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Mountain Uplift and Oceanic Carbon Cycle Response under Subduction Zone Tectonic-Climate Coupling

Abstract

This study investigates the complex interplay between tectonic processes in circum-Pacific subduction zones and the global carbon cycle, with a particular focus on the Andean mountain system. Through integration of geochemical data, climate modeling, and paleoceanographic records, we demonstrate that subduction-driven mountain uplift significantly influences marine carbon sequestration via its effects on silicate weathering and riverine fluxes. Our findings reveal that the carbon cycle response to orogenic processes is more nuanced than previously understood, with evidence for both carbon release and sequestration depending on erosion rates and lithology. Using strontium isotope ratios and sediment core analysis, we quantify the contribution of Andean weathering to oceanic carbon burial over million-year timescales. The results indicate a strong coupling between tectonic forcing and climate feedback mechanisms that may help explain long-term climate stability despite significant variations in atmospheric CO_2. This research provides critical insights into the geological carbon cycle that may inform predictions of future carbon cycle perturbations.

Keywords: Subduction zones;Carbon cycle;Mountain uplift;Chemical weathering;Andean orogeny;Silicate weathering;Oceanic carbon sequestration

1 Introduction

The global carbon cycle operates across multiple timescales, from rapid exchanges between atmosphere and biosphere to the slow geochemical processing of carbon through weathering, burial, and volcanic emissions over millions of years. Within this complex system, mountain ranges formed at convergent plate boundaries represent critical interfaces where tectonic processes directly influence atmospheric carbon dioxide concentrations and, consequently, global climate .

Carbon cycle response to orogenic processes is more nuanced than previously understood, with evidence for both carbon release and sequestration depending on erosion rates and lithology[1].Rock organic carbon oxidation CO_2 release offsets silicate weathering sink[2]. According to this paradigm, mountain building enhances silicate weathering rates, drawing down atmospheric CO_2 and cooling global climate. However, recent research has highlighted the complexity of this relationship, suggesting that mountain uplift can simultaneously act as both a source and sink for atmospheric carbon.

The Andean mountain range, extending over 7,000 kilometers along the western margin of South America, represents Earth's longest continental volcanic arc formed by the subduction of the Nazca oceanic plate beneath the South American continental plate. This ongoing tectonic process has created a diverse array of lithologies and

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topographic gradients that interact with regional climate patterns to produce varied weathering regimes. Despite extensive research on Andean tectonics and climate individually, the coupling between these systems and their collective impact on the marine carbon cycle remains incompletely understood.

2 Geological Setting and Tectonic Framework

The Andean mountain system formed as a result of the subduction of the Nazca oceanic plate beneath the South American continental margin, a process that has been active since the Jurassic period. Unlike many other mountain ranges that result from continental collision, the Andes represent a unique case of mountain building in a subduction zone setting without significant terrane accretion events during most of its history.

The Andean orogeny initiated in the middle to Late Cretaceous (approximately 120-70 million years ago), following a period of Jurassic-Early Cretaceous backarc extension. Distinct phases of deformation and uplift have occurred throughout the Cenozoic, with significant variations in intensity along the length of the mountain chain. Enhanced mineral dissolution in microchannels significantly impacts carbon sequestration efficiency through weathering processes[3].

Recent geophysical studies have revealed complex patterns of slab dip angles and mantle flow beneath the Andes, which help explain the spatial and temporal patterns of deformation and magmatism along the mountain chain. Temperature sensitivity of the mineral permafrost feedback plays a crucial role in continental-scale carbon cycling[4].

3 Field Sampling and Geochemical Analysis

We collected rock, soil, river sediment, and water samples along several transects across the Andean range, focusing on watersheds with different uplift histories, lithologies, and climate regimes. Sampling locations included the Northern Andes (Colombia and Ecuador), Central Andes (Peru and Bolivia), and Southern Andes (Chile and Argentina). At each site, we documented local topography, measured stream parameters, and collected samples for subsequent laboratory analysis.

Rock and soil samples were analyzed for major and trace element compositions using X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS). Mineralogical compositions were determined through X-ray diffraction (XRD) analysis. Strontium isotope ratios ($^{87}Sr/^{86}Sr$) in river waters and sediments were measured to trace weathering sources and processes, using a thermal ionization mass spectrometer (TIMS) with precision better than ±0.000015.

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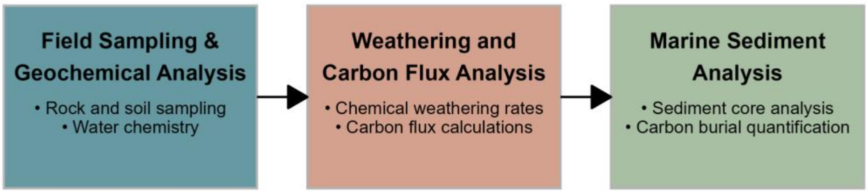

Figure 1:Analytical Framework for Subduction Zone Carbon Cycling

River water samples were analyzed for dissolved ion concentrations, alkalinity, and carbon species using ion chromatography and titration methods. Dissolved organic carbon (DOC) and particulate organic carbon (POC) concentrations were determined by high-temperature combustion. Carbon and oxygen isotope ratios of dissolved inorganic carbon (DIC) were measured to distinguish between carbonate and silicate weathering contributions.

Chemical weathering rates were calculated from dissolved load data using established methods that account for atmospheric and evaporite contributions. We employed multiple proxies to distinguish between silicate and carbonate weathering, including Ca/Na ratios, Sr isotopes, and Ge/Si ratios. Enhanced weathering in agricultural soil shows promise for carbon sequestration and climate mitigation strategies[5].

Carbon fluxes associated with silicate weathering were calculated based on the stoichiometry of weathering reactions, converting silicate-derived alkalinity to CO_2 consumption rates. Similarly, carbonate weathering fluxes were determined from carbonate-derived alkalinity, though these represent a transient rather than long-term carbon sink.Comparing potential carbon dioxide removal fluxes from enhanced rock weathering with baseline fluxes provides critical insights for climate mitigation[6].

To relate weathering processes to tectonic forcing, we compiled uplift rate data from published thermochronology studies, GPS measurements, and geomorphic indicators. Regional climate data, including precipitation rates, temperature gradients, and seasonal patterns, were obtained from meteorological stations and climate reanalysis products.

These datasets were integrated into a spatial framework using Geographic Information Systems (GIS) to identify correlations between tectonic variables (uplift rates, fault density), climate parameters (precipitation, temperature), and weathering indicators (dissolved loads, isotope ratios). Inherited heterogeneities can control viscous subduction zone deformation of carbonates at seismogenic depths[7].

To assess the ultimate fate of weathering products and their contribution to marine carbon sequestration, we analyzed sediment cores from the continental margin offshore South America. Core samples were analyzed for total organic carbon (TOC)

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content, carbonate content, and isotopic compositions. Sedimentation rates were determined through radiocarbon dating and biostratigraphy, allowing calculation of carbon burial rates through time.
Provenance analysis using radiogenic isotopes (Sr, Nd) and trace element signatures helped distinguish Andean-derived sediments from other sources. Enhanced olivine dissolution through continuous grain collisions demonstrates the importance of mechanical processes in geochemical reactions[8].

4 Results

4.1 Spatial Patterns of Weathering and Erosion in the Andean System

Our analysis revealed distinct spatial patterns in weathering intensity and erosion rates across the Andean range. The highest chemical weathering rates were observed in the Northern and Central Andes, coinciding with areas of high precipitation and intermediate elevation (1500-3000m). In contrast, the arid high-elevation regions of the Altiplano-Puna Plateau showed minimal chemical weathering despite significant physical erosion during periodic high-intensity rainfall events.
Silicate weathering intensity, measured by the depletion of mobile elements relative to immobile elements, showed a strong correlation with mean annual precipitation ($r^2 = 0.78$, $p < 0.001$) and a weaker but significant correlation with mean annual temperature ($r^2 = 0.45$, $p < 0.01$). Implications of the riverine response to enhanced weathering for CO_2 removal require careful consideration in regional carbon management strategies[9].
The flux of dissolved elements from Andean watersheds to the ocean was dominated by calcium, magnesium, and bicarbonate ions, with higher silicon fluxes from regions with more intense silicate weathering. Total dissolved solids (TDS) in river waters ranged from 50 mg/L in pristine high-elevation catchments to over 500 mg/L in lowland rivers draining evaporite-rich formations.

4.2 Carbon Consumption via Silicate Weathering

Based on our river chemistry data, we calculated CO_2 consumption rates via silicate weathering ranging from 0.5 to 12×10^6 mol/km²/yr across the Andean watersheds. When integrated over the entire Andean region, this corresponds to approximately $18\text{-}22 \times 10^{12}$ mol/yr of atmospheric CO_2 consumption, representing about 8-10% of the global silicate weathering carbon sink despite covering only about 1% of Earth's continental area.
The efficiency of CO_2 drawdown varied significantly with lithology and erosional regime. Watersheds dominated by fresh volcanic material showed the highest CO_2 consumption per unit area, approximately 2-3 times higher than watersheds draining plutonic or metamorphic terrains. This pattern aligns with laboratory studies showing enhanced dissolution rates for volcanic glasses and minerals compared to their crystalline equivalents.
However, a surprising finding emerged when comparing CO_2 consumption with erosion rates. In areas with extremely high erosion rates (>1000 t/km²/yr), such as

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parts of the Eastern Cordillera in Peru and Bolivia, the net carbon effect of weathering was neutral or even positive (releasing CO_2). This counterintuitive result appears to be related to the oxidation of sulfide minerals and petrogenic organic carbon exposed by rapid erosion, which generates carbonic and sulfuric acids that in turn dissolve carbonate minerals and release CO_2 to the atmosphere.

4.3 Rock Organic Carbon Oxidation and CO_2 Release

Analysis of river water and sediment samples revealed significant fluxes of petrogenic organic carbon in Andean systems, particularly those draining organic-rich sedimentary formations. Using rhenium as a tracer for rock organic carbon oxidation, we estimated that between 4 and 7×10^{12} mol/yr of CO_2 is released to the atmosphere through this process in the Andean region, consistent with the findings of Zondervan et al. (2023) who identified the Andes as a hotspot for CO_2 release through rock organic carbon oxidation.

The spatial pattern of this carbon source showed a strong correlation with areas of rapid uplift and high erosion rates, particularly in the eastern foreland basin where organic-rich shales are exposed. In some watersheds, this CO_2 source approached 40-50% of the magnitude of the silicate weathering sink, substantially offsetting the net carbon sequestration effect of mountain building.

These findings suggest that the carbon cycle consequences of mountain uplift are more complex than previously recognized, with simultaneous operation of both carbon sequestration via silicate weathering and carbon release via organic matter oxidation. The net effect depends on the specific lithological and erosional characteristics of each mountain system.

4.4 Marine Carbon Burial Associated with Andean Weathering

Analysis of sediment cores from the Peru-Chile Trench and continental margin revealed significant spatial and temporal variations in carbon burial rates. Modern burial rates ranged from 2-15 g C/m²/yr, with higher rates in areas receiving greater terrigenous input from Andean rivers. Organic carbon preservation was enhanced in regions with high sedimentation rates and development of oxygen minimum zones offshore.

Provenance analysis confirmed that Andean-derived material constitutes 60-85% of the sediment accumulating along the continental margin, with the remainder derived from coastal erosion and marine productivity. Carbon isotope data indicated that 30-45% of the buried organic carbon was terrigenous in origin, with the remainder derived from marine productivity stimulated in part by nutrient input from Andean weathering.Extrapolating these measurements across the South American continental margin, we estimated that approximately 4-6 $\times 10^{12}$ mol/yr of carbon is sequestered in marine sediments as a direct consequence of Andean weathering processes. This represents about 20-25% of the carbon consumed by silicate weathering in the Andean system, suggesting that a significant fraction of weathered carbon is returned to the atmosphere through various oxidation pathways before final burial.

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4.5 Temporal Evolution of Carbon Fluxes During Andean Uplift

By combining our modern process measurements with paleoceanographic records and tectonic reconstructions, we developed a model of how carbon fluxes evolved during the major phases of Andean uplift. Sediment cores extending back several million years showed significant increases in sedimentation rates and carbon burial coinciding with periods of enhanced tectonic activity and uplift.

Strontium isotope records from marine carbonates showed a gradual increase in $^{87}Sr/^{86}Sr$ ratios from the Late Oligocene to Present, consistent with increasing exposure and weathering of radiogenic rocks in the Eastern Cordillera. This trend was punctuated by more rapid increases during periods of enhanced uplift in the mid-Miocene and Pliocene.

Our model suggests that the net carbon sequestration effect of Andean uplift increased progressively from the Late Oligocene to mid-Miocene, reaching a maximum during the period of most rapid uplift approximately 10-15 million years ago. Subsequently, as erosion rates increased in response to the developing topography, the counterbalancing effect of rock organic carbon oxidation became more significant, reducing the net carbon sink effect in the Late Miocene and Pliocene.

5 Discussion

5.1 Tectonic Control on Weathering Regimes and Carbon Cycling

Our results demonstrate that tectonic processes in the Andean subduction zone exert fundamental control on weathering regimes and associated carbon fluxes through multiple mechanisms. First, uplift creates the topographic gradients necessary for physical erosion, which in turn exposes fresh mineral surfaces to chemical weathering. Second, the subduction-related magmatism produces volcanic and plutonic rocks that weather more rapidly than many other lithologies, enhancing CO_2 consumption. Third, deformation and metamorphism associated with mountain building affect the distribution of different rock types at the surface, including carbon-bearing lithologies.

The spatial patterns of weathering intensity across the Andes reflect these tectonic influences, modulated by climate gradients. The highest weathering rates occur where active uplift, suitable lithology, and adequate moisture coincide—typically on the eastern flanks of the mountain range where precipitation is abundant and fresh mineral surfaces are continuously exposed by erosion.

However, our findings also highlight the role of tectonic processes in mobilizing geological carbon sources. The exposure and oxidation of organic-rich sedimentary rocks in rapidly uplifting regions represents a previously underappreciated carbon source that partially offsets the weathering sink. This balance between carbon sequestration via silicate weathering and carbon release via organic matter oxidation appears to be a fundamental aspect of the carbon cycle response to mountain building, as recently demonstrated by Zondervan et al. (2023) at the global scale.

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5.2 Climate Feedback Mechanisms and Carbon Cycle Stability

The coupling between tectonic processes, weathering, and climate revealed by our study has important implications for understanding long-term climate stability. The traditional view of silicate weathering as a negative feedback mechanism stabilizing Earth's climate over geological timescales requires refinement in light of our findings about concurrent carbon release processes.

Our data suggest that the net effect of mountain building on atmospheric CO_2 may be self-limiting: initial uplift enhances silicate weathering and CO_2 drawdown, but as erosion rates increase in response to developing topography, carbon release from organic matter oxidation becomes more significant. This creates a more complex feedback system than previously recognized, potentially explaining why periods of intense mountain building have not always corresponded to dramatic climate cooling in Earth's history.

Furthermore, our results indicate that the climate response to tectonic forcing may vary depending on the specific characteristics of the mountain system, particularly its lithological composition. Mountain ranges dominated by volcanic rocks with low organic carbon content may act as stronger carbon sinks than those with abundant organic-rich sedimentary formations, as supported by recent work by Harrington et al. (2024) on enhanced weathering processes.

5.3 Implications for the Marine Carbon Cycle

The influence of Andean weathering extends beyond atmospheric carbon dynamics to affect marine carbon cycling and sequestration. Our sediment core analyses demonstrate that a significant fraction of weathered material is ultimately buried in marine sediments, providing a long-term carbon sink. However, the efficiency of this burial process varies with oceanographic conditions and biological productivity.

The enhanced nutrient flux associated with Andean weathering stimulates marine productivity along the western South American margin, creating a biological carbon pump that complements the inorganic carbon sequestration via weathering. This biological pump is particularly effective in the regions influenced by coastal upwelling, where nutrients from both deep waters and terrestrial sources combine to support high productivity.

The presence of an extensive oxygen minimum zone along the Peru-Chile margin enhances organic carbon preservation in sediments by limiting oxidative degradation. This oceanographic feature, maintained in part by the high productivity stimulated by nutrient inputs from Andean weathering, creates a positive feedback loop that amplifies carbon burial efficiency in this region.

6 Conclusion

This study has demonstrated the complex interplay between tectonic processes, weathering reactions, and carbon cycling in the Andean subduction zone. Our findings reveal that mountain uplift in this setting simultaneously drives carbon sequestration through silicate weathering and carbon release through organic matter oxidation, with

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the net effect varying spatially and temporally depending on erosion rates, lithology, and climate conditions.

The coupling between tectonic forces and climate feedback mechanisms emerges as a fundamental aspect of Earth's long-term carbon cycle. The Andean system, as a representative of circum-Pacific subduction zones, plays a significant role in regulating atmospheric CO_2 over million-year timescales through both direct weathering effects and indirect influences on marine carbon burial.

Several key conclusions can be drawn from our research:

The carbon cycle response to mountain building is more nuanced than previously recognized, with concurrent operation of both carbon sequestration and release processes.Enhanced weathering in the US corn belt delivers carbon removal with agronomic benefits[10].

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