wedge, albeit with some sediment contamination [e.g., *Woodhead and Fraser*, 1985; *Ewart and Hawkesworth*, 1987; *Vroon et al.*, 1993]. We conclude that the flux of continental material through the global subduction systems is not dominated by shallow, short-term recycling of subducted material through the arc magmatic roots. Instead, continental materials entering the subduction zone are prone to deeper subduction, with possible recycling into mantle plumes or mid-ocean ridges [e.g., *Eiler et al.*, 1996, 2000]. In order to maintain a balance of continental crustal mass the extraction of new material from the upper mantle must be proceeding at a similar high rate.

14. CONCLUSIONS

[53] In this study we demonstrate that rates of tectonic erosion and sediment subduction have generally been underestimated as processes that shape the global subduction systems and consequently drive the generation and recycling of the continental crust. Indeed, 57% of the global active margins seem to be of the erosive type in which significant volumes of forearc basement are tectonically removed and recycled either to the roots of the volcanic arc or back into the upper mantle. Globally, eroded forearc basement constitutes approximately 55% of the crustal material subducted to depth, the remainder being subducted sediment. Even at the accretionary margins, typically ~83% of the incoming sedimentary pile is subducted beneath the forearc wedge and appears to be only partially reworked into the arc volcanic front. Both accretionary and erosive convergent margins are major sites of net crust loss back into the upper mantle. Although there is some overlap in characteristics, accretionary margins are typically marked by forearc slopes of $<3^\circ$ and form in active margins where the rate of orthogonal convergence is <7.6 cm yr^{-1} and where the trench sediment thickness is >1 km. The faster the rate of convergence is, the steeper the forearc slope is,

implying that basal friction increases with convergence rate. Not surprisingly, the faster sedimentary rock is supplied to the margin the quicker an accretionary complex is built, provided the section is >1 km thick. Convergence rate also appears to exercise some control over the thickness of trench sediment because it determines how long any given piece of the oceanic plate resides in the high-sedimentation-rate trench zone.

[54] No simple first-order controls on the rate of forearc basement erosion could be determined from this study because the rate of trench retreat does not appear to be controlled by either convergence rate, sediment thickness, or the age of the oceanic lithosphere. Instead, we conclude that long-term erosion rates are largely controlled by the episodic collision of large topographic ridges with the trench (e.g., hot spot tracks on the subducting plate). Although fast erosive margins are the most efficient recyclers of crustal material back into the mantle, accretionary margins are so inefficient that they too allow large volumes of crust to be subducted to depth at a rate linked closely to the rate of sediment delivery to the trench.

[55] We calculate that in order to maintain the current volume of continental crust the global average magmatic productivity must be ~90 km^3 $m.y.^{-1}$ km^{-1} of active margin. If a moderate rate of net continental crustal growth is proposed to account for the constant level of continental freeboard, the average rate increases to 91 km^3 $m.y.^{-1}$ km^{-1} of active margin. Geological constraints indicate that this is not uniformly distributed but is instead higher in faster converging margins, which are often erosive. Convergence rates, not crustal thickness and melt column heights, appear to be the chief control on melting rates in arcs over long periods of geologic time. The magmatic product rates estimated for the oceanic arcs (81–149 km^3 $m.y.^{-1}$) are broadly in accord with rates estimated from recent seismic refraction experiments after accounting for crust lost by subduction erosion. The model predicts that eroding oceanic arcs cannot maintain crustal thicknesses >36 km because higher thicknesses require excessive rates of convergence and melting in order to maintain the volume. Conversely, the maximum rate of trench retreat cannot exceed 8.0 km $m.y.^{-1}$ over long periods without the loss of oceanic arc crust, which geological constraints preclude. The picture of crustal mass flux that emerges from this study is one of net crustal loss in the eroding continental margins and growth in the oceanic arcs and accretionary continental arcs, with a volume equal to the entire mass of the modern continental crust being flux through the subduction zones every 2.2 Ga.

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