SUBDUCTION EROSION AND ARC VOLCANISM

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ABSTRACT

Tectonic or subduction erosion refers to the removal of upper plate material from the forearc at convergent margins. Subduction erosion has been suggested to represent a major process associated with the transfer of crustal material into the Earth's mantle at subduction zones[1-4]. However, few studies have attempted to trace the fate of eroded forearc crust beneath volcanic arcs, where the eroded crust might first emerge after mixing with the upper mantle, owing to the formidable challenge associated with quantifying the rate of subduction erosion and the contribution of eroded crust to arc magmas. In this Review, we summarize the evidence for subduction erosion at convergent margins and show that, through integration of geochemical and geological data in arc settings where critical crustal lithologies can be accessed, quantification of the contribution of eroded forearc crust to arc magmas is possible[5-8]. We further emphasize the importance of establishing arc-forearc compositional links, and illustrate the role of arc petrogenetic models for determining whether the eroded forearc crust contributes substantially (that is, greater than a few percent) to the construction of new arc crust in subduction zones[5,9], or whether it is primarily exported to the deeper mantle.

[H1] INTRODUCTION

Plate tectonics results in the transfer of crustal material into the Earth's convecting mantle at subduction zones[1,10-13]. Subducted crust can include marine sediment, which forms through deposition of eroded material from the upper continental crust on the subducting lithospheric plate[14]; altered oceanic crust (AOC); and tectonically eroded crust ('subduction erosion **[G]** ') removed from the crustal basement of the overriding plate[1,3,4,15,16]. Trench sediment and AOC have measurable volumes and distinct compositions, which allow their distribution in the mantle to be traced through the composition of arc[10,11,17-20] and intraplate magmas[13,21,22]. However, despite the clear potential for eroded material to influence arc[3,5,6,8,23] and intraplate magmatism[13,24,25], as well as the Phanerozoic balance of crustal destruction and growth[3,26], the role of the eroded crust in magma petrogenesis remains uncertain.

Subduction erosion removes crustal material from the forearc **[G]** of the upper plate along modern subduction zones. Although subduction erosion operates at depths that are largely inaccessible[2], it can be indirectly inferred from geological data of the forearc (Fig. 1). For example, the large-scale and long-term subsidence of the forearc (up to 5,000 meters)[1,26,27], alongside bathymetric and seismic images consistent with a dynamic, time-progressive erosion of the forearc[2,4,28,29], indicates that subduction erosion can transfer similar quantities of crust to the mantle as subduction of trench sediment[3,16,23].

After mixing with the mantle, subducted crustal material first emerges at volcanic arcs located above the descending slab[30-32]. Comparative trench-arc studies demonstrate that, following transfer of crustal components to relatively shallow mantle depths (~100-200 km), the geochemical signatures of trench sediments[10,11,14], AOC[31,33-37], and lithospheric serpentinites[38-40] re-emerge in arc magmas. However, few studies have addressed whether eroded crust is recycled in the mantle wedge and, therefore, contributes to arc magmas[5,6,8,13,23]. Detecting the presence of eroded crust in arc magmas is challenging as it blends with the other recycled crustal components, particularly trench sediment[3,23]. In addition, contribution from eroded crust can also present similar geochemical signatures to those produced by interaction of primary arc magmas **[G]** with pre-existing crustal basement en route to the surface[41] (Fig. 1).

In this Review, we present a summary of subduction erosion processes at convergent margins and discuss how erosion recycling in arcs can be identified through detailed arc-forearc analysis. In addition, we note that recent analyses of erosion recycling beneath several volcanic arcs worldwide, alongside new models of arc petrogenesis, indicate that subduction erosion can have an important role in the geochemical modification of both the shallow and deep mantle.

[H1] THE SUBDUCTION PATHWAY OF ERODED CRUST

Convergent margins are typically classified as either 'erosive' or 'accretionary', based on the balance between the removal of crustal material by subduction erosion and growth of the upper plate owing to 'frontal accretion **[G]** '[42-45] or 'underplating **[G]** '[46] (Fig. 2, Supplementary Information)[1,16]. At erosive margins, there is a net removal of material from the upper plate[46,47], whereas at accretionary margins there is net growth. However, it is important to note that subduction erosion can still occur beneath accretionary margins, and thus contribute to the geochemical signature of arc volcanoes worldwide.

A common feature of actively eroding margins is the 'frontal prism **[G]** ' (Fig. 1[a]), which has a semi-constant width of ~10 to 20 km, variable thickness (<1 km to ~5-6 km) and is commonly characterized by landward-dipping seismic reflectors. Frontal prisms are typically composed of upper plate material (that is, sediment and disaggregated basement), which accumulates at the toe (Fig. 1[b]) of the outer forearc[2], or sediment scraped off the incoming plate to form a small accretionary prism **[G]** [48]. The frontal prism is backed by a resistive 'backstop **[G]** ' (Fig. 1[c]), which represents the dynamically stronger rock framework of the forearc.

As the incoming oceanic plate subducts beneath the overriding plate, basal erosion **[G]** of the forearc occurs. Erosion of the forearc causes the trenchward migration of the strong material of the backstop, which is then gradually weakened until it becomes part of the frontal prism. As the process continues, material that was once part of the strong backstop is eventually eroded away[2]. On the mid to upper continental slope (Fig. 1[d]) high-angle, landward-dipping normal faults (Fig. 1[e]) with small to moderate ~50-300 m displacements can herald the impending fracturing of the rock framework[2,28].

The frontal prism can reduce the plate boundary friction by 'loading' (that is, overpressuring) fluid-rich sediments. Dewatering and upward fluid migration results in weakening of the upper plate and upward migration of the plate boundary shear zone[2]. The consequent incorporation of upper plate material to the top of the subduction channel **[G]** (Fig. 1[f]) causes 'basal erosion'. In addition, fluid percolation assists fracturing at the base of the upper plate, beneath the middle continental slope, and thus incorporation of this upper plate material into the subduction channel (Fig. 1[g]). The thinner the incoming sediments, the higher the plate boundary friction and, therefore, the fracturing of the upper plate[2]. The physical damage to the forearc is at a maximum when seamounts, oceanic plateaus and ridges on the lower plate collide with the forearc[4,28]. Material entering the subduction channel is likely to be accommodated by grabens and half-grabens (Fig. 1[h]) that dissect the lower plate.

If the eroded crust escapes immediate re-accretion (that is, underplating) beneath the forearc, it will be transported into the mantle alongside the downgoing plate. Fluids released from the lower plate are absorbed by the forearc mantle wedge, forming serpentinite. As mantle wedge temperatures rise with increasing distance from trench, release of fluids from the slab (Fig. 1[i]) and/or resulting serpentinites could trigger melting at slab depths >80-100 km (ref.[49,50]). With increasing slab depth, the efficiency of material transfer from the slab to the wedge increases owing to the buoyant rise of 'slab diapirs **[G]** ' (Fig. 1[k])[51-53] or, if the slab solidus is intersected beneath the arc front, slab partial melts **[G]**[54].

Diapirs rising from the subducting slab transfer large volumes of low-density crustal material, such as eroded crust or sediment, into the core of the mantle wedge[51]. Additionally, mélanges diapirs (Fig. 1[l]), which rise from intensely sheared and mixed, high-pressure mélange zones between the eclogitic slab and overlying mantle peridotite, can integrate transport the bulk of the AOC, instead of only low-mass AOC fluids, into the core of the mantle wedge[34,52,55,56]. As the rising slab material mixes with the hot core of the mantle wedge it will begin to melt (alongside the surrounding mantle peridotite) and subsequently erupt as arc magmas after ascent through the crustal basement (Fig. 1[m]). The residual slab material is then exported to the deeper mantle (Fig. 1[n]).

[H1] DISCOVERING SUBDUCTION EROSION

Subduction erosion cannot be directly observed or quantified. Instead, the process of subduction erosion, and the rate of crustal destruction, can be inferred from a combination of geological and geophysical forearc observations[1,15,16,23,57-59].

Characteristic features of upper plate destruction, such as forearc thinning or truncation, can also be caused by extension or the presence of strike-slip faults parallel to the trench. However, where subduction erosion is inferred (Fig. 2 and Supplementary Information) it is the only process that can account for the entirety of the observations, which implies net loss of forearc material. In addition, subduction erosion provides a framework for quantifying forearc crustal loss.

[H2] Destruction of the upper plate crust.

Early evidence for the importance of subduction erosion comes from the large-scale loss of forearc crust at convergent margins[60-64]. For example, the 200 km landward migration of the active central and southern Andean volcanic arc (~15-46°S), evidenced by the eastward younging remnants of older arcs located between the coast and the Holocene arc[60], indicates that there has been time-progressive destruction of the Andean forearc crust since the Early Jurassic[1,60]. At different arc systems worldwide, evidence for forearc loss includes the missing portions of accretionary prisms (for example, in Nankai)[65], unaccountable forearc subsidence in Japan[66] and Costa Rica[26,27], truncation of the crystalline roots of older magmatic belts near the shoreline and offshore (as in the Mexican Pacific coast)[67,68], or the testimony of detrital zircon chronology that records the existence of now-vanished Paleozoic and Mesozoic batholiths of the proto-Japan arc[69].

Major strike-slip faults have also been suggested to cause largescale forearc loss. However, along trench transport of the forearc by trench-parallel strike-slip faults would generate doubled-up forearcs in addition to forearc loss, which are not observed. Instead, in the late 1970s, ocean drilling revealed the presence of forearc subsidence[66,70]. For example, drilling ~90 km from the trench axis offshore Japan, in water 1560 m deep, penetrated an erosional angular unconformity 1200 m below sea floor, which could be seismically traced regionally to ~10 km from the trench axis. The sediments above the unconformity are 48 m thick, unconsolidated, non-marine Oligocene, which were interpreted as nearshore/beach deposits[66]. Thus, since the Oligocene, broad, regional outer forearc subsidence of nearly 2800 m, at a rate of ~140 m/my (ref.[66]), must have occurred to accommodate the burial of these sub-aerial sediments beneath the overlying marine slope sediments[1].

In a simple model of an accretionary prism, subsidence of the outer forearc is unexpected as plate convergence and under-thrusting should result in isostatic uplift of the prism's outer slope, owing to thickening of lower density crustal material[71,72]. However, forearc subsidence can also result from changes in slab dip[73-76], crustal thinning by forearc extension or basal erosion. Although normal, extensional faults are found in erosive margins[2], their displacement and resulting crustal thinning cannot account for the measured forearc subsidence[27,66]. For example, there are no major extensional structures large enough to explain the ~3000 m of subsidence in the Japan outer forearc[66,77,78]. In addition, models that consider the subsidence of the outer Japan forearc to be driven by variations in plate kinematics, associated with the post-Oligocene opening of the Japan Sea[79,80], assume that there has been a constant forearc volume since the Oligocene. Yet, the Oligocene outer forearc volume, inferred from the upper plate cross-sectional area between the trench and the drilled Oligocene coastline, only accounts for about 25% of the modern outer forearc volume, inconsistent with constant-volume models.

Subsequent work has documented large-scale and long-lived subsidence in other forearcs[1,16], such as Costa Rica, where multi-beam bathymetry provided spectacular images of the visual damage to the forearc by the head-on collision of incoming high-relief seamounts. Seamounts plow through the frontal prism and leave grooved, elongate depressions in the forearc slope up to ~55 km landward[2,28,81], indicating that seamount subduction is able to effectively remove fragmented upper plate material[2].

To the south, subduction of the aseismic Cocos Ridge, a ~18 km thick and ~200 km-wide basaltic ridge[82] that rises ~2000 m high above the surrounding seafloor (Fig. 2), is associated with the landward retreat of the Middle America Trench[83,84]. Ocean drilling indicates ~1 km of uplift of the forearc continental shelf within only ~0.3 My, starting at ~2±0.2 Ma, which was followed by equally fast subsidence of ~1.5 km (refs.[4,83,85]). The rapid vertical motion of the forearc, and retreat of the trench, suggests that the onset of Cocos Ridge subduction caused accelerating compression, followed by outer forearc removal and thinning by basal erosion[4,86].

An alternative hypothesis states that the arrival of the Cocos Ridge at the trench would cause horizontal shortening and thickening of the forearc, without mass loss, and thus trench retreat. In this model, the subduction of a much smaller seamount is required to explain the initial, rapid vertical forearc movements[84,87]. However, contemporaneous thickening and subsidence of the outer forearc is required[84,87], inconsistent with the isostatic uplift predicted following subduction of an ~18 km thick basaltic ridge.

As a result, time-progressive forearc destruction by basal erosion[1,4] represents the only process that can explain the observed subsidence of forearcs worldwide, and the volumes of crustal forearc that are lost. In addition, subduction erosion is consistent with, several forearc features that have been revealed by seismic images, such as the existence of frontal prisms in Costa Rica and Guatemala (Fig. 1)[2], high-angle normal faulting patterns on the continental slope of Costa Rica, Nicaragua and South America[28], mega-lenses of upper plate material embedded in the subduction channel in Costa Rica[28,88] and upper plate imbricate landward-dipping forearc thrusts that are truncated by plate boundary shear zones in the Japan Trench[77]. Additionally, high-temperature (~85-150°C) vents located along forearc normal faults document the upward fluid drainage from the lower plate that causes the subsurface hydrofracturing **[G]** of the rock framework[89].

Although the volume of forearc data available for the Central American margin is rarely seen elsewhere[4] (see Supplementary Information), sufficient observations exists to demonstrate that erosive destruction of the upper plate is a common consequence of plate convergence[15]. In contrast, the hydrated, less brittle lower plate largely escapes physical destruction except for the loss of the incoming sediment that is accreted to the forearc (~70% on average; see Supplementary Information).

[H2] Eroded crustal volumes.

The influence of subduction erosion on the solid rock geochemical cycle is controlled by the rate of forearc erosion, or forearc volume lost, within a given timespan. Erosion rates are estimated through reconstruction of the volume lost using data on the forearc crustal thickness, the extent and duration of forearc subsidence, and the rate of landward trench migration[15,16,27] (Supplementary Information).

As the capacity of the subduction channel to consume eroded material is a function of several parameters, including the topography of the incoming plate, the convergence rate and the hydrogeology of the forearc and plate boundary[90-92], erosion rates can be difficult to constrain in the highly dynamic forearc environment. For example, the subduction channel might widen at depth, and thus allow more eroded material to enter the plate boundary shear zone, or shrink, causing underplating down to at least ~30-40 km depth (as imaged by reflection and refraction seismic profiles and inferred from tell-tale forearc uplifts)[93-95]. As a result, a single margin might display along-strike changes from an erosive to an accretionary and underplating regime[4,96,97]. Similarly, a margin with a large, long-lived accretionary prism can turn erosive, removing the accreted material by frontal erosion **[G]** [95].

The classification of a given margin as erosive or accretionary typically represents a time-integrated, long-term average (Fig. 2)[3,15]. As forearc data improve, the rates of forearc erosion are constantly revised. The most up-to-date estimates of the rates of forearc erosion and sediment subduction, calibrated on Pliocene-Pleistocene (≤5 Ma) geophysical and geological forearc data and the tectonic background of the modern subduction zones, are presented in the Supplementary Information. Critically, the new rates are the first that have been adjusted for sediment loss by underplating and forearc accretion and confirm that most margins (>60%) are erosive (consistent with earlier compilations)[1,15,16].

Erosive and accretionary margins can also have distinctive forearc characteristics[15]. Accretionary margins are characterized by lower (orthogonal) convergence rates (~36±22 km/my) and higher sediment fluxes (trench fill >1 km thick). They are commonly found near continents and large river mouths that have had a high terrigenous sediment flux through the Cenozoic[14,15] and, in particular, since the onset of the Northern hemisphere glaciation at ~2.6 Ma (ref.[1]). Frontal prisms constructed from accreted sediments tend to have shallow forearc slopes <3° and taper angles <10° (the angle between the subducting slab surface and forearc slope). In contrast, erosive margins have higher convergence rates (~71±23 km/my) and thin (<1 km) trench fills. Their forearcs are built of stronger lithified sediments, magmatic and crystalline rocks with steeper slopes (>3° and 8°) and bigger taper angles (>7° up to 20°)[4,15].

The dominance of erosive margins implies a global net loss of forearc, especially since mass balances points toward forearc loss even at accretionary margins[66,96,98]. However, the volumes of eroded crust at accretionary margins are difficult to estimate[57,97] and, as a result, global averages of erosion rates are currently based on estimates from erosive margins[1,3]. Despite the inherent uncertainties and data gaps, some important features emerge. First, the most recent estimates of the average global erosion rates (~66±34 km^3/per km of trench length/my (km^3/km/my); Supplementary Information) are higher than the early estimates of ~26 km^3/km/my (ref.[1]), owing to the improved quality and quantity of forearc data. Second, once the influence of crustal underplating is taken into account, the estimated rate of sediment subduction decreases from the early estimates of ~23 km^3/km/my (ref.[1]), or ~41-45 km^3/km/my if 100% sediment subduction at erosive margins is assumed, to ~14±8 km^3/km/my. Third, all estimates agree that tectonically eroded crust contributes at least half and likely up to ~80% of the total crust lost to mantle through trench sediment and subduction erosion (~77 to 81 km^3/km/my)[1,3,15,16]. Fourth, the combined rate of crust loss via sediment subduction and forearc erosion is similar to the estimated global arc crust production rate **[G]** by melting of the mantle, which is usually estimated to be ~30 to 150 km^3/km/my (refs.[1,3,15,16]). As a result, tectonically eroded crust should influence arc volcanism[5], mantle evolution[13], and also models of continental crust destruction and growth[3,99].

[H1] CONNECTING SUBDUCTION EROSION AND ARCS

Arc magmas have radiogenic isotope ratios (that is, $^{87}Sr/^{86}Sr$, $^{206}Pb/^{204}Pb$, $^{206}Pb/^{204}Pb$, $^{206}Pb/^{204}Pb$, $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$) that are intermediate between those of the depleted upper mantle and the enriched continental crust[11,32]. For example, the $^{143}Nd/^{144}Nd$ ratios of arc magmas (expressed as εNd **[G]**) are lower than that of the depleted upper mantle (εNd ~10), but typically higher than that of continental crust (εNd <0)[13,100,101]. A simple first-order assumption is that eroded crust resembles continental crust in major elements, trace elements and radiogenic isotope ratios[1,3,23]. As a result, it has been suggested that the εNd of primary arc magmas **[G]** should scale to the total amount of continental crust (trench sediment + eroded crust) recycled beneath each arc[3]. The proportion of eroded crust involved in the petrogenesis of arc magmas can then be determined through the ratio of eroded crust to subducted trench sediment calculated from forearc observations[3]. As tectonically eroded crust contributes substantially to the total subducted crust (~75% on average, Supplementary Information), low-εNd arcs should contain the largest contribution of recycled eroded crust.

A global map of arc εNd (Fig. 2), however, does not support such a simple compositional link between the rate of subduction erosion and arc magma compositions. Although volcanoes of the Central (CVZ, ~15-28°S) and Southern (SVZ, ~33-46°S) Volcanic Zones have low average εNd signatures of -5 and +4, respectively, consistent with the long-term erosional history of the margin[1], εNd is high in other erosional margins (>+5). For example, εNd values up to +7 and +9 are observed in the Costa Rica and Tonga arcs where subduction of the Cocos and Louisville Ridges, respectively, increase forearc erosion[1,4]. In fact, in both locations, arc εNd values reach a maxima at the intersection of ridge and forearc, which points to the erosion recycling of the high-εNd crustal forearc basement.

The often-made assumption that subduction erosion only recycles continental crust is an oversimplification. Instead, as expected from the location of active subduction zones, forearc erosion may abrade any material that builds forearc basement, which can include upper continental crust, depleted or enriched oceanic crust, accreted sediments, allochthonous terranes, or the poorly characterised lower continental crust. In an end-member scenario, erosion recycling of various crustal materials could produce the global distribution of εNd in arc magmas. In addition, erosion recycling likely contributes to the highly heterogeneous nature of the mantle by recycling materials other than continental crust[102], oceanic lithophere[103] and AOC[104].

There are, however, other factors that can influence the εNd of global arc magmas. For example, crustal assimilation can systematically lower the εNd of arcs constructed on ancient continental basement relative to the εNd of oceanic arcs[41,105]. Arc εNd might also be influenced by variations in the mantle wedge composition, which appears to be more depleted beneath oceanic arcs[106] than continental arcs[107-109]. Chemical variety can also be introduced by variations in the amount and composition of trench sediment[11,19,33,110,111]. To distinguish between the different possibilities, comprehensive major element, trace element and isotope studies from the trench, fore-arc, arc basement, and arc magmas are needed in individual arc settings. Modeling of such datasets, supported by experimental data, can determine whether forearc recycling controls arc magma composition, or is subordinate to the other processes.

[H1] CASE STUDIES IN VOLCANIC ARCS

It is a formidable challenge to distinguish and quantify the contribution of an eroded crustal component, of unknown composition, to arc magmas, especially owing to the influence of other co-mingled source components. The debate surrounding the contribution of eroded forearc crust to arc magma petrogenesis in several arc systems worldwide illustrate the challenge.

[H2] The Central and Southern Andean arc.

There is strong geological evidence for subduction erosion along the Andean margin between Peru and South Chile (~10-46°S), for example, large-scale crustal loss, forearc subsidence[1] and characteristic fault patterns[112], have led several studies to consider the influence of recycled eroded forearc on Andean arc magmas[8,23,113]. For example, an early study indicated that the increase in the $^{87}Sr/^{86}Sr$ of Holocene Andean arc magmas north of ~34°S was causally related to a contextual increase of ongoing subduction erosion[114]. However, subsequent studies of the Andean arc's Cenozoic evolution inferred that erosion recycling was not continuous, but episodic[8,115-117].

In the Andean CVZ and SVZ, the compositional evolution of the arc between the Oligocene (~25 Ma) and present day can be reconstructed from the remnants of the older arcs. The older arcs are exposed between the coast and the Holocene arc in trench-parallel, eastward younging volcanic belts that were left behind as the Andean volcanic front retreated to the east[60]. The exposed compositional evolution of the Andean arc allow the identification of two Neogene periods (~19-16 Ma and ~8-3 Ma) that are characterized by the presence of small-volume, primitive arc magmas that have up to 700 ppm Cr, 300 ppm Ni, and 10 wt% MgO (refs.[8,115,116]), as well as steep rare earth element (REE) patterns and high Sr/Y, Sr/Yb and Sm/Yb ratios that are characteristic of 'adakitic' magmas. The lower εNd and higher $^{87}Sr/^{86}Sr$ of the adakitic magmas, compared to their preceding magmas, points to an origin from an enriched mantle source[8,115].

The two Neogene pulses coincide with periods of heightened eastward arc retreat, a change from an extensional to a compressional basement regime, crustal thickening, and a decrease in the volcanic productivity of the eastwards migrating volcanic arc[8,115,118]. At a constant subduction geometry, accelerated arc retreat points to enhanced tectonic forearc erosion, which can cause mantle wedge enrichment through the incorporation of the subducted eroded crust[8,115,116]. In addition, similar chemo-temporal correlations were observed in the Central Aleutian arc, where adakitic magmas preferentially erupt during peaks of forearc erosion and arc retreat (~7-5 Ma) or in the waning stages of short-term enhanced magmatic activity (~37–29; ~16–11 and ~7–5 Ma)[119,120].

The combination of adakitic signatures, crustal thickening and tectonic evolution has also been hypothesized to be driven by crustal thickening, rather than enhanced subduction erosion. Crustal thickening stalls the underlying mantle flow field, which in turn forces the arc front to migrate away from the trench[121], and causes an increase in trace element ratios such as La/Yb. However, although there is strong evidence for fluctuations between extensional and compressional upper plate regimes in the Andean SVZ since the Miocene[122], tectonically driven crustal thickening cannot account for the large scale loss of forearc crust along the Andean margin, the presence of older arc products at the coast and forearc subsidence[112].

Intriguingly, in the Andean subduction erosion model presented above, compositional links between the forearc and arc are only visible in rare, periodic, small-volume mafic magmas[8,115], which implies that most of the eroded material must be returned to the mantle[8,115]. However, the question of whether strong arc-forearc compositional links are present, outside of the two Neogene periods of adakitic magmatism, remains debated.

A recent study of the northern SVZ (~34-35°S) used Sr-Nd-Pb isotopes and incompatible trace element ratios to suggest that primitive, high-Mg# **[G]** arc magmas are sourced from a mantle that contains an enriched low-εNd, upper crustal component[113]. Isotope mixing systematics rule out a substantial contribution from low-εNd trench sediment and instead point to a low-εNd upper continental crust component that was recycled by forearc erosion[113,123]. However, the role of subduction erosion on controlling the composition of Andean arc magmas was recently challenged by a study that approximated the composition of the SVZ and CVZ Andean eroded forearc crust though a compilation of published data from the outcropping igneous and metamorphic Andean basement[124]. No basement composition found in the compilation was able to recreate the Sr, Ba, Eu/Eu* and ^{87}Sr/^{86}Sr systematics of mafic rocks from Maipo and Don Casimiro in the SVZ (~34.16°S)[124], a volcanic system that had previously been connected with erosion recycling[113]. Similar ambiguity is also present in two CVZ volcanoes near~28°S, ~700 km farther to the north, which show consistency with erosion recycling in Sr-Nd isotope space, but a clear signal of crustal contamination in their Pb-isotope compositions[116].

The crustal proxies used in studies of the CVZ[116,125] and SVZ[8,41] represent the accessible upper Phanerozoic Andean crust. However, the deep Andean basement between Colombia and Patagonia is composed of various Grenvillian-age (1-1.5 Ga) crustal terranes[126]. Assimilation of the inaccessible deep crustal basement[41,127] by either crustal contamination or tectonic erosion of the deeper Andean forearc basement[8,115] is imaginable, but difficult to test in face of the rare inliers of Grenvillian-age crust.

Further complexity is introduced into the petrogenesis of the Andean arc magmas by the possible presence of an enriched mantle, low-εNd component in the mantle wedge. The enriched mantle component is hypothesized to be either low-εNd subcontinental lithospheric mantle[109] or components derived from it[107]. In such a scenario, the low εNd of the mafic CVZ and SVZ magmas is not related to subduction erosion[125], but originates from a heterogeneous mantle that is transported by corner flow **[G]** [128] from behind the arc to the arc front (where it is overprinted by low-mass slab fluids **[G]**)[107,124,129-131]. Thus, to fully understand the influence of subduction erosion on Andean magmatism through time, the challenge remains to find means of quantitatively distinguishing between contributions from mantle, deep crustal basement and forearc to the composition of arc front magmas.

[H2] The Central American Volcanic Arc (CAVA).

The CAVA (Fig. 2) is a well-studied, long-term Neogene erosive system[132]. Multiple ocean drilling expeditions on the forearc reveal that the forearc erosion rate increased from ~12 to 80 km^3/km/my between ~6 and ~2.5 Ma, and then to ~140-153 km^3/km/my in the Pleistocene. In addition, a regional Pleistocene maximum forearc erosion rate of ~1125 km^3/km/my (ref.[132]) is observed at the intersection of the forearc with the aseismic Cocos Ridge, which arrived at the trench at ~2.5 Ma and represents oceanic crust that has been thickened from ~6 to ~18 km (ref.[82]) by Galapagos hotspot magmatism[83,133].

Concurrent with increasing forearc erosion between ~6 and 1.5 Ma, the CAVA magmas in central Costa Rica and western Panama transitioned from normal calc-alkaline arc magmas to enriched, 'OIB-type' magmas that resemble, in some trace element and isotope ratios, the intraplate magmas of the Galapagos hotspot[133-135]. The temporal change in the magmatic compositions of the CAVA could be related to the onset of recycling of the Cocos Ridge at ~2.5 Ma (ref.[83]). However, the contribution of eroded forearc crust to the CAVA magmas remains unclear.

It has been suggested that subduction erosion could transfer the OIB-type Pb isotope signatures to the arc from a forearc, that is constructed of accreted OIB-type Cretaceous ophiolites and fragments of the Caribbean Large Igneous Province[135]. However, several other models have been proposed to explain the OIB-type Pb isotope signature of the CAVA magmas, including advection of enriched mantle by trench-parallel flow beneath the CAVA[136]; a slab window allowing Galapagos asthenosphere to flow into the mantle wedge[137]; a mantle wedge infested with Galapagos plume components[138], and a mantle wedge metasomatized by slab components from subducted Galapagos-type oceanic crust[134,139]. Thus, the Pleistocene – Holocene CAVA provides an example of a forearc-arc setting where eroded forearc might be recycled, but the influence of the recycled eroded crust on arc magma petrogenesis cannot be determined owing to the compositional diversity of the source components that might be present.

[H2] The Transmexican Volcanic Belt (TMVB).

The TMVB allows the influence of erosion recycled to be directly tested as it has an accessible and distinct trench and forearc input[5-7], and a well-investigated arc output[140]. In addition, the composition of the ambient mantle **[G]** wedge can be approximated through contemporaneous rear-arc magmas that erupt directly behind the volcanic front[141,142].

The crystalline roots of deeply eroded, older Mesozoic-Cenozoic arcs are commonly uplifted above sea level along the Pacific coast[67,68] and their sharp truncation indicates that substantial tectonic removal of the Mexican forearc has occurred[143]. In addition, along the northwest coastal segment, forearc loss by subduction erosion is strongly supported by observed subsidence[15], arc retreat and forearc uplift[68,143-146]. To the southeast, truncation of the Mexican margin might have been enhanced since at least the early Miocene by the left-lateral translation of a large crustal basement block ('Chortís block') from southern Mexico to its present position in Central America[147-150]. Therefore, contribution of recycled eroded crust to the composition of the Plio-Quaternary TMVB arc magmas is likely.

The TMVB produces high-Mg# basalts and andesites with up to 600 ppm Cr and 280 ppm Ni (ref.[140]). The presence of high-Ni olivines (up to 5400 ppm Ni) with mantle-like $^3He/^4He$ signatures (7-8 R_a)[151], indicate that the TMVB magmas undergo negligible contamination during passage through the ~30-50 km thick continental basement[140,152]. Intriguingly, olivines with the mantle-like $^3He/^4He$ ratios also have high, crustal $\delta^{18}O$ signatures (+5.6 to +6.6‰; Fig. 3a,b), which points towards the contribution of slab-derived continental crustal material to the TMVB mantle wedge[6].

Contribution of recycled continental crust to the TMVB mantle wedge is also consistent with the radiogenic isotope and trace element systematics of the TMVB arc magmas. Regardless of being erupted from large-volume composite (several hundreds of km^3) or small monogenetic centers (<1 km^3), the TMVB magmas form tight, linear arrays in radiogenic isotope space that are bracketed by forearc and/or trench lithologies and the composition of the TMVB mantle wedge[6,7,153]. In addition, the isotopic arrays of the TMVB magmas cut through the much broader spectrum of isotopic compositions measured in the TMVB continental basement, which varies widely in thickness, composition and age[140,154-156].

Critically, the Nd-Hf isotope and trace element systematics of the TMVB arc magmas exclude the trench sediment as an important endmember in magma petrogenesis[6]. The trench sediment has a high Nd/Hf ratio of ~ 17 (ref.[157]); however, the linear TMVB array in εNd vs εHf **[G]** space requires that all slab components have a low Nd/Hf ratio of ~4-5, similar to the mantle wedge (Fig. 3). Recycled mid-ocean ridge basalt (MORB) type AOC has a low Nd/Hf ratio (~4-5), but has a similarly high εNd-εHf to the mantle wedge[6]. Thus, the low-εNd-εHf eroded forearc crust with a low Nd/Hf of ~5 is the only possible unradiogenic endmember of the TMVB array. If recycled in sufficient quantities, the eroded crust will be able to conceal the signature of the subducted trench sediment in the TMVB magmas (that is, a curved isotopic mixing trend in εNd vs εHf space; Fig. 3)[5,6].

Comparison of alongstrike radiogenic isotope trends in the arc and forearc have recently been used to further investigate the influence of erosion recycling in the TMVB, testing the hypothesis that the composition of the arc volcanics should reflect the parallel trend of the respective forearc lithologies[5]. The forearc trend was reconstructed through river mouth sediments at the Pacific coast, which are lithological composites of larger, but regionally limited, catchment areas[5]. Critically, the along-strike trends observed in the forearc data are similar to the parallel trends of major andesitic volcanoes (Sangangüey, Tequila, Colima), consistent with a compositional control by forearc crust recycling[5] (Fig. 4).

Further evidence for erosion recycling in the TMVB emerges from zircons in a Holocene andesite lava flow from the summit of Malinche, a major stratovolcano of the

Eastern TMVB (Fig. 5)[7]. The cores of the zircons have a Paleo-Proterozoic to Miocene age distribution that are inconsistent with the Ordovician to Jurassic ages and poly-deformed metamorphic lithologies of the deep crustal basement beneath Malinche[158] (indicating that they are not assimilated during passage through the crust). However, the zircon age distribution is remarkably similar to that of detrital zircons in crustal sediments from the Papagayo river, which drains into the Pacific where the trajectory of the slab subducting beneath Malinche intersects the trench, and from a hemipelagic mud unit recovered offshore at DSDP Site 467, <100 km to the southeast of Papagayo's river mouth (Fig. 5). As such, the Malinche zircon cores could be unmolten residues of eroded forearc crust that survived burial, erosion, subduction and ascent from the slab in comparatively cool silicic mélange diapirs **[G]** that traverse through a hot mantle wedge (>1000°C), to eventually re-appear as rare xenocrysts in the Malinche magmas[7].

Overall, the TMVB displays the best evidence for contribution of tectonically eroded crust to arc magma petrogenesis. The apparent presence of eroded forearc crust in in all major TMVB magmas series indicates that erosion recycled might widely affect global arc magmas[5,6].

[H1] SUMMARY AND FUTURE PERSPECTIVES

Subduction erosion is a common process in subduction zones and is responsible for the removal of large volumes of crust from the upper plate forearc. The volumes of eroded crust are so large that they must factor into the perpetual cycle of crustal destruction through subduction and new crust formation from the mantle as strongly as the subduction of AOC, trench sediment and hydrated mantle. In this Review, we have shown that integrated trench-forearc-arc studies at convergent margins, where eroded crust is formed and subducted, are crucial in determining the volume and composition of eroded material. However, although case studies provide strong arguments for the importance of erosion recycling, many questions still remain. Specifically, ongoing work continues to highlight several areas of research that need to be targeted in future studies to further explore and investigate the influence of erosion recycling at convergent margins.

[H2] Forearc exploration.

Establishing compositional connections between the arc and forearc provides key evidence for erosion recycling in arcs. The TMVB highlights what can be achieved in a favorable setting, whereas the Andean SVZ and CVZ demonstrate the issues that can arise if critical lithologies are not available or indistinct in composition. Future studies of the compositional variations along an arc and forearc must take into account the greater compositional variability of the forearc compared to the incoming plate. As a result, more sampling sites along the forearc are required to test along-strike arc-forearc correlation. Pilot studies could be used to identify the potential of a possible study areas. In addition, drilling to the zones of active subduction erosion, which is now technically possible[159], could help characterize the age, composition and origin of the eroding lithologies and thus improve constraints on the mechanism and rates of forearc erosion[4].

[H2] The origin of arc andesites.

Current estimates for the proportion of recycled eroded crust contributing to arc magmas range from a few (~2-6) percent in the Andean and Aleutian arcs[8,113,115,119,135] to several tens (~20-50) of percent in the TMVB[5,6,160,161]. A low percent contribution of eroded crust to arc magmas implies that the subducted eroded crust is mostly returned to the deep mantle[1] and new arc crust is primarily extracted from mantle[107,109,162]. However, a high percent contribution implies a more balanced distribution of eroded crust between the shallow arc and the deeper mantle, and indicates that new arc crust might be partially rebuilt from subducted eroded crust[5].

The disparity in the numbers estimated for the contribution of eroded crust to arc magmas is dependent on the arc genetic model employed and, more specifically, on the long-standing problem of whether primary arc magmas are basaltic or silicic[151,163-168]. Primary arc basalts (MgO ≥10 wt%; Mg#≥72)[169], and high-Mg# andesites that form by hydrous mantle melting[170-172], contain only a few percent of slab materials (eroded crust+AOC+trench sediment) prior to crustal differentiation. However, in primary andesitic and dacitic (that is, silicic) melts that erupt with little need for additional crustal differentiation, the contribution of slab material can be much larger[5,151,165,173,174].

Few arc magmas display the steep heavy REE patterns and high Sr/Y and Sr/Yb ratios that are considered characteristic of melts from a garnet-bearing source, which precludes global arc magmas originating from silicic partial melts of the subducting eclogitic slab[175,176]. However, in recent years two models have been proposed that aim to explain the formation of primary silicic magmas (that is, andesites to dacites) that are rich in slab material but do not have a 'garnet signature'. The first model proposes that reactive infiltration of silicic slab melts into the peridotite mantle wedge produces secondary, silica-oversaturated pyroxenite segregations[151], which then produce primary silicic melts upon melting at shallower levels in the mantle wedge[177,178]. Formation of mantle pyroxenite consumes tens of percent of silicic slab material, and results in the presence of melts that contain contributions from both slab and mantle , in which only a few elements, such as Mg, Fe, Ti and the tell-tale heavy REE, remain mantle-controlled[151,160,161,179]. This process could create high-Mg# andesites[151] independent from melt water content in all arc settings, such as the TMVB[140], Kamchatka[180-182], New Zealand[183-185], the Western Aleutians[186] and the Cascades[187-190]

The second model that has been proposed builds on the idea of slab diapirs and mélanges[9,51,52,191], which are predicted to buoyantly rise from a layer of silicic, low-density crustal material on top of the slab, between the dense eclogitic below and mantle peridotite above[51,52]. Silicic diapirs can either rise to the base of the crust where they 'relaminate'[9,191], or erupt as arc magmas after reactive interaction and melting in the mantle wedge[5-7]. Slab diapirs transfer a substantial mass of bulk crust to the wedge, and can include elements not mobilized in slab partial melts, such as Fe, Mg, and Ti from granodiorites[6] or as part of 'mélange diapirs' that contain mafic material from the AOC[34,55,56]. The compositional consequences of slab or mélange diapirs for arc magmas has only recently begun to be explored[5-7,34,52,56]. Nevertheless, there is clear potential for the creation of an enriched, heterogeneous mantle that produces a diverse spectrum of basaltic and silicic primary arc melts with flat heavy REE patterns[5,6,173].

Importantly, a global evaluation of arc magma compositions does not support the traditional model of melt silica increase by crustal contamination, providing additional evidence for the presence of primary silicic magmas generated in the mantle wedge (Fig. 6). An increase in the silica content of a magma by incorporation of fusible, silicic upper plate crust into hot basaltic mantle melts seems intuitive, especially given the strong and pervasive melt mixing features observed in all arc magmas[105,151,192-199]. However, contrary to expectations, melt SiO_2 contents do not correlate with radiogenic isotope ratios, such as $^{207}Pb/^{204}Pb$, that are highly sensitive to assimilation of continental crust (Fig 6, 7).

It is possible that the isotope ratios of basaltic arc magmas, especially Pb isotopes, are fixed by small amounts of contamination in the deep crustal basement[116,127,200]. Basaltic melts might then evolve to silicic melts by closed system fractional crystallization[201], and mix by recharge mixing **[G]** during polybaric, multi-stage melt ascent. Rigorous testing of arc input-output relationships, using microanalysis of crystalline phases (phenocrysts)[160,181,195,202-204] and their melt inclusions[205,206], is required to investigate the possible assimilation of additional components in the deep crust. However, detailed microbeam studies of phenocrysts in both the simple magma systems of monogenetic volcanoes[161,207] and the complex systems of composite volcanoes[198,199] have, so far, failed to reveal a co-genetic evolution from basalt to dacite. Instead, the observed melt diversity, as evidenced by the range of both phenocryst and bulk-rock compositions, has been attributed to the presence of multiple, basaltic to silicic, melt components in the sub-volcanic plumbing system[153,161,195,199,208,209]. In some cases, the range of melt compositions that are present have been interpreted to represent primary melts from a heterogeneous mantle created by active subduction[151].

[H2] Mantle wedge heterogeneity.

Aside from determining the contribution of crustal assimilation, another factor that influences the estimated contribution of subducted material to arc magmas is the composition of the ambient mantle wedge. Traditionally, the mantle wedge has been considered to represent depleted upper mantle[210], which is actively enriched by subduction through addition of enriched slab components, including high-mass slab partial melts and diapirs[6,19,33,113]. However, it has recently been suggested that low-mass fractionated slab fluids, added to an enriched, heterogeneous mantle can create similar trace element and isotopic variations as strong subduction enrichment[107,124,131].

Distinguishing between the presence of an inherent enriched component and contribution of recycled eroded crust is complicated[107,129], owing to the similar composition of the source components involved in each model. For example, inherently enriched mantle (EM) is believed to form through the deep subduction of slab materials beyond the arc volcanic front and their integration into the sources of ocean island basalts (OIB)[13,21,25,103].

EM1 and EM2, the two most common 'flavours' of enriched mantle in OIBs, have been related to the deep recycling of eroded crust[24,25,102] and sediment[13,21], respectively (although EM1-type mantle has also been connected with the metasomatised subcontinental lithosphere)[103,107,109,131,211,]. Nd and Hf are largely immobile in slab fluids, but sensitive to contribution of slab materials recycled via partial melts[19,33] and diapirs[5,6]. As a result, Nd-Hf isotope and trace element systematics should reveal whether EM-type magmas and arc magmas have a common mantle source. In a plot of εNd vs. εHf, arc magmas fall into two groups (Fig. 7). One group, which is represented by only a few arcs (Sunda, Banda, southern Lesser Antilles, and Luzon), forms concave downward mixing trends between a radiogenic, depleted mantle and a low εNd-εHf crustal end member (Curve A in Fig. 3c). Arcs that fall into this first group also have high $^{207}Pb/^{206}Pb$ ratios (Fig 6a), indicative of sediment recycling. Only clay-rich sediment with a high Nd/Hf >10 (ref.[157]) can re-produce these curved trends[6,19,212,213], given that the mantle has low Nd/Hf ~4-5 (ref.[210]).

Most arcs, such as the TMVB, Central American arc and the Andean SVZ, form straight arrays in εNd-εHf space (Fig. 7), which overlap with the composition of EM-type OIBs[102] and are thus consistent with a common EM-type source[107]. However, the linear arrays displayed in εNd-εHf space by most arcs can also be explained by slab-mantle mixing in the active subduction regime, provided that the slab components share the low Nd/Hf ratio of the mantle (~5-6). A range of low Nd/Hf slab components exist, including terrigenous trench sediment[110,157], eroded continental rocks[214], and MORB and OIB-type oceanic crust[215,216]. As the high Nd/Hf sediment subgroup[14,157] has a clear influence on some arc magmas (Curve A on Fig. 7), and must be related to the presence of subduction materials, the 'straight' εNd-εHf arc trends are also likely to have a subduction origin.

The εNd-εHf trends observed in arc magma compositions are best revealed from unfiltered arc data. Filtering for mafic arc magmas (that is, those with MgO>6 wt% or Mg#>60) would remove ~70% of the arc εNd-εHf data and thus reduce the clarity of the mixing systematic. Considering unfiltered datasets implicitly assumes that there is no major influence of crustal contamination, consistent with the $^{207}Pb/^{204}Pb$ vs. SiO_2 trends (Fig. 6) and supported by the combined $^3He/^4He$ and $\delta^{18}O$ systematics of the olivines from the TMVB (Fig. 3)[6].

Future studies should focus on analysis of the cosmogenic isotope ^{10}Be in arc magmas, as it is the only geochemical tracer that can conclusively distinguish a subduction-related input from inherent mantle enrichment. ^{10}Be is formed by cosmic ray spallation in the atmosphere[30,217] and, owing to its short half-life of 1.5 Myr, it is enriched in upper marine sediments, but never in the mantle[30]. The presence of measurable ^{10}Be in arc magmas proved sediment recycling beyond doubt[10,218]. ^{10}Be is expensive and difficult to measure, yet a detection in arcs may allow to test for links between an enrichment and slab processing, at least in those arcs where the transit time from trench to arc remains with the ≤ 6 Myr lifespan of ^{10}Be (ref.[30]).

The influence of underlying mantle heterogeneity and/or eroded crust on arc magmas can also be tested through integrative and comprehensive geochemical analyses of single arc setting. Future studies of arcs and forearcs should make use of the available toolbox of geochemical tracers (that is, major and trace elements and Sr-Nd-Pb-Hf-He-O-Os-B-Be isotopes), as well as emerging new isotope tracers, such as $^{238}U/^{235}U$ (refs.[20,219]), $^{205}Tl/^{203}Tl$ (ref.[220]) or $^{138}Ce/^{142}Ce$ (ref.[221]). Analysis of all end-member materials, including next to trench, forearc and arc lithologies, and rear-arc magmas, which may be considered free from subduction influence while still close enough to the active arc to approximate the regional ambient mantle[107,129], must be considered. For example, rear-arc magmas of the TMVB[142,222,223] have εNd values that are too radiogenic to account for the most unradiogenic TMVB magmas[5,6,153,224,225], which confirms that the εNd-εHf systematics of the TMVB are controlled by forearc crust recycling[5,6]. In the Andean SVZ, where rear-arc volcanism is abundant[226-228], rear-arc and arc front magmas have a similar range in εNd vs εHf space, which seems to point to common, inherently enriched EM-type mantle source[107,129,131]. However, a larger dataset revealed that the SVZ arc front and rear-arc magmas form two parallel trends in εNd vs εHf space[131], which indicates that the arc magmas are also influenced by active subduction recycling[107].

We stress that regional-scale, multidisciplinary studies that integrate geological and geochemical data from the trench, forearc, arc and rear-arc are needed to understand the impact of erosion recycling on volcanic arcs and, ultimately, its role in generating mantle heterogeneity as well as growth and destruction of the continental crust.

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ACKNOWLEDGEMENTS

SMS acknowledges support from National Science Foundation grants OCE 09-61359, EAR 12-20481, EAR 19-21624 and a Kyoto University Visiting Fellowship. AGT studies were supported by Consejo Nacional de Ciencia y Tecnología (CONACyT, Mexico) grant 239494.

AUTHOR CONTRIBUTIONS

SMS perceived and drafted the manuscript, which was revised and amended by PV and AGT. PV provided updated the rates of forearc erosion and sediment subduction (Supplementary Information). All authors contributed to the discussion.

COMPETING INTERESTS

The authors declare no competing interests.

Peer review information

Nature Reviews Earth & Environment thanks A. Stracke, C. Stern, S. Kay and the other anonymous reviewer(s) for their contribution to the peer review of this work

Publisher's note

Supplementary information:

Supplementary information is available for this paper at https://doi.org/10.1038/s415XX-XXX-XXXX-X

KEY POINTS

- Subduction zones recycle upper plate crust by subduction erosion in volumes that can exceed those of the subducted trench sediments.
- The composition of the eroded crust is varied and can include upper and lower continental crust as well as oceanic crust.
- Strong compositional forearc-arc links exist.
- Arc magma petrogenesis plays a key role in elucidating forearc-arc connectivity.

- Tectonically eroded crust can refertilize shallow and deep mantle alike.

FIGURE CAPTIONS

Figure 1: **Subduction zone cartoon of erosive margin**. The location of the frontal prism, resistive backstop and the subduction channel are shown in the right-hand inset. AOC – altered oceanic crust. Material from the frontal prism can be eroded by incorporation into the subduction channel. Adapted with permission from refs.[2,5,6].

Figure 2: **Classification of margins as erosive or accretionary and comparison to arc εNd values**. Data represents the average εNd values for n=785 Quaternary arc volcanoes, calculated from available GeoROC data[229] and pre-compiled data sets of the Central American Volcanic Arc[230] and of the Central Andean Volcanic Zone[231].

Figure 3**: Geochemical variations of global arcs with details from the Transmexican Volcanic Belt (TMVB)**. **a:** εNd vs εHf of the TMVB (n=598)[229], global arc data (grey, n=4742)[229], the Mexican forearc crust[5,6] and average trench sediment (brown diamond)[157]. **b:** $^3He/^4He$ (Ra) vs. $\delta^{18}O$ (‰) of olivine phenocrysts from a subgroup of TMVB basalts and andesites. Combined high, mantle-like $^3He/^4He$ (~7-8 R_a) and high crustal $\delta^{18}O$ (>5 ‰) indicates that the melt originated from a mantle infiltrated by crustal slab components[6]. **c:** Mixing systematics in εNd vs εHf space. Curved (A) vs straight (B) trends resulting from mixing of end member with similar εNd and εHf, but different Nd/Hf ratios. M - mantle, S - trench sediment, C - crust with low Nd/Hf (such as continental crust or unradiogenic intraplate crust). Modified and updated after ref.[6].

Figure 4: **Arc and forearc compositional variations in the Western Transmexican Volcanic Belt**. Data is presented from andesite volcanoes Sangangüey, Tequila and Colima and forearc lithologies (river mouths sediments and bedrock). Forearc lithologies include the Late Cretaceous Puerto Vallarta Batholith (PVB, ~82 Ma) and coeval rhyolites (R), the Manzanillo Batholith (MS, ~73 Ma), and the Paleocene Jilotlán Batholith (JP ~58 Ma), which intrude early Cretaceous rocks and associated volcano-sedimentary sequences (VS), and Paleocene felsic plutonic rocks (FP). Colored stippled lines represent the trajectories followed by subducted material. EPR—East Pacific Rise. Modified and updated from ref.[5].

Figure 5: U-Pb dating of Malinche zircons. a: U-Pb concordia diagram of Malinche zircons compared to detrital zircons from the Papagayo river and a Pliocene-Quaternary, 182 m thick hemipelagic gray mud unit of 0-5 Ma drilled at DSDP Site 487 (near the trench). Data-point error ellipses at the 2σ level. Constructed with IsoplotR[232]. **b:** Cathodoluminescence images of Malinche's zircon xenocrysts with $^{238}U/^{206}Pb$ ages in Ma. Inherited cores of Proterozoic and Paleozoic age (red) are overgrown by effectively zero age (<2 Ma) rims (green), which grew in Quaternary Malinche magmas. Modified from ref.[7].

Figure 6: Major element versus isotopic systematics of global arc magmas. **a:** SiO_2 wt% vs $^{207}Pb/^{204}Pb$ for global arc volcanic rocks (n=3683). A subset of six arcs is highlighted: Mexico, Central America (Costa Rica, Nicaragua, and El Salvador), Andean Southern Volcanic Zone (SVZ), Sunda, Banda and the Southern Antilles. Horizontal lines represent the average $^{207}Pb/^{204}Pb$ of an arc. **b:** Histogram of correlation coefficients for SiO_2 vs. $^{207}Pb/^{204}Pb$ from 38 arc segments[229]. All arc data are from ref.[229].

Figure 7: Isotopic systematics of global arc magmas. a: εNd *vs* εHf of global arc volcanic rocks of

Quaternary age (n=1054) compared to MORB[215], oceanic intraplate basalts[216] and global trench sediments[110]. **b:** εNd *vs* εHf of global arcs with six arcs highlighted: Mexico, Central America (Costa Rica, Nicaragua, and El Salvador), Andean Southern Volcanic Zone (SVZ), Sunda, Banda and the Southern Antilles. εHf is available for only ~22% of the samples for which εNd data is available. Notably, εHf is missing for some samples that have the lowest εNd values (-1.7 to -10.6) of any magmas from the Andean Central Volcanic Zone (CVZ). Red stippled lines indicate typical 'curved' mantle-sediment mixing trends. All arc data are from ref.[229].

GLOSSARY TERMS

Subduction erosion	*[tectonic removal of upper plate material in subduction zones]*
Frontal erosion	*[tectonic removal of material from the frontal part of the forearc]*
Basal erosion	*[tectonic removal of upper plate material from the underside of the upper plate]*
Forearc	*[region between arc and trench]*
Frontal prism	[*an actively deforming wedge at the toe of the forearc]*
Backstop	*[Point of coherent, resistive upper plate rock framework closest to the trench]*
Accretionary prism	*[wedge-shaped body constructed mostly of sediment that has been scraped off the subducting plate]*
Frontal accretion	*[accretion of lower plate material to the forearc]*
Subduction channel	*[Plate boundary shear zone conveying material from the shallow part of the subduction zone toward the mantle].*
Underplating	*[accretion of lower plate material to the base of the upper plate]*
Hydrofracturing	*[rock failure induced by overpressured fluids]*

Slab fluids	*[fluid expelled from subducting lithospheric plate into the mantle wedge]*
Slab partial melts	*[partial melt released from subducted lithologies into the mantle wedge]*
Slab diapirs	*[low density material that buoyantly rises from the slab into the mantle wedge]*
Mélange diapirs	*[slab diapirs rising from zones of the intensely sheared and mixed metamorphic sedimentary and igneous rocks at the interface between the subducted slab and the mantle*]

Primary arc magmas	*[mantle wedge magmas prior to modification in the crustal basement*].
Arc crust production rate	*[rate of arc crustal growth by addition of mantle-derived melts to arc crust per time increment, given in km^3/per km of arc length/my, or km^3/my, when normalized to length of global arcs].*
εNd	*[deviation of ^{144}Nd/^{143}Nd from the Chondritic Uniform Reservoir (CHUR) ratio; calculated as* $\boldsymbol{\varepsilon}\textit{Nd} = (^{144}\textit{Nd}/^{143}\textit{Nd}/0.51263)-1]*10000]$.
εHf	*[deviation of ^{176}Hf/^{177}Hf from the Chondritic Uniform Reservoir (CHUR) ratio; calculated as* $\boldsymbol{\varepsilon}\textit{Hf}: (^{176}\textit{Hf}/^{177}\textit{Hf}/0.282785)-1]*10000]$.
Recharge mixing	*mixing of different magma batches incited by the ascent of new primary melt*.
Corner flow	*mantle wedge flow towards the subducting slab induced by viscous coupling between the downgoing slab and overlying mantle wedge.*
Ambient mantle	*mantle wedge that is not affected by a slab component*.
Mg#	*the molar ratio of Mg/(Mg+Fe^{2+}) in magmas. Primary mantle melts usually have a Mg#*≥72.

TOC summary

Subduction erosion transports crustal material from the upper plate at subduction zones into the mantle and thus likely contributes to the composition of arc magmas. This Review discusses the evidence for subduction erosion globally and outlines how a contribution of tectonically eroded crust can be identified in arc magmas.