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Deep regolith evolution in an active temperate margin: the roles of uplift, topography and lithology

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ABSTRACT

The Critical Zone (CZ) regulates global biogeochemical cycles, yet its deep architecture and evolutionary pace under the coupled influence of active tectonics and temperate climates remain controversial. We combine whole-rock geochemistry from 114 residual regolith profiles

with topographic analysis across 25 km² in the South-Central Chilean Coastal Cordillera (~36°S). Our goal is to delineate the relative roles of uplift, topography and lithology. Using CIA, WIP, and major-element mass-balance (τ), we document an exceptionally deep, highly depleted CZ (CIA>90; WIP<5) at decameter depths, while τ mass-balance reveals near-complete Ca-Na depletion and no approach to parent-rock composition at depth, demonstrating that advanced matrix-scale chemical weathering can penetrate deeply despite active Quaternary uplift (~0.5 mm/yr). We show that while modern slope gradients dictate physical stripping, regolith thickness increases systematically with elevations of the stepped, low-gradient paleo-surfaces (<11°). Lithological controls on regolith thickness are significant on intermediate surfaces but are erased on older platforms. We propose a hybrid evolution model where transient landscape stabilization shields inherited Pliocene weathering mantles from erosion while concurrent vertical meteoric infiltration drives active front propagation. These deep weathering profiles represent domains shielded from surface processes demonstrating that slowly eroding active forearcs can develop and preserve thick residual regolith.

KEYWORDS: Critical Zone; weathering front; Chilean Coastal Cordillera; geochemical mass-balance; Chemical Index of Alteration; Weathering Index of Parker

INTRODUCTION

The Critical Zone (CZ), where rock, water, air, and life interact, regulates ecosystems, water circulation, and landscape evolution [1]; [2]; Oeser et al., 2018). Its deeper portion, the weathering mantle that converts bedrock into regolith, stores and routes groundwater, hosts supergene mineral resources, and sustains the silicate dissolution that consumes atmospheric CO₂

over geological timescales ([2]; [Bowell and Butt, 2025](#)). Recent global compilations show that net inorganic carbon sequestration is non-linearly sensitive to physical erosion, peaking at moderate denudation rates (~ 0.07 mm/yr) where reactive minerals are continuously renewed but not prematurely stripped away ([Bufe et al., 2024](#)). Yet while the upper 1-2 m of the CZ are well characterized, the controls on deep subsurface weathering remain poorly constrained, largely because technical limitations hinder the sampling of a regolith architecture that may extend tens of meters below the surface ([Vázquez et al., 2016](#); [2]). How lithology and topography set the depth of the weathering front and the thickness of the resulting regolith therefore remains an open question, particularly in active orogenic settings.

Key factors that govern regolith formation and the architecture of the deep CZ include lithology, tectonics, climate, and biota ([Jenny, 1941](#); [Schaller and Ehlers, 2022](#)). At the bedrock scale, mineralogical composition determines alteration susceptibility, because individual phases possess highly variable intrinsic dissolution kinetics ([Pope et al., 2015](#); [Bowell and Butt, 2025](#)): granitoids develop thick saprolite driven by the rapid hydrolysis of their plagioclase fraction ([White et al., 2001](#); [Brantley et al., 2011](#); [Vázquez et al., 2016](#); [Krone et al., 2021](#)), whereas low-porosity metamorphic rocks dominated by slower-weathering phases exhibit significantly thinner regoliths ([Behrens et al., 2015](#); [Brantley et al., 2018](#)). Tectonic pre-fracturing creates pathways for fluid and gas transport, and chemical alteration and physical fracturing are further coupled through weathering-induced fracturing, whereby the oxidation of Fe(II)-bearing silicates, particularly biotite, drives volumetric expansion and generates self-propagating micro-cracks that create the porosity required for saprolite development and continuously expose fresh reactive surfaces to meteoric fluids, enabling matrix-scale weathering to propagate to decameter depths ([Hampl et al., 2022, 2023](#); [Cosans et al., 2024](#)). Mineral dissolution nevertheless exerts a non-

linear dual control on subsurface hydraulics: matrix disaggregation and the swelling of interstratified clays initially enhance vertical permeability, whereas the accumulation of secondary phases such as kaolinite in the upper profile can clog pore throats and seal fracture networks, retarding infiltration and mitigating further mineral transformation at depth (Hampl et al., 2023).

At the landscape scale, tectonics and climate jointly set the pace of weathering; surface uplift drives base-level lowering and hillslope steepening, which regulate physical erosion and therefore the rate at which fresh bedrock is supplied to, or stripped from, the weathering zone (Gabet and Mudd, 2009; Braun et al., 2016; Brantley et al., 2018; Perri, 2020), while vegetation stabilizes hillslopes and precipitation controls chemical leaching and solute export (Riebe et al., 2004; Gabet et al., 2015; Li et al., 2017; Bowell and Butt, 2025). At the profile scale, the outcome depends on the interaction of temperature, water throughput, and mineral residence times (Braun et al., 2016; Perri, 2020). Numerical and reactive-transport models formalize these dependencies and predict steady-state regolith thickness from the balance between weathering-front advance and denudation (Brantley et al., 2008; Lebedeva and Brantley, 2013, 2018; Maher and Chamberlain, 2014; Braun et al., 2016), but they have rarely been tested against deep, spatially dense field data.

What remains unresolved is how deep the weathering front can reach, and with what mineralogy, when surface uplift is rapid, but denudation is not. Geophysical surveys have imaged the lateral continuity of regolith and bridged local to regional scales (e.g., Holbrook et al., 2014; Harman and Cosans, 2018; Moravec et al., 2020), but they lack systematic deep physical calibration, and the direct profile data that could provide it are geographically dispersed and therefore scarcely comparable. As a result, active margins that combine high surface uplift

with transiently low denudation (~ 0.03 mm/yr), such as the forearc of the South-Central Chilean Coastal Cordillera (CC), remain a geomorphic paradox; instead of the thin, erosion-limited mantles expected in steep orogenic belts, they preserve deep and highly depleted weathering profiles whose geomorphic and lithological controls, and whose role as long-term carbon sinks, are still unquantified.

The South-Central Chilean CC (Fig. 1) offers an exceptional natural laboratory to address this gap. Whereas granitoid weathering fronts in temperate and humid settings are generally restricted to <20 m, drilling in this region has revealed active weathering fronts up to 76 m deep (Krone et al., 2021), and regolith profiles commonly reach ~ 60 m (Bustos et al., 2022), substantially deeper than the ~ 30 m documented farther north at $\sim 33.5^\circ\text{S}$ under a drier Mediterranean climate (Vázquez et al., 2016). These deep profiles are spatially associated with low-slope geomorphic surfaces developed on basement rocks of contrasting composition and subsequently dissected by fluvial incision (Kaizuka et al., 1973; Melnick et al., 2009; Jara-Muñoz et al., 2015; Encinas et al., 2021). Here we analyze 114 residual regolith profiles developed on four lithologies: biotite-garnet tonalite (GTON), biotite granite (BG), biotite diorite (DRT) and micaceous schist (metapelite, MP) across ~ 25 km² of this landscape, none of which intersects unweathered parent rock over depths of up to 44 m. Because slope gradient and basement lithology vary over such a small area under broadly uniform climatic conditions, this setting isolates their respective controls on regolith thickness and weathering intensity. Combining whole-rock geochemistry with terrain analysis, we test the hypothesis that transient geomorphic stabilization of low-slope surfaces promotes the development and preservation of exceptionally deep, pervasively weathered profiles, and thereby distinguish topographic from lithological controls.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The study area is situated in the active convergent margin of the Andean Orogen, where the oceanic Nazca Plate subducts beneath the continental South American Plate at a convergence rate of approximately 70 mm/a (Melnick et al., 2009; Tolorza, 2015), specifically within the segment where the Nazca Plate subducts at an angle that increases around 22°S (Herrera et al., 2024). This setting defines a macro-scale zonal arrangement parallel to the margin, consisting of the Peru-Chile Trench, the CC, the Central Depression, and the Main Andean Cordillera (Kaizuka et al., 1973; Tolorza, 2015). The basement of the South-Central Chilean CC at ~36°S (Fig. 1), is characterized by a Late Paleozoic paired metamorphic belt (Gianni, 2021; Glodny et al., 2008). This belt comprises the deep-seated, high-pressure/low-temperature Western Series and the adjacent low-pressure/high-temperature (LP/HT) Eastern Series (Deckart et al., 2014; Gianni, 2021). The contemporaneous LP/HT metamorphism in the Eastern Series was primarily caused by the intrusion of the extensive, calc-alkaline Coastal Batholith, dated mostly between 300 and 320 Ma (Deckart et al., 2014; Glodny et al., 2008). Isotopic evidence from the batholith and the presence of Triassic extensional basins to the north and east of the study area suggest a period of crustal recycling and magmatic contraction during the Late Carboniferous-Permian, followed by an episode of extension/rifting and potential subduction interruption during the Triassic-Early Jurassic, which featured bimodal magmatism and shallow emplacement of post-kinematic plutons (Del Rey et al., 2016; Glodny et al., 2008; Vásquez et al., 2011).

Thermochronological studies on the area reveal a history of overall low long-term exhumation rates of 0.03 to 0.04 mm/a (Glodny et al., 2008; Tolorza, 2015), while the mean uplift rate (U) is ~0.5 mm/a since the Late Pliocene (Farías et al., 2008; Freisleben et al., 2023).

The area is characterized by a humid-temperate (Csb) climate, with a present-day mean annual precipitation (MAP) of $\sim 1300 \text{ mm yr}^{-1}$ (Garreaud et al., 2024). Low erosion rates $\sim 0.03 \text{ mm/a}$ have been reported (Tolorza, 2015; Carretier et al., 2018), indicating transient landscape conditions.

Regional physiography is characterized by a stepped landscape of elevated geomorphic surfaces that record active Quaternary tectonic uplift and block deformation along this convergent margin (Melnick et al., 2009; Encinas et al., 2021). Both north and south of the study area, this coastal deformation is recorded by well-documented sequences of uplifted marine terraces, such as those recognized north of the Itata River (Jara-Muñoz et al., 2015) and south of the Biobio River in the Arauco Peninsula (Kaizuka et al., 1973; Melnick et al., 2009; Encinas et al., 2021; Vega-Ruiz et al., 2026). Concurrently, the high-altitude domains of the CC, particularly the Nahuelbuta range, preserve remnants of older, low-relief continental surfaces at high elevations, reflecting the transition between the CC and the shoreline, shaped by Quaternary uplift and deformation (Melnick et al., 2009; Encinas et al., 2021).

The landscape includes coastal-draining valleys and stepped low-slope surfaces extending from the shoreline to CC summits at $\sim 430 \text{ m a.s.l.}$ (*e.g.* Encinas et al., 2021). The highest, low-relief, surfaces are interpreted as denudational remnants dating to the Pliocene – Early Pleistocene, representing a period of regional landscape stability prior to incision during the Middle - Late Pleistocene (*e.g.* Velásquez et al., 2025). Successive lower remnants are interpreted as uplifted Quaternary marine terraces formed by coastal abrasion during Middle to Late Pleistocene, documented north and south of the study area (Kaizuka et al., 1973; Melnick et al., 2009; Jara-Muñoz et al., 2015). This setting allows comparison of regolith development on stable low-slope surfaces and incised valleys. CC summit uplift during the Plio-Pleistocene

marked transition to a subaerial forearc (Encinas et al., 2021). Thick residual regolith has been documented throughout the humid-temperate CC: Vázquez et al. (2016) reported saprolites exceeding 30 m at ~33°S, while Bustos et al. (2022) observed profiles reaching 60 m south of the study area (~38°S), and has been observed to be developed in a wide range of lithological units in the study area (Fig. SM-II).

At the local scale, these regional magmatic and metamorphic basements translate into four distinct lithological units across the sampled 114 profiles: biotite-garnet tonalite (GTON), biotite granite (BG), biotite diorite (DRT), and micaceous schist (metapelite; MP). The three plutonic granitoids (GTON, BG, and DRT) represent crystalline mineralogists dominated by quartz, plagioclase, and alkali feldspar, with varying proportions of highly alterable iron-bearing phases such as biotite, chlorite, and hornblende, which are highly susceptible to chemical dissolution and oxidation-induced microfracturing. In contrast, the micaceous schist (MP) represents a low-porosity metamorphic unit dominated by slower-weathering quartz-muscovite mineral assemblages with highly anisotropic foliation fabrics. This local lithological diversity, combined with the presence of stepped geomorphic surfaces under a uniform temperate climate, provides an ideal natural configuration to isolate parent rock mineralogy from topographic controls on deep CZ development.

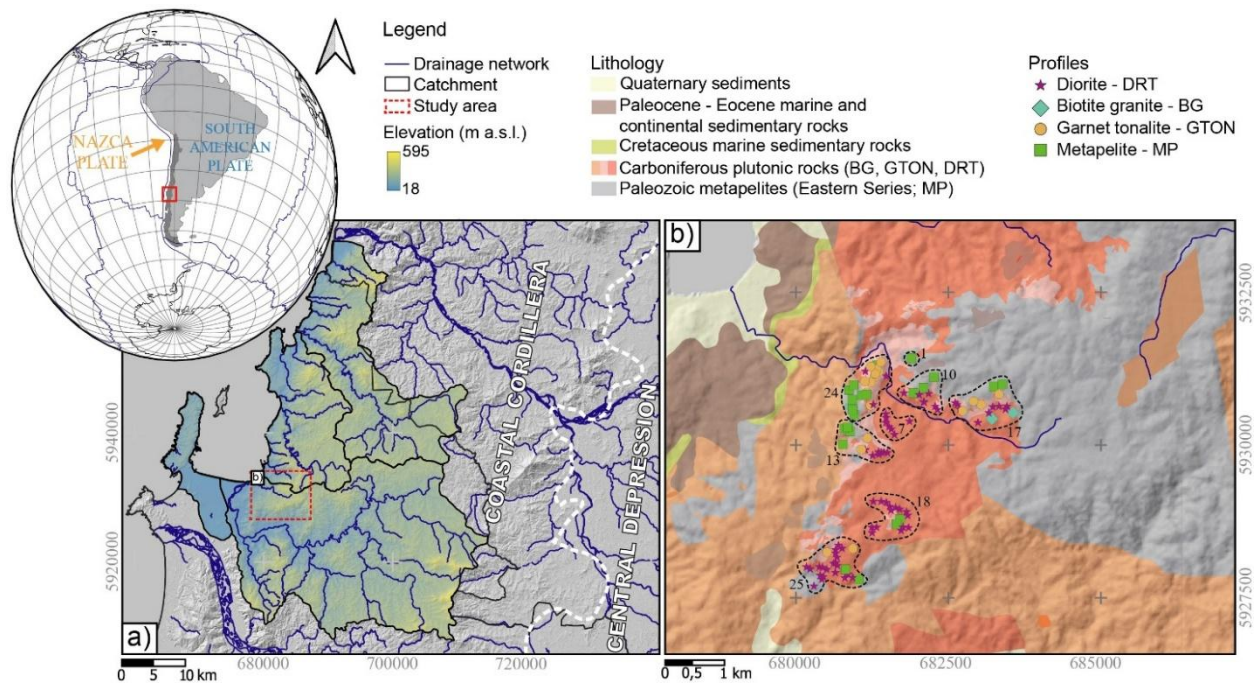


Figure 1: Study area setting. (a) Regional tectonic framework and location of the study area. (b) Geological map of the study area. Black dashed polygons show sampling areas; numbers indicate profile counts. Due to map scale, some profiles may not exactly match mapped lithologies. Lithological units were mapped from SERNAGEOMIN, 2003 and this study. Hillshade map was derived from ALOS PALSAR.

RESULTS

Geomorphic Surfaces Mapping

Field and GIS analysis identified seven low-slope and low-relief geomorphic surfaces (S1-S7) between ~45 and ~380 m a.s.l. (Fig. 2a). These surfaces are preserved as isolated, spatially disconnected patches that have been dissected by subsequent fluvial incision.

The surfaces define a stepped spatial arrangement across the study area. Lower surfaces (S1-S3; ~45-150 m a.s.l.) occupy the lower-elevation sector of the landscape, whereas upper surfaces (S4-S7; >200 m a.s.l.) occur progressively higher across the interior and summit

domains. Individual remnants are separated by incised valleys, producing a discontinuous staircase of low-relief surfaces from the lower coastal sector toward the higher parts of the landscape.

Whole-rock geochemical data from 114 in situ regolith profiles extend to investigated depths of up to 44 m and reveal a consistent vertical geochemical structure with no evidence of a weathering front within this depth. Unweathered bedrock was not reached in any profile, indicating that the investigated depths represent minimum regolith thicknesses rather than the total thickness of the weathering profiles. Profiles were sampled vertically at nominal 2 m intervals where possible. Throughout the profiles, the CIA decreases with depth but remains remarkably high in most samples at the bottom of the profiles (Fig. 2b, Fig. 3a-d), revealing thick regolith profiles at a wide slope range (Fig. 2c). For the lithologies concerned, regolith thickness shows a general tendency to increase with elevation; in particular, for DRT and MP (Fig. 2d-g).

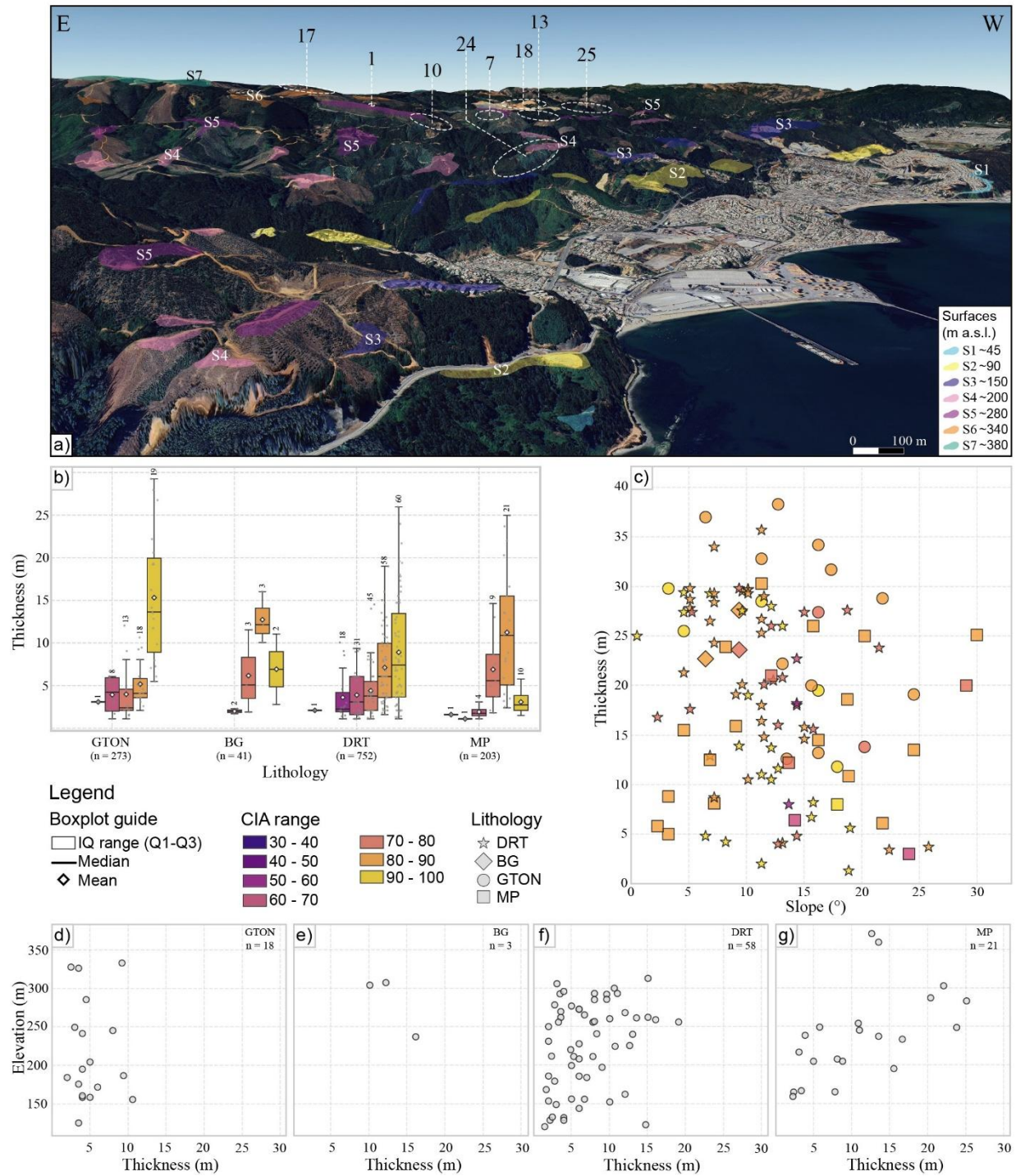


Figure 2: Geomorphic surfaces and main regolith-profile results. (a) Perspective view of the geomorphic surfaces (S1-S7) recognized in this study. White dashed polygons indicate the sampling areas shown in Fig. 1b. (b) Regolith thickness by lithology across CIA ranges. The ‘n’

below each lithology code indicates the total number of samples for that lithology, whereas the 'n' above each box indicates the number of samples within each CIA range. Gray dots represent individual samples. (c) Regolith thickness versus slope, grouped by lithology and mean CIA range. (d-g) Scatter plots of sample elevation (m a.s.l.) versus regolith thickness (m) for samples with CIA values of 80-90, shown separately for GTON (d), BG (e), DRT (f), and MP (g). Regolith thickness shows a general tendency to increase with elevation, particularly in DRT and MP; similar trends are observed for other CIA ranges (Fig. SM-R4.3). The total number of samples 'n' and lithology code are shown in the upper-right corner of each panel.

Our results show similar vertical geochemical trends; namely, a systematic downward transition from high CIA (>90) near the surface to moderate-to-high CIA (>80) at decameter depths, across both low- (<11°) and high-slope (>15°) domains (Fig. 2c, Fig. 3a-d). WIP shows the inverse but equivalent pattern, with the lowest values near the surface and progressively higher values at depth (Fig. 3e-h), consistent with decreasing weathering intensity downward. This intense chemical alteration signature is statistically indistinguishable at decameter depths across all slope classes (low-, intermediate-, and high-slope domains). However, the physical thickness and structural preservation of the weathering mantle are highly variable across the landscape.

Open-system mass-transfer coefficients (τ) were calculated for CaO, Na₂O, K₂O, Al₂O₃ and Fe₂O₃ using Ti as the reference element, as its monotonic enrichment toward the top of the regolith profiles is consistent with predominantly immobile behavior and residual accumulation during weathering (Table SM-R4.4); the least-weathered rock samples available for each lithology were used as parent proxies. Because completely unweathered bedrock was not recovered, the resulting τ values are conservative, minimum estimates of net elemental loss. We

selected one profile per lithology to represent the behavior observed across the regolith profiles in the study area (Fig. 3i-l). A common mobility sequence, $\text{Ca} \approx \text{Na} > \text{K} > \text{Fe} \approx \text{Al}$, is reproduced across lithologies, slope classes and geomorphic surfaces. τCaO and $\tau\text{Na}_2\text{O}$ approach -1 (*i.e.* $>80\text{--}100\%$ loss) from the shallowest to the deepest samples in most granitoid profiles, indicating near-complete depletion of plagioclase-derived Ca and Na-bearing phases down to 25-30 m, with no convergence towards $\tau = 0$ at the base of the profiles (Fig. 3i-l). $\tau\text{K}_2\text{O}$ is systematically less negative and, unlike τCaO and $\tau\text{Na}_2\text{O}$, depth-dependent: it decreases upwards from values near or above zero at depth (up to $+0.65$ in the DRT profiles) to -1 to -0.5 in the upper ~ 10 m, consistent with progressive but incomplete breakdown of K-feldspar and biotite (Fig. 3i-l). Where CIA is uniformly high, $\tau\text{K}_2\text{O}$ therefore resolves a vertical weathering gradient that the bulk indices no longer capture (Fig. 3). $\tau\text{Al}_2\text{O}_3$ and $\tau\text{Fe}_2\text{O}_3$ remain within ± 0.3 in most profiles, consistent with residual retention in kaolinite and Fe-oxyhydroxides, although several profiles record internal redistribution rather than strict immobility: Al and Fe gains at depth (τ up to $+0.8$; Fig. 3i-k) and moderate Fe depletion throughout the profile ($\tau\text{Fe}_2\text{O}_3 \approx -0.2$ to -0.45), the latter pointing to periodic reducing conditions and Fe export. A minority of profiles yields large positive τ for all elements; we interpret this as an artefact of the parent proxy rather than as mass addition, since a reference sample that is itself leached and residually enriched in Ti inflates τ for every other element. These profiles are therefore used only to assess relative down-profile trends. Because this bias acts in a single direction, the depletions reported above are lower bounds: the mass-balance results independently confirm the CIA and WIP patterns and indicate that the decameter-thick weathering mantles are pervasively leached throughout, with no geochemical evidence of a weathering front within the investigated depth.

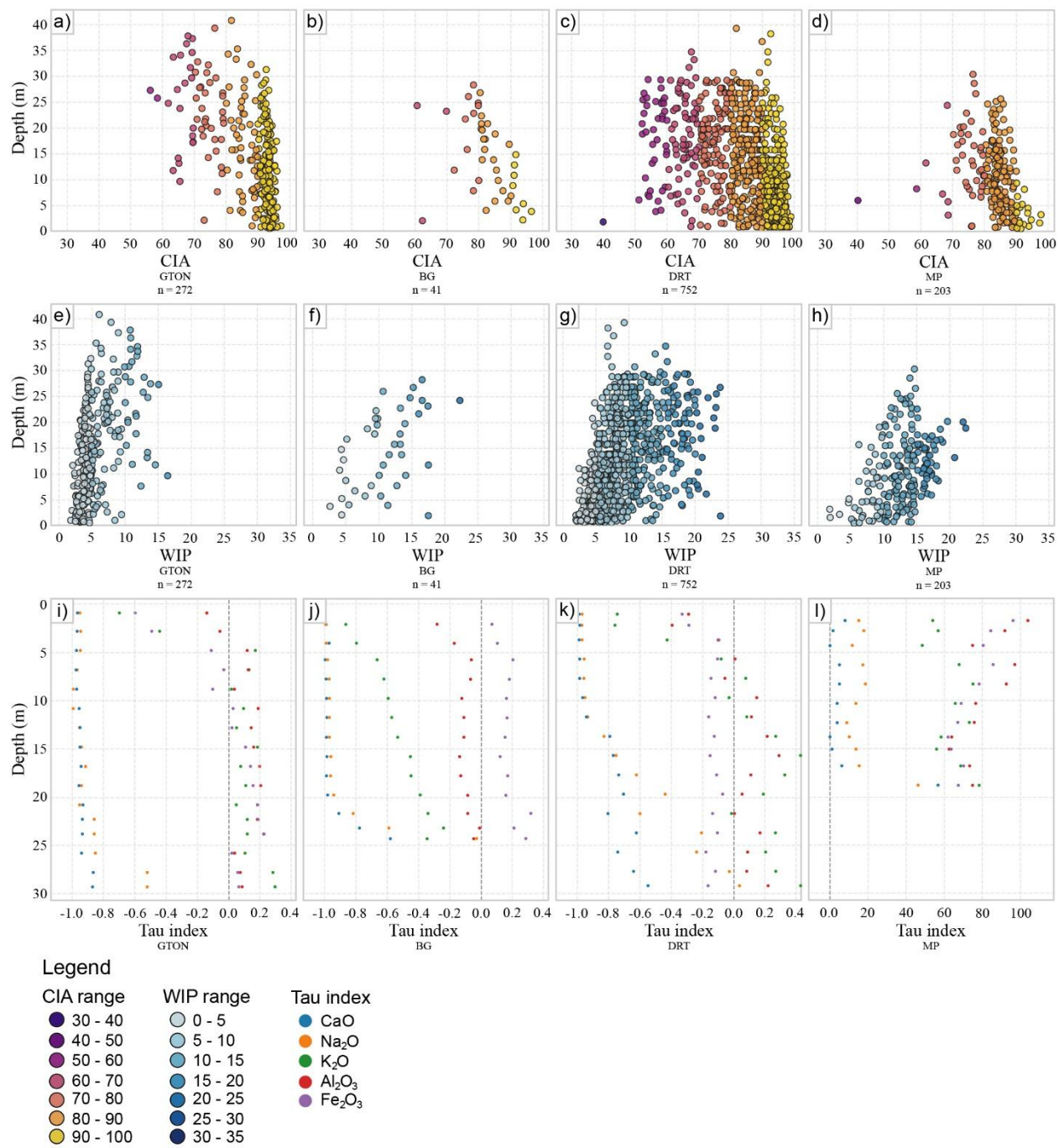


Figure 3: Vertical geochemical patterns of regolith weathering and elemental mass transfer across the four lithologies. (a-d) Chemical Index of Alteration (CIA) versus sample depth, shown separately for GTON (a), BG (b), DRT (c), and MP (d). Points represent individual samples from the nominal vertical interval of 2 m of regolith profiles and are colored according to CIA ranges.

(e-h) Weathering Index of Parker (WIP) versus sample, shown separately for GTON (e), BG (f), DRT (g), and MP (h). Points represent individual samples from the nominal vertical interval of 2 m of regolith profiles and are colored according to WIP ranges. The total number of samples ‘n’ for each lithology is indicated below the corresponding panel. (i-l) Down-profile mass-transfer coefficients (τ) for CaO, Na₂O, K₂O, Al₂O₃, and Fe₂O₃ in one representative regolith profile from each lithology. τ values were calculated using Ti as the reference element, whose down-profile behavior is consistent with predominantly immobile behavior and residual enrichment during weathering, and the least-weathered available sample of each lithology as the parent-material proxy. The vertical dashed line in dark-gray marks $\tau = 0$, corresponding to no net elemental mass change relative to the parent proxy; negative and positive values indicate net depletion and enrichment, respectively.

Topographic and Lithological Controls

Descriptive statistical analysis of 114 regolith profiles reveals two systematic controls on regolith thickness operating at different spatial scales (Fig. SM-R4.1; Table SM-R4.2; Fig. SM-R4.3). To ensure a robust comparison between contrasting geomorphic domains, our analyses focus exclusively on low- and high-slope classes ($S < 11^\circ$ and $S > 15^\circ$, respectively) due to topographic ambiguity in confidently classifying the profiles with intermediate slope ($11^\circ \leq S \leq 15^\circ$) as either flat relict platforms or active steep hillslopes. Statistical tests (Table SM-R4.2) show that low-slope domains preserve significantly thicker regolith columns, revealing maximum investigated profile depths exceeding 30 m (Mann-Whitney U, $p=0.0073$), whereas high-slope domains exhibit significantly thinner profiles, with maximum investigated depths of < 25 m ($p = 0.0193$), with CIA values systematically spanning 60–100 across both slope classes.

282 This pattern of thickness segregation occurs within individual geomorphic surfaces of
283 similar elevation and across all lithologies (Fig. 2b-g). In contrast, when comparing surfaces of
284 different elevations, regolith thickness increases with surface elevation: from <30 m at ~150 m
285 a.s.l. to >40 m at ~280 m a.s.l., regardless of lithology. At the scale of individual geomorphic
286 surfaces, the influence of lithology on regolith thickness varies between surfaces (Table SM-
287 R4.2): significant differences among lithologies are observed on S4 (Kruskal-Wallis, $p =$
288 0.0004), whereas no significant lithological differences are detected on S5 (Kruskal-Wallis, $p =$
289 0.9559). Importantly, despite this variability, regolith remains exceptionally thick across all
290 lithologies and surfaces.

291 Whole-rock geochemical data from depth profiles were also used to interpolate the spatial
292 distribution of chemical alteration, using CIA as a proxy for weathering intensity. The resulting
293 three-dimensional reconstruction (Fig. SM-R4.5) represents the CIA ranges as laterally
294 continuous, mantle-like domains beneath the landscape. Across the three topographic transects
295 (Fig. 4a), the model reproduces the vertical geochemical pattern observed in the studied profiles
296 (Fig. 4b-d), with the highest CIA values generally occurring closer to the surface and
297 progressively lower CIA values at depth. The interpolated domains also show substantial lateral
298 variability in their elevation and geometry, allowing the relationship between chemical
299 alteration, topography, and the mapped geomorphic surfaces (S1-S7).

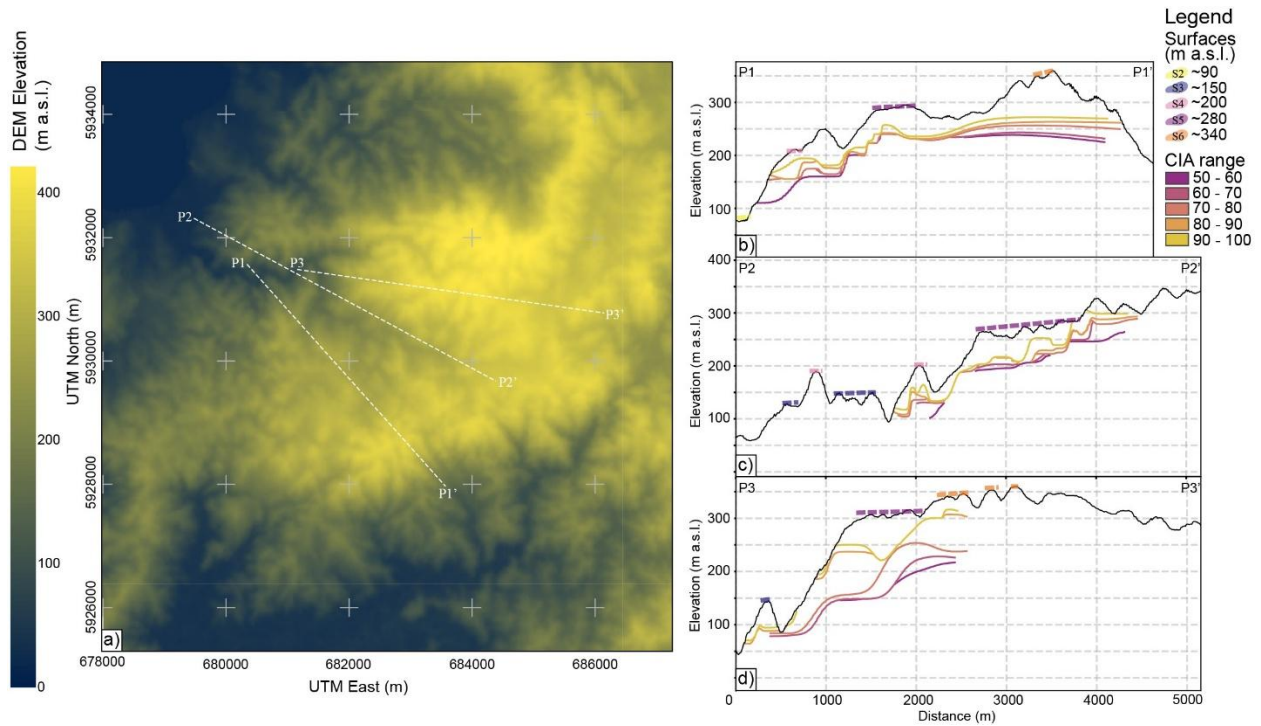


Figure 4: Profiles from three-dimensional reconstruction of chemical weathering across the study area based on interpolated CIA values. (a) Digital elevation model (DEM) showing the location of the three topographic transects (P1–P1', P2–P2', and P3–P3'). (b–d) Topographic profiles along P1–P1', P2–P2', and P3–P3', respectively, showing the interpolated mantle-like distribution of CIA ranges beneath the landscape. Colored lines represent the geometry of the interpolated CIA domains, whereas dashed line segments along the topographic profile indicate the mapped geomorphic surfaces (S2–S6) from Fig. 2a. The reconstruction is based on whole-rock geochemical measurements from regolith samples collected at different depths and illustrates the spatial relationship among weathering intensity, topography, and geomorphic surfaces.

DISCUSSION

While the identified geomorphic relicts (Fig. 2a) are topographically compatible with both the uplifted marine terrace sequences as documented at the north and south of the study area, and the subaerial pediments recognized in the higher parts of the coastal range (Encinas et al., 2021), their specific genetic origin remains speculative. Regardless of their origin, these well-defined flat platforms represent key geomorphic boundary conditions that allow us to test the relative controls of terrain steepness and lithology on subsurface regolith thickness.

The statistically indistinguishable intense chemical alteration signature at decameter depths across all slope classes shows that while present-day slopes may regulate surficial physical erosion (Gabet et al., 2015), they do not limit the depth or intensity of pervasive chemical alteration within the investigated interval. Persistently high CIA >90 and consistently low WIP <5 (Fig. SM-R4.1) at decameter depths reflect intensive, pervasive chemical alteration and leaching of mobile elements.

Because τ_{Ca} does not converge towards $\tau = 0$ at depth even in the deepest samples, the profiles do not approach parent-rock composition at depth, indicating that the weathering front lies below the investigated interval. Such deeply weathered profiles, which may reach hundreds of meters in stable cratonic settings, are conventionally attributed to millions of years of uninterrupted chemical weathering under warm-humid tropical climates (Braun et al., 2016; Perri, 2020; Howell and Butts, 2025). Here, however, tropical-like chemical alteration occurs across all lithologies under a temperate climate, within an active orogenic setting. Furthermore, regional paleoclimate models indicate that this margin experienced even colder conditions during Pleistocene glacial intervals (Holbrook et al., 2014; Brantley et al., 2018), which would have further restricted temperature-dependent chemical kinetics. The preservation of exceptionally deep regolith profiles, reaching 60 m (Bustos et al., 2022) to over 100 m in field-observed

exposures, under these geodynamically active and temperate climate conditions suggests that the development and preservation of deep chemical alteration are not controlled by climate alone.

The similarity in vertical geochemical trends indicates that the depth and intensity of chemical weathering are widespread and decoupled from modern hillslope gradients. However, the high variability in the physical thickness and structural preservation of the weathering mantle across the landscape demonstrates that geomorphic controls on regolith residence time (via surface stripping) differ from those governing chemical alteration intensity at depth (Bustos et al., 2022). The preservation of exceptionally deep regolith profiles across multiple surfaces, despite active Quaternary uplift of ~ 0.5 mm/yr (Farías et al., 2008; Tolorza, 2015), is sustained by exceptionally low physical denudation rates of ~ 0.03 mm/yr (Schaller et al., 2018). This geomorphic disequilibrium suggests that the landscape behaves as a transient relict, preserving a cumulative “weathering legacy” over time. Consequently, active tectonic uplift and steep topography do not preclude the preservation of mature, tropical-like CZ profiles.

At the landscape scale, this contrast in slope-dependent thickness carries profound geomorphic significance. Mechanistically, while both domains share highly altered and overlapping surface weathering signatures, the low-slope domains act as transient geomorphic shields. This topographic shielding isolates the deep regolith from physical erosion, maximizing regolith residence times and allowing for the preservation of mature upper pedolith horizons. In contrast, the significantly thinner profiles observed on steep slopes are consistent with enhanced physical stripping and probable truncation of the upper weathering profile, thereby limiting preserved CZ thickness without necessarily restricting chemical alteration at depth (Bustos et al., 2022). This spatial partitioning of CZ architecture, where stable low-gradient summits preserve thick, highly altered weathering columns while steep slopes undergo probable active physical

truncation, parallels observations in other deeply weathered crystalline landscapes, such as the North American Piedmont, where ridge boreholes preserve deep weathering blankets compared to actively eroding valleys (Cosans et al., 2024).

The elevation-dependent pattern suggests that higher surfaces were exposed to weathering for longer periods, consistent with a chronosequence in which longer surface exposure favors the development and preservation of thicker regolith. This interpretation is consistent with the regional tectono-geomorphic evolution of the Chilean margin, where episodic Quaternary uplift and progressive base-level fall led to the abandonment of stepped paleosurfaces. Although these ancient surfaces have experienced prolonged subaerial exposure, physical erosion should be transport-limited due to their flat, low-gradient topography, shielding them from slope-driven sediment transport and active fluvial headward dissection. While physical erosion is comparatively low on these perched platforms, chemical weathering continues to propagate downward driven by vertical meteoric infiltration, allowing the development of thick regolith columns over geological timescales. The localized lithological control indicates that while parent rock mineralogy exerts a fundamental control on initial weathering susceptibility, its physical expression on regolith thickness can be progressively overridden by geomorphic stabilization and prolonged cumulative exposure times on older, flat surfaces.

Although the thinner regolith profiles observed in steep domains ($S > 15^\circ$) are consistent with enhanced physical stripping and probable truncation of the upper pedolith (Oeser et al., 2018; Bustos et al., 2022), the persistence of continuous, slope-conforming regolith blankets across these steep hillslopes indicates that subsurface weathering-front propagation remains active. Because the soil-saprolite boundaries physically parallel the modern topography (Fig. 4

and Fig. 5) rather than being horizontally truncated by it, these profiles cannot be explained solely as passive, unweathered remnants of prior flat paleosurfaces, but must reflect continued downward propagation of chemical weathering. The presence of regolith on steep slopes ($>15^\circ$) suggests that erosion does not always outpace weathering in these domains. Instead, preservation efficiency varies gradually rather than by a strict erosional threshold. Once low-gradient stability is established ($<11^\circ$), regolith thickness scales primarily with inferred exposure time rather than bedrock composition.

The step-like spatial arrangement of the mapped surfaces, from lower-elevation remnants to isolated high-elevation summit surfaces (Fig. 2a), provides the geomorphic framework for evaluating their possible origin and preservation. We interpret this as progressive surface emergence during sustained uplift, where these perched summits remain geomorphologically stable and temporarily isolated from active fluvial dissection because migrating river knickpoints have not yet propagated to the highest headwater interfluves (Vázquez et al., 2016; Encinas et al., 2021). On these flat summits with low slopes, gravity-driven sediment transport is strictly limited, maintaining exceptionally low physical denudation rates that shield the deep weathering mantle from physical stripping and allow for prolonged, cumulative weathering while adjacent valleys actively incise. In this framework, deep regolith development reflects the interaction between time-dependent surface stability and slope-controlled preservation. Because these geomorphic surfaces (S1-S7) were mapped strictly on morphometric criteria prior to and independently of the subsurface geochemical interpolation, this striking spatial alignment suggests that regional weathering evolved through discrete, episodic stabilization phases during tectonic uplift rather than a continuous accumulation over time.

We evaluate two idealized geomorphic end-member scenarios to explain the preservation and ongoing development of these exceptionally deep regolith columns. The “inherited model” (Fig. 5a) represents the limiting case in which the deep weathering mantle formed entirely beneath an older, probably Plio-Pleistocene paleosurface (PSI), developed under rainier climates, and later dissected and uplifted by subsequent Quaternary uplift and dissection that generated PSII and PSIII (Encinas et al., 2021). In this end-member scenario, the inherited weathering architecture retains the geometry established beneath the original paleosurface and is therefore progressively truncated by later incision. Chronologically, such a fully inherited origin is plausible, as the development of highly depleted saprolite profiles ($CIA > 80$ at > 30 m depth) under modern temperate conditions would require prolonged water-rock interaction over geological timescales.

We also propose the “concurrent model” (Fig. 5b), which represents the opposite idealized end-member, in which the regolith develops entirely synchronously with Quaternary uplift and the progressive development of geomorphic surfaces, without an inherited pre-existing weathering mantle. In this limiting scenario, low-slope surfaces (PSI - PSIII) become zones of enhanced preservation as they emerge and stabilize through time. The correlation between surface elevation and regolith thickness therefore reflects differences in the duration of surface stability, with higher surfaces preserving thicker regolith through successive windows during which chemical weathering continues while physical erosion is minimized. Each surface thus develops its regolith according to its exposure time, such that older, higher surfaces (PSI) record longer cumulative weathering than younger, lower surfaces (PSIII).

Over a 2 Ma interval, a first-order rate-time calculation illustrates how differences in long-term denudation could affect the preservation of an inherited weathering mantle. Vázquez

et al. (2016) estimated denudation rates of 20-72 m/Ma for a deeply weathered granitic profile in the Chilean Coastal Cordillera, corresponding to ~40-144 m of cumulative surface lowering over 2 Ma. In contrast, a denudation rate of ~0.03 mm/yr (~30 m/Ma; Bustos et al., 2022; Schaller et al., 2018) would correspond to ~60 m of cumulative lowering over the same period. Such differences in cumulative denudation could strongly influence the preservation of inherited weathering profiles. Regolith profiles reaching ~60 m have been reported regionally (Bustos et al., 2022), while field exposures exceed 100 m in thickness, indicating that low-denudation surfaces could preserve a substantial portion of an initially very thick weathering mantle. Thus, the deep geochemical signature may, at least in part, represent an inherited legacy of past weathering.

However, the weathering legacy of the inherited model is not necessarily passive. Instead, we propose a hybrid model in which inherited weathering columns are actively maintained and continuously deepened by concurrent weathering. These stable summits act as transient geomorphic shields where gravity-driven sediment transport is transport-limited, effectively minimizing physical erosion (~0.03 mm/yr). This geomorphic decoupling creates discrete windows of stability during which vertical meteoric water infiltration can sustain continued downward chemical weathering while physical stripping remains limited.

Net solute weathering fluxes on these stable platforms are ~9.5 to 32.8 t/km²/yr, equivalent to a chemical mass-loss thickness of ~0.004-0.013 mm yr⁻¹ assuming a bedrock density of 2.6 g cm⁻³ (Oeser et al., 2018). These values quantify chemical mass export rather than weathering-front advance but demonstrate sustained chemical removal under low-denudation conditions. This active vertical leaching explains why unweathered plagioclase is still present at depth and has not been completely depleted. Rather than proceeding to a CIA of 100, chemical

weathering kinetics are moderated by negative feedback: the in-situ precipitation of secondary kaolinite within plagioclase etch pits acts as a protective mineralogical coating, shielding the remaining feldspar cores and maintaining a stable, long-term local thermodynamic equilibrium (Vázquez et al., 2016).

This hybrid framework offers a plausible hypothesis that could explain (i) the slope-thickness relation, (ii) thicker regolith on higher surfaces, and (iii) persistent deep weathering fronts across the study area (Brantley et al., 2018; Howell and Butt, 2025). Under this scenario, regolith architecture would reflect coupled surface evolution and deep weathering during uplift (Howell and Butt, 2025).

If low-gradient surfaces persist, uplift could create accommodation space for deep weathering, while low denudation prolongs regolith residence times and allows chemical alteration to penetrate progressively into bedrock (Brantley et al., 2018; Howell and Butt, 2025), potentially allowing the weathering front to penetrate deeply into bedrock and preserve thick regolith under humid-temperate conditions. Ultimately, these two scenarios, pure geomorphic inheritance versus concurrent, uplift-driven development, need not be mutually exclusive, and the deep regolith architecture of this active margin may be best understood as a spectrum where both processes interact. Given this morphotectonic context, we interpret the lower-elevation geomorphic surfaces (S1, S2, and S3, spanning ~45 m a.s.l. to ~150 m a.s.l.) as uplifted marine terraces that correlate with regional marine terraces reported to the north (Jara-Muñoz et al., 2015) and to the south (Kaizuka et al., 1973; Melnick et al., 2009; Encinas et al., 2021). In contrast, the genesis of the higher-elevation surfaces (S4 to S7; > 200 m a.s.l.) remains poorly constrained and open to alternative geomorphic interpretations.

Within this hybrid framework, a pre-Quaternary weathering mantle on the older, higher surfaces could have provided a deep, porous, and highly fractured structural template (Krone et al., 2021; Howell and Butt, 2025). During subsequent Quaternary uplift, the transient survival of these low-slope summit platforms of uncertain origin (S4-S7) may have shielded these ancient profiles from active stripping. Meanwhile, modern meteoric waters could have continued to circulate, maintaining or slowly deepening the active weathering front (Brantley et al., 2018; Howell and Butt, 2025).

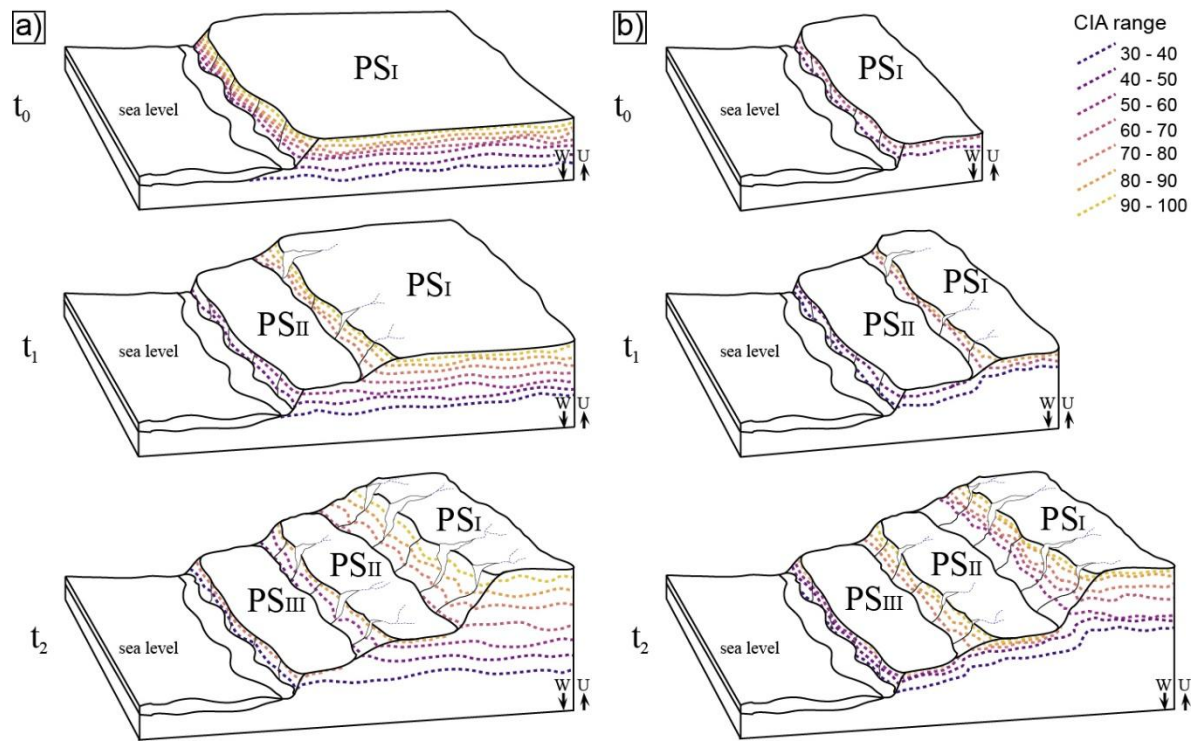


Figure 5: Idealized end-member models of regolith evolution. (a) Inherited model, in which the weathering architecture forms beneath the initial paleosurface before subsequent uplift and incision progressively truncate the inherited profile. (b) Concurrent model, in which regolith development and downward weathering-front propagation occur synchronously with geomorphic surface development. Dashed line segments represent CIA ranges limits.

CONCLUSIONS

Our study provides a comprehensive geomorphological and geochemical assessment of the deep CZ architecture along the active temperate margin of the CC of Central Chile, leading to several key conclusions regarding the evolution of weathering profiles:

- The study area hosts exceptional subsurface weathering depth, with a CZ characterized by extreme chemical alteration ($CIA > 90$ near the surface and > 80 at depths exceeding 35 m). This matrix-scale chemical weathering penetrates deeply despite ongoing Quaternary tectonic uplift (~ 0.5 mm/yr), demonstrating that active geodynamic settings can preserve deep weathering profiles.
- Topography exerts primary control on preservation of regolith profiles, where low-slope domains ($S < 11^\circ$) act as geomorphic shields, minimizing physical erosion (~ 0.03 mm/yr) and maximizing regolith residence times to preserve deep weathering columns. Conversely, high-slope domains ($S > 15^\circ$) experience active physical stripping, which truncates the upper profile without restricting downward chemical weathering kinetics at depth.
- Inferred exposure duration progressively overrides lithological controls, as the increase in regolith thickness with paleosurface elevation of stepped geomorphic surfaces (S1-S7) is consistent with a chronosequence of landscape abandonment.

We therefore propose a hybrid evolutionary model that reconciles geomorphic inheritance with concurrent weathering over time. Under this framework, inherited weathering columns on perched, low-gradient summits may be physically preserved where migrating river knickpoints driven by base-level fall have not yet reached the highest headwater interfluves. These stable platforms minimize physical stripping, creating discrete windows of stability during

which vertical meteoric water infiltration during which vertical meteoric water infiltration can sustain continued downward chemical weathering despite ongoing surface lowering. Rather than a static relict, the CZ architecture at our site represents a dynamic balance between time-dependent topographic stability and continued meteoric infiltration and subsurface weathering during sustained tectonic uplift. These deep weathering profiles represent domains shielded from disruptive surface processes, showing that a slowly eroding active forearc can develop and preserve thick residual regolith.

METHODS

Field campaigns were conducted to characterize terrain and assess geomorphology, including identification of low-slope geomorphic surfaces and high-slope hillslopes. Low-slope surfaces were defined using slope thresholds ($<11^\circ$) based on pediment preservation criteria and empirical data (Merritts et al., 1991; Bustos et al., 2022). Candidate surfaces were mapped from terrain metrics derived from ALOS-PALSAR Digital Elevation Models (DEMs) using Surface Classification Models (Bowles and Cowgill, 2012; Fig. SM-M3.1) and then verified in the field.

A total of 114 residual regolith profiles, comprising a combination of road cuts and drillholes reaching depths of up to 44 m, were analyzed: 69 DRT, 23 MP, 19 GTON, and 3 BG. The profiles were sampled at a nominal vertical interval of 2 m. Although complete recovery at this high resolution was occasionally precluded by variable subsurface physical conditions, systematic efforts were made to retrieve representative materials at every target depth. To systematically evaluate the role of topographic boundary conditions on CZ architecture, the local hillslope gradient (S) at each profile location was calculated from the DEM by calculating the slope from the grid cells directly surrounding the specific spatial coordinates of each profile.

Based on these topographic attributes, the weathering profiles were categorized into three geomorphic classes to analyze the influence of terrain steepness on subsurface alteration: low-slope ($S < 11^\circ$), intermediate ($11^\circ \leq S \leq 15^\circ$), and high-slope ($S > 15^\circ$), all of which were subsequently validated during field surveys.

To quantify the intensity of chemical weathering and the mobilization of major elements within the regolith profiles, three well-established geochemical indices were applied: the Chemical Index of Alteration (CIA; Nesbitt and Young, 1982), the Weathering Index of Parker (WIP; Parker, 1970), and the element mass transfer coefficient (Brimhall and Dietrich, 1987; Anderson et al., 2002). The CIA tracks the progressive hydrolysis of feldspars to clay minerals. However, a critical limitation of the CIA is its susceptibility to parent-material composition; because it is a closed-system ratio, variations in starting mineralogy, such as different initial plagioclase-to-alkali feldspar proportions, can be easily conflated with actual weathering intensity, particularly when comparing distinct lithologies (Oeser et al., 2018; Moravec et al., 2020; Perri, 2020). The WIP, in turn, tracks the progressive loss of highly mobile alkali and alkaline-earth elements (Na, K, Ca, and Mg); however, because these elements can become strongly depleted during advanced weathering, the index loses sensitivity and provides limited discrimination among intensely weathered materials (Price and Velbel, 2003). To overcome this compositional closing effect and isolate true mass transfer, we employed an open-system mass-balance metric, specifically the element mass transfer coefficient (τ) (Brantley et al., 2011, 2013; Vázquez et al., 2016; Li et al., 2020; Krone et al., 2021). Derived from constitutive mass-balance relations (Brimhall and Dietrich, 1987) and expanded by subsequent pedological mass-balance frameworks, the τ index normalizes elemental concentrations in weathered zones against both an immobile reference element (*e.g.*, Ti or Zr) and the specific unweathered parent material

composition (*e.g.*, Anderson et al., 2002; Brantley et al., 2011, 2013; Lebedeva and Brantley, 2013; Oeser et al., 2018; Li et al., 2020). This parent-normalization directly quantifies the actual fraction of mass gained or lost ($\tau = 0$ indicating immobility, $\tau = -1$ representing complete depletion, and $\tau > 0$ representing enrichment), enabling a rigorous and unbiased comparison of weathering pathways across lithologies and depth profiles (Moravec et al., 2020; Li et al., 2020).

The CIA is defined as:

$$CIA = \frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O} \times 100$$

,where all elemental concentrations are expressed in molar proportions. In this equation, CaO^* represents the correction applied to calcium; to ensure accurate calculations, total CaO must be corrected to exclude calcium hosted in non-silicate phases, such as carbonates (*e.g.*, calcite, dolomite) and phosphates (*e.g.*, apatite). CIA values typically range from approximately 50 for unaltered bedrock to near 100 for intensely weathered, mature materials composed almost entirely of secondary aluminous clays.

The WIP incorporates individual element-to-oxygen bond strengths as weighting factors, reflecting the energy required to break these bonds during hydrolysis, and is calculated using the following expression:

$$WIP = \left[\frac{(Na_2O)_a}{0.35} + \frac{(MgO)_a}{0.9} + \frac{(K_2O)_a}{0.25} + \frac{(CaO)_a}{0.7} \right] \times 100$$

where $(X)_a$ represents the atomic proportion of element X , defined as the atomic percentage divided by its atomic weight. The denominators correspond to the respective bond strengths. Unlike the CIA, which increases with alteration, the WIP yields higher values for fresh rocks and exhibits a continual decrease as weathering progresses and mobile cations are leached from the profile.

To complement these bulk indices and directly quantify the open-system gain or loss of individual chemical elements, we calculated the element mass transfer coefficient ($\tau_{j,w}$) following the constitutive mass-balance framework of Brimhall and Dietrich (1987) and Anderson et al. (2002). The τ index accounts for physical deformation (strain) and residual enrichment effects by normalizing the concentrations of a mobile element (j) normalizing the concentrations of a mobile element against a reference element assumed to remain immobile during weathering (i , commonly Zr or Ti) and the unweathered composition of the specific parent rock (Brantley et al., 2011, 2013; Oeser et al., 2018; Li et al., 2020). The mass transfer coefficient is calculated as follows:

$$\tau_{j,w} = \left[\frac{C_{j,w}}{C_{j,p}} \times \frac{C_{i,p}}{C_{i,w}} \right] - 1$$

where $C_{j,w}$ and $C_{j,p}$ represent the concentrations of the mobile element j in the weathered material and the parent rock, respectively, and $C_{i,w}$ and $C_{i,p}$ are the corresponding concentrations of the immobile reference element i . A $\tau_{j,w}$ value of 0 indicates strict elemental immobility (isomass weathering) relative to the parent rock. Negative values ($\tau_{j,w} < 0$) represent net elemental depletion or mass loss (leaching) from the profile, where a value of -1 represents complete depletion. Conversely, positive values ($\tau_{j,w} > 0$) denote net elemental enrichment or mass gain, typically associated with secondary mineral precipitation, mechanical translocation, or external inputs (Brimhall and Dietrich, 1987; Moravec et al., 2020). For the mass-balance calculations in this study, Ti was selected as the reference element because its monotonic enrichment toward the top of the regolith profiles is consistent with predominantly immobile behavior and residual accumulation during progressive weathering. The samples (Fig. SM-IIb-i) are from the field and represent the freshest samples we could get for every lithology. Because

the reference material itself is variably weathered, τ values represent minimum estimates of elemental loss.

Because unweathered bedrock was not systematically intersected across all vertical profiles, regolith development was assessed by stratifying the profiles into distinct, geochemically defined weathering intensity intervals (based on CIA ranges: 100–90, 90–80, etc.). To evaluate slope gradient (S) and lithology as simultaneous controls on regolith thickness and weathering depth, we employed a stratified analytical approach. We decoupled these factors by performing lithology-specific correlation and regression analyses; this allowed us to isolate the geomorphic control of slope gradient within each individual lithological template. To further test potential confounding factors, a comprehensive multivariate correlation matrix integrating additional topographic and environmental metrics is provided in the Supplementary Material. Sample depths were measured directly in the field from the surface; hence CIA classes were used solely to group samples with comparable degrees of chemical weathering, allowing comparisons among profiles developed at different elevations and with varying total thicknesses. The thickness associated with each CIA interval was calculated from the observed depth distribution of samples within that interval. This approach provided a consistent basis for comparing weathering profiles despite the absence of a reliable soil horizon classification.

We also interpolated the three-dimensional distribution of CIA-defined weathering domains using the Inverse Distance Weighting (IDW) method with an exponent of $p = 6$ and a grid resolution of 10 m. Several interpolation approaches were evaluated during model development, and IDW with $p = 6$ provided the most representative surfaces relative to the spatial distribution and observed depths of the weathering profiles. The resulting interpolated surfaces were subsequently displayed in a 3D framework to visualize the geometry and spatial

variability of subsurface CIA domains across the study area. This interpolation was used solely as a graphical visualization tool and not as a quantitative predictive model. Therefore, the interpolated surfaces are intended to illustrate general spatial trends in subsurface weathering intensity and their relationship with surface morphology, rather than the position of the weathering front.

REFERENCES CITED

- [1] Brantley, S. L. et al. *Frontiers in Exploration of the Critical Zone: Report of a Workshop* Sponsored by the National Science Foundation (NSF) (National Science Foundation, 2006).
- [2] Riebe, C. S., Hahm, W. J. & Brantley, S. L. Controls on deep critical zone architecture: a historical review and four testable hypotheses. *Earth Surf. Process. Landf.* 42, 128–156 (2017).
- [3] Oeser, R. A. et al. Chemistry and microbiology of the Critical Zone along a steep climate and vegetation gradient in the Chilean Coastal Cordillera. *Catena* 170, 183–203 (2018).
- [4] Howell, R. J. & Butt, C. R. M. (eds) *Geology, Geochemistry and Formation of Supergene Mineral Deposits in Deeply Weathered Terrain* (Springer Nature Switzerland, 2025).
- [5] Bufer, A., Rugenstein, J. K. C. & Hovius, N. CO₂ drawdown from weathering is maximized at moderate erosion rates. *Science* 383, 1075–1080 (2024).
- [6] Vázquez, M. et al. Regolith production and chemical weathering of granitic rocks in central Chile. *Chem. Geol.* 446, 87–98 (2016).
- [7] Jenny, H. *Factors of Soil Formation: A System of Quantitative Pedology* (McGraw-Hill, 1941).

- 645 [8] Schaller, M. & Ehlers, T. A. Comparison of soil production, chemical weathering, and
646 physical erosion rates along a climate and ecological gradient (Chile) to global
647 observations. *Earth Surf. Dyn.* 10, 131–150 (2022).
- 648 [9] Pope, G. A. Regolith and weathering (rock decay) in the Critical Zone. In *Principles and*
649 *Dynamics of the Critical Zone* (eds Giardino, J. R. & Houser, C.) 113–145 (Elsevier,
650 2015).
- 651 [10] White, A. F. et al. Differential rates of feldspar weathering in granitic regoliths. *Geochim.*
652 *Cosmochim. Acta* 65, 847–869 (2001).
- 653 [11] Brantley, S. L., Buss, H., Lebedeva, M., Fletcher, R. C. & Ma, L. Investigating the complex
654 interface where bedrock transforms to regolith. *Appl. Geochem.* 26, S12–S15 (2011).
655 <https://doi.org/10.1016/j.apgeochem.2011.03.017>
- 656 [12] Krone, L. V. et al. Deep weathering in the semi-arid Coastal Cordillera, Chile. *Sci. Rep.* 11,
657 13057 (2021).
- 658 [13] Behrens, R. et al. Mineralogical transformations set slow weathering rates in low-porosity
659 metamorphic bedrock on mountain slopes in a tropical climate. *Chem. Geol.* 411, 283–
660 298 (2015).
- 661 [14] Brantley, S. L. et al. Susquehanna Shale Hills Critical Zone Observatory: Shale Hills in the
662 context of Shaver’s Creek Watershed. *Vadose Zone J.* 17, 180092 (2018).
- 663 [15] Hampl, F. J. et al. The role of iron-bearing minerals for the deep weathering of a
664 hydrothermally altered plutonic rock in semi-arid climate (Chilean Coastal Cordillera).
665 *Chem. Geol.* 604, 120922 (2022).
- 666 [16] Cosans, C. L., Hayes, J. L., Carr, B. J., Holbrook, S. & Harman, C. J. Anatomy of a deep
667 Piedmont critical zone: evaluating hypotheses on regolith depth controls through

668 comparison of ridge and valley boreholes. *Earth Surf. Process. Landf.* 49, 5254–5268
669 (2024).

670 [17] Hampl, F. J. et al. Feedbacks between the formation of secondary minerals and the
671 infiltration of fluids into the regolith of granitic rocks in different climatic zones (Chilean
672 Coastal Cordillera). *Earth Surf. Dyn.* 11, 511–528 (2023).

673 [18] Gabet, E. J. & Mudd, S. M. A theoretical model coupling chemical weathering rates with
674 denudation rates. *Geology* 37, 151–154 (2009).

675 [19] Braun, J., Mercier, J., Guillocheau, F. & Robin, C. A simple model for regolith formation by
676 chemical weathering. *J. Geophys. Res. Earth Surf.* 121, 2140–2171 (2016).

677 [20] Perri, F. Chemical weathering of crystalline rocks in contrasting climatic conditions using
678 geochemical proxies: an overview. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 556, 109873
679 (2020).

680 [21] Riebe, C. S., Kirchner, J. W. & Finkel, R. C. Erosional and climatic effects on long-term
681 chemical weathering rates in granitic landscapes spanning diverse climate regimes. *Earth
682 Planet. Sci. Lett.* 224, 547–562 (2004).

683 [22] Gabet, E. J. et al. Local topography and erosion rate control regolith thickness along a
684 ridgeline in the Sierra Nevada, California. *Earth Surf. Process. Landf.* 40, 1779–1790
685 (2015).

686 [23] Li, M. Y. H., Zhou, M.-F. & Williams-Jones, A. E. Controls on the dynamics of rare earth
687 elements during subtropical hillslope processes and formation of regolith-hosted deposits.
688 *Econ. Geol.* 115, 1097–1118 (2020).

689 [24] Brantley, S. L., Bandstra, J., Moore, J. & White, A. F. Modelling chemical depletion
690 profiles in regolith. *Geoderma* 145, 494–504 (2008).

- 691 [25] Lebedeva, M. I. & Brantley, S. L. Exploring geochemical controls on weathering and
692 erosion of convex hillslopes: beyond the empirical regolith production function. *Earth*
693 *Surf. Process. Landf.* 38, 1793–1807 (2013).
- 694 [26] Lebedeva, M. I. & Brantley, S. L. A clarification and extension of our model of regolith
695 formation on hillslopes. *Earth Surf. Process. Landf.* 43, 2715–2723 (2018).
- 696 [27] Maher, K. & Chamberlain, C. P. Hydrologic regulation of chemical weathering and the
697 geologic carbon cycle. *Science* 343, 1502–1504 (2014).
- 698 [28] Holbrook, W. S. et al. Geophysical constraints on deep weathering and water storage
699 potential in the Southern Sierra Critical Zone Observatory. *Earth Surf. Process. Landf.*
700 39, 366–380 (2014).
- 701 [29] Harman, C. J. & Cosans, C. L. A low-dimensional model of bedrock weathering and lateral
702 flow coevolution in hillslopes: 2. Controls on weathering and permeability profiles,
703 drainage hydraulics, and solute export pathways. *Hydrol. Process.* 33, 1168–1190 (2019).
- 704 [30] Moravec, B. G. et al. Resolving deep Critical Zone architecture in complex volcanic terrain.
705 *J. Geophys. Res. Earth Surf.* 125, e2019JF005189 (2020).
- 706 [31] Bustos, N., Marquardt, C., Belmar, A. & Cordeiro, P. Regolith-hosted rare earth exploration
707 in the Chilean Coastal Range of the Central Andes. *J. Geochem. Explor.* 234, 106934
708 (2022).
- 709 [32] Kaizuka, S., Matsuda, T., Nogami, M. & Yonekura, N. Quaternary tectonic and recent
710 seismic crustal movements in the Arauco Peninsula and its environs, central Chile.
711 *Geogr. Rep. Tokyo Metrop. Univ.* 8, 1–49 (1973).

- 712 [33] Melnick, D., Bookhagen, B., Strecker, M. R. & Echtler, H. P. Segmentation of megathrust
713 rupture zones from fore-arc deformation patterns over hundreds to millions of years,
714 Arauco Peninsula, Chile. *J. Geophys. Res. Solid Earth* 114, B01407 (2009).
- 715 [34] Jara-Muñoz, J., Melnick, D., Brill, D. & Strecker, M. R. Segmentation of the 2010 Maule
716 Chile earthquake rupture from a joint analysis of uplifted marine terraces and seismic-
717 cycle deformation patterns. *Quat. Sci. Rev.* 113, 171–192 (2015).
- 718 [35] Encinas, A. et al. Tectonosedimentary evolution of the Coastal Cordillera and Central
719 Depression of south-Central Chile (36°30'–42°S). *Earth-Sci. Rev.* 213, 103465 (2021).
- 720 [36] Tolorza, V. Magnitud y Dinámica de la Erosión Integrada de Cuenca en el Río Biobío. PhD
721 thesis, Universidad de Chile (2015).
- 722 [37] Herrera, M. T., Crempien, J. G. F., Cembrano, J. & Moreno, M. Seismic cycle controlled by
723 subduction geometry: novel 3-D quasi-dynamic model of Central Chile megathrust.
724 *Geophys. J. Int.* 237, 772–787 (2024).
- 725 [38] Gianni, G. M. The late Paleozoic paired metamorphic belt of southern Central Chile:
726 consequence of a near-trench thermal anomaly? *EarthArXiv*
727 <https://doi.org/10.31223/X58S4B> (2021).
- 728 [39] Glodny, J., Gräfe, K., Echtler, H. & Rosenau, M. Mesozoic to Quaternary continental
729 margin dynamics in South-Central Chile (36°–42°S): the apatite and zircon fission track
730 perspective. *Int. J. Earth Sci.* 97, 1271–1291 (2008).
- 731 [40] Deckart, K. et al. U-Pb geochronology and Hf-O isotopes of zircons from the Pennsylvanian
732 Coastal Batholith, South-Central Chile. *Andean Geol.* 41, 49–82 (2014).

733 [41] del Rey, A., Deckart, K., Arriagada, C. & Martínez, F. Resolving the paradigm of the late
734 Paleozoic–Triassic Chilean magmatism: isotopic approach. *Gondwana Res.* 37, 172–181
735 (2016).

736 [42] Vásquez, P., Glodny, J., Franz, G., Frei, D. & Romer, R. L. Early Mesozoic plutonism of
737 the Cordillera de la Costa (34°–37°S), Chile: constraints on the onset of the Andean
738 Orogeny. *J. Geol.* 119, 159–184 (2011).

739 [43] Farías, M. et al. Late Miocene high and rapid surface uplift and its erosional response in the
740 Andes of central Chile (33°–35°S). *Tectonics* 27, TC1005 (2008).

741 [44] Freisleben, R. et al. Deciphering permanent uplift along the Pacific coast of South America
742 through signal analysis of various tectonic processes. *Tectonics* 42, e2023TC007815
743 (2023).

744 [45] Garreaud, R. D., Jacques-Coper, M., Marín, J. C. & Narváez, D. A. Atmospheric rivers in
745 South-Central Chile: zonal and tilted events. *Atmosphere* 15, 406 (2024).

746 [46] Carretier, S. et al. Review of erosion dynamics along the major N–S climatic gradient in
747 Chile and perspectives. *Geomorphology* 300, 45–68 (2018).

748 [47] Vega-Ruiz, A. et al. Tectonic and climatic controls on uplift transients of the Nahuelbuta
749 Forearc Range, Northern Patagonian Andes. *Earth Planet. Sci. Lett.* 690, 120098 (2026).

750 [48] Velásquez, R. et al. Geología del Área Concepción–Talcahuano, Región del Biobío. Carta
751 Geológica de Chile, Serie Geología Básica No. 222 (Servicio Nacional de Geología y
752 Minería, 2025).

753 [49] SERNAGEOMIN. Mapa Geológico de Chile: Versión Digital, Escala 1:1,000,000.
754 Publicación Geológica Digital No. 4 (Servicio Nacional de Geología y Minería, 2003).

755 [50] Schaller, M., Ehlers, T. A., Lang, K. A. H., Schmid, M. & Fuentes-Espoz, J. P. Addressing
756 the contribution of climate and vegetation cover on hillslope denudation, Chilean Coastal
757 Cordillera (26°–38°S). *Earth Planet. Sci. Lett.* 489, 111–122 (2018).

758 [51] Merritts, D., Chadwick, O. & Hendricks, D. Rates and processes of soil evolution on
759 uplifted marine terraces, northern California. *Geoderma* 51, 241–275 (1991).

760 [52] Bowles, C. & Cowgill, E. Discovering marine terraces using airborne LiDAR along the
761 Mendocino–Sonoma coast, northern California. *Geosphere* 8, 386–402 (2012).

762 [53] Nesbitt, H. W. & Young, G. M. Early Proterozoic climates and plate motions inferred from
763 major element chemistry of lutites. *Nature* 299, 715–717 (1982).

764 [54] Parker, A. An index of weathering for silicate rocks. *Geol. Mag.* 107, 501–504 (1970).

765 [55] Brimhall, G. H. & Dietrich, W. E. Constitutive mass balance relations between chemical
766 composition, volume, density, porosity, and strain in metasomatic hydrochemical
767 systems: results on weathering and pedogenesis. *Geochim. Cosmochim. Acta* 51, 567–
768 587 (1987).

769 [56] Anderson, S. P., Dietrich, W. E. & Brimhall, G. H. Weathering profiles, mass-balance
770 analysis, and rates of solute loss: linkages between weathering and erosion in a small,
771 steep catchment. *Geol. Soc. Am. Bull.* 114, 1143–1158 (2002).

772 [57] Price, J. R., Bryan-Ricketts, D. S., Anderson, D. & Velbel, M. A. Weathering of almandine
773 garnet: influence of secondary minerals on the rate-determining step, and implications for
774 regolith-scale Al mobilization. *Clays Clay Miner.* 61, 34–56 (2013).

775 [58] Brantley, S. L., Holleran, M., Jin, L. & Bazilevskaya, E. Probing deep weathering in the
776 Shale Hills Critical Zone Observatory, Pennsylvania (U.S.A.): the hypothesis of nested

chemical reaction fronts in the subsurface. *Earth Surf. Process. Landf.* 38, 1280–1298 (2013).

[59] Li, M. Y. H., Zhou, M.-F. & Williams-Jones, A. E. Controls on the dynamics of rare earth elements during subtropical hillslope processes and formation of regolith-hosted deposits. *Econ. Geol.* 115, 1097–1118 (2020).

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COMPETING INTERESTS

The author(s) declare no competing interests.

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