

# Tectonic Erosion

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*"In space, no one can hear you think."*

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# 1 Tectonic Erosion

## 1.1 Defining Tectonic Erosion

Tectonic erosion represents one of Earth's most fundamental yet long-overlooked geodynamic processes, operating silently beneath oceans and continents to reshape our planet's architecture over millions of years. Unlike the familiar surface erosion sculpted by wind, water, and ice, tectonic erosion operates in the crushing depths where tectonic plates converge, systematically stripping material from the overriding plate and recycling it into the mantle. This profound mechanism stands as a counterpoint to continental growth, challenging earlier assumptions that subduction zones primarily built continents through accretion. Its discovery fundamentally altered our understanding of plate tectonics, revealing that Earth's crust undergoes not just creation and deformation, but also profound, irreversible consumption at its margins.

The core concept centers on the removal of material from the base or leading edge of an overriding tectonic plate during subduction. This occurs through two primary, often synergistic mechanisms. Mechanical scraping, or frontal erosion, happens when rugged topography on the descending plate – submerged volcanoes (seamounts), fractured oceanic crust, or sedimentary ridges – acts like a geological rasp. As these asperities plunge beneath the overriding plate, they physically scrape and pluck rock fragments from its underside. A dramatic example unfolded during the 2011 Tohoku earthquake off Japan, where seismic data revealed seamounts on the Pacific Plate gouging material from the Eurasian Plate's margin just before the catastrophic rupture. Simultaneously, chemical dissolution, or basal erosion, operates where high-pressure fluids released from the subducting slab percolate upwards. These fluids, enriched in volatiles like water and carbon dioxide, react with the overlying mantle wedge, forming serpentine minerals that weaken the base of the overriding crust. Hot, chemically aggressive fluids then infiltrate fractures, dissolving silicate minerals and transporting the dissolved material downwards or laterally. The Costa Rica Seismogenesis Project (CRISP) drilling documented this process, finding highly altered, weakened rocks permeated by fluid pathways directly above the subduction interface, indicating pervasive chemical corrosion.

Distinguishing tectonic erosion from its counterpart, subduction accretion, is crucial for understanding convergent margin dynamics. Accretion occurs when sediments and fragments of oceanic crust are scraped off the downgoing plate and plastered onto the leading edge of the overriding plate, building outward and thickening the crust. This process creates characteristic, thick sedimentary wedges like the Cascadia margin off North America's west coast. In stark contrast, erosional margins, such as much of the Andean coast in South America, appear starved. Diagnostic signatures reveal this stark difference: eroded margins typically lack substantial accretionary wedges, display unusual forearc subsidence (where the region between the volcanic arc and the trench sinks rather than rises), and show truncated geological structures abruptly cut off at the trench. Geophysical profiles across the Peru-Chile Trench, for instance, reveal a steep, narrow continental slope devoid of the chaotic, thrust-faulted sediments common in accretionary prisms. Instead, seismic images show older basement rocks exposed near the trench, their edges sheared off, providing direct evidence of material loss rather than gain. The presence of submarine canyons cutting across the forearc, funneling sediments directly into the trench rather than being trapped in an accretionary wedge, further signals an

erosive regime.

The global significance of tectonic erosion extends far beyond individual subduction zones; it profoundly impacts Earth's long-term evolution and crustal budget. Over geological timescales, it acts as a primary mechanism for recycling continental material back into the mantle, counterbalancing crustal growth via magmatism at volcanic arcs. While arc magmatism adds new crust, studies integrating geochemical mass balances and plate reconstructions suggest that net continental crust volume may have remained relatively constant or even decreased slightly over the last 3 billion years, largely due to the pervasive effects of tectonic erosion operating at many convergent boundaries. This process plays a critical role in the supercontinent cycle. Extensive erosion weakens and thins continental margins, potentially facilitating the rifting phase when supercontinents like Rodinia or Pangea begin to fragment. Conversely, the transition from accretion to erosion at a margin can influence the dynamics of continental collision. Furthermore, the material lost through erosion – sediments rich in incompatible elements and volatiles, fragments of continental crust – is transported deep into the mantle. This subducted mélange contributes significantly to mantle heterogeneity, forming distinct geochemical reservoirs (like the EM1 and EM2 components) that are later sampled by mantle plumes feeding ocean island volcanoes such as Hawaii or Pitcairn. Thus, tectonic erosion acts as a crucial, though destructive, conveyor belt within Earth's deep geochemical cycles.

Understanding this fundamental process of planetary recycling sets the stage for exploring its intricate history, mechanisms, and far-reaching consequences. We now turn to the fascinating evolution of scientific thought that gradually unveiled this hidden dimension of plate tectonics.

## 1.2 Historical Discovery

The profound implications of tectonic erosion for Earth's crustal budget and mantle geochemistry, as established in Section 1, emerged only after decades of scientific struggle against deeply entrenched paradigms. The recognition that convergent boundaries could devour continental crust rather than build it unfolded as a fascinating saga of overlooked evidence, technological breakthroughs, and intellectual resistance – a classic example of how scientific revolutions challenge even the most elegant theories.

### 1.2.1 Early Plate Tectonics Models (1960s-1980s)

The plate tectonics revolution of the 1960s provided an extraordinarily powerful framework for understanding Earth's dynamism, yet its initial formulations harbored a significant blind spot. Early models, heavily influenced by the elegant symmetry of seafloor spreading and the Vine-Matthews-Morley hypothesis explaining magnetic stripe patterns, overwhelmingly conceptualized subduction zones as sites of net crustal growth. Accretion was the expected norm, driven by the mechanical offscraping of sediments and upper oceanic crust from the downgoing slab to form growing wedges. This perspective was reinforced by studies of margins like the Cascadia subduction zone off North America, where thick, chaotic sedimentary sequences clearly indicated material accumulation. The paradigm was so dominant that anomalous observations elsewhere were often dismissed or forced into the accretionary model. For instance, seismic reflection profiles

across the Peru-Chile Trench in the 1970s revealed a startlingly thin sediment cover and an apparent absence of the expected accretionary prism. Rather than questioning the model's universality, researchers initially speculated about unusually efficient sediment subduction or atypical oceanic crust composition. The concept that the overriding plate itself could be actively consumed seemed geologically heretical, contradicting the prevailing narrative of progressive continental growth. Furthermore, the focus on large-scale plate motions and the success of magnetic anomaly mapping overshadowed the subtle, destructive processes occurring at the plate interface itself, processes not easily captured by the broad brushstrokes of early global tectonics.

### 1.2.2 Pioneering Research Breakthroughs

The paradigm began to fracture in the late 1980s and early 1990s, spearheaded by meticulous marine geophysical surveys and deep-sea drilling campaigns that focused on non-accreting margins. A seminal moment came with the work of geophysicists Roland von Huene and David Scholl. Their extensive seismic studies along the Mariana Trench and the Middle America Trench off Central America provided undeniable evidence that large volumes of material were missing. They observed that the geological structure of the forearc, the region between the trench and the volcanic arc, was truncated. Older rocks, which should have been buried deep within a growing accretionary wedge, were instead exposed near the trench axis, their edges sheared off. Their landmark 1991 synthesis paper, "Observations at Convergent Margins Concerning Sediment Subduction, Subduction Erosion, and the Growth of Continental Crust," crystallized the evidence, proposing tectonic erosion as a fundamental global process responsible for the "missing" mass. This breakthrough was technologically enabled by advances in seismic reflection and refraction techniques, particularly multi-channel seismic systems and early seismic tomography. These tools revealed the true structure beneath the seafloor, showing not just the absence of accretionary wedges, but also abnormal subsidence patterns in the forearc – a key diagnostic signature of underlying material removal. Concurrently, geochemical studies began identifying unexpected tracers in arc magmas, such as cosmogenic Beryllium-10. This isotope, formed only in the atmosphere and with a short half-life, should not survive recycling into the mantle unless carried down rapidly by subducted sediments *and* fragments of the overriding plate. Its presence in volcanic rocks far from the trench provided an isotopic smoking gun for the erosion and deep recycling of surface material.

### 1.2.3 Paradigm Shift Acceptance

Despite mounting evidence, the concept of tectonic erosion faced substantial resistance within the geological community. Accepting that continents could shrink challenged core tenets of geology that emphasized crustal growth and permanence. Critics argued that the observed subsidence and structural truncation could be explained by localized extension or strike-slip faulting rather than wholesale removal. The breakthrough toward widespread acceptance came primarily from two sources: the Ocean Drilling Program (ODP, and later IODP) and catastrophic earthquakes. ODP Leg 67 drilled into the forearc slope off Guatemala, part of the erosive Middle America Trench. Core samples recovered highly fractured, fluid-altered rocks directly above the subduction interface – not the expected sedimentary wedge. Geochemical analyses revealed intense fluid-rock interaction and mineral dissolution consistent with basal erosion processes. Even more compelling was

the recovery of rocks with geological histories proving they were once part of the overriding plate but were now being undercut and destabilized. Meanwhile, the devastating 2011 Tohoku-Oki earthquake (Mw 9.0) off Japan provided a dramatic real-time demonstration. High-resolution bathymetric surveys before and after the quake, combined with seismic rupture models, showed that seamounts on the Pacific Plate had acted like geological rasps, scraping material off the underside of the Eurasian Plate during the megathrust event. This direct link between erosive processes and major seismic hazards forced a fundamental reevaluation. By the early 2000s, the combined weight of geophysical, geochemical, drilling, and seismological evidence had become overwhelming. Tectonic erosion was recognized not as a rare anomaly, but as a dominant process at approximately half of the world's subduction zones, fundamentally altering our understanding of crustal evolution and Earth's deep geochemical cycles.

This hard-won understanding of how continents can be consumed at their margins sets the stage for delving into the intricate physical and chemical mechanisms that drive tectonic erosion itself – the subject of our next exploration.

### 1.3 Geological Mechanisms

The hard-won recognition that tectonic erosion actively consumes continental margins, as chronicled in our historical review, inevitably leads to a deeper question: *how* does this profound destruction actually operate? Unveiling the intricate mechanisms—physical scraping, chemical dissolution, and the complex interplay of fluids and rock under extreme conditions—reveals a dynamic and often violent process operating at the very interface where Earth's tectonic plates collide and one descends into the abyss.

**Frontal Erosion Processes** represent the most visually intuitive mechanism, often likened to a geological rasp or bulldozer operating at a continental scale. This destructive force manifests primarily along the leading edge of the overriding plate, driven by the relentless advance of the subducting slab and its inherent ruggedness. Imagine the subducting oceanic plate not as a smooth conveyor belt, but as a landscape scarred by immense seamounts (undersea volcanoes), fractured ridges, horst-and-graben structures formed at spreading centers, and thick piles of trench sediments. As this topographically complex slab descends, these asperities act as tools of destruction. Seamounts, acting like indenters or chisels, gouge directly into the toe of the overriding plate. The impact is not merely superficial scraping; it involves large-scale fracturing, plucking of massive rock blocks, and the wholesale collapse of the upper plate margin into the trench. The 2011 Tohoku-Oki earthquake provided a chillingly clear demonstration. High-resolution bathymetry before and after the event, combined with seismic rupture models, revealed that seamounts on the Pacific Plate acted as pivot points during the megathrust slip. Their movement fractured and displaced vast sections of the Eurasian Plate's leading edge, effectively bulldozing crustal material down into the subduction zone – estimated volumes reached several cubic kilometers in this single event. This process, termed “tectonic rasping,” leaves unmistakable signatures: deeply incised grooves or “subduction scars” on the trench slope (observed offshore Nicaragua and Peru), pervasive normal faulting near the trench axis indicating collapse, and the incorporation of large, angular blocks of continental material within the subducting mélange, identifiable in seismic profiles as “knockers” or chaotic reflectors. Furthermore, the subducting plate rarely

descends smoothly; it often bends sharply just before entering the trench, creating horst-and-graben structures. The leading edges of these horsts (uplifted blocks) act like chisels, systematically chipping away at the overriding plate base, a process particularly evident along sediment-starved margins like the Mariana Trench.

**Basal Erosion Dynamics**, operating beneath the frontal edge and along the underside of the overriding plate, are less visually dramatic but equally potent and pervasive. This mechanism hinges on the profound influence of fluids and the consequent weakening of the rock mass. As the subducting oceanic plate descends, it undergoes progressive metamorphism, releasing vast quantities of bound water and other volatiles ( $\text{CO}_2$ , chlorine) from minerals like chlorite, lawsonite, and serpentinite. These fluids ascend into the overlying “mantle wedge,” the hot, viscous region between the subducting slab and the base of the overriding plate. Here, they trigger a critical transformation: serpentinization. The influx of water reacts with olivine and pyroxene minerals in the mantle peridotite, forming serpentine group minerals. While serpentinite is stable under high pressure, it is significantly weaker – up to two orders of magnitude less strong – than the original mantle rock. This creates a pervasive zone of weakness right at the critical interface. Think of it as transforming a solid foundation into a layer of slippery mudstone. This serpentinized mantle layer, directly beneath the crust of the overriding plate, provides a mechanically weak detachment zone. Crucially, these high-pressure, chemically reactive fluids don’t just weaken the rock; they actively invade the base of the overriding continental crust. They exploit fractures, shear zones, and grain boundaries, hydrating and altering crustal rocks, further reducing their strength and cohesion. The Costa Rica Seismogenesis Project (CRISP) drilling provided direct evidence. Cores recovered from the Costa Rican forearc slope revealed highly fractured and altered rocks immediately above the plate interface, permeated by veins and showing extensive evidence of dissolution and replacement minerals formed by fluid-rock interaction. The net effect is a gradual, pervasive “undercutting” of the overriding plate. Material along this weakened basal detachment becomes susceptible to ductile shearing, hydrofracturing, and eventual detachment, being dragged down or smeared along with the subducting slab. The analogy used by researchers like Robert Stern is apt: the base of the overriding crust becomes like a sugar cube dissolving in hot tea, progressively losing mass from below.

**Chemical Corrosion** operates synergistically with, and often as a consequence of, basal erosion processes, representing the deep geochemical engine of material dissolution and transport. The high-pressure fluids liberated from the subducting slab and circulating through the mantle wedge are not benign; they are hot ( $300\text{--}700^\circ\text{C}$ ), acidic, and enriched in silica-undersaturated components derived from the dehydrating slab. These include elements like silica ( $\text{SiO}_2$ ), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), and various incompatible trace elements liberated during breakdown of slab minerals. When these aggressive fluids infiltrate the base of the overriding plate, they initiate complex metasomatic reactions. Silicate minerals within the crust, particularly quartz and feldspars, become thermodynamically unstable in the presence of these fluids. Under high pressure and temperature, dissolution occurs: the minerals break down, and their constituent elements are liberated into the fluid phase. The dissolved load – silica, alumina, alkalis – is then transported away. This transport can be downward into the mantle via the circulating fluids, laterally along the plate interface, or potentially upwards to contribute to arc magmatism. Evidence for this pervasive chemical stripping is found in exhumed terranes – slices of ancient subduction zones thrust to the surface by later

tectonic events. The Zermatt-Saas ophiolite in the Swiss Alps, once part of the Tethyan subduction system, exposes rocks that were the mantle wedge beneath an overriding plate. Within these peridotites, scientists find veins and diffuse zones enriched in silica, amphibole, mica, and garnet – minerals crystallized from the very fluids that dissolved material from the overlying crust. These metasomatic assemblages are direct fingerprints of fluid-mediated chemical exchange and removal. Laboratory experiments simulating subduction zone pressures and temperatures, such as those by Tenthorey et al., confirm the efficacy of this dissolution. They show that quartz, a primary component of continental crust, dissolves readily in slab-derived fluids at depths corresponding to 30-80 km, with dissolution rates increasing dramatically with temperature and fluid flux. The cumulative effect over millions of years is the wholesale chemical “corrosion” of the continental crust’s underbelly, transforming solid rock into a mobile ionic soup destined for mantle recycling.

Thus, tectonic erosion emerges not as a single process, but as a destructive symphony orchestrated by immense physical forces and intricate geochemical reactions. Frontal erosion acts as the battering ram, fracturing and collapsing the margin’s leading edge. Basal erosion, facilitated by fluid-mediated weakening and detachment, systematically undercuts the plate’s foundation. Chemical corrosion, driven by reactive fluids, dissolves the very minerals binding

## 1.4 Diagnostic Evidence

The intricate physical scraping and chemical dissolution mechanisms driving tectonic erosion, as detailed in the previous section, operate over geological timescales and at crushing depths, making direct observation profoundly challenging. Yet, the cumulative impact of this continental consumption leaves indelible fingerprints across multiple scientific disciplines. Identifying these diagnostic signatures requires the integration of geophysical imaging, geochemical forensics, and geomorphological detective work – a multidisciplinary approach that has transformed tectonic erosion from a theoretical concept into a quantifiable global phenomenon.

**Geophysical Signatures** provide the most direct spatial evidence of material loss at convergent margins. Seismic reflection profiling, the geological equivalent of medical ultrasound, is paramount. Across erosional margins like the Peru-Chile Trench or the Mariana system, these profiles consistently reveal the stark absence of a substantial accretionary wedge – the chaotic, thrust-faulted pile of sediments that typifies building margins like Cascadia. Instead, seismic images show older, often crystalline, basement rocks of the overriding plate truncated abruptly near the trench axis. These rocks appear structurally “cut off,” their expected continuation beneath an accretionary prism simply missing. Furthermore, detailed velocity models derived from seismic refraction and tomography often detect anomalously thin crust within the forearc region. This thinning isn’t uniform; it frequently increases towards the trench, signaling progressive removal rather than initial structure. A critical diagnostic pattern is abnormal forearc subsidence. While accretionary margins typically experience uplift due to crustal thickening, erosional forearcs subside, often rapidly. This subsidence manifests as deep forearc basins filled with younger sediments overlying older, truncated sequences. The Costa Rica Seismogenesis Project (CRISP) seismic data vividly illustrates this: the margin offshore Osa Peninsula shows a forearc basin subsiding at rates exceeding 1 km per million years, with



seismic horizons tilting trenchward – a telltale sign of basal erosion undermining support. Modern high-resolution techniques like 3D seismic tomography, exemplified by projects such as ALPArray in the Alps (investigating the fossilized Tethyan margin), reveal subtle details: low-velocity zones along the plate interface indicating fluid-rich, serpentized mantle that facilitates basal erosion, and fractured, disrupted crustal fabric in the overriding plate. The 2011 Tohoku earthquake rupture zone, imaged in unprecedented detail, provided a seismic snapshot: high-resolution bathymetry combined with seismic rupture models showed distinct zones of compressional deformation landward of the trench (where material was bulldozed) and extensional collapse trenchward, directly correlating with seamount-induced frontal erosion mapped before the quake.

**Geochemical Tracers** offer a powerful, albeit indirect, method to fingerprint the erosion and recycling of crustal material, acting as isotopic detectives probing deep Earth processes. The most compelling tracer is cosmogenic Beryllium-10 ( $^{10}\text{Be}$ ). This radioactive isotope (half-life 1.39 million years) is produced only in the atmosphere by cosmic ray spallation of nitrogen and oxygen, adsorbed onto sediment particles, and deposited on the seafloor. Its presence in arc magmas erupted hundreds of kilometers from the trench is profound evidence.  $^{10}\text{Be}$  cannot survive prolonged residence in the hot mantle; its detection in volcanic rocks like those from the Lesser Antilles, Central America, or Japan necessitates rapid recycling – within a few half-lives – of surface sediments *and* fragments of the overriding plate itself down the subduction zone. Elevated  $^{10}\text{Be}$  concentrations correlate strongly with known erosive margins, providing a geochemical proxy for erosion intensity. Beyond  $^{10}\text{Be}$ , systematic shifts in radiogenic isotope systems (Sr, Nd, Hf, Pb, Os) in arc lavas can signal the contribution of eroded continental crust. For instance, lavas from the Central Andean arc exhibit elevated  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios and negative  $\epsilon\text{Nd}$  values compared to lavas from accretional arcs like the Aleutians, indicating incorporation of ancient, radiogenic continental material stripped from the South American Plate's base. Mantle xenoliths – fragments of the mantle wedge brought rapidly to the surface in volcanic eruptions – serve as direct archives. Xenoliths from the Colorado Plateau (above the ancient Farallon subduction) and Kamchatka contain pyroxenite veins with isotopic signatures (e.g., high  $\delta^{18}\text{O}$ ) unequivocally derived from subducted and eroded continental crust that has metasomatized the mantle. Uranium-series disequilibria ( $(^{23}\text{Th}/^{23}\text{U})$ ,  $(^{22}\text{Ra}/^{23}\text{Th})$ ) in young arc lavas provide constraints on the timescales of fluid release from the slab and mantle wedge processes; anomalies consistent with fluid flux from recently eroded, altered crust provide further temporal constraints on the erosion-magmatism link.

**Geomorphological Markers** sculpted by tectonic forces over millennia provide visible, often dramatic, surface expressions of the underlying erosion. Perhaps the most persuasive are mismatches in coastal terrace uplift and forearc subsidence patterns. At accreting margins, terraces typically record progressive uplift. However, at erosive margins, coastal terraces often show complex, discontinuous sequences: uplifted terraces recording periods of seismic slip may be juxtaposed with submerged terraces or rapidly subsiding coastal zones. The Mejillones Peninsula in northern Chile, situated above an intensely erosive segment of the Peru-Chile Trench, exemplifies this. Here, marine terraces rise to over 400 meters elevation, indicating long-term uplift, yet modern geodetic data (GPS) and tide gauges show localized subsidence exceeding 1 cm/year – a stark contradiction explained by basal erosion undercutting the crust while seismic locking temporarily uplifts the coast. This “yo-yo tectonics” creates a distinctive staircase of terraces with variable tilting.

Submarine geomorphology provides equally compelling evidence. The absence of a broad continental shelf and slope is common. Instead, erosional margins often feature steep, narrow continental slopes dissected by deep submarine canyons that extend right to the trench axis, bypassing any potential accretionary wedge. These canyons, like the massive Nazca Canyon off Peru, act as direct conduits funneling sediments eroded from the continent, both by surface processes and tectonic undercutting, straight into the trench abyss. The lack of sediment ponding landward of the trench is a key morphological indicator. Furthermore, large-scale mass wasting features – giant submarine landslides and scarps on the trench slope – are prevalent. These collapse structures, triggered by the oversteepening and weakening caused by basal erosion, leave massive headwall scarps and debris aprons. Seismic data offshore Nicaragua reveals multiple generations of such slides, directly overlying zones predicted by models to be undergoing intense basal dissolution. Even the coastline shape itself can be suggestive: cusped indentations or embayments sometimes align with subducting seamounts or ridges, hinting at localized zones of enhanced frontal erosion, as inferred along the Japan Trench where the Sanriku coast recedes landward above a large subducting seamount.

This constellation of geophysical anomalies, geochemical anomalies, and geomorphological scars provides the irrefutable diagnostic toolkit for identifying tectonic erosion. Moving beyond detection, the next imperative is quantifying its impact across diverse global settings, where the interplay of geology, oceanography, and seismicity creates distinct erosional regimes. We now turn to the planet’s most revealing natural laboratories.

## 1.5 Global Case Studies

The compelling diagnostic signatures of tectonic erosion—geophysical anomalies, geochemical fingerprints, and geomorphological scars—transform from abstract indicators into profound reality when examined across Earth’s diverse subduction zones. These natural laboratories, ranging from the volatile Pacific Rim to fossilized Precambrian terranes, reveal how local variations in plate convergence rate, subducting plate roughness, sediment supply, and crustal composition shape the erosional process. By dissecting these global case studies, we witness the universal principles of crustal consumption manifest in strikingly different geological theaters.

**Pacific Rim Hotspots** showcase erosional dynamics in action, where intense seismic activity and cutting-edge research converge. The **Japan Trench**, particularly its northern segment hosting the 2011 Tohoku-Oki earthquake (Mw 9.0), exemplifies frontal erosion driven by seamount subduction. Pre-event bathymetric surveys meticulously mapped the Kashima and Kitakami seamounts on the Pacific Plate. Post-quake comparisons revealed these asperities had bulldozed a staggering 50-80 cubic kilometers of material from the Eurasian Plate’s leading edge during the rupture, leaving a distinct 40-km-wide scarp. This event wasn’t isolated; it capped a million-year history documented by tilted forearc basin strata (e.g., the Sanriku Basin) and truncated Neogene volcanic sequences exposed on the trench slope, collectively indicating long-term landward trench retreat at 1-2 km per million years. Moving southeast, the **Central American margin**, intensely studied by the Costa Rica Seismogenesis Project (CRISP), reveals basal erosion’s dominance. IODP drilling at Sites U1412 and U1413 penetrated the eroded forearc offshore the Osa Peninsula, recovering serpentinitized

mantle peridotites and highly altered crustal rocks directly overlying the plate interface. Geochemical analysis of pore fluids showed chloride depletion and lithium enrichment—fingerprints of fluid release from the subducting Cocos Plate reacting with the overriding plate. The margin's unusual subsidence, recorded by drowned Miocene carbonate platforms now 2 km below sea level, correlates spatially with zones of highest fluid flux and basal dissolution rates exceeding 130 km<sup>3</sup> per million years. Furthermore, arc volcanoes like Arenal exhibit elevated <sup>10</sup>Be and radiogenic Pb isotopes, confirming eroded forearc material is recycled into magmas.

**Ancient Erosion Records**, preserved in mountain belts and ancient cratons, provide crucial deep-time perspectives on erosional impacts. The **Neotethyan subduction system**, whose closure built the Alpine-Himalayan chain, left compelling erosional imprints. In the European Alps, the exhumed remnants of the Adriatic continental margin display a dramatic “subduction erosion gap.” Pre-collision passive margin sequences, well-preserved inland, are abruptly truncated beneath the Penninic Front nappes near the suture zone. This missing section, representing 20-40 km of crustal excision, correlates with high-pressure metamorphic rocks (eclogites) containing garnets with geochemical signatures indicating metasomatism by crustally derived fluids—direct evidence of basal chemical corrosion during Cretaceous subduction. Similarly, the Indus-Yarlung suture zone in the Himalayas exposes the eroded northern Indian margin, where Paleozoic strata are cut out directly beneath the suture, overlain by ophiolitic mélange containing continental crust fragments. This truncation explains the absence of a significant accretionary prism despite India's thick sediment cover. Even older evidence emerges from **Precambrian greenstone belts**. The Archean Abitibi belt in Canada preserves a 2.7-billion-year-old accretionary complex juxtaposed against the Opatika tonalite-trondhjemite terrane. Seismic reflection profiles reveal the Opatika's eastern edge is sharply truncated, lacking the expected deep crustal root. Geochemical studies of adjacent volcanic rocks show contamination by sialic (continental) material, while structural analysis indicates the missing crustal section was removed by subduction erosion before greenstone obduction, challenging notions that early Earth margins were purely accretionary.

**Extreme Modern Examples** push erosional processes to their limits, offering unparalleled insights into end-member behaviors. The **Mariana Trench**, the planet's deepest subduction zone, represents perhaps the most sediment-starved and erosive active margin. Its near-vertical trench walls plunge over 11 km, exposing peridotite and gabbro basement rocks with minimal sediment cover. Multibeam mapping by AUV Sentry reveals pervasive normal faulting and massive landslide headwalls scarring the inner trench slope—direct results of gravitational collapse driven by profound basal undercutting. The forearc is exceptionally thin; seismic refraction data indicates crustal thinning from ~20 km at the volcanic arc to less than 10 km near the trench. Forearc peridotites drilled during ODP Leg 195 contain veins of amphibole and chlorite formed by infiltration of slab-derived fluids, while serpentinite mud volcanoes like those at Conical Seamount actively erupt material altered by fluid-rock interaction at the plate interface, providing a rare window into active chemical corrosion. Equally dramatic is the **Peru-Chile Trench** where the subduction of the buoyant **Nazca Ridge** creates a localized erosional hotspot. This 1.5-km-high, 450-km-wide bathymetric feature acts as a colossal bulldozer. Geophysical surveys show it has overridden 150 km of the South American Plate since the Miocene, causing localized uplift of the Peruvian coast (creating the Marcona Formation marine

terraces) followed by accelerated subsidence as the ridge migrates southward. The ridge's passage leaves a wake of intense deformation: seismic profiles reveal deeply truncated continental basement beneath the ridge axis, disrupted forearc basins, and the Nazca Canyon—one of Earth's largest submarine canyons—scoured directly into the continental slope, funneling eroded debris into the trench. Geodetic data shows current subsidence rates exceeding 5 cm/year above the ridge's leading edge, while earthquakes exhibit unusual rupture patterns constrained by the ridge's rigid geometry.

These diverse case studies collectively demonstrate tectonic erosion's pervasive role in shaping Earth's convergent margins. From the seismic fury of Japan to the chemical dissection beneath Costa Rica, the fossilized scars of vanished oceans, and the abyssal extremes of the Mariana and Peru-Chile trenches, the mechanisms detailed earlier—frontal scraping, basal detachment, and chemical dissolution—manifest with startling clarity. The volume and nature of material consumed, however, raise profound questions about its ultimate fate: how does this recycled crust contribute to Earth's long-term crustal mass balance and mantle geochemical evolution? This leads us to examine the deep geodynamic consequences of tectonic erosion.

## 1.6 Crustal Recycling Impacts

The staggering volumes of continental crust consumed at erosional margins, exemplified by the case studies from Japan to the Mariana Trench, raise a profound geodynamic question: what becomes of this vast quantity of lost lithosphere? The journey of tectonically eroded material is not merely one of destruction, but of deep recycling – a process with far-reaching consequences for Earth's crustal architecture, mantle geochemistry, and the very evolution of mountain belts. Understanding these impacts reveals tectonic erosion not as an endpoint, but as a crucial stage in Earth's grand material cycles.

**Continental Mass Budget** hinges on the delicate balance between crustal creation and destruction. Tectonic erosion acts as a primary agent of net continental loss, operating alongside sediment subduction and lower crustal delamination. Quantifying this loss reveals its significance: studies integrating seismic imaging of crustal thinning, subsidence rates of forearc basins, and plate reconstructions yield long-term average erosion rates of 1-3 km<sup>3</sup> per km of trench length per million years (km<sup>3</sup>/km/Ma). Along highly erosive segments like the Middle America Trench offshore Costa Rica, rates can surge to over 130 km<sup>3</sup>/km/Ma during periods of intense subducting plate roughness or accelerated convergence. Cumulatively, estimates suggest subduction erosion removes approximately 1.3–1.6 km<sup>3</sup> of continental crust globally *annually*. This relentless stripping poses a fundamental challenge to the continental crust's long-term volume. While arc magmatism generates new continental material – estimated at 2-3 km<sup>3</sup>/year globally – this output must compensate not only for tectonic erosion but also for losses via chemical weathering and sediment subduction. Mass balance models, incorporating radiogenic isotope tracers (like neodymium and hafnium) that track crustal residence times, suggest net continental volume may have peaked in the Proterozoic and experienced a slight decline (~15%) over the Phanerozoic Eon. The Costa Rican example starkly illustrates this competition: despite prolific arc volcanism building the Central American land bridge, geophysical and drilling data indicate the margin has retreated landward by 100-150 km since the Oligocene, with the net crustal volume potentially decreasing despite surface magmatism. This delicate balance underscores that continents are not permanent fixtures but

dynamic entities engaged in a continuous, planet-scale exchange with the mantle.

**Mantle Geochemical Cycling** represents the ultimate destination for much of the eroded crustal cargo, transforming it into a key ingredient in mantle heterogeneity. The subducted *mélange* – a complex mixture of eroded continental fragments, trench sediments, altered oceanic crust, and serpentinized mantle – undergoes progressive metamorphism and dehydration as it plunges deeper. However, complete homogenization within the mantle is elusive. Geochemical fingerprints of this recycled material emerge in volcanic rocks sourced from the deep mantle, particularly Ocean Island Basalts (OIBs). The EM1 (Enriched Mantle 1) reservoir, characterized by low  $^{206}\text{Pb}/^{208}\text{Pb}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$ , and high  $^{143}\text{Nd}/^{142}\text{Nd}$  ratios, is strongly implicated. The Pitcairn hotspot in the South Pacific provides a compelling case: its lavas exhibit extreme EM1 signatures coupled with negative  $\Delta\epsilon_{\text{Hf}}$  values (deviations in hafnium isotopes from the mantle array). This unique combination is best explained by incorporating ancient subducted sediments and, crucially, fragments of eroded continental crust derived from the South American margin during earlier subduction episodes. Similarly, the EM2 reservoir (characterized by high  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{206}\text{Pb}/^{208}\text{Pb}$ ) found in Samoa and the Societies likely contains a significant contribution from eroded arc crust or forearc fragments. The journey is complex: uranium-thorium disequilibria in OIBs suggest recycling timescales of hundreds of millions to over a billion years. The eroded material contributes not just trace elements but also volatiles. Water, carbon dioxide, sulfur, and halogens liberated from the subducted *mélange* flux mantle melting, influence magma viscosity, and ultimately outgas through volcanism, impacting long-term climate regulation. Tectonic erosion thus acts as a primary conveyor belt, injecting continent-derived components like potassium, rubidium, barium, and light rare earth elements into mantle domains, creating the enriched “streaks” sampled by plumes millennia later.

**Orogenic Evolution Effects** manifest in the contrasting architectures of mountain belts, heavily influenced by the pre-collisional history of their margins, particularly whether they were dominantly accretionary or erosional. **Thin-crust mountain building**, exemplified by the Andes, is a direct consequence of prolonged tectonic erosion. The Andean Cordillera rests upon a crust only 50-70 km thick at its widest point – significantly thinner than the 70-90 km crust beneath the Himalayas. This relative thinness stems from the erosive history of the western South American margin prior to and during Andean uplift. Basal erosion, particularly during periods of flat-slab subduction like the current situation under Peru, has thinned and weakened the forearc foundation. Consequently, during the Cenozoic Andean orogeny driven by Nazca Plate convergence and ridge subduction, the crust deformed differently. Shortening was distributed over a wider area, leading to the broad, high-altitude Altiplano-Puna plateau, but the overall crustal root remained relatively modest. The pre-thinned, weakened lithosphere buckled rather than thickened massively. Furthermore, evidence from the Central Andean forearc shows extensive destruction of potential foreland basins; instead of preserving thick sedimentary sequences like the Himalayan foreland (Ganges Basin), much of the eroded forearc material was cannibalized, recycled, or lost down the trench during pre-collisional subduction erosion. In stark contrast, **thick-crust collisional belts** like the Himalayas result from the closure of oceans where *both* converging margins were primarily accretionary or had thick passive margins relatively unscathed by significant pre-collisional erosion. The Indian margin, despite some evidence of Tethyan erosion near the suture, retained its thick continental lithosphere. When it collided with Asia, the thick, strong crust resisted subduction

and instead underwent massive underthrusting and pure-shear thickening, piling up to form the immense Himalayan-Tibetan orogen with its deep crustal root. The **forearc basin destruction patterns** characteristic of erosional margins also leave a lasting legacy. The subsided, fragmented forearcs seen offshore Japan or Central America, often buried under younger sediments, create complex weak zones in the overriding plate. During subsequent tectonic events, like the collision that built the Alps, these weakened zones become preferred sites for deformation, fault reactivation, or even the nucleation of new plate boundaries. The fragmented forearc terranes of the ancient Farallon Plate subduction, weakened by erosion, are now integral components of the San Andreas fault system's complex geology.

Thus, the impacts of tectonic erosion resonate far beyond the immediate subduction zone. It regulates the continental crust's volume over geologic time, subtly tilting the balance against growth. It seeds the mantle with geochemical heterogeneities that resurface eons later in oceanic island volcanoes, carrying isotopic messages from vanished continental margins. Most visibly, it preconditions the very architecture of mountain belts, determining whether continents crumple into towering, thick-crustal ranges like the Himalayas or rise as

## 1.7 Technological Frontiers

The profound impacts of tectonic erosion on continental mass balance, mantle heterogeneity, and orogenic architecture, as revealed through decades of painstaking field observation and inference, underscore a fundamental challenge: directly observing processes occurring kilometers beneath the ocean floor or locked within ancient mountain belts requires technological ingenuity. The quest to move beyond indirect proxies and witness erosion in action—or recreate its extreme conditions—has driven remarkable innovations across marine geoscience, geophysics, and experimental petrology. These technological frontiers are revolutionizing our ability to probe the mechanics, chemistry, and dynamics of tectonic erosion, transforming it from an inferred process to one increasingly illuminated by direct measurement and simulation.

**Deep-Sea Exploration** technologies provide unprecedented access to the most inaccessible landscapes on Earth—the abyssal trenches and forearc slopes where tectonic erosion actively sculpts the planet. Autonomous Underwater Vehicles (AUVs) like the Woods Hole Oceanographic Institution's *Sentry* and Japan's *Urashima* are indispensable. Equipped with multibeam sonar, sub-bottom profilers, and high-resolution cameras, they map the seafloor with centimeter-scale precision, revealing erosional signatures invisible to ship-based systems. During a 2017 *Sentry* mission mapping the Middle America Trench offshore Nicaragua, the AUV identified intricate networks of fresh, steeply dipping normal faults scarpering the continental slope. These faults, occurring directly above a zone of intense basal erosion inferred from seismic tomography, displayed scarps only meters high—too fine for conventional mapping but critical evidence of ongoing, small-scale collapse driven by undercutting. Furthermore, AUVs can fly close to treacherous trench walls, documenting talus piles from recent landslides and exposing outcrops of serpentinized peridotite or truncated continental basement rocks—direct windows into the erosional process. Complementing AUVs, human-occupied submersibles like *Alvin* and remotely operated vehicles (ROVs) like *Jason* enable visual inspection and sampling at critical sites. Dive 4983 of *Alvin* to the Costa Rica forearc in 2019 provided stun-



ning visual evidence: thick microbial mats and chemosynthetic communities thriving around active fluid seeps emanating from fractured outcrops directly above the plate interface. Sampling these seeps revealed fluids with elevated lithium and boron concentrations and depleted chlorinity—chemical fingerprints confirming active fluid-rock interaction and dissolution processes predicted by basal erosion models. Deep drilling remains the ultimate direct probe. The International Ocean Discovery Program’s (IODP) advanced drilling vessel, *Chikyu*, with its riser capability allowing drilling in deeper, unstable formations, has targeted erosional margins. Expedition 362 off Sumatra drilled into the input sediment section of the 2004 earthquake rupture zone, revealing how thick, unconsolidated sediments can promote frontal erosion by reducing basal friction and facilitating large-scale collapse during seismic slip. These deep-sea platforms, integrating high-resolution mapping, visual observation, and direct sampling, are turning the deep forearc from a theoretical zone into a tangible, dynamic environment.

**High-Resolution Seismology** has undergone parallel revolutions, enabling scientists to image the subduction interface—the very locus of tectonic erosion—with astonishing clarity. Dense, broadband seismic arrays deployed across entire regions capture ground motions with unprecedented fidelity. Projects like the AlpArray in Europe, comprising over 600 stations blanketing the Alps and surrounding regions, image the fossilized structure of the Neotethyan subduction zone. Using ambient noise tomography—a technique that utilizes the constant low-level hum of ocean waves and atmospheric disturbances as a seismic source—AlpArray researchers constructed detailed 3D velocity models. These revealed intricate, dipping low-velocity zones beneath the Ivrea-Verbano zone in the Western Alps, interpreted as remnants of serpentized mantle wedge material. This fossilized mantle wedge exhibits complex metasomatic veining, corroborating ancient chemical erosion processes inferred from exhumed rocks. For active margins, onshore-offshore deployments are key. The Japan Trench Ocean Bottom Seismograph Network, deployed before and after the 2011 Tohoku earthquake, recorded the megathrust rupture with exceptional detail. Analysis of high-frequency seismic waves showed distinct bursts of energy precisely correlated with the subducting Kashima seamount, proving its role in generating intense fracturing and plucking crustal material during the rupture—a direct seismic recording of frontal erosion in real-time. Full-waveform inversion (FWI), a computationally intensive technique, pushes resolution further. Applying FWI to data from the Cascadia Initiative array off Washington State revealed subtle velocity variations along the plate interface, interpreted as localized pockets of high fluid pressure within a serpentized mantle layer. These zones, correlating with forearc subsidence measured by seafloor geodesy, pinpoint areas where basal erosion via fluid-mediated weakening is most active. Seismic reflection technology also leaped forward. Ultra-high-resolution 3D seismic surveys, employing advanced streamer configurations and source arrays, can now image structures only tens of meters thick. Off Costa Rica, such surveys resolved networks of sub-vertical conduits cutting through the overriding plate above the seismogenic zone. These conduits, filled with low-velocity material, are interpreted as pathways for overpressured fluids generated by dehydration reactions, facilitating both chemical dissolution and hydrofracturing critical for basal erosion.

**Experimental Simulations** recreate the extreme pressure-temperature-stress conditions of subduction zones within the laboratory, allowing direct observation of erosion mechanisms impossible in nature. Rock deformation apparatuses, like gas-medium Griggs rigs and solid-medium Paterson presses, subject rock cores to

confining pressures exceeding 1.5 gigapascals (equivalent to ~50 km depth) and temperatures over 1000°C, while applying differential stress. Pioneering experiments by Niemeijer et al. at Utrecht University simulated the plate interface by shearing quartzite (representing continental crust) against serpentinite (representing the mantle wedge) under subduction zone conditions. They documented a dramatic switch: above 450°C, the quartzite weakened drastically due to pressure solution creep—a process where quartz dissolves at grain contacts under stress and precipitates in adjacent pores. This provided the first direct experimental proof that chemical dissolution, not just brittle fracturing, can dominate weakening and material removal at the base of the overriding plate under warm subduction conditions. Parallel experiments explore fluid-mediated reactions. Hydrothermal diamond anvil cells (HDACs) coupled with synchrotron X-ray sources allow real-time observation of mineral dissolution in fluids at pressures up to 10 GPa (mantle transition zone depths). Tenthorey et al. at the Australian National University used this setup to measure quartz dissolution rates in saline fluids at 3 GPa and 600°C. They found dissolution rates increased tenfold compared to lower pressures, demonstrating the profound efficiency of chemical corrosion at depths relevant to basal erosion. Advanced numerical modeling bridges laboratory and field scales. Coupled thermo-hydro-mechanical-chemical (THMC) codes, incorporating realistic rock rheologies from experiments and fluid properties from molecular dynamics simulations, model long-term evolution. Models using code ASPECT (Advanced Solver for Problems in Earth's ConvecTion) simulating the Central American margin over 10 million years successfully reproduced the observed forearc subsidence patterns and crustal thinning rates only when incorporating both frontal seamount impacts and pervasive basal dissolution driven by focused fluid flow. These models predict transient pulses of accelerated erosion triggered by subduction of large asperities, reconciling conflicting short-term geodetic and long-term geologic rate estimates.

The relentless march of technology—from robotic explorers illuminating the abyssal frontiers to seismic arrays dissecting the deep crust and laboratory rigs replicating mantle conditions—is demystifying tectonic erosion. These tools provide not just snapshots but dynamic narratives of how continents are consumed. Yet, translating these observations into predictive frameworks for Earth's evolution and associated hazards requires sophisticated computational

## 1.8 Modeling Approaches

The technological frontiers explored in the previous section—robotic mappers illuminating abyssal trenches, seismic arrays dissecting the deep crust, and laboratory rigs replicating mantle conditions—generate torrents of data detailing *how* tectonic erosion operates. However, understanding its long-term evolution, quantifying its cumulative impact, and predicting its consequences demand integrating these observations into sophisticated computational frameworks. Modeling tectonic erosion presents unique challenges: it spans spatial scales from mineral grains to entire plates and temporal scales from seismic seconds to millions of years, involving complex couplings between rock mechanics, fluid flow, heat transfer, and chemical reactions. Overcoming these challenges has spurred the development of diverse modeling approaches, each illuminating different facets of this destructive dance between converging plates.

**Thermo-Mechanical Models** form the bedrock of understanding short-to-medium-term erosion dynamics



at the plate interface, focusing on the interplay of stress, temperature, and material properties. These models typically simulate a cross-sectional “slice” through a subduction zone over thousands to millions of years, incorporating realistic rheologies derived from laboratory experiments. A key prediction revolves around **strain localization**. Models consistently show that the combination of high fluid pressure from the dehydrating slab and the presence of mechanically weak phases like serpentinite leads to intense strain focusing within a narrow shear zone just below the base of the overriding crust. This localized deformation is the computational signature of basal detachment and undercutting. The University of Bergen’s models of the Costa Rica margin, incorporating detailed seismic velocity structures to define rock strength variations, successfully replicate the observed pattern of forearc subsidence by predicting pervasive ductile shearing and brittle fracturing within this weakened basal layer. Furthermore, these models provide crucial insights into modifications of **critical taper theory**. Originally developed for accretionary wedges, critical taper describes the stable slope angle maintained by a wedge of material being pushed against a backstop. Thermo-mechanical models for erosional margins reveal a profoundly different behavior. As material is removed from the toe and base, the critical taper angle decreases, leading to gravitational collapse and pervasive normal faulting in the upper plate. Numerical experiments simulating the subduction of large seamounts, like those off Japan, demonstrate how the seamount acts as a rigid indenter. During its passage, it locally increases basal friction and compresses the forearc (increasing taper), but as it subducts deeper, the unsupported overhang collapses catastrophically (dramatically decreasing taper), generating large-scale normal faults and mass wasting events mirroring the observed morphology of the Japan Trench inner slope. This dynamic interplay explains the ubiquitous extensional tectonics observed geomorphologically at erosive margins.

**Geodynamic Codes** tackle the grander scale, simulating the long-term evolution of entire subduction systems over millions of years, often incorporating global mantle flow dynamics. Advanced finite-element or finite-difference codes like ASPECT (Advanced Solver for Problems in Earth’s ConvecTion) and LaMEM (Lithosphere and Mantle Evolution Model) have become indispensable tools. These codes incorporate complex physics: buoyancy-driven plate motion, visco-elasto-plastic rheologies for the lithosphere, temperature-dependent viscosity for the mantle, and crucially, parametrizations for tectonic erosion. The power of ASPECT was demonstrated in simulations of the Central American margin spanning 15 million years. By incorporating constraints from CRISP drilling (e.g., degree of serpentinitization, rock strength) and IODP pore fluid chemistry, the models successfully replicated the observed landward retreat of the volcanic arc and the progressive subsidence of the forearc basin. They revealed that basal erosion driven by fluid-mediated weakening was the dominant mechanism, contributing ~70% of the total material loss, while frontal erosion from seamounts accounted for the remaining ~30%. This quantitative breakdown aligns with geochemical mass balance estimates. A major frontier involves **coupled fluid-transport models**. Traditional codes treated fluid release from the slab as a simple depth-dependent function. Modern approaches, like those implemented in LaMEM, dynamically couple fluid generation (dehydration reactions), multiphase fluid flow through porous and fractured media, and fluid-rock interactions (serpentinization, dissolution). Simulations of the Hikurangi margin off New Zealand, where a large seamount is approaching the trench, show how fluid pathways become focused around the asperity. This leads to enhanced serpentinitization and weakening *ahead* of the seamount, priming the margin for more efficient frontal erosion upon its arrival. These models

also predict transient pulses of accelerated chemical corrosion during major seismic events, when fracturing increases permeability and fluid flux, offering an explanation for discrepancies between short-term geodetic and long-term geologic erosion rates. The ability to simulate fluid-mediated mass transfer provides crucial links to geochemical observations, predicting, for instance, the depth ranges where dissolved silica from corroded crust is most likely to precipitate as quartz veins within the mantle wedge or be transported deeper.

**Hazard Implications** arising from tectonic erosion are no longer speculative; they are tragically tangible, and modeling provides critical tools for risk assessment. The most direct link is to **megathrust earthquake potential**. Thermo-mechanical models reveal how erosion shapes the seismogenic zone. Basal erosion thins and weakens the overriding crust, often bringing the mantle wedge closer to the trench. This displaces the locked zone—where stress builds until released in earthquakes—further landward. Crucially, this landward shift often places the down-dip end of the seismogenic zone directly beneath coastal populations and infrastructure, as seen in Japan and Cascadia. Furthermore, the weakened, undercut crust creates a complex fault network that can influence rupture propagation. Models of the Japan Trench incorporating the geometry of subducting seamounts accurately simulated the 2011 Tohoku earthquake’s unique rupture behavior: the seamounts initially acted as barriers, arresting rupture propagation, but once failure occurred around them, they acted as asperities, focusing slip and generating the devastating high-frequency shaking and tsunami near the coast. Similarly, coupled fluid-transport models highlight how zones of intense fluid flux and chemical alteration, common in eroded margins, can localize strain and nucleate seismic swarms or slow-slip events. **Tsunami genesis scenarios** are profoundly impacted. The structural damage caused by frontal and basal erosion directly influences seafloor deformation during earthquakes. Models show that eroded margins, characterized by steep, unstable slopes and thin, weakened crust, are prone to much larger coseismic subsidence near the trench compared to accretionary margins. This “trench-breaching” subsidence, dramatically observed in 2011 off Japan (where the seafloor dropped by over 50 meters), acts like a piston, displacing massive water volumes and generating the initial, destructive tsunami wave. Geodynamic models incorporating long-term erosion histories, like those for the Mariana Trench—the world’s deepest erosional margin—predict that the extreme structural weakening there makes it highly susceptible to large-scale, seismically triggered landslides from the inner trench wall. Such landslides could generate local but devastating tsunamis, distinct from those caused directly by megathrust rupture. Numerical tsunami simulations using bathymetry shaped by millions of years of erosion, incorporating these complex coseismic deformation patterns and potential landslide sources, are essential for refining coastal inundation forecasts and designing effective early warning systems for vulnerable, erosion-weakened margins worldwide.

These computational frameworks—from grain-scale thermo-mechanics to global-scale geodynamics—transform the fragmented observations of tectonic erosion into predictive syntheses. They reveal not just how continents are consumed, but how this consumption shapes seismic hazards and rewrites the rules of subduction zone behavior. Yet, as models grow more sophisticated, they also illuminate persistent gaps in understanding and fuel ongoing debates about quantification, mechanisms, and the very language used to describe this fundamental process. This leads us inevitably into the contested terrain of scientific controversy.

## 1.9 Controversies and Debates

The sophisticated computational frameworks explored in Section 8, capable of simulating the intricate interplay of rock mechanics, fluid flow, and chemical reactions driving tectonic erosion over millions of years, paradoxically illuminate not just certainties but profound uncertainties. As models grow more complex and datasets more detailed, the field has entered a phase of vigorous debate, where foundational concepts, quantification methods, and even the very interpretation of diagnostic evidence are contested. These controversies are not signs of weakness but of a dynamic, maturing science grappling with Earth's inherent complexity.

**9.1 Erosion vs. Subduction Erosion Terminology** A seemingly semantic debate over nomenclature masks fundamental disagreements about process scope and dominance. The term “subduction erosion,” championed by pioneers like David Scholl and Roland von Huene, specifically denotes material removal *at* the subduction interface, primarily via frontal scraping and basal dissolution driven by subduction dynamics. This framing emphasizes the plate boundary itself as the engine of destruction. However, critics argue this terminology is overly restrictive. They advocate for the broader “tectonic erosion,” encompassing *all* mechanisms leading to net crustal loss at convergent margins, including processes operating landward of the immediate trench. This expanded view incorporates phenomena like forearc extension driven by slab rollback, gravitational collapse of underplated material, or even lower crustal foundering potentially triggered by subduction-induced weakening but occurring deeper within the overriding plate. The Costa Rica margin exemplifies the debate. Proponents of “subduction erosion” point to CRISP drilling evidence of direct basal dissolution and frontal seamount impacts as the primary drivers. Conversely, advocates for “tectonic erosion” highlight the pervasive normal faulting and large-scale slumping observed across the forearc, suggesting gravitational collapse facilitated by subduction-induced weakening is a significant, distinct contributor to net material loss, potentially exceeding the interface-specific removal. The terminology choice influences research priorities and hazard assessment. Focusing solely on “subduction erosion” directs resources towards imaging the plate interface and modeling fluid fluxes. Embracing “tectonic erosion” necessitates broader studies of upper plate deformation, stress fields, and the long-term structural evolution of the entire forearc block. The debate underscores a key question: Is the destruction primarily a narrow, interface-focused process, or a broader system response to subduction forcing?

**9.2 Quantification Challenges** Quantifying erosion rates remains arguably the field's most persistent and contentious challenge, with discrepancies often spanning an order of magnitude depending on the methodology employed. **Disputes over long-term rates** highlight the limitations of different geological clocks. Paleomagnetic studies, tracking the apparent landward migration of the volcanic arc relative to stable continental interiors, provide million-year averages. For example, paleomagnetic data suggests the Andean volcanic front retreated westward at  $\sim 1\text{--}2$  km/Ma since the Cretaceous. However, critics question the fidelity of paleomagnetic markers in volcanic rocks and whether arc migration solely reflects crustal loss or also changes in subduction angle or magma transport. Geodetic techniques (GPS, seafloor geodesy), measuring contemporary vertical motions (subsidence) and horizontal strain, offer decadal snapshots. Off northern Chile, near the subducting Nazca Ridge, GPS records rapid coastal subsidence exceeding 5 cm/year, interpreted as active basal erosion. Yet, translating this short-term deformation into long-term volume loss is

fraught. Is the subsidence elastic (recoverable) or inelastic (permanent)? Does it represent steady erosion or a transient pulse? The stark contrast is exemplified at the Japan Trench: geodetic inversions post-2011 suggest localized frontal erosion rates exceeding 10 km/Ma during the co-seismic event, while long-term geological markers (subsided terraces, truncated strata) indicate average rates closer to 1-2 km/Ma, implying highly episodic removal dominated by seismic shaking.

This leads directly to the **missing mass paradox**. If erosion rates inferred from paleomagnetic arc migration or forearc subsidence histories are accurate, the cumulative volume of continental crust consumed should be immense. Geochemical models predicting the composition of arc magmas or mantle reservoirs, however, often struggle to account for this volume. Lavas from the Central American arc, sitting atop one of Earth's most erosive margins, show only subtle isotopic shifts (e.g., slightly elevated  $\delta^{87}\text{Sr}/\delta^{86}\text{Sr}$ ) compared to lavas from accretional arcs like the Aleutians. Where is the geochemical fingerprint of all that missing continental crust? Several contentious resolutions vie for acceptance. One school argues that eroded material is efficiently homogenized within the mantle wedge and subducted slab, its isotopic signature diluted before contributing to arc magmatism. Another posits that much of the dissolved load (silica, alkalis) is not deeply recycled but reprecipitated within the mantle wedge as metasomatic veins or incorporated into hidden plutons beneath the arc, sequestering the signature. A third, more radical view suggests that geophysical techniques overestimate the *continental* component of the lost mass, arguing that much of the removed "volume" consists of previously accreted sediments or serpentinized mantle, which carry distinct, less radiogenic signatures. Resolving this paradox requires tighter integration of geophysical volume estimates, high-precision isotope analyses of diverse mantle and crustal samples, and sophisticated reactive transport models.

**9.3 Alternative Interpretations** Despite the weight of evidence supporting tectonic erosion as a major process, several alternative interpretations challenge its dominance or even its existence in specific contexts, forcing critical re-evaluation of data. The most provocative is the "**tectonic anorexia**" hypothesis, proposed as a counter to explanations invoking pervasive basal dissolution for forearc thinning. Advocates argue that observed crustal thinning and subsidence, particularly in regions like Central America or the Mariana forearc, could result primarily from *inherited* structural weakness – a pre-existing thin or rifted crust – rather than active removal. They contend that subduction exploits this inherent fragility, causing extension and collapse driven by slab rollback forces, without requiring significant mass transfer into the mantle. While acknowledging fluids weaken the system, they downplay dissolution as a major mass-loss mechanism. This view clashes directly with geochemical evidence like lithium and boron enrichments in forearc pore fluids and serpentinite muds, and the presence of  $^1\text{Be}$  in arc magmas, all demanding active fluid-mediated transport of surface material. Proponents counter that fluids might simply redistribute elements locally or that  $^1\text{Be}$  could be sourced solely from deeply subducted sediments without requiring upper plate erosion. The debate hinges on distinguishing cause from effect: is the thin crust a cause of collapse or a consequence of erosion?

**Structural duplication arguments** represent a more localized but persistent challenge. Critics of high erosion rates inferred from truncated stratigraphic sequences, particularly in ancient orogenic belts like the Andes or Alps, propose that deformation could mimic removal. Thrust faulting or large-scale folding might

tectonically repeat stratigraphic sections, creating the illusion of missing rock where none was actually lost. Careful mapping is required to distinguish true excision from structural repetition. For instance, interpretations of significant crustal loss in the Peruvian Andes based on apparent truncation of Paleozoic sequences beneath the Mesozoic arc were challenged by studies proposing complex thrust duplication. While detailed structural analysis and geochronology often resolve such disputes (

### 1.10 Planetary Perspectives

The vigorous debates surrounding tectonic erosion on Earth—its mechanisms, rates, and diagnostic signatures—naturally prompt a broader cosmic question: does this fundamental process of crustal consumption operate beyond our planet? Examining other worlds through the lens of comparative planetology provides profound insights, not only testing the universality of subduction-driven erosion but also revealing how different planetary conditions—composition, heat flow, presence of volatiles—reshape its expression. These extraterrestrial perspectives offer unique constraints on Earth’s own tectonic evolution, especially its enigmatic early history.

**Venusian Analogs** present the most compelling potential case for large-scale tectonic erosion beyond Earth, despite the absence of active plate tectonics as we know it. Venus’s surface, reshaped by global resurfacing events within the last billion years, displays enigmatic structures called **coronae**—vast, elliptical to circular features often exceeding 1,000 km in diameter, characterized by concentric fractures and a raised rim surrounding a depressed interior. While their origins are debated, Artemis Corona—the largest at over 2,600 km across—exhibits morphology strikingly suggestive of a fossilized erosional system. Detailed analysis of Magellan radar altimetry and imagery reveals a complex structure: a deep, trench-like topographic moat partially encircling the corona, interpreted as a possible zone of lithospheric downwelling. Inside this moat, the terrain appears heavily deformed, with evidence of crustal thinning and collapse. Crucially, geological mapping suggests the removal of pre-existing tessera terrain (ancient, highly deformed highland crust) from within the corona’s interior, its fragmented remnants now forming knobby “outliers” along the margins. This pattern mirrors the truncated sequences seen in terrestrial forearcs. The proposed mechanism differs from Earth: rather than cold, rigid plate subduction, models suggest hot, ductile lower crust or even lithospheric mantle delaminating and sinking into the hotter Venusian interior—a process termed “drip tectonics” or “viscous delamination.” As this dense material sinks, it drags down and erodes the overlying crust, potentially facilitated by high-temperature metamorphic reactions weakening the lithosphere. The immense gravity anomaly associated with Artemis, requiring significant subsurface mass deficit, supports the interpretation of crustal thinning and removal. While lacking the seismicity and fluid-mediated chemical corrosion of Earth, Artemis and similar large coronae like Quetzalpetlatl may represent Venus’s unique expression of tectonic erosion, driven by gravitational instability in a single-lid tectonic regime under a scorching, water-poor environment. Studying these structures helps define the minimum requirements for crustal recycling and highlights the role of lithospheric density and heat flow in enabling erosion-like processes.

**Icy Moon Implications** shift the context dramatically to cryogenic environments, where water ice acts as the lithosphere. Jupiter’s moon **Europa**, with its young, fractured icy shell overlying a global subsurface

ocean, displays tantalizing features hinting at processes analogous to both plate tectonics and erosion. High-resolution imagery from the Galileo spacecraft reveals complex bands—linear to curvilinear features often hundreds of kilometers long and tens of kilometers wide—interpreted as sites of crustal extension or convergence. Some convergence bands, like the **Tyre Macula region**, exhibit fold-and-thrust structures suggestive of compression. More intriguingly, features termed “subsumption bands” show evidence where one block of ice appears to override and potentially consume another. While pure water ice is too buoyant to subduct like silicate crust, the presence of salts (sulfates, chlorides) and potentially hydrated minerals within Europa’s ice shell could create density heterogeneities. Buoyant, relatively pure ice might resist sinking, but denser, salt-enriched or silicate-laden icy material could founder. Observations of “chaos terrain”—regions of disrupted, blocky ice resembling terrestrial landslide debris or collapsed forearcs—adjacent to some convergence zones hint at crustal destruction and removal. The process might involve basal decollements facilitated by briny fluids or warm, ductile ice acting as a weak layer—akin to serpentinized mantle on Earth. Material could be “eroded” via mechanical disaggregation and downward transport along these weak zones, potentially facilitated by tidal stresses and diurnal flexing. Evidence is circumstantial but compelling: double ridges flanking bands may represent localized melt and refreeze of ice crushed during convergence; the scarcity of very ancient surface features implies crustal recycling; and thermal-orbital models suggest tidal dissipation could generate sufficient heat and stress to drive such processes episodically. Future missions like Europa Clipper will search for geophysical signatures (gravity anomalies, radar reflectors) indicative of subsurface mass removal and potential crustal thinning beneath convergence bands. Europa thus serves as a critical laboratory for understanding how erosion mechanisms might operate in volatile-rich, low-gravity regimes, potentially crucial for icy ocean worlds throughout the galaxy.

**Early Earth Models** bring the focus back to our own planet’s infancy, where the controversies surrounding tectonic erosion’s modern operation find resonance in debates about the very onset of plate tectonics. The **Hadean and Eoarchean eons** (4.6 to 3.6 billion years ago) represent Earth’s most enigmatic period. Was modern-style plate tectonics, complete with subduction erosion, operating? Evidence is sparse and hotly contested. Detrital Jack Hills zircons (~4.4–4.0 Ga) show geochemical signatures (high  $\delta^{18}\text{O}$ , crust-like trace elements) implying interaction with liquid water and possibly recycled crust, hinting at processes *like* erosion early on. However, the significantly higher mantle potential temperatures ( $>1500^\circ\text{C}$  vs.  $\sim 1350^\circ\text{C}$  today) would have profound implications. Warmer oceanic lithosphere would be more buoyant, resisting subduction initiation. If subduction occurred, the plates would likely sink more steeply (“rollback”), potentially favoring extension and foundering of the overriding plate—a scenario conducive to erosion. Conversely, thicker, more buoyant oceanic plateaus might act as “plateshields,” resisting consumption and promoting shallow underthrusting rather than deep subduction. Geodynamic models incorporating these hotter conditions often predict a “drip tectonics” regime similar to Venus, where dense lower crustal mafic-ultramafic material would delaminate and sink, eroding the base of the proto-continents. The scarcity of well-preserved Archean accretionary complexes compared to abundant granite-greenstone belts (like the 3.8–3.7 Ga Isua supracrustal belt or the 3.5 Ga Barberton belt) is cited by some as evidence that erosion dominated over accretion in the early Earth, preventing the long-term growth of thick forearc prisms. Greenstone belts themselves, often interpreted as volcanic sequences deposited in back-arc or intra-arc basins, frequently show structural truncation



along their margins, possibly indicating tectonic erosion of adjacent proto-continental blocks. However, the role of fluids—so crucial to modern erosion—remains a major uncertainty. Was water sufficiently abundant and cycled into the mantle wedge early

## 1.11 Societal Connections

The profound debates surrounding tectonic erosion's operation on early Earth and its potential expressions across our solar system, while captivating in their cosmic scope, inevitably lead us back to the tangible realm of human experience. The silent, grinding consumption of continental crust at subduction zones is not merely an abstract geological process; it reverberates through human societies, shaping landscapes we inhabit, influencing the resources we depend upon, and weaving into the cultural fabric of communities living in the shadow of these dynamic margins. Understanding these societal connections transforms tectonic erosion from a deep-Earth phenomenon into a force intimately linked to human vulnerability, prosperity, and cultural memory.

**11.1 Geohazard Relationships** The most direct and often devastating societal impact of tectonic erosion lies in its intimate relationship with seismic and tsunami hazards. Eroded margins, characterized by their thin, weakened crust, steep slopes, and structural damage, fundamentally alter the behavior of megathrust earthquakes and their cascading consequences. The 2011 Tohoku-Oki earthquake (Mw 9.0) off Japan stands as a tragic testament. As detailed in previous sections, frontal erosion by subducting seamounts had already structurally compromised the Eurasian Plate's leading edge. During the rupture, these seamounts acted not just as geological rasps but as pivotal asperities. They initially impeded slip, causing stress to build, but once failure occurred around them, they focused enormous energy release. This generated the intense, high-frequency shaking that devastated coastal towns and critically, triggered unprecedented trench-breaching co-seismic subsidence exceeding 50 meters locally. This sudden, massive seafloor displacement acted like a piston, generating the colossal tsunami that overwhelmed defenses designed for historical precedents from less eroded segments of the margin. The disaster, claiming nearly 20,000 lives, underscored how erosion-induced weakening directly amplified the hazard. Similarly, the Peru-Chile Trench, another intensely erosive margin, exhibits a pattern of giant earthquakes (e.g., 1868 M~9.0, 1877 M~8.8, 1960 M 9.5) where rupture zones often correlate with areas of significant basal erosion and forearc subsidence, such as that induced by the subducting Nazca Ridge. The thinned crust displaces the locked seismogenic zone landward, placing its down-dip end closer to densely populated coastlines. Furthermore, the pervasive normal faulting and landslide headwalls created by gravitational collapse above zones of basal undercutting provide ready-made failure planes. During seismic shaking, these pre-weakened slopes are prone to massive submarine landslides, which can generate local but devastating tsunamis independent of the main megathrust rupture, as potentially occurred during the 1946 Aleutian Islands earthquake. Recognizing these erosion-amplified risks drives critical adaptations in **early warning systems**. Japan's nationwide system, upgraded post-2011, now incorporates real-time data on crustal strain and seafloor pressure changes specifically calibrated to the unique deformation patterns of its eroded margin. In Chile, hazard maps for tsunami inundation explicitly factor in the enhanced subsidence potential above subducting ridges and seamounts, influencing evacua-

tion zone boundaries and the siting of critical infrastructure. Understanding the “erosional personality” of a subduction zone is no longer academic; it is fundamental to saving lives.

**11.2 Resource Implications** Tectonic erosion presents a complex duality for resource exploration: a potent destroyer of certain deposits yet a crucial architect of others. Its most significant destructive impact falls upon **hydrocarbon potential**. Thick, stable sedimentary basins are prime targets for oil and gas generation and trapping. However, the intense deformation, pervasive faulting, and subsidence characteristic of erosional forearcs are anathema to preserving such accumulations. The classic example is the Peruvian forearc. While the prolific hydrocarbon basins of the continental shelf further east (e.g., Talara, Salaverry) thrive, the forearc region directly above the erosive Peru-Chile Trench shows virtually no significant hydrocarbon discoveries. This stark contrast is attributed to the destruction of potential reservoir rocks and source kitchens by the combined effects of frontal bulldozing by the Nazca Ridge and pervasive basal dissolution preventing stable basin development. Drilling campaigns targeting supposed forearc basins off Central America similarly encountered heavily fractured, fluid-altered rocks devoid of viable source rocks or trapping structures. Conversely, tectonic erosion plays a fundamental, albeit indirect, role in creating the world’s most valuable **metalogenic provinces**. Eroded margins are frequently associated with giant porphyry copper-gold deposits and epithermal gold-silver systems. The mechanism involves the deep recycling facilitated by erosion. Fluids released from the dehydrating slab, enriched in metals scavenged from the subducting sediments and oceanic crust, percolate upwards through the mantle wedge. Crucially, fragments of eroded continental crust, rich in incompatible elements like copper, gold, and molybdenum, are also dragged down and incorporated into this flux. As these metal-laden fluids interact with the mantle and lower crust, they contribute to the formation of hydrous, oxidized magmas characteristic of volcanic arcs above eroded margins. The extraordinary fertility of the Andean copper belt (Chuquibambilla, Escondida in Chile; Antamina, Cerro Verde in Peru) is widely attributed, in part, to the efficiency of this recycling conveyor belt driven by tectonic erosion along the Peru-Chile Trench. Geochemical tracers like tellurium/gold ratios and copper isotopes increasingly support this deep-crustal contribution. Exploration geologists now use signatures of erosion, such as forearc subsidence patterns and geochemical anomalies in volcanic rocks, as vectors towards potentially metal-rich magmatic systems. Furthermore, the serpentinite mud volcanoes generated by fluid expulsion in erosive forearcs, like those in the Mariana Trench, are being investigated for their potential to concentrate critical metals (cobalt, nickel, platinum group elements) derived from the underlying mantle wedge and subducted slab. Thus, while erosion destroys near-surface hydrocarbon potential, it acts as a vital deep-earth alchemist for mineral wealth.

**11.3 Cultural Dimensions** Beyond immediate hazards and resources, tectonic erosion weaves into the cultural narratives and historical memories of communities living along active margins. **Indigenous interpretations of coastal changes** often encode observations of landscape evolution driven by these deep-seated processes. Along the Hikurangi margin of New Zealand’s North Island, where the Pacific Plate subducts beneath the Australian Plate with significant erosional components, Māori iwi (tribes) like Ngāti Porou possess rich oral histories (pūrākau) describing land subsidence, coastal retreat, and the submergence



## 1.12 Future Research Horizons

The rich tapestry of cultural narratives and historical records woven into the human experience of tectonic erosion, as explored in the preceding section, underscores that this deep Earth process is far from an abstract scientific concept. It shapes landscapes, resources, and societies. Yet, despite decades of intensive research fueled by technological leaps and conceptual breakthroughs, fundamental aspects of tectonic erosion remain shrouded in uncertainty, driving an ambitious agenda for future exploration. The scientific voyage to demystify this planetary-scale recycling mechanism now stands at a pivotal juncture, poised to tackle profound unresolved questions through innovative technologies and collaborative global initiatives, with implications reaching far beyond crustal dynamics into the very story of Earth's evolution and its enduring habitability.

**Unresolved Mechanistic Questions** lie at the heart of future endeavors, demanding a deeper dive into the complex interplay of forces operating at the plate interface. A critical frontier is understanding **transient erosion episodes during seismicity**. While the 2011 Tohoku earthquake dramatically illustrated co-seismic frontal scraping, the full spectrum of erosive processes unleashed during the seismic cycle remains poorly quantified. Do major ruptures trigger pulses of accelerated basal dissolution due to fracturing-enhanced permeability and fluid flux? Evidence from rapidly uplifted then subsided coastal terraces, like those along the Mejillones Peninsula in Chile, suggests cyclical deformation possibly linked to seismic cycles, but the direct link to mass loss is elusive. Laboratory experiments simulating seismic-frequency deformation under high pressure-temperature conditions are beginning to reveal how rapid stress cycling can dramatically enhance pressure solution and hydrofracturing in quartz-rich rocks, potentially validating models predicting transient chemical erosion spikes during and immediately after megathrust events. Furthermore, the role of slow-slip events and non-volcanic tremor—common phenomena above the seismogenic zone in many erosive margins like Cascadia and Hikurangi—in facilitating incremental basal erosion via persistent, aseismic shearing and fluid migration is a tantalizing unknown. Resolving these temporal dynamics requires continuous, long-term monitoring networks capable of capturing deformation, fluid flux, and microseismicity simultaneously at the seafloor.

Equally pressing is deciphering the **lower plate roughness controls** on erosion efficiency and style. While subducting seamounts like those off Japan are recognized erosional agents, the integrated impact of smaller-scale features (grabens, horsts, fracture zones) and the evolution of plate topography over time are poorly constrained. Does a uniformly rugged plate cause steady, distributed erosion, or do specific topographic wavelengths dominate? The Nazca Ridge offshore Peru demonstrates how large features create localized erosional hotspots, but the pervasive influence of smaller asperities along sediment-starved margins like the Marianas is less understood. Advanced numerical models using high-resolution bathymetry, such as those applied to the Hikurangi margin where the Hikurangi Plateau approaches the trench, reveal complex feedbacks: smaller ridges focus fluid flow, enhancing serpentinization and weakening *ahead* of the main plateau, potentially priming the margin for more efficient erosion upon collision. Future research aims to map seafloor roughness globally at meter-scale resolution using AUV swarms and correlate these maps with geodetically measured strain patterns and seismic imaging of the plate interface structure to establish predictive relationships between incoming plate morphology and erosional response. The challenge extends

beyond mere topography to the *rheological* roughness – variations in the strength and hydration state of the subducting slab itself, inherited from its spreading ridge history or intraplate volcanism, which may dictate where and how efficiently it can rasp or dissolve the upper plate.

**Next-Gen Projects** are already mobilizing to tackle these questions, leveraging unprecedented technological capabilities and international collaboration. The **International Ocean Discovery Program (IODP)** continues to spearhead direct investigation of erosive margins. Ambitious expeditions target the Nankai Trough (Japan) and Hikurangi (New Zealand) margins, deploying the riser-equipped drilling vessel *Chikyu* to penetrate the seismogenic zone and plate interface directly. These missions aim to recover cores across the décollement, install long-term borehole observatories (CORKs) to monitor pore pressure, temperature, and seismicity *in situ*, and sample fluids actively migrating from the subducting slab. The goal is to directly observe the conditions facilitating basal erosion and detect transient changes during slow-slip events. Beyond drilling, the **Sensors Under Sand and Sea (SUSS)** initiative is pioneering dense arrays of seafloor geodesy instruments (pressure gauges, absolute gravity meters, seafloor GPS-Acoustic systems) combined with ocean-bottom seismometers. Deployments planned for the erosive Costa Rica and Mexico margins will provide the first continuous, high-resolution measurements of vertical motion (subsidence/uplift) and strain accumulation/release across the forearc, crucial for distinguishing between elastic deformation and permanent inelastic strain (erosion) and resolving the debate over short-term vs. long-term rates. Projects like **SUN2SENSE** (Subduction Under Near-real-time Tracking of Seafloor Elevation and Seismic Network Experiment) aim to integrate these seafloor data streams with satellite observations in near-real-time, creating an early warning system sensitive to deformation patterns diagnostic of active erosion or slope instability.

Complementing these ocean-focused efforts, **space geodesy networks** are undergoing revolutionary upgrades. The **GNET (GPS Network of the Andes)** and its counterparts in Japan (GEONET) and Cascadia (PANGA) are expanding station density and incorporating new technologies like **GNSS-Reflectometry** to measure coastal erosion/subsidence and **InSAR** (Interferometric Synthetic Aperture Radar) from satellites like NISAR to map millimeter-scale ground deformation over vast areas. The integration of these datasets with **Absolute Gravimetry** campaigns, which measure subtle changes in Earth's gravity field indicative of subsurface mass redistribution, offers a powerful tool to detect volume changes associated with erosion deep within the forearc crust. Furthermore, initiatives like the **EarthScope-Oceans** program envision extending the continental-scale seismic and geodetic coverage pioneered by EarthScope into the submarine realm, creating seamless observational networks spanning from stable craton to trench axis. These projects don't just collect data; they feed into increasingly sophisticated **coupled multi-physics models**. Next-generation codes incorporating realistic grain-scale processes (informed by advanced synchrotron X-ray experiments under simulated subduction conditions) into continuum-scale thermo-hydro-mechanical-chemical (THMC) simulations, running on exascale supercomputers, will finally allow predictive modeling of erosion across spatial and temporal scales, from seismic seconds to orogenic millions of years.

**Broader Implications** of resolving tectonic erosion's mysteries extend far beyond refining subduction zone mechanics, promising transformative insights into Earth's grand narrative. A crucial goal is the **reconciliation with continental drift theory**. While plate tectonics provides the kinematic framework, the dynamic feedbacks involving crustal growth via magmatism and destruction via erosion remain incompletely quanti-

fied. Precise global erosion rate estimates, validated by next-gen observations and models, are essential for closing the continental mass balance over geological time. Did net crustal volume peak in the Proterozoic? Is the current configuration of continents a transient state in an ongoing cycle of growth and loss? Understanding erosion's efficiency in different tectonic settings (e.g., during supercontinent assembly vs. breakup) is key to modeling the supercontinent cycle itself. The fate of subducted continental material holds clues to **mantle evolution**. Tracing the geochemical journey of eroded crust – its dehydration, melting, and eventual contribution