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Volume Special Issue Tectonostratigraphic Evolution of Patagonia: Preface

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ABSTRACT

This Volume Special Issue of the Journal of South American Earth Sciences is dedicated to honoring the career of Professor Dr. Raúl Eduardo Giacosa, a distinguished geologist in Stratigraphy, Structural Geology, and Tectonics of Patagonia, Argentina. Throughout his tenure at the Servicio Geológico Minero Argentino (SEGEMAR), Dr. Giacosa has made pioneering contributions to various topics, including basement geology, stratigraphy of the volcano-sedimentary cover, brittle-to-ductile deformation, structural and kinematic analysis, tectonics, and related mineral resources of Patagonia. His dedication, innovative research, and steadfast mentorship have profoundly impacted the field, leaving a lasting legacy that inspires future generations. This special issue pays tribute to his remarkable achievements and extends heartfelt gratitude for his enduring influence and the contributions of all who made this issue possible.

1. Introduction

This Volume Special Issue of the Journal of South American Earth Sciences is a tribute to Professor Dr. Raúl Eduardo Giacosa in honor of his career in Stratigraphy, Structural Geology, and Tectonics of Patagonia, Argentina. During his long-lasting and influential career as a structural geologist of the Servicio Geológico Minero Argentino-SEGEMAR (Argentine Geological and Mining Survey), scientist, and educator, Raúl has made significant contributions to basement geology, stratigraphy of the volcano-sedimentary cover, brittle-to-ductile deformation, structural and kinematic analysis, tectonics, and related mineral resources of the hidden and untamed Patagonia.

With profound gratitude and admiration, we seize this opportunity to honor Raúl in this special issue. His unparalleled dedication, pioneering contributions, and unwavering mentorship have left an indelible mark on our field. This tribute acknowledges his remarkable achievements and celebrates the lasting legacy he has created, inspiring generations to come. We extend our heartfelt thanks to Raúl for his enduring impact and all the contributors who have made this special issue possible.

2. Brief life history of the honoree

Raúl E. Giacosa was born in 1955 and grew up in San Jorge, Santa Fé, Argentina. After he earned a BA-MA from the Universidad Nacional de Córdoba (Geólogo, 1979) at Córdoba City, his geological profession was early involved with Patagonia. After a brief period in the oil industry at Yacimientos Petrolíferos Fiscales (YPF), Comodoro Rivadavia Oil Field (Chubut, 1979–1980), Raúl conducted his entire career as a geologist in the Servicio Geológico Minero Argentino (SEGEMAR), participating in activities in the Patagonia-Comahue, San Antonio Oeste, and Comodoro Rivadavia mining geological exploration plans (Neuquén, Río Negro, and Chubut provinces) from 1980 to 1991. In parallel, Raúl earned an early career scholarship from the DAAD (German Academic Exchange Service) at the Institute of Endogenous Geology, Ruhr University, Bochum (Germany, 1992), under the supervision of Dr. B. Stoeckhert. He then received a Doctorate in Geology at the Universidad Nacional de la Patagonia San Juan Bosco (UNPSJB) at Comodoro Rivadavia, completing a thesis on the pre-Cretaceous geological and petrological evolution of the eastern North Patagonian Massif. The PhD in Geology as a career at UNPSJB began in 1989, and its first graduate was Raúl in 1994. After that, he continued at SEGEMAR and developed a one-year

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postdoctoral stay in Structural Geology at the Geodynamics & Geology Department of the University of Oviedo (Spain, 1999–2000). Continuing geological and structural activities at SEGEMAR led him to serve as chief researcher of projects in regional geology at the Instituto de Geología y Recursos Minerales (1992–2007). Then he, and his family, moved from Comodoro Rivadavia to General Roca (Río Negro) to take over as Head of Geology of the SEGEMAR office in this city until his retirement (2007–2022).

Raúl had outstanding university teaching and management activities in undergraduate and graduate courses from a teaching assistant in charge of labs (1980–1989), through a professor in Structural Geology and Regional Geology (1991–2011), Head of the Geology Department (1992–1994), and then Director of the PhD program in Geology (2002–2007) at UNPSJB. His activity was as profuse as that of a professor at other Patagonian universities. He also taught as a tenure-track professor in Structural Geology and Regional Geology at Universidad Nacional del Comahue (Neuquén, 2012–2014) and Universidad Nacional de Río Negro (UNRN, 2014–2022). He has trained numerous

Fig. 1. Raúl E. Giacosa through his life. (a–c) The years at the UNPSJB, during fieldwork, or simply celebrating life with their usual camaraderie. (d) A journey during fieldwork mapping basement terrane at Lago Lácar, San Martin de los Andes. (e–f) Field season training with undergraduate students from UNPSJB at Tres Hermanas, Santa Cruz. (g–h) Field season training with undergraduate students from UNRN at Curaco Batholith, Río Negro. (i) Field trip work with colleagues from UNPSJB, UNRN, YPF, Instituto Geológico y Minero de España, Oviedo and Rey Juan Carlos universities (Spain) at Cuesta de Rahue, Precordillera of Neuquén.

undergraduate and graduate students at the universities mentioned above, many of whom contribute to this Special Volume. He bestowed the title of Professor Emeritus at UNRN upon his retirement in 2023 for his character as an outstanding educator and researcher.

2.1. Personal testimonials

Witnessing the daily life stories of the people that Raúl has influenced over time would result in several pages, which, however, we can summarize with brief testimonies of his students from UNPSJB and UNRN, peers and colleagues from SEGEMAR, and the Guest Editors of this Volume Special Issue. Our memories of Raúl transcend his professional excellence as a teacher, researcher, chair leader, colleague, or thesis advisor. We cherish his wisdom, the stories he shared, the moments we spent together, and his human warmth (Fig. 1). We will always be grateful to him for allowing us to be part of his journey, and we will forever treasure his friendship.

Raúl's influences at UNPSJB in Comodoro Rivadavia left an indelible legacy, as he became the institution's first doctoral graduate. His unwavering dedication then extended beyond undergraduate teaching. He spearheaded research projects, supervised undergraduate and graduate program theses, and taught numerous courses on structural analysis. Initially trained in basement rock studies, Raúl excelled in analyzing sedimentary rock deformation. His critical and integrative approach inspired new generations of professionals, emphasizing the importance of data as a cornerstone in geological interpretations and models. His generosity and forward-thinking vision laid the groundwork for strengthening the teaching and research of structural geology. Decades later, his legacy at UNPSJB is evident in several graduates, professionals, and geoscience researchers.

Raúl's encouragements at UNRN in General Roca also transcended beyond the scope of the classrooms or training in fieldwork. There is a little-known story, but no less critical. He was involved with outlining the germ and taking the first steps in establishing the Geology degree at the UNRN. Then, with the degree's official and regular launch, his mentorship and guidance have also shaped the careers of many professionals who graduated from this university.

His contributions to advancements in structural geology at UNPSJB and UNRN have been just as significant as a "trainer of geological trainers." His students continue his geological legacy today by teaching structural geology and tectonics at these universities.

3. Raúl's contributions and impact on the field

Patagonia, including the continental shelf of the Malvinas Islands, is a geographical, geological, historical, and cultural region in southernmost South America. It is a bi-oceanic continental region geographically bounded to the north and south by the Colorado River and the Cape Horn, respectively. Several morphostructural regions depict the extra-Andean and Andean Patagonia covering from north to south the

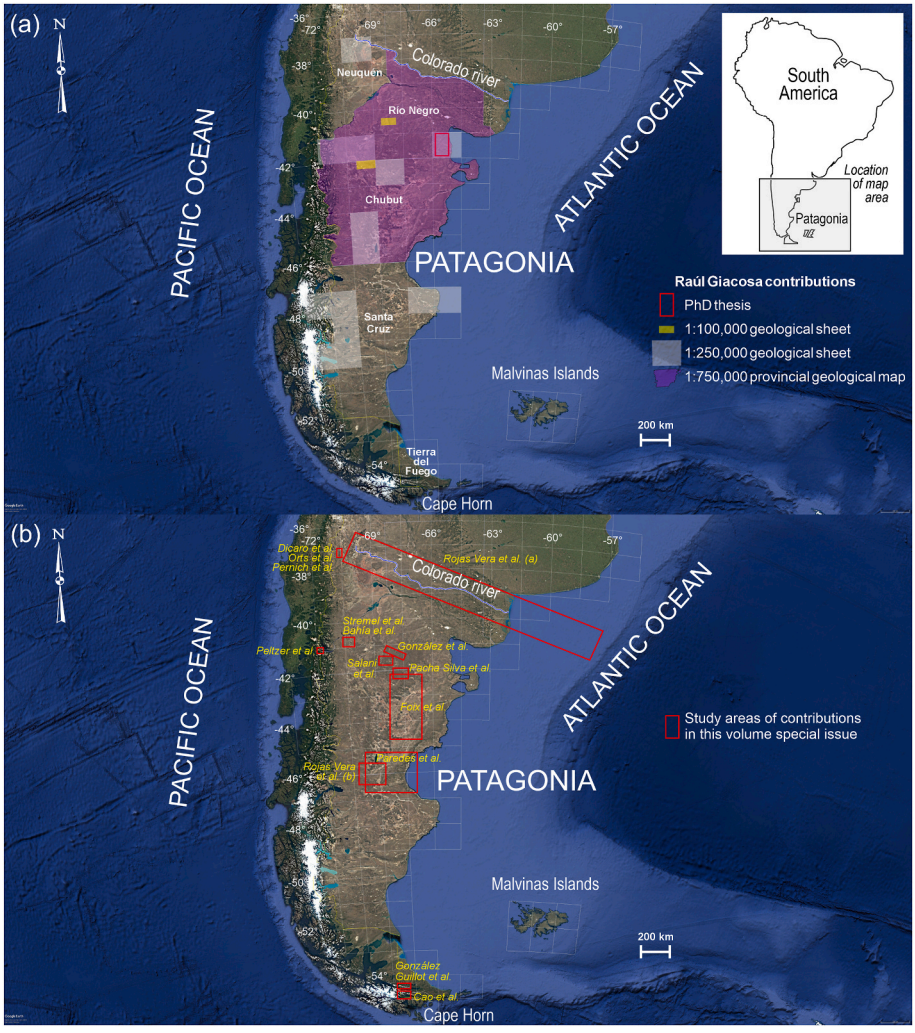

Fig. 2. Regional geographical situation of Patagonia in South America. Satellite images are available from Google Earth Pro (https://earth.google.com/). (a) The sketch map depicts the main contributions of Raúl E. Giacosa from SEGEMAR's work. (b). Study areas of this Volume Special Issue contributors.

Neuquén, Río Negro, Chubut, Santa Cruz, Tierra del Fuego, Malvinas, Antártida and South Atlantic Islands provinces of Argentina. Also, the south Chilean regions (Fig. 2a).

In the broadest sense, the geology of Patagonia comprises an Early-Middle Paleozoic igneous-metamorphic basement, the Late Paleozoic to Quaternary volcanic and continental-marine sedimentary successions, and the Meso-Cenozoic Patagonian Batholith. Raul focused his geological work on large parts of this vast stratigraphic column. His first influential work was his PhD thesis (Giacosa, 1994a) on "Geology and petrology of the pre-Cretaceous rocks of the Arroyo Tembrao-Arroyo Salado area, the eastern sector of the North Patagonian Massif, Province of Río Negro" (https://sistema-biblio.unp.edu.ar/). It was northern Patagonia's first comprehensive geological treatment, shedding novel petrological light on the Paleozoic igneous-metamorphic basement and the Mesozoic volcano-sedimentary cover, then derived in several contributions (e.g., Giacosa, 1993, 1994b, 1997, 2001; Giacosa and Paredes, 2001, among others).

Raúl's career at SEGEMAR is marked by a profound dedication to geological research, significant contributions, and the mentoring of human resources (this not fully recorded formally at the institution), spanning over four decades. He played a crucial role in Patagonia's geological and geochemical exploration, actively participating in the Plan de Exploración Geológico Minera Patagonia-Comahue. His primary focus was on conducting extensive geological mapping and structural studies at several scales and regions (Giacosa et al., 1997; Giacosa and Heredia, 1999, 2004a, 2004b; Giacosa et al., 2004a, 2005, 2010, 2012; Giacosa, 2020, and many others as co-author).

He was the Chief Project Researcher in Regional Geology at the Instituto de Geología y Recursos Minerales of the SEGEMAR in Comodoro Rivadavia and General Roca. His main activities (Fig. 2a) included leading the national geological mapping program at a 1:250,000 scale in regions such as Chos Malal (Neuquén); San Carlos de Bariloche, Sierra Grande, and Ingeniero Jacobacci (Río Negro), Gan Gan, José de San Martín, and Sarmiento (Chubut); Puerto Deseado, Lago Posadas-Lago Belgrano, El Chaltén, Lago Cardiel, and Tres Lagos (Santa Cruz), and also at a 1:100,000 scale in Cerro Abanico and Colonia Ganzu Laufquen (Río Negro), Gastre and Sierra del Medio (unpublished, in progress, Chubut), and La Celestina and Cerro Meridiano (unpublished, in progress, Santa Cruz). He also participated in mapping the geological map of Argentina at a 1:2,500,000 scale (2021) and the provincial maps of Chubut at a 1:750,000 scale (2022) and Río Negro (2025, in press).

Additionally, Raul was Editor-in-Chief of the special volume on the geology of Chubut, which accompanies the 1:750,000 scale map (Giacosa, 2021). Raúl also conducted structural and tectonic studies in the Cordillera del Viento, Sierra de la Vaca Muerta, Anticlinal del Agrio, Dorso de Los Chihuidos, Picún Leufú (Neuquén), Cerro Vanguardia, and El Tranquilo (Santa Cruz), and performed geological risk and hazard assessments in Mirador del Lago Traful and Bosque Sumergido Lago Traful, as well as aggregate quarry evaluations in the Nahuel Huapi National Park (Río Negro). Through his work, Raúl has significantly advanced geological mapping, structural analysis, and the understanding of geological hazards, leaving a lasting impact on the geological community and contributing to the sustainable management of Argentina's natural resources. To download these maps, memoirs, and technical reports (diamond open access), please visit the SEGEMAR repository at https://repositorio.segemar.gov.ar/browse.

Raúl's commitment to education is evident in his mentoring and developing human resources through extensive involvement in guiding undergraduate, graduate, and PhD students at UNPSJB and UNRN, fostering the growth of future geologists and researchers. He co-advised doctoral theses on diverse topics such as fluid inclusions in Cerro Vanguardia (Santa Cruz), the tectonic development of pre-Permian metamorphic basement in the northeast Deseado Massif, and the sequential and evolutionary analysis of the Patagonian basin. He advised a PhD thesis and CONICET fellowship, focusing on the tectonics and sedimentation of the Paleogene record in the Golfo San Jorge Basin. Raúl also co-advised PhD theses and postdoctoral fellowships of researchers contributing to significant structural geology and sedimentology studies. His mentorship extended to supervising BA-MA projects and scholarship recipients, ensuring detailed regional structural analyses. Raúl's guidance fostered notable careers in geosciences and continued to shape future geologists and researchers through ongoing doctoral and postdoctoral supervision. His dedication to education and research significantly strengthened geology, particularly in Patagonia and beyond.

4. Overview of the special issue: contributions

With this Special Issue, we take the opportunity to celebrate Raúl's contributions and reflect on his research's impact on the field geology of Patagonia. We anticipate that these articles will contribute to a better understanding of Patagonia's regional geological and tectonostratigraphic evolution and its implication for the crust's short- and long-term growth and stabilization.

The collection of research papers on the issue presents a valuable multidisciplinary approach considered in most contributions, focusing on stratigraphical, structural, geophysical, and petrological data, among others, at different crustal levels, geological times, and scales. The authors who contributed to this volume are Raúl's students, postdocs, colleagues, collaborators, and scholars he has influenced. We summarize the contributions geographically, from northern to southern Patagonia. They overlap many areas Raul already studied (Fig. 2a and b).

From northernmost Patagonia, three contributions from the Precordillera of Neuquén at Cordillera del Viento highlight the pre-Andean to Andean structural evolution of the igneous-metamorphic basement and the volcanic cover, early funded by Giacosa et al. (2014). The contribution of Dicaro et al. (2024, this issue) presents new lithofacies description, classification, and association from outcrops and drill core samples and LA-ICP-MS U-Pb zircon ages of the volcanic products from the Gondwanide Choiyoi Magmatic Province belonging to the Carboniferous basement. They interpret the eruptive dynamics, evolution, and time scales of the volcanism, proposing an evolutive scheme associated with extensional tectonics in the regional tectono-magmatic framework of the Gondwanide magmatism of northern Patagonia.

Orts et al. (2024, this issue) focus on the structural evolution and exhumation events recorded in a Permian plutonic-volcanic complex, also belonging to the Gondwanide Choiyoi Magmatic Province of the Cordillera del Viento. The contribution characterizes the cooling history within the context of the regional deformation in the Chos Malal Fold and Thrust Belt through detailed thermochronological and thermobarometric data. It also provides new insights into the thermal and exhumation history, integrating surface geological mapping, estimates of emplacement depth (via mineral chemistry), and kinematic modeling of structures.

Pernich et al. (2025, this issue) describe the petrography, magnetic fabrics, and emplacement timing concerning the same plutonic-volcanic complex studied by Orts et al. (2024). The anisotropy of magnetic susceptibility (AMS) studies of granitoids and volcanic rocks characterize their internal magmatic to solid-state structures integrated into the regional geodynamic framework. They concluded about the syn-to post-tectonic emplacement of the plutonic-volcanic complex regarding the Late Paleozoic deformation of the San Rafael Orogenic Phase, likely reflecting the transition from a compressional regime associated with the final stages of Gondwana amalgamation to an extensional context-related to supercontinent subsequent breakup.

The Paleozoic E-W to WNW-ESE trending igneous-metamorphic basement fabric of Patagonia likely controls the formation of Meso-Cenozoic sedimentary basins and their tectono-stratigraphic evolution (e.g., Giacosa, 2020). For instance, Rojas Vera et al. (2024, this issue) studied several rift basins, separated by basement highs and limited to the south by the E-W anomaly of Huincul High, that extend more than 1500 km from the Andes to the Atlantic continental shelf along the

Colorado River, i.e., the northern Patagonia limit, structurally controlled by this basement fabric. They depict an integrated geodynamic interpretation of those basins in the subsurface since Jurassic times, using off-shore marine and on-shore continental gravity data constrained by oil wells and seismic data. They became new exploration targets, increasing the economic potential of these intracontinental basins.

Structural inheritance is also a significant control in the Northpatagonian Andes structural architecture and magma emplacement, where the genesis of sedimentary basins and magmatic arcs has also been influenced mainly by basement fabrics (Giacosa et al., 2001; Giacosa and Heredia, 2004b). Based on new geologic, structural, microstructural, and geochronologic data, Peltzer et al. (2024, this issue) evaluated the influence of pre-existing structural anisotropies in the Paleozoic basement on the Jurassic-Neogene tectonic evolution of the Northpatagonian Andes, west of Bariloche area. They informed a new U-Pb zircon data consistent with the Jurassic magmatism reported in that region, which also correlates with retrograde metamorphism and deformation in its metasedimentary country rock. Fault kinematic data indicate a Jurassic transtensional regime, strongly controlled by basement reactivation, and a Neogene transpression recorded mainly as strike-slip.

In the extra-Andean Patagonia region, the Jurassic continental rifting also developed volcano-sedimentary basins structurally controlled by the basement fabric (Giacosa et al., 2005). In that region, Stremel et al. (2025, this issue) geochemically and isotopically (Lu-Hf zircon) describe calc-alkaline I-type hybrid volcanic rocks associated with the extensional setting, constraining the tectonic characteristics of magmas and their evolution within the retro-arc volcanic system. Likewise, the contribution of Bahía et al. (2025, this issue) complements the study of the volcano-tectonic system within this extra-Andean area through subsurface gravity and magnetic characterization of the depocenters boundaries, internal volcano-sedimentary arrangement and thickness variations, and location of the ancient volcanic conduits. They proposed an evolutionary model connecting subsurface anomalies with the surface's structural, stratigraphical, and depositional features.

Combining remote sensing techniques and fieldwork, González et al. (2024, this issue) studied the development of a regional E-W left-lateral strike-slip fault system controlling the emission of the Oligocene-Miocene basaltic volcanism of Somún Curá Large Igneous Province in the foreland central Patagonia. They present novel structural evidence of the regional strike-slip system and provide additional insights into this magmatic province's structural complexities, shedding light on its overall petro-tectonic evolution. These authors interpret the strike-slip kinematics as representing the waning in the evolution of the fault system during the Cenozoic, likely originating from a longstanding basement faults reactivation.

Salani and Schneider Santos (2024, this issue) contributed to the analysis of geology, stratigraphy, and petrography of the early Miocene felsic volcanic rocks differentiated from the central basaltic plateau of the Somún Curá Large Igneous Province. Volcanics are bimodal, rhyolite-dacite lava flows, domes, coulees, and related pyroclastic rocks in the lower part of the volcanic succession, and minor basalts covering them along the southwestern margin of the plateau. New U-Pb zircon ages allow for constraining the main felsic volcanic activity within the Burdigalian early Miocene. Salani and Schneider Santos (2024) also discuss the likely structural control made by regional structures on volcanic emissions.

Likewise, Pachá Silva et al. (2025, this issue) contributed with field mapping, analysis of the volcanic stratigraphy, petrographic descriptions, and U-Pb geochronology of a trachytic caldera complex lying on the central-eastern margin of the Somún Curá Large Igneous Province plateau. They gathered all results data and a U-Pb apatite age to constrain the Upper Oligocene evolutionary trend of a central caldera, separating the volcanic episodes into pre-, syn, and post-caldera.

Central and southern Patagonia was the locus of the honoree's geologic contributions (Fig. 1a, b, e.g., Giacosa et al., 2004b; Fracchia and Giacosa, 2006; Giacosa et al., 2010; Foix et al., 2008, 2012; Giacosa et al., 2012; Giacosa, 2020, among others). In this regard, the study of Foix et al. (2024, this issue), also related to previous contributions, describes the characteristics of a late Aptian to Cenomanian-early Turonian fluvial systems of the Chubut Group in the Canadón Asfalto Basin, spanning ~30,000 km^2 and featuring over 7,000 exhumed paleochannels. These WNW-ESE oriented, low sinuosity, and narrow profiles paleochannels, preserved within ~350 m thick volcaniclastic and epiclastic units, define the region's distinctive "mesetiform" landscape. Multi-scale architectural analyses identify different fluvial lithosome hierarchies, and fixed-channel and mobile channel belts are the main types of channel arrangements. The distribution of paleochannels suggests a dominance of shallow lacustrine and lagoonal deposits in the western basin region, likely shaped by the topography of the Jurassic-Lower Cretaceous depocenters.

In the Golfo San Jorge Basin, Rojas Vera et al. (2025, this issue) provide an updated perspective on the structural architecture of the San Bernardo Fold Belt at the Los Perales oil field. This contribution offers a novel interpretation of inverted structures and their kinematics based on surface geological mapping, 2D/3D seismic data, and gravimetric analysis. The robust structural assessment documents 3D deformation associated with the reactivation of Neocomian extensional faults during the early Upper Cretaceous. Additionally, the study identifies uncoupled WNW extensional faults with synsedimentary records, which constrain the maximum uplift linked to positive tectonic inversion. These findings provide critical constraints on the timing of a Cretaceous inversion phase, a persistent debate in Patagonia's tectonic evolution at these latitudes, and underscore the need for a comprehensive reassessment of existing structural models.

Within the same Golfo San Jorge Basin area, Paredes et al. (2024, this issue) contributed to the size, shape, and organization of depositional systems in this endorheic basin, which is influenced by tectonic and climatic history. Studies of depositional systems through a 150 km transect and subsurface data revealed that the Aptian Matasiete Formation, a high-accommodation fluvial system sourced from the Cañadón Asfalto Basin, flowed towards the Pozo D-129 Formation with low-sinuosity channels and braided rivers. The Albian Castillo Formation, deposited in an E-W elongated depocenter and disconnected from the Cañadón Asfalto Basin, comprised volcaniclastic floodplain deposits and narrow-sheet fluvial channels, showing variations in fluvial styles and channel sizes. Alluvial architecture among the Matasiete and Castillo formations reflect basin boundary reconfigurations, channel network reorganizations, and variable volcaniclastic supply changes, likely reflecting tectonic processes, climate change, or a combination of both.

From the southernmost reaches of southern Patagonia, González Guillot et al. (2025, this issue) analyzed the field geology, petrography, and geochemistry (whole rock and minerals) of a dike-pluton system belonging to the late Cretaceous Fuegian Batholith to constrain their evolutionary mode of emplacement and crustal intrusion level into the Fuegian fold-and-thrust belt. The petrographic, electron probe microanalysis, thermobarometric, and geochemical data indicate a composite magmatic body constructed by magmas feeding from different, deep magma reservoirs in an inferred trans-crustal plumbing system, even though lately emplaced into shallow crustal levels. Internal magma injection into crystallized regions leads to sharp dike contacts, whereas injection within local magma mushes leads to magma mingling and mixing. These authors interpreted dikes as representing discrete increments of the growing pluton in a protracted process of successive magma injections, evolving during two main magmatic episodes separated by a phase of ductile deformation.

Cao et al. (2025, this issue) give new insights into the overall geologic evolution of the Jurassic-Lower Cretaceous Rocas Verdes Basin in Tierra del Fuego, also revisiting petrographic, stratigraphic, and geochronological aspects. They propose that the heterogeneous felsic

volcanic and sedimentary record of the basin should be more appropriately gathered into the Lemaire Complex, assessed with new Jurassic U-Pb zircon crystallization ages coinciding with the V2 and V3 magmatic events related to the breakup of Gondwana. Later in the tectonostratigraphic evolution, the Albian U-Pb zircon maximum depositional ages of the sedimentary record support previous interpretations that some lithostratigraphic units laterally correlate between distinct depositional settings of the Rocas Verdes back-arc basin of the Fuegian Andes.

5. Legacy and future directions

Raúl E. Giacosa's structural legacy provides a solid foundation for advancing the understanding of Patagonian geology. His mapping and research established the basis for studying several geological processes associated with many continental-scale orogenic events in Patagonia. Inspired by Giacosa's work, new generations will expand their structural analyses by incorporating new field techniques and laboratory methods to refine geological models. In this context, a comprehensive reassessment of sedimentary basin structures is necessary to refine fundamental models, emphasizing the role of basement controls in polyphase deformation. From an evolutionary perspective, evaluating exhumation processes, their controlling factors, and their spatial-temporal variations is crucial in distinguishing upper-crustal stress processes from deep geodynamic forces. From an applied perspective, advancing the understanding of multi-scale geomechanics is of great importance, particularly in analyzing fracture controls to assess potential hydrocarbon reservoirs, mineralization and formation of ore deposits, and underground gas storage solutions that contribute to mitigating climate change (e.g., CO_2 sequestration, green and blue H_2 storage, etc.).

CRediT authorship contribution statement

Pablo D. González: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Nicolás Foix:** Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **José O. Allard:** Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Mariano Hernández:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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