

Research Article

Revised Timing of Cenozoic Atlantic Incursions and Changing Hinterland Sediment Sources during Southern Patagonian Orogenesis

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New detrital zircon U-Pb geochronology data from the Cenozoic Magallanes-Austral Basin in Argentina and Chile ~51° S establish a revised chronostratigraphy of Paleocene-Miocene foreland synorogenic strata and document the rise and subsequent isolation of hinterland sources in the Patagonian Andes from the continental margin. The upsection loss of zircons derived from the hinterland Paleozoic and Late Jurassic sources between ca. 60 and 44 Ma documents a major shift in sediment routing due to Paleogene orogenesis in the greater Patagonian-Fuegian Andes. Changes in the proportion of grains from hinterland thrust sheets, comprised of Jurassic volcanics and Paleozoic metasedimentary rocks, provide a trackable signal of long-term shifts in orogenic drainage divide and topographic isolation due to widening of the retroarc fold-thrust belt. The youngest detrital zircon U-Pb ages confirm timing of Maastrichtian-Eocene strata but require substantial age revisions for part of the overlying Cenozoic basinfill during the late Eocene and Oligocene. The upper Río Turbio Formation, previously mapped as middle to late Eocene in the published literature, records a newly recognized latest Eocene-Oligocene (37-27 Ma) marine incursion along the basin margin. We suggest that these deposits could be genetically linked to the distally placed units along the Atlantic coast, including the El Huemul Formation and the younger San Julián Formation, via an eastward deepening within the foreland basin system that culminated in a basin-wide Oligocene marine incursion in the Southern Andes. The overlying Río Guillermo Formation records onset of tectonically generated coarse-grained detritus ca. 24.3 Ma and a transition to the first fully nonmarine conditions on the proximal Patagonian platform since Late Cretaceous time, perhaps signaling a Cordilleran-scale upper plate response to increased plate convergence and tectonic plate reorganization.

1. Introduction

Tectonics, climate, and eustasy in convergent plate settings control first-order fluctuations between marine and terrestrial environments along continental margins and the transfer of sediment from orogens to basin depocenters. With the emergence of a new paradigm in the last three decades recognizing dynamic interactions and feedbacks between tectonics and climate [1–3], it is all the more essential to differentiate between their signals in the stratigraphic record. For instance, enhanced tectonism in foreland basin settings can cause crustal load-driven basin subsidence and deepening of marine environments [4, 5]. Climate variations and orography influence precipitation and temperature gradients, which in turn affect erosion rates, vegetation cover, and even the location of deformation and drainage divides [6–9]. Globally, climate modulates the growth and ablation of continental ice sheets and sea level [10]. Cenozoic marine transgressive-regressive cycles are well-studied in terms of sequence stratigraphic models for global sea level change (e.g., Miocene US Atlantic history of [11]) and the dominant control of climatic optima are suitable for passive continental margins. However, in tectonically active, shallow-marine basins, resolving the relative contributions of regional tectonics and eustasy, driven by global mechanisms, must be carefully considered [12]. For example, work in the Cretaceous interior seaway has demonstrated that tectonism is an important player in controlling parasequence progradation and subsidence [13], in addition to eustatic sea-level variations [14, 15].

An improved understanding of the controls on subaerial emergence or subsidence of these landmasses is fundamental to evaluating potential linkages between mountain building and climate (e.g., [16]), eustatic sea level changes [11], sediment delivery to the oceans [17–19], and biotic responses to changing ecosystems ([20–22]; Palazzesi et al. 2014; Eronen et al. 2015). Moreover, better knowledge of the dynamic response of sedimentary and tectonic systems is critical to current scientific issues, including long-term climate change, biogeochemical fluxes to lakes and oceans, and conservation of mineral and energy resources [23]. A central requirement to unravel these competing processes is detailed chronology of sedimentation and changes in provenance preserved in the sedimentary basin fill. Lithologic variations and detrital geochronologic signals indicating the appearance of sediment that is associated with a diagnostic tectonic terrane or geologic unit are commonly used to infer timing of source area unroofing and to make paleogeographic, tectonic, or climatic interpretations (e.g., [24–27]). However, the decline of a source as a prominent sediment contributor to basin infill—potentially through erosional removal, topographic blocking, or burial—is less commonly preserved in the depositional record. Sediment recycling and weathering of source areas can further complicate the cause of a waning source signal [28–31].

The Patagonian Andes, a high-latitude convergent orogen in South America, provides sediment to the genetically linked Magallanes-Austral Basin, which extends ~200 km from a retroarc thrust front to the southern Atlantic Ocean (Figure 1). This relatively narrow distance results in the east-

ern Atlantic continental margin in Patagonia that is sensitive to sea level fluctuations driven by dynamic and tectonic loading of the flexural foredeep [32]; variations in sediment flux across the coastal plain, eustasy, and global climate; and far-field tectonics. The proximal Patagonian foredeep depocenter near 51° S remained predominantly deep marine from ca. 100 to 80 Ma [33–36] followed by basin filling and shoaling to shallow marine to marginal continental conditions ca. 78–60 Ma [37–43]. This western part of the Magallanes-Austral Basin coevolved with the Cenozoic development of the southeastern Magallanes-Austral and Malvinas depocenters related to the Fuegian orocline [44–46] and opening of the Drake Passage between Antarctica and South America [47, 48]. Following N-S early foreland development of basin subsidence and infilling, deformation across the Patagonian thrust-belt promoted a general eastward shift of deposition in Paleocene-Miocene time [49, 50].

Near ~51° S, the proximal Cenozoic Magallanes-Austral Basin preserves shelfal facies overlain by near-shore and continental facies. Documented middle Cenozoic transgressions in Patagonia and Tierra del Fuego have been linked to Cenozoic global sea level rise due to climate [51–53] and phases of Andean orogenesis [50, 54, 55]. Most notably, stratigraphic units like the El Huemul Formation (late Eocene-early Oligocene) and the slightly younger San Julián Formation (late Oligocene) represent latest Paleogene shallow marine deposition along much of the Atlantic coast [56–60]. These units mark the beginning of the “Patagonian Sea” incursion recorded as the *Juliense* (25–22 Ma) and *Leonense* (22–17.9 Ma) stages [60]. Previous work has suggested that the Patagonian Sea was largely influenced by climate optima and eustatic transgressions [60] and/or tectonics [61, 62]. It is yet undetermined (1) if the inland sea reached the proximal part of the Magallanes-Austral Basin during the Oligocene, (2) how upland source areas changed during Cenozoic foreland sedimentation, and (3) to what extent these marine phases were driven by tectonic subsidence, changes in upland sediment routing/sediment flux, or eustasy. Differentiating among the relative impacts of these large-scale factors is important for recognizing the effects of external controls, such as global climate transitions, versus internal orogenic wedge dynamics [3, 63] and source to sink connections in the transfer of sediment to the world’s oceans.

We present new sediment provenance data and a new chronostratigraphy of Eocene-Miocene strata in the Magallanes-Austral Basin of southern Patagonia that (1) revise the age of marine incursions and changes in orogenic paleogeography during the transition to nonmarine conditions in southern Patagonia, (2) highlight the rise and subsequent isolation of a major hinterland source area due to basinward development of younger orogenic topography, and (3) suggest recycling of Mesozoic grains from Upper Cretaceous sedimentary rocks, rather than direct sourcing from the Mesozoic batholith.

2. Tectonic Setting and Basin Stratigraphy

The Upper Cretaceous-Cenozoic Magallanes-Austral Basin (Figure 1) records deposition during structural growth of

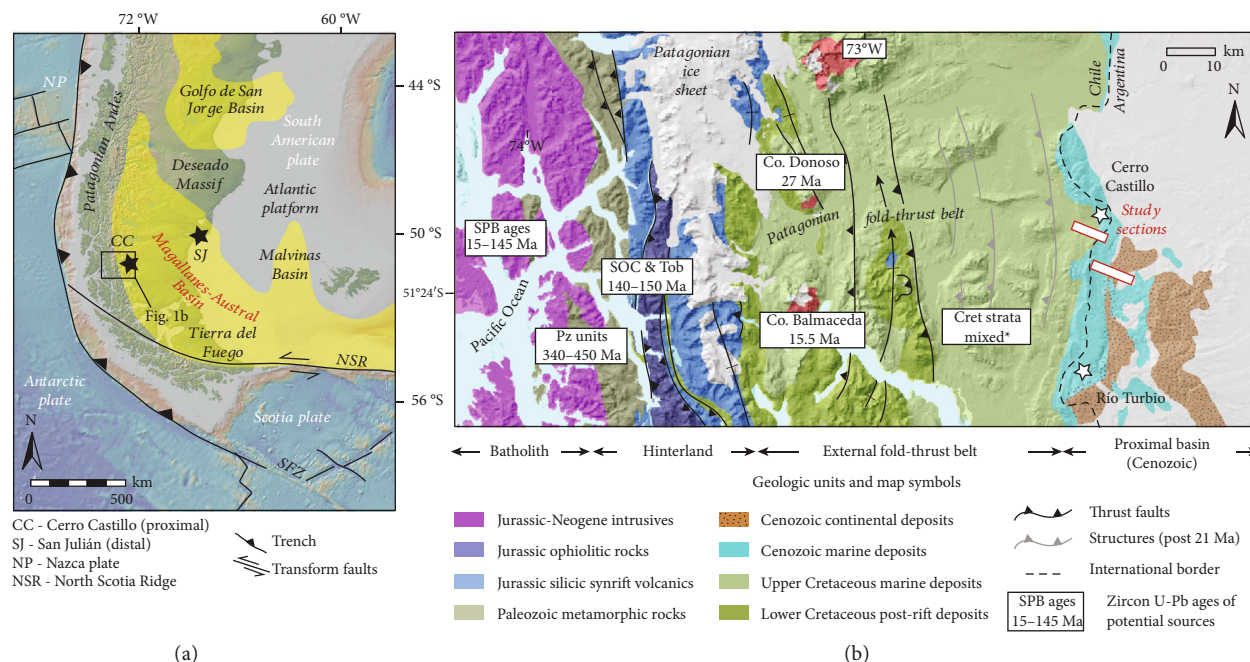


FIGURE 1: (a) Tectonic setting of the Magallanes-Austral Basin and other Cenozoic depocenters (yellow) in relation to key southern plate boundary features (after [44, 50, 154]). Global Multi-Resolution Topography (GMRT) base map from GeoMapApp©. Black stars denote stratigraphic areas discussed in the text: CC: Cerro Castillo; SJ: San Julián; NP: Nazca plate; NSR: North Scotia Ridge; MFFZ: Magallanes-Fagnano Fault Zone; SFZ: Shackleton Fracture Zone. (b) Location of the Cerro Castillo-Cancha Carrera study area within the Cenozoic Magallanes-Austral Basin outcrop belt along the eastern margins of the Patagonian thrust belt. Geologic map was compiled from Malumián et al. [98], SERNAGEOMIN [155], and Fosdick et al. [50]. Zircon crystallization ages are summarized from igneous and recycled sediment sources [29].

the Patagonian-Fuegian Andes [35, 44, 45, 50, 64]. Following marine conditions that have generally persisted since Late Jurassic time, the early foreland basin history was predominantly deep marine, with southward deepening from a narrow continental shelf in the north [37, 58, 65, 66] to bathyal conditions in the south [33]. Shoaling of the Upper Cretaceous marine depocenter led to dominantly shallow-marine, coastal, and deltaic sedimentation that persisted until Paleocene time [35, 37–39, 67]. Thrust front advancement of the Patagonian retroarc thrust belt promoted an eastward shift of the foreland deposition in Paleocene-Miocene time [50]. The primary sediment sources to the Magallanes-Austral Basin include the Mesozoic-Cenozoic Southern Patagonian Batholith and related volcanics, Mesozoic basal rocks of the Rocas Verdes Basin, and to a lesser extent, Paleozoic metamorphic rocks (Figure 1). The proximity of the basin to an active magmatic arc throughout its history has resulted in intercalated volcanic ashes and abundant magmatically derived zircons proven useful for assessing controls on sedimentation, with prior focus on the Cretaceous strata [65, 66, 68–73].

During the Cenozoic, much of the South American extra-Andean regions north of Patagonia underwent predominantly continental sedimentation, briefly punctuated by middle and late Miocene epicontinental marine incursions, and development of tidal-dominated wetland systems, like the *Paranean Sea* and the Pebbas lake [74–77]. In contrast, most of the eastern Patagonian foreland south of the Desierto

Massif seems to have been largely submerged in shelf to shallow marine and transitional depositional environments, during the structurally complicated development of the Magallanes-Austral and Malvinas foreland depocenters related to the oroclinal curved plate boundary with the Scotia plate [44, 45] and tectonic separation of Antarctica from South America continents during opening of the Drake Passage [47, 78, 79]. In the Última Esperanza District of the Magallanes-Austral Basin (Chile), Cenozoic strata are disconformable on Maastrichtian tide-influenced shelf-edge deltaic Dorotea Formation [33, 39, 42, 67, 80, 81]. However, the timing and extent of this unconformity and its geologic significance are unresolved given limited chronology and stratigraphic correlation along the basin axis [29, 33, 80]. In our study area (Figure 1), the Dorotea Formation is overlain by the laterally discontinuous Paleocene Cerro Dorotea Formation [38, 81] and unconformably overlying Eocene shallow marine, estuarine, and deltaic Río Turbio Formation. [42, 81–83]. Geological observations in Brunswick Peninsula, Isla Riesco, and Río Figueroa show that this Paleogene stratigraphic separation decreases southward through Tierra del Fuego, where the Maastrichtian/Danian unconformity is restricted and more continuous sedimentation occurred until Miocene time [84–87].

A key stratigraphic unit within our study area is the Río Turbio Formation, which is characterized by glauconitic shallow-marine to lagoonal sandstone, siltstone, claystone, coquina, and interbedded minable coal seams [38, 53, 88]

and fossil assemblages of subtropical macroflora, palynomorphs, and marine invertebrates [81, 89–93]. Debate persists on the depositional age of the Río Turbio Formation, with early biostratigraphic studies reporting Eocene through Miocene [94] or exclusively Eocene biozones [38, 95, 96]. This depositional unit records high-latitude organic-rich shallow marine and transitional deposition. Therefore, its age is highly relevant for understanding paleoenvironmental conditions and tectonic influences on sedimentation during past climate optima.

The Río Turbio Formation is unconformably overlain by the Río Guillermo Formation, a mostly fluvial sandstone, conglomerate, and coaly claystone with notable abundant silicified tree trunks preserved in life position [38, 53, 81, 97]. Most previous workers have proposed an upper Eocene to early Oligocene age for the Río Guillermo Formation [98–100]. Fluvial sedimentation in the Magallanes-Austral Basin was briefly interrupted by a shallow marine incursion, resulting in sandstone and mudstone deposits of the Estancia 25 de Mayo Formation [57, 58, 101] and coeval informal units (“Estratos de Río del Oro”). This unit has been correlated to the distal Monte León Formation along the Atlantic coast that, together, records the *Leonense* marine incursion of the Patagonian Sea at this latitude [56, 59, 60, 62]. The overlying Santa Cruz Formation marks the last phase of major syntectonic sedimentation and fluvial deposition in the Patagonian Andes ca. 19–16 Ma, prior to regional surface uplift and incision of the foreland basin [54, 102–104]. Multiple explanations have been postulated for this abrupt end to proximal foreland sedimentation along the Andean foothills and a shift to offshore deposition [46]. Potential mechanisms include (1) reduced sediment supply caused by an orographic rain shadow during topographic surface uplift [105, 106], (2) effects of flat slab subduction [107–109], and (3) regional surface uplift caused by migration of the Chile Ridge collision [110] and dynamic response to opening of an asthenospheric slab window beneath Patagonia [111, 112] or some combination of these processes.

3. Detrital U-Pb Geochronology

3.1. Sampling and Analytical Methods. We collected twelve sandstone samples from the Paleocene-Miocene outcrop belt exposed near Cerro Castillo township, Chile, and Estancia Cancha Carrera, Argentina, in Patagonia (Figure 1) from previously studied stratigraphic sections [38, 53, 81, 97, 113]. Sample information and locations are outlined in Table 1. Detrital zircons were extracted from ~5 kg medium-grained sandstone hand samples using standard mineral separation techniques, including crushing and grinding, fractionation of magnetic minerals with a Frantz isodynamic magnetic separator, and settling through heavy liquids to exclude phases with densities less than 3.3 g/cm^3 . Final zircon separates were mounted in epoxy resin together with fragments of the Sri Lanka standard zircon. The mounts were polished to a depth of $\sim 20\ \mu\text{m}$ to expose grain interiors, CL and BSE imaged, and cleaned prior to isotopic analysis. U-Pb geochronology of zircons was conducted by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-

ICPMS) using a Photon Machines Analyte G2 excimer laser using a spot diameter of $30\ \mu\text{m}$ at the Arizona LaserChron Center [114, 115]. Analytical methods and data are available in the data repository.

Preferred calculated U-Pb ages use the ^{204}Pb -corrected $^{206}\text{Pb}/^{238}\text{U}$ ratio for $<900\ \text{Ma}$ grains and the ^{204}Pb -corrected $^{206}\text{Pb}/^{207}\text{Pb}$ ratio for $>900\ \text{Ma}$ grains. Uncertainties shown in these tables are at the 1σ level and include only measurement errors. Analyses that are $>20\%$ discordant and 5% reverse discordant (by comparison of $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages) were excluded from provenance interpretations and maximum depositional age interpretations. Pb^*/U concordia diagrams (Figure A1) and probability density plots (Figures A2 and A3) were generated using the routines in Isoplot [116]. The age-probability diagrams show each age and its uncertainty (for measurement error only) as a normal distribution and sum all ages from a sample into a single curve. Probability density plots for individual samples are presented in Figures A2 and A3, and compiled formation-level datasets are shown in Figure 2. For samples that yielded youngest age groups that could represent conceivable maximum depositional ages, we calculated error-weighted mean ages based on the following criteria: age clusters contained at least two overlapping concordant grains at 2σ uncertainty (Figure 3; Table 1). For published samples from the Punta Barrosa, Cerro Toro, Tres Pasos, and Dorotea Formations (Figures 2 and 4), we recalculated relative probability density curves from published U-Pb geochronological data [27, 29, 50, 68, 69].

3.2. Results and Interpretations. Detrital zircon U-Pb geochronology results (1,579 dated grains) from the Cerro Castillo-Cancha Carrera area reveal distinctive age groups in variable proportions upsection (Figure 2): (1) Cenozoic age clusters that include early Miocene-Oligocene (20–30 Ma), Eocene (33–45 Ma), and Paleocene (60–65 Ma) ages; (2) a range of Cretaceous ages with clusters at ca. 66–80 Ma and 80–136 Ma; (3) a Late Jurassic-earliest Cretaceous age group (136–175 Ma); (4) smaller proportions of Devonian-Permian ages (250–420 Ma); (5) early Paleozoic and Mesoproterozoic ages (420–1600 Ma); and (6) few Mesoproterozoic and older grains. Cenozoic and Cretaceous zircon grains are mostly large ($>100\ \mu\text{m}$), euhedral to subhedral, magmatically zoned zircons. In contrast, Jurassic zircons are mostly small ($<60\ \mu\text{m}$ in width), subangular, or broken fragments of long and narrow volcanic crystals. Paleozoic and Proterozoic grains are mostly small ($<50\ \mu\text{m}$) subrounded to rounded grains.

3.2.1. Dorotea and Cerro Dorotea Formations. Detrital geochronology from four stratigraphic horizons (649 grains) within the mapped Cerro Dorotea Formation and its contact with the underlying Dorotea Formation yields major age groups between 60 and 66 Ma, 74 and 115 Ma, 123 and 160 Ma, 473 and 630 Ma, and 960 and 1130 Ma and fewer early Paleozoic and Proterozoic zircons. The lowest sample (15LDC05) collected from a horizon considered part of the uppermost exposures of the Dorotea Formation yields an MDA of $65.8 \pm 1.3\ \text{Ma}$. In the Cerro Dorotea Formation,

TABLE 1: Sample information and calculated maximum depositional ages (MDAs) from the Magallanes Basin for detrital zircon U-Pb LA-ICP-MS geochronology.

Sample	Formation	Latitude (° N)	Longitude (° W)	Elevation (m)	No. of grains analyzed	Interpreted MDA (Ma \pm 2 σ)	Age of youngest grain (Ma \pm 2 σ)
JCF09-237B	Río Guillermo	-51.30338	-72.18670	389	115	22.8 \pm 0.2 (n = 65)	20.7 \pm 0.8
Rt28DZ6	Río Guillermo	-51.31373	-72.21932	346	94	24.3 \pm 0.6 (n = 8)	23.0 \pm 0.5
Rt28DZ5	Río Turbio (upper)	-51.31163	-72.22042	323	103	26.6 \pm 0.5 (n = 5)	25.9 \pm 0.9
Rt28DZ7	Río Turbio (upper)	-51.29761	-72.23581	349	101	35.4 \pm 0.2 (n = 45)	32.2 \pm 1.9
Rt28DZ8	Río Turbio (upper)	-51.29667	-72.23819	282	110	36.6 \pm 0.3 (n = 65)	33.4 \pm 0.6
17CCRT2-29	Río Turbio (lower)	-51.31735	-72.29126	464	157	41.3 \pm 0.3 (n = 56)	38.7 \pm 1.5
14LdCdZ2	Río Turbio (lower)	-51.28071	-72.28936	443	106	46.3 \pm 1.3 (n = 2)	45.7 \pm 0.8
14LdCdZ4	Río Turbio (lower)	-51.27997	-72.28916	411	108	47.1 \pm 2.7 (n = 2)	46.1 \pm 0.5
15LDC02/14DZ3	Cerro Dorotea	-51.28001	-72.28927	351	227	60.2 \pm 1.3 (n = 3)	60.0 \pm 1.0
14AVDZ2	Cerro Dorotea	-51.28475	-72.30764	433	107	60.5 \pm 0.8 (n = 3)	60.2 \pm 0.8
14AVDZ1	Cerro Dorotea	-51.28473	-72.30828	434	103	61.9 \pm 0.3 (n = 4)	61.4 \pm 1.2
15LDC05	Dorotea	-51.27793	-72.31254	312	212	65.8 \pm 1.3 (n = 2)	65.4 \pm 1.1

two samples (14AVDZ1 and 14AVDZ1), collected from thick trough cross-bedded tan and orangish brown sandstone with interbedded siltstone and coal-bearing mudstone, yield MDAs of 61.9 ± 0.3 Ma and 60.5 ± 0.8 , respectively (Figure 3). The stratigraphically highest level was sampled twice in the exact location (to overcome low zircon yield in the first sample), ~ 3 m below the top of the formation (14AVDZ3+15LDC02) and yields a MDA of 60.2 ± 1.3 Ma.

3.2.2. Lower Member of the Río Turbio Formation. Three samples (413 grains) collected from the overlying greenish gray and brown glauconitic sandstone units, interpreted as subaqueous deltaic deposits, yield similar zircon U-Pb age distributions with a pronounced Eocene peak, two Late Cretaceous age clusters, and few Jurassic ages (Figure 2). Estimation of MDAs from the youngest zircon population indicates sedimentation of the basal glauconitic sandstone by ca. 47.1 ± 2.7 Ma (14LDC-DZ4) and the overlying brown deltaic sandstone unit by 46.3 ± 1.3 Ma (14LDC-DZ2). The uppermost sample collected from a glauconitic sandstone at the top of the exposed unit yields a youngest age cluster with a MDA of 41.3 ± 0.3 Ma (17CCRT2-29).

3.2.3. Upper Member of the Río Turbio Formation. We collected three detrital zircon U-Pb geochronology samples (312 grains) from fossiliferous and highly bioturbated marine strata of the upper member of the Río Turbio Formation. Using the stratigraphic subdivisions of Rodríguez Raising [53] and the presence of a mappable and distinct coal seam as a reference, samples RT28DZ08 and RT28DZ07 were positioned in the upper half of Sequence VIII, and sample RT28DZ05 was collected from the top of Sequence IX [53] of the upper Río Turbio Formation. These samples yield robust age populations between 29 and 45 Ma, 63 and 109, 113 and 137 Ma, and 218 and 288 Ma and few Late Jurassic grains (Figure 2). Proterozoic grains are noticeably lacking compared to underlying detrital age distributions. Youngest

age clusters from the upper half of the unit yield a MDA ca. 36.6 ± 0.3 Ma (RT28DZ08) and 35.4 ± 0.2 Ma (RT28DZ07). At the top of the ~ 506 m thick succession, organic-rich mudstones below the contact with the Río Guillermo Formation yield a MDA of ca. 26.6 ± 0.2 Ma (RT28DZ05).

3.2.4. Río Guillermo Formation. Two samples (205 grains) collected from the base of the Río Guillermo Formation yield U-Pb age peaks between 23 and 26 Ma and 33 and 36 Ma; a broad range of mid to late Cretaceous age between 72 and 128 Ma, 149 and 154 Ma, 275 and 304 Ma; and lesser numbers of Proterozoic grains (Figure 2). The youngest zircon age peak from the bottom of the formation gives a MDA of ca. 24.3 ± 0.6 Ma (RT28DZ06). A second sample collected from the top of the Río Guillermo Formation, directly below a dated volcanic tuff (21.7 Ma zircon U-Pb SHRIMP-RG, [50]), yields a MDA of 22.8 ± 0.2 Ma (JCF09-237B).

The sampled section exhibits an upsection younging of zircons, increase in Cenozoic and Late Cretaceous zircons, and decrease in all zircon age groups older than ca. 135 Ma (Figure 2). The most pronounced loss of Late Jurassic-Early Cretaceous ($\sim 20\%$ to $\sim 6\%$) and Paleozoic (40-17% to 7%) and Mesoproterozoic-Archean (20% to 8%) is observed across the Paleocene Cerro Dorotea Formation-middle Eocene Río Turbio Formation contact (Figures 2 and 3). Only the Río Guillermo Formation exhibits a slight covarying increase in both the Late Jurassic-Early Cretaceous group and Paleozoic age group. These percentage trends persist, even when accounting for the large influx of Cenozoic grains, as shown by the normalized zircon age groups > 66 Ma (Figure 4).

4. Discussion

4.1. Revised Timing of Foreland Sedimentation. New geochronological constraints on depositional ages in the Magallanes-Austral Basin suggest significantly younger timing for middle Cenozoic inland sea transgressions and onset of exclusively

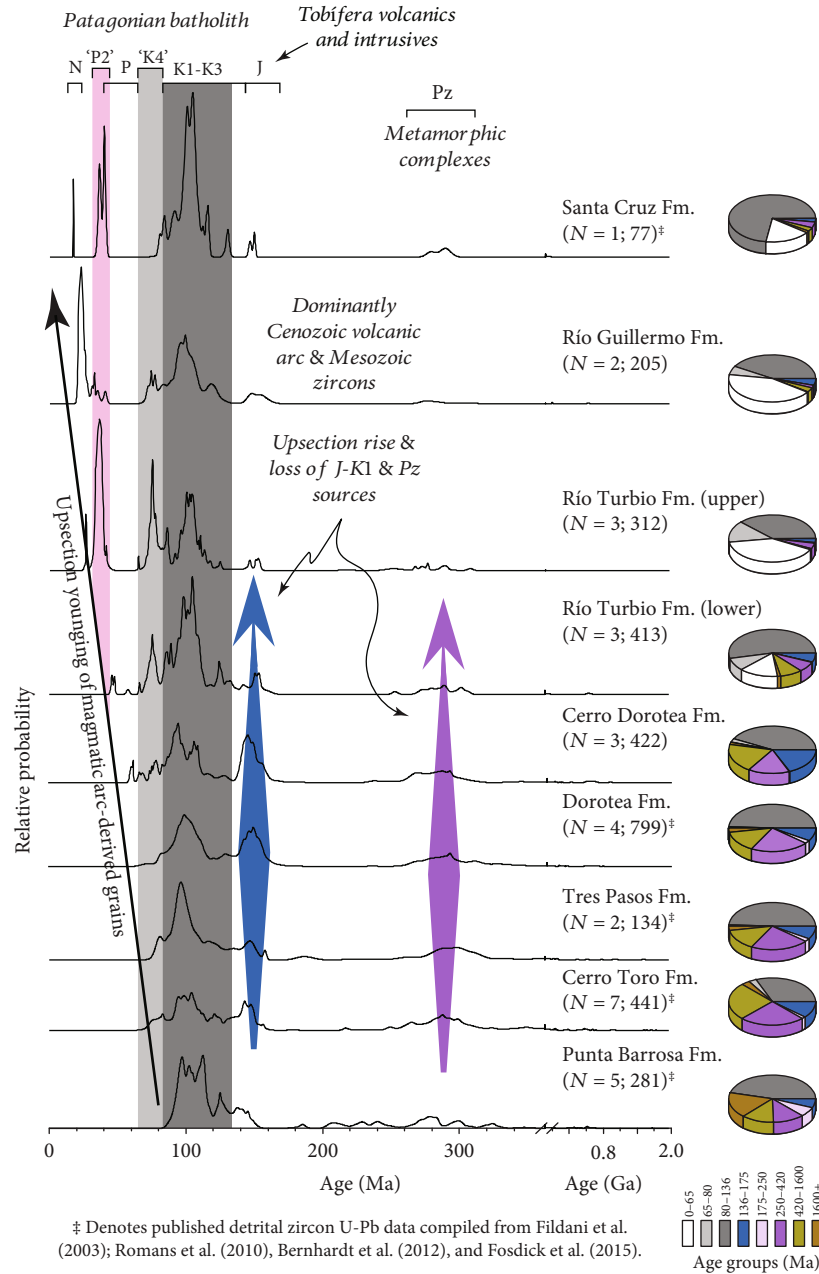


FIGURE 2: Detrital zircon U-Pb geochronology data compiled by formation (<600 Ma only), showing probability density plots of Upper Cretaceous through lower Miocene stratigraphy. For each formation, N refers to the number of individual samples included in the formation, followed by number of total grains analyzed. Published data from the Santa Cruz, Dorotea, Tres Pasos, and Punta Barrosa Formations are included for comparison [27, 29, 68, 69]. Note break in scale at 360-600 Ma and change of scale after 600 Ma. Southern Patagonian Batholith age groups after Hervé et al. (2007): N: Neogene; P: Paleogene; K1: Cretaceous I; K2: Cretaceous II; K3: Cretaceous III; J: Jurassic; PZ: Paleozoic. We identify “K4” and “P2” age groups in our detrital datasets.

fluvial sedimentation in the study area (Figure 5). These results redefine our understanding of the genetic relationship between sedimentation and changes in relative sea level, climate, and phases of deformation in the Andean orogenic belt (Figure 6). Under the prevailing view, there are four major Cenozoic Atlantic transgressions in the Magallanes-Austral Basin of Patagonia and Tierra del Fuego: Maastrichtian-Danian, late Middle Eocene, late Oligocene-early Miocene (*Juliense*), and early Miocene (*Leonense*) [52, 57, 60, 117].

In the proximal Magallanes-Austral Basin near Cerro Castillo (Figure 1), the Maastrichtian deltaic Dorotea Formation is overlain by the laterally discontinuous Paleocene Cerro Dorotea Formation and overlying Eocene estuarine and deltaic Río Turbio Formation (Figure 5; [38, 53, 80, 81, 118]). Debate persists on the age of the Río Turbio Formation [38, 53, 93]. Riccardi and Rolleri [94] reported an Eocene through Miocene age, whereas more recent biostratigraphic work suggests exclusively Eocene biozones [38, 90, 95, 96]. Based on

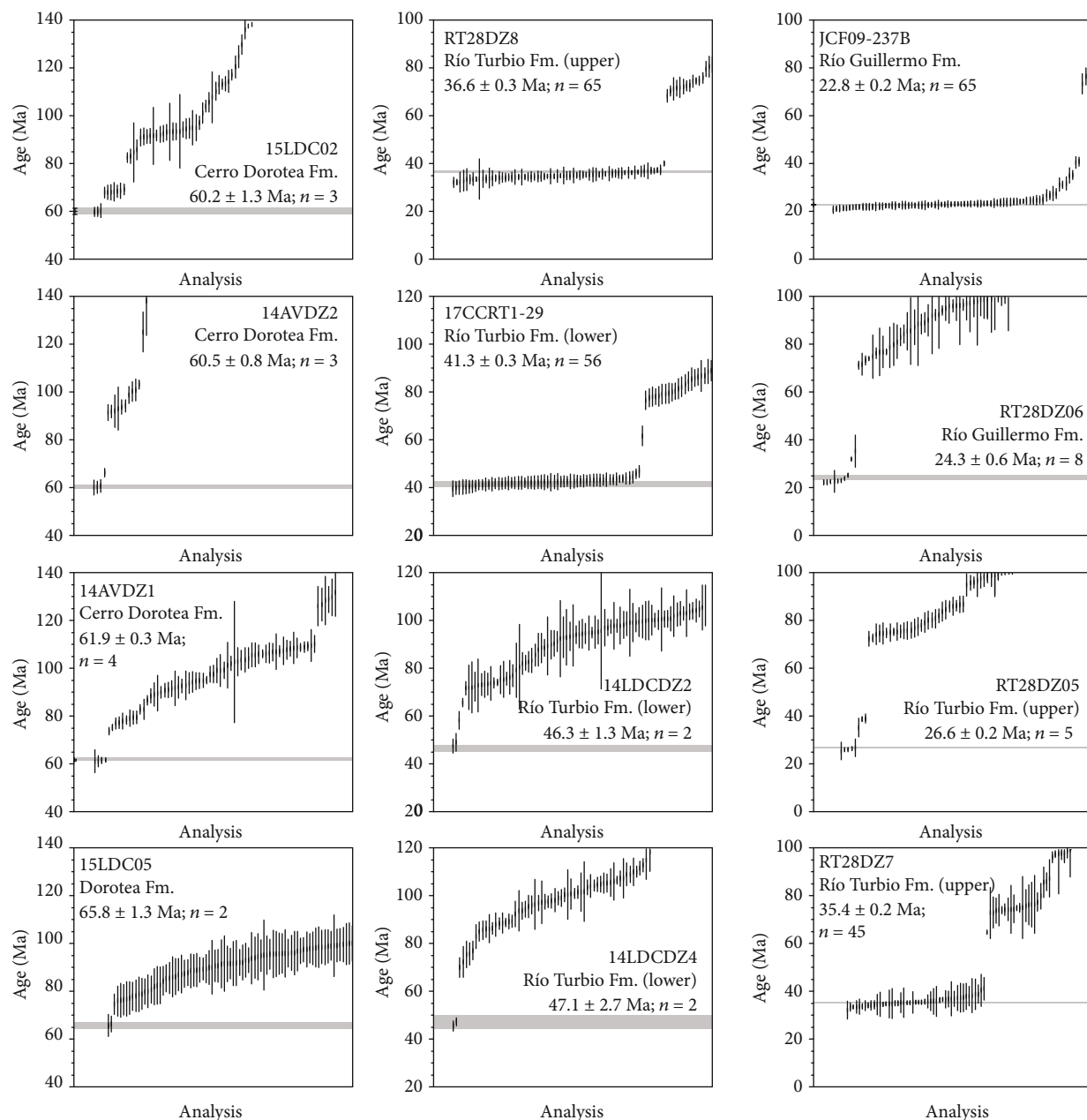


FIGURE 3: Maximum depositional ages (MDA) interpreted from the youngest detrital zircon U-Pb data from each sample (individual analyses shown at 2σ uncertainty). MDA are the error-weighted mean age ($\pm 2\sigma$ uncertainty) of all grains (n) that define the youngest age cluster represented by the horizontal grey bars.

such age assignments for these strata, many workers have interpreted the upper Cerro Dorotea through Río Turbio deposits within the paleoclimatic context of Paleogene climatic optima such as the Paleocene-Eocene Thermal Maximum and Early Eocene Climatic Optimum (Figure 6; e.g., [88]). Our data support this age (61–60 Ma) and paleoclimatic interpretation for the Cerro Dorotea Formation through only the basal portion of the lower Río Turbio Formation, which is Lutetian (47–41 Ma) in age (Figure 5). The Cerro Dorotea Formation is recognized in Argentina and assigned to the Danian mostly based on the foraminiferal content [52], but our radiometric age suggests a later, Selan-

dian, maximum depositional age, also giving the first formal confirmation of the occurrence of this Paleocene lithostratigraphic unit in Chile.

The subaqueous deltaic lower Río Turbio Formation contains detrital zircons that indicate Eocene sedimentation starting at ca. 47 Ma and continued through at least ca. 41 Ma (Figure 5). These depositional ages are compatible with middle Eocene age estimates from dinoflagellate cyst biozonation, ranging from 46 to 39 Ma (Zone I of [95] and RTF 1 and 2 from [96]); leaf impressions; shark teeth; and marine invertebrate fossils recovered from these deposits [82, 89, 91, 119, 120]. Moreover, these strata show similar

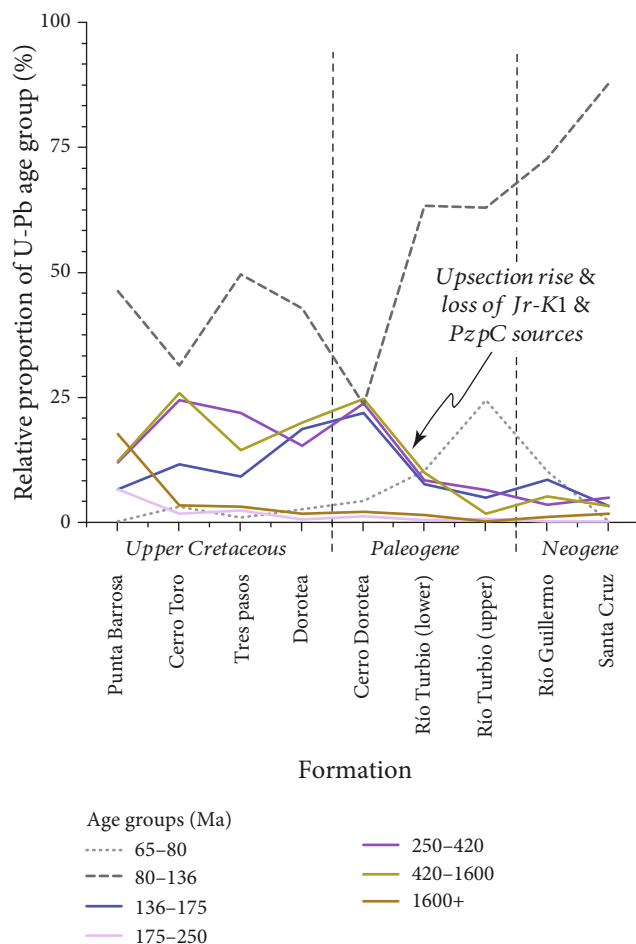


FIGURE 4: Changes in relative proportions of zircon age groups for pre-Cenozoic age groups. Results show upsection rise and subsequent loss of Jurassic-Early Cretaceous Jr-K1 grains, a progressive loss of Paleozoic grains (PzpC), and an overall increase in Paleogene igneous sources. The largest shift in provenance signature occurred across the Paleocene Cerro Dorotea Formation-middle Eocene Río Turbio Formation boundary.

age, sedimentary facies, fossil content, and mineral composition to those of its northern equivalent in the Man Aike Formation near Lago Argentino [53, 58, 121, 122] and Sierra Baguales [55, 83], pointing to stratigraphic correlation of a regional, renewed depositional phase of foreland sedimentation across the Paleocene unconformity surface [80].

In contrast, our findings from the upper Río Turbio Formation show substantially younger ages ca. 37-27 Ma (Figure 5), indicating that these deposits are not associated with early/middle Eocene climatic events. Rather, they record late Eocene through Oligocene paleoenvironmental and tectonic conditions (Figure 6). The new depositional ages on the middle and upper part of the upper Río Turbio Formation are compatible with the recently proposed dinoflagellate cyst biozonation for this unit: samples RT28DZ08 and RT28DZ07 belong to stratigraphic levels included within Zone III of González Estebenet et al. [95] or RTF4 of González Estebenet et al. [96]. These biostratigraphic levels were indirectly dated between 35.5 and 33.5 Ma (latest Eocene),

making a good match with our observed U-Pb maximum depositional ages. However, González Estebenet et al. [95, 96] note that preserved palynomorphs were not recovered from the top of the Río Turbio Formation, and thus, no independent biostratigraphic age is presently available for the contact between the Río Turbio and Río Guillermo formations. Our maximum depositional ages of ca. 27 Ma fill this important gap in basin chronology.

We suggest a latest Eocene through Oligocene age (this work) for the upper Río Turbio Formation. This interpretation is also more compatible with paleobotanical data that suggest mesothermal conditions at high latitude, based on the abundance and diversity of fossilized *Nothofagus* morphotype leaf impressions and wood fragments [81, 92, 120]. Whereas the warm early to middle Eocene conditions in Patagonia favored high tropical to subtropical (mega/mesothermal) plant diversity [91, 123, 124], the late Eocene-Oligocene transition ushered forth increased diversification and abundance of meso- and microthermal floral elements across southern Gondwana, including the widespread dominion of genus *Nothofagus* [20, 92, 120, 125].

Our younger basin age model suggests that the deepening to offshore conditions in the upper Río Turbio Formation ca. 37 Ma coincides with basin subsidence and deepening observed in Tierra del Fuego during propagation of the Fuegian fold-thrust belt ensuing after the first opening of the Drake Passage [78, 126]. This deepening was also notably concurrent with a late Eocene marine transgression (Figure 6) and the beginning of the Antarctic ice sheet expansion [127, 128]. Sustained shallow-marine conditions along the margin of the Magallanes Basin between ca. 37 and 27 Ma, despite Oligocene eustatic sea level fall, suggest an additional tectonic mechanism for marine conditions. More broadly, we suggest that the upper Río Turbio Formation marks a phase of overall early Oligocene basin deepening, eastward loading of the foreland, and diachronous marine flooding driven by topographic loading from the fold-and-thrust belt [50] and coeval transpression across the North Scotia Ridge [47] (Figure 6). It follows that the subsurface marine succession of the El Huemul Formation on the southern extreme of the Golfo de San Jorge Basin [129] could represent the distal record of tectonically driven lithospheric flexure and basin deepening. Continued marine sedimentation evolved to a more extensive incursion along the Atlantic coast, represented by the San Julián Formation, during the beginning of the *Juliense* stage of the “Patagonian Sea” [60]. Tectonic basin deepening in southern Patagonia may have followed deepening episodes in the Drake Passage, as suggested by changes in neodymium isotope ratios interpreted to record an influx of Pacific seawater into the Atlantic Ocean ca. 41-37 Ma [48, 126]. However, relative sea level highs around Antarctica due to near-field processes during glaciation (e.g., [130]) may have also affected sea level in southeastern Patagonia prior to a global sea level decrease through the Oligocene.

New geochronological data from the overlying fluvial Río Guillermo Formation suggest its deposition took place between latest Chattian through Aquitanian time ca. 24-21 Ma (Figure 5). These radiometric results revise the

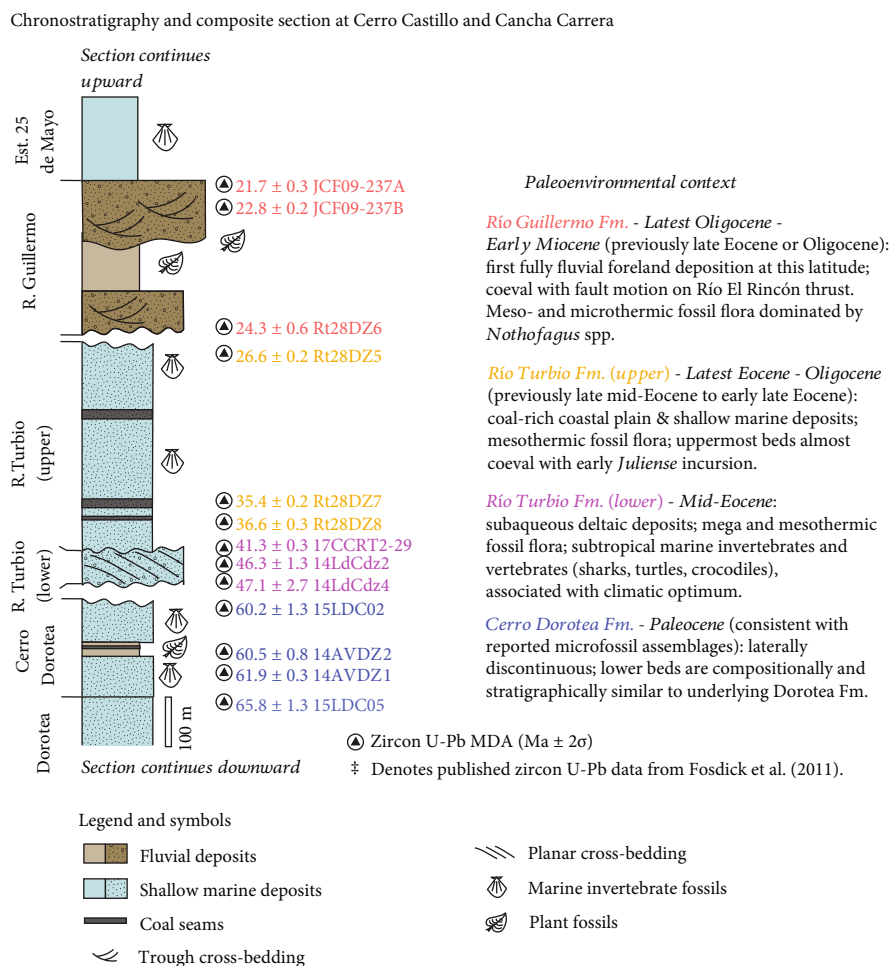


FIGURE 5: Summary of new depositional age constraints and paleoenvironmental context in the Magallanes-Austral Basin near 51° S. Cenozoic stratigraphy and revised timing of sedimentation based on new maximum depositional ages (MDA) calculated from the youngest detrital zircon U-Pb age cluster from each sample.

previously accepted biostratigraphic upper Eocene to lower Oligocene age [38, 100] and the interpretation that the Río Guillermo Formation predates a rejuvenated phase of Andean orogenesis. These coarse-grained strata reflect the first Cenozoic fully continental conditions on the Patagonian foredeep depocenter (cf. [36]) in the area. The onset of fluvial deposition coincides with ca. 27–21 Ma fault motion on the Río El Rincón-Castillo thrusts [50], suggesting these deposits reflect increased supply of tectonically generated sediment (cf. [131]) during structural uplift and unroofing of the Patagonian orogen. This interpretation is consistent with published subsurface data just to the south of our study area (Figure 1) that record latest Eocene through early Miocene prograding clastic strata [84, 132].

4.2. Reorganization of Sediment Provenance and Routing. Detrital provenance data from the Upper Cretaceous-Miocene basin infill track changes in relative proportions of zircon age groups for pre-Cenozoic age groups (Figure 2). A comparison with the Upper Cretaceous basin record and our new data shows the upsection rise and subsequent loss of Jurassic-Early Cretaceous (J-K1) grains (blue wedge), a pro-

gressive loss of Precambrian and Paleozoic grains (browns and pink wedges), and an overall increase in Late Cretaceous and Cenozoic igneous sources (gray and white wedges). Notably, the Paleocene Cerro Dorotea Formation maintains similar provenance and gross depositional character to the underlying Dorotea Formation. This similarity indicates little to no drainage divide reorganization nor exposure of new sources during southward building of the continental shelf [42] from Maastrichtian to earliest Selandian time. Moreover, this observation is noteworthy because of the discontinuous nature of the Cerro Dorotea Formation along the frontal monocline, which has invited debate regarding its original lateral extent and subsequent erosion versus heterogeneous depositional footprint (e.g., [29]). The Paleocene foreland basin phase along this sector of the Andes may have once been more geographically widespread prior to erosional removal and resumed deposition of the middle Eocene Río Turbio Formation that forms the Paleogene unconformity (Figure 6).

The largest shift in sediment provenance signature occurred across the Paleocene Cerro Dorotea and the middle Eocene Río Turbio Formation boundary, marked by a conspicuous decline of Late Jurassic and Paleozoic zircons

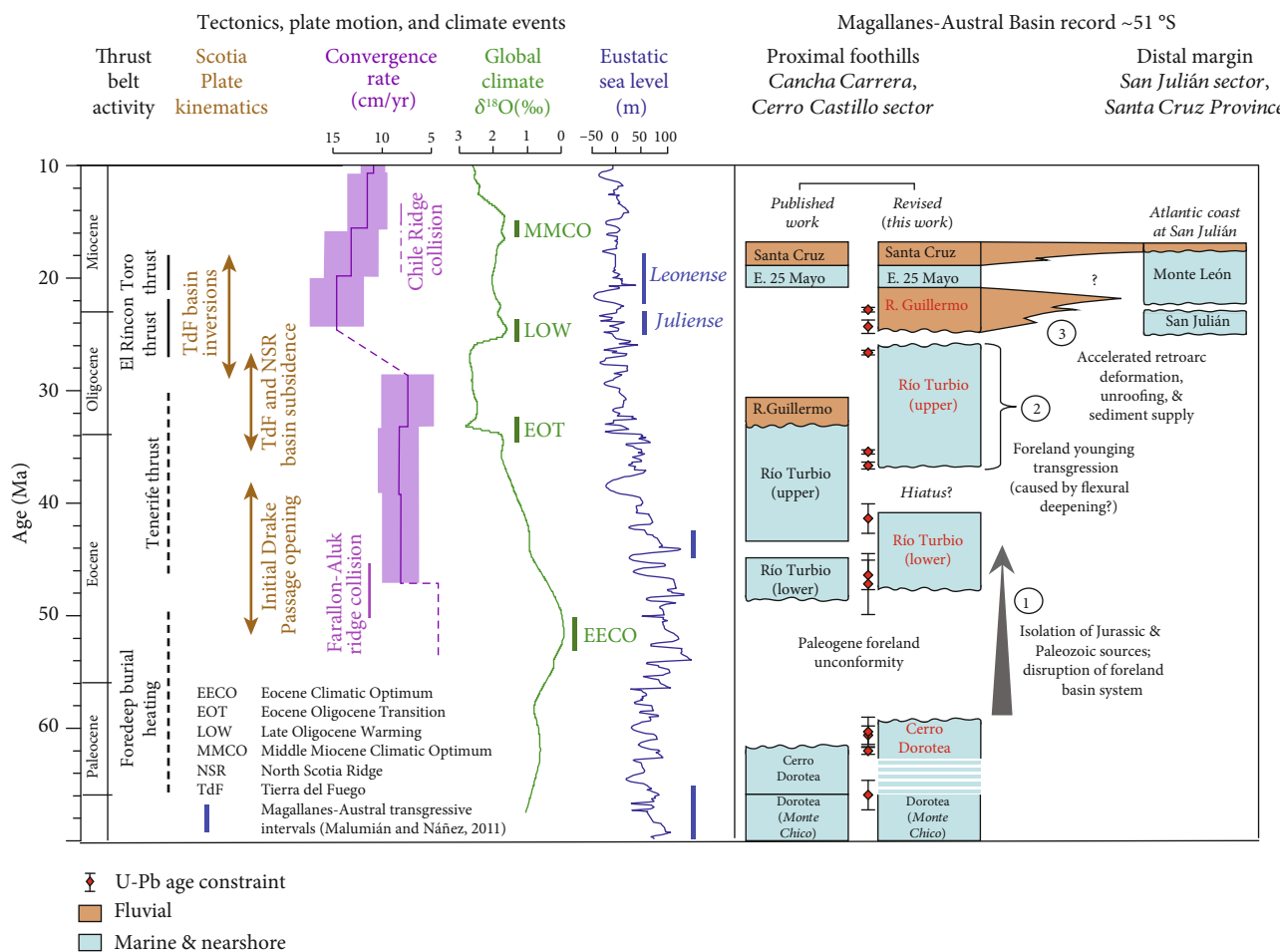


FIGURE 6: Implications for revised timing of sedimentation of the middle Cenozoic Magallanes-Austral Basin strata compared to changes in regional tectonics [47, 50, 156], plate convergence rate [151], global climate [157], and eustatic sea level [158]. Published chronostratigraphy of proximal foothills was compiled from Malumián et al. [98], Malumián and Nández [52], Perkins et al. [117], and references therein. Chronostratigraphy of the San Julián sector of the Atlantic coast from Parras et al. [60, 159]. New age estimates and sediment provenance highlight (1) isolation of Jurassic and Paleozoic zircon sources and disruption of the foreland basin system across the Paleogene foreland unconformity, (2) a potential foreland younging transgression caused by flexural deepening during Tenerife thrusting and synchronous basin subsidence in Tierra del Fuego, and (3) accelerated sediment supply of the Río Guillermo Formation linked to retroarc deformation and unroofing along the El Rincón thrusts.

(Figures 2 and 4). Zircons of these ages are sourced from hinterland thrust sheets (Figure 1) that expose the Upper Jurassic volcanic Tobifera Formation [133, 134] and Paleozoic basement [135–137]. The concurrent increase in Cenozoic zircons from the Patagonian Batholith may act to swamp out the signal from these older zircon sources. However, a comparison of relative proportion of pre-66 Ma age groups show similar trends in the rise and decline of the Jurassic and Paleozoic age groups (Figure 4). We interpret this initial shift as likely a consequence of tectonic or surface changes in sediment routing between ca. 60 and 44 Ma, when the basin became topographically isolated from northwestern hinterland sources during uplift across the external fold-thrust belt.

Our age control of the Paleogene unconformity in our study area improves upon the work of Fosdick et al. [29] who compared provenance and burial histories of the Dorotea Formation with the upper Río Turbio Formation but lacked higher provenance resolution from intervening

deposits. Additionally, the ca. 15 m.y. hiatus estimated by our model partially matches recently published ages in Sierra Baguales and Río Las Chinas, ~40 km north of our study area [55, 80]. There, a ca. 20 m.y. hiatus across the Paleogene unconformity has been proposed by George et al. [80], also based on detrital zircon U-Pb geochronology. Evidence of coeval basin burial thermal heating [29, 138] in the central thrust belt and development of a basin-wide foreland unconformity are consistent with this timeframe. New provenance data sheds light on the timing of Tenerife thrusting (Figure 6) and further supports an Eocene phase of orogenesis that is well-documented in the Fuegian Andes [24, 33, 139] but remains enigmatic in the Southern Patagonian Andes. This finding suggests that, rather than being an inactive foreland basin during this time [140, 141], a more continuous fold-and-thrust belt and basin depocenter may have connected the Patagonian and Fuegian Andes during development of the Fuegian orocline [44].

These upsection trends continue into late Eocene–Oligocene time when sediment provenance of the upper Río Turbio Formation reflects predominantly Cretaceous and younger age peaks. Prominent Eocene and Late Cretaceous age clusters include two prominent new populations—denoted here as K4 (ca. 80–66 Ma) and P2 (ca. 35–25 Ma)—that are not well-recognized in in situ batholith geochronology datasets (Hervé et al. 2007) and extend the record of pulsed activity of arc magmatism (Figure 2). In the most comprehensive summary of the Southern Patagonian Batholith magmatism, Hervé et al. (2007) document a Paleogene phase of magmatism from 67 to 40 Ma and a Neogene phase from 25 to 16 Ma. These detrital findings of K4 and P2 zircon populations highlight the value of the sedimentary archive in recognizing phases of magmatism not represented in available bedrock records. By ca. 26 Ma and the end of the marine sedimentation at this latitude, detrital zircons derived from the Late Jurassic Tobifera thrust sheets (Figure 1), which were once a dominant sediment source to the Cenomanian–Paleocene basin, are virtually absent in the basin fill. Synchronous with this change in depositional environment is a marked provenance shift to increased mafic volcanic and recycled sedimentary sources, suggesting that the change in environment is linked to upland tectonic/climate changes with a lesser control from low stand in global sea level [97, 113]. This timing of transition to fully continental sedimentation coincides with deformation in the fold-and-thrust belt at Río El Rincón thrust and related structures [50]. We suggest the Río Guillermo Formation represents tectonically generated sediment (e.g., [14, 131]) associated with this phase of deformation.

Fluvial sedimentation was temporarily disrupted by flooding of the foreland basin by the Leonense marine incursion [56, 57, 60, 62, 101], which may have been further enhanced by subsidence loading during Toro thrust faulting (Figure 6). Resumed fluvial deposition of the Santa Cruz Formation is classically cited as the molasse deposits of the main phase of early Miocene Andean orogenesis and surface uplift (e.g., [54, 99, 102, 104, 105]). Published detrital geochronology from the overlying early Miocene Santa Cruz Formation yields dominantly (>70%) Late Cretaceous zircons [29]. Based on modeling of detrital zircon U–Pb–He thermochronological data, Fosdick et al. [29] suggested that these grains were recycled from the Upper Cretaceous clastic wedge rather than direct sourcing of the Mesozoic batholith. Our data from underlying strata corroborate this interpretation and capture a more complete transition of provenance loss of the Jurassic and Paleozoic age groups.

The rise and subsequent isolation of diagnostic sediment sources or detrital zircon age groups bear on resolving complexities from sediment recycling [142, 143] and variability in zircon fertility [144]. As such, a geologically diagnostic age source—especially one with smaller and/or more fragile grains (e.g., volcanics)—is a useful tracer for identifying primary versus recycled sources and constraints on movement of orogenic drainage divides during changes in orogenic wedge behavior. The Eocene through Oligocene upsection depletion of Jurassic and Paleozoic sources near 51° S, concurrent with sustained dominance of plutonic arc-derived

Cretaceous zircons (Figure 4), suggests recycling of the Cretaceous strata in the Río Turbio Formation and winnowing of the smaller and more fragile Jurassic volcanic and Paleozoic zircons during sediment transport. Moreover, the isolation of hinterland and primary Cretaceous batholith sources requires a cratonward shift in the drainage divide by ca. 44 Ma. This change in sediment routing was followed by subsequent hinterland shift in the drainage divide that occurred sometime after ca. 18 Ma, at which point sedimentation shifted to a more distal, offshore location [46].

This synchronous adjustment in retroarc basin configuration after ca. 15 Ma has been observed along >600 km length of the Patagonian and Fuegian Andes [102, 105–107], with multiple mechanisms considered, including (1) a reduction in sediment supply to the retroarc foreland basin caused by fold-and-thrust belt deformation and growth of an orographic rain shadow [105, 106], (2) effects of a shallowing slab geometry and associated eastward arc migration between 14 and 12 Ma (e.g., [107, 108]) or subduction erosion without minor changes in the slab dip (e.g., [109]), and (3) regional surface uplift in response to formation of the Chile Ridge slab window beneath Patagonia (Figure 6; [111, 112]). Today, the hinterland high peaks of the Patagonian Andes constitute the upland sediment sources to rivers and glacial valleys that drain both sides of the Andes and Tobifera thrusts (Figure 1; [145]).

5. Summary and Implications

In summary, new estimates of maximum depositional ages from detrital geochronology data require a revised chronostratigraphy of the middle Cenozoic strata. Our study confirms a Selandian maximum depositional age for the Cerro Dorotea Formation, previously constrained by biostratigraphy to the Danian. Sediment provenance data from the Cenozoic Magallanes–Austral Basin at 51° S track the decline of once prominent hinterland sources between ca. 60 and 44 Ma. We suggest a major change in sediment routing and paleogeography during this time that we attribute to a phase of Eocene orogenesis and uplift of a topographic barrier that isolated the basin from Paleozoic and Late Jurassic–Early Cretaceous sources (Figure 6). We also identify a previously unrecognized latest Eocene through Oligocene period of marine deposition from ca. 37 to 27 Ma in the proximal foredeep depozone (upper Río Turbio Formation), followed by a major change to nonmarine sedimentation ca. 24.3 Ma. Here, we propose that the upper Río Turbio and Río Guillermo Formations, together, reflect a genetically linked stratigraphic pair that shows Oligocene basin deepening and subsequent latest Oligocene–early Miocene deposition of coarse-grained sediments derived from the Patagonian hinterland, during a renewed phase of orogenesis (Figure 6).

Moreover, an eastward incursion of an embayed foredeep trough may link the upper Río Turbio Formation to the distal El Huelmul Formation and potentially the San Julián Formation, suggesting a tectonic loading origin for the *Juliense* phase of the Patagonian Sea. Additional stratigraphic correlation to the Atlantic margin is needed to test this hypothesis. The late Oligocene–early Miocene synchronicity of (1)

proximal fluvial facies (Río Guillermo Formation) and distal marine facies (Juliense and Leonense), (2) active orogenic deformation (Río El Rincon and Toro thrust faults), and (3) sustained global sea level highstand, taken together, indicates high sediment supply during shortening of the thrust belt (Figure 6). In the case of the Oligocene-early Miocene Patagonian record, we suggest that the combined effects of tectonics—flexural loading of the upper plate and increased sediment supply from actively exhuming orogenic sources—are primary drivers for marine incursions.

Rejuvenated late Oligocene through early Miocene retroarc foreland sedimentation in southern Patagonia—and elsewhere along the Andean margin (e.g., [140, 146–148])—may signal a Cordilleran-scale upper plate transition to a dominantly compressional margin and active retroarc foreland basin systems [149, 150] that include the southern Patagonian Andes sector. This response was likely due to increased plate convergence [151] and initiation of the Nazca plate subduction regime (e.g., [152]). In Patagonia, regional retroarc deformation and basin development may have been enhanced by three-dimensional stress from transpressional tectonics along the North Scotia Ridge [47, 64, 153]. These findings underscore central requirements of detailed chronology and provenance to develop basin age models and understanding of long-term changes in sources that reflect orogen-scale responses to tectonics, climate, and eustasy.

Data Availability

All data are available in the supporting information and publicly archived at <http://www.geochron.org>.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

A description of the detrital zircon U-Pb LA-ICPMS analytical methods, data, concordia plots, and relative probability distributions. (*Supplementary Materials*)

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