

TRINITY COLLEGE DUBLIN

DOCTORAL THESIS

Seismic Tomography of South
America: Continental Lithosphere,
Subduction-Zone Structures, and the
Origins of Intraplate Magmatism

Author:

Bruna CHAGAS DE MELO

Supervisors:

Dr. Sergei LEBEDEV

Dr. David CHEW

*A thesis submitted in fulfilment of the requirements for the degree of Doctor
of Philosophy*



Trinity College Dublin

Coláiste na Tríonóide, Baile Átha Cliath

The University of Dublin

2024

I declare that this thesis has not been submitted as an exercise for a degree at this or any other university and it is entirely my own work.

I agree to deposit this thesis in the University's open access institutional repository or allow the Library to do so on my behalf, subject to Irish Copyright Legislation and Trinity College Library conditions of use and acknowledgement.

I consent to the examiner retaining a copy of the thesis beyond the examining period, should they so wish (EU GDPR May 2018).

Signed:

Electronically signed by Bruna Chagas de Melo

Date:

1st of October, 2023

Summary

Seismic Tomography of South America: Continental Lithosphere, Subduction-Zone Structures, and the Origins of Intraplate Magmatism

By Bruna CHAGAS DE MELO

The lithospheric structure of South America records its long and complex tectonic evolution, during which it has influenced the distribution and composition of local magmatism, the geometry of the subduction at its western margin, and the behaviour of the Andean orogeny. Throughout the years, seismic tomography models have provided increasingly accurate images of the Earth's structure beneath South America. However, our understanding of the upper mantle underlying the continent and its surroundings is still limited by the sparse and uneven distribution of seismic data. In this work, we present a new seismic tomography model of South America and surrounding oceans, including the crust and upper mantle. To address the heterogeneous data coverage in South America, our model SACI-24 (South America Continental Imaging 2024) is based on the inversion of more than 970,000 waveforms from ~300,000 earthquakes, recorded by more than 9000 seismic stations globally and locally. The combined regional and global dataset ensures the densest possible data sampling of the South American continent, its margins, and the surrounding oceans. We invert the waveforms using the Automated Multimode Inversion (AMI) of S-, multiple S-, and surface waves. AMI generates a set of independent linear equations with uncorrelated uncertainties for each source-receiver path. These equations describe the path-average S-wave velocity structure within approximate sensitivity kernels. We assemble these equations into a large linear system and solve it to obtain the 3D distribution of S-wave velocities in the crust, upper mantle, and transition zone. Our model is calculated globally; however, the parametrization and regularisation values are optimized for the South American region, and the data coverage is maximized only in the hemisphere centred on South America.

Within the lithosphere, our model reveals a more complex structure of the cratonic lithosphere than previously proposed. Internal heterogeneities within cratonic boundaries include regions of thinner lithosphere, which correspond to areas of proposed rifting in previous tectonic cycles. Inside the boundaries of the Amazon Craton, two distinct cratonic

blocks are identified, separated by the Amazon basin. In the São Francisco Craton, newly imaged thin lithosphere underlies the Paleoproterozoic Paramirim Aulacogen area. Our work further reveals separate, high-velocity lithospheric blocks beneath the Parnaíba and Paraná basins. South of the Paraná Basin, our model maps for the first time evidence of the cratonic root of the Rio de la Plata Craton. The detailed mapping of the lithospheric structure reveals its control on several geodynamic processes. Comparison of cratonic lithosphere with the reconstructed position of hotspots reveals that lithospheric thickness is the main control on the distribution of volcanism in large igneous provinces. Under the roots of the Andean Cordillera, our model finds multiple regions of underthrusting of continental lithosphere from South America. Our high-resolution images of the active margin reveal highly heterogeneous subduction, indicating several slab segments from the Nazca and Caribbean plates. East of the Peruvian flat slab, we find areas of thick lithosphere that we attribute to the Amazon Craton, indicating the role of cratonic hydrodynamic suction in flat slab formation. Furthermore, we identify regions under the Altiplano and Puna Plateaus undergoing lithospheric root growth and delamination, indicative of varying stages of Cordillera cyclicity.

Within the mantle transition zone, we detect segments of colder mantle from the subduction of the Nazca plate. East of these subduction segments, we identify fast seismic anomalies we interpret as remnants of past lithospheric delamination events. Underlying the thick continental lithosphere, our model reveals prominent low-seismic velocity anomalies extending as deep as the transition zone, with the strongest anomaly found beneath southeast Brazil. Whole-mantle tomography shows that this anomaly extends to a depth of at least 2000 km depth, suggesting a deeply rooted mantle plume. We postulate that interaction with past slab fragments from the long-lived Nazca subduction modifies the plume ascension path, causing it to branch out and travel horizontally to areas of thin oceanic lithosphere, where we find the present-day location of the many hotspots in the Atlantic Ocean.

Statement of co-authorship

Chapter 2 is a review article submitted to Gondwana Research as part of their invitation-only ‘GR Focus Review. I obtained and processed the newest data for half the globe since 2015. Janneke de Laat obtained and processed the remaining data. Marcelo Assumpção contributed with the data from the temporary deployment from FAPESP “3-Basin Project”. I computed the tomographic models, analysed, interpreted the model, and made the figures. I digitized the tectonic information and assembled the remaining supporting material to make the figures. Nicolas Celli contributed to the discussion and comments on the text. I wrote the manuscript with input and revisions from Sergei Lebedev, my co-supervisor at the Dublin Institute for Advanced Studies (DIAS).

Chapter 3 is in preparation for submission. I assembled the supporting dataset of magmatic provinces and igneous rocks. I analysed and interpreted the results and made the figures. Nicolas Celli and Sally Gibson provided valuable input for discussion. I wrote the manuscript with input from Sergei Lebedev.

Chapter 4 is in preparation for submission. I analysed and interpreted the results and made the figures. Nicolas Celli provided valuable input for discussion. I wrote the manuscript with input from Sergei Lebedev.

Acknowledgements

This journey has been a remarkable rollercoaster, and I could not have navigated it without the support of some truly amazing people.

First on the list, Sergei, you have been my chief academic navigator, turning my confusing ideas and wonky text into this piece of science I am proud of. Your knack for making complex concepts understandable with precision has truly transformed my approach to writing. Slow and steady, I am learning from the best.

I am grateful to my supervisor at Trinity College Dublin (TCD), David Chew, who has patiently advised me on the PhD bureaucracy. Marcelo Assumpção, you were my gateway into the world of seismology. Your welcome and insightful guidance during my masters degree were essential in leading me to this point in my academic journey. Special cheers to Marcelo Bianchi and Jackson from IAG, USP. Your support during my master's has evolved into a true friendship.

To all field technicians of the South American networks, you are the backbone of this research. To my professors from CEFET Araxá, Lúcia Hildor and Chico—your passion for Earth sciences is contagious. You have inspired many of us to follow in your footsteps, and I am grateful for that. My high school crew—Paulinha, Mari, Jana, and Gustavo—despite the distance, I know you will always be there for me (and I for you).

To everyone at DIAS, you have made Dublin feel like a second home from the moment I arrived. I am grateful for all the craic, Thursday cakes, Gingerman pints, BBQs, and library parties. I will not name everyone, as all of you have a place in my heart. To my PhD besties—Clara, Janneke, and Laura—I am so glad to have met you; you have made this journey so much more enjoyable. Chris, Huda, and Emma, you are the solid foundation of Geo, always there with open doors to support us at any moment.

To my family, who have supported me through this wild ride. My mom and best friend, Luciene, your unwavering belief in me has been my anchor. My father Bruno, who in his own (grumpy) way, has always been there for me. A warm embrace to my extended family—Ivy, Ricardo, Arthur, and Paulinho. Being part of this large and somewhat 'new' family brings me immense joy.

Last but never least, Nicolas, my better half. You have kept me grounded when I needed stability and pushed me forward when I needed momentum. Your unconditional support, both academic and emotional, has been my most important superpower through this PhD journey.

Table of Contents

1	Introduction	1.1
1.1	SEISMOLOGY.....	1.1
1.1.1	<i>Body Waves</i>	1.2
1.1.2	<i>Surface Waves</i>	1.3
1.2	1D EARTH MODELS	1.3
1.3	SEISMIC TOMOGRAPHY: MAPPING THE 3D EARTH	1.4
1.4	SEISMIC TOMOGRAPHY OF SOUTH AMERICA	1.5
1.5	MOTIVATION AND OUTLINE	1.8
2	Methodology.....	2.11
2.1	DATA PRE-PROCESSING.....	2.12
2.2	WAVEFORM INVERSION	2.13
2.3	PARTITIONED WAVEFORM INVERSION (PWI).....	2.14
2.3.1	<i>Automated Multimode Inversion (AMI)</i>	2.16
2.4	3D TOMOGRAPHIC LINEAR INVERSION	2.23
2.4.1	<i>The data vector d</i>	2.23
2.4.2	<i>The model vector m</i>	2.24
2.4.3	<i>The sensitivity matrix A</i>	2.24
2.4.4	<i>Tomographic Inversion</i>	2.25
2.5	AUTOMATIC OUTLIER REMOVAL.....	2.25
2.6	OPTIMIZATION OF REGULARISATION PARAMETERS.....	2.27
2.6.1	<i>Resolution Tests</i>	2.28
3	The lithosphere of South America from seismic tomography: Structure, evolution, and control on tectonics and magmatism	3.31
3.1	INTRODUCTION	3.32
3.2	TECTONIC SETTINGS IN SOUTH AMERICA.....	3.33
3.2.1	<i>Amazon Craton</i>	3.35
3.2.2	<i>São Francisco Craton and Surroundings</i>	3.38
3.2.3	<i>Parnaíba Basin</i>	3.39
3.2.4	<i>Paraná Basin</i>	3.40
3.2.5	<i>Rio de La Plata Craton</i>	3.41

3.3	DATA AND METHOD	3.42
3.3.1	<i>Data</i>	3.42
3.3.2	<i>Waveform Tomography</i>	3.45
3.4	THE MODEL	3.46
3.4.1	<i>Resolution Tests</i>	3.48
3.4.1.1	Spike tests	3.48
3.4.1.2	Synthetic Craton Structure	3.49
3.5	VALIDATION OF SACI-24 FROM MANTLE PERIDOTITES	3.52
3.6	DISCUSSION	3.54
3.6.1	<i>The Upper Mantle Beneath South America: the State of the Art</i>	3.54
3.6.2	<i>South America's Cratons</i>	3.60
3.6.2.1	Amazon Craton	3.61
3.6.2.1.1	Guiana Shield	3.63
3.6.2.1.2	Central Brazil Shield	3.64
3.6.2.2	Parnaíba Block	3.65
3.6.2.3	São Francisco Craton	3.65
3.6.2.4	Paraná Block	3.67
3.6.2.5	Rio de La Plata Craton	3.68
3.6.3	<i>Lithospheric structure and magmatism</i>	3.70
3.6.3.1	Cenozoic volcanism	3.70
3.6.3.2	Large igneous provinces	3.72
3.6.3.3	Diamondiferous kimberlites	3.74
3.7	CONCLUSIONS	3.76
3.8	SUPPLEMENTARY MATERIAL	3.78
3.8.1	<i>Global Data Distribution</i>	3.78
3.8.2	<i>Data Sampling per Depth – Column Sums</i>	3.79
3.8.3	<i>Model Comparison with Body Wave Models</i>	3.79
3.8.4	<i>Model Comparison with SAAM23</i>	3.80
3.8.5	<i>Synthetic Column Tests</i>	3.82

4 Origin and Distribution of the Intraplate Magmatism of South America4.84

4.1	INTRODUCTION	4.85
4.2	MAIN MAGMATIC PROVINCES OF SOUTH AMERICA	4.86
4.3	WAVEFORM TOMOGRAPHY	4.88
4.3.1	<i>Resolution Tests</i>	4.90
4.4	RESULTS	4.96
4.5	MODEL COMPARISON	4.100
4.6	DISCUSSION	4.103
4.6.1	<i>The Upper Mantle under South America</i>	4.105
4.6.1.1	Origin of Lithospheric Material under the South Atlantic	4.105
4.6.1.2	Galápagos Plume and the Nazca Slab	4.106

4.6.1.3	Mantle Plume under Continental South America	4.108
4.6.1.4	Plume Branching due to Slab Interaction since the Mesozoic	4.111
4.6.2	<i>Lithospheric Control on Magmatism Distribution</i>	4.111
4.6.2.1	Fernando Hotspot and its correlation to CAMP and northern volcanism in Brazil	4.113
4.6.2.2	Paraná Large Igneous Province	4.115
4.6.2.3	Impact of the Trindade Hotspot under South America	4.116
4.6.3	<i>Final Remarks on Sources and Distribution of Volcanism</i>	4.117
4.7	CONCLUSIONS	4.118
4.8	SUPPLEMENTARY MATERIAL	4.119
4.8.1	<i>Additional details on the magmatism dataset</i>	4.119
4.8.1.1	Igneous Rocks Locations	4.119
4.8.1.2	Large Igneous Provinces	4.120
4.8.2	<i>Model Comparisons</i>	4.120

5 Deciphering Andean Tectonics with High-Resolution Seismic Tomography 5.123

5.1	INTRODUCTION	5.124
5.1.1	<i>Northwest South America</i>	5.125
5.1.2	<i>Flat slab subduction</i>	5.128
5.1.3	<i>Central Andes</i>	5.129
5.2	WAVEFORM TOMOGRAPHY MODEL SACI-24	5.130
5.2.1	<i>Resolution Tests</i>	5.131
5.3	RESULTS AND DISCUSSION	5.136
5.3.1	<i>Northwestern South America</i>	5.137
5.3.1.1	Identification of Multiple Slab Segments	5.138
5.3.2	<i>Peruvian flat-slab segment</i>	5.141
5.3.2.1	Geometry of the flat slab	5.143
5.3.2.2	Underplating of subducted lithosphere	5.145
5.3.3	<i>Central Andes and Chile-Pampean flat slab</i>	5.146
5.3.3.1	Dynamics of the crust	5.148
5.3.3.2	Cordillera Cyclicity	5.149
5.3.3.3	Chile-Pampean segment	5.152
5.3.4	<i>Payenia and Patagonia Segment</i>	5.153
5.3.4.1	Payenia Segment	5.153
5.3.4.2	Patagonia Segment	5.155
5.4	CONCLUSIONS	5.156

6 Conclusions 6.158

6.1	CRATONIC LITHOSPHERE AND TECTONIC PROCESSES	6.158
6.2	INTRAPLATE MAGMATISM AND MANTLE PLUMES	6.159
6.3	SLAB GEOMETRY	6.160

6.4	CORDILLERA CYCLICITY	6.161
6.5	FINAL CONSIDERATIONS AND FUTURE WORK	6.161

7	Bibliography	7.163
----------	---------------------------	--------------

I Introduction

In this chapter, I aim to provide a comprehensive overview that acquaints the reader with the key themes of seismology and seismic tomography, and their development in the context of the South American continent. While this chapter offers a broad contextual understanding, each subsequent chapter is structured as a standalone, publication-based work and will provide more specific details regarding the data used, methods, and target geological features.

Understanding the Earth

The Earth, with its 4.54 billion-year history, is a dynamic and ever-changing planet. Its activity, evident in shifting landscapes, volcanic eruptions, and seismic events, has been at the centre of interest for humanity for thousands of years due to its impact on the formation of communities. Historical efforts to comprehend Earth's complexities can be traced back to ancient civilizations, including the Hebrews, Egyptians, Babylonians, and Chinese. Modern geophysics, however, took shape in the Victorian era, focusing primarily on understanding the structure of the Earth. Since the end of World War II, the scientific community has shifted its focus towards the Earth's surface, particularly after the consolidation of plate tectonics in 1968. This theory has been instrumental in explaining the mechanics of Earth's crust and mantle (Fowler, 2005).

1.1 Seismology

Seismology is currently the most powerful geophysical tool for understanding the structure of the Earth. When earthquakes occur, they release energy in the form of elastic waves that traverse the Earth and cause varying degrees of ground motion. These ground vibrations can be picked up by instruments known as seismometers deployed on the Earth's surface. The speed of these waves is influenced by the density and elastic properties of the rocks they traverse. Elastic waves are generally categorized into two types: body waves and surface waves.

1.2

1.1.1 Body Waves

Body waves are a category of seismic waves that move through the Earth's interior. Their behaviour is akin to light and sound waves, as they get reflected and transmitted at boundaries where there are changes in seismic velocity or density. There are two types of body waves:

P-Waves: Also known as primary, compressional, or longitudinal waves, P-waves consist of a sequence of compressions and expansions (Figure 1.1-A). The ground particles move back and forth in the same direction as the wave, resulting in a wave speed of approximately 6–7 km/s in the Earth's crust. P-waves are the fastest among seismic waves.

S-Waves: Standing for secondary or shear waves, S-waves result from shear deformation. These waves move particles perpendicular to their direction of travel, making them transverse waves. S-waves are further split into a horizontal (SH) and a vertical (SV) components (Figure 1.1-B). With speeds ranging 3.5–4 km/s in the crust, S-waves are slower than P-waves. Importantly, S-waves can only propagate through materials that support shear strain; therefore they cannot travel through fluids.

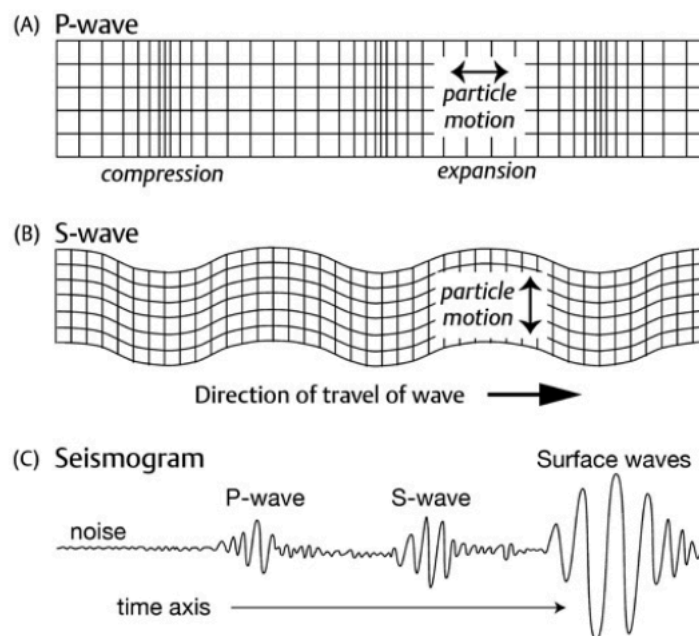


Figure 1.1: A,B) Representation of the particle displacement of seismic waves. C) Hypothetical seismogram (figure taken from Lowrie, (2018)).

1.1.2 Surface Waves

Surface waves radiate along the Earth's surface from a point known as the epicentre, which is situated directly above the earthquake's source. These waves behave in a manner akin to ripples expanding across a pool following a splash. Small, deep earthquakes generally do not generate strong surface waves, while shallow and large events can produce surface waves that have very large amplitudes and can be highly destructive. This is because unlike body waves, which disperse in three dimensions within the Earth's interior, the energy of surface waves is confined near the Earth's surface. This results in more concentrated energy, leading to the largest amplitudes that can be produced by an earthquake and causing the most significant ground motion and damage. Surface waves are categorised into two main types:

Rayleigh Waves: These waves merge the longitudinal vibrations of P-waves with the vertical vibrations of S-waves. This combination causes particles on the surface to move in an elliptical path within the vertical plane.

Love Waves: These waves arise when the horizontal components of shear vibrations are confined to the boundary layer between the Earth's surface and a lower interface.

1.2 1D Earth Models

The travel times and amplitudes of seismic waves offer insights into the physical properties of the medium they traverse. In particular, strong, distant earthquakes excite waves that can travel thousands of kilometres inside the Earth, sensing its deep layers, and variations in the arrival time, frequency and amplitude of these waves can be directly related to changes in the temperature and composition of the Earth's interior. These measurements are the core data for the construction of seismic models of the Earth's structure, which detail the seismic velocity at various depths, achieved through mathematical inversion of the recorded seismic data. While the Earth's properties do exhibit significant lateral and vertical variations, the most pronounced changes occur with depth. As a result, the Earth's structure can be effectively approximated by one-dimensional models (Figure 1.2) that account for changes in seismic velocities, density, and attenuation as functions of depth (e.g. Bullen, 1942; Dziewonski & Anderson, 1981). It is important to note that one-dimensional reference models serve as a basic approximation of the Earth's structure. These models are often least

1.4

accurate in representing the crust and uppermost mantle, where lateral seismic velocity variations are most pronounced.

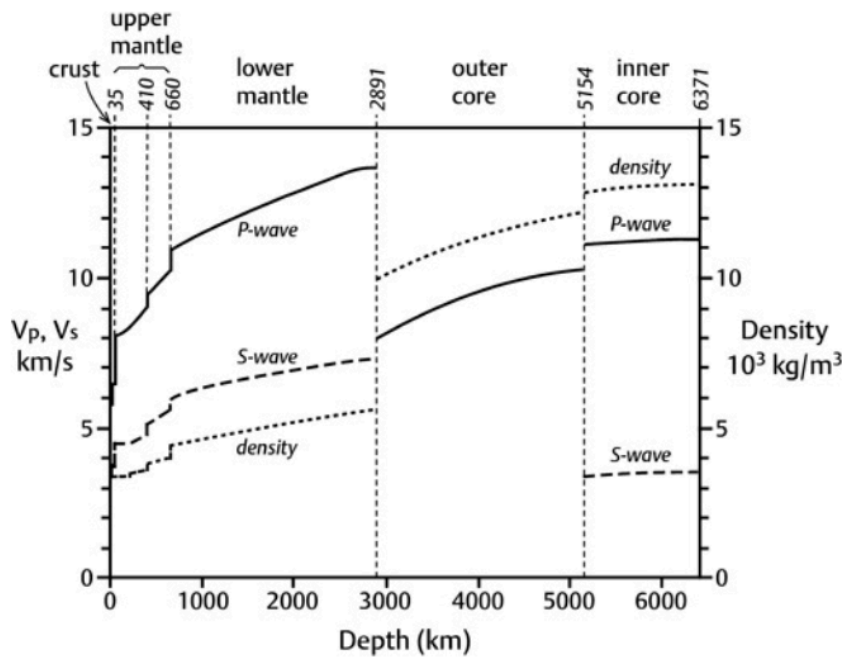


Figure 1.2: Variations of body wave velocities and density with depth in the Earth's interior (figure taken from Lowrie, (2018)).

1.3 Seismic Tomography: Mapping the 3D Earth

In a realistic Earth, the internal composition and temperature are more complicated than in an idealized, 1D, layered Earth. The observed travel-times of individual seismic phases often show deviations from those predicted by the 1D Earth models. These deviations, known as travel-time residuals, may arise from local or regional variations in the seismic velocity structure along the path travelled by the wave from the source to the recording station. By combining residuals from multiple crossing paths, we can infer the distribution of these velocity variations in space, crafting three-dimensional images of the seismic structure of the Earth. These variations in velocity can then be mapped to variations in the temperature and composition of the Earth, which can in turn be related to the different physical properties of 3D geological features. Large-scale geological features have distinctly different temperature and composition that allow them to be “seen” by seismic waves. For example, the lithosphere of cratons—the stable cores of the continents—and subducting slabs show seismic velocities that are characteristically higher than the surrounding mantle,

while mid-ocean ridges and mantle plumes—deep seated upwellings of hot material—show seismic velocities that are lower than average. It is important to note, however, that the sensitivity of seismic waves to temperature and composition is complex, so that different geological bodies can be identical to seismic waves in certain conditions, requiring additional constraints for interpretation.

The first P-wave travel-time tomographic models could mostly resolve large-scale heterogeneities in the Earth's lower mantle (e.g. Dziewonski, 1977). Subsequent years saw the use of normal modes (Masters et al., 1982) and surface waves to model the upper mantle and its anisotropic properties (e.g. Anderson & Dziewonski, 1984; Woodhouse & Dziewonski, 1984).

Concurrently, the varying sensitivities of the different seismic waves led to the development of tomographic models based on waveform modelling (e.g. Fichtner et al., 2009; Lebedev & Van Der Hilst, 2008; Mégnin & Romanowicz, 2000; Rickers et al., 2013; Ritsema et al., 2011). These models utilise data from both surface and body waves, and in some instances, normal modes. Waveform tomography is capable of sampling the crust and a significant portion of the mantle with varying degrees of accuracy.

1.4 Seismic Tomography of South America

If seismic tomography relies on the combination of seismic data, its efficacy depends strongly on the distribution and availability of seismic stations. Early tomographic models relied on relatively few seismic stations and were able to sample heterogeneities only in the scale of thousands of kilometres (~3000-5000 km) (e.g. Dziewonski, 1977; Masters et al., 1982; Romanowicz, 1995a; Woodhouse & Dziewonski, 1984b). In South America, until the year 2000, seismic stations were mostly located on the Andes and in south-eastern Brazil (Figure 1.3). The distribution of these stations reflected the target area of the first regional models, which focused on the Nazca subduction (Engdahl et al., 1995) and the upper mantle below SE Brazil (Vandecar et al., 1995).

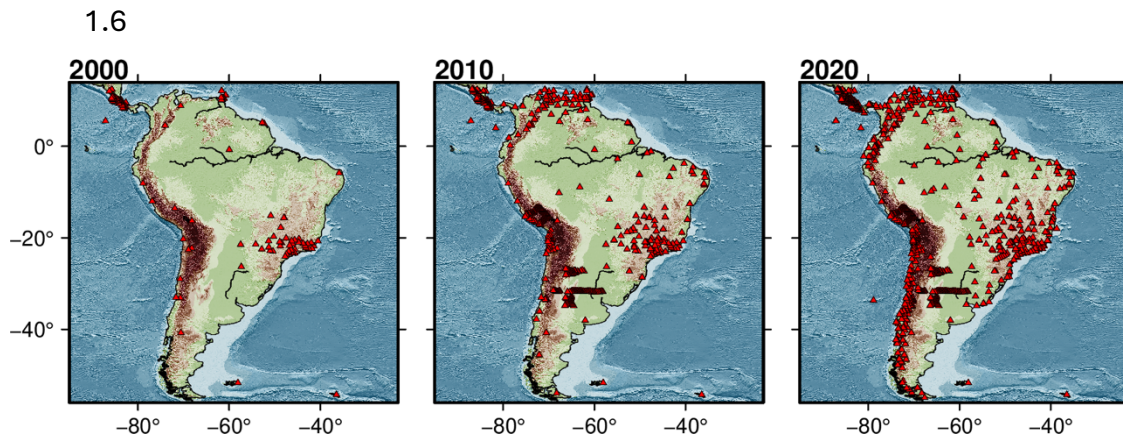


Figure 1.3: Evolution of the distribution of permanent seismic stations in South America from 2000 to 2020. Seismic station data from USGS.

From the 2000s, the number of broadband seismic stations deployed worldwide increased dramatically. Global models (Houser et al., 2008; Montelli et al., 2006; Panning et al., 2010; Ritsema et al., 2011; Romanowicz, 2008) could now resolve the heterogeneities to the scale of hundreds of kilometres (500-1000 km). In South America, global S-wave models (Houser et al., 2008; Panning et al., 2010; Ritsema et al., 2011) identified the high seismic velocities of the thick continental lithosphere as forming one or two large units in the northeast-centre of the continent (Figure 1.4). The regional, mostly S-wave models developed (Feng et al., 2007; Heintz et al., 2005; van der Lee et al., 2001; Vdovin et al., 1999) had better resolution in the upper mantle, due to the specific choice of parametrization and regularisation values to reflect the seismic data coverage in South America. As shown in Figure 1.3, deployments of seismic stations in the 2010's in the northern Andes and Amazon regions, and in the interior of the continent filled the large seismic gap on most of South America. As a result, the regional models computed with the newly available data showed improved definition on the lithospheric structure, usually identifying regions of higher velocities in the north and southeast South America (Figure 1.4). Despite the seismic networks' growth, the distribution of seismic stations in the 2000's was still highly heterogeneous.

S-wave Tomography Models from 2000-2010

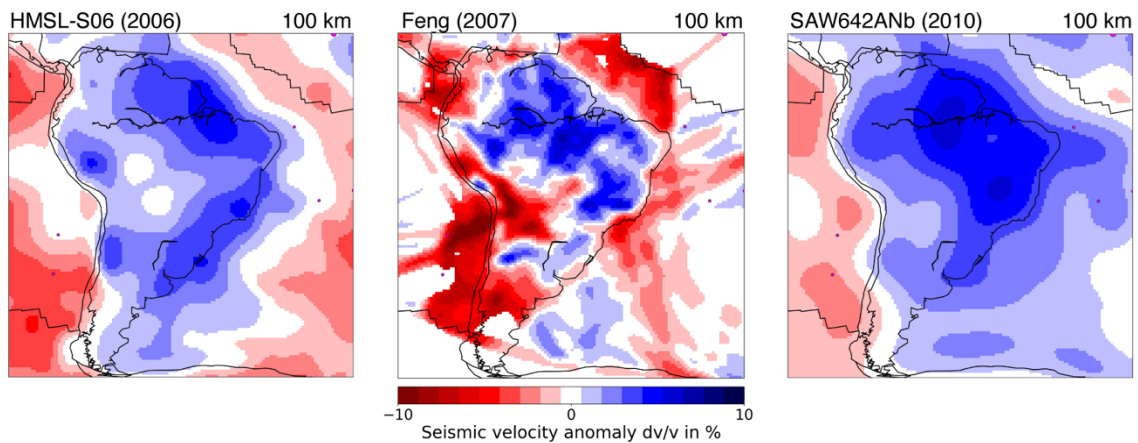


Figure 1.4: S-wave tomography models published between 2000 and 2010. The models HMSL-S06 (Houser et al., 2008) and SAW642ANb (Panning et al., 2010) are global and Feng (Feng et al., 2007) was constructed with emphasis on the South American stable platform. Figures were made with SubMachine (Hosseini et al., 2018).

In 2011, the Brazilian Seismic Network (RSBR; (Bianchi et al., 2018b)) was founded, with efforts to expand the seismic stations coverage specially in the large Amazon region. Additionally, efforts to understand the Nazca subduction and its seismic hazard resulted in significant improvements to the distribution of seismic stations on the western coast and Andean Cordillera (Figure 1.3). This explosive growth in the regional and global seismic data led to the creation of a broad range of seismic tomography models (Figure 1.5). These advancements in the seismic coverage of South America also lead to improved crustal maps (Rivadeneyra-Vera et al., 2019; Shirzad et al., 2020), more accurate definition of the cratonic boundaries (Affonso et al., 2021; Celli et al., 2020b; Ciardelli et al., 2022; Neto et al., 2019; Rocha et al., 2019), and a better understanding of the complex geometry of the subduction slab (Portner et al., 2020; Rodríguez et al., 2020).

S-wave Tomography Models from 2010-2020

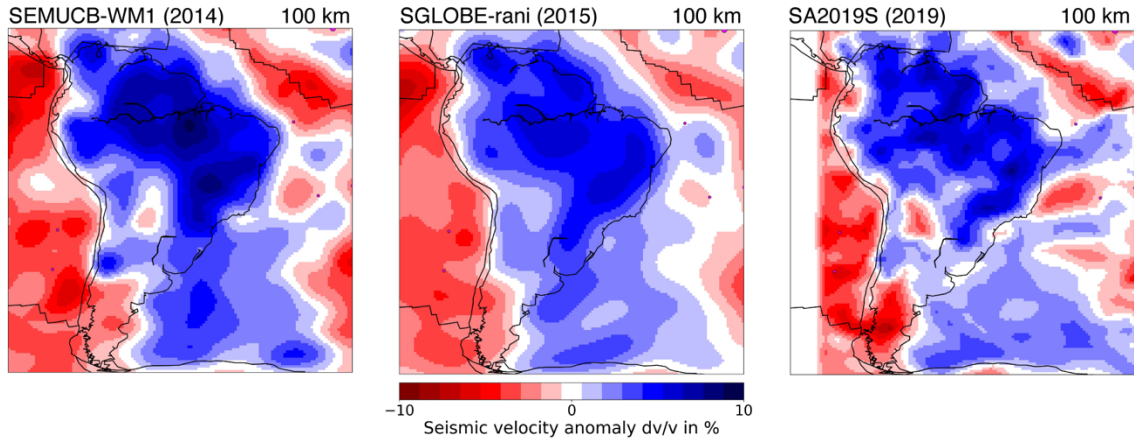


Figure 1.5: S-wave tomography models published between 2010 and 2020. Seismic models SEMUCB-WM1 (French and Romanowicz, 2014) and SGLOBE-rani (Chang et al., 2015) are global. SA2019S (Celli et al., 2020b) is a model including South America, Africa and the South Atlantic. Figures were made with SubMachine (Hosseini et al., 2018).

1.5 Motivation and Outline

Despite considerable global improvements in seismic data coverage over the past decade, challenges persist in many remote or inaccessible regions and particularly in the Southern Hemisphere. In South America, these regions include the Amazon Forest, the Peruvian Andes, the remote regions of southern Patagonia and the surrounding oceans. The scarcity of information on surface geology in these areas further amplifies the necessity for indirect geophysical studies.

To capture fine-scale details of the crust and upper mantle, seismic tomography must efficiently utilise the extensive, but uneven, seismic data currently available, a task that demands significant computational resources. In this context, this thesis employs the Automated Multimode Inversion (AMI) technique (Lebedev et al., 2005). AMI enables the efficient extraction of structural information from millions of seismograms and has been successfully applied in several tomographic models (Celli et al., 2020b; De Laat et al., 2023; Lebedev and Van Der Hilst, 2008; Schaeffer and Lebedev, 2014). Its computational efficiency makes AMI an ideal tool to study regions with sparse or uneven data coverage, where including the largest amount of seismograms to constrain tomographic models is key.

This thesis presents a new seismic tomography model of South America and its surroundings by applying AMI to a very large database of over 970 thousand waveform fits and fine-tuning the resulting model to South America. The model reveals the detailed

structure of the lithosphere and the underlying mantle, down to 660 km depth. The thesis consists of three research chapters, with each focussing on a relevant feature of the upper mantle. In each chapter, we address and discuss the new structures revealed by our model, previously unseen in past tomography models.

Chapter 2 discusses in detail all the processes involved in achieving the final tomography model. These include data pre-processing, model calculation and details on the choice of regularisation parameters and resolution analysis.

Chapter 3 was developed as an invited publication on the upper mantle seismic structure of South America. The manuscript is submitted to Gondwana Research as part of their invitation-only ‘GR Focus Review’ category. The chapter investigates the lithospheric structure of the major cratonic blocks of South America, namely the Amazon, São Francisco, Rio de la Plata Cratons, and Paraná and Parnaíba Blocks. The chapter also examines the spatial distribution of magmatic events, such as Cenozoic volcanism and diamondiferous kimberlites and their correlation with lithospheric thickness. Notable findings include the identification of several regions within cratons where the lithosphere is thinner, corresponding to areas of historical rifting and the first-ever mapping of the cratonic root of the Rio de la Plata Craton.

Chapter 4 delves into the origins and distribution of intraplate magmatism in South America, focusing on Mesozoic large igneous provinces and igneous rock locations. The chapter compares the new tomography model with existing models and discusses potential sources of magmatism in the mantle and processes responsible for magma generation and emplacement. Key findings include evidence of complex plume-lithosphere interactions and plume branching due to slab subduction, as well as a detailed description of the role of lithospheric structures in the control of the distribution of magmatism.

In **Chapter 5** we apply our high-resolution seismic model to decipher the complexities of Andean tectonics, with a focus on the structures of the subduction zone and the lithosphere beneath the Andean Cordillera. In this chapter, we analyse the influence of the continental lithosphere in the formation of flat-slab segments, the underplating of subducted lithosphere, and cordillera cyclicity. The main findings include the identification of multiple slab segments in northwestern South America, evidence of slab tearing and delamination in the Peruvian and Chile-Pampean flat-slab segments, and the influence of the Payenia and Patagonia segments on the crustal deformation and magmatism.

Chapter 6 concludes the thesis with a summary of the principal results and contributions as well as possible pathways for future research directions stemming from our new findings.

2 Methodology

In this chapter, I will describe all the necessary steps (Figure 2.1) required to produce the final tomographic model presented and discussed in this thesis. The methodology employed in the computation of the tomographic model has been extensively described in peer-reviewed journals (Celli et al., 2020b; De Laat et al., 2023; Lebedev et al., 2005) and doctoral theses (Celli, 2020; Schaeffer, 2014) and has been successfully applied in a number of global (Lebedev and Van Der Hilst, 2008; Schaeffer and Lebedev, 2013) and continental studies (Celli et al., 2020a; De Laat et al., 2023; Lebedev and Nolet, 2003; Schaeffer and Lebedev, 2014).

I will briefly discuss the standard pre-processing steps applied to seismic data prior to waveform inversion. Subsequently, I will outline Partitioned Waveform Inversion (PWI) schemes, including the Nolet (1990) implementation and the Automated Multimode Inversion (AMI) (Lebedev et al., 2005). These are followed by the 3D linear inversion (Lebedev and Hilst, 2008; Schaeffer and Lebedev, 2013), outlier removal, and tuning of model regularisation parameters. If not expressly specified in the text, I refer the reader to two books that extensively treat the subject: Nolet (2008) and Dahlen and Tromp (1998).

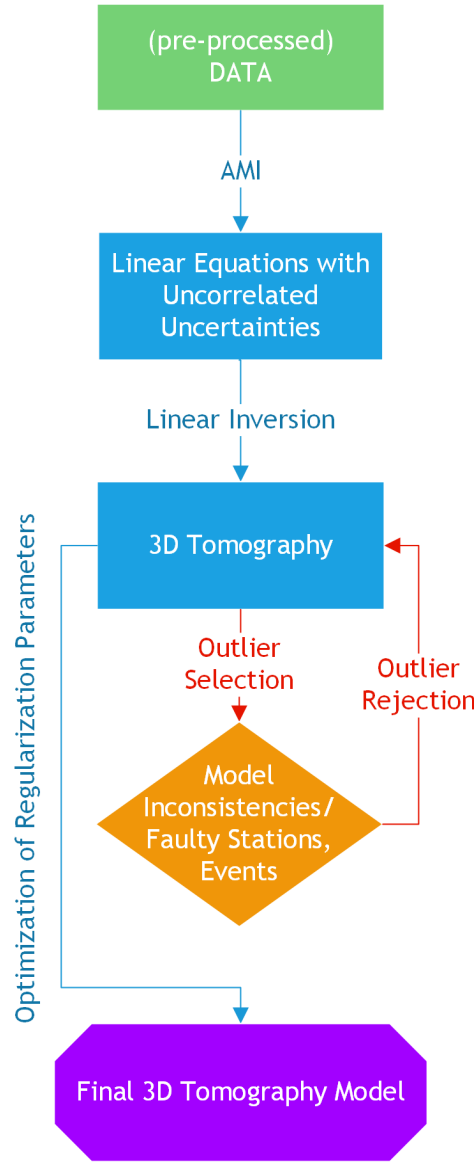


Figure 2.1: Simplified flowchart description of all necessary steps to compute the final tomography model we will present in the following chapters.

2.1 Data Pre-Processing

The seismic data used to calculate the tomographic model was acquired from the FDSN (International Federation of Digital Seismograph Networks) Web Service (<https://www.fdsn.org/>) and downloaded and processed using the Obspy tools (Beyreuther et al., 2010). The acquisition of the broadband waveforms is followed by automated quality checks and pre-processing including: checks for fragmentation, clipping (seismograms with which are removed), detrending and response correction to displacement. Additionally, we check the station response information provided by the data centres. We did so by comparing

the response files provided by different data repositories and making sure to use the one that is most up to date (de Laat et al. 2023). Finally, the vertical component seismograms are downsampled to one sample per second. For the application of the AMI codes, the seismograms need to be formatted into an organized data tree structure.

The earthquake source parameters used are provided by the Global Centroid Moment Tensor Catalogue (GCMT) (Ekström et al., 2012) with a distance-magnitude dependent threshold (Figure 2.2). The empirically generated linear cut-off filters out low-magnitude and long-distance events, which would only lead to lengthier computational times with a small percentage of fits due to low signal to noise ratios.

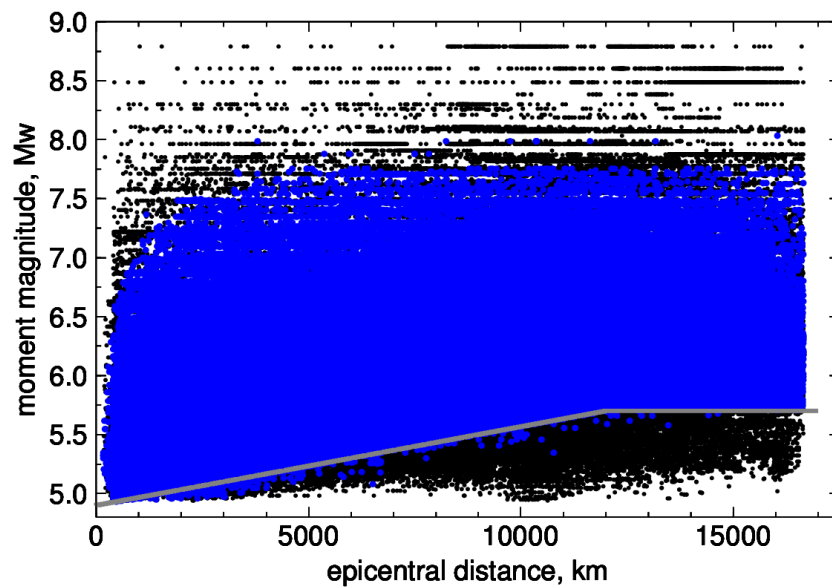


Figure 2.2: Plot of all seismograms pre-processed for fitting with AMI. Black points are all unsuccessfully fit seismograms and blue points represent those successfully fit. The empirical cut-off is indicated by the grey line at the bottom of the figure. Figure from Schaeffer, (2014).

2.2 Waveform Inversion

Waveform inversion techniques aim to constrain Earth's structure by leveraging the abundant information contained within seismic waveforms. This process requires three principal components: a forward modelling step to generate a synthetic seismogram based

on an Earth model, an objective measure for comparing synthetic and real data, and an algorithm for updating the Earth model.

Starting from a simplified model of the Earth (e.g., Figure 1.2), it is possible to calculate synthetic seismograms. For the methods discussed herein, the generation of a synthetic seismogram is presented in the framework of efficient frequency domain mode summation, utilising the Jeffreys-Wentzel-Kramers-Brillouin (JWKB) approximation, as detailed by (Dahlen and Tromp, 1998). This approximation serves as the surface-wave analogue of ray theory. The limitations of the JWKB approximation are related to the phenomena of scattering, which occurs due to the presence of heterogeneities of certain sizes that can influence the propagating waveform. An illustrative example is the scattering of high-frequency components of the seismogram as they traverse the highly heterogeneous crust, encountering scatterers of sufficient size to impact the modelled wavelengths (Nolet, 2008; Lebedev et al., 2005; Schaeffer and Lebedev, 2013). The comparison of observed and synthetic data is conducted in the time domain through waveform fitting.

Waveform fitting consists of matching the observed and synthetic waveforms by the application of perturbations to the model. The calculated perturbations indicate areas of lateral heterogeneity, not predicted by the initial, simplified model of the Earth. Constraining the perturbations means decoding the Earth structure—or solving the nonlinear inverse problem.

2.3 Partitioned Waveform Inversion (PWI)

In this section, we present the conceptual basis of the nonlinear Partitioned Waveform Inversion (PWI) method, introduced by Nolet (1990) and applied successfully in many studies (e.g., Bedle and Van Der Lee, 2006; Feng et al., 2007; van der Lee et al., 2001; van der Lee and Nolet, 1997). The Automated Multimode Inversion (AMI) (Lebedev et al., 2005) method used in the present work was developed with PWI as a basis. It inherited from it the basic approach of fitting seismograms independently and some of PWI's routines used in waveform fitting and applied in order to obtain linear equations with independent estimated uncertainties. The general approach effectively reduces the complexity of large-scale two- or three-dimensional seismic modelling challenges by dividing them into smaller, more manageable segments. The fundamental concept involves utilising path integrals over seismic velocities as the model parameters, instead of the seismic velocities themselves,

thereby transforming a large-scale optimisation issue into several independent small-scale challenges.

The procedure consists of two phases to optimize efficiency. Synthetic seismograms are computed using the JWKB approximation (Dahlen and Tromp, 1998):

$$s(\omega) = \sum_m A_m(\omega) \exp[i\omega\Delta/(C_m^0(\omega) + \overline{\delta C_m(\omega)})], \quad (1)$$

where the sum is over modes m and Δ is the source-receiver distance. The complex amplitudes of the modes $A_m(\omega)$ depend on the source mechanism (e.g. Dziewonski et al. 1994) and the Earth model assumed for the source region, as well as on geometrical spreading and attenuation (detailed calculations in, e.g. Aki & Richards 1980; Dahlen & Tromp 1998). Phase-velocity perturbations $\overline{\delta C_m(\omega)}$ are functions of the path averaged S-velocity perturbation:

$$\overline{\delta C_m(\omega)} = \int_0^a \frac{\partial C_m^0(\omega)}{\partial \beta(r)} \overline{\delta \beta(r)} dr. \quad (2)$$

The reference phase velocities $C_m^0(\omega)$ and their Fréchet derivatives $C_m^0(\omega)/\beta(r)$ are calculated for a 1-D model with an estimated average structure of the mantle and crust along the source–station path, and a is the Earth’s radius.

Waveform fitting is using the Fourier-transformed synthetic $s(t)$ and the data $d(t)$ in the time domain by minimizing a least-squares misfit function:

$$F(\delta \beta(r)) = \int |\mathbf{R}d(t) - \mathbf{R}s(t, \delta \beta(r))|^2 dt \quad (3)$$

where $\mathbf{R}$ is a filtering, windowing and weighting operator. The fitting involves executing the non-linear inversion for each path separately, yielding path-average perturbations in the model parameters (Nolet, 2008, see eqs. 10.14 and 10.15).

We parametrize $\overline{\delta \beta(r)}$ using a set of 1-D basis functions $h_i(r)$ spanning the crust, upper mantle, and the upper part of the lower mantle:

$$\overline{\delta \beta(r)} = \sum_{i=1}^M \gamma_i h_i(r). \quad (4)$$

The number M of the inversion parameters γ_i is 15–20 for S-velocity perturbations $\overline{\delta\beta(r)}$. PWI refines seismic modelling through the diagonalization of the path integral parameters' correlation matrix, facilitating the subsequent linear inversion. Given that surface wave dispersion reflects the cumulative property of all layers, rotation of the parameters using the Hessian matrix $H_i^j = \partial^2 F / \partial \gamma_i \partial \gamma_j$ delineates a new parameter set with uncorrelated errors

$$\int_{\oplus} G_i^\beta(\mathbf{r}) \delta\beta(\mathbf{r}) d^3\mathbf{r} = \eta_i \pm \Delta\eta_i, \quad (5)$$

where $i = 1, \dots, M$. New parameters η_i correspond to new basis functions $g_i(r)$:

$$\overline{\delta\beta(r)} = \sum_{i=1}^M \eta_i g_i(r), \quad (6)$$

with each $g_i(r)$ a linear combination of the M original basis functions $h_i(r)$ (for details see Nolet 1990). $G_i^\beta(\mathbf{r})$ define the S-velocity sensitivity volumes within the 3-D Earth volume $\oplus$.

The inversion partitioning process enhances computational efficiency and facilitates the management and analysis of extensive seismic datasets, as each waveform is individually inverted and then collectively assessed. Beyond reducing computational demands, this segmentation simplifies the incorporation of new data into the inversion: rather than recalculating the entire dataset for each tomographic model, only new paths require inversion, and the linear tomographic inversion is reiterated with the updated dataset.

Following this, in the second phase, the path averages are consolidated into a comprehensive damped linear system of Eqs (5) obtained from different seismograms are weighted with their uncertainties $\Delta\eta_i$ and solved together for a 3-D tomographic model.

2.3.1 Automated Multimode Inversion (AMI)

The Automated Multimode Inversion (AMI) algorithm (Lebedev et al., 2005) is a fully automated approach to waveform fitting and inversion. AMI's numerical efficiency primarily stems from its ability to discern signals for which theoretical approximations are applicable, effectively weighting and integrating data from various segments of the wave

train (see the simplified flowchart Figure 2.3). Additionally, AMI implements the use of 3D reference models and the estimation of approximate sensitivity regions.

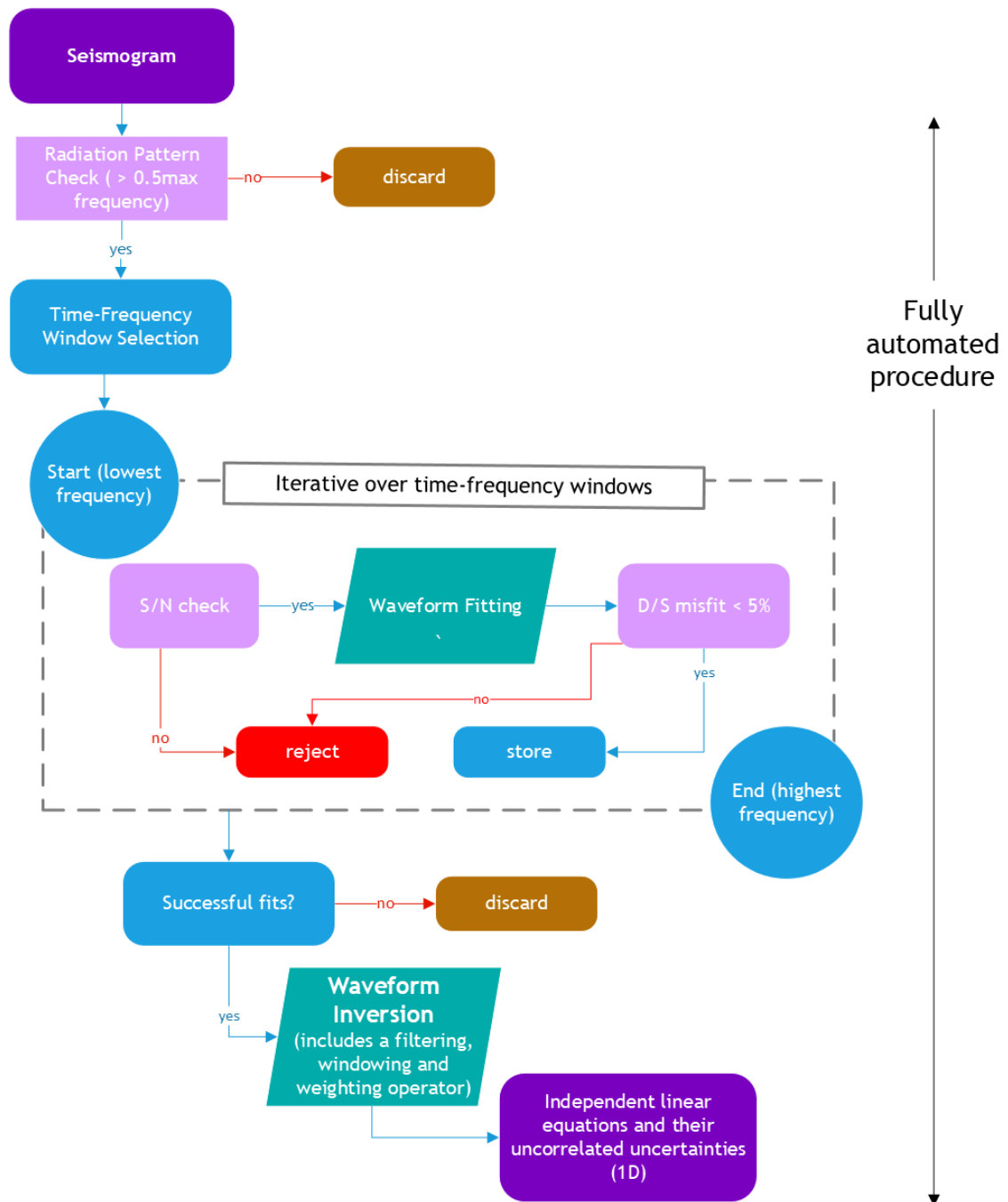


Figure 2.3: Simplified flowchart of AMI, including checks for the validity of the JWKB approximation, waveform fitting at each time-frequency window and waveform inversion of all successful fitted windows. The resulting linear equations with uncorrelated uncertainties will be inverted together for a 3D seismic tomography model.

The key elements of AMI which enable the generation of high-resolution tomographic models (Celli et al., 2020b; Lebedev and Van Der Hilst, 2008; Schaeffer and Lebedev, 2013) are:

1. **3D reference model.** While previous PWI implementations used a simplified 1D reference model (Nolet, 2008, 1990), AMI calculates the initial phase velocities and the path average perturbations $C_m^0(\omega)$ and $\overline{\delta C_m^0(\omega)}$, respectively. The path average phase velocities are expressed as derivatives with respect to P- and S-wave velocities $\overline{\delta \alpha_p(r)}$ and $\overline{\delta \beta_p(r)}$ (Fréchet derivatives), using a 3D reference model:

$$\overline{C_m^p(\omega)} = \int_0^a \frac{\partial C_m^0(\omega)}{\partial \beta(r)} \overline{\delta \beta_p(r)} dr + \int_0^a \frac{\partial C_m^0(\omega)}{\partial \alpha(r)} \overline{\delta \alpha_p(r)} dr, \quad (7)$$

where a is the radius of the Earth. These derivatives are then averaged over approximate sensitivity regions (Lebedev and Van Der Hilst, 2008). The 3D model incorporates the CRUST2.0 (Bassin et al., 2000) for the crust with added topography and bathymetry, and a modified version of AK135 (Kennett et al., 1995) for the mantle (Schaeffer and Lebedev, 2013). The model is parametrised on a triangular grid (Wang and Dahlen, 1995) with an approximate spacing of 28 km.

2. **Sensitivity kernels.** AMI improves on the ray path approximation by implementing approximate sensitivity areas. These areas are defined in terms of Fresnel zones (Lebedev and Van Der Hilst, 2008):

$$\delta = \sqrt{\frac{\lambda/2}{|\cot \Delta_1 + \cot \Delta_2|}} \quad (8)$$

encompassing all nodes within the reference model grid where the phase shift between the source and the point, and the source and receiver, is less than $\pi/2$ (as shown in Figure 2.4). In Equation (2) Δ_1 and Δ_2 are the distances from a point on the source-station great circle path to the source and to the receiver, δ is the path-normal distance from this point to the Fresnel-zone boundaries, and λ is the wavelength (Wang & Dahlen 1995b).

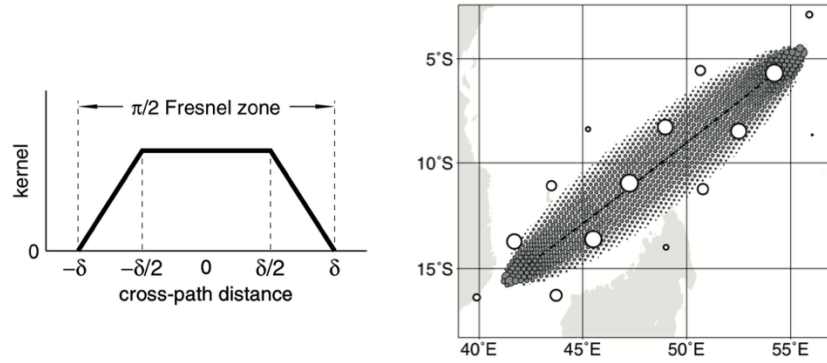


Figure 2.4: Example of the calculation of a sensitivity kernel used by AMI. Left: path-perpendicular cross-section through a kernel illustrating the trapezoidal shape. Right: grey circles show the nodes of the integration grid and white the tomographic model grid; both circle sizes are scaled with the weights of the knots in the area integral. Figure from Lebedev and Van Der Hilst, (2008).

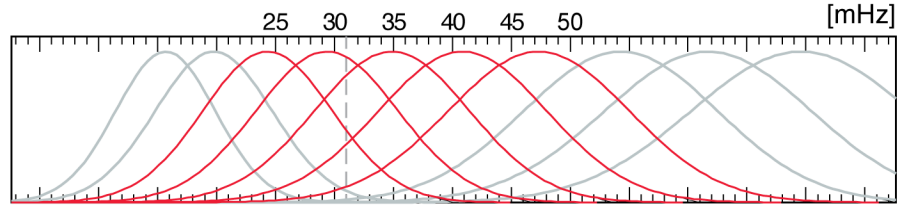
3. **Near-nodal radiation check.** AMI to selects and assesses time-frequency windows to ascertain the applicability of the JWKB approximation. This is crucial as, in instances where the source-station azimuth aligns with a nodal point in the radiation pattern of a wave, the observed energy is likely predominantly scattered. Therefore, AMI calculates the earthquake radiation pattern for each path, frequency, and mode. Segments of the seismogram corresponding to near-nodal azimuths in the radiation pattern are excluded due to their likelihood of being dominated by scattered energy. Paths also tend to exhibit increased complexity as they approach near-nodal azimuths (Lebedev et al., 2005).
4. **Time-frequency windows.** AMI employs a series of Gaussian filters for the selection of time-frequency windows (Figure 2.5-a). By applying these filters to the seismogram, the complex broadband waveform is simplified into a sequence of simpler waveforms. The minimum frequency is determined to ensure that the far-field approximation holds, requiring at least 3–4 wavelengths of the fundamental mode to span the distance between the source and station. the high-frequency threshold is established to validate the point source approximation, set at $1/(3\tau)$, where τ denotes the estimated duration of the event (taken from a catalogue, e.g. Dziewonski et al. 1994). Wave periods akin to τ are likely influenced by the unmodelled complexities of the source, finite in both space and time.

5. **Window selection and waveform fitting.** Within the defined minimum and maximum frequency boundaries, the selection of time-frequency windows must surpass a predetermined signal-to-noise ratio. The signal to noise ratio is calculated based on the amplitude of the envelope before the P-wave arrival. If the signal to noise ratio of the first filter exceeds a fraction of the maximum amplitude of the signal envelope within the S- wave–fundamental mode window, we increment the centre frequency of the filter until **detecting an acceptable signal-to-noise ratio**. If it is not detected within the frequency range, the seismogram is discarded. Having chosen the first frequency, we attempt to obtain a waveform fit of it and, if successful, add higher frequency filters one after another (Figure 2.5-b).

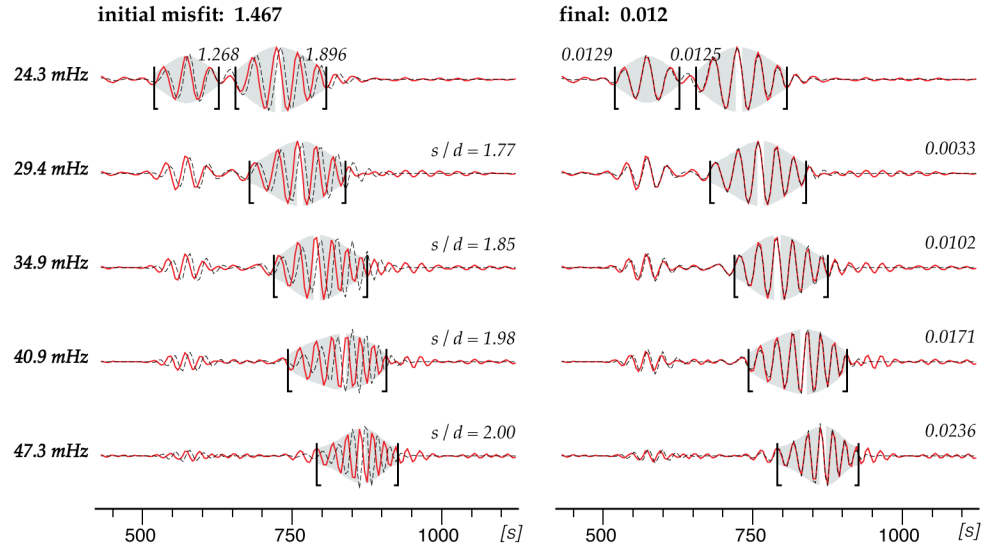
Waveform inversion within a time–frequency window is considered successful—and, thus, the window is accepted—if the relative data-synthetic misfit within it is smaller than 5 per cent. A single, widest possible time window is initially attempted at every frequency. If the fit is acceptable only in parts of the window, then it is either narrowed to include only the well-fit wave train(s) or split into two or more windows with an acceptable fit within each.

Waveforms in all time–frequency windows are inverted together, that is, we search for the velocity perturbation that minimises the cumulative misfit over all windows. The simplicity of the waveforms ensures the computed value of the misfit becomes an accurate and sufficient measure of similarity between the actual and synthetic signals. For each wave train (one or more in each of the time– frequency windows) we can obtain an almost perfect data-synthetic fit as long as the scattered-wave and noise contributions are small.

a) Frequency windows selection



b) Waveform fitting procedure



c) Resulting structural information along path

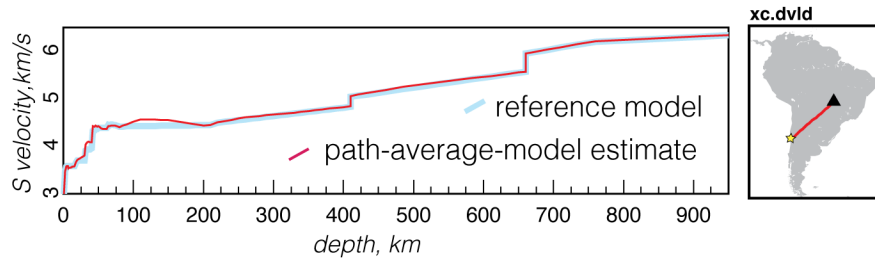


Figure 2.5: AMI fit example of a Chilean earthquake recorded by the DVLD station from the XC network on 25th of October, 2016 (d). a) Time frequency windows Gaussian filters. b) Waveforms (solid lines) are matched with synthetics (dashed lines). c) The reference model used for the waveform inversion and the path-average-model obtained from the inversion of all selected time–frequency windows.

6. **Cycle-skip prevention.** We decrease the likelihood cycle skipping (2π phase ambiguity) we initiate the fitting at the lowest frequency, and not lower than a defined number (here 12) of the fundamental-mode wavelengths. This approach ensures that once the phase is accurately identified in the initial frequency band, it remains

correctly established in subsequent, higher frequency bands. If an acceptable fit cannot be achieved at sufficiently low frequencies, the seismogram is excluded from further analysis.

7. **Weights and energy equalization.** We want to account for the contributions of different wave types from the distinct parts of the signal, in order to prevent the wave trains with the largest amplitudes (e.g. fundamental mode) from dominating the final misfit measurement. We do so, by applying a weight value that incorporates the product of the ‘envelope’ weighting $w_i^{\text{env}}(t)$, the ‘wave-type’ weight $w_i^{\text{type}}(t)$ and the ‘error-suppressing’ weight $w_i^{\text{err}}(t)$ for each time-frequency window in the form:

$$w_i(t) = w_i^{\text{env}}(t)w_i^{\text{type}}(t)w_i^{\text{err}}(t) \quad (9)$$

such that the misfit of body wave arrivals (higher modes) contributes equally compared to the fundamental mode arrival (Lebedev et al., 2005). Without this balanced weighting, the misfit function could be dominated by fundamental mode surface waves, potentially compromising the tomographic model's resolution at specific depths, such as the transition zone. Additionally, we remove the absolute amplitude of the seismograms, so that the misfit function for the i -th window is defined as:

$$F_i = \frac{\int_{t_1}^{t_2} w_i(t) \left(d_i(t) - f_i^{\text{eq}} s_i(t) \right)^2 dt}{\int_{t_1}^{t_2} w_i(t) d_i^2(t) dt} \quad (10)$$

and is only dependent on the shape of the waveforms (Lebedev et al., 2005). In Equation (4) d_i and s_i are the observed and synthetic seismograms, respectively, t_1 and t_2 the beginning and end time of the i -th time window and the factor f_i^{eq} equalizes the energy of the synthetic with that of the data.

8. **Automatization.** The automated execution of each of the above key points enables the efficient processing of massive volumes of both vertical- and transverse-component seismic data, which would not be feasible if the procedure required human interaction. A direct advantage of this extensive dataset of waveform fits is

the substantial increase in data redundancy, which can be leveraged to enhance both the resolving power and accuracy of the final tomographic model.

The efficacy of AMI is demonstrated by a series of benchmark simulations (Qin et al., 2008) which use the spectral element method to compute seismograms through several synthetic Earth models. The result of the waveform inversion of each seismogram is a set of linear equations with uncorrelated uncertainties (Nolet, 1990). This set of linear equations describe the average S- and P-wave velocity deviations from a 3D reference within approximate sensitivity volumes between the sources and stations (eq. (5), Lebedev and Van Der Hilst, 2008). The uncorrelated uncertainties associated with these linear equations are directly linked to the seismic waveforms and serve to weight the equations accordingly. In summary, AMI offers three key advantages:

- It enables the processing of voluminous data sets through full automation.
- It maximises information extraction from broad-band seismograms while maintaining the validity of relevant theoretical approximations.
- It balances the extracted information, particularly by weighting waves of varying amplitudes and types, to constrain unbiased Earth models.

2.4 3D Tomographic linear inversion

The linear equations with uncorrelated uncertainties (eq. (5), Lebedev and Van Der Hilst, 2008) generated by AMI offer robust constraints on the path-average Earth structure. The computational efficiency of AMI facilitates the production of millions of waveform fits. These fits are then combined in a large linear tomographic inversion (Paige and Saunders, 1982) to solve for P- and S-wave velocities, moving from the path-averaged models to a full 3D tomography model of the Earth's upper mantle.

The individual waveform fits, created for hundreds of thousands of seismograms, are amalgamated into a unified linear system represented by the equation $\mathbf{A}\mathbf{m} = \mathbf{d}$.

2.4.1 The data vector $\mathbf{d}$

The system's equations are parameterized using 18 and 10 vertical basis functions for S- and P-wave velocities, respectively, leading to a significant number of rows in the system. To limit the number of equations to those essential for the tomographic inversion, only eigenvalues of the adjusted parameters exceeding a specified threshold are retained (on average, 3.5 equations per path). The incorporation of S- and multiple-S waves results in a slower decay of the eigenvalues with depth, indicating that waveform fits including these additional phases will contribute a larger set of equations. We then group all source-station paths, encompassing the reduced, weighted equations, into a single data vector d .

2.4.2 The model vector m

The model vector m represents a global, 3D model. Vertically, the model is parameterized using the same set of basis functions as employed in waveform inversion, 18 for S-wave and 10 for P-wave velocities. Horizontally, the model vector is parameterized using a grid that is similarly spherically tessellated into triangular knots, akin to the reference model grid (integration grid), albeit typically with a coarser spacing. As the grids are co-registered, equations can be seamlessly interpolated from the finer integration grid onto the coarser model grid.

The tomographic model inverts for P- and vertically polarized S-wave velocities, as well as for 2ψ S-wave azimuthal anisotropy. The primary focus lies on the structure of the shear wave velocity, although the P-wave velocity component is incorporated due to Rayleigh waves' marginal sensitivity to compressional waves. We calculate azimuthal anisotropy by making phase velocity (and later the shear-velocity) direction dependent (eq. (1), Smith and Dahlen, 1973).

2.4.3 The sensitivity matrix A

The matrix A connects the data vector and the model vector, representing the sensitivity of the data to the model parameters mathematically. It is constructed from scaled kernel functions, which are the product of transformed basis functions and sensitivity areas. As a result, A is predominantly a sparse matrix, with most elements outside the sensitivity regions being zero. To optimize memory usage during the inversion, the storage is limited to non-zero elements of A and associated indexing arrays.

Given the extensive number of waveform fits processed, we combine many source-station paths that are nearly identical. Direct inclusion of each path without modification could lead to a bias in the tomographic inversion, giving relatively higher weight to highly sampled model knots. To address this issue, each seismogram is assigned a path-similarity weight. The weight is a sum of an individual measure of each seismogram path similarity with all the other seismograms (eq. (2.127), Schaeffer, 2014).

After constructing the sensitivity matrix, we compute the path-similarity weights and scale the data with them, defining the new, scaled data vector $\mathbf{d}$ where equations with high path-similarity are down-weighted.

2.4.4 Tomographic Inversion

The resulting system of equations is overparameterized, necessitating the imposition of regularisation conditions to stabilize the inversion process. The regularisation conditions applied encompass slight norm damping, along with lateral and vertical smoothing. These conditions are integrated into the linear system as additional operators within the sensitivity matrix A (eq. (2.129), Schaeffer, 2014). The inversion then proceeds through the minimisation of a weighted sum, which includes the data misfit, the norm of the model, and the gradient of the solution (eq. (19), Zielhuis and Nolet, 1994).

2.5 Automatic outlier removal

Errors in the data, such as inaccuracies in source locations, event origin times, source mechanisms, and station timing, can introduce velocity artefacts into the final tomographic model. Outlier analysis and rejection (*e.g.*, Lebedev & van der Hilst, 2008) are essential for enhancing equation consistency, improving inversion convergence, and increasing the accuracy of the tomography. To quantitatively evaluate the consistency and relative quality of hundreds of thousands of waveform fits, an objective search is performed to identify significantly deviating equations.

This outlier analysis procedure involves conducting an initial tomographic inversion to obtain the model m , followed by generating synthetic coefficients d through the matrix multiplication $d=Am$. The distribution of data-synthetic misfits is then analysed, identifying equations that reside in the distribution's tails, beyond the $2-3\sigma$ level (95-99%), for potential examination and rejection. Empirically, discarding 1–2% of outliers substantially enhances

inversion convergence and model quality. Given the vast size of the dataset, a more selective approach to data retention is feasible, allowing for the elimination of up to 15% of data outliers—a strategy that has been empirically validated and successfully implemented in previous tomographic studies (Celli et al., 2020b; De Laat et al., 2023; Schaeffer and Lebedev, 2013).

For the tomographic model developed in this thesis, and discussed in subsequent chapters, I assessed the impact of varying outlier rejection thresholds, including 5%, 10%, 15%, and 20% of outlier data. This comparison aims to identify the most effective strategy for removing seismic artefacts, such as bulls-eye patterns or smearing, which do not represent real Earth structures but are instead indicative of data errors such as station timing errors and event mislocations. Upon evaluation, a 15% outlier data rejection rate was found to most effectively eliminate errors without compromising the model's data sampling (Figure 2.6). Smaller scale variations observed between the models (Figure 2.6) are due to regularisation values applied to a different dataset, reducing the dataset will result in the same regularisation values affecting the model differently.

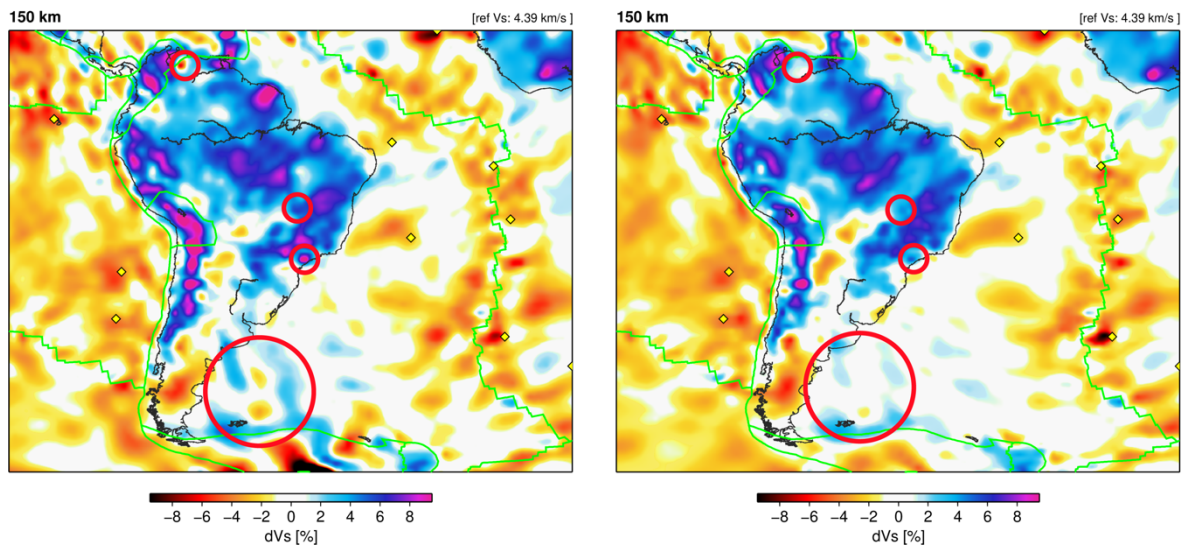


Figure 2.6: On the left, we show a tomographic model built with the full dataset, prior to outlier removal. On the right, we show the resulting model after 15% of data outlier removal. Red circles indicate areas of possible seismic artefacts, before and after outlier removal, consisting of bull's eyes and smearing.

2.6 Optimization of regularisation parameters

Regularisation parameters play a pivotal role in tomographic inversion due to the inherently ill-posed nature of these problems. The application of smoothness is designed to mitigate the influence of noise and data gaps, yet it is critical that it does not oversimplify the model to an unrealistic degree. The model must also maintain sufficient flexibility to accurately fit the data within its error bounds (Loris et al., 2007; Nolet, 1990). This often involves iterative processes and the application of subjective judgment, which should be grounded in both geophysical and geological insights, as well as the specific characteristics of the seismic dataset and the study area.

Regularisation is implemented through lateral and vertical smoothing along with mild norm damping to stabilize the mixed-determined inversion. Smoothing acts as the primary mechanism of control, with slight damping serving a supplementary function. Two forms of smoothing may be applied: one that penalises the deviation between the anomaly at a node and the average anomaly across the node and its 6 (or 5) nearest neighbours, and another (gradient damping) that penalizes variations between adjacent model knots. In both instances, we set the intensity of these coefficients to diminish with depth, countering potential over-smoothing in areas of lower sampling at greater depths, where the sensitivity of the fundamental mode of surface waves is lower. Vertical gradient damping acts against abrupt changes within the model across depth layers (Schaeffer, 2014), while norm damping aims to minimise the anomaly magnitudes relative to the 3D reference model, with damping strength variably applied according to depth. All smoothing and damping parameters are non-dimensional and heavily parametrisation-dependent, and have to be set empirically for each inversion. An example of an input file used for inversion that sets and adjusts the regularisation parameters is demonstrated in Figure 2.7.

Determining the optimal regularisation parameters for the model involves conducting a series of inversions, each time varying a single parameter. Initially, several levels of norm damping are tested to identify the minimal amount required to effectively reduce noise within the model. Following an initial visual assessment, two to three models with distinct norm damping values are selected for further testing with varying levels of smoothness. Despite the qualitative nature of this preliminary parameter selection, a-priori knowledge of the area is employed to validate the model's velocity structures. This includes geological surface data such as bedrock composition and age, areas of sutures or rifting, and comparisons with other tomographic models.

```

40000      ! Number of iterations
43         ! Number of solutions to keep; next line: which solutions to keep
1 100 500 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000 13000 14000 15000 16000 17000 18000 19000 20000 21000 220
00 23000 24000 25000 26000 27000 28000 29000 30000 31000 32000 33000 34000 35000 36000 37000 38000 39000 40000
3.0 3.0 3.0 0.0      ! norm damping factors for each parameters      (a,b,c,d: a*dVs=0, b*dVsA1=0, c*dVsA2=0, d*dVp=0)
20.0 1.0             ! Vp-Vs Difference Damping                    (a,b: a*[b*dVs-dVp]=0)
5.0 0                ! Lateral Smoothing [dVs]
100.0 1 0.5          ! Lateral Smoothing [A1,A2]
0 1 1               ! lateral velocity gradient damping [dVs]      (dgr0, ifcsgdr[does not work], sepsgr)
0.0 0 0             ! lateral anisotropy grad. damp. [A1,A2]      (dgra0, ifcsgdra, sepsgra)
2.0 2.0             ! Vertical gradient damping factors      (dvg, dvga)
1                   ! path weighting for similar paths      yes (1) or no (0)
0.2                 ! path weighting epsilon value
1 1 1 1             ! Norm damp scaling with column sums      yes (1) or no (0) (dVs,dVsA1,dVsA2,Vp)
1 1 1 1             ! Norm damp scaling epsilon      dVs,dVp,A1,A2
1                   ! N of layers to adjust norm damping
8 0.4 1.0           ! 440
0                   ! N of layers to adjust Lateral Smoothing
0                   ! N of layers to adjust Lateral gradient
11                  ! N of layers to adjust Vertical gradient
3 10.0 1.0          ! 661
4 1.0 1.0
7 10.0 1.0          ! 411
8 0.5 1.0           !

```

Figure 2.7: Example of an input file containing the regularisation parameters used in the tomographic inversion.

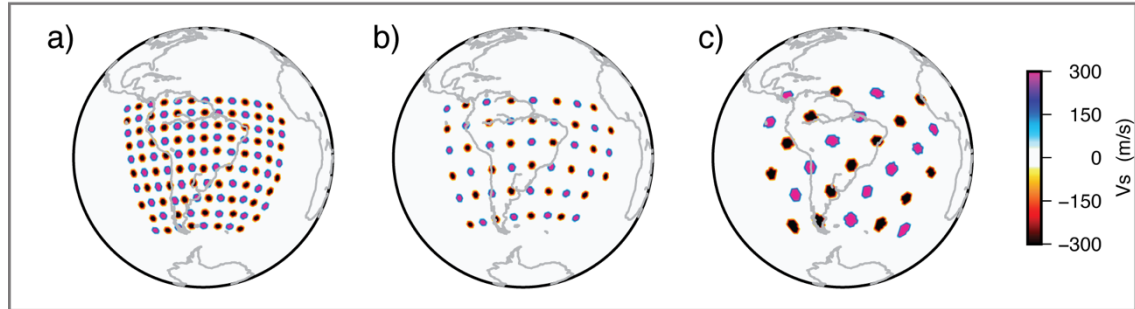
2.6.1 Resolution Tests

Resolution tests offer a robust method to validate the choice of regularisation parameters in seismic tomography. They consist of calculating synthetic data from a synthetic velocity structure and then inverting them for a tomographic model, using the same regularisation parameters as the real data inversion. Tuning of the regularisation parameters, including smoothing and damping factors, influences the inversion's ability to resolve specific features, the balance between model simplicity and data fit, and mitigate the effects of noise and incomplete data coverage. The effectiveness of the selected parameters is evaluated by comparing the inverted “output” model against the known, “input” synthetic model, focusing on the accuracy of anomaly locations, shapes, and amplitudes. This comparison not only highlights the capability of the regularisation scheme to recover true subsurface features but also identifies potential biases or artefacts introduced by over- or under-regularisation.

In order to assess the accuracy of the model presented in this thesis and its capability to resolve structures of different dimensions and separation distance, we perform a series of “checkerboard type” resolution tests consisting of vertical columns with alternating positive and negative velocities. The synthetic vertical columns are input with ± 300 m/s extending from 80 km to 660 km depth (Figure 2.8). In Figure 2.8, model a) consists of columns of two nodes width and approximately three node spacing; model b) consists of columns of two nodes width and approximately six node spacing; and model c) consists of columns of four nodes width and ~ 12 nodes spacing. The distances between nodes are ~ 120 km. With this

first set of input models, we mainly aim at evaluating the horizontal resolving power of the model at different scales.

input models



output

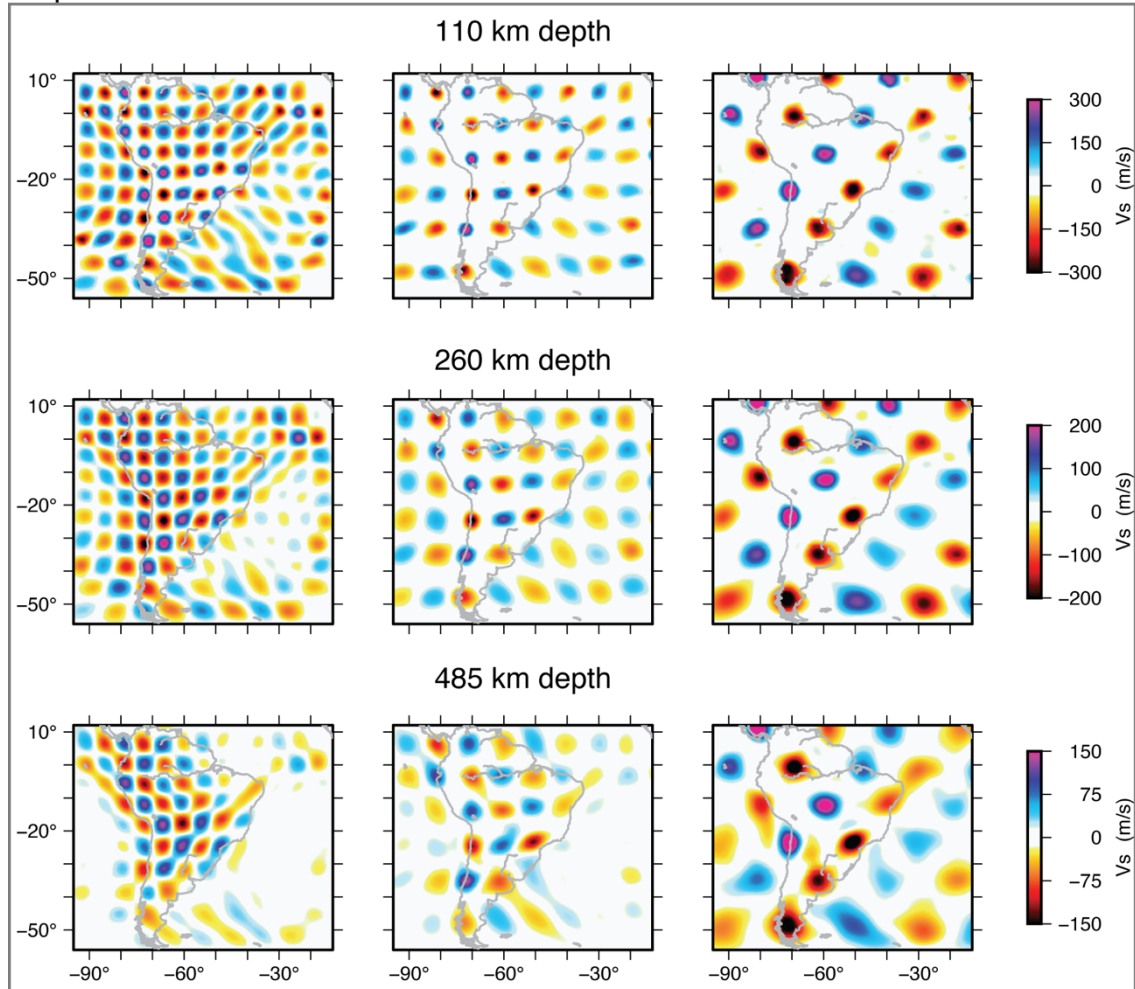


Figure 2.8: Vertical column resolution tests. The input structures are defined with positive and negative columns of 300 m/s, from 80 km to 660 km depth. The three different input models consist of varied dimension and spacing, shown on the top row. The resulting models are shown below at 110 km, 260 km, and 485 km.

In Figure 2.8, model a) includes small scale structures separated by approximately 250 km, a smaller distance than in models b) and c). In the Earth's upper mantle, anomaly

of the sizes of model a) are comparable to geological features such as a mantle plume tail originating from the deep mantle, small fractured cratonic blocks within the lithosphere, or fragmented subduction slabs. The results for model a) indicate accurate recovery of both the amplitude and shape of the input features at all depths, particularly within continental regions. At depths of 110 km and 260 km, structures are well recovered in the Pacific Ocean, whereas the east coast of South America and Atlantic Ocean exhibit notable smearing and reduction in the amplitude of the anomalies. At 485 km depth, increased smearing across structures and amplitude attenuation in most oceanic regions and north-eastern Brazil are observed.

Model b) includes structures with identical size to those of model a), but with an increased spacing of approximately 650 km. This configuration aims to explore the model's efficacy in distinguishing between more distantly spaced structures. The inversion outcomes from model b) demonstrate well-delineated spatial columns and amplitudes, exhibiting reduced smearing compared to the results of model a). At 485 km depth, minor smearing and amplitude reduction are particularly noticeable in oceanic areas, especially in the Atlantic.

Model c) features large scale structures with increased spacing between them. The model's input structures are approximately 500 km wide, with a separation of around 1500 km from each other. In a real Earth scenario, such larger scale structures could represent larger plume conduits, large blocks of cratonic lithosphere, or flat subduction zones. The output from model c) closely matches the input in both amplitude and shape across all model depths. At 485 km depth, smearing is observed in oceanic regions, indicating averaging lengths that surpass the column-footprint width on the map. However, at this scale, the model successfully resolves the input structures in terms of both space and amplitude across all depths, in both continental and oceanic areas.

These tests illustrate qualitatively the ability of the tomography to resolve gaps between anomalies, of different widths and in different locations in the study region. More importantly, we validated the choice of regularisation parameters of the inversion. The model resolves a range of dimensions and separation distances between structures, and anomalies are well resolved in space and amplitude. The model efficiently recovers small scale structures within continental regions at depths extending into the transition zone, while oceanic regions show worse recovery due to the decreased data sampling in there.

These resolution tests thoroughly explore the resolving capabilities of our model, in amplitude and scale, both laterally and vertically.

3 The lithosphere of South America from seismic tomography: Structure, evolution, and control on tectonics and magmatism

Abstract

The thickness, temperature and mechanical strength of the lithosphere vary greatly across South America, controlling tectonic and magmatic processes during the continent's evolution. Here, we compare state-of-the-art tomographic models to geological and geophysical data on lithospheric thickness complementing them with our new tomographic model of the South American upper mantle, SACI-24. The model is obtained by waveform inversion of surface, S and multiple S waveforms globally, but is optimised for South America and the surrounding oceans and is constrained by ~970,000 seismogram fits from 9259 stations.

SACI-24 maps the details of cratonic lithosphere across the continent, highlighting new internal complexities and fragmentation. Within the Amazon Craton, the Guiana and Central Brazil blocks are separated by the low velocities below the Amazon Basin at 80-150 km depth, matching the location of ancient rifting and the flood basalts of the Central Atlantic Magmatic Province. In the São Francisco Craton, high velocities extend north and southwest beyond the previously proposed boundaries. Warmer, thinner lithosphere underlies the Paramirim and Pirapora aulacogens.

A fragmented cratonic root underlies the Paraná Basin, with thinner lithosphere along its central rift. High velocities south of the Paraná Block indicate the cratonic root of the northern Rio de la Plata Craton. The model shows that Cenozoic intraplate basalts in the Borborema province, the southern Atlantic coast and Paraguay occurred in areas of thin lithosphere and near strong lithospheric gradients, suggesting horizontal asthenospheric flow. Most flood basalts of the Phanerozoic large igneous provinces map on low velocity areas, but smaller portions sit atop cratonic lithosphere, providing new evidence for lateral flow of magma in the crust. About 80% of known diamondiferous kimberlites locate on thick lithosphere, whereas the remaining indicate cratonic erosion and thinning since their emplacement.

Keywords: South America; Lithosphere; Cratons; Seismic tomography; Waveform Inversion; Continental Evolution; Intraplate Volcanism.

3.1 Introduction

Earth's lithosphere provides a unique insight into the long-term growth and tectonic evolution of continents and, also, the break-up of supercontinents. Moreover, the interaction of the lithosphere with the underlying asthenosphere exerts primary controls on the distribution and composition of intraplate volcanism. This is because mantle melting is controlled by the thickness of the lithosphere, the temperature of the asthenosphere, and dynamic processes that perturb the two (e.g. Ball et al., 2021; Gibson et al. 2024; McKenzie and Bickle, 1988). Variations in lithospheric thickness of the continents have also been shown to control the distribution of mineral resources, including diamondiferous kimberlites (e.g. Priestley & McKenzie 2006; Celli et al., 2020a; Faure et al., 2011) and sediment hosted metal deposits (Hoggard et al., 2020).

Seismic tomography is an effective tool for the investigation of the structure of the lithosphere and underlying mantle (Celli et al., 2020a; De Laat et al., 2023; Heintz et al., 2005; Rocha et al., 2011). Seismic surface waves offer a rich source of information on the temperature and thickness of the lithosphere, with a much smaller sensitivity to the compositional heterogeneity in the upper mantle (e.g., Fulla et al. 2012, 2021; Lebedev et al., 2024). Seismic body waves sample deeper mantle and, thus, offer complementary sensitivity. Regional and global waveform tomography extracts structural information from both surface and body waves and combines their structural sensitivity (e.g., Celli et al., 2020b; Ciardelli et al., 2022; Debayle et al., 2016; French and Romanowicz, 2014; Priestley and McKenzie, 2006; Schaeffer and Lebedev, 2013).

In seismic-velocity images, the cold, thick lithosphere of a craton is clearly distinguishable by the high-velocity anomalies in the depth range around 100-150 km depths (e.g., Lebedev et al., 2009). Tomography-based tectonic regionalisations have thus shown impressive accuracy in mapping the lateral extent of cratons (Lekić and Romanowicz, 2011; Schaeffer and Lebedev, 2015). According to the tomography-based tectonic regionalization of Schaeffer and Lebedev (2015), the boundaries of cratonic mantle tend to match closely the surface geology-based craton boundaries, except in areas where cratonic roots have eroded or where the cratons are unexposed and could not be mapped (e.g., Celli et al., 2020a). This confirms that the cold, thick lithosphere detected by tomography is the mantle part of the cratons that comprise Archean mantle lithosphere and Archean crust, even if the latter does not outcrop. Griffin et al. (2009) argued that high velocities under many cratons

considered to be Proterozoic, based on the latest tectonic or magmatic episodes at some locations within the units, indicate cratonic lithosphere of Archean age. The cratonic lithosphere is compositionally buoyant due to its high degree of depletion in basaltic constituents (Jordan 1975), and it could only have been produced by high degree melting in the hot Archean upper mantle.

Our study is focused on the architecture of South America's lithosphere. The lateral variations in its thickness and strength have controlled tectonics, including multiple episodes of deformation and rifting (Brito Neves and Fuck, 2014; Cordani et al., 1984; Fuck et al., 2008; McKenzie and Priestley, 2008; Santos, 2003a). Considerable gaps remain in our knowledge of the tectonic evolution, magmatism, and the location of mineral resources due to the uneven coverage of the continent with seismic stations and other geophysical instrumentation the paucity of mantle xenoliths, and because geological mapping is hindered, in many places, by thick sedimentary cover and access difficulties. The coverage of South America with broadband seismic stations in has, however, increased dramatically over the past decade (Bianchi et al., 2018b). Regional (Chaves et al., 2016; Neto et al., 2019; Rocha et al., 2011; Shirzad et al., 2020) and continent-scale (Celli et al., 2020b; Ciardelli et al., 2022; Feng et al., 2007) studies are targeting increasingly detailed mapping of the upper mantle. The now available tomographic models show increasing mutual consistency on the large-scale features but disagree on much of the smaller-scale structure.

In this paper, we present a new seismic tomography model of South America and surrounding oceans, SACI-24, derived with waveform tomography using very large regional and global datasets. We also analyse the new model jointly with the other available seismic tomography models. We appraise the current state of the art and discuss what features can now be considered well established, where our new tomography may achieve improvements in resolution, and the main remaining open questions. We then review in detail the deep structure of the lithosphere across South America and discuss its influence and controls on the continent's tectonic evolution and varied magmatism.

3.2 Tectonic Settings in South America

The South American continent comprises a large stable platform in its central and eastern parts and the active mountain ranges and inter-montane plateaus of the Andes in the west (Figure 3.1). Most of the South American platform is Precambrian and includes Archean cratons surrounded by younger mobile belts, predominantly of Neoproterozoic age

(Brito Neves and Fuck, 2013). From the Paleoproterozoic to Late Mesoproterozoic, multiple blocks assembled to form the Amazon Craton and surroundings and it is proposed that together with Baltica and Laurentia it formed the Paleoproterozoic supercontinent Columbia (Brito Neves and Fuck, 2014; Cordani et al., 2009). After the fragmentation of Columbia, the Amazon Craton remained stable and formed a part of the Rodinia supercontinent and, following another rifting and assembly cycle, became part of Gondwana at 600-550 Ma (Cordani et al., 2009).

East of the Amazon craton, the Brasiliano Domain—which makes up the eastern part of stable South America—includes Neoproterozoic fold belts that formed during the assembly of West Gondwana (Brito Neves and Fuck, 2013). These fold belts surround the São Francisco and Rio de la Plata Cratons, as well as the Parnaíba and Paraná blocks (Brito Neves and Fuck, 2014; Fuck et al., 2008). The latter two may be cratons (Almeida et al., 1981; Cordani et al., 1984) but this is not universally accepted (Chaves et al., 2016; Padilha et al., 2015). These cratons are believed to be results of the fragmentation of Rodinia, but evidence for the subsequent rifting, break up and drift is scarce and controversial (Fuck et al., 2008).

In the Late Paleozoic, the Patagonia Terrane was docked to southern South America but its origins are debated, with two end member theories (Pankhurst et al., 2006; Ramos, 2008). Some authors propose that Patagonia is an allochthonous accreted terrane (Ramos, 1984), while others (Forsythe, 1982) believe that it is an autochthonous block that separated from South America in the Devonian (~401 Ma) and reconnected with it in the late Paleozoic (~295-307 Ma; Ramos, 2008). The oldest known basement rocks are Neoproterozoic (<0.6 Ga), although recent xenolith studies show Meso- to Paleoproterozoic ages of some of the lithospheric mantle (Schilling et al., 2017).

A large portion of the South American stable platform is now covered by Phanerozoic sediments (Heilbron et al., 2017). The major basins include the Amazon, Paraná and Parnaíba Basins, as well as the sub-Andean depocenters (De Brito Neves, 2002; Mabesoone et al., 1981; Ultiana et al., 1995).

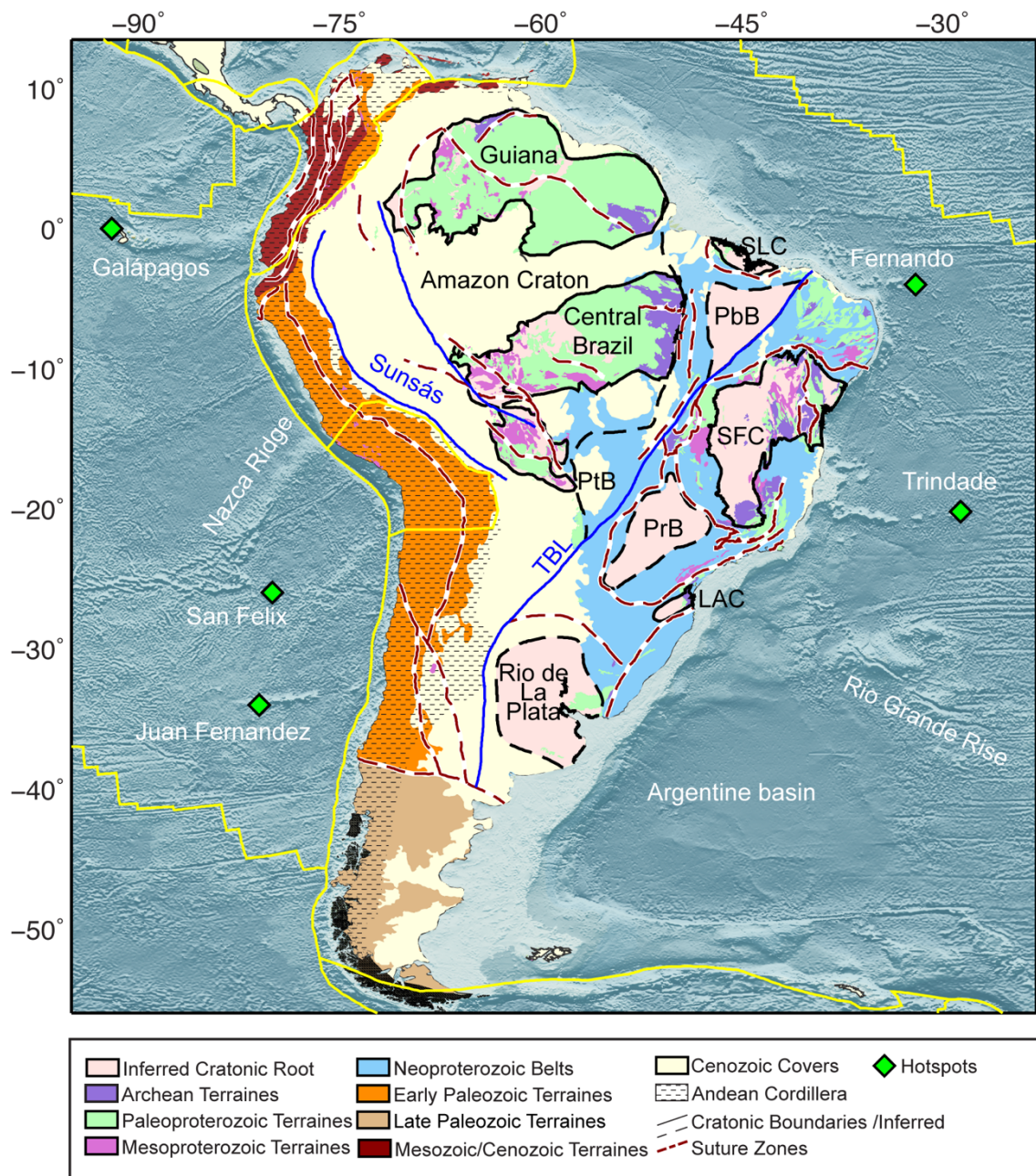


Figure 3.1: Simplified tectonic map of the South American continent and surrounding oceans. Different ages of bedrock geology are plotted with different colours (see legend). SLC: São Luiz Craton; PbB: Parnaíba Block; SFC: São Francisco Craton; PtB: Pantanal Basin; PrB: Paraná Block; RA: Rio Apa Craton; LAC: Luis Alves Craton; TBL: Transbrasiliano Lineament. The main tectonic boundaries and bedrock ages are from the “Tectonic Map of South America” (Cordani et al., 2016). Yellow lines are plate boundaries from Bird (2003).

3.2.1 Amazon Craton

The Amazon Craton (AC) (Tassinari and Macambira, 2004) is one of the largest and best-preserved products of the Rodinia amalgamation in South America (Fuck et al., 2008).

It is divided into the Guiana and Central Brazilian Shields, separated by the Paleozoic Amazon basin (Tassinari and Macambira, 2004). Archean crust outcrops only in the Carajás, Amapá and Imataca areas of the craton (Figure 3.2-a) (Kroonenberg and de Roever, 2010). Phanerozoic sedimentary basins cover most of the AC boundaries, which makes it difficult to define them accurately based on the basement rock ages. There are two main conceptual models for the AC evolution. The first one defines it as a large Archean platform reworked and reactivated during the Proterozoic (Almeida et al., 1981) and later modified by several magmatic pulses over time (Teixeira et al., 2021). The other describes the Amazonia Central and Carajás regions as the nuclei that converged and collided, successively, with multiple magmatic arcs, to form the present Amazon Craton. In the latter, the different magmatic arcs have Paleoproterozoic ages that decrease from northeast to southwest (Cordani et al., 1979; Tassinari, 1981).

Based on geochronology, a number of sub-divisions have been proposed (Delor et al., 2003; Santos, 2003b; Santos et al., 2000; Tassinari and Macambira, 1999; Vasquez and Rosa-Costa, 2008). Here, we adopt the model of Vasquez and Rosa-Costa, (2008), which uses updated boundaries based on new geochronology and geological data. It identifies seven tectonic provinces within the Guiana and Central Brazil Shields: Carajás (3000 – 2500 Ma), Transamazonas (2260 – 1990 Ma), Tapajós – Parima (2030 – 1860 Ma), Amazônia Central (1900 – 1860 Ma), Rondônia – Juruena (1850 – 1540 Ma), Rio Negro (1820 – 1520 Ma) and Sunsás (1450 – 1000 Ma) (Figure 2a). We note that some authors disagree with this definition of the geochronological provinces of the AC (Fraga et al., 2008; Kroonenberg, 2014; Kroonenberg and de Roever, 2010). For example, rubidium-strontium (Rb-Sr) age measurements used to define the different geochronological boundaries in the Guiana Shield are now considered obsolete. Newer and more accurate SHRIMP uranium-lead (U-Pb) measurements show basement ages up to 400 Ma older than originally thought (Kroonenberg and de Roever, 2010).

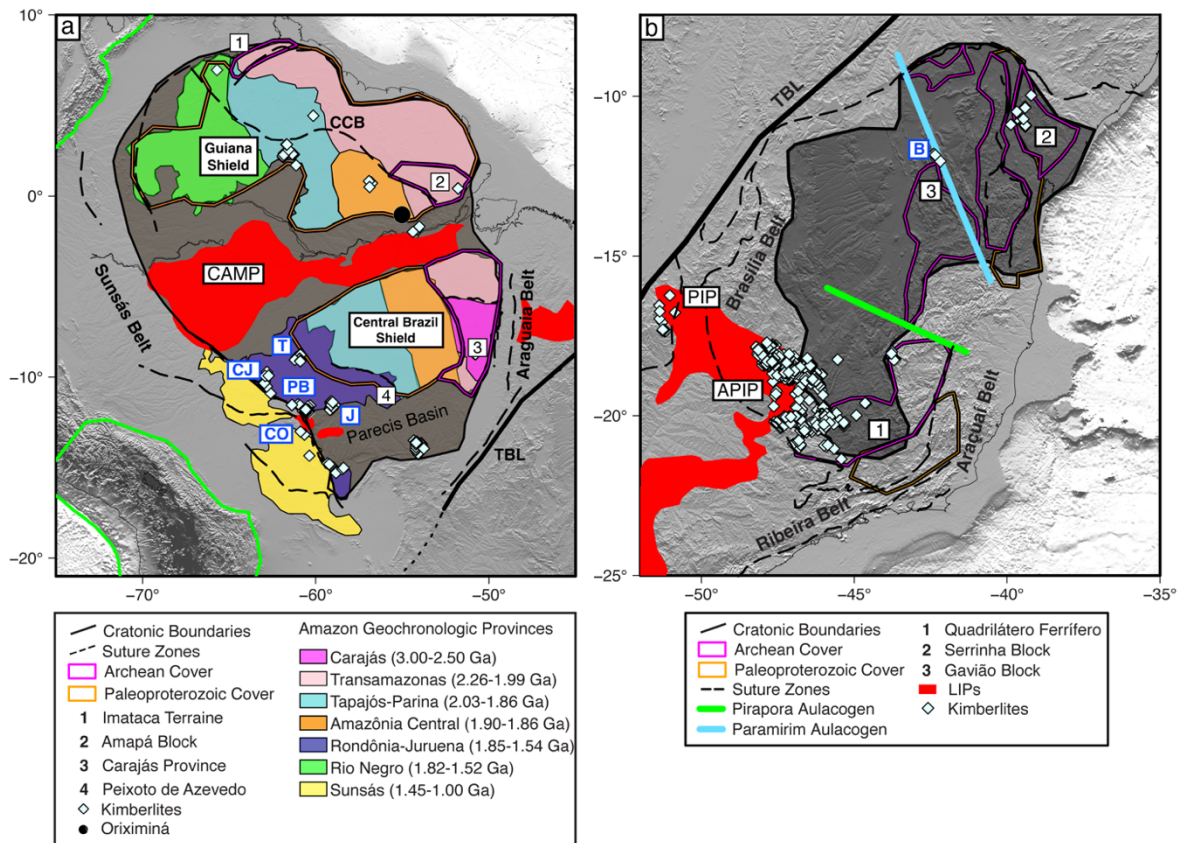


Figure 3.2: a) The Amazon Craton and surrounding units. Geochronological provinces are from Vasquez and Rosa-Costa (2008). CCB: Cauarane-Coeroeni Belt; CAMP: Central Atlantic Magmatic Province. Kimberlite Clusters are T: Traíra (Nannini et al., 2017); CJ: Cujubim (Neto et al., 2014); PB: Pimenta Bueno (Masun and Scott Smith, 2008); J: Juína (Kaminsky et al., 2009); CO: Colorado do Oeste (Zolinger, 2005). b) The São Francisco Craton and the surrounding belts. Kimberlite clusters are: APIP, Alto Paranaíba Igneous Province; PIP, Iporá Igneous Province (Gibson et al., 1995) and B: Brauna (Donatti-Filho et al., 2013). TBL: The Transbrasiliano Lineament. The thick continuous line indicates the mapping of the lineament using surface or geophysical measurements, and the dashed line (a) is the proposed continuation of the lineament further south under the Paraná Basin (Pinto and Vidotti, 2019). Archean and Paleoproterozoic boundaries are simplified from the tectonic map of Cordani et al. (2016).

Multiple large igneous provinces were emplaced in the AC (Klein et al., 2012; Santos et al., 2002; Teixeira et al., 2019). The Central Atlantic Magmatic Province (CAMP) (Deckart et al., 2005) in South America includes extensive lava flows, dikes and sills. Its emplacement occurred around 200 Ma ago, near the Triassic–Jurassic boundary. It has been linked to reactivation of older rift structures during the initial breakup of Pangaea (Davies

et al., 2017; Deckart et al., 2005) and to the arrival of a mantle plume from the deep mantle (A M Leitch et al., 1998; Marzoli et al., 1999b; Wilson, 1997a).

In the Oriximiná region, pyroxenites, jacupirangites and syenites recovered from the basement of the Amazon basin indicate roughly 565 Ma age (Cordani et al., 1984). These samples are collocated with positive gravity anomalies and with the depocenter of the overlying basin (Nunn and Aires, 1988; Van der Meijde et al., 2013). These ultramafic rocks have been proposed to result from the same rifting event that led to the development of the Amazon basin (Bahia and Abreu, 1985).

3.2.2 São Francisco Craton and Surroundings

In the São Francisco Craton (SFC, Alkmim et al., 1993; Almeida, 1977) in southeastern Brazil (Figure 3.2-b) Archean basement outcrops mainly in the north and south, surrounded by Paleoproterozoic orogenic belts (Barbosa and Sabaté, 2002; Teixeira et al., 2017). The northern exposure is formed by a mosaic of Archean blocks with ages of up to ca. 3.6 Ga (Barbosa et al., 2012; Teixeira et al., 2017). The southern exposure is largely overprinted by Paleoproterozoic deformation episodes with ages up to 3.2 Ga (Lana et al., 2013; Teixeira et al., 1998). Between these domains, the Paramirim Aulacogen represents an intracontinental rift system (Cruz and Alkmim, 2017; Pedrosa-Soares and Alkmim, 2011), with the first proposed rifting event at 1775 ± 7 Ma (Danderfer Filho et al., 2015). The Paramirim Aulacogen then hosted at least eight events of rifting and anorogenic magmatism over a 1.3 Ga long period (Cruz and Alkmim, 2017; Pedrosa-Soares and Alkmim, 2011).

Cutting across the central portion of the craton, the Pirapora aulacogen (Alkmim et al., 1993) is a prominent NW-SE structure and is the largest Proterozoic rift structure preserved in the São Francisco Basin (Alkmim and Martins-Neto, 2012; Reis et al., 2017). The opening of the Pirapora aulacogen is described as the first tectonic rift event corresponding to the opening of the São Francisco Basin. The second tectonic event recorded by the basin is the Pirapora rift reactivation in the Mesoproterozoic, associated with the Columbia supercontinent breakup (Alkmim and Martins-Neto, 2012; Reis and Alkmim, 2015).

It has been proposed from surface geology that the SFC boundaries do not correspond to the lateral extent of the cratonic lithosphere at depth (Pereira and Fuck, 2005). Bouguer gravity anomalies (Pereira and Fuck, 2005), seismological observations (Assumpção et al., 2004a; Soares et al., 2006) and petrophysical studies (Fernandes et al., 2021) suggest that the cratonic lithosphere extends beneath the Brasília Belt in the west and

the Araçuaí Belt in the east. The lithosphere beneath the SFC may have been an inner part of an older paleo-plate, with its peripheral parts reworked during the Paleo- to Neoproterozoic eras with the assembly of Gondwana (Almeida et al., 1981; Pereira and Fuck, 2005).

3.2.3 Parnaíba Basin

The Parnaíba Basin (PB) is an intracratonic basin (Figure 3.3-a), underlain by Neoproterozoic basement. Its subsidence spans from the Silurian to the late Cretaceous (Góes and Feijó, 1994; Porto et al., 2022). Despite the lack of known Archean outcrops, it has been proposed that cratonic lithosphere underlies the basin (Almeida et al., 2000; Brito Neves, 2003; Cordani et al., 1984; Fuck et al., 2008). In the north, the basin is bounded by the São Luís Craton, a continental fragment linked to the West African Craton (Almeida et al., 1981; Brito Neves and Fuck, 2014).

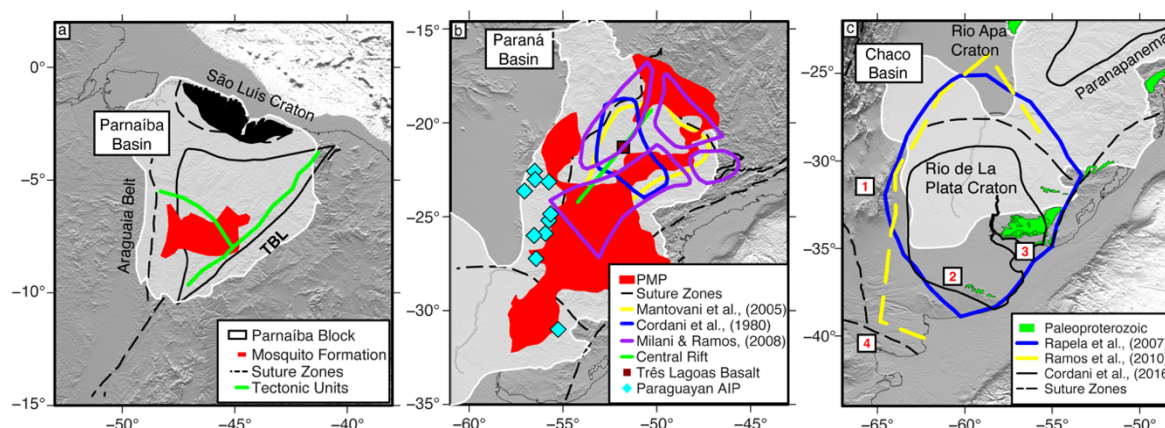


Figure 3.3: The Parnaíba and Paraná-Chaco Basins and surrounding belts. a) The Parnaíba Basin. TBL: Transbrasiliano Lineament. b) The Paraná Basin. Different boundaries previously proposed for the cratonic nucleus under the basin are shown with lines of different colour. PMP: Paraná Magmatic Province; Paraguayan AIP: Unconfirmed diamonds of the Paraguayan Alkaline Igneous Province (Gibson et al., 2006; Peate et al., 1992; Presser Baez, 2016). c) The Rio de La Plata Craton and surrounding regions. 1: Pampean Orogenic Belt; 2: Tandilla Belt; 3: Cuchulla de Dionisio Terrane; 4: Sierra de la Ventana Fold Belt (Rapela et al., 2007).

According to aeromagnetic, aerogravity, seismic reflection and borehole data (Lopes De Castro et al., 2016), the basin can be divided into three tectonic domains. The eastern

part contains NE-oriented rift systems. In the central area of the basin, the rift trend direction is WNW-ESE. The northern part is characterized by sparse or absent graben-like structures (Lopes De Castro et al., 2016). The sedimentary fill of the Parnaíba basin is punctuated by two episodes of basaltic magmatism. The Mosquito Basalts are from the Jurassic Period and are believed to be related to the CAMP (Merle et al., 2011) whereas the Sardinha basalts are thought to be related to the Cretaceous Paraná LIP (e.g., Klöcking et al., 2018).

According to aeromagnetic, aerogravity, seismic reflection and borehole data (Lopes De Castro et al., 2016), the basin can be divided into three tectonic domains. The eastern part contains NE-oriented rift systems. In the central area of the basin, the rift trend direction is WNW-ESE. The northern part is characterized by sparse or absent graben-like structures (Lopes De Castro et al., 2016). The sedimentary fill of the Parnaíba basin is punctuated by two episodes of basaltic magmatism. The Mosquito Basalts are from the Jurassic Period and are believed to be related to the CAMP (Merle et al., 2011) whereas the Sardinha basalts are thought to be related to the Cretaceous Paraná LIP (e.g., Klöcking et al., 2018).

3.2.4 Paraná Basin

The Paraná Basin in south-eastern Brazil (Figure 3.3-b) is another typical intracratonic basin in South America (Milani and Ramos, 1998; Zalán et al., 1990). Cordani et al. (1984) were the first to propose a cratonic lithosphere under the basin, based on basement samples with ages > 2 Ga. The model of a single cratonic nucleus underlying the basin—commonly referred to as Paranaípanema Block (Mantovani et al., 2005)—is, currently, the most commonly accepted (Cordani et al., 2016, 1984; Mantovani et al., 2005; Zalán et al., 1990). However, a fragmented basement under the basin has also been proposed (Milani and Ramos, 1998). This would have facilitated the development of the central rift as the cause for the initial mechanical subsidence at ~ 470 – 440 Ma (Julià et al., 2008; Milani, 2004; Milani and Ramos, 1998). This lithospheric thinning of the Paraná Basin is associated with basaltic magmatism at Três Lagoas in the Neo-Ordovician (443 ± 10 Ma; Milani, 2004). Receiver function measurements indicated high velocity lower crust at a few sites on the basin (Julià et al., 2008), consistent with some localized mafic underplating under the proposed rift location.

The Paraná Magmatic Province (PMP) formed in the Cretaceous times, at ~ 137 – 127 Ma (Piccirillo and Melfi, 1988 ; Renne et al., 1996; Thiede and Vasconcelos, 2010; Turner et al., 1994) and is believed to be the result of the impact of the Tristan Plume prior to the opening of the South Atlantic Ocean (e.g., O'Connor and Duncan, 1990). Based on

the flood-basalt TiO_2 content, the composition of the southern Paraná basalts has been reported to differ substantially from the northern ones (Bellieni et al., 1984). This difference was suggested to be due to chemical heterogeneity of the lithosphere under the Paraná Basin (Bellieni et al., 1984; Gibson et al., 2006, p. 199; Marques et al., 1999; Peate et al., 1992). Recently, it was also proposed that cratonic lithosphere may have been a contributing melt source region of Paraná basalts in the north-central region of the basin (Rocha-Júnior et al., 2020).

3.2.5 Rio de La Plata Craton

The Rio de la Plata Craton (RPC) comprises the southernmost outcrops of the Precambrian basement of South America (Figure 3.3-c). Its basement is largely concealed by the sediments of the Paraná-Chaco Basin, making it the least exposed craton of the continent (Cordani et al., 2010; Cordani and Sato, 2000; Hartmann et al., 2001). The oldest exposed rocks are of Paleoproterozoic age, and the dating of zircon inclusions in them indicated Archean ages (Hartmann et al., 2001). Due to the lack of data of its basement, the current boundaries of the RPC are a matter of debate, especially in the west. The unexposed northern boundary is hypothesized to lie under the Paraná Basin (Ramos, 1988). In the northwest, the limit proposed by Ramos et al. (2010) is located southwest of the Rio Apa Craton and the Paraná Block. In the west, the RPC may extend as far as the Pampean Orogenic Belt, based on the Paleoproterozoic U-Pb SHRIMP ages of the basement samples from boreholes (Rapela et al., 2007). The eastern boundary of the unit in Uruguay is placed next to the Cuchilla de Dionisio Terrane, and the one in Argentina—at the Atlantic coast (Pankhurst et al., 2003; Rapela et al., 2007). The southern boundary is placed at the limit of the Patagonia Terrane, at the Sierra de la Ventana Fold Belt (Cordani et al., 2010; Rapela et al., 2007).

3.2.6 Rio Apa Craton

East of the Paraná Basin, outcrops of the Rio Apa Craton (Figure 3.3-c; Cordani et al., 2010; Teixeira et al., 2020), also referred to as Rio Apa Terrane (Faleiros et al., 2016) are poor and mostly covered by the sediments of the Pantanal Basin. The Paleo- to Mesoproterozoic basement of the Rio Apa Craton is considered to be a fragment of the Amazonian Craton, and is an example of a long-lived accretionary orogen developed along

the SW Amazonian margin, which has undergone a long and complex metamorphic evolution (Faleiros et al., 2016). The Rio Apa Craton is predominantly composed of (meta)igneous and subordinate metasedimentary rock units ranging from 2100 to 1720 Ma, overprinted by regional thrusting at c. 1300 Ma (Cordani et al., 2010; Ribeiro et al., 2022; Teixeira et al., 2020).

3.3 Data and Method

3.3.1 Data

In the construction of the tomographic model, we use a very large global dataset (> 1.7 million) of vertical component seismograms, each successfully fit using the automated multimode inversion (AMI) of surface, S- and multiple S-waveforms (Lebedev et al., 2005). The dataset includes waveform fits collected in previous studies (Lebedev and van der Hilst 2008; Schaeffer and Lebedev 2013, 2014; Celli et al. 2020; de Laat et al. 2023) and new ones computed in this study. In South America, in particular, the dataset includes all available seismograms from the long running permanent stations and from the dense recent deployments in the Andean Cordilla from 1994 to the beginning of 2019, for a total of 1120 stations. We also include the data from the 41 stations of the temporary FAPESP "3-Basins Thematic Project" (Assumpção and Bianchi, 2016) operating in southeast South America since 2016 (e.g., Chagas de Melo et al., 2018), which contribute seismograms from 1298 events (Figure 3.4). The regional coverage given by the stations in South America is complemented by global stations, with data from a total of 9259 stations included in the dataset and contributing to the data sampling of South America, its margins, and the surrounding oceans (Figure 3.4). For computational efficiency, we discard the source-station paths that have no part in the hemisphere centred at the continent. Our dataset then reduces to waveform fits of over 1.2 million vertical component seismograms.

The total period range of the data is 10-450 s, with most of the data in the 30-350 s range. These fits include regional measurements (up to 5000 km) that tend to carry more high-frequency information, in particular information on the crustal structure from the fundamental mode, as well as information on the entire upper mantle from the fundamental and higher modes (Lebedev and van der Hilst 2008; Schaeffer and Lebedev 2013). These are complemented by fits for longer event-station distances, up to 18000 km, generally with

longer periods at which the fundamental mode samples the entire upper mantle and with multiple-bounce S waves (SS, SSS, SSSS, etc.) The combined regional and global dataset ensures the densest possible data sampling of the South American continent, its margins, and surroundings. The inclusion of S and multiple S waves adds essential structural information on the mantle transition zone depths (Lebedev et al., 2005). The model is calculated as a global one and does not have any boundaries. The model parametrization and regularisation values are optimized for the South American region, and the data coverage is maximized only in the hemisphere centred at South America. Therefore, we only show this portion of the model.

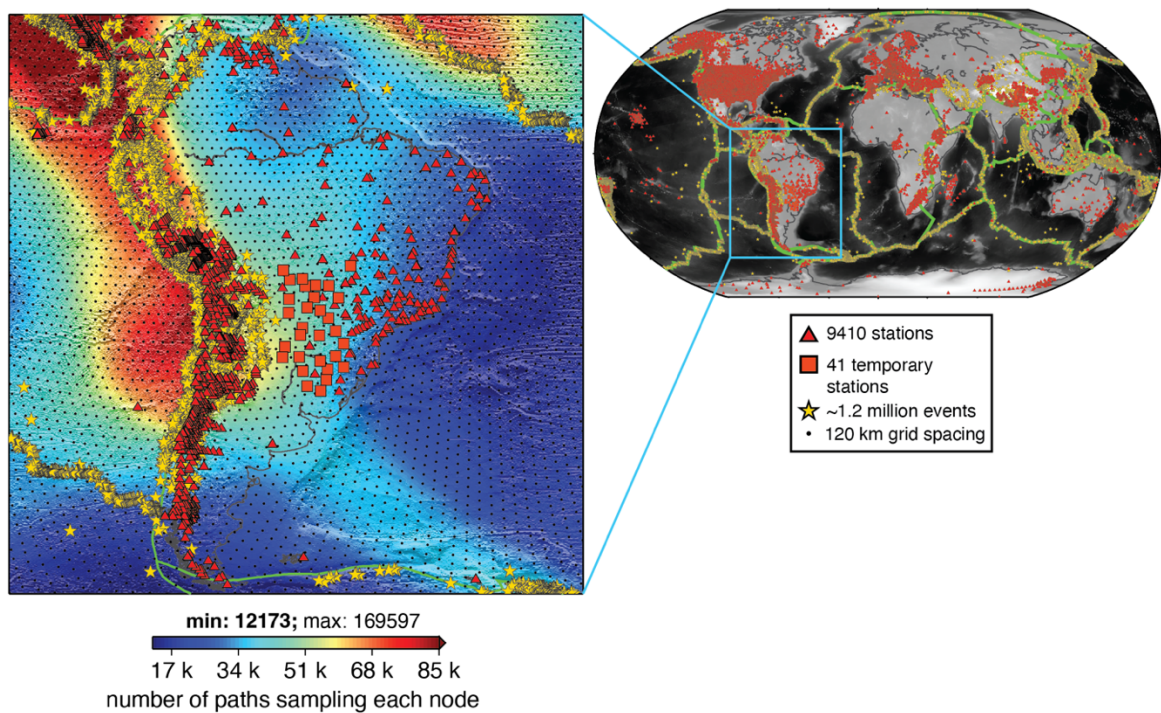


Figure 3.4: Seismic Data Coverage. Global seismic stations are plotted as red triangles, temporary deployment of the "3-Basin Project" are squares. Yellow stars show the events used in the waveform tomography, after data selection. Black circles indicate the location of the nodes of the model grid. The colour shows the hit-count map of data sampling in the region. A grid node is considered hit if it is within the sensitivity area between the source and the station calculated for a waveform fit and used in the tomographic inversion (Lebedev and van der Hilst 2008).

After an initial tomographic inversion for the 3-D model, we select a subset of the most mutually consistent seismograms using automated outlier analysis (Lebedev and Van Der Hilst, 2008). Afterwards, manual identification and removal of stations and events that

appear to be affected by errors is performed, resulting in a final dataset comprising ~970 thousand seismogram fits.

Application of regularization constraints in the model is necessary due to the inherently ill-posed nature of the problem. A smoothness constraint base of value 5.0 is applied on the inversion to penalize the difference between the anomaly at a knot and the average over anomalies at this and the six (in a few cases, five) closest-neighbour knots. The coefficient that determines the strength of the smoothing (Lebedev and van der Hilst, 2008) is 5.0. Norm damping aims to minimize the anomaly magnitudes relative to the 3D reference model, and we apply a damping strength starting at 3.0. All smoothing and damping parameters are chosen for the particular parametrisation and have been tuned for the inversion in this study.

Figure 3.4 illustrates the data coverage. The colour scale shows the total number of source-station-pair sensitivity areas sampling each model grid node. An alternative, more quantitative mapping of the total waveform data sensitivity, which also accounts for the path similarity weighting we apply and the depth-variable sensitivity of each waveform fit, is given by the column sums of the sensitivity matrix of the tomographic problem (Lebedev and Van Der Hilst, 2008), shown in the Supplementary Figure 3.2.

The broadband data were obtained from numerous online data centres, including RSBR (Bianchi et al., 2018a; <http://rsbr.gov.br>), RNAC (<https://www.sgc.gov.co>), Ecuador Seismic Network (<https://www.igepn.edu.ec>), RSSN (<http://www.funvisis.gob.ve>), RSN (<https://www.sismologia.cl>), IRIS (<http://www.iris.edu>) and GEOFON (<https://geofon.gfz-potsdam.de>). The temporary stations were deployed and afterwards made available by projects including PULSE/UNC (https://doi.org/10.7914/SN/ZD_2010), CAUGHT (https://doi.org/10.7914/SN/ZG_2010), SIEMBRA (https://doi.org/10.7914/SN/ZL_2007), LaMa (https://doi.org/10.7914/SN/ZR_2015), MEJIPE (https://doi.org/10.7914/SN/8G_2013) and CARMA (https://doi.org/10.7914/SN/YU_2016).

The waveforms are downloaded through the FDSN (International Federation of Digital Seismograph Networks) Web Service (<https://www.fdsn.org/>) using ObsPy (Beyreuther et al., 2010). The acquisition of waveforms is followed by pre-processing, including checks for fragmentation and clipping (seismograms with which are removed), detrending and response correction to displacement. One step of the quality control is checking the station response information provided by the data centres. We do so by comparing the response files provided by different data repositories and making sure to use

the one that is most up to date (de Laat et al., 2023). Finally, the vertical component seismograms are downsampled to 1 sample per second.

We use earthquake source parameters from the Global Centroid Moment Tensor catalogue (GCMT) (Ekström et al., 2012) with a distance-dependent magnitude threshold (Schaeffer and Lebedev, 2013). This results in a highly sampled model (Figure 3.4), where each node in our map area is sampled by 50000 fits on average, with the most well-sampled by 169597 and the least sampled by 12173 fits.

3.3.2 Waveform Tomography

The inversion procedure used to compute the tomographic model comprises three steps. First, we apply the Automated Multimode Inversion (AMI) (Lebedev et al., 2005) to the pre-processed vertical component displacement seismograms. AMI performs an accurate and efficient automated waveform fitting of large datasets. This is achieved by an elaborate selection of time-frequency windows and phase weighting, using strict data-synthetic misfit criteria. For each waveform, the synthetic seismograms used in the fitting procedure are computed through mode summation, with the fundamental and first 20 Rayleigh modes included. The result of the waveform inversion of each seismogram is a set of linear equations with uncorrelated uncertainties (Nolet, 1990). The set of linear equations describes the average S- and P-wave velocity deviations from a 3D reference model within approximate sensitivity volumes between the sources and stations (Lebedev and Van Der Hilst, 2008).

In the second step, the equations generated by AMI for all seismograms are inverted together for the 3D distribution of P- and S-wave velocity deviations from the reference model and S-wave azimuthal anisotropy. The 3D reference model comprises different 1D velocity profiles at different points on the surface computed using CRUST2.0 (Bassin et al., 2000) in the crust, smoothed at cell boundaries, with added topography, and with a 1D velocity correction to bring the average S-wave velocities to the global average values at different depths (Lebedev and van der Hilst 2008). Beneath the Moho, the reference model is a 1D global average seismic-velocity model of the upper mantle and uppermost lower mantle (Lebedev and Van Der Hilst, 2008), with AK135 (Kennett et al., 1995) below that. The tomographic model is parametrized laterally using a dense triangular grid (Wang and Dahlen, 1995) with an average 120 km internode spacing, and vertically--using 18 and 10 depth nodes for S- and P-wave velocities, respectively (S-wave velocities: 7, 20, 36, 56, 80, 110, 150, 200, 260, 330, 410-, 410+, 485, 585, 660-, 660+, 809 and 1007 km; P-wave

velocities: 7, 20, 36, 60, 90, 150, 240, 350, 485 and 585 km). Values between the nodes of the model grid are computed using linear interpolation.

The linear inversion is subject to smoothing and slight norm damping. Extensive testing of different regularisation coefficients was performed to find the values that effectively suppress data errors but, at the same time, allow us to achieve a model with the most detailed seismic structure the data sampling and data errors can afford.

In the last step of the inversion procedure, the automatic outlier analysis is performed (Lebedev and Van Der Hilst, 2008), selecting the most mutually consistent equations and exploiting the data redundancy given by the large amount of waveforms in our dataset. In this a posteriori re-selection of the data, we first compute an initial tomographic model, then compute synthetic data from this model, compare them to the original data, and discard the data with the largest misfits. For further details on the methods, we refer the reader to Lebedev et al. (2005), Lebedev and Van Der Hilst (2008) and Schaeffer and Lebedev (2013).

3.4 The Model

Our azimuthally anisotropic, Sv velocity model SACI-24 (South American Continent Imaging, 2024) has been computed in a global inversion but with a focus on South America. Specifically, we maximized the data sampling in the hemisphere centred at the continent, tuned the regularisation of the tomography for it, and removed the outliers affecting the model in and around the continent using elaborate automatic and then, manual procedures. All these measures were aimed at maximising the resolution beneath the South American continent and its surroundings (Figure 3.5).

On the stable platform, high-velocity anomalies of $>5\%$ dVs are prominent at lithospheric depths between 80 and 200 km. These high velocities indicate cold, thick cratonic mantle. The model also resolves substantial internal heterogeneity within the different cratons. Lower velocities, with anomaly $\leq -2\%$ at lithospheric depths, indicate thin, warm lithosphere. In the west of the continent, high velocity anomalies ($>5\%$ dVs in the shallow and $>3\%$ dVs in the deep upper mantle) correspond to the subducting Nazca slab. Following the eastward subduction direction, these anomalies migrate east with increasing depth and are observed down to the bottom of the mantle transition zone (the bottom of our model).

Figure 3.5 shows that there are pronounced low velocity anomalies ($< -2\%$ dVs) east of the subducting slab at 150-260 km. Beneath the stable platform of central and eastern

South America, low velocities are dominant from 260 km to the bottom of the mantle transition zone. In the transition zone beneath eastern South America, a particularly strong low-velocity anomaly is observed under the southern tip of the São Francisco Craton.

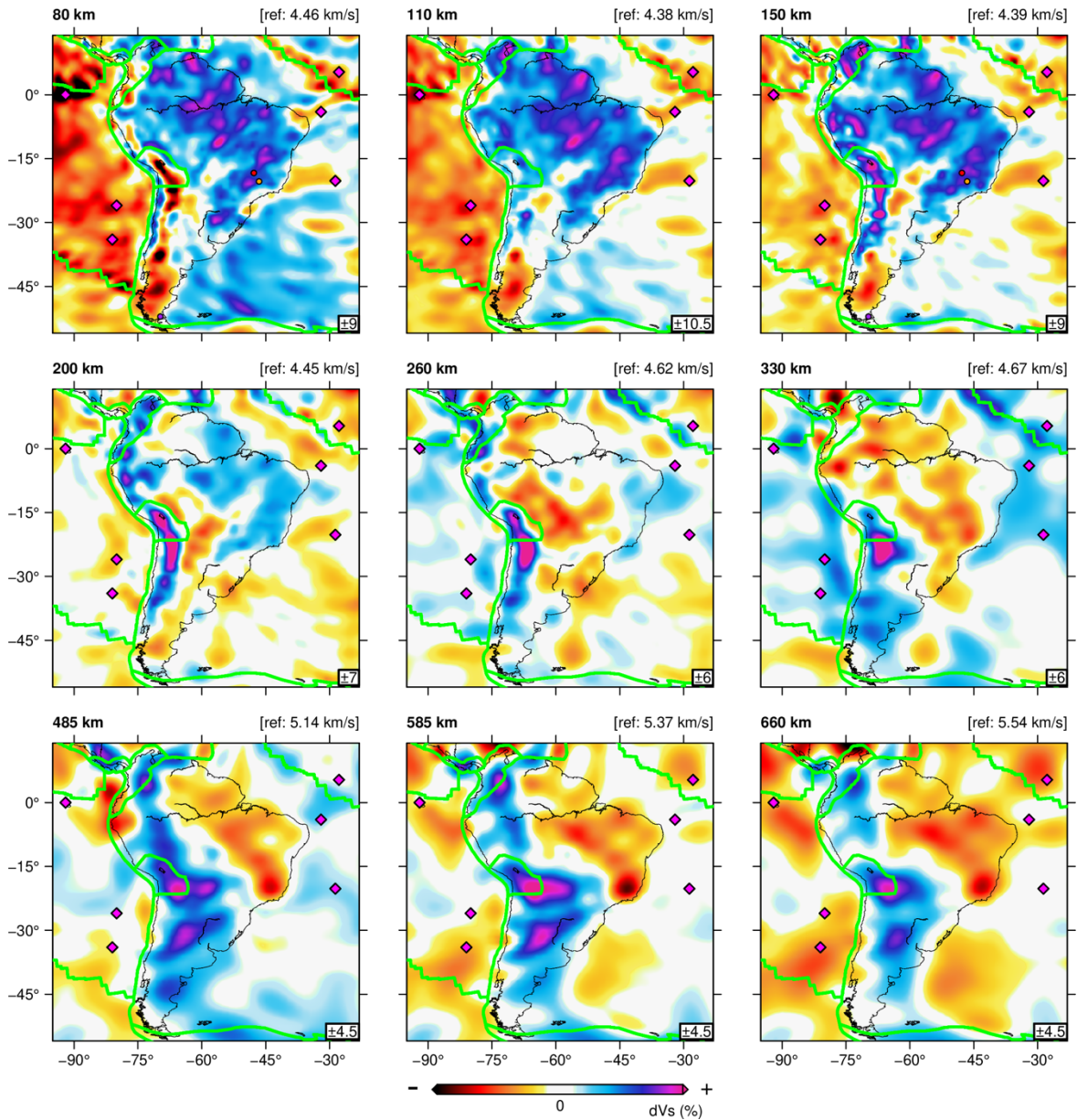


Figure 3.5: Map views of the model at nine different depths. Perturbations in S-wave velocity are plotted in percent with respect to the reference value indicated above each frame. The scale limits are given at the bottom right of each frame. Pink diamonds represent hotspot locations (Whittaker et al., 2015). At 80 and 150 km depth, circles are mantle peridotite xenolith samples (see Section 3.5). Orange is the Canastra-1 sample (Fernandes et al., 2021), red is Três Ranchos (Leonardos et al., 1995) and purple is Pali Aike (Gibson et al., 2020).

3.4.1 Resolution Tests

A useful way to test the resolving power of the data sampling that constrained a tomographic model is via resolution tests using synthetic models. The general procedure comprises calculating synthetic data from a synthetic velocity structure and then, inverting the synthetic data for a tomographic model, using the same regularisation parameters as the real data inversion. The ability of the inversion to recover the input model can be used as an indication of the real model accuracy (Rawlinson et al., 2010) and will depend on the data coverage and regularisation parameters. Apart from traditional resolution tests that assume that the wave propagation theory behind the inversion scheme is correct, AMI has also been tested previously using inversion of two benchmark datasets calculated using numerical wave propagation and showed high accuracy in the recovery of unknown synthetic anomalies (Lebedev and van der Hilst, 2008; Qin et al., 2008). Here, we performed three different types of resolution tests: spike tests (Figure 3.6, Supplementary Figure 3.5), column tests (Supplementary Figure 3.6), and two synthetic cratonic structure tests (Figure 3.8).

3.4.1.1 Spike tests

Spike tests yield an estimate of point-spread functions and the lateral and radial resolution (averaging lengths) at the location of the spikes (e.g., Bonadio et al. 2021; Celli et al. 2020b). In the first test we show here, several S-velocity anomaly spikes of 250 m/s at 150 km depth were placed in different locations, spaced widely enough so that the spikes did not interfere with one another (Figure 3.6; Supplementary Figure 3.5). The lateral and radial averaging lengths in the lithosphere at the different locations depend on the data coverage. In Figure 3.6, we show two examples: 1) a spike in Southeast Brazil, a well-sampled area (Figure 3.4, Supplementary Figure 3.2) and the location of structures of interest such as the São Francisco Craton, the Paraná, and Pantanal Basins; 2) a spike in a region with fewer stations and the location of the southern Amazon Craton. In both resolution tests, the output synthetic model recovers well the location of the input spike. The lateral spreading of the velocity anomaly is greater in spike 2, indicating lower lateral resolution there. More spike tests in different locations are shown in Supplementary Figure 3.5. For the narrow spikes, we see the expected loss of amplitudes at the spike location due to the lateral and radial spreading of the anomaly. For features of finite size, resolution tests with specific sizes and shapes of anomalies can be performed to check the accuracy of the amplitude recovery.

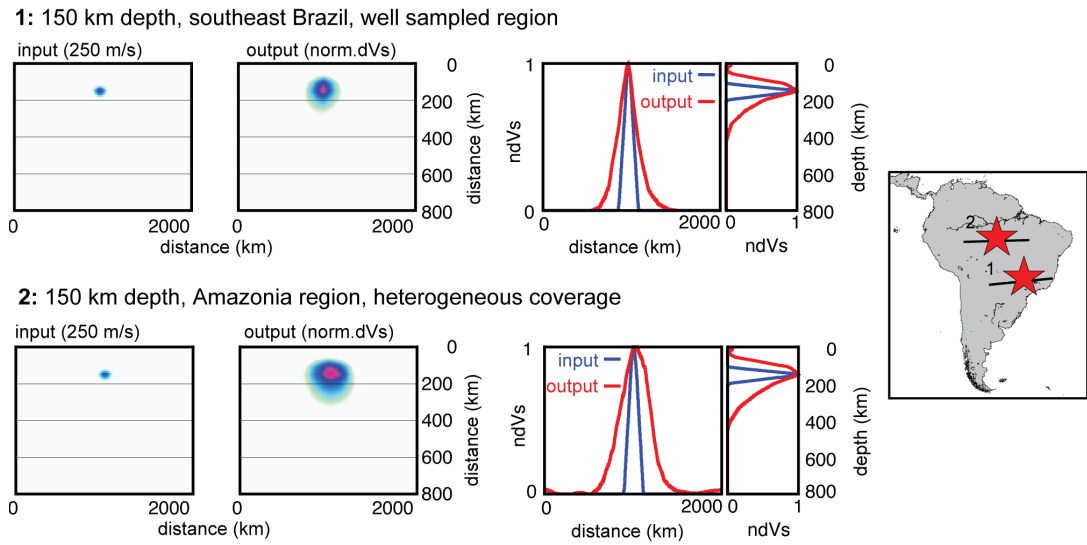


Figure 3.6: Spike resolution tests. The spike input anomalies are at a 150 km depth and have a 250 m/s velocity perturbation. For each spike we plot (from left to right): a vertical cross-section through the input and output models; horizontal and vertical, 1-D, S-wave speed anomaly profiles along the cross-section. The amplitudes are normalized in each plot independently. The location of the spikes are indicated with red stars on the map on the right.

3.4.1.2 Synthetic Craton Structure

These tests examine the ability of the tomography to recover finite size structures, in particular the cratons of South America. First, we constructed an input synthetic structure derived from the most frequently used geological cratonic outlines in South America (same as in shown Figure 3.1, Cordani et al., 2016 and references therein). These outlines depict broad, continuous cratons. Within these synthetic cratons, a 300 m/s S-wave velocity anomaly was assigned in the 80-200 km depth range (Figure 3.7). The output of the test demonstrates that if the cratonic lithosphere at depth followed these outlines, then the tomography would be able to recover the shapes accurately. The test confirms that the fragmentation of the cratonic lithosphere mapped by the model is not an artefact of the imaging.

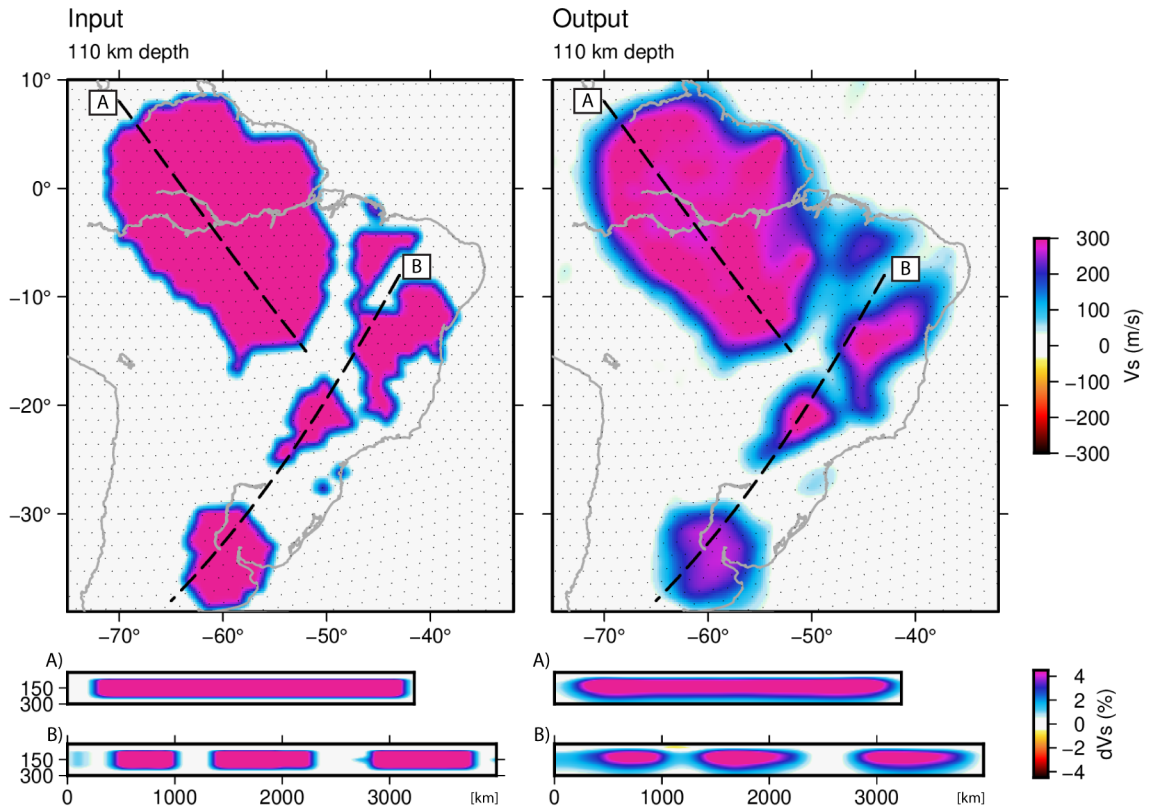


Figure 3.7: A “cratonic lithosphere” resolution test. The shapes follow the geologic cratonic boundaries. The input S-velocity anomaly is 300 m/s everywhere within the blocks, from 80 to 200 km depth. Cross sections are indicated by the dashed lines.

Secondly, we construct the input synthetic structure using seismic velocities from our model. We trace the 6% dVs contours at 110 km depth and assign a 300 m/s S-wave velocity anomaly in the 80-200 km depth range within the areas enclosed by the contours (Figure 3.8). The goal is to test the model’s recovery of the shapes and amplitudes of the craton anomalies and, also, how well the tomography can distinguish closely spaced structures.

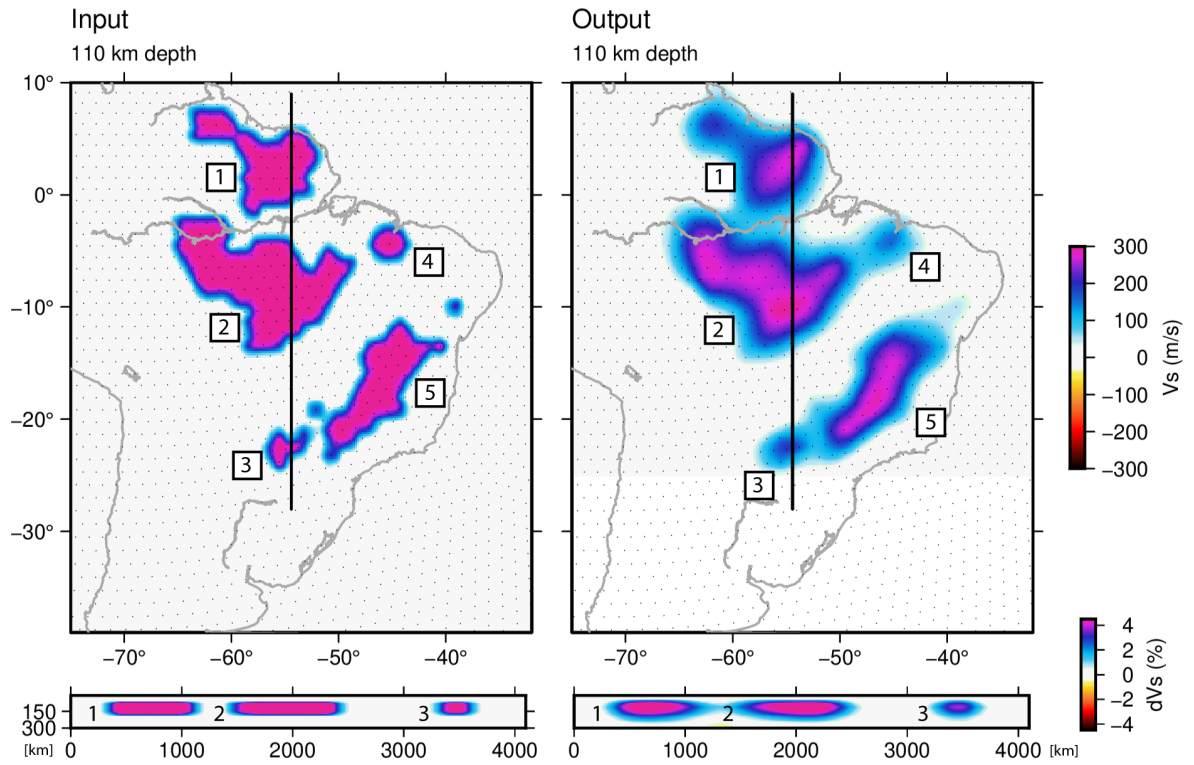


Figure 3.8: In this resolution test, the shapes are taken from the actual tomographic model but with sharp block boundaries, defined by the 6% dVs contour at a 110 km depth. The input S-velocity anomaly is 300 m/s everywhere within the blocks, from 80 to 200 km depth. Cross sections are indicated by the black lines.

In the recovered models shown in Figure 3.7 and Figure 3.8, we see the effect of the lateral and radial averaging in the model: small-amplitude anomalies appear outside of the input structures, and lateral averaging broadens the anomalies' boundaries. Apart from this, we accurately retrieve the lateral and radial shape of the input structures.

In Figure 3.8, the closely spaced, thick-lithosphere blocks with a ~ 240 km gap between them (Figure 3.8, blocks 1 and 2), a weak (~ 25 m/s) artificial anomaly appears between them, due to lateral averaging. Small anomalies (Figure 3.8, block 3 and 4) are resolved with a loss in amplitude, although their location is mapped correctly. For the larger blocks (Figure 3.8, blocks 1, 2 and 5), both the amplitude and the lateral extent are recovered accurately.

Resolution tests targeting 'cratonic' structures validate the model's capacity to delineate the boundaries of cratonic lithosphere, regardless of whether it is defined by the geologic mapping in the surface or if its extension in depth is more complex and fragmented than previously thought. The various resolution tests confirm that our data sampling is sufficient to resolve the varied lithospheric structures discussed in the following sections.

3.5 Validation of SACI-24 from mantle peridotites

The thickness of the lithosphere can be independently constrained from mantle peridotite xenoliths; this is because the compositions of phases in fully-equilibrated xenoliths permit estimates of the pressures and temperatures (*PTs*) that existed in the mantle, prior to their entrainment. From these *PT* estimates it is possible to calculate conductive geotherms and the thickness of the lithosphere (Figure 3.9). The *PT* calculations are iterative and based on parameterisations of experimental studies; the most accurate results are from garnet-bearing peridotites (see Nimis and Grütter, 2010).

In cratonic settings, mantle xenoliths are typically bourn by kimberlites and lamproites whereas in off-craton regions they are hosted by nephelinites, basanites and alkali basalts. Considering the widespread occurrence of these various types of magma in South America (e.g. Figure 3.17, Figure 3.18 and Figure 3.19) there have been remarkably few discoveries of mantle peridotites compared to other major continents. Examples from South America include: Três Ranchos (Leonardos et al., 1995) and Canastra 1 (Fernandes et al., 2021) in the Alto Paranaíba Igneous Province, on the southern margin of the São Francisco craton (Figure 3.2-b); and the Pali Aike Volcanic Field in southern Patagonia (Gibson et al., 2020), which is in an off-craton setting (locations indicated in Figure 3.5-a,c). Despite the rarity of garnet lherzolites in South America, the contrasting tectonic settings in which they have been found provide important independent constraints on our new tomographic model for the continent.

Only a few mantle peridotites have been recovered from the 87 Ma Três Ranchos kimberlite (Guarino et al., 2024; Leonardos et al., 1995, 1993) but these occupy a wide range in *PT* space, which reduce the uncertainties in the geotherm estimate. Based on published analyses of mantle peridotites by Leonardos et al. (1993) and Guarino et al. (2024) we estimate a surface heat flow of 47.2 mW/m² and that the base of the lithosphere beneath the south-west margin of the São Francisco craton resided at a depth of 181 km at the time of xenolith entrainment. This is entirely consistent with the present-day Vs tomography from SACI-24, which shows high velocities beneath this part of the São Francisco craton (Section 3.6.2.3).

Numerous studies have analysed garnet peridotites from the recent (< 4 Ma) Pali-Aike Volcanic Field in southern Patagonia (see Gibson et al., 2020). Pressure and temperature estimates from these off-craton mantle xenoliths correspond to a geotherm with a surface heat flow of 60.3 mW/m² and a lithospheric thickness of 92 km (Gibson and

Mckenzie, 2023). Accordingly, SACI-24 shows that Pali Aike is located in a low velocity region.

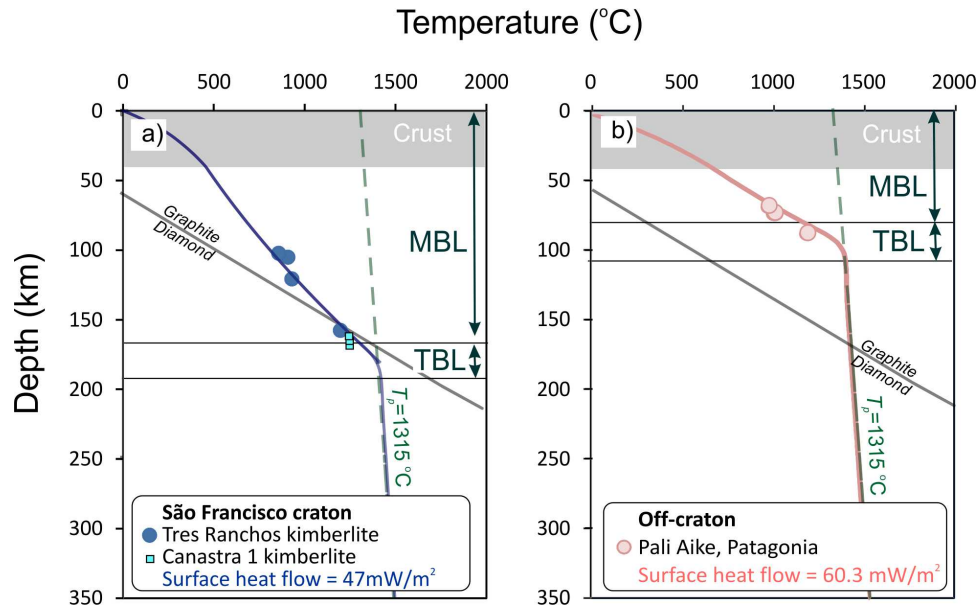


Figure 3.9: Thermal structure of the S. American lithosphere derived from the compositions of mantle peridotites. MBL and TBL denote the Mechanical and Thermal Boundary Layers, respectively, following the convention of McKenzie et al. (2005). We assume that the base of the lithosphere is where the shallow conductive part of the geotherm reaches an isentropic potential temperature TP of 1315 °C (see McKenzie et al, 2005). Panel a) shows a geotherm calculated from mantle peridotites entrained by the Três Ranchos kimberlite in the Alto Paranaíba Igneous Province, on the southern margin of the São Francisco craton (18.36° S, 47.78° W), using data from Leonardos et al. (1993) and Guarino et al. (2024). PT estimates are also shown for peridotites from the nearby Canastra 1 kimberlite (20.34° S, 46.55 °W Fernandes et al., 2021). We estimate that the base of the lithosphere beneath Três Ranchos was at 181 km depth at the time of xenolith entrainment (i.e. ~90 Ma). Panel b) shows a geotherm calculated from the compositions of mantle peridotites from the recent (<4 Ma) Pali Aike Volcanic Field in Southern Patagonia (52.11° S, 69.74° W; see Gibson et al., 2020). We estimate the base of the lithosphere beneath the volcanic field to reside at a depth of 92 km at the time of volcanism.

3.6 Discussion

S-wave velocities are sensitive to temperature and composition at depth and can also be affected by the presence of water and partial melt in the rock (e.g., Bonadio et al. 2018; Fulla et al., 2021; Griffin et al., 2009; Priestley and McKenzie, 2006; Schutt and Leshner, 2006; Sobolev et al., 1996). Although temperature is the main control on seismic velocities in the upper mantle, the effect of composition may be significant in special local cases (e.g., Sobolev et al. 1996; Eeken et al. 2018). Some of the velocity reduction in the sub-lithospheric seismic low velocity zone (LVZ) may originate from the presence of partial melts and volatiles, which could play a role in the dynamics of plate tectonics (Chantel et al., 2016; Karato, 1995, 1986). In the Central Andes region, very low seismic velocities and other data suggest a large area of partially molten rock in the crust (Schilling et al., 2006; Schmitz et al., 1997; Schurr et al., 2003). The melt in the mid-crustal zone associated with the observed low seismic velocities is believed to give rise to strong mechanical weakening, which may be the cause for the development of the flat topography of the Altiplano Plateau (e.g., Schilling et al., 2006). In the upper mantle beneath stable continental regions, however, seismic velocity variations reflect primarily those in temperature, so that the upper-mantle anomalies in the different tomographic models discussed in the following are primarily temperature-controlled: shear waves propagate slower through warm and faster through cold mantle (e.g., Finger et al., 2021; Priestley and McKenzie, 2006; Schutt and Leshner, 2006).

3.6.1 The Upper Mantle Beneath South America: the State of the Art

The early global seismic tomography models resolved structures at long wavelengths (~3000-5000 km), with young oceanic lithosphere adjacent to the mid-ocean ridges and major cratons being the most prominent negative and positive anomalies in the upper mantle, respectively (Don L Anderson and Dziewonski, 1984; Romanowicz, 1995b; J. H. Woodhouse and Dziewonski, 1984; Zhang and Tanimoto, 1993). In South America, the first regional models focussed, in particular, on the Nazca-Plate subduction (Engdahl et al., 1995) and the upper mantle below south-eastern Brazil (Vandecar et al., 1995). At the turn of the century, with increasingly abundant seismic data and improved methodologies, global seismic models began to achieve the lateral resolution of 500-1000 km (Reid et al., 2001; Zhao, 2001). In 2011, the Brazilian Seismic Network (RSBR, Bianchi et al., 2018) was

founded, with efforts to expand the seismic stations coverage from southeast Brazil towards the Amazon Basin. The growth in the regional and global seismic data has led to the creation of a broad range of seismic tomography models. These encompass regional (e.g., da Silva et al., 2021; de Azevedo et al., 2015; Neto et al., 2019; Shirzad et al., 2020), continental (e.g., Ciardelli et al., 2022; Rodríguez et al., 2020) and global (e.g., French and Romanowicz, 2014; Hosseini et al., 2020; Schaeffer and Lebedev, 2013; Simmons et al., 2021) models.

A range of methodologies have been employed in seismic tomography studies to map South America's deep structure. These include travel time tomography (e.g., Chaves et al., 2016; Neto et al., 2019; Rocha et al., 2011; Schimmel and Marcelo Assumpção, 2003), ambient noise surface-wave tomography (e.g., Dias et al., 2015; Goutorbe et al., 2015; Shirzad et al., 2020) and waveform inversion (e.g., Celli et al., 2020b; Ciardelli et al., 2022; van der Lee et al., 2001). Each technique has advantages and disadvantages. For instance, teleseismic body waves dive deep into the Earth at steep angles, primarily sampling the upper mantle beneath the seismic events and stations. Consequently, these body waves provide high resolution in areas like the subduction zone in western South America, which hosts numerous seismic sources and stations. However, in regions where there is an uneven distribution of seismic stations and a scarcity of earthquakes, the resolution of body-wave models is limited.

Our new model, SACI-24, is calculated using waveform inversion that extracts structural information from surface waves and S and multiple S waves. Surface waves travel along the Earth's surface between sources and receivers and are highly sensitive to the structure of the lithosphere and underlying upper mantle. The inclusion of S and multiple S waves in the waveform inversion allows us to sample greater depths than we could with surface waves alone, with substantial resolution in the transition zone. As our model SACI-24 is built from a global dataset, it is not affected by the loss of resolution, or artefacts associated with boundary effects in regionally constructed models.

A comparison of a range of recent tomography models yields a useful overview of the current state of the art in the imaging of the lithosphere and underlying upper mantle beneath South America. This comparison can also highlight the areas where our new model offers advances over existing ones.

We first compare SACI-24 with a representative selection of global S-wave tomographic models at the lithospheric depths (110, 150 and 260 km, Figure 3.10). The models are CAM2016_Vsv (Ho et al., 2016), 3D2016_09Sv (Debaille et al., 2016), SGLOBE_rani (Chang et al., 2015) and SL2013 (Schaeffer and Lebedev, 2013) listed chronologically by publication date. All models show the high velocity cratonic lithosphere

in the centre and east of the continent, although with varying levels of detail. In particular, SL2013 and SGLOBE_rani, as well as SACI-24, distinguish the cratonic domains in the northwest and southeast as separate anomalies. By contrast, CAM2016_Vsv and 3D2016_09Sv show the lithospheric high-velocity anomalies as a single, large-scale feature.

At 150 km depth, all models show high velocities near the active western boundary of the continent, associated with the subducting Nazca slab. At 260 km depth, the Nazca slab is visible most clearly in SACI-24 and SL2013. Below the continental lithosphere, all models show low seismic velocities, indicating hot asthenosphere.

In Figure 3.11, we compare SACI-24 with the recent regional models SAAM23 (Ciardelli et al., 2022) and SA2019 (Celli et al., 2020b) and the earlier model by Feng et al. (2007). Larger-scale structures are consistent across all the models. The model of Feng et al. (2007) was the first to map a separation between the lithosphere of the Amazon and São Francisco Cratons. Since then, the increase in data sampling and imaging resolution have allowed the SA2019 model to map more clearly, and in greater detail, the reduction in seismic velocities between the Amazon Craton in the north-west and the São Francisco Craton and Paraná Block in the south-east, as well as other lithospheric structures across the continent.

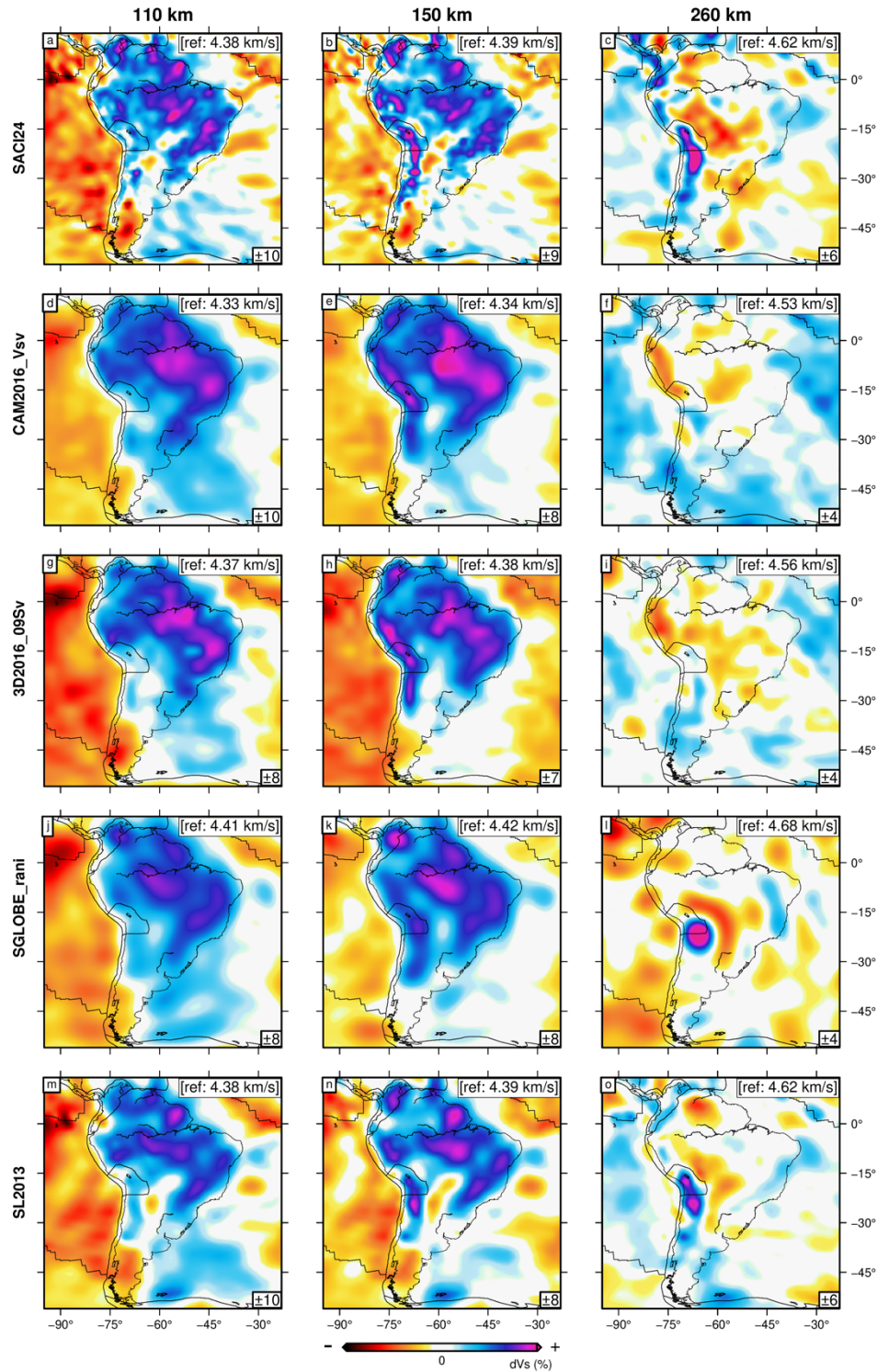


Figure 3.10: Model Comparison at 110, 150, and 260 km depths. Global models are plotted below SACI-24 (this study) in chronological order (most recent first): CAM2016_Vsv (Ho et al., 2016), 3D2016_09Sv (Debayle et al., 2016), SGLOBE_rani (Chang et al., 2015), SL2013 (Schaeffer and Lebedev, 2013). All models are plotted with respect to the reference velocity at each depth that is specified at the top right of the images. The limits of the colour scale are given at the bottom right of each panel.

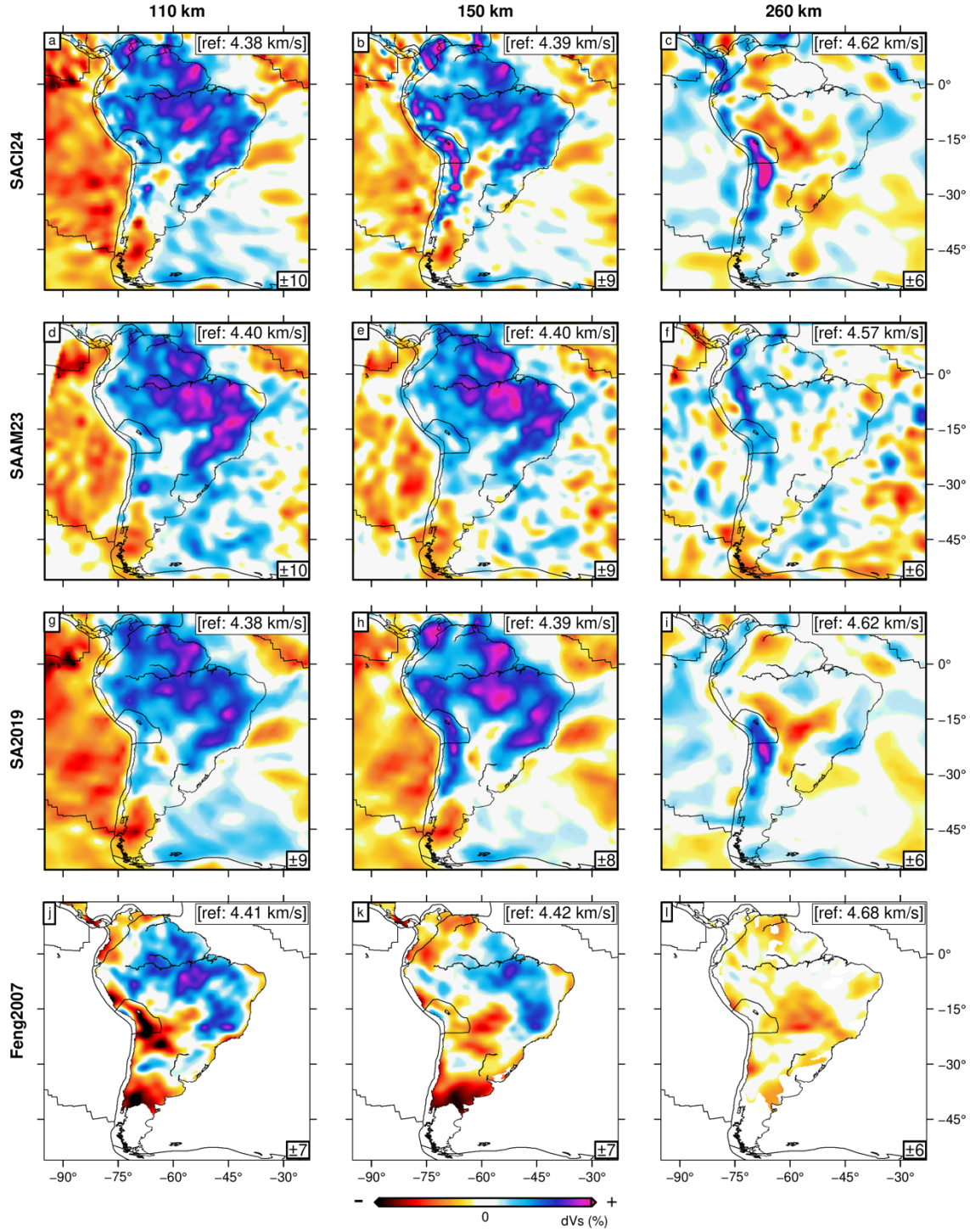


Figure 3.11: Continent-scale model comparison at 110, 150, and 260 km depths. The models are: SAAM23 (Ciardelli et al., 2022), SA2019 (Celli et al., 2020b); Feng2007 (Feng et al., 2007). All models are plotted with respect to their own reference velocity at each depth, shown at the top right of the frames. The limits of the colour scale are at the bottom right of each frame.

The recent continent-scale model of South America SAAM23 (Ciardelli et al., 2022) was computed using adjoint waveform tomography. A key advantage of SACI-24 is the very large global dataset that constrains it whereas SAAM23 is constructed using selected earthquakes and stations limited to South and Central America and a few stations in the surrounding oceans and Antarctic Peninsula, with the total of 20,884 source-station pairs used.

SAAM23 and SACI-24 have many similarities, as highlighted in the Supplementary Figure 4.1. These include the high velocities associated with the Amazon Craton, Parnaíba Block, and São Francisco Craton. There are, however, significant differences as well. One such difference is in the north, under the Transbrasiliano Lineament. At 110 km depth, SAAM23 displays craton-like high velocity anomalies between the Parnaíba Block and SFC, whereas SACI-24 shows lower, non-cratonic seismic velocities. Furthermore, SAAM23 does not resolve the high velocities associated with the Nazca plate subduction—which we know to be occurring—at depths shallower than 260 km.

Near the southern extremity of the continent, SACI-24, SAAM23 and SA2019 all map low seismic velocities associated with the thin lithosphere of the Patagonia terrane, which has been attributed to the subduction of the Chilean rise, forming a slab window (Breitsprecher and Thorkelson, 2009). The boundary between the seismic velocities of the continental platform and Patagonia are similar in SACI-24 and SAAM23.

Overall, when compared to previous models, SACI-24 displays more detailed, clearly defined boundaries of different lithospheric blocks, including cratons and subducting slabs. It also maps the substantial structural heterogeneity within each craton. Despite the model differences, it is important to note that the current generation of waveform tomography models of South America (SACI-24, SAAM23, SA2019) mutually agree and validate each other at much finer scales compared to earlier models. This demonstrates the advance of the state of the art in the imaging of the continent, driven primarily by the rapid growth in the broadband data sampling.

We also compare SACI-24 with P-wave velocity models computed using teleseismic travel times in Supplementary Figure 3.3. At 150 km depth, the body wave models map the high velocities within the subducting Nazca slab, but not the cratonic lithosphere inside the continent. Most models also show low P-wave velocities in the deep upper mantle beneath central and eastern South America, consistent with our observations of low S-wave velocities in SACI-24. The structure and dynamics of the transition zone beneath South America will be discussed in a forthcoming publication.

3.6.2 South America's Cratons

In the stable platform of South America, outcrops of exposed Archean crust are relatively scarce, with vast cratonic regions either inaccessible or covered by Phanerozoic sediments (e.g., Schobbenhaus et al., 2003). Mapping craton boundaries based on surface observations alone is, thus, uncertain. SACI-24 provides a detailed new mapping of the cratonic lithospheric mantle beneath South America, which is independent from and complementary to the evidence from outcrops of Precambrian rock.

Our model displays strong high velocity anomalies preferentially within the boundaries of the major Amazon and São Francisco cratons, with the boundaries drawn based on geological and geophysical observations and inferences (Cordani et al., 2016). There is strong lithospheric heterogeneity within these major cratons as well. Our tomography shows that large parts of them are not currently underlain by cratonic mantle (Figure 3.12). The new evidence on the lateral extent of the cratonic lithosphere provided by our model is explored in detail in the sections below.

In order to distinguish the lithosphere of different temperature and thickness more clearly, from Figure 3.13 onwards we plot seismic velocity anomalies using a discrete colour scale. Higher velocities indicate colder, thicker lithosphere (e.g., Fulla et al. 2021). Yellow colour in the lithospheric depth range represents low seismic velocities ($<1\%$ dVs anomaly), indicating warm, thin lithosphere. Light blue represents dVs between 2% and 5%, indicating velocities slightly higher than the global reference, common in stable but non-cratonic continental lithosphere. A threshold of 5-6% dVs was used to delimit cratonic lithosphere in a number of previous tomography studies (Celli et al., 2020a; de Laat et al., 2023). Here, we do not adopt a single dVs threshold to define the boundaries of cratonic mantle lithosphere but use a colour scale with the 5.5%, 6.5% and 7.5% dVs thresholds clearly visible. This colour scale highlights both where the thick, cold cratonic lithosphere is and the seismic velocity variations within the cratonic blocks. The plotting of the multiple threshold boundaries indicates, qualitatively, the intra-cratonic variations in the lithospheric temperature and thickness.

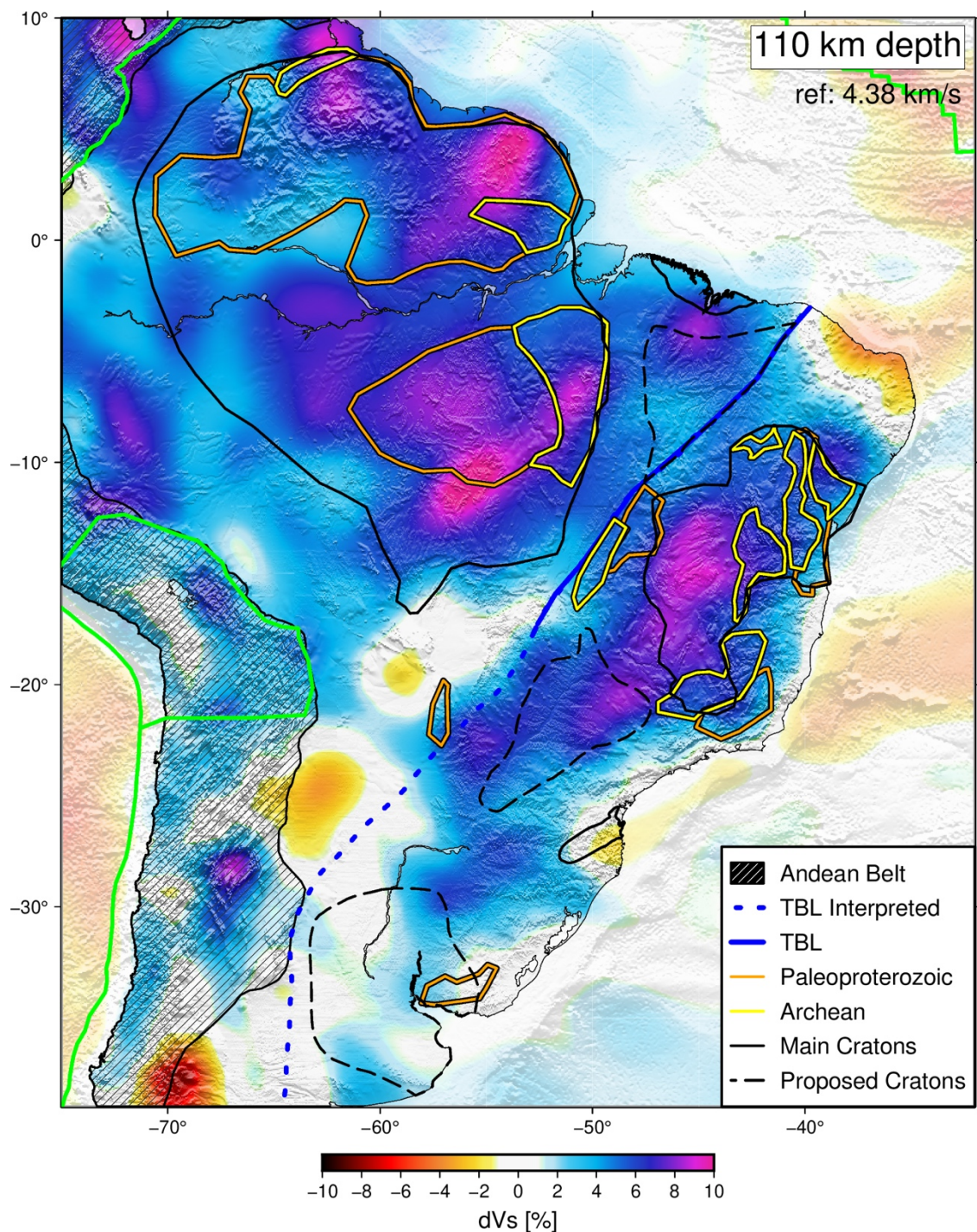


Figure 3.12: Seismic Velocities at 110 km depth and the main tectonic provinces. Tectonic overlays are as in the legend box. Seismic velocities in the oceanic areas are shaded, as the main focus of this paper is on the continental lithosphere.

3.6.2.1 Amazon Craton

Within the boundaries of the AC shown in Figure 3.13, seismic velocity anomalies are positive everywhere, but with strong lateral heterogeneity. Instead of one continuous

cratonic core, we observe two major blocks divided by the Amazon River basin, and each of the blocks comprises both cratonic and non-cratonic lithospheric units. In previous studies, different sub-divisions of the AC were proposed based on seismic tomography (Heintz et al., 2005) and Bouguer gravity anomalies (Nunn and Aires, 1988; Van der Meijde et al., 2013). A gravity high coincides with a Neoproterozoic magmatic area (Cordani et al., 1984) and has been linked to an intracontinental rift preceding the formation of the Amazon Basin (Burke and Lytwyn, 1993). The 10 mGal gravity high contour (Figure 3.13-yellow line) is matched closely by the 6.5% dVs contour, which confirms a deep lithospheric boundary. The relatively low seismic velocities indicate that the lithosphere under the Amazon River is thinner and mechanically weaker than that of the neighbouring blocks, which is likely to localise deformation, rifting and magmatic activity in this area.

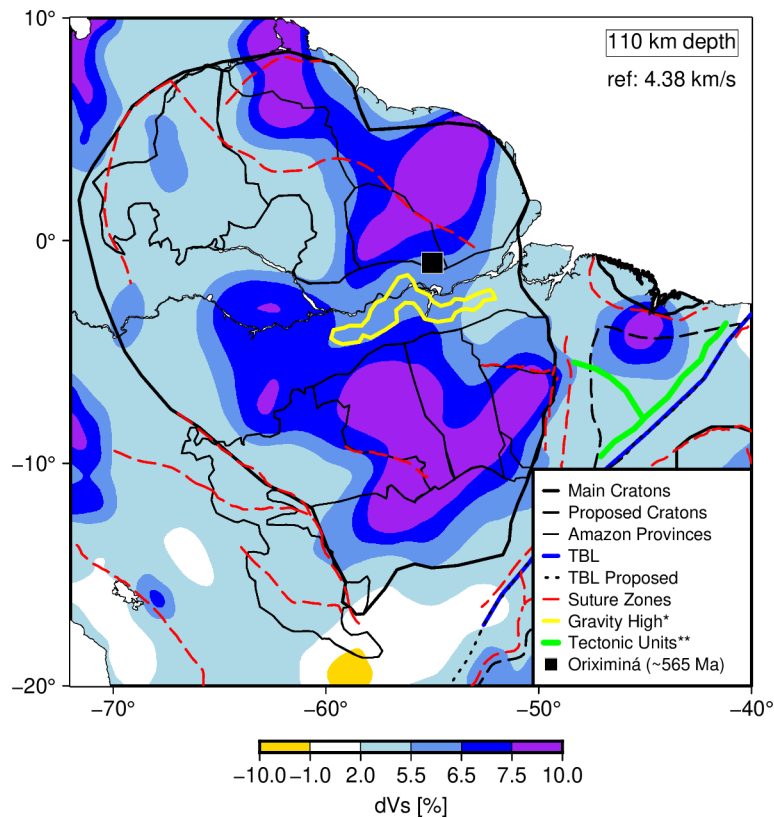


Figure 3.13: The lithosphere of the Amazon Craton and the Parnaíba Domain. See Figure 3.2-a for the information on the tectonic overlays and Amazon geochronologic provinces. *Bouguer gravity anomaly high contour corresponds to -20 mGal (Nunn and Aires, 1988). **Tectonic units from Lopes De Castro et al., (2016).

The presence of two separate major blocks under the AC can be interpreted in two ways:

- A. The Amazon Craton evolved as a single block, as suggested by a number of workers (Cordani et al., 1984; Tassinari and Macambira, 1999; Teixeira et al., 1989). A subsequent Neoproterozoic rifting event modified the deep cratonic lithosphere, leading to the craton's division into the two lithospheric blocks. This event then triggered the initiation of the subsidence of the Amazon basin, as proposed by (Burke and Lytwyn, 1993)). Afterwards, the thinner lithosphere under the basin could act as a “thin spot” where hot asthenosphere could flow into, localising the magmatism of CAMP (Boscaini et al., 2022; Sleep, 2003; Thompson and Gibson, 1991).
- B. The Amazon region was assembled as two separate major cratonic blocks, with somewhat thinner lithosphere between them. The thinner-lithosphere area localised the Neoproterozoic magmatic event, rifting and basin formation and the Mesozoic CAMP (Deckart et al., 2005). The S-velocity anomaly beneath a large part of the Amazon Basin exceeds 5.5% at 110 km depth (Figure 3.13) and the lithosphere here can be considered cratonic, although warmer and thinner than beneath the neighbouring units to the north and south. The lack of known diamondiferous kimberlites beneath the Amazon Basin is consistent with its lithosphere having always been relatively thin. We note the possibility of a sampling bias, but to establish the presence of thick cratonic lithosphere beneath the Amazon Basin in the past, evidence from diamondiferous kimberlites would be necessary.

3.6.2.1.1 Guiana Shield

In the Guiana Shield in the north of the Amazon Craton, highest-velocity anomalies at lithospheric depths are observed predominantly within the Transamazonas and Amazônia Central Provinces (Figure 3.2, Figure 3.13), east of the Cauarani-Coeroeni Belt (Fraga et al., 2009, 2008; Kroonenberg et al., 2016). The Amazônia Central Province is characterised by most geochronology models as Paleoproterozoic (Santos, 2003a; Santos et al., 2000; Vasquez and Rosa-Costa, 2008). Some authors (Almeida et al., 2000; Cordani et al., 1979; Tassinari and Macambira, 1999) define this area as the oldest cratonic nucleus from which the remaining of the Amazon craton evolved.

Hadean and Archean ages from zircon xenocrysts, ranging from 2519 to 4219 Ma, have been reported from the country Guyana (Nadeau et al., 2013), east of the CCB.

Together with the evidence from our tomography, this confirms the presence of Archean cratonic lithosphere in the eastern Guiana Shield.

3.6.2.1.2 Central Brazil Shield

In the Central Brazil Shield in the southern AC, we detect a large block of cratonic lithosphere, which we will refer to as the Central Brazil Block. The cratonic lithosphere extends east as far as the eastern boundary of the craton. In the south, cratonic mantle lithosphere extends beneath the Parecis Basin, beyond the cratonic boundaries mapped at the surface (Figure 3.2). The presence of cratonic lithosphere beneath the basin is consistent with published evidence from potential field methods (Bahia et al., 2007; Faria, 2015) and petrology (Lima et al., 2021).

High velocity anomalies exceeding 5.5% dVs underlie the four oldest geochronologic provinces of the Central Brazil Shield. The Carajás province has the oldest Archean basement of the AC and is underlain by very high seismic velocities (dVs > 7.5% at 110 km depth). Other provinces within the shield, however, show greater variability of the lithospheric structure.

In the southern Amazônia Central province, seismic velocities are lower in the north and increase to the south, where Archean-Paleoproterozoic rock ages have been reported (Tassinari and Macambira, 2004). The lithosphere in the north of the province may be warmer and thinner due to its modification by the processes that gave rise to the anorogenic magmatism of the 1.88Ga Uatumã LIP (Klein et al., 2012; Teixeira et al., 2019).

The oldest dated crust in the Amazônia Central is 1.9 Ga (Vasquez and Rosa-Costa, 2008). Contrary to previous suggestions (Santos, 2003a; Tassinari and Macambira, 1999; Teixeira et al., 1989) regarding the basement under the Amazon basin, tomography indicates that the lithosphere of the craton does not extend homogeneously from the Guiana Block to the Central Brazil Block but includes different units with different lithospheric temperature and thickness.

West of the Amazonia Central province, the Tapajós-Paraná Province is underlain by very high seismic velocities (>7.5% dVs), indicating cold, thick cratonic lithosphere. This is consistent with rock ages of 2.80–1.87 Ga (Figure 3.1) measured in the south of the province (Paes de Barros, 2007). High seismic velocities are also observed further west, beneath the Rondônia-Juruema province, and south, under the Parecis Basin.

High seismic velocities are evident beneath the Amazon-Solimões basin, to the north of the Rondônia-Juruema province (Figure 3.13). Kroonenberg and de Roever (2010)

highlighted the similarities in the rock age and lithology between the Amazônia Central and Tapajós-Paraná provinces. Given the mapped seismic velocities and limited occurrence of Archean crustal rocks (Kroonenberg et al., 2016; Lafon et al., 2003; Motta et al., 2019), we infer that most of the AC's basement was formed in the Archean Era but some of it was altered in the Proterozoic, as previously proposed by Almeida et al. (1981) and Zheng et al. (2006), and that thick, depleted Archean mantle lithosphere underlies large parts of the Amazon Craton. Across the craton, the lithosphere shows strong lateral variations in its structure and thickness.

3.6.2.2 Parnaíba Block

The presence of cratonic lithosphere beneath the Parnaíba Basin to the east of the Amazon Craton (Figure 3.2) has been proposed in a number of studies (Cordani et al., 1984; Daly et al., 2014; Lopes De Castro et al., 2016; Tozer et al., 2017). Our imaging reveals a pronounced high-velocity anomaly beneath the northern part of the basin, indicative of cold, thick, mechanically strong cratonic lithosphere (Figure 3.13). It is bordered by the TBL to the east, the Araguaia Belt to the west, and the São Luiz Craton to the north (Figure 3.3). The rifts and grabens of the basin lie predominantly in its eastern and southern parts (Lopes De Castro et al., 2016), where the lithosphere is warmer, thinner and mechanically weaker, as inferred from the lower seismic velocities, and where deformation localised. Our model thus offers a more accurate mapping of the basin's cratonic lithosphere than available previously and can explain the distribution of the lithospheric deformation in the basin.

The São Luiz Craton to the north of the Parnaíba Block (Daly et al., 2014) is thought to be a fragment of the West African Craton. It does not show high velocities characteristic of cratonic lithosphere, consistent with lithospheric modification and erosion during the fragmentation of western Gondwana (Klein and Moura, 2008).

3.6.2.3 São Francisco Craton

High seismic velocities beneath the São Francisco Craton indicate the presence of thick cratonic lithosphere. The boundaries of the craton in the mantle are substantially different from the geological boundaries mapped at the surface (Almeida, 1977) (Figure 3.14). The extent of the cratonic lithosphere beyond the western geological boundary of the craton, seen in our tomography, has already been proposed previously based on gravity

(Pereira and Fuck, 2005), seismology (Assumpção et al., 2004a; Rocha et al., 2019) and petrophysical studies (Fernandes et al., 2021).

In the craton's northernmost region, a small high-velocity anomaly is observed beneath the Archean Serrinha Block (Figure 3.2-b), indicating thick lithosphere of this Archean core. The reduction of seismic velocities towards the south aligns with the location of the complex rift system of the Paramirim Aulacogen (upper green line in Figure 3.14). This region has recorded activity of at least eight rifting and/or anorogenic magmatic events. Our tomography indicates thinned lithosphere here, which must have localised the recurrent tectonic activity. The south-central part of the SFC is dominated by high seismic velocities ($>7.5\%$ dVs; Figure 3.14), which evidence thick, cold cratonic lithosphere.

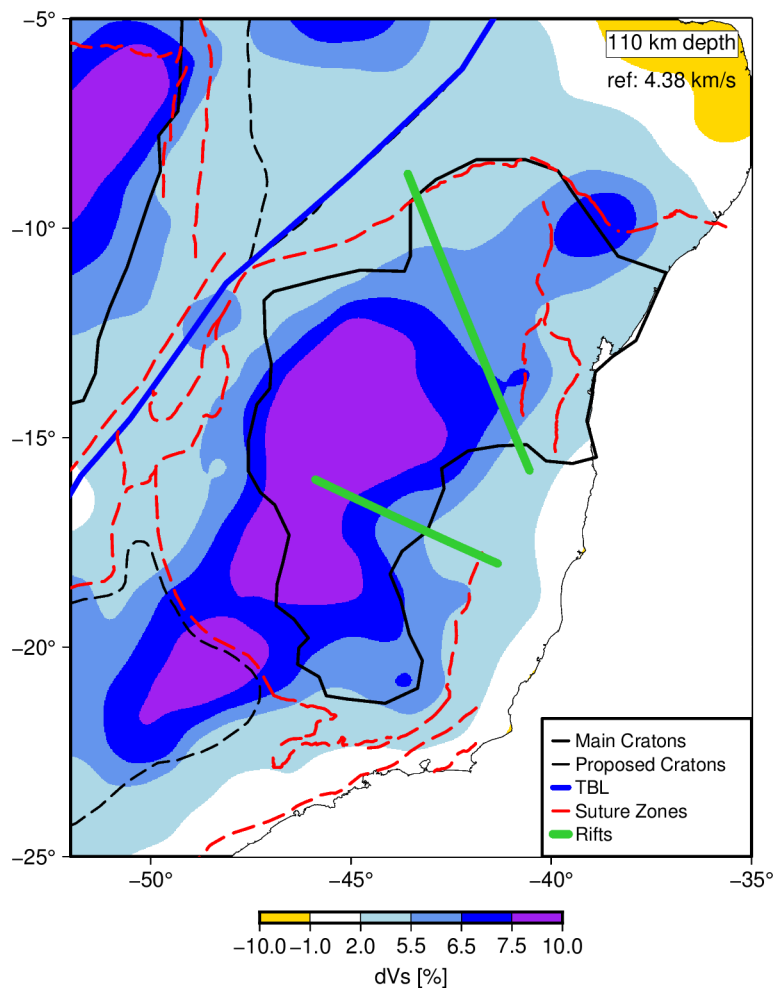


Figure 3.14: Seismic velocity map of the São Francisco Craton. See Figure 3.2-b for information on the tectonic overlays and SFC provinces.

3.6.2.4 Paraná Block

Evidence for cratonic lithosphere beneath the Paraná Basin, commonly referred to as the Paranapanema Block (Mantovani et al., 2005), has been reported in several previous seismic studies (Affonso et al., 2021; Celli et al., 2020b; Chaves et al., 2016; Ciardelli et al., 2022; Feng et al., 2007; Heintz et al., 2005; Lebedev et al. 2009; Rocha et al., 2011). Our new model (SACI-24) shows high seismic velocities down to a depth of 200 km beneath the Paraná Basin (Figure 3.5, Figure 3.15), which is consistent with a number of previous models (Celli et al., 2020b; Ciardelli et al., 2022; Heintz et al., 2005; Lebedev et al. 2009).

Whereas most tomographic models depict a single high-velocity feature stretching across the Paraná Basin and the São Francisco Craton, our model shows closely spaced but distinct cratonic blocks. Paraná's largest cratonic block is just southeast of the SFC (Figure 3.11). Between the two cratons, seismic velocities decrease somewhat ($< 7.5\%$ dVs; Figure 3.14). The Brasília foldbelts here are also locations of magmatism of the Goiás and Alto Paranaíba alkaline provinces (Figure 3.2). To the west, we also observe two smaller high-velocity regions, with western boundaries along the inferred extension of the Transbraziliano Lineament.

In Figure 3.15, we compare our seismic velocities with various previously proposed boundaries for the cratonic blocks beneath the Paraná Basin (Cordani et al., 1984; Mantovani et al., 2005; Milani and Ramos, 1998). The lateral extent of the observed high velocities does not quite match any of them. In general terms, our model supports the concept of a fragmented craton around a central rift (Marques et al., 1993). Evidence for a fragmented craton beneath the basin was also reported previously based on receiver functions and Rayleigh wave dispersion analysis (Julià et al., 2008). The relative location of cratonic blocks and rifts suggests that deformation and rifting associated with the basin formation was localised in the areas with thinner, weaker lithosphere.

The westernmost high-velocity block is situated between the Paraná Basin and the Rio Apa Craton (Cordani et al., 2010) (Figure 3.1, Figure 3.3-c). It is an open question whether this high-velocity block and its evolution are associated more with the Paraná Cratonic Block or the cratonic lithosphere of the Rio Apa Craton.

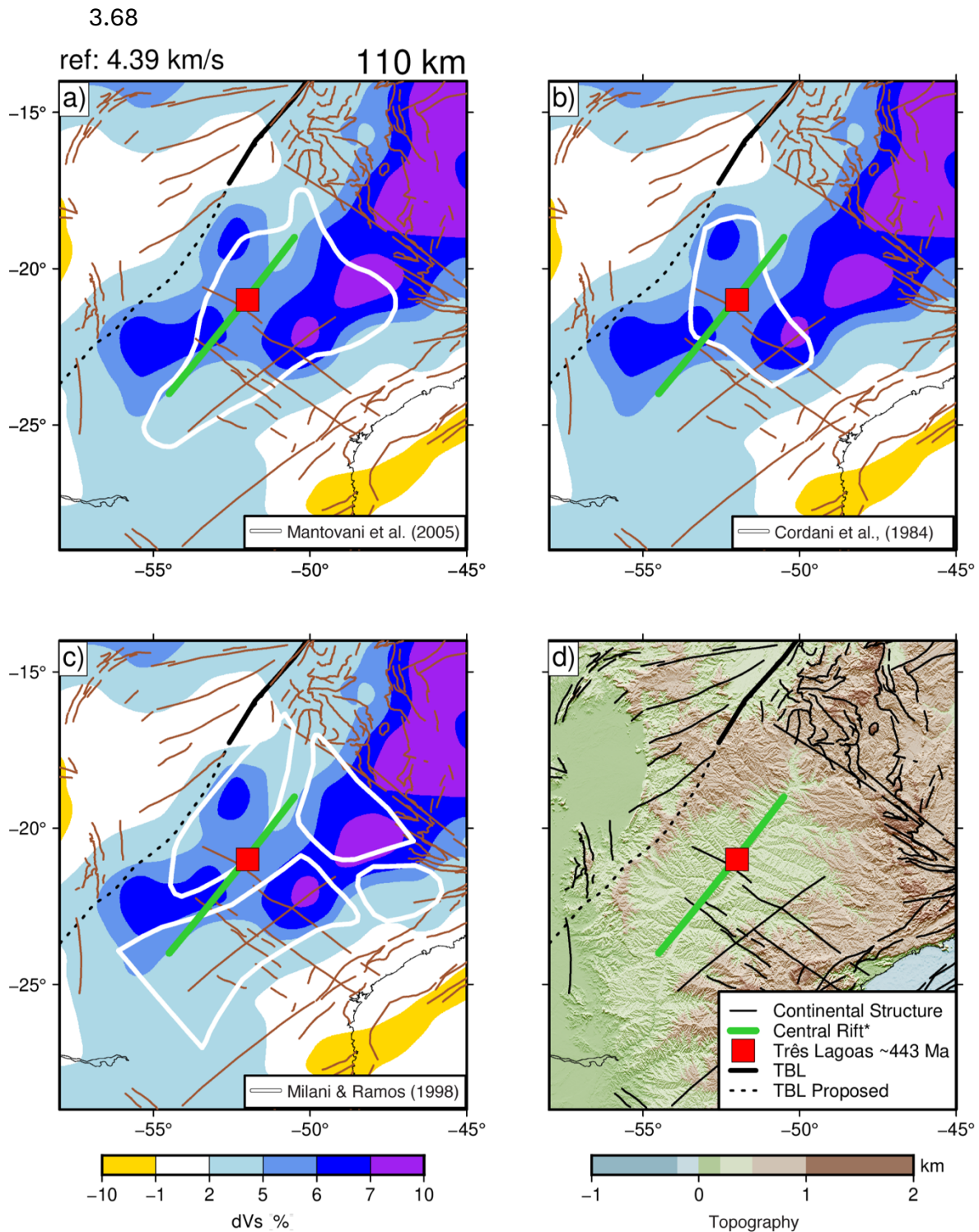


Figure 3.15: Seismic Velocities under the Paraná Basin. Comparison between seismic velocities at 110 km depth and the different, previously proposed boundaries of the cratonic block(s) under the Paraná Basin. Central rift and the location of the Paleoproterozoic Três Lagoas Basalt are from (Milani and Ramos, 1998).

3.6.2.5 Rio de La Plata Craton

The lateral extent of the Rio de La Plata Craton (RLC), based on surface geology and geochronology is much debated (e.g. Oyhantçabal et al., 2011; Ramos et al., 2010; Rapela et al., 2007; Santos et al., 2019; Figure 3.16). We have observed a relatively small, in terms of its lateral extent, high velocity anomaly in the north of the craton. It is particularly prominent (up to 9-10% dVs) at 80 km depth and weakens gradually with increasing depths to 1-3% at 150 km depth (Figure 3.5). A number of previous models (Celli et al., 2020b; Ciardelli et al., 2022; Feng et al., 2007; Schaeffer and Lebedev, 2013) show some high velocities in this region, but with little mutual consistency regarding their location. SACI-2024 uses improved data sampling of the area, combining new regional and global data (Figure 3.4), and localises the anomaly in the northern part of the craton. The high seismic velocities we detect are near the northeastern boundary of the craton, according to most models, and extend over a relatively small portion of the craton's area. Within the central part of the craton, seismic velocities in the mantle-lithosphere depth range are close to the global average (-2% to 2% dVs).

The pronounced seismic velocity anomaly in the north of the RPC is just southeast of the Paraná Block (Ramos et al., 2010) and extends northwest beneath Paraná. The boundaries of the RLC and Paraná are difficult to map based on surface observations due to the thick sedimentary cover of the Paraná-Chaco Basin (Oyhantçabal et al., 2011; Ramos, 1988; Rapela et al., 2007).

Near the southern boundary of the craton, where it borders—and possibly comprises—the Tandilia Belt (Figure 3.3) (Rapela et al., 2007), we observe a band of positive velocity anomalies with amplitudes around 3%, indicating non-cratonic lithosphere. This region is known to host the southernmost Archean basement samples of the continent (Hartmann et al., 2002; Oyhantçabal et al., 2011; Pankhurst et al., 2003), which generally suggests that cratonic lithosphere formed here in the Archean. The eastern coast of South America, however, underwent significant reworking due to the Brasiliano collisions, associated with substantial magmatic activity (Oyhantçabal et al., 2011; Santos et al., 2019). Cratonic mantle lithosphere beneath the southern Rio de la Plata Craton is likely to have been eroded during the craton's evolution.

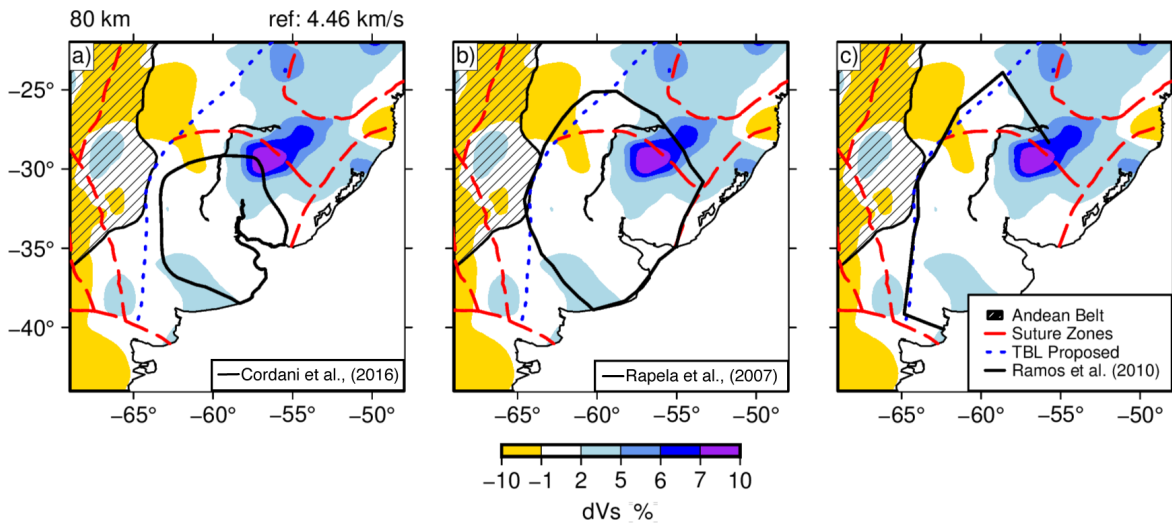


Figure 3.16: Seismic velocities beneath the Rio de La Plata Craton. Comparison between seismic velocities at 80 km depth, with different previously proposed boundaries of the Rio de La Plata Craton and surrounding belts. A) Cratonic boundary from Cordani et al., (2016). B) Cratonic boundary proposed by Rapela et al., (2007). C) Cratonic boundary from Ramos et al., (2010).

3.6.3 Lithospheric structure and magmatism

3.6.3.1 Cenozoic volcanism

Low shear-wave velocities in the lithospheric depth range indicate warm, thin lithosphere (Mckenzie and Bickle, 1988; Priestley et al., 2024). Intraplate basaltic volcanism is known to occur in areas with thin lithosphere and, in some but not all cases, warmer-than-average asthenosphere. Ball et al. (2021) combined petrological and tomographic evidence at the global scale and reported a strong correlation of the Neogene-Quaternary intraplate volcanism with low upper mantle shear-wave velocities and small estimated thicknesses of the lithosphere (< 100 km). Recent high-resolution, continent-scale tomographic models show an even stronger correlation, with all intraplate basaltic volcanism located on thin lithosphere (e.g., Civiero et al., 2022; de Laat et al., 2023; El-Sharkawy et al., 2024).

We compare seismic velocities at 110 km depth and the locations of Cenozoic (< 66 Ma) intraplate basaltic volcanism in South America in Figure 3.17. We consider only the Cenozoic volcanoes because the lithosphere they erupted on is most likely to be similar to what we observe today, in contrast with the lithosphere further back in time, whose thickness is more likely to have changed substantially (e.g., Meier et al., 2016). We complement the

magmatism compilation from Mizusaki et al. (2002) with additional data points (de Souza et al., 2003; Knesel et al., 2011; Perlingeiro et al., 2013; Skolotnev et al., 2011) and add the Patagonia dataset from D’Orazio et al. (2004). We cluster together the samples located within a radius of 10 km from each other and consider the cluster to be a single datum, so that heavily sampled areas do not bias the resulting histogram (Figure 3.17). Similar correlations of low velocities with late Cretaceous intraplate magmatism had also been found with a regional P-wave tomography study in SE Brasil (Assumpção et al., 2004b).

We observe that a large majority of volcanic areas are where the seismic velocity anomaly is negative, which indicates thin lithosphere. The remaining ones are where S-velocity anomaly is 0-4%, and almost all of them are very close to a boundary with a lower-velocity structure. This suggests that these volcanoes probably erupted on the thinner lithosphere, indicated by the lower velocities, but the lateral averaging of the tomography smooths the boundaries of the thick and thin lithospheric blocks, which produces the few outliers to the, nonetheless, very clear pattern (Figure 3.17).

The common occurrence of intraplate basaltic volcanism near the boundaries of lithosphere of contrasting thickness is an important observation in itself. This suggest that the origin of much of this volcanism is likely to have involved lateral flow of warm asthenosphere from beneath the thick lithosphere to the “thin spots,” where diabatic decompression melting and basaltic eruptions eventually occurred (Thompson and Gibson 1991; Sleep 2003; Lebedev et al 2006; de Laat et al. 2023).

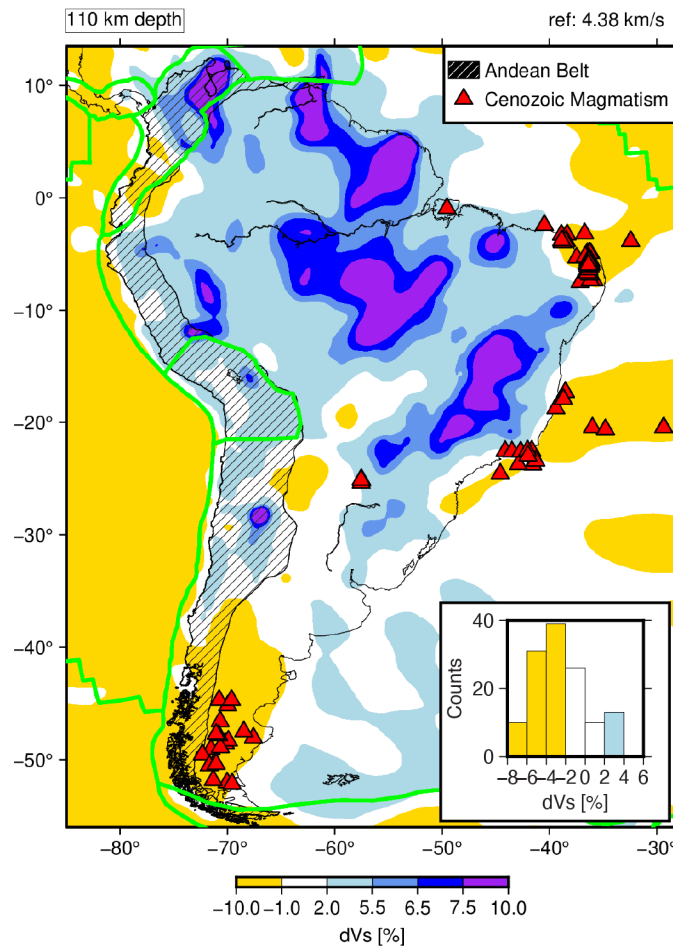


Figure 3.17: Locations of intraplate Cenozoic volcanism on the background of seismic velocity anomalies at 110 km depth. The histogram at the bottom right shows seismic velocities at sites of volcanism.

3.6.3.2 Large igneous provinces

The upper mantle structure, in particular that of the mantle lithosphere, also appears to have controlled the distribution of volcanism within South America's major Large Igneous Provinces (LIPs): the Central Atlantic Magmatic Province (CAMP, e.g., de Min et al., 2003; Wilson, 1997) and the Paraná Magmatic Province (PMP, e.g., Peate et al., 1992). The emplacement of CAMP occurred around 201 Ma, prior to the breakup of Pangaea and the opening of the central Atlantic Ocean (e.g., de Min et al., 2003; Deckart et al., 2005; Marzoli et al. 1999; Milani and Zalán, 1999), whereas the Paraná Magmatic Province formed at around 134 Ma (e.g., Piccirillo and Melfi, 1988; Renne et al., 1996), just before the opening of the South Atlantic.

The large volumes of the flood basalts, dyke swarms and other magmatic features within LIPs (e.g., Ernst et al. 2021) set them apart from the low-volume intraplate eruptions,

such as those of Cenozoic age in South America discussed in Section 3.6.3.1. The origin of LIPs is commonly attributed to adiabatic decompression melting in upwelling mantle plumes (e.g., Richards et al. 1989; White and McKenzie 1989). The LIP magmatism, however, is often distributed unevenly over very broad areas, which continues to fuel debate on whether a plume—or only one plume—can account for the dispersed eruptions within a LIP (e.g., Sleep, 2003; Steinberger et al., 2019; Peace et al., 2020; Civiero et al. 2022).

It has been postulated previously that the LIP basalts erupt where the lithosphere is thin (e.g., White & McKenzie, 1995; Lebedev et al., 2018; Niu, 2021; Civiero et al. 2022). Stephenson et al. (2023) compared the distribution of recent LIP magmatism globally with the lithospheric thickness, calculated from seismic tomography and geochemical data, and concluded that LIP eruptions occur on lithosphere thinner than about 80 km. They also noted that the lithosphere beneath older continental LIPs often looks cratonic (cold and thick), in contrast to the warm and thin lithosphere beneath younger LIPs, and suggested that cratonic lithosphere may re-grow with time after being thinned by a mantle plume.

In Figure 3.18, we compare the distribution of magmatism associated with South America's Phanerozoic LIPs with seismic velocities at 110 km depth. The igneous rock sample locations were obtained from the GEOROC Continental Flood Basalt Compilation (DIGIS Team, 2022). CAMP magmatism is distributed preferentially at the boundaries of the blocks of the thick cratonic lithosphere in the Amazon Craton and the Parnaíba Block. The PMP igneous rock locations are also mostly on average-low seismic velocity anomalies. The exceptions are the high velocities beneath parts of the flood basalts. A part of the CAMP flood basalts just south of the Amazon River is atop a high-velocity anomaly indicative of cratonic lithosphere. Within the contours of the Paraná flood basalts, the lithosphere is non-cratonic and thin in the south, where most volcanic sites are observed, but in the north the velocities are high, indicative of the presence of cratonic lithosphere below the Parana Block. Flood basalts are known to spread on the Earth's surface over hundreds of kilometres from the location of the lava outpouring (e.g., Hooper, 1997; Self et al., 2008) and dyke swarms can transport basaltic magmas over similarly long distances (e.g., Ernst et al., 2001), so their appearance on top of the thick lithosphere (Figure 3.18) does not require the unlikely re-growth of cratonic lithosphere (cf. Stephenson et al., 2023). Cratonic lithosphere needs to be compositionally buoyant in order to be stable when thick and cold (e.g., Jordan, 1975), and it is unclear how it could be created without pervasive melting, as in the hot Archean mantle. Similar to our observations in South America, seismic tomography also shows relatively thin, non-cratonic lithosphere in the central parts of other LIPs, in Siberia (Lebedev et al, 2018) and Africa (Celli et al. 2020a).

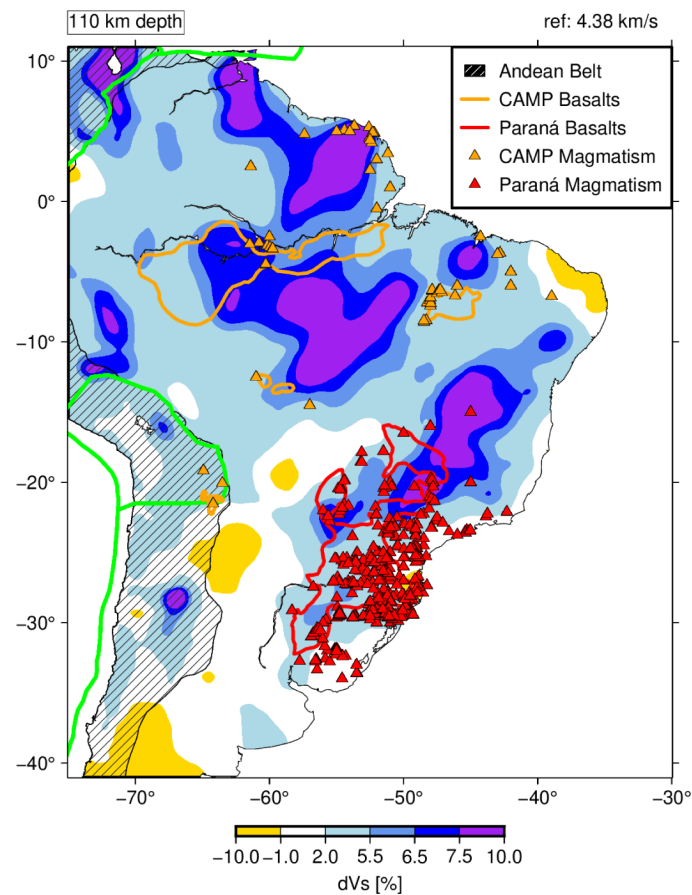


Figure 3.18: Mesozoic Large Igneous Provinces (LIPs) in South America. Shear-wave velocity anomalies at 110 km depth are overlain by the locations of volcanic areas and flood basalts from the CAMP and PMP. The boundaries of the CAMP flood basalts are based on the 100 m thickness contour of the sills (de Min et al., 2003; Heimdal et al., 2018).

3.6.3.3 Diamondiferous kimberlites

The presence of diamonds in kimberlites requires lithosphere exceeding about 150 km in thickness at the time of magmatism (Boyd et al., 1985; Pearson et al., 2003).

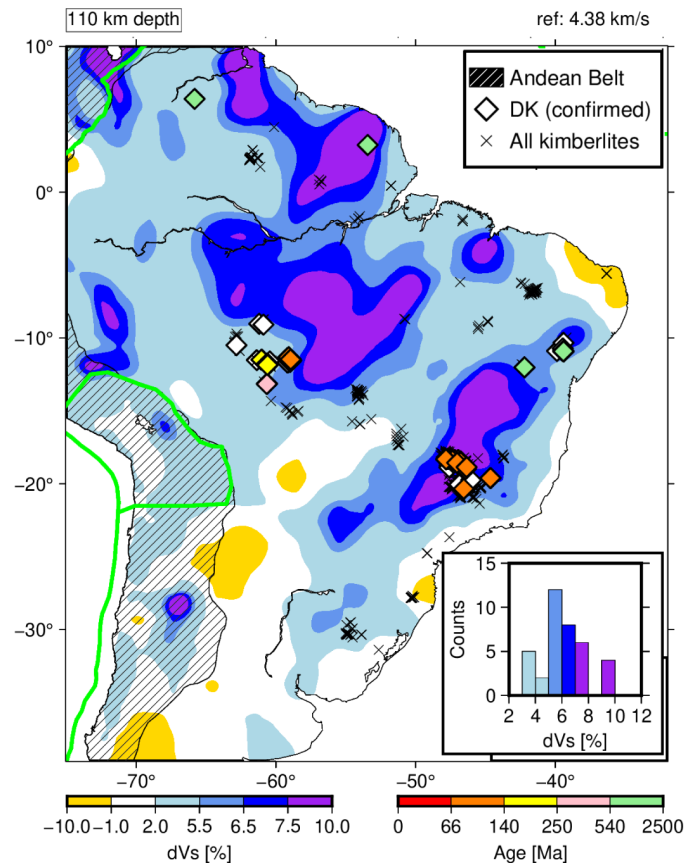


Figure 3.19: Seismic velocities at 110 km depth overlain by the locations of kimberlites, including diamondiferous kimberlites (DK). Open diamonds have no age information.

In Figure 3.19 we compare diamondiferous kimberlite locations in South America (Matos Cunha et al., 2017) with seismic velocities at 110 km depth. The histogram of seismic velocities shows that over 80% of diamondiferous kimberlites in South America are where seismic velocities are over 5% above the global average, indicating thick cratonic lithosphere. For the remaining minority of samples, the absence of cratonic mantle lithosphere implies its probable erosion since the time of the kimberlite eruption (Celli et al., 2020a).

A large proportion of the diamondiferous kimberlites found on apparently non-cratonic lithosphere are situated along the western boundary of the Central Brazil Shield (southern Amazon Craton). This region has long been considered anomalous (Hunt et al., 2009), with diamondiferous kimberlites emplaced through crust believed to be Mesoproterozoic in age, and outside the commonly accepted boundary of the AC. Two distinct clusters of kimberlites, Pimenta Bueno (Burnham et al., 2016; Hunt et al., 2009; Masun and Scott Smith, 2008) and Juína (Kaminsky et al., 2010, 2010, 2009), contain diamonds probably formed within the mantle transition zone. Yet, there is also compelling

evidence pointing to diamonds of lithospheric origins from both clusters (Burnham et al., 2016; Hunt et al., 2009; Kaminsky et al., 2009).

We infer that the cratonic lithosphere of the southwestern Amazon Craton has been eroded or altered since the eruption of the diamondiferous kimberlites. Within the Juína cluster, only the older (~92-95 Ma) pipes are diamond-bearing, whereas younger kimberlites dated to 79-80 Ma are barren (Kaminsky et al., 2010). This is consistent with the erosion and thinning of the cratonic mantle lithosphere at 80-90 Ma. This also suggests that the basement along the western AC boundary is likely to be Archean-Paleoproterozoic, older than has been suggested by some authors (Santos, 2003a; Tassinari and Macambira, 1999).

In the São Francisco Craton and its adjacent areas, all diamonds are found within regions of high seismic velocities, indicative of cratonic lithosphere.

3.7 Conclusions

Seismic tomography provides essential information on the structure of the lithosphere of South America and how it controls tectonics and volcanism. Together with complementary geological evidence, seismic tomography can also help us reconstruct the temporal evolution of the lithosphere. Our new waveform tomography model, SACI-24, offers significant improvements in the resolution of the shear-wave velocity structure across the South American continent and its margins, particularly at lithospheric depths, compared to previous regional and global models. This is due to the substantially improved data sampling, achieved thanks to the recently expanded seismic networks in South America and the large, complementary global dataset. Elaborate error analysis, data culling and the tuning of the tomographic inversion for the South American continent have helped us to extract accurate structural information from the massive datasets and increase the resolution of the imaging.

The current generation of waveform tomography models of South America show mutual agreement at much finer scales than earlier models. This illustrates the ongoing progress in seismic imaging, driven mainly by the rapid growth in the data sampling.

Tomography maps in detail the cratonic and intra-cratonic boundaries and other basic structural variations across the continent. The lithospheric structure variations indicated by the seismic velocities in SACI-24, in particular, show clear relationships with the locations of the deformation and rifting, basin formation and magmatism. These relationships offer insights into the mechanisms of the lithospheric control on these processes. The primary

specific conclusions from our analysis of South America's lithospheric structure are as follows.

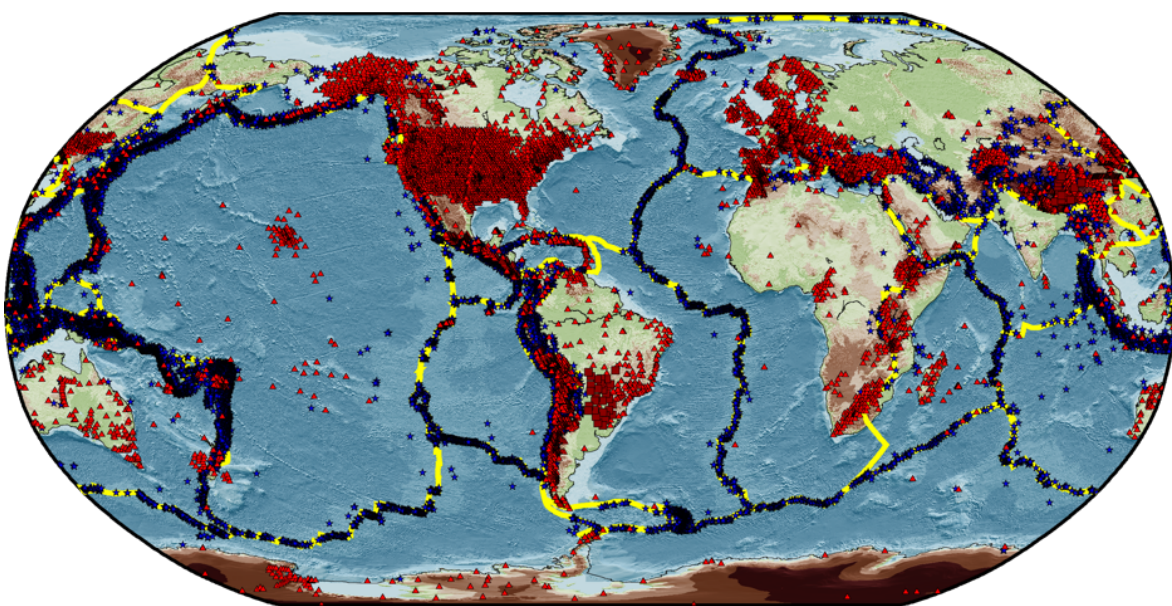
9. Within the Amazon Craton's surface boundaries, we identify two distinct units of cratonic lithosphere, the Guiana and Central Brazil blocks, separated by the Amazon Basin. The lithosphere beneath the Amazon Basin is relatively warmer and thinner. This can account for the fact that it has been a location of recurrent magmatism and, as previously proposed, a site of a failed rifting event that formed the Amazon Basin.
10. In the northern Guiana Shield, we map thick cratonic lithosphere east of the Cauarani-Coeroeni Belt and under the Amazônia Central province. In the southern Central Brazil Shield, thick cratonic lithosphere extends from the Archean Carajás province to the Mesoproterozoic Rondônia Juruema province.
11. We identified a cratonic lithosphere under the sedimentary cover of the Parnaíba Basin. The Parnaíba cratonic block is bound on the east and south by rift and graben structures, where deformation is localized by the warmer and weaker lithosphere.
12. In the São Francisco Craton, the cratonic lithosphere extends beyond the previously proposed north and southwest boundaries. The craton's internal structure shows variability, with warmer, thinner lithosphere beneath the Paramirim and Pirapora aulacogens, which have been locations of magmatic and rifting cycles.
13. We confirm the presence of cratonic lithosphere under the Paraná Basin. Contrary to the previously proposed hypothesis of a continuous block of cratonic lithosphere under the basin, we resolve multiple units of cratonic lithosphere. While many authors have posited the existence of a fragmented cratonic root, it has not been imaged by seismic tomography until now. The region of thinner lithosphere is oriented NE-SW and aligns with the previously proposed location of a central rift, also evidenced by the Paleozoic Três Lagoas basalt.
14. High seismic velocities indicative of cratonic lithosphere are observed south of the Paraná Block. We interpret these velocities as the cratonic root of the northern part of the Rio de la Plata Craton, observed from 80 km to 150 km depth. No cratonic lithosphere is observed beneath the southern Rio de la Plata Craton, where Archean crust has been mapped, which suggests lithospheric reworking there.
15. Cenozoic intraplate basaltic volcanism is observed primarily in areas with low seismic velocity and, by inference, thin lithosphere, especially in the Borborema province, the southern Atlantic Coast, and Paraguay. The high concentration of the volcanic sites near the thick lithosphere-thin lithosphere boundaries is consistent

with the volcanism caused by horizontal asthenospheric flow from under the thick lithosphere towards the thin rifted lithosphere, with subsequent decompression melting below the thin lithosphere causing the magmatism.

16. Most basalts of the CAMP and Parana LIPs are also observed in areas with relatively low seismic velocity, compared to neighbouring blocks, indicating that they erupted through relatively thin lithosphere. Parts of the flood basalts, however, are exceptions and overlie thick cratonic lithosphere. These melts are likely to have undergone lateral flow in hypabyssal intrusions or lava flows, from thin-lithosphere sites. Tomography thus provides new evidence on the importance and the extent of lateral transport of basaltic melts in and atop the crust of LIPs.
17. Approximately 80% of known diamondiferous kimberlites in South America are situated in regions marked by high seismic velocity anomalies ($>5\%$ dVs), indicative of thick cratonic lithosphere. The remaining diamondiferous kimberlites are found on presently thin (non-cratonic) lithosphere, which is likely to indicate the erosion and thinning of cratonic lithosphere in these locations since the time of their eruptions.

3.8 Supplementary Material

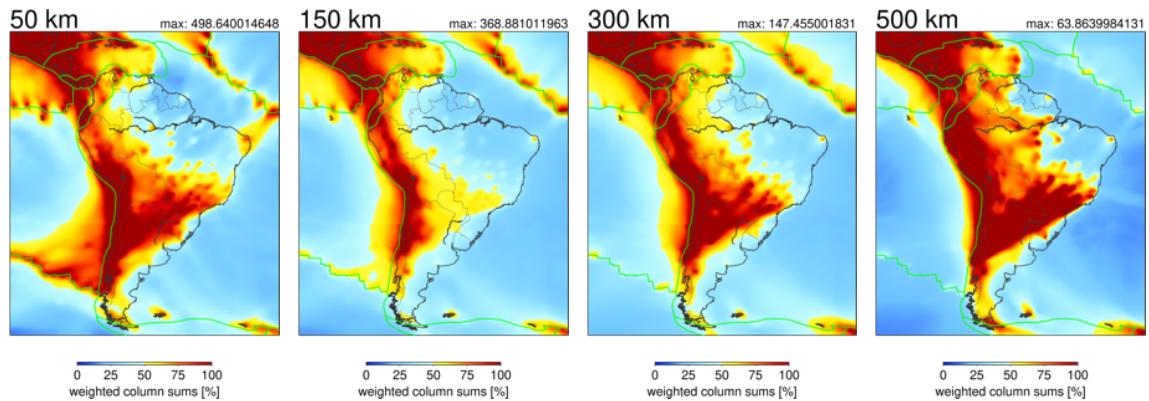
3.8.1 Global Data Distribution



Supplementary Figure 3.1: Global seismic data coverage used in the construction of SACI-24. Seismic stations are plotted in red; triangles indicate global stations with freely available data

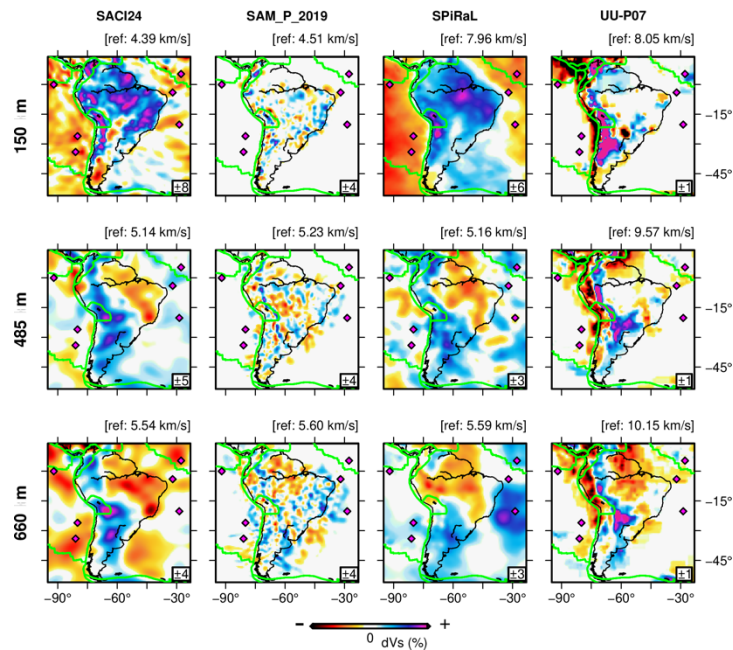
and squares the stations from "3-Basin" network in South America; Events are blue stars, all used in the tomography.

3.8.2 Data Sampling per Depth Column Sums



Supplementary Figure 3.2: Data Sampling at Four Different Depths. The sums of the matrix columns yield a better measure of the relative sampling of each model knot, taking into account the variability in structural information provided by each waveform fit, the sensitivity volumes, and the path similarity weights.

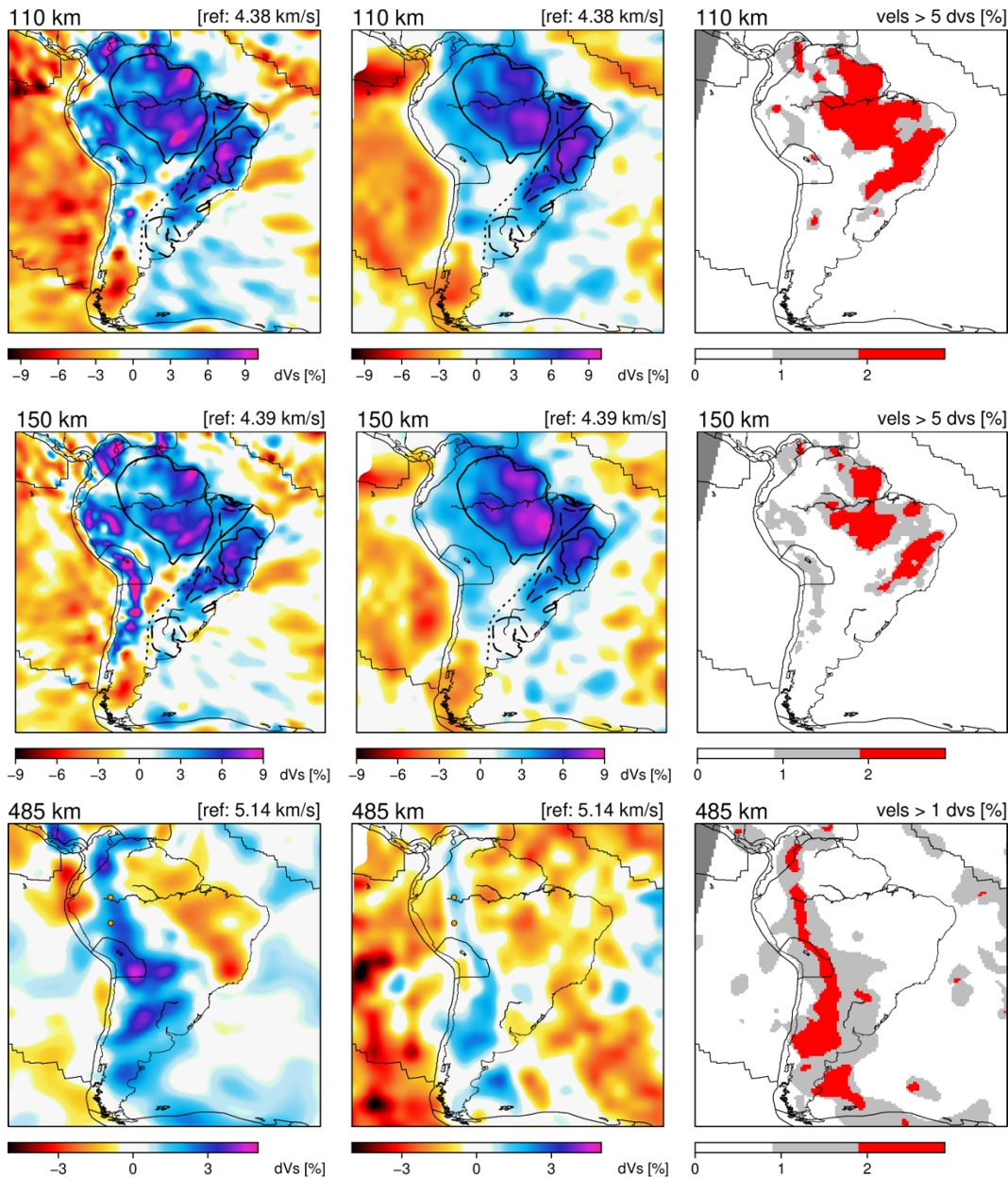
3.8.3 Model Comparison with Body Wave Models



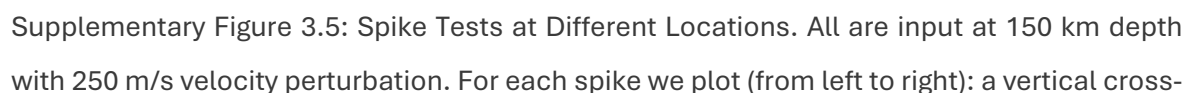
Supplementary Figure 3.3: Comparison of the model with body-wave velocity models at the upper mantle depths. The models are: SAM5_P_2019 (Portner et al. 2020); DETOX-P2 (Hosseini et al. 2020); LLNL_G3Dv3 (Simmons et al., 2012); UU-P07 (Amaru, 2007); PRI-P05 (Li

et al., 2005). All models are plotted with respect to their mean velocity at depth, shown at the top right of the images. The limits of the colour scale are at the bottom right of each image. Plate boundaries are plotted in green.

3.8.4 Model Comparison with SAAM₂₃



Supplementary Figure 3.4: Comparison of SACI-24 and SAAM₂₃. Columns from left to right: our model SACI-24, the SAAM₂₃ model by Ciardelli et al. (2022) and the vote map for the two. The vote map displays areas where seismic velocities exceed a specified threshold (indicated at the top of the plot) in either or both models. A '1' value is registered at points where velocities surpass the threshold in a model. The cumulative vote map is an aggregate of votes from each



section through the input and output models. Horizontal and vertical 1-D S-wave anomaly profiles along the cross-section. The location of the spikes on the map as red stars.

3.8.5 Synthetic Column Tests

Supplementary Figure 3.6 presents a series of synthetic column tests. The synthetic pattern, in each case, comprised columns of constant diameter of approximately 2.2° and a velocity perturbation of 300 m/s, distributed across the continent. These columns are set at different distances from each other in different tests—approximately 9° , 5.5° , and 3° .

In the first test, where the columns are separated by 9° , the output model closely matches the amplitudes and shapes of the input one, particularly in well-sampled areas. The recovery of anomalies is the most accurate along the western coast. Beneath the continental interior and the oceans, the amplitudes are reduced and the anomalies broaden, indicating averaging lengths exceeding the column-footprint width on the map. At this separation distance between the columns, there is no smearing or leaking of amplitudes between them.

In the second test, with a 6° separation, the results are similar to the first test in well-sampled areas. In the southern Atlantic Ocean and north-eastern Brazil, we observe smearing of the seismic anomalies between neighbouring columns.

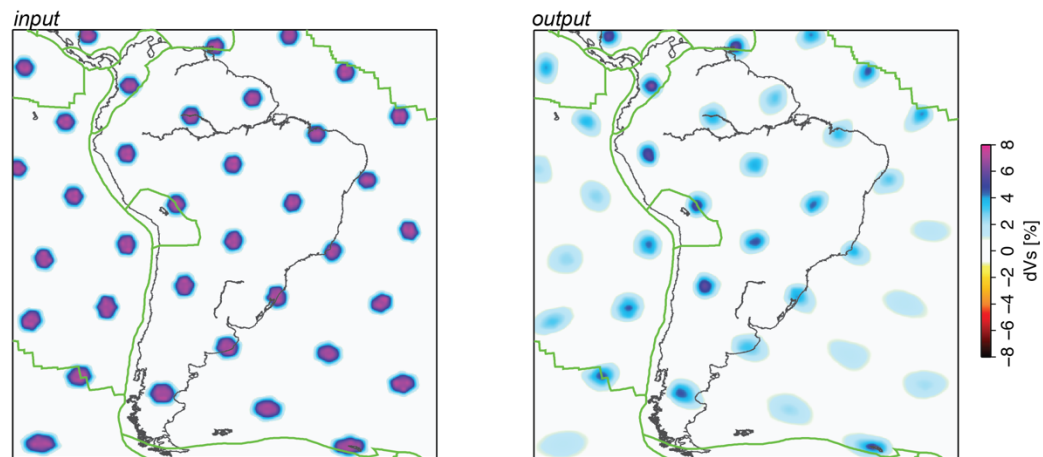
In the test featuring a 3° column spacing, greater smearing between the structures appear in most parts of the oceans, north-eastern Brazil, and the Amazonia region. Despite the tight spacing, the model still recovers accurately the amplitude and shape of anomalies in the best-sampled areas, such as along the subduction zones and the central continental region. IN the NE part of the continent, low-amplitude artificial anomalies connect some of the pairs of columns, but the locations of the columns are still resolved correctly, clearly identifiable by high anomaly amplitudes.

These tests illustrate qualitatively the ability of the tomography to resolve gaps between anomalies, of different widths and in different locations in the region. In parts of the continent, gaps may be partly filled with elongated artefacts along the NE-SW azimuth, but the artefacts have amplitudes substantially lower than those of the recovered true anomalies.

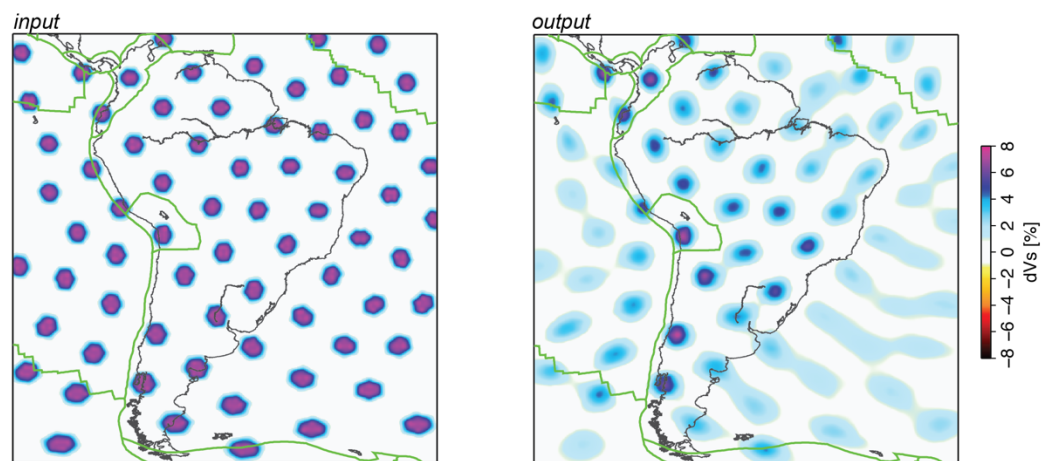
Synthetic Column Tests (80-200 km depth; 300 km/s).

Figures at 110 km depth, with a velocity reference of 4.38 km/s.

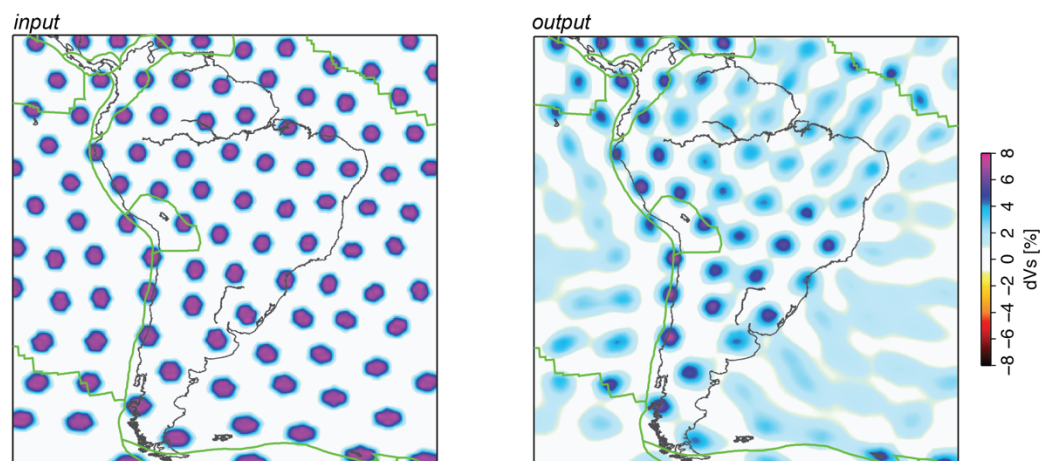
1) 8 nodes spacing



2) 5 nodes spacing



3) 3 nodes spacing



Supplementary Figure 3.6: Column resolution tests. The input synthetic columns have hexagonal cross-sections in the map view and extend from 80 to 200 km depth. The width of the columns is $\sim 2.2^\circ$, and the velocity perturbation within them is 300 m/s. From top to bottom, we decrease the separation distance from $\sim 9^\circ$ to 5.5° and 3° .

4 Origin and Distribution of the Intraplate Magmatism of South America

Abstract

The South American platform experienced significant intraplate volcanism during the Mesozoic and Cenozoic Eras, much of it associated with the break-up of Gondwana. This includes the large-scale Central Atlantic Magmatic Province and Paraná-Etendeka Large Igneous Province. The origins of the magmatism are debated, with models ranging from a mantle plume impact to lithospheric extension and edge-driven convection. Here, we investigate the origins and mechanisms of the magmatism using a new, high-resolution, S-wave velocity tomographic model of the South American Plate. The model was calculated with a large dataset of global and regional seismic waveforms and resolves the upper mantle structure at a new level of detail. We also compile an extensive Mesozoic-Cenozoic magmatism dataset and analyse it jointly with the tomography, also including evidence from hotspot tracks and from recent whole-mantle tomography models. Prominent low-seismic-velocity anomalies under the South American platform's lithosphere extend down into the deep upper mantle, with the strongest anomaly in the mantle transition zone found beneath southeast Brazil. Whole-mantle tomography shows that this anomaly extends to ~2000 km depth, suggesting a deeply rooted mantle plume. Interaction with slab fragments from the long-lived Nazca subduction modifies the plume ascension path, causing it to branch out and travel horizontally to areas of thin oceanic lithosphere, where we find the present-day location of the many hotspots in the Atlantic Ocean. On the western coast, the low velocity anomaly associated with the Galápagos plume extends westwards, where it leads to a strong slow velocity anomaly ponding under the Peruvian segment of the Nazca subduction. In the lithosphere, our model SACI-24 maps the intricate shape of cratons, that, together with the reconstructed position of hotspots, reveals that lithospheric thickness is the main control on the distribution of volcanism in large igneous provinces.

Keywords: Waveform Tomography, South America, Brazil, Intraplate Volcanism, Mantle Plumes, Lithosphere, Asthenosphere, Large Igneous Provinces, Hotspots.

4.1 Introduction

The South American platform comprises the stable central and eastern parts of the continent. It experienced numerous episodes of volcanism during the Mesozoic and Cenozoic Eras, much of it at the time of the protracted break-up of Gondwana. That included the extensive Central Atlantic Magmatic Province (CAMP), contemporaneous with the opening of the Central Atlantic around 201 Ma, and the Paraná Magmatic Province (PMP), which preceded the opening of the South Atlantic at approximately 135 Ma. Additionally, sporadic, small-volume volcanism occurred throughout the Borborema province in northeastern Brazil, from the Mesozoic era to as recently as 7.1 Ma (Knesel et al., 2011), and, post-PMP, along the southeast Brazilian coast, ranging in age from 95 to 28 Ma (Almeida et al., 1996) (Figure 4.1).

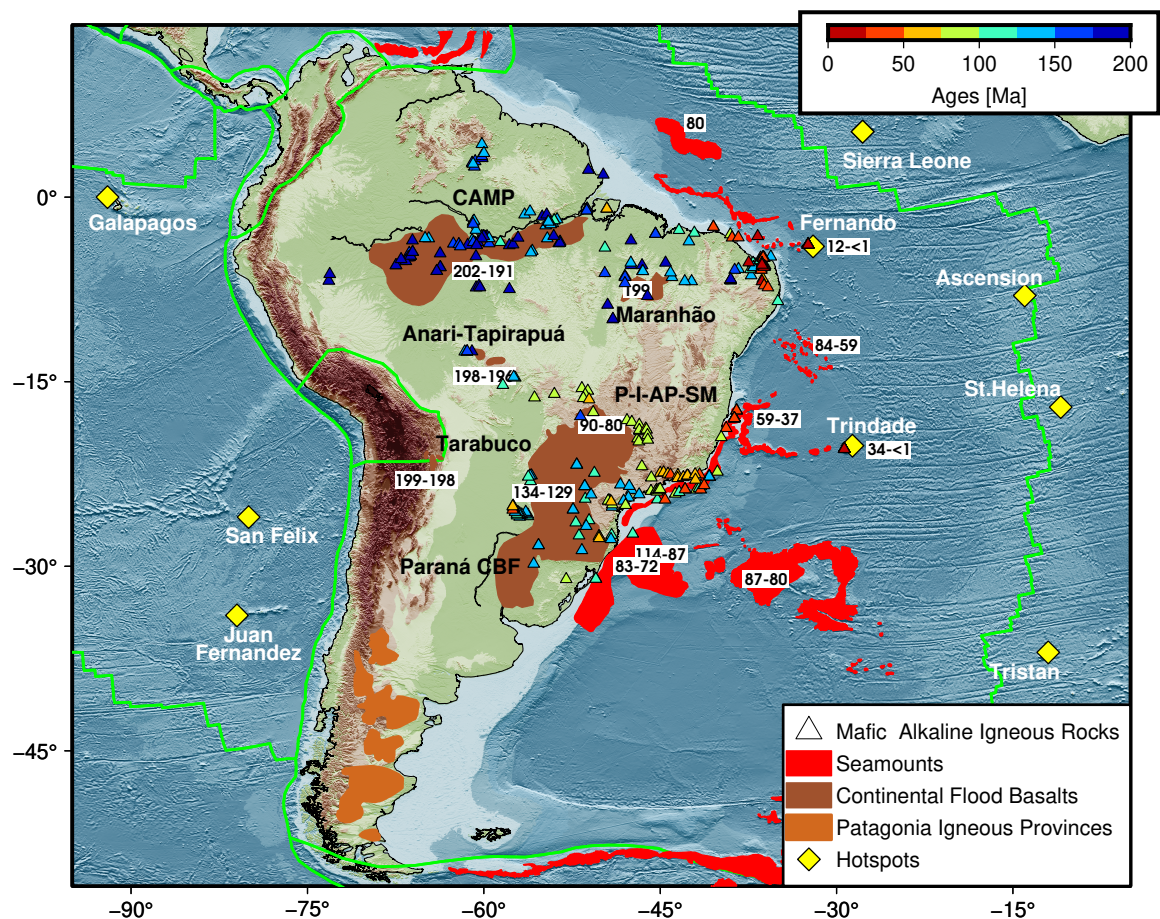


Figure 4.1: Main Magmatic Provinces of South America. Samples of mafic alkaline igneous rocks (Mizusaki et al., 2002; Ribeiro et al., 2018; Tassinari, 1996) are plotted as triangles, with the colour fill representing the measured age. In the continent, brown filled contours are continental flood basalts (CBF). In the oceans, contours filled in red are seamounts and volcanic plateaus. The numbers indicate the province age in millions of years (Ma). P-I-AP-SM:

Poxoréu, Iporé, Alto Paranaíba and Serra do Mar Provinces (Gibson et al., 1995). Hotspot locations are from Whittaker et al. (2015). Major plate boundaries are marked in green lines (Bird, 2003).

The origin of the intraplate volcanism is a subject of debate. More evidence is required on the current and past dynamics of the mantle and melting within it. In this study, we use our new S-wave velocity tomographic model, SACI-24, to constrain the structure of the crust and upper mantle beneath South America and the surrounding oceans. SACI-24 is computed using an extensive dataset of waveform fits from both regional and global seismograms, enabling us to significantly enhance the resolution of the imaging beyond that of the existing continental scale and global models. The model reveals detailed upper mantle structure beneath the hotspots on the South America and Nazca plates and provides evidence on their interactions with the lithosphere and subducting slabs. We also compile a large dataset of magmatic events in South America since the Mesozoic, containing mafic and alkaline igneous rock locations and ages (Mizusaki et al., 2002; Ribeiro et al., 2018; Tassinari, 1996) and flood basalt data (Heimdal et al., 2018; Peate et al., 1992).

We do not limit the tomographic evidence to that from our own new model but compare a range of recent models which, together, represent the current state of the art. We complement the tomography evidence with complementary geophysical, geochemical, and geological data. The results of our analysis suggest that the thermal upper mantle anomalies and associated magmatism have a deep mantle basic origin. The enigmatic distribution of the magmatism is likely to have been shaped both by the complexities in the morphology of hot mantle upwellings and by the lateral variations in the thickness of the lithosphere.

4.2 Main Magmatic Provinces of South America

Two significant magmatic events have notably impacted the South American continental margins and interior since the Mesozoic. The Central Atlantic Magmatic Province (CAMP) comprises flood basalts, mafic dyke swarms and layered sills, emplaced in Pangea at around 201 Ma (Davies et al., 2017; de Min et al., 2003; Marzoli et al., 2018).

CAMP is a unique magmatic province due to its vast spatial extent, the large volume of intruded mafic magmas, and the relative rarity of preserved lava piles (Marzoli et al., 2018). In South America, the CAMP tholeiitic magmatism extends from the continental margin into the Amazon Craton (de Min et al., 2003) and is proposed to have reached as far

as Bolivia (Bertrand et al., 2014). It has been suggested that CAMP's origin is related to a mantle plume associated with either the Fernando or the Cape Verde hotspot (A.M. Leitch et al., 1998; Marzoli et al., 1999a; Wilson, 1997b). Alternative explanations include the incubation of hot upper mantle beneath thick continental lithosphere (de Min et al., 2003) and edge driven convection caused by steps in the lithospheric thickness (de Min et al., 2003; McHone, 2000). The enriched signature of the CAMP mantle source has been attributed to a deep mantle plume and, alternatively, to recycled continental crustal material (Callegaro et al., 2013; Merle et al., 2011; Whalen et al., 2015) and to the mantle enriched by subducted continental sediments (Merle et al., 2014).

The following major magmatic event in South America was the emplacement of the Paraná-Etendeka large igneous province (LIP). It preceded and was partly coeval with the break-up of Gondwana and the opening of the South Atlantic Ocean. The Paraná-Etendeka LIP is connected to seamounts, oceanic plateaus and age-progressive volcanic chains on both the South American and African plates (Darros de Matos, 2021; Fairhead and Wilson, 2005; Will and Frimmel, 2018).

The origin of the Paraná-Etendeka LIP has been attributed to the arrival a mantle plume between 135-130 Ma, with its tale causing the recent volcanism at Tristan da Cunha (Turner et al., 1994). This igneous province is one of only three globally where flood basalt emplacement was followed by small volume magmatism forming linear, age-progressive volcanic chains, as can be expected for the plume head-plume tail volcanism sequence (Courtillet et al., 2003). Using plate reconstructions, the Tristan Plume can be tracked back to the South American continent along the Rio Grande rise (Mohriak et al., 2010) and Santos and Pelotas basins (Geraldès et al., 2013), where it reaches southeast Brazil and the Paraná Igneous Province.

There are a few other hotspots in the South Atlantic Ocean: the Trindade, Sierra Leone, Ascension and St. Helena hotspots (e.g., Darros de Matos, 2021). The Trindade hotspot is thought to be located beneath the Trindade and Martin Vaz Islands, offshore southeast Brazil, at the end of the E-W Trindade volcanic chain. The Abrolhos magmatic province at the ocean-continent transition is considered the link between the oceanic volcanic island chain and the Poxoréu, Iporá, Alto Paranaíba, and Serra do Mar igneous provinces (Stanton et al., 2021). The earliest volcanism attributed to the Trindade hotspot is the mafic alkaline eruptions of the Poxoreú igneous province (Figure 3.1) at 85 Ma on the continental interior (Gibson et al., 1997).

For the Sierra Leone and St. Helena hotspots, there is no clearly visible trail of volcanic islands and seamounts on the South American plate as there is on the African plate

(Darros de Matos, 2021). Recently, the Pernambuco and Bahia seamounts offshore northeast Brazil have been attributed to the St. Helena hotspot (Skolotnev et al., 2012a, 2012b), and the Demerara Plateau—to the Sierra Leone hotspot (Basile et al., 2020). There is ongoing debate on whether the volcanic Ascension Island has a deep mantle plume origin that is linked to the St. Helena hotspot (Kawabata et al., 2011; Montelli et al., 2006; Zhang et al., 2021) or a mid-ocean ridge origin (Hoernle et al., 2011; Paulick et al., 2010).

The Borborema province in north-eastern Brazil hosts the youngest continental volcanism of the South American stable platform, dated at 7.1 Ma (Knesel et al., 2011). Recurrent magmatic events occurred in this area since 200 Ma (Mizusaki et al., 2002). This region is also a site of Cretaceous tectonic uplift, which has been proposed to be due to asthenospheric upwelling or lithospheric thinning (e.g., Morais Neto et al., 2009). The Cenozoic volcanism in this area is often attributed to the Fernando hotspot offshore (Almeida, 1987; Fodor et al., 1998; Mizusaki et al., 2002). The long duration and the lack of the spatial age progression of the volcanism motivated other explanations for it, including edge-driven convection (King and Ritsema, 2000; Knesel et al., 2011). Alternatively, Sleep (2003) suggested that both the Fernando and Trindade volcanic island chains originate from lateral flow from plume material that had been ponding under the continent and was then transported horizontally from west to east along ocean fracture zones.

4.3 Waveform Tomography

Our high-resolution tomographic model, SACI-24 (Chapter 2), was constructed using over 1.2 million global and regional seismograms with the source-station paths crossing the half hemisphere centred on South America. They were obtained from more than 27,000 earthquakes and over 9,000 broadband seismic stations (Figure 4.2).

SACI-24 was computed as a global model, so that it does not have any model boundaries, but the inversion tuning, and error analysis were focussed particularly on the South American Plate region. We gathered all freely accessible broadband data from global data centres and complemented it with data from the stations from the temporary FAPESP "3-Basins Thematic Project". In the deep upper mantle, SACI-24 is constrained by long-period fundamental and higher mode surface waves. In the shallow upper mantle and crust, the sensitivity of those waves is complemented by that of the shorter period surface waves. The combined regional and global dataset ensures the densest possible data sampling of the South American continent, its margins, and surroundings.

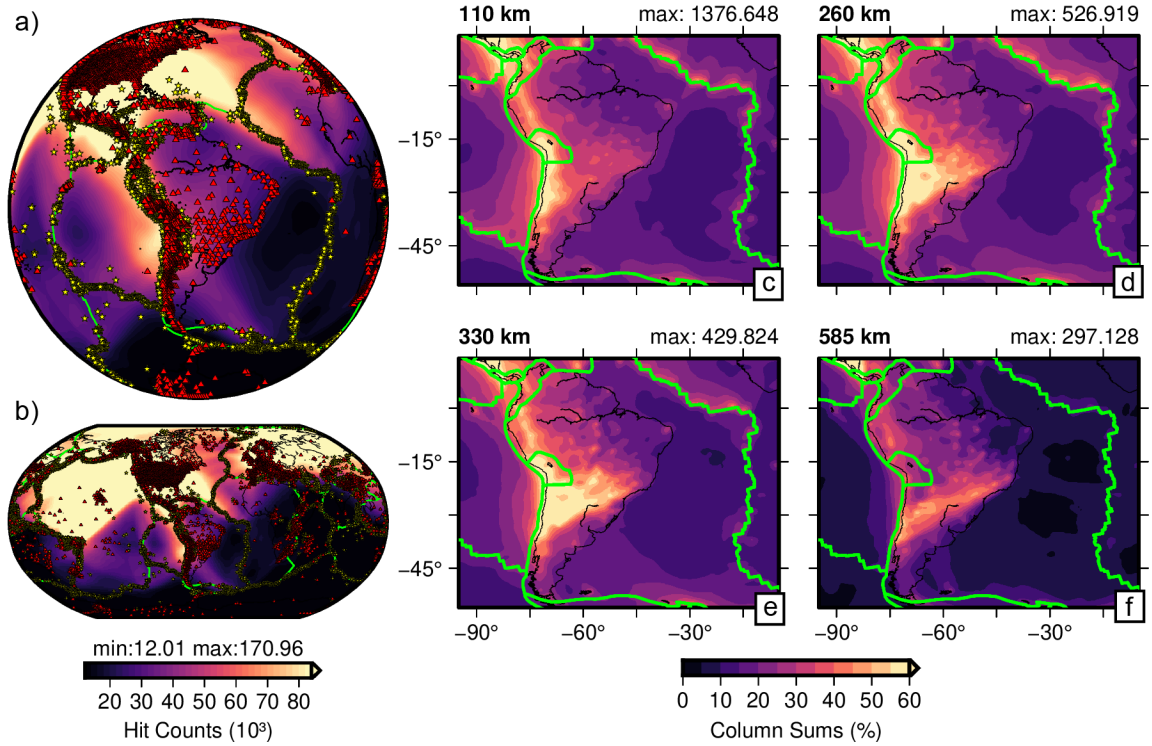


Figure 4.2: Seismic data coverage. a, b) number of approximate sensitivity areas sampling each node in the study region and globally. Red triangles represent the seismic stations used in the study, and yellow stars—the events. c-f) The sums of the columns of the sensitivity matrix are proxies for the structural information provided by each waveform fit, accounting for sensitivity volumes and path similarity weights at each depth. Values are plotted in percentage in relation to the maximum value, shown in the top right corner of each figure.

The seismograms were inverted for a 3D Earth model in a three-step inversion procedure. Firstly, the Automated Multimode Inversion (AMI) technique is employed to fit the waveforms (Lebedev et al., 2005). This method calculates synthetic seismograms using mode summation and fits the surface, S, and multiple S waves in a seismogram-specific set of weighted time-frequency windows. AMI minimises the misfit in the time domain and, as the result of the waveform inversion, produces a set of linear equations with uncorrelated uncertainties for each seismogram (Nolet, 1990). These equations quantify the average S- and P-wave velocity deviations from a 3D reference model within approximate sensitivity volumes (Lebedev et al., 2005; Lebedev and van der Hilst 2008).

In the next step, all the equations are jointly inverted for the 3D distribution of P- and S-wave velocities in addition to 2Ψ S-wave azimuthal anisotropy (Lebedev and Van Der Hilst, 2008). This is achieved using the LSQR method (Paige and Saunders, 1982) with

smoothing and small norm damping (Nolet, 1990; Lebedev and van der Hilst, 2008). Our tomographic model is parameterised using a dense triangular grid (Wang and Dahlen, 1995) with approximately 120 km lateral knot spacing. Radially, the grid comprises 18 and 10 triangular radial basis functions for S- and P-wave velocities, respectively. For S-wave velocities, the basis functions are centred at 7, 20, 36, 56, 80, 110, 150, 200, 260, 330, 410-, 410+, 485, 585, 660-, 660+, 809, and 1007 km; for P-wave velocities—at 7, 20, 36, 60, 90, 150, 240, 350, 485, and 585 km. Model parameter perturbations are computed with respect to the same 3D model as used in AMI, which combines a modified CRUST2 (Bassin et al., 2000)—with added topography and smoothed at cell boundaries—and our own global 1D mantle average (Lebedev and Van Der Hilst, 2008).

In the third step of the inversion procedure, the automatic outlier analysis is performed (Lebedev and Van Der Hilst, 2008), selecting the most mutually consistent equations and exploiting the data redundancy given by the large amount of waveforms in our dataset.

We employ the Global Centroid-moment-tensor (GCMT) catalogue (Ekström et al., 2012) to determine earthquake source parameters from 1994 onwards. Then, we apply a threshold varying on a distance-magnitude scale (Schaeffer and Lebedev, 2013, p. 200). In our final model, each node within the research area is sampled by a minimum of 12,000 fits, with optimally sampled regions reaching up to 170,000 fits.

4.3.1 Resolution Tests

A common way of validating specific features in seismic tomography is by the construction of synthetic resolution tests. It consists of calculating synthetic data from a synthetic velocity structure and then, inverting the synthetic data for a tomographic model, using the same regularisation parameters as the real data inversion. The ability of the inversion to recover the input model can be used as an indication of the real model accuracy (Rawlinson et al., 2010) and will depend on the data coverage and regularisation parameters. AMI been tested previously using inversion of two benchmark datasets calculated using numerical wave propagation and showed high accuracy in the recovery of unknown synthetic anomalies (Lebedev and van der Hilst, 2008; Qin et al., 2008). Additionally, we have performed several resolution tests on SACI-24, including columnar checkerboard tests (Section 2.6.1), spike tests and “cratonic type” structural tests (Section 3.4.1).

Here we will show and discuss resolution tests developed to specifically test features of the model discussed in this chapter. These include: alternating velocity columns within

the mantle intermediate depths (Figure 4.3) and transition zone depth nodes (Figure 4.4 and Figure 4.5); vertical synthetic columns at the proposed hotspot locations on the surroundings of South America (Figure 4.6); and the removal of the structures below the cratonic areas, to investigate the effect of the strong positive velocities of the cratonic lithosphere in the continent in the greater depths (Figure 4.7 and Figure 4.8).

In Figure 4.3, we show a checkerboard resolution test we constructed in order to evaluate the model's accuracy in resolving seismic structures in the intermediate mantle depths (200 – 410 km). The input model consists of alternating ± 300 m/s velocity columns, with a geometry similar to model c) in Figure 2.8 (four nodes width and ~ 12 nodes spacing). The resulting model shows seismic structures that are well resolved in both location and amplitude, over the continental and oceanic regions.

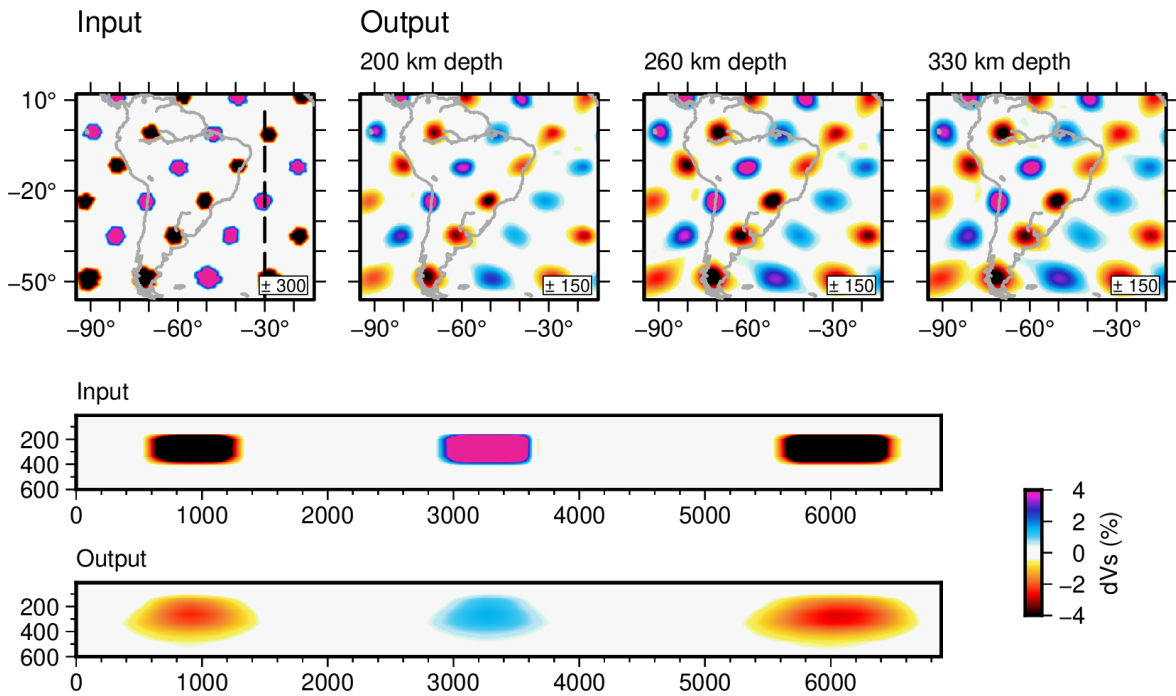


Figure 4.3: Column resolution tests at the depth nodes 200, 260, 330 and 410 km. The input structures are defined with alternating positive and negative columns of 300 m/s. Vs colour scale boundaries are shown at the bottom right of each top panel. The input and output models are shown as depth slices at the top and vertical cross sections at the bottom. The cross section is shown as a black line in the first plot on the left.

In Figure 4.4 and Figure 4.5, we construct input synthetic models to test the model's resolution within the mantle transition zone (410-660 km depth). Figure 4.4 consists of vertical synthetic columns located at 410, 485, 585 and 660 km depth, and Figure 4.5 consists of vertical columns at 485 and 585 km depth only. Both input structures consist of alternating

± 300 m/s velocity columns, with a geometry similar to model c) in Figure 2.8 (four nodes width and ~ 12 nodes spacing).

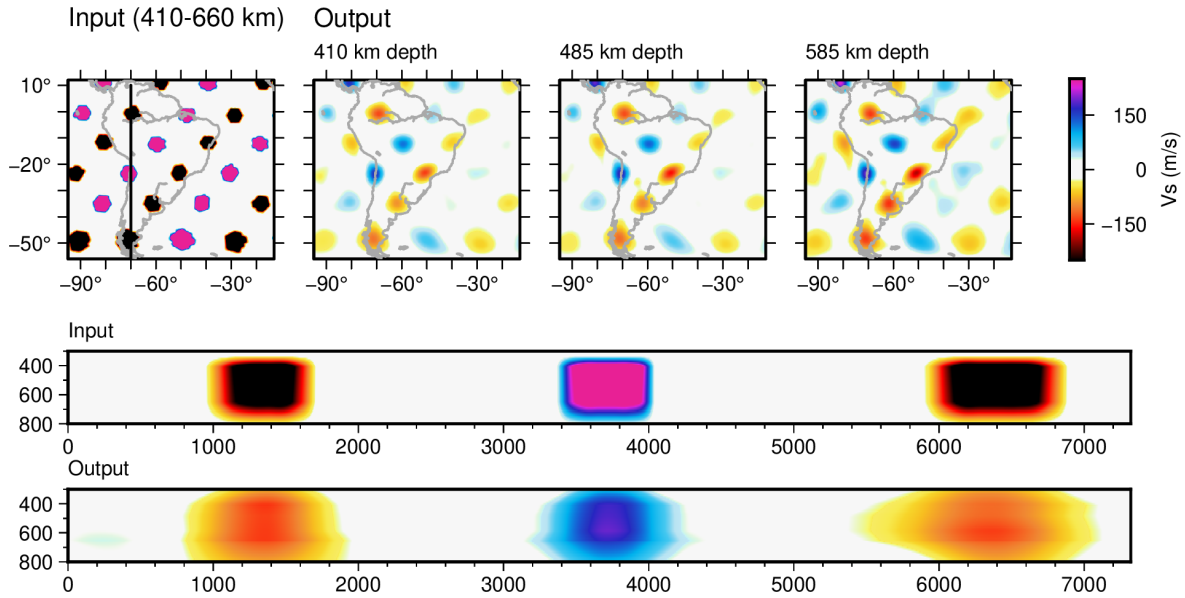


Figure 4.4: Column resolution tests at the depth nodes 410, 485, 585 and 660 km. The input structures are defined with alternating positive and negative columns of 300 m/s. The input and output models are shown as depth slices at the top and vertical cross sections at the bottom. The cross section is shown as a black line in the first plot on the left.

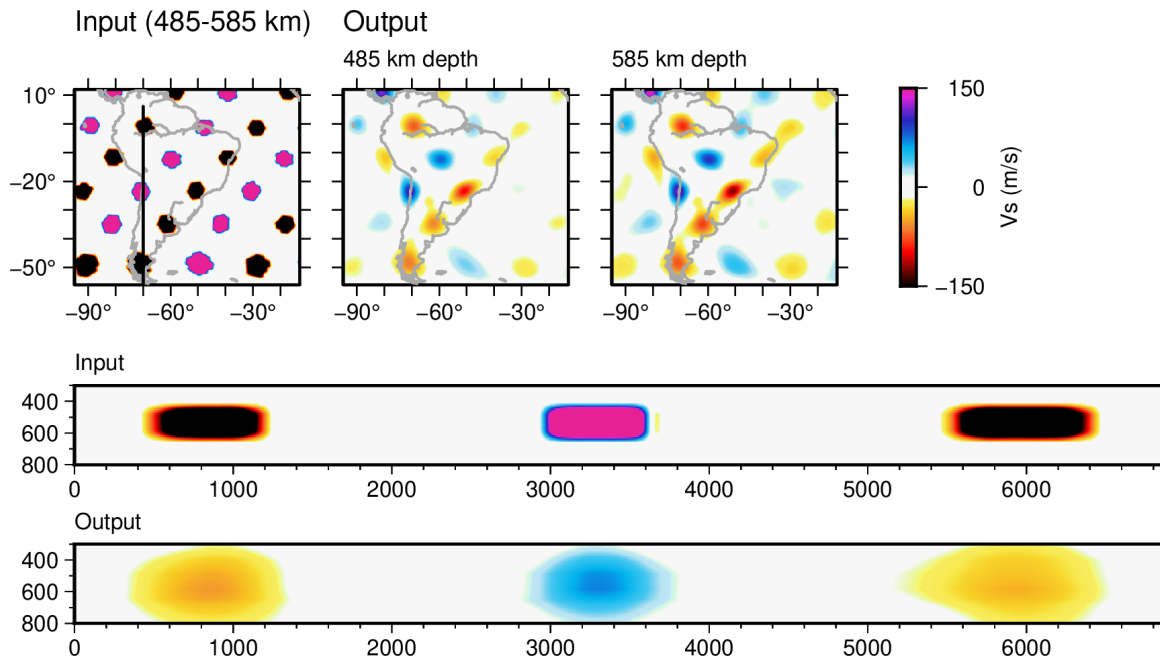


Figure 4.5: Column resolution tests at the depth nodes 485 and 585 km. The input structures are defined with alternating positive and negative columns of 300 m/s. The input and output

models are shown as depth slices at the top and vertical cross sections at the bottom. The cross section is shown as a black line in the first plot on the left.

In Figure 4.4 and Figure 4.5 the output model recovers the shape of the input structures, especially in the continental region. The longer input structures spanning the entire transition zone at the depth nodes from 410 to 660 km are recovered slightly better in the output model than the shorter anomalies spanning only the 485-585 km depth nodes range. Despite having slight loss of the lateral shape and smearing in the oceanic regions, all input columns are recovered in the output model both in the continent and the ocean. For the shorter columns, spanning the two depth nodes at 485 and 585 km, some loss of the structures on the oceanic areas is observed. In the continents, however, the model resolves the structures both in location and shape. Small scale vertical smearing in the output models is observed where anomalies are smoothed out to the nearby depth nodes above and below.

In Figure 4.6 we show the input synthetic structure, which consists of vertical columns from 80 to 660 km depth and laterally of two nodes width. The columns are constructed with -300 m/s and located at the hotspot locations given by the catalogue of (Whittaker et al., 2015). The geometry of the input structure have the function of simulating a vertical thin mantle plume on the oceanic regions surrounding South America.

From the resulting model, we can observe that SACI-24 resolves the location and amplitude of the columnar structure across all depths. The very closed spaced hotspots in the south Pacific appear as one, and we observe small scale smearing of the anomalies (~10% of the amplitude) from the ocean towards the continent. Despite that, the resolution model offers further validation on the model's regularisation and sampling to resolve structures in the oceanic regions and of this scale.

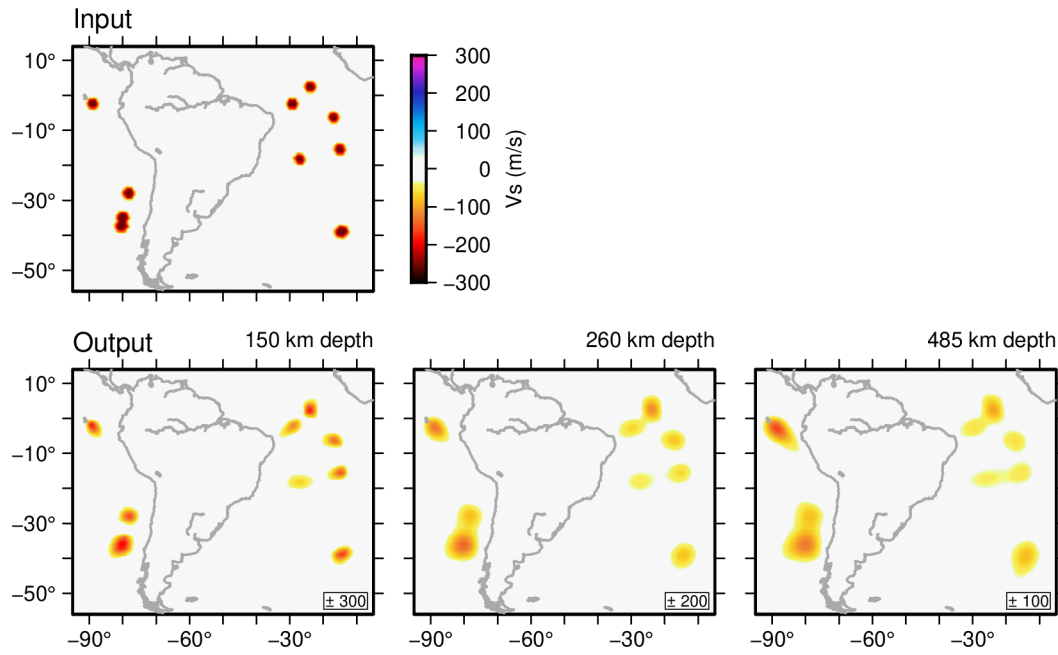


Figure 4.6: Vertical columns at hotspot locations. In this resolution test, we input vertical columns of 2 nodes width and -300 m/s seismic velocity at the hotspot locations of our model area from the catalogue of (Whittaker et al., 2015). The output velocities are shown with the colour scale boundaries shown on the bottom of each map.

The following resolution tests shown in Figure 4.7 and Figure 4.8, consist of the removal of the velocity anomalies at a desired area from the final model, instead of designing a synthetic structure from a blank model. After modification of the model, we calculate the synthetic data, and from it, re-invert for the seismic velocities. Doing so, we wish to remove data that are sampling specific structures. The resulting model is then expected to not find velocity anomalies at the region where we removed the data. If a seismic anomaly is found where the data is removed, we can conclude that the anomaly is not calculated from the data and is in fact a seismic artefact. We wish to investigate if the broad low seismic velocities we find under the lithosphere is a seismic artefact created for example, from the high seismic velocities of the continental cratonic lithosphere or of the western Nazca slab.

In Figure 4.7 we defined the -1.5% dVs velocities contour at 485 km depth and used it to remove all velocity anomalies located within the contour in the transition zone, from 410 to 660 km depth. In the resulting model, the slow anomaly is removed completely, indicating that the strong slow velocity we find in the transition zone is not the result of a seismic artefact and is explained by the data.

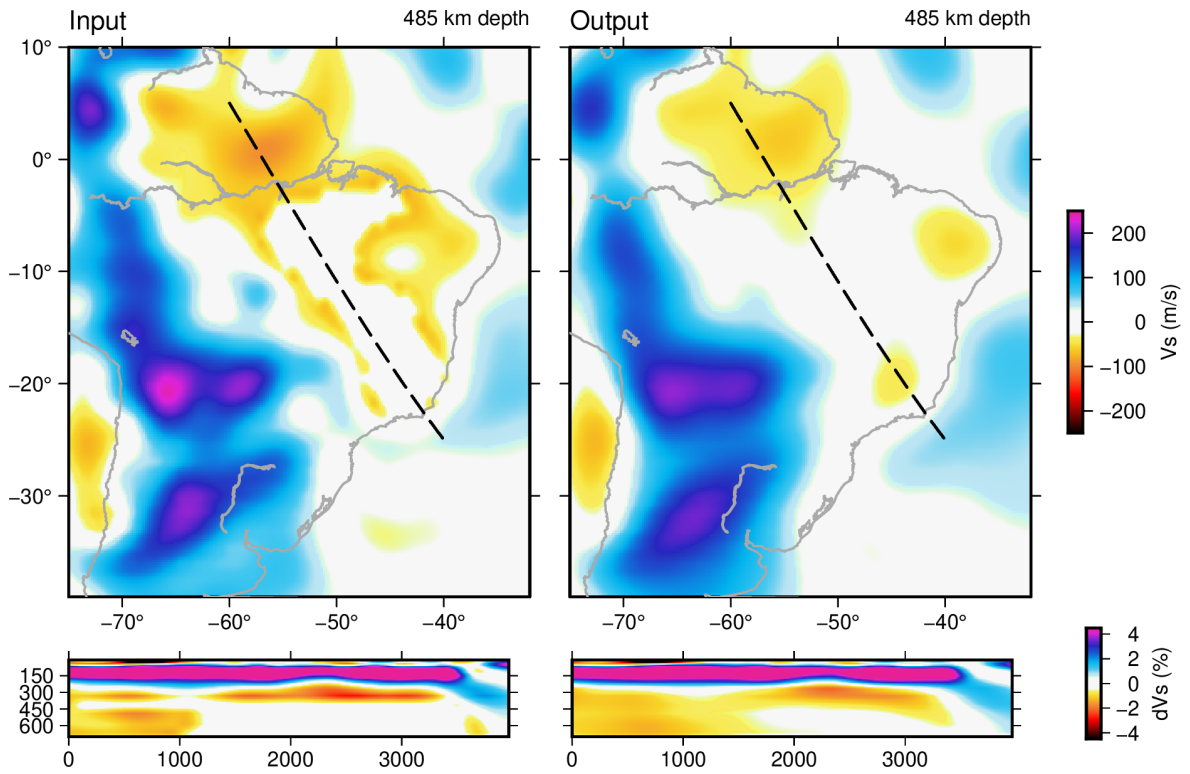


Figure 4.7: The input of the resolution test consists of a modified seismic structure from SACI-24. We removed from our final model the slow velocity anomaly located in the mantle transition zone from 410 km to 660 km depth.

In the following resolution test (shown in Figure 4.8), we wish to investigate further the possible effect of the thick cratonic lithosphere on the underlying mantle depths. From the final SACI-24 model, we remove the block of seismic velocities located below the continental cratonic lithosphere, starting from 200 km depth down to 810 km depth. In the resulting model, seismic velocities are removed completely from below the cratonic lithosphere. With these resolution tests, we can confirm that the seismic velocities shown by our model below the continent's cratons are not seismic artefacts and must be explained by the data.

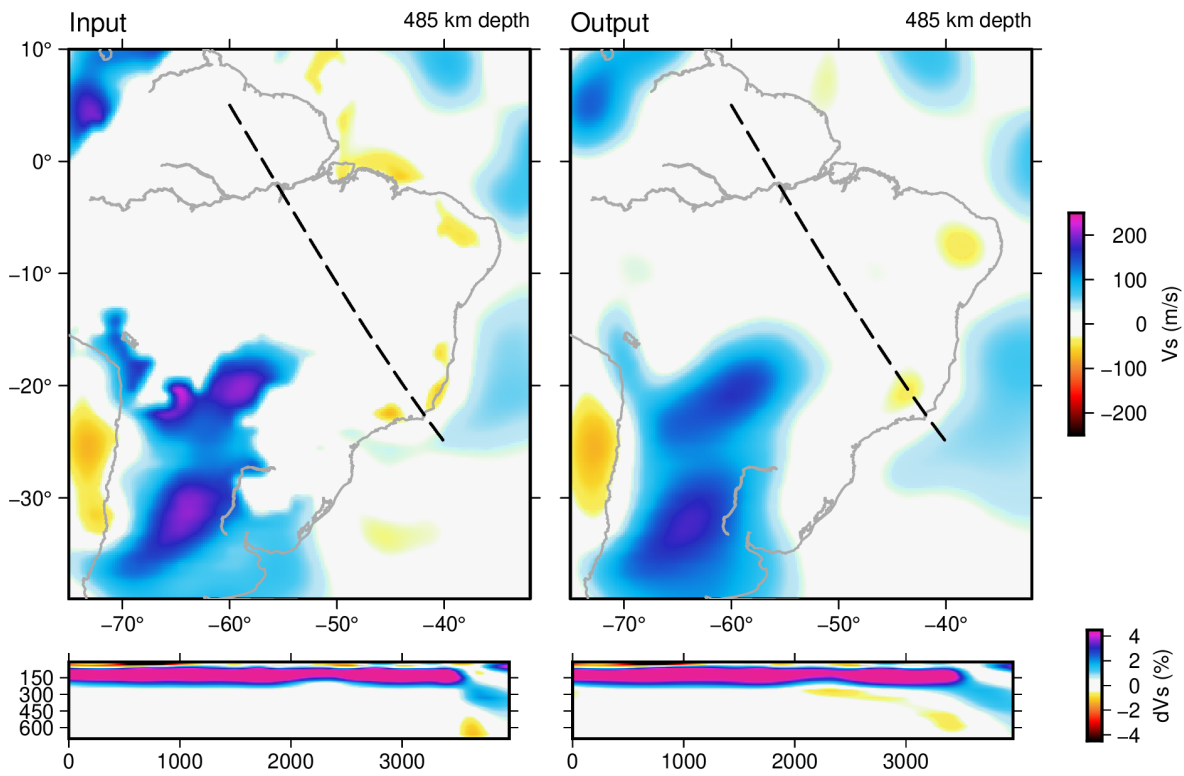


Figure 4.8: In this resolution test, we removed all anomalies from below cratonic lithosphere, from 260 km to 660 km depth.

4.4 Results

The model SACI-24 captures the upper mantle structure of both the South American continents and the surrounding oceans—the South Atlantic Ocean and the eastern Pacific Ocean (Figure 4.9). Within the lithosphere and upper asthenosphere (80-150 km depth range) seismic velocities beneath the eastern Pacific Ocean are, on average, substantially lower than beneath the South Atlantic. Particularly high velocities are observed beneath the Argentine Basin in southwest South Atlantic, which is characterised by anomalously deep bathymetry (Crosby et al., 2006).

On the continent, high seismic velocities ($>5.5\%$ dV_s) indicate blocks of cratonic lithosphere in the centre and east of the continent, as well as the subducting slabs on the north and west. At a depth of 80 km, a prominent area of low seismic velocities is evident in the Central Andes region. This is the area where independent studies indicate a vast region of partially molten crust (Schilling et al., 2006; Schmitz et al., 1997; Schurr et al., 2003). In the stable platform, regions characterised by relatively low seismic velocities ($<0\%$ dV_s) underlie locations of recent volcanic activity, including the Borborema Province in the northeast and Patagonia in the south.

In the west of the continent, the high velocities associated with the Nazca slab subduction are a dominant feature from 150 to 660 km depths. To the east of the slab, high velocities associated with the cratonic lithosphere are observed down to a depth of 200 km. At 260 km depth and below, we observe anomalously low seismic velocities. The low velocity anomalies extend laterally across much of South America's stable platform and down—to the bottom of the transition zone. A particularly strong low-velocity anomaly is observed from 485 km to 660 km depth south of the São Francisco Craton and East of the Paraná continental flood basalts (CFB). A low velocity anomaly in this location was seen in some of the previous tomographic models as well (Rocha et al., 2011; Rodríguez et al., 2020; Vandecar et al., 1995).

Vandecar et al., (1995) proposed that this anomaly indicated a fossil conduit of the Tristan da Cunha mantle plume that moved with the continent as it drifted westward from the South Atlantic Ridge. Van Der Lee and Wiens, (2006) proposed a compositional explanation for this anomaly, attributing it to the water release from the deep Nazca slab. Rodríguez et al., (2020) interpreted the anomaly, instead, as a focused upwelling formed in response to the slab stagnation in the lower mantle. In Section 4.3.1 we developed structural resolution tests specifically to investigate the slow velocity anomaly found below the continental lithosphere in South America. Based on the results, we show that the slow anomalies are not a seismic artefact derived from the high seismic velocities of the cratons above or from the Nazca subduction on the west.

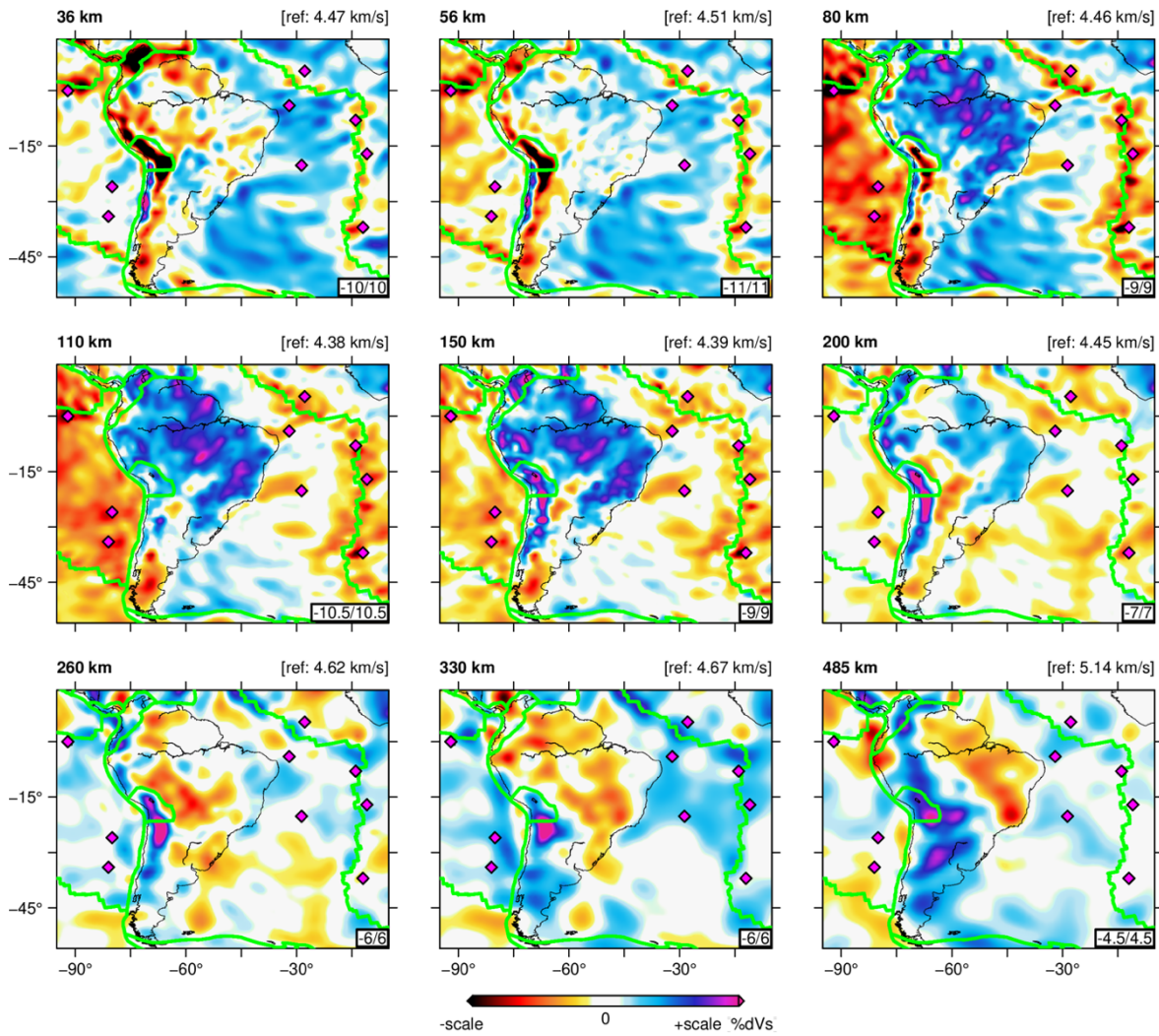


Figure 4.9: S-wave velocities anomalies at 9 depths in the upper mantle. S-wave velocity variations are plotted in percentage with respect to the reference velocity at each depth, indicated at the top of each map.

In Figure 4.10 and Figure 4.11, we present east-west cross sections through the model. For the Nazca plate subduction, we observe a markedly heterogeneous pattern. Low seismic velocities are prominent beneath the continental lithosphere, in particular beneath the central and northern parts of the continent (van der Lee et al. 2002). The strong low-velocity anomaly in the transition zone beneath south-eastern Brazil stands out in Figure 4.10-e near the 5200 km lateral distance mark.

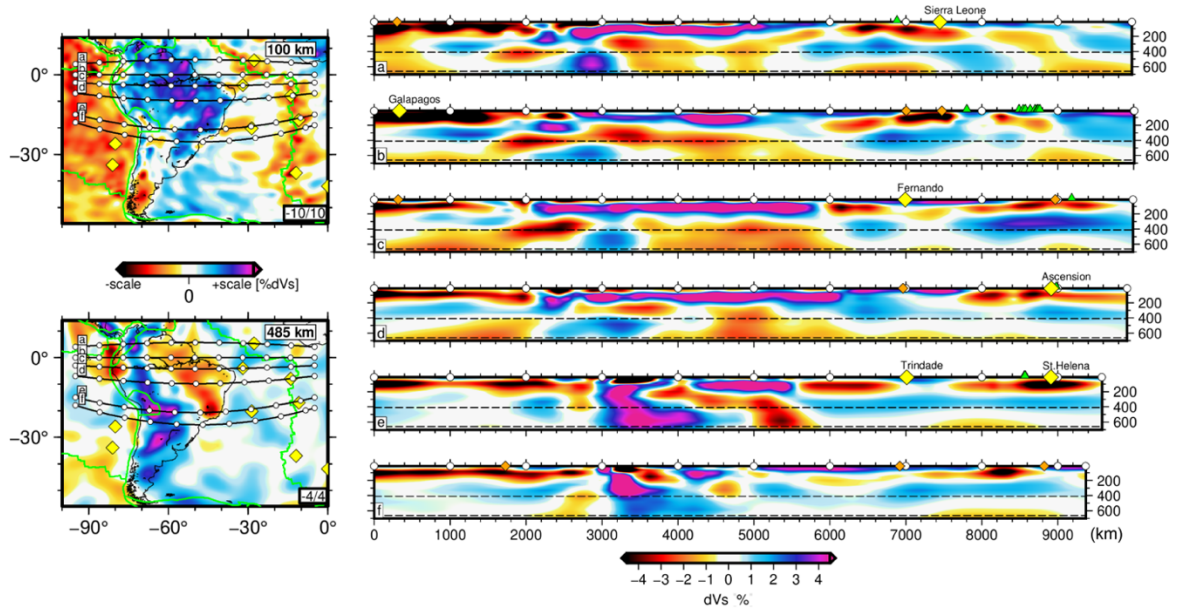


Figure 4.10: Northern South America E-W cross-sections. Yellow diamonds are hotspot locations and green lines (the map) and triangles (the cross-sections) indicate the mid-Atlantic ridge. The locations of the cross-sections (black lines) are shown on the map views of the model at 100 km and 485 km depth.

Around most proposed locations of oceanic hotspots, low seismic velocities are evident in the shallow upper mantle down to 150-200 km depths. However, the same is not observed for the Fernando (Figure 4.10-c) and Trindade (Figure 4.10-f) hotspots, where no substantial slow anomalies are observed. In the resolution test from Figure 4.6, we showed that our model has the data sampling to resolve accurately slow velocity (-300 m/s) vertical columns on the oceans of the scale of small plume conduits (~ 250 km width). In the resolution test from Figure 4.6, we showed that our model has the data sampling to resolve accurately slow velocity (-300 m/s) vertical columns on the oceans of the scale of small plume conduits (~ 250 km width). From the resolution test results we confirm that the model can resolve anomalies of the expected location and dimension of oceanic hotspots. Therefore, we can infer that no hot material conduit is present in these locations.

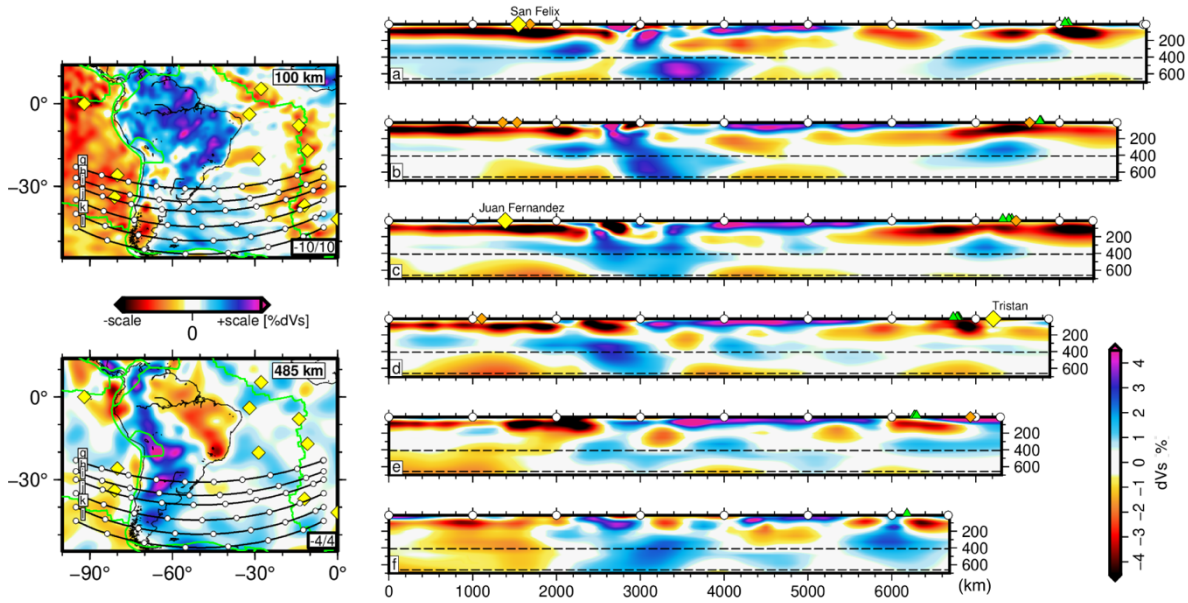


Figure 4.11: Southern South America E-W cross-sections. The locations of the cross-sections (black lines) and hotspots (yellow diamonds) are shown on the map views of the model at 100 km and 485 km depth.

In the Eastern Pacific, prominent low-velocity anomalies are observed to the west of the Nazca slab. Near the Galápagos hotspot, low velocities underlie the ocean across a large area of thousands of kilometers (Figure 4.10-a, b.). To the north of it, we observe a column of low velocities that extends vertically across all depths shown Figure 4.10-a.

4.5 Model Comparison

In Figure 4.12, we compare SACI-24 with the S-wave velocity models SAAM23 (Ciardelli et al., 2022), SA2019 (Celli et al., 2020b) and SL2013 (Schaeffer and Lebedev, 2013) in the upper part of the upper mantle (80 km, 110 km, 150 km and 260 km depth). All models show low seismic velocities under the mid-Atlantic ridge (MAR) down to 150 km depth. At 260 km depth, SACI-24, SA2019 and SL2013 show slightly positive velocities under or close to most hotspots located at or close to the MAR. The model SAAM23 (Ciardelli et al., 2022) is relatively noisy in the oceans, because it was constructed for the South American continent and has a much sparser data sampling in the oceans around it. SACI-24, SA2019 and SL2013, by contrast, use a global distribution of seismic data and offer a more uniform resolution across the region (Celli et al. 2020).

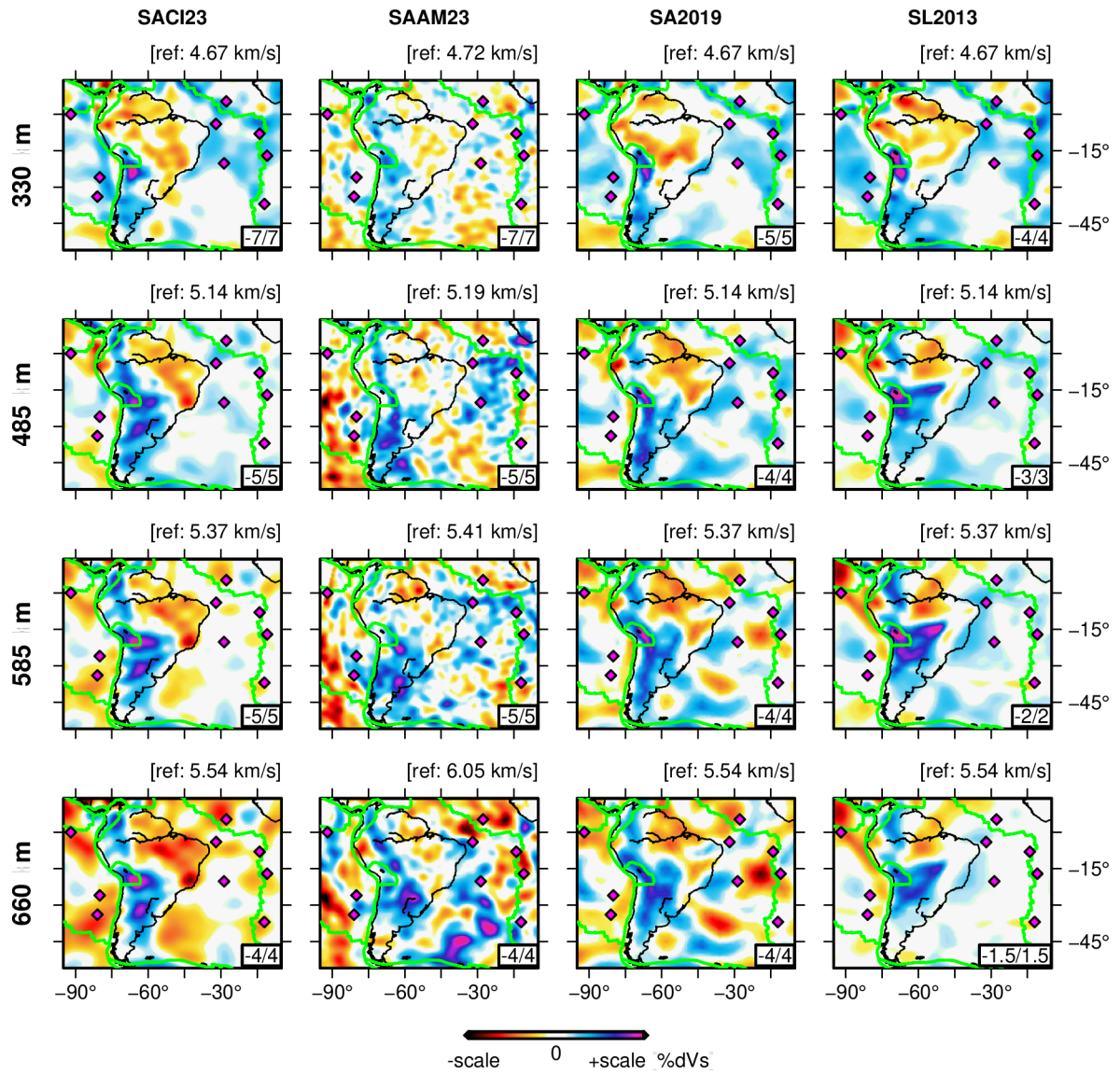


Figure 4.12: Comparison of SACI-24 with three other S-wave velocity models of the upper mantle. All models are plotted with respect to their own reference velocity. Colour scale limits are indicated at the bottom right of each map. Pink diamond symbols are hotspot locations (Whittaker et al., 2015).

The lower seismic velocities in the Pacific and higher velocities in the South Atlantic are consistent across all models down to 150 km depth. In the Pacific, all known hotspots are underlain by low velocities down to 150 km depth, with higher velocities at 260 km depth. In the South Atlantic, there are only two hotspots (Fernando, Trindade) that are not located on the MAR. Beneath the Fernando hotspot, we image low seismic velocities down to 150 km; previous models show no consensus on the anomaly here. At the Trindade hotspot, we image low seismic velocities that appear to connect the island with the coast of the continent. The models SA2019 and SL2013 show a similar anomaly, whereas SAAM23 shows velocities close to the reference value.

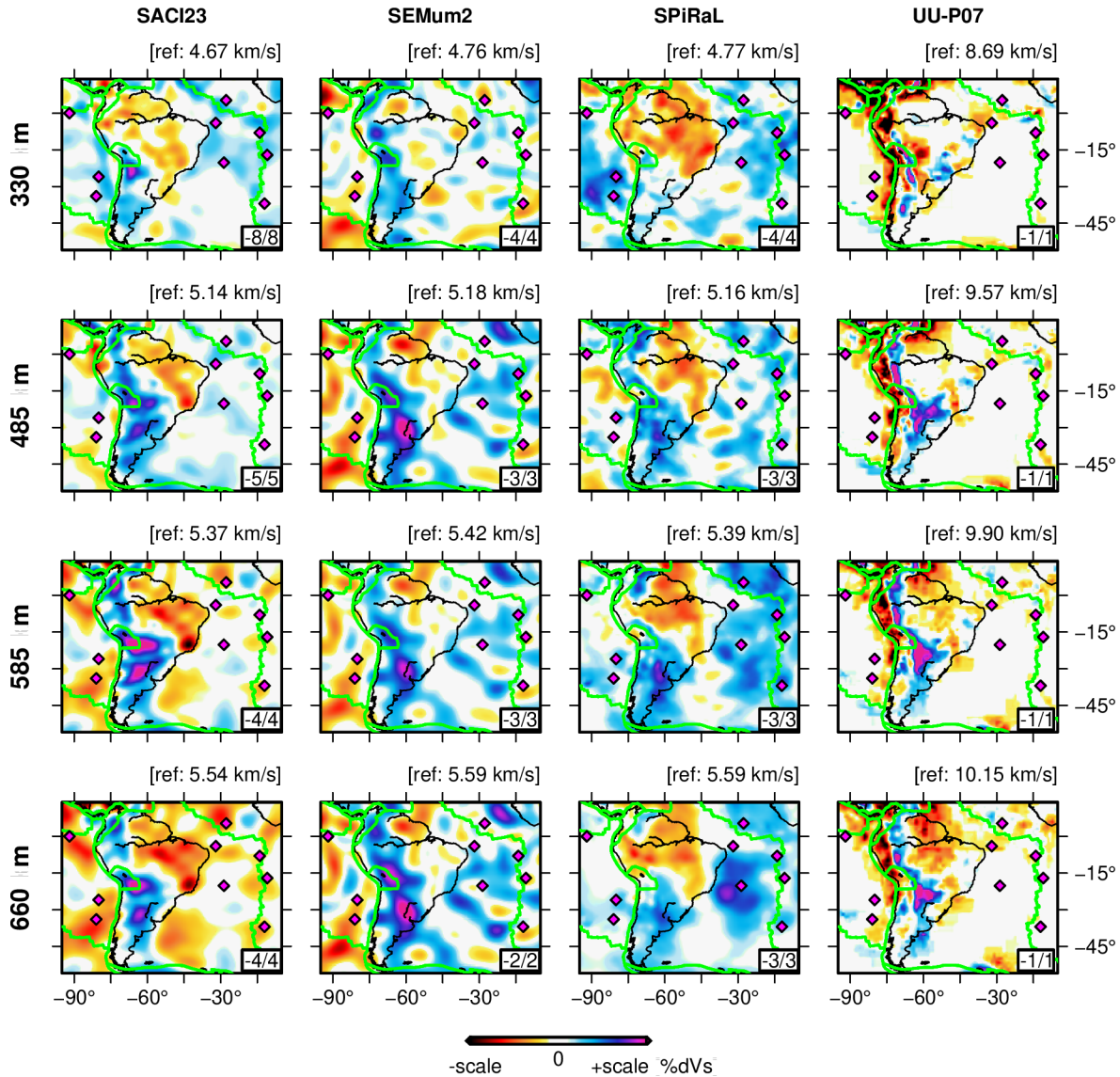


Figure 4.13: Comparison of SACI-24 with global, whole-mantle models in the deep upper mantle (330, 485, 585, 660 km depth). All models are plotted with respect to their own reference velocity. Colour scale limits are indicated at the bottom right of each map. Pink diamond symbols indicate hotspot locations.

At the greater depths, we also compare our seismic velocities with the global S-wave tomography models SEMum2 (French and Romanowicz, 2014), SPiRaL (N A Simmons et al., 2021) and P-wave model UU-P07 (Amaru, 2007) in Figure 4.13. The global models SPiRaL and UU-P07 agree with SACI-24 on the occurrence of prominent low-velocity anomalies in the mantle transition zone beneath South America's stable platform, although the fine structure of the anomaly differs from model to model. Low velocities were also observed here in several regional tomographic models (Rocha et al., 2011; Rodríguez et al., 2020; Vandecar et al., 1995).

4.6 Discussion

We assembled a comprehensive dataset of intraplate mafic and alkaline magmatic occurrences in South America. This dataset encompasses the locations of igneous rocks (Mizusaki et al., 2002; Ribeiro et al., 2018; Tassinari, 1996), flood basalts (Heimdal et al., 2018; Peate et al., 1992), dikes (Pessano et al., 2021), carbonatites (Woolley, 1987), kimberlites and lamproites (Matos Cunha et al., 2017). We analyse this dataset together with the hotspot tracks according to several plate motion models (Matthews et al., 2016; Müller et al., 2016; Seton et al., 2012) (Figure 4.14), upper-mantle seismic velocities from our model SACI-24, and lower mantle velocities from whole-mantle tomography, to investigate the deep sources of the magmatism.

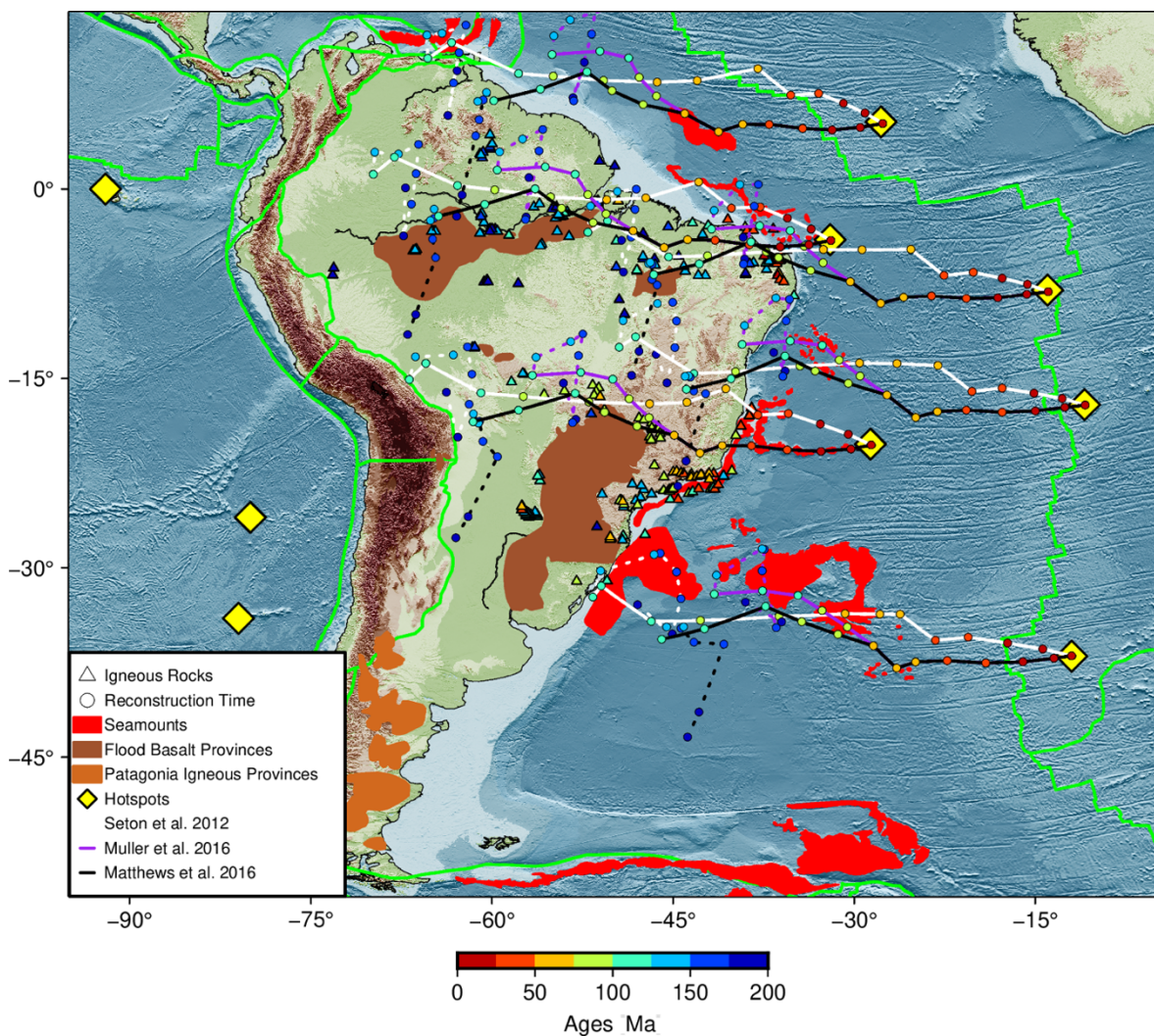


Figure 4.14: Hotspot tracks from different plate motion models. Tracks connected by solid lines span from 0 to 130 Ma. Reconstructions at 130-200 Ma are more uncertain and the

hotspot tracks for these ages are plotted as dashed lines. The hotspot track in magenta is an alternative reconstruction with the Tristan da Cunha hotspot located on the ridge. Circles are the reconstructed location of each hotspot at the colour indicated by the colour scale. Triangles are the locations of volcanic rocks (same as Figure 4.1), also plotted with the ages indicated by the colour scale.

In Figure 4.14 we show locations of igneous rocks formed in the last 200 Ma, continental flood basalts and seamounts, together with plate motion trails of all known hotspots that might have affected the South American continent (refer to Figure 4.1 for the names of hotspots and province ages). These include from north to south: Sierra Leone (Basile et al., 2020), Fernando, Ascension, St. Helena, Trindade and Tristan hotspots (Whittaker et al., 2015). The hotspot tracks are reconstructed back to 200 Ma, using plate motion models from Seton et al., (2012), Müller et al., (2016) and Matthews et al., (2016). Plate motion over a fixed thermal source is best observed in oceanic crust with the formation of linear volcanic chains. For this reason, plate motion reconstructions have better accuracy up to 130 Ma in South America (Müller et al., 2016). In Figure 4.14 we represent the reconstructed tracks with a continuous line up to 130 Ma, and dashed lines from 130 Ma to 200 Ma.

By visually inspecting each hotspot track and the South Atlantic seamounts in Figure 4.14, we can infer that the plate models from Müller et al., (2016) and Matthews et al., (2016) show better agreement with the South American seamounts in this specific time span. The two models are identical from 0-80 Ma, due to the fact that the reconstruction from Matthews et al., (2016) incorporated the reconstruction from Müller et al., (2016) from 230 to 0 Ma. A few modifications from Müller et al., (2016) to Matthews et al., (2016) include a reference frame update, with the addition of a transitional period from 70-100 Ma. Overall, in the period from 80-200 Ma the difference between the two models is not significant and for later comparisons we will adopt the model from Matthews et al., (2016), which seems to have better tracking of the Tristan and St. Helena seamounts.

The focus of this paper is, however, the understanding of magmatic processes that affected continental South America. In continental lithosphere the mapping of hotspot tracks is more complex than in the oceans, as continental lithosphere is thicker, older, and more heterogenous when compared to oceanic lithosphere.

In the following sections we will integrate the most recent available constrains on the upper and lower mantle under South America with the seismic images from our model SACI-24 in the upper mantle, and global, full mantle models at greater depths. Finally, we

will compare the seismic velocities in the lithosphere with hotspot tracks and locations of igneous rocks to elucidate how heterogeneity in the continental lithosphere might influence the distribution of magmatism at the surface.

4.6.1 The Upper Mantle under South America

4.6.1.1 Origin of Lithospheric Material under the South Atlantic

Using evidence from tomography and mantle flow modelling, Hu et al., (2018) suggested that the observed positive seismic velocities beneath the South Atlantic Ocean might have originated as delaminated segments of continental lithosphere. Consistent with this, our model shows a horizontal layer of positive seismic velocities from 200 km to ~500 km in depth, across both central and northern sectors of the South Atlantic. In the resolution tests shown in Figure 4.3, we demonstrated that the model SACI-24 can accurately resolve seismic structures at these depths on the Atlantic oceanic regions of width equal or larger than ~650 km. The delaminated segments we identify are larger than the column width used in Figure 4.3, therefore we can confirm that they are within the resolution range of the model. These positive seismic anomalies are also corroborated by the global models SEMum2, SPiRaL (Figure 4.13) and SL2013 and the regional models SAAM23 and SA2019 (Supplementary Figure 1).

We offer further evidence to explain the origins of the delaminated lithospheric material. In Africa, lithospheric erosion due to plume impact has been evidenced through seismic tomography combined with the locations of diamondiferous kimberlites (Celli et al., 2020a). A parallel can be drawn with South America, specifically within the southwestern Amazon Craton (Chapter 3), which is marked by numerous clusters of diamondiferous kimberlites, spanning from 230 Ma (Zolinger, 2005) to 90 Ma (Kaminsky et al., 2010). Such occurrences imply the presence of cratonic lithosphere during the time of kimberlite emplacement (Boyd et al., 1985).

However, our model does not reveal cratonic lithosphere beneath all the diamondiferous kimberlite sites. This was confirmed by resolution tests which showed that SACI-24 accurately resolves either a continuous and homogeneous cratonic lithosphere (Figure 3.7) as well as multiple smaller scale, fragmented blocks of cratonic lithosphere (Figure 3.8). This suggests a potential loss of the local cratonic lithosphere post-90 Ma, potentially due to a plume impact. Studies of the Juína kimberlite cluster suggest a change

in the lithospheric structure: while older conduits are diamondiferous, younger kimberlitic pipes (79-80 Ma) are barren (Kaminsky et al., 2010). Even though most Juína diamonds have their origins in the deep mantle, some diamonds have a lithospheric origin that requires thick, cratonic lithosphere.

This temporal shift from diamond-rich to diamond-scarce suggests a thermal event influencing the southwestern border of the Amazon Craton. Additionally, the most accepted mechanism for the transport of super deep diamonds to the lithosphere is by upwelling of hot material (Kaminsky et al., 2001), which reinforces the proposition of plume impact under the southwestern Amazon craton.

Comparing SACI-24 to other studies indicate that cratons in South America are, on average, less thick than those found in regions such as Africa or North America (Celli et al., 2020b; Schaeffer and Lebedev, 2013). The model's accuracy in resolving the cratonic depths are supported by the resolution tests shown in Figure 3.7 and Figure 3.8. In the “cratonic type” resolution tests we confirm that the model has great accuracy at the lithospheric depths, and it can clearly delineate the lithosphere-asthenosphere boundary. This disparity might also be attributed to the impact of mantle plumes, which could have partially eroded the base of these cratons (Wang et al., 2015), in addition to the southwestern edge of the Amazon Craton discussed in previous sections. As the South American plate proceeded in its westward motion, the eroded lithospheric material remained buoyant, above the transition zone beneath the South Atlantic Ocean.

4.6.1.2 Galápagos Plume and the Nazca Slab

The South American continent is marked by the long-lived subduction on its western edge. The Andean tectonic cycle started around 190 Ma (Mpodozis and Ramos, 1989), leading to the subduction of vast amounts of oceanic lithosphere material into both the upper and lower mantle. In different regions of the globe, interactions between ascending mantle plumes and subducted oceanic material have been described to alter the plume trajectories (Kincaid et al., 2013; Rogers et al., 2023). Based on this understanding, we postulate that beneath South America, subducted lithospheric material might have interacted with a deep-sourced mantle plume. This interaction could induce plume branching, potentially accounting for the closely spaced hotspots observed in the South Atlantic Ocean and the apparent absence of vertical conduits beneath them. The resolution test from Figure 4.6 shows the model's ability to resolve the potential geometry of a vertical plume conduit on

oceanic regions. Therefore we confirm that the lack of vertical columns of slow velocities under hotspot areas is not caused by modelling limitations.

To validate this hypothesis in South America, and further investigate the distribution of low seismic velocities in the mantle, we compare the seismic velocities of our model SACI-24 and the full mantle tomographic models SPiRaL (N A Simmons et al., 2021), UU-P07 (Amaru, 2007) and SEMum2 (French and Romanowicz, 2015) in Figure 4.15 and Supplementary Figure 3.1.

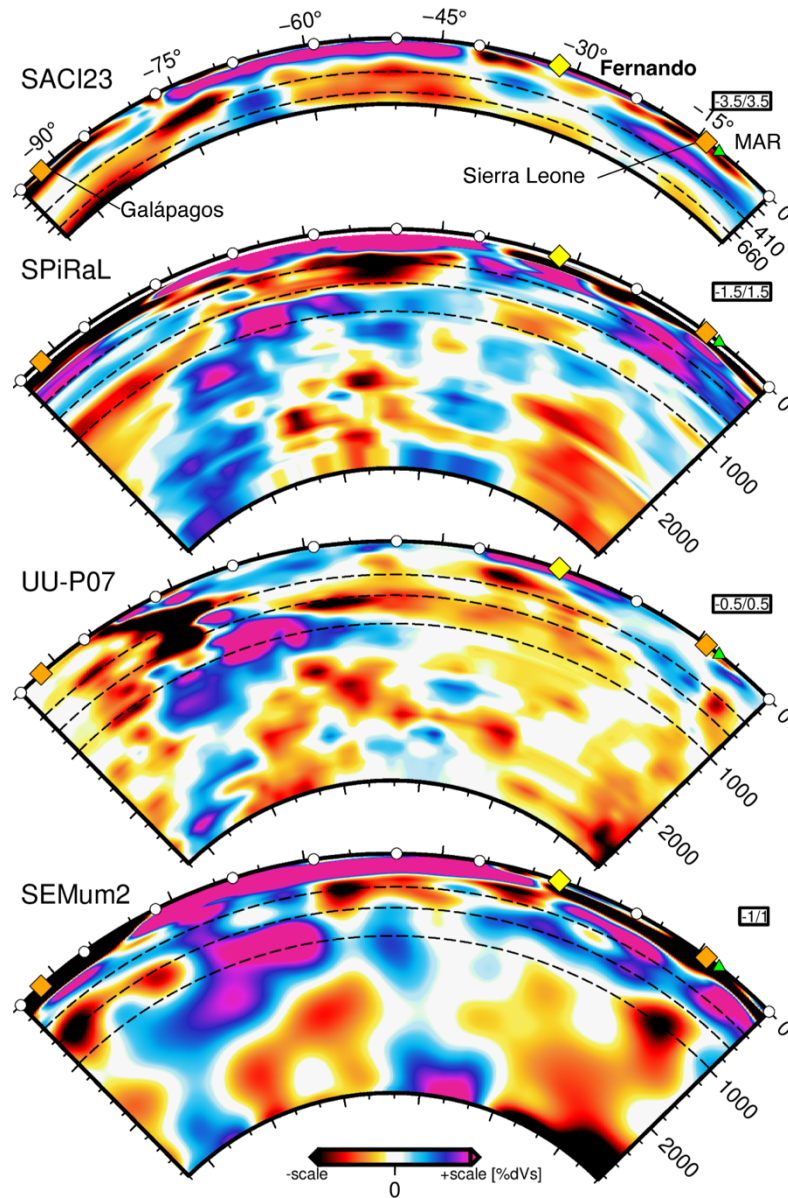


Figure 4.15: Comparison of SACI-24 with whole-mantle models in the South American Plate. Cross section location is indicated in Figure 4.10-b. Yellow diamond symbol represent the closest hotspot location ($<2^\circ$ radius). Orange diamond symbols are hotspots in $<5^\circ$ radius. Green triangles indicate the mid-Atlantic ridge (MAR). SACI-24, UU-P07 and SEMum2 are plotting using their own velocity reference values. SPiRaL is plotted in respect to the global

velocity value at each depth. Colour scale of the seismic anomaly values are indicated at top right of each cross section.

In Figure 4.15, which consists of a section crossing the continent and the Galápagos and Fernando hotspots (same as Figure 4.10-b), a strong low velocity anomaly under the Peruvian flat slab is evident in all models. As previously discussed, the low velocities under the Galápagos, the Peruvian flat slab, and its eastward extension into the lower mantle appear to be connected in the SACI-24, SPiRaL, and UU-P01 models.

Given the absence of vertical upwelling beneath the Galápagos hotspot, as indicated by all four models, we infer that the subduction is altering the path of the plume, as observed in Figure 4.15. Hot material is present within the mantle transition zone under the hotspot location and deviates eastward towards the slab. The low seismic anomaly ponds under the Peruvian flat slab, and horizontal material transport could possibly occur from under the continent, west of the slab, to the thin oceanic lithosphere where the current volcanic islands are located. This low seismic anomaly has been previously observed by many seismic tomography models in this region (Antonijevic et al., 2015; Bishop et al., 2017; Scire et al., 2016) and has been suggested as one of the causes for the flattening of the slab under Peru (Bishop et al., 2017).

In the cross section of Figure 4.15, all models consistently reveal low seismic velocities throughout the upper mantle beneath the continental lithosphere east of the slab. However, there is no clear evidence of vertical upwelling of hot material from the lower mantle or the slab. In the lower mantle, the full mantle models show that positive velocities of the Nazca slab below 660 km depth cut at depth the low seismic velocities in the upper mantle above. These observations suggest that similar to the Galápagos, horizontal displacement of hot material from under the continent, rather than vertical upwelling may be feeding the current volcanism of the Fernando hotspot.

4.6.1.3 Mantle Plume under Continental South America

In our model, strong low seismic velocities are imaged beneath the thick lithosphere of the continent, to the west of the cold lithosphere of the Nazca subduction slab. This feature is visible starting at ~260 km and reaching to 700 km (Figure 4.9, Figure 4.10). Several of the resolution tests included in this thesis support the model's resolution to define large scale structures in the continental area, such as the slow velocity anomaly we discuss here. In the

tests shown in Figure 4.4 and Figure 4.5 anomalies contained within the transition zone depths are well resolved in the continental region. Despite the visible low amplitude smearing of the anomalies to the depth nodes above and below the anomaly, likely due to the effect of smoothing, the model can accurately resolve the location of the anomaly. In the resolution tests shown in Figure 4.7 and Figure 4.8, we investigate whether the observed slow velocity anomaly could be a seismic artefact due to the thick high velocity layer of the cratonic lithosphere above. After removal of seismic structures the below cratonic lithosphere, the resulting models do not show low velocity seismic artefacts below the high velocities of the lithosphere high velocities.

To understand the deep origin of these low seismic velocity anomalies and their correlation to present-day hotspot locations, we compare cross sections of our model with full mantle tomographic models SPiRaL (N A Simmons et al., 2021), UU-P07 (Amaru, 2007) and SEMum2 (French and Romanowicz, 2015) in Supplementary Figure 4.2.

In Figure 4.16, we present sections crossing the Trindade and St. Helena hotspots, and the deep low-velocity anomaly under eastern South America (cross-section f in Figure 4.10). Within the upper mantle, all models consistently show positive anomalies of the Nazca slab and the low velocities under the continent. Under the South Atlantic, positive seismic velocities are also observed in SPiRaL and SEMum2, in agreement with the discussion in .

From the full mantle tomography models shown, we cannot identify a clear deep mantle plume under either the Trindade or St. Helena hotspots. Yet, in the SPiRaL, UUP-07, and SEMum2 models, we observe low velocities originating deep in the lower mantle, east of the subducting slab and beneath the South Atlantic. We propose that this conduit of low seismic velocity, which leads to the slow velocity anomaly we image beneath the continent in SACI-24, likely represents a mantle plume currently located under the South American plate. This inference aligns with the observations about the Fernando hotspot. It suggests that this mantle plume, rooted in the lower mantle and ascending beneath continental South America, could be the source of the volcanic material of the Trindade islands: after ascending and reaching the bottom of the thick continental lithosphere of the São Francisco Craton, the buoyant, hot plume deviates horizontally, following the lithospheric gradient, towards the thin oceanic lithosphere beneath Trindade. This interpretation is further validated by the wide, horizontally elongated anomaly beneath the Trindade islands (Figure 4.10, Figure 4.16), which is in stark contrast to the thin, vertical conduits expected for the classic oceanic hotspot paradigm.

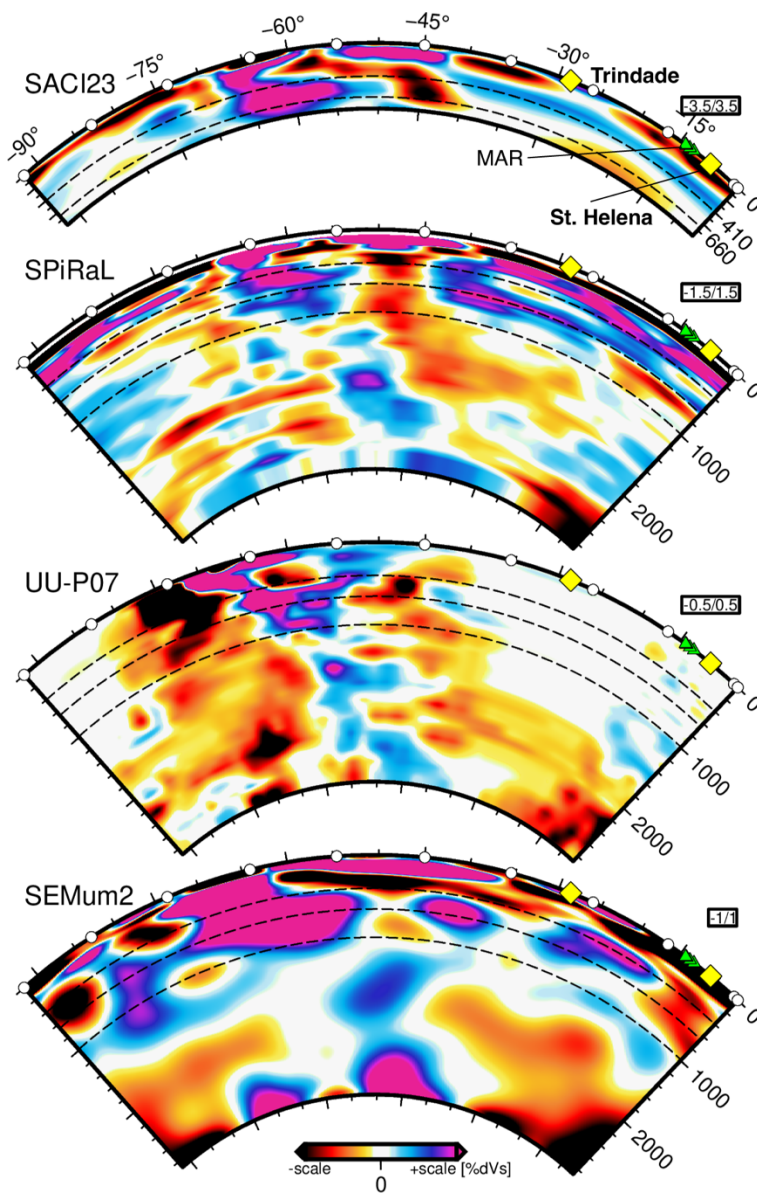


Figure 4.16: Comparison of SACI-24 with whole-mantle models in the South American Plate. Cross section location is indicated in Figure 4.10-f. Yellow diamond symbol represent the closest hotspot location ($<2^\circ$ radius). Orange diamond symbols are hotspots in $<5^\circ$ radius. Green triangles indicate the mid-Atlantic ridge (MAR). SACI-24, UU-P07 and SEMum2 are plotting using their own velocity reference values. SPiRaL is plotted in respect to the global velocity value at each depth. Colour scale of the seismic anomaly values are indicated at top right of each cross section.

4.6.1.4 Plume Branching due to Slab Interaction since the Mesozoic

In the previous sections, we postulated that a single superplume rooted under the continent is likely the primary source of most magmatism in South America since the Mesozoic. This hypothesis is supported by our model SACI-24, where we identify a strong low-seismic anomaly in the mantle transition zone beneath the southeast, and other, full-mantle global models, where it appears to be connected to the lower mantle, consistent with the characteristics of a deeply rooted mantle plume (Figure 4.16). The seismic data presented in this work did not reveal any evidence of a deep mantle plume beneath any known offshore South American hotspots.

We argue instead in favour of horizontal flow of hot mantle material modulated by the topography of the lithosphere-asthenosphere boundary, similar to what proposed by Sleep, (2003). As evidenced by the various tomography models we use for comparison, a high volume of oceanic lithosphere underlies the South American plate from the subduction of the Nazca plate since 190 Ma (Mpodozis and Ramos, 1989). The subducted oceanic plate material, combined with the delaminated lithosphere we observed beneath the oceans, may have influenced the distribution of this plume material, causing it to branch out. This mechanism can also explain the presence of superdeep diamonds in the western Amazon Craton.

It is believed that superdeep diamonds from the mantle transition zone originate from subducted oceanic crust (Zhu et al., 2019) and are potentially transported to the lithosphere via upwelling hot material from a mantle plume (Kaminsky et al., 2010, 2001). Furthermore, numerical models suggest that the mixing of mantle plumes with subducted oceanic crust can alter the ascent of this heterogeneous material in ways more complex than those predicted by classical plume theory. Such effects can result in temporal and spatial variations in the composition and volume flux of magmatism (Ballmer et al., 2013; Rogers et al., 2023). For instance, these effects might include ponding at the upper mantle discontinuities, which is apparent under South America at above the 410 km depth discontinuity.

4.6.2 Lithospheric Control on Magmatism Distribution

One significant challenge in understanding the source of magmatism in intraplate continental settings is often the absence of age progression between potentially related

magmatic provinces. This has been noted in North America (Kincaid et al., 2013), Australia (De Laat et al., 2023; Mather et al., 2020), and South America (e.g. Comin-Chiaramonti and de Barros Gomes, 2005; De Barros Gomes et al., 2013; Mizusaki et al., 2002; Neves et al., 2020). Due to this lack of age-progressing information, reconstructed tracks from the South Atlantic hotspots alone (Figure 4.14) cannot fully explain the observed magmatism locations and ages.

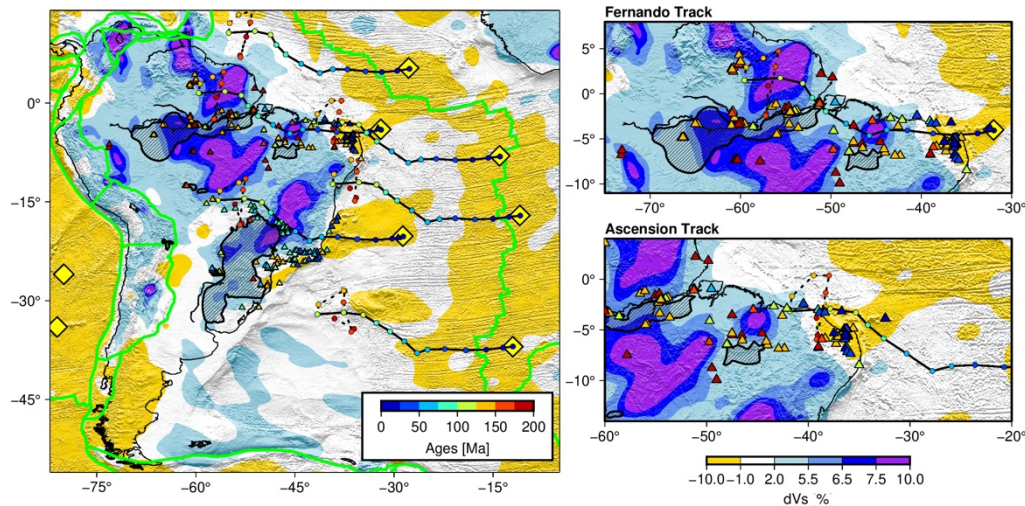


Figure 4.17: Reconstructed hotspot tracks (Müller et al., 2016) on South American lithosphere. Continuous lines are from 0-130 Ma, dashed lines range 130-200 Ma and represent pre-Gondwana break up. Hotspot locations are shown as yellow diamond symbols (Whittaker et al., 2015). We show locations of alkaline mafic igneous rocks as triangles and dashed filled black contours are large basaltic provinces (intrusive sills for CAMP and flood basalts for Paraná CBF – refer to Figure 4.1 for additional information on symbols and province names and ages). Seismic velocities shown are from 110 km depth.

Plume impact under thick cratonic lithosphere is proposed to flow towards thin lithosphere following the lithospheric gradient (Duvernay et al., 2022; Gorczyk et al., 2018; Sleep, 1997). To analyse this hypothesis, we compared lithospheric seismic velocities with the locations of igneous rock samples, large igneous provinces, and hotspot plate motion reconstruction (Matthews et al., 2016). From this comparison, we find that plume impact under South America is responsible for most, if not all, intraplate volcanism, with the thickness of the lithosphere acting as the main control on the distribution of volcanism.

In the following sections, the discussion regarding the seismic structures within the continental lithosphere from SACI-24 are fully supported by results from resolution tests shown previously (Chagas de Melo, B. et al., 2024, submitted). In this thesis' previous

chapter, we have provided a fully detailed discussion on this model's limitations based on resolution tests (see Section 3.4.1). The inferences we present here consider seismic structures of dimensions we have showed to be accurately resolved by the model within the continent and lithospheric depths (~250 km length, for example in Supplementary Figure 3.6).

4.6.2.1 Fernando Hotspot and its correlation to CAMP and northern volcanism in Brazil

In Figure 4.17 the reconstructed tracks of two hotspots, Fernando and Trindade, reach the South American continent. In the north of the continent, the reconstructing the position of the Fernando hotspot indicates that it would have been located beneath the Amazon Craton from 200 Ma to 100 Ma (Figure 4.17-top right). Volcanism within and surrounding the Amazon Craton boundaries also spans approximately from 200-100 Ma. The region is largely cratonic, and we previously identified and discussed two, separate cratonic blocks beneath the Amazon Craton, divided by the Amazon River basin (Chapter 2). Volcanism in the area is primarily distributed outside the boundaries of the thick lithosphere of the Amazon craton, with many occurrences located in the lithospheric "channel" between the two cratonic blocks suggesting a lithospheric control on their location. In Figure 4.18 we also compare our lithospheric seismic velocities to the thickness of the CAMP basaltic sills (de Min et al., 2003) on the Amazon basin. The sills exhibit maximum thickness in regions of thin lithosphere, which suggests their probable path of ascent to the surface where the lithosphere is thinner. When the ascending magma encountered the stratified media of the basin's sedimentary layers, it could have travelled horizontally towards the regions represented by the thin basalt contours.

A similar pattern is observed along the Fernando hotspot track from 130 Ma to 40 Ma. The track intersects the cratonic Parnaíba Block, and volcanism and flood basalts occur at the boundaries of the thick lithosphere mapped by our model. At 40-20 Ma, where the Fernando track first reaches mainland South America, we identify a discrepancy between the volcanism ages and the hotspot track. While many ages of the volcanism in this region agree with the ages predicted by the hotspot track, we also observe older Mesozoic volcanism. This volcanism has been previously attributed to the St. Helena hotspot (Bezerra Maia de Hollanda et al., 2006; Mizusaki et al., 2002). However, using more up-to-date plate reconstruction models, we find that the Ascension hotspot track shows better agreement for

both location and age (Figure 4.17-bottom right). The reconstructed position of the Ascension hotspot from 200 Ma to 100 Ma places it under northeast Brazil. Thus, the older Mesozoic volcanism in the northeast could have originated from the Ascension hotspot, before the passage of the Fernando hotspot under the region.

In northeastern Brazil, the Borborema province is predominantly underlain by low seismic velocities. This region, characterized by the youngest continental volcanism of the platform at 7.1 Ma (Knesel et al., 2011), and tectonic uplift (Morais Neto et al., 2009), exhibits thin lithosphere, as shown by several studies (Celli et al., 2020b; Klöcking et al., 2020; Neto et al., 2019), which can explain the recurrent volcanic activity.

Although we do not image a clear deep plume under the Fernando hotspot, comparing our new, detailed images of the lithosphere to the distribution of volcanism and plate reconstruction suggests that this hotspot originated the CAMP and most of the intraplate volcanism in northern South America. Despite recent studies questioning a classical plume origin for CAMP (de Min et al., 2003; McHone, 2000), they fail to provide an explanation for an alternative heat source for magmatism on the scale of CAMP. Using our images from SACI-24, we can reconstruct the Fernando "plume" to have underlain the thick cratonic lithosphere of the Amazon Craton within the past 100 Ma, which explains the distribution of volcanism in northern South America. However, we cannot confirm whether a differently positioned branch or a different plume origin is responsible for other LIPs attributed to the CAMP in North America, Europe, and Africa.

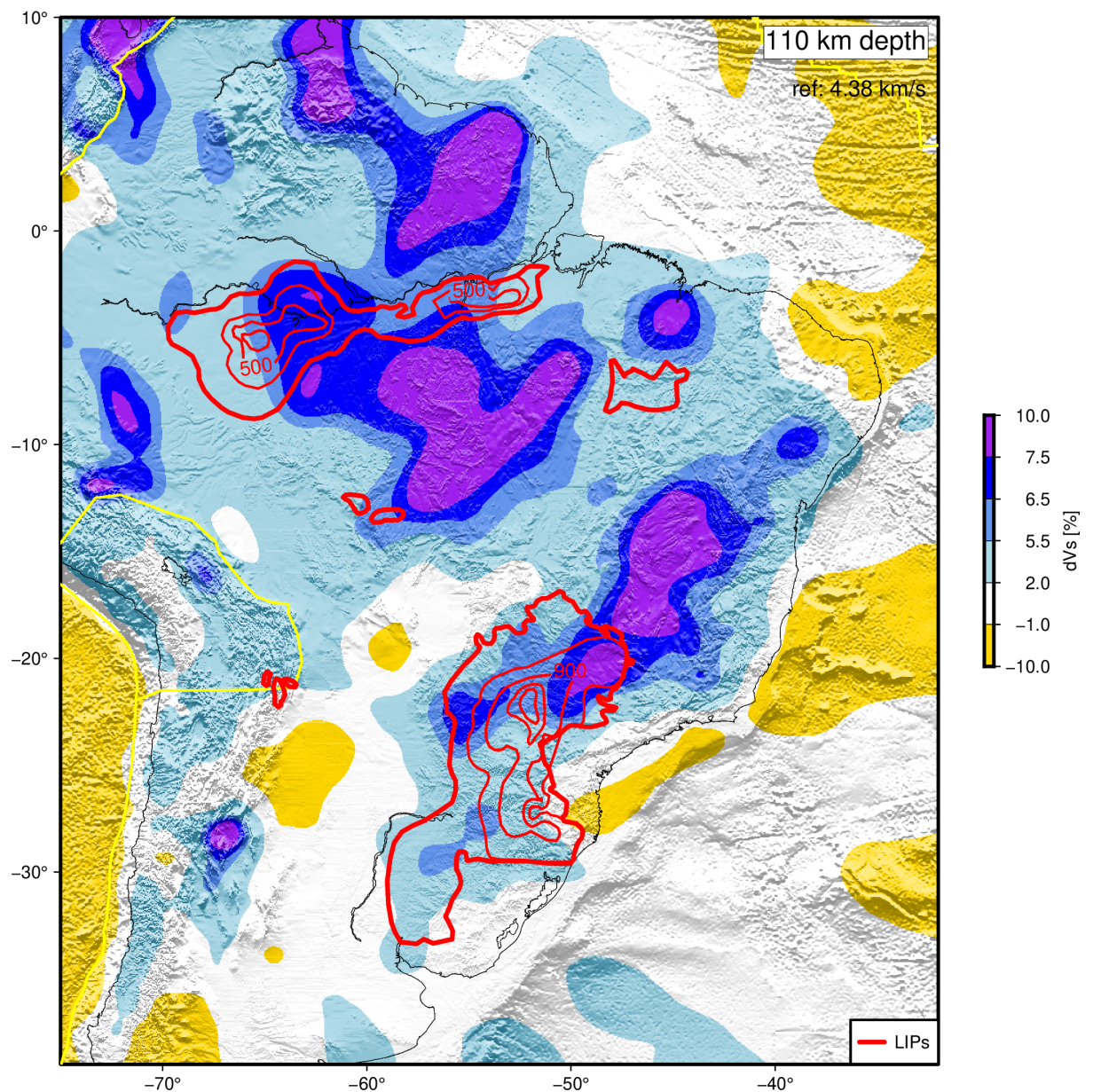


Figure 4.18: Comparison between seismic velocities in the lithosphere at 110 km depth with the thickness of basalts in South America. Camp sills basalt thickness with a minimum contour of 100m (de Min et al., 2003) and Paraná extrusive flood basalts (Peate et al., 1992).

4.6.2.2 Paraná Large Igneous Province

In south-eastern Brazil, two igneous events are known to have affected the continent: the Paraná LIP and the alkaline volcanic provinces of Poxoréu, Iporá, Alto Paranaíba, and Serra do Mar.

The large extrusive flood volcanism of the Paraná LIP (Piccirillo and Melfi, 1988) peaked at ~134 Ma and constitutes one of the largest igneous province in the world (Renne et al., 1996). Impact from the Tristan da Cunha plume is the most accepted origin for this

province (Courtillot et al., 1999; Gibson et al., 2006), although some authors proposed alternative causes (Ernesto et al., 2002; Foulger, 2018).

In Figure 4.18, we can observe the lithospheric influence over the distribution of lavas of the Serra Geral flood basalts of the Paraná LIP. In the centre-north of the Province, the thickest lavas (Peate et al., 1992) approximately coincide with the basin's sedimentary depocenter. In this location, our tomographic model images a lithospheric “gap”, where thinner lithosphere between two blocks of thick lithosphere is found. We propose that the thinner lithosphere at the centre of the basin has provided a path for the lavas to reach the fractures on the surface, from where it flowed horizontally.

We also observe thin lithosphere on the coast, east of the Serra Geral province, where there is evidence for widespread volcanism over a wide range of ages (134-121 Ma) (Mizusaki et al., 2002). There, several dikes extend from the basin to the coast and could indicate lateral transport of magma at the time of the onset of volcanism. The younger volcanism could thus represent the position of the plume later in time, due to the westward plate motion after continental break-up. The current proposed location of the Tristan hotspot is on the African plate, outside the boundaries of our seismic model. Therefore, we do not have evidence to discuss the possible origin of the igneous material related to this hotspot.

4.6.2.3 Impact of the Trindade Hotspot under South America

North of the Serra Geral flood basalts, we find the Poxoréu, Iporá, Alto Paranaíba, and Serra do Mar alkaline volcanic provinces (Costa dos Santos et al., 2021; Fodor and Hanan, 2000; Gibson et al., 1997, 1995; Thompson et al., 1998). These provinces are thought to represent a plume track of the Trindade hotspot on the continent, with magmatic ages ranging from 85 to 55 Ma. The proposed track continues seaward to the continental shelf in the Abrolhos Province (59-37 Ma) and the seamounts of the Vitória-Trindade (last volcanic activity 0.25 Ma (Pires et al., 2016)). While most authors agree on the Trindade hotspot as the source of these igneous provinces, alternative hypothesis include a dying Tristan da Cunha plume (Bizzi et al., 1995; Vandecar et al., 1995) and the partial melting of metasomatized lithospheric mantle (Guarino et al., 2013).

For the previously discussed Fernando and Tristan hotspot tracks, we identified a large igneous province associated with the initial plume impact on the continent. However, there is no evidence of a similar province related to the Trindade plume. Most studies associate the earliest volcanism at 90 Ma in the Poxoréu province with the Trindade plume (Gibson et al., 1997, 1995; Thompson et al., 1998). Yet, others indicate instead the 92-95

Ma kimberlite occurrences southwest of the Amazon Craton—almost 1000 km to the northwest of Poxoreú—as a result from the passage of the Trindade plume under the continent (Bulanova et al., 2010; Greenwood et al., 1999), a suggestion supported by our observations. Using our selected plate motion model, we note the reconstructed Trindade plume track intersects the southern Amazon craton at 180-130 Ma. Nearby, we find 230-90 Ma kimberlites and 201 Ma small lava flows southwest of the craton (Figure 4.17). Typically, these flows are attributed to CAMP due to age similarities (de Min et al., 2003). However, we argue they align better spatially with the Trindade plume's reconstructed path. Furthermore, a study linked the superdeep diamonds from the Juína kimberlites to the interaction of subducted lithosphere with the Trindade plume (Bulanova et al., 2010), similar to what we discuss in the section .

4.6.3 Final Remarks on Sources and Distribution of Volcanism

We do not detect a deep mantle plume beneath the suggested location of the Trindade and Fernando hotspot. Instead, we propose a mechanism of horizontal flow from the mantle plume beneath the South American continent. Both Fernando and Trindade oceanic seamounts have a E-W distribution, aligned with oceanic fracture zones, which could have facilitated the transport of hot, buoyant material. This hypothesis is supported by the east-west distribution of both Fernando and Trindade oceanic seamounts, which align with oceanic fracture zones and, we believe, enabled the lateral flow of the plume branch.

We also link the distinct temporal and spatial distribution of continental intraplate volcanism to interactions with subduction slabs, a connection corroborated by the superdeep diamonds in the western Amazon Craton. Around 201 Ma, a deep mantle plume originating beneath present-day South America would have encountered lithospheric material from oceanic subduction, resulting in plume branches. A more voluminous branch would have initiated the CAMP in the Amazon basin, while a secondary branch would have assimilated diamonds formed in the slab and transported them to the surface thousands of kilometres away in the southwestern Amazon Craton. These plume branches continued their trajectories beneath the continental lithosphere, presently feeding two volcanic islands. The shared superplume source could account for the similarities in the earliest flood basalts and why they are ascribed to the same source (CAMP). The plume branches would supply the heat

source, while contamination from subduction slabs and heterogeneous continental lithosphere would explain the observed compositional differences.

4.7 Conclusions

In this study, we combined the evidence from our new S-wave velocity upper-mantle tomographic model, SACI-24, with that from a large intraplate-magmatism dataset, plate reconstructions and lower-mantle tomography to investigate the origins of the magmatism and its distribution.

- Anomalous low seismic velocities are observed under large portions of the stable continental lithosphere of South America.
- The low-velocity anomalies extend down to the mantle transition zone, with the strongest one observed beneath SE Brazil.
- Whole-mantle tomography shows low velocities in the lower mantle beneath SE Brazil. We interpret this as convincing evidence for an upwelling of hot material from the deep lower mantle to under the thick lithosphere of the continent.
- No deep-seated mantle plumes are present directly under any of the recognised hotspots on the South American plate, including the Fernando, Trindade and St. Helena hotspots. Relatively high velocities under the South Atlantic lithosphere probably indicate the lithospheric material delaminated as a consequence of the plume impact.
- Diamonds in the SW Amazon Craton reveal that this region once had thick, cratonic lithosphere, now lost as shown by the tomography. South American cratons elsewhere appear to be thinner, on average, than beneath other continents, consistent with South America losing the lowermost lithospheric cratonic layer as a result of the plume impact(s) and ponding of the hot plume material, proposed previously (Sleep 2003) and confirmed by tomographic models.
- West of the South American plate, subduction started at 190 Ma. We propose that subducting oceanic lithosphere deflected the conduit of an ascending mantle plume (Civiero et al., 2022; Mather et al., 2020) and divided it into several branches, giving rise to multiple, different hotspots.

- Several of the current hotspots of the South American plate are likely to have originated from a single “super” plume, which we locate under the continent in the deep upper mantle. In the shallow asthenosphere, the hot material then flows horizontally towards thin lithosphere and erupts in the ocean where the current hotspots are placed.
- By combining the lithospheric thickness inferred from seismic tomography with hotspot plate motion reconstructions, we can trace most of South America's Mesozoic intraplate magmatism back to hotspot origins. Specifically, we found that the Fernando hotspot was positioned beneath the thick lithosphere of the Amazon Craton when CAMP was formed. The maximum thickness of sills from CAMP aligns with the eruption of hot mantle material from the Fernando hotspot through thin lithospheric channels (Sleep, 2003; Thompson and Gibson, 1991), as mapped by our model. This leads us to propose that the thick cratonic lithosphere effectively channelled the igneous material from these hotspots towards the surrounding weaker and thinner lithosphere.
- Therefore, the lithosphere thickness, indicated by tomography, exerts the main control on the location of the outpouring of the igneous material. The lithospheric thickness also controls the location of the flood basalt eruptions. For CAMP and PMP, we show that volcanic material erupts where the lithosphere is thinner, as indicated by the maximum thickness of basaltic material. From these areas, the volume of material decreases, indicating lateral flow.

4.8 Supplementary Material

4.8.1 Additional details on the magmatism dataset

4.8.1.1 Igneous Rocks Locations

Volcanism locations (Mizusaki et al., 2002)

Types of rocks (as originally described): Andesite, Ankaratrite, Bas. tr./alk., Bas.tholeiitic, Basalt, Basanite, Breccia, Breccia alk., Breccia tholeiit., Dacite, Diab. tr./alc,

Diab. tr./alk., Diab.tr./alk.?, Diab.tholeiitic, Diab.tr./alk., Diabase, Essexite, Hauynite, Limburgite, Nephelinite, Rhyolite, Tinguaita, Trachyte, Tufo tr./alk.

Alkalines in the Southeast (Ribeiro et al., 2018)

Types of rocks: Basalt-syenite-monzonite-granite, Bebedourite-phonolite, Carbonatite-Glimmerite, Carbonatite-kimberlite-lamproite-kamafugitic, Essexite-gabbro-syenite, Essexite-missourite-lamprophire-malignite, Gabbro, Gabbro-clinopyroxenite, Granite-quartz-monzonite-syenite-nordmarkite, Kamafugite, Kamafugite-sub_volcanic_phonolite, Katungite-mafurite-ugandite-(kamafugitic-rocks), Kimberlite, Magnetite, Peridotite, Phlogopite-picrite, Phonolite-jacupiranguite-bebedourite, Syenite-gabbro-pyroxenite, Tinguaita-phonolite-nepheline-syenite-pyroclastic_rocks

Additional locations in Amazonia from Tassinari, (1996)

4.8.1.2 Large Igneous Provinces

CAMP contour (100m sill): (Heimdal et al., 2018)

Maranhão contour: (Merle et al., 2011)

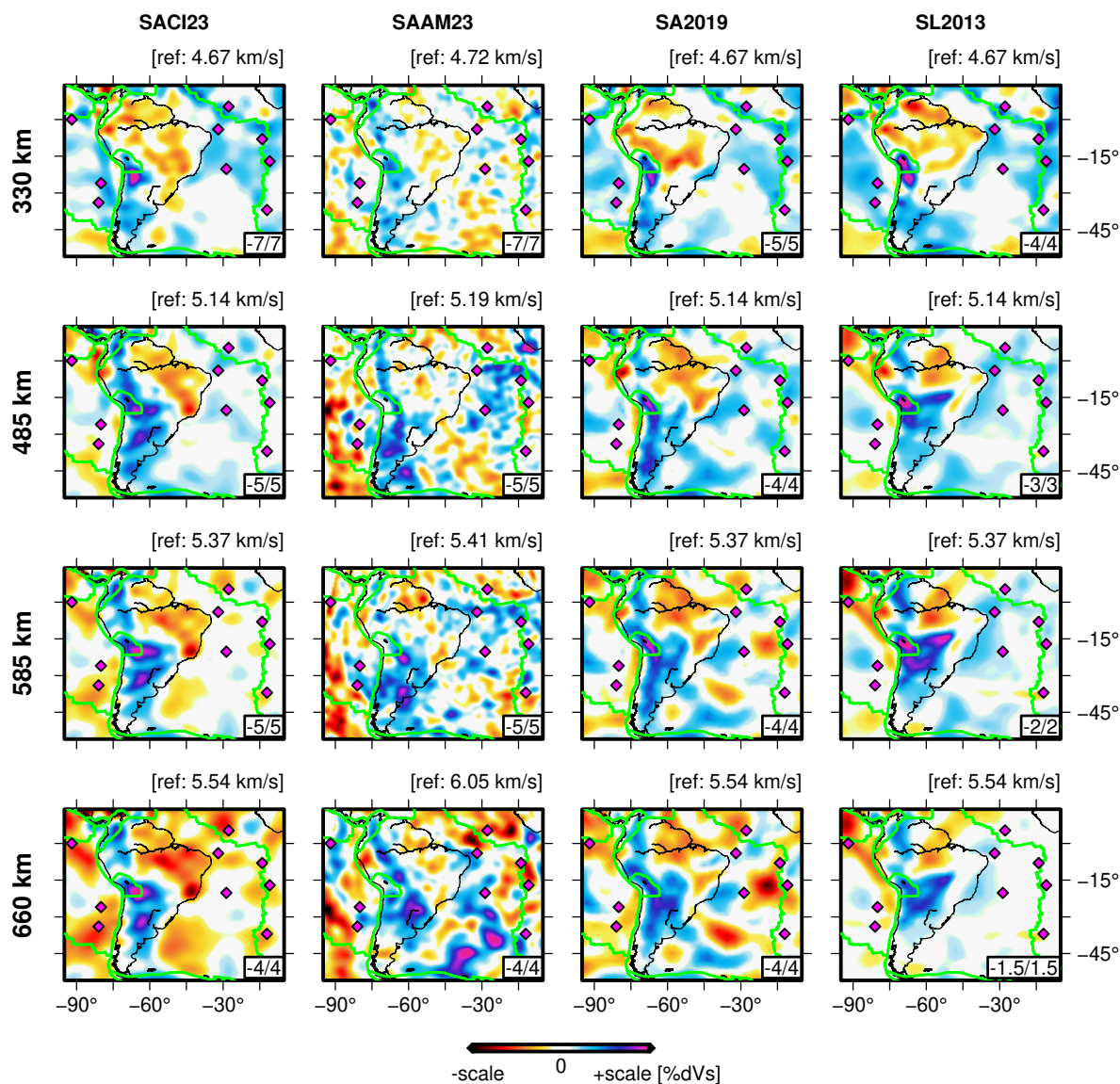
Anari Tapirapua contour: (de Min et al., 2003)

Tarabuco contour: (Bertrand et al., 2014)

Serra Geral/Parana contour: (Peate et al., 1992; Renne et al., 1996)

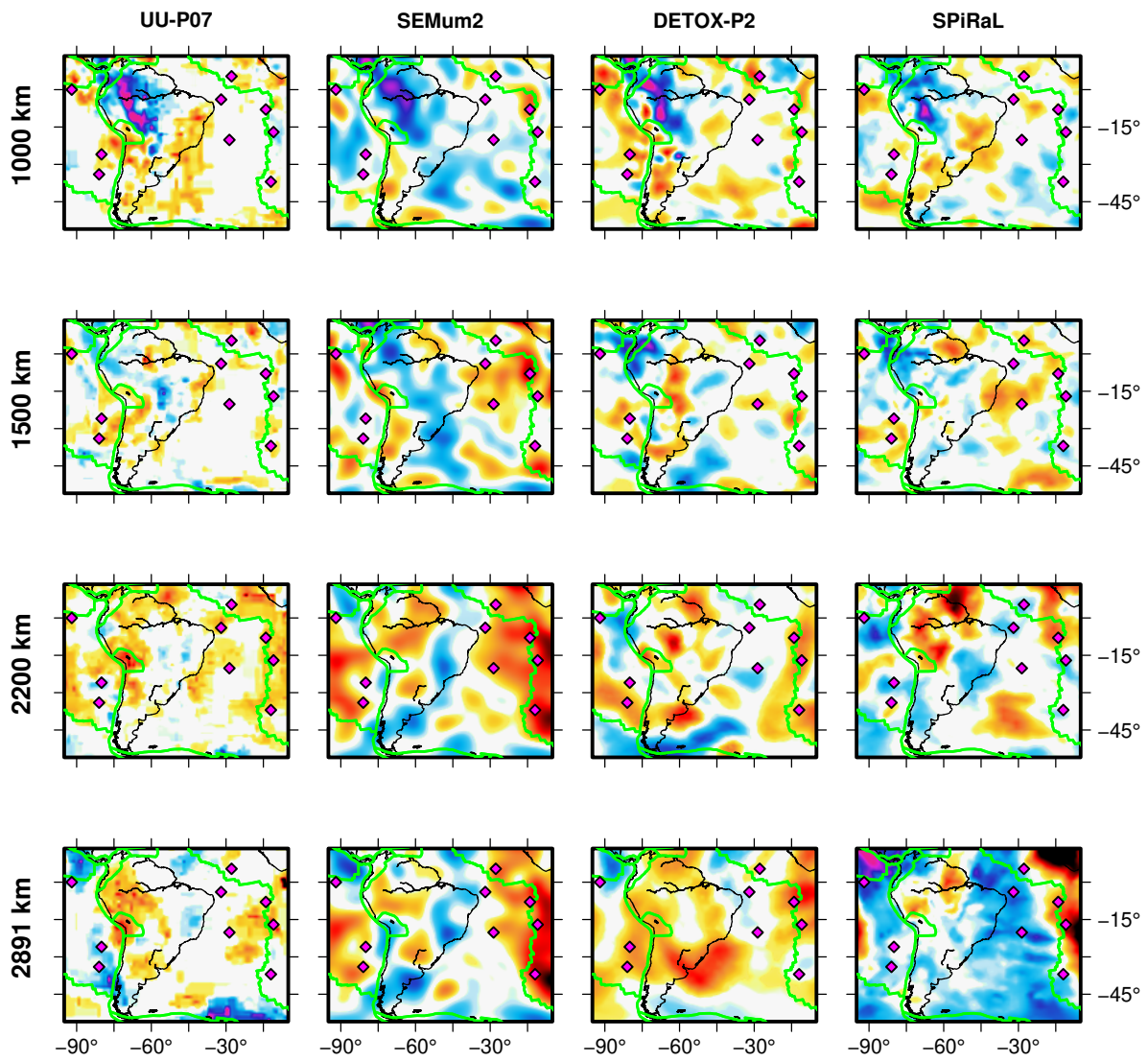
Patagonia contours: (Kay et al., 2007)

4.8.2 Model Comparisons



Supplementary Figure 4.1: Model Comparison between SACI-24 and the S-wave velocity models SAAM23, SA2019 and SL2013 at 330-660 km depths.

4.122



Supplementary Figure 4.2: The lower mantle beneath the South American Plate according to the whole-mantle models UUP07, SEMum2, DETOX-P2 and SPiRaL.

5 Deciphering Andean Tectonics with High-Resolution Seismic Tomography

Abstract

Situated along South America's western margin, the Andean orogenic belt extends over 7,000 km and serves as a natural laboratory for studying plate tectonics, subduction dynamics, and orogenesis. From north to south, the subduction behaviour and its surface manifestation on the South American continent vary drastically and are usually associated to portions of flat slabs, slab tearing, and lithospheric delamination. To target the mountain range heterogeneity and change in behaviour of the subduction style, we employ our high-resolution seismic tomography model, SACI-24. SACI-24 utilises an extensive dataset of both global and regional seismic waveforms, complemented by recently available temporary deployments in the Andes. In northwestern South America, SACI-24 identifies distinct slab segments from the Nazca and Caribbean plates and confirms active continental lithosphere underthrusting in multiple regions. In the Peruvian flat slab segment, the model reveals a fast seismic anomaly attributed to the buoyant oceanic lithosphere of the Inca Plateau, which has underplated South America, leading to multiple slab tears. On South America, we map the thick lithosphere of the Amazon Craton's bordering the western side of the subduction zone, suggesting its role in slab flattening through hydrodynamic suction. Furthermore, we identify regions under the Altiplano and Puna Plateaus undergoing stages of lithospheric root growth and delamination, indicative of Cordillera cyclicity processes. Within the mantle transition zone depths, we detect colder mantle regions east of the subduction, interpreted as remnants of past lithospheric delamination events.

Keywords: Seismic Tomography; South America; Lithosphere; Subduction; Andes; Mountain Building; Flat Slab.

5.1 Introduction

The Andean Subduction Zone is a long-lived, continuous active plate boundary, with a history of subduction extending back to at least the Mesozoic era (Horton, 2018; Mpodozis and Ramos, 1989; Ramos, 1999). This tectonic boundary is defined by the eastward subduction of the oceanic Nazca Plate beneath the continental South American Plate, spanning approximately 7000 km along the strike, and by the Caribbean Plate's oblique subduction in the north (Figure 5.1). Along most of this margin, the Nazca Plate converges at a relatively uniform rate, ranging from 5.3 to 6.3 cm per year (Kendrick et al., 2003). By contrast, the Caribbean Plate subducts beneath South America at a much slower rate of approximately 20 mm per year (Sella et al., 2002). The observed variations in topography and geological structure across the Andean range in South America have been attributed to lateral variations in the parameters of the convergence between the Nazca and South American Plates (e.g. Cedié et al., 2003; Contreras-Reyes and Carrizo, 2011; Ramos, 1999).

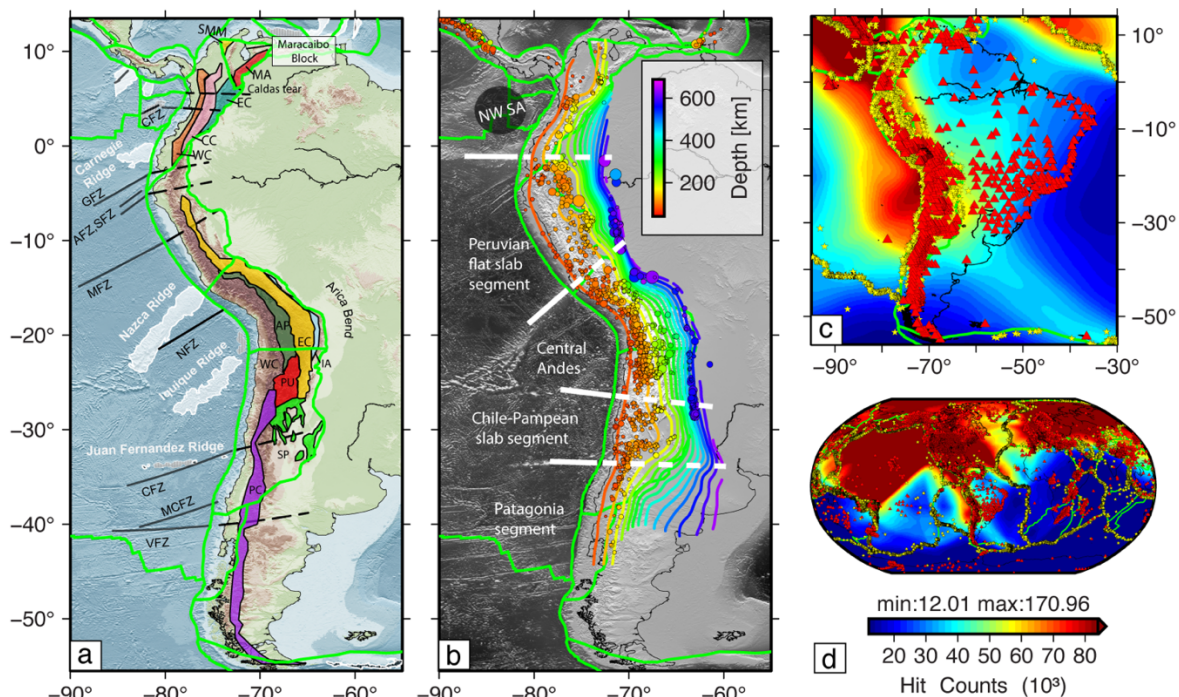


Figure 5.1: a) Boundaries of deforming tectonic units: SMM, Santa Marta Massif; MA, Merida Andes; CC, Central Cordillera; AP, Altiplano Plateau; EC, Eastern Cordillera; IA, Interandes; PC, Principal Cordillera; PU, Puna Plateau; SP, Sierras Pampeanas; WC, Western Cordillera. Fracture Zones: Grijalva Fracture Zone (GFZ), Alvarado Fracture Zone (AFZ), Sarmiento Fracture Zone (SFZ), Mendaña Fracture Zone (MFZ), Nazca Fracture Zone (NFZ), Challenger Fracture Zone (CFZ), and Mocha Fracture Zone (MCFZ) (Bloch et al., 2017; Contreras-Reyes and Carrizo, 2011). b) Circles are the seismicity from the USGS dataset, filtered by depth > 40

km and $M_w > 4$. Contours are the predicted depth to the top of the subducting slab from the Slab2 model (Hayes et al., 2018). NWSA: Northwestern South America. C,d) Regional and global distribution of seismic stations (red triangles) and events (yellow stars) used in the tomography, plotted on the hit-count map of data sampling.

Seismic tomography studies targeting the subduction under South America produced images of the regional, upper-mantle structure beneath various sections of the Andes Cordillera (e.g. Ammirati et al., 2015; Bianchi et al., 2013; Marot et al., 2014; Syracuse et al., 2016); at the upper mantle depths at the boundary between the South American and Caribbean plates (e.g. Mojica Boada et al., 2022; Yarce et al., 2014); and including the South Atlantic-South America region (e.g., Celli et al., 2020). Studies targeting the upper mantle structure of the subduction zone as a whole include, for example, Liu and Gao, 2022; Portner et al., 2020 and Rodríguez et al., 2020. Prior to the expansion of regional, temporary deployments on the Cordillera regions, much of our understanding of the deep subduction structure beneath South America was derived from global-scale tomography models (Amaru, 2007; Fukao and Obayashi, 2013; Lei et al., 2020; Montelli et al., 2006). These global studies have delineated the eastward-dipping, margin-parallel slab of the Nazca Plate and its ancestral Farallon Plate, descending to depths of approximately 900 km, and exhibiting significant fragmentation along strike.

In order to capture the interaction between the continental lithosphere and the subducting plate, as well as the spatially variable patterns of subduction and seismicity, tomographic imaging of the entire upper mantle of the region is required—radially, from the lithosphere to the deep upper mantle and, laterally, from the oceanic Nazca Plate to the continental interior. Our newly developed S-wave seismic tomography model, SACI-24, is constructed to optimise the data sampling of the South American continent and surroundings. Data from both regional and global seismic stations yield dense data coverage. The waveform tomography that uses this data sampling reveals complex patterns of the interactions between the subduction zones and continental lithosphere and prompts new inferences on the geodynamic processes at play.

5.1.1 Northwest South America

The north-western region of South America features a complex geodynamic setting resulting from the convergence of the South American, Nazca, and Caribbean Plates and the

northern Chocó and Panamá blocks. The complexity of the interaction between these plates and blocks prompted differing hypotheses regarding the subduction mechanisms.

The Cordilleras, the extensive system of mountain ranges in the west of South America, rose, fundamentally, due to the subduction and are segmented into three main branches: the Western, Central, and Eastern Cordilleras. These branches are further separated by two key valleys, the Middle Magdalena and the Cauca-Patía valleys (e.g., Vargas, 2019).

Seismicity data and seismic tomography studies reveal the existence of multiple plate segments, slab tears and regions of flat subduction. West of the Panamá Block, active arc volcanism terminates north of approximately 5.5°N latitude (e.g., Wagner et al., 2017). Concurrently, a right-lateral displacement of about 240 km is observed in the Wadati-Benioff zone at this latitude. These unique characteristics strongly suggest a shift in subduction style, leading to the hypothesis of a potential east-west tear that segments the subducting slab in this region (Taboada et al., 2000; Wagner et al., 2017). This hypothesised tear, known as the Caldas Tear (Vargas and Mann, 2013), demarcates the subduction zone with a flat slab to the north from a steeper segment to the south, commonly referred to as the Bucaramanga and Cauca segments, respectively (Pennington, 1981). The Bucaramanga segment also encompasses the Bucaramanga nest, a localised area of seismic activity that contains some of the highest concentrations of intermediate-depth seismicity worldwide (e.g., Zarifi et al., 2007).

Several models were proposed to explain the interactions between these plates and the origins of the Bucaramanga and Cauca segments (Figure 5.2).

- 1) **Nazca and Caribbean plates origin.** According to this class of models, the Cauca segment originates from the Nazca Plate, while the Bucaramanga segment is derived from the Caribbean Plate (Prieto et al., 2012; Sun et al., 2022; Taboada et al., 2000; Yarce et al., 2014). Some of these models also suggest an overlap between the northern boundary of the Cauca segment and the southern boundary of the Bucaramanga segment (Mojica Boada et al., 2022; Taboada et al., 2000; Vargas et al., 2007).
- 2) **Nazca origin.** In this scenario, the Bucaramanga nest is linked to a second tear within the Nazca Plate (Syracuse et al., 2016). It is usually proposed that the Caribbean slab may be overlapping the Nazca subduction to the north (Van Der Hilst et al., 1994).

- 3) **Bucaramanga segment with Nazca and Caribbean origins.** This model implies that the Bucaramanga nest is at the boundary between the Nazca and Caribbean slabs (Corredor, 2003; Zarifi et al., 2007; Sanchez-Rojas and Palma, 2014).

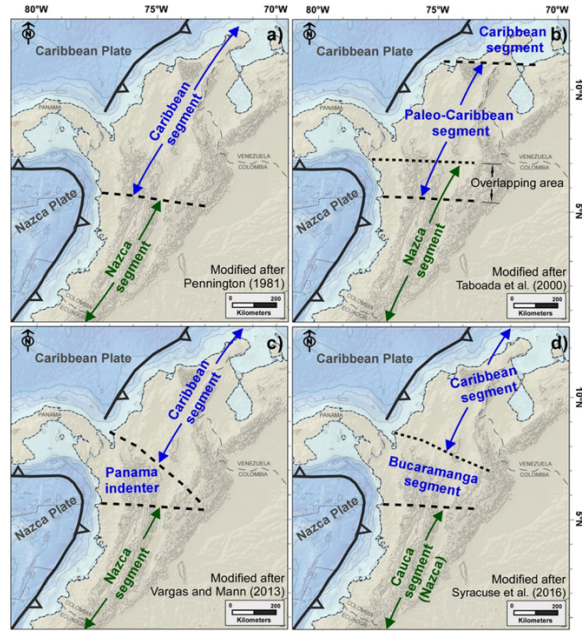


Figure 5.2: Examples of previous interpretations of the slab boundaries beneath the northwest South America. Figure from González et al., (2023).

At the northern boundary of South America, the geometry of the Caribbean plate subduction is also not fully understood. Moving southwards, the Caribbean plate underthrusts a part of northern Colombia and Venezuela (Miller et al., 2009; Van Der Hilst et al., 1994). In northern Colombia, under-thrusting gives way to subduction (Taboada et al., 2000; Van Der Hilst et al., 1994), but where the transition occurs remains unclear. The situation may be complicated by other slabs interacting with the Caribbean-Plate on at depth (Chiarabba et al., 2016; Syracuse et al., 2016; Taboada et al., 2000).

High seismic velocities have been observed in front of the flat slab portion of the Nazca slab segment, where it meets the South American platform (Chiarabba et al., 2016). These fast anomalies are located beneath the Eastern Cordillera (EC), an area distinguished by its unique double-verging topographical features. A widely accepted hypothesis to explain this phenomenon posits that the flat subduction of the Caribbean slab initiates a process of continental lithosphere subduction beneath the EC (Colletta et al., 1990; Cortés and Angelier, 2005; Mojica Boada et al., 2022; Taboada et al., 2000).

Geodynamic models have been used to suggest that flat subduction could displace continental lithosphere material in one of two ways: by forming a keel in front of the flat subduction if the material is buoyant, or by causing the material to sink if it is dense (Axen et al., 2018). Delamination of the lower lithosphere beneath the EC and mantle melting are consistent with the compositions of the igneous rocks in the Paipa-Iza area (Monsalve et al., 2019), which indicate partial melting in the upper mantle.

5.1.2 Flat slab subduction

In South America, two most prominent flat slabs are located in the Peruvian segment and the Chile-Pampean segment (Figure 5.1). The underlying causes of flat subduction and its effects on the upper plate are debated (e.g., Antonijevic et al., 2015; Hayes et al., 2018; Manea et al., 2017). The factors behind the formation of South American flat slabs could include buoyant features in the oceanic lithosphere such as the Inca Plateau and the Nazca and Juan Fernandez aseismic ridges (Gutscher et al., 1999), hydrodynamic suction from a thick overriding plate (Ma and Clayton, 2015; Manea et al., 2012) and the advance of the South American plate over a retreating Nazca plate (Schepers et al., 2017).

The flat slab subduction has been studied extensively (e.g. Ammirati et al., 2015; Antonijevic et al., 2015; Bishop et al., 2017; Gao et al., 2021; Manea et al., 2017), but the impact of along-strike variations in the slab dip on the deformation of the overlying plate remains uncertain. As the angle of subduction varies along strike, the subducting plate undergoes bending and deformation, which can cause thinning or even tearing of the slab at the transitions between steep and flat subduction regions (e.g., Hu and Liu, 2016). This slab morphology would, in turn, influence mantle flow patterns.

In the Peruvian region, several seismic studies documented the existence of a large (~1500 km in length) flat-slab segment in central-northern Peru (Antonijevic et al., 2015; Bishop et al., 2017; Cahill and Isacks, 1992; Scire et al., 2016). The Nazca plate contains a series of well-defined bathymetric highs corresponding to aseismic ridges and fracture zones. Among them, the one of a likely relationship with the Peruvian flat slab is the aseismic Nazca ridge (Figure 5.1). It has been proposed to contribute to the slab flattening beneath Peru (Antonijevic et al., 2015) together with the hypothetical, now completely subducted, Inca plateau (Gutscher et al., 1999).

Among the many ridges located on the Nazca Plate, the Juan Fernandez Ridge (JFR; Figure 5.1) is likely to have caused the development of the Pampean flat slab. The JFR is a roughly 900 km long volcanic hotspot chain, its origin attributed to a mantle

plume (French and Romanowicz, 2015; Steinberger, 2000). Plate reconstructions suggest that the JFR has been migrating southward along the western margin of South America (Yáñez et al., 2002).

While the flat subduction is generally attributed to the subduction of the JFR, this ridge is probably too small to account for the full extent of the flat slab, which measures between 200 and 250 km parallel to the trench (Yáñez et al., 2002). The western proto-Gondwana margin has been significantly shaped by three major terrane accretions over the past 600 million years, profoundly affecting the structure and tectonic evolution of central Chile (Ramos et al., 2002). These terranes vary in their origins, compositions, and ages: the Pampia terrane amalgamated around 530–515 Ma; the Cuyania terrane accreted approximately 460 Ma ago; and the Chilenia terrane, whose existence remains a matter of debate, was added between 420 and 315 Ma (Ramos et al., 2002).

5.1.3 Central Andes

The most striking feature in the Central Andes is the expansive Puna-Altiplano Plateau (Figure 5.1). It has an average elevation of 3,700 meters and covers an area of around 700 x 200 km. In contrast with the Tibetan Plateau, the uplift of the Puna-Altiplano Plateau is not the result of continental collision. Instead, it arises from a compressional tectonic regime linked to the collision between a continental plate and a relatively shallow subducting oceanic slab (e.g., Isacks, 1988). Similar to the Tibetan Plateau, the crust of the Altiplano is anomalously thick, with seismic data indicating thicknesses up to 80 km (e.g., Beck et al., 1996; Yuan et al., 2002; McGlashan et al., 2008).

The Altiplano in southern Bolivia (18° - 23°S) is the broadest region of the central Andes, measuring ~700 km in width. It has undergone a significant crustal shortening of approximately 300–400 km over the last 40 million years (Eichelberger et al., 2015). Currently, the Altiplano reaches a surface elevation of ~4 km and features low relief within the plateau interior. The topography descends gradually eastward from the elevated plateau to the lower foreland basins over a distance of ~300 km. Various mechanisms have been proposed to account for this elevated topography, including crustal shortening (Beck and Zandt, 2002), lithospheric mantle loss (Andersen et al., 2022; Göğüş et al., 2022) and magmatic addition from the mantle (Haschke et al., 2002).

5.2 Waveform Tomography Model SACI-24

SACI-24 is an S-wave tomographic model of the South American continent and surrounding regions, spanning the depth range from the surface to the bottom of the mantle transition zone. The development of SACI-24 involved the analysis of more than 1.2 million regional and global seismograms, sourced from more than 9000 stations globally (Figure 5.1).

The seismograms were waveform-fitted using the Automated Multimode Inversion (AMI) (Lebedev et al., 2005). This method inverts the surface-, S-, and multiple S-wave components of the wave train. S and multiple S waves sample the deep upper mantle and uppermost lower mantle and complement the sensitivity of the fundamental mode surface waves, sampling primarily the lithosphere and asthenosphere.

Although computed in a global inversion, SACI-24 is built specifically for South America. This is achieved through specific parameterisation and regularisation, coupled with an emphasis on maximising regional data coverage. Meticulous manual quality control was used to detect and eliminate imaging artefacts and data originating from problematic stations.

The areas around the subduction zone in northern and central South America are among the most densely sampled regions. In these areas, each grid node of the tomographic model is sampled by over 12000 waveform fits, and the maximum number per node reaches 169597.

Upon downloading the data, we first check for quality-control the waveforms. We check for clipping and gaps, ensuring the entire waveform is fully recorded. Subsequent to this quality control, each trace undergoes response correction and is downsampled to 1 Hz. The seismograms are then subjected to a structured three-step inversion procedure.

1. Waveform Fitting. The Automated Multimode Inversion (AMI) method (Lebedev et al., 2005) is employed at this stage. It computes synthetic seismograms through mode summation and fits the surface, S, and multiple S waves with the observed waveforms within a set of weighted time-frequency windows, calculated for each seismogram specifically. Once the misfit is minimised in the time domain, AMI produces a series of linear equations with uncorrelated uncertainties (Nolet, 1990) that constrain the average S and P wave velocity variations from a 3D reference model within approximate sensitivity volumes (Lebedev et al., 2005).

2. Joint Inversion for 3D Velocity Distribution. All the equations from the first step are inverted jointly to determine the distribution of P and S wave velocities, as well as

the S-wave azimuthal anisotropy, in three dimensions (Lebedev and Van Der Hilst, 2008). The inversion is calculated using the LSQR method (Paige and Saunders, 1982) and incorporates smoothing and slight norm damping (Nolet, 1990). The tomographic model is parameterised using a dense triangular grid (Wang and Dahlen, 1995). We choose a grid of approximate 120 km lateral knot spacing and 18 and 10 triangular radial basis functions for S and P wave velocities, respectively. The maximum-value depths of the triangular basis functions for S-wave velocities are 7, 20, 36, 56, 80, 110, 150, 200, 260, 330, 410–, 410+, 485, 585, 660–, 660+, 809, and 1007 km. For P-wave velocities, they are 7, 20, 36, 60, 90, 150, 240, 350, 485, and 585 km. Model parameter perturbations are computed relative to the same 3D model used in AMI, a modified CRUST2 (Bassin et al., 2000) with added topography, a global-average baseline correction and smoothed cell boundaries, and a global 1D mantle average (Lebedev and Van Der Hilst, 2008).

3. Automated Outlier Removal. Outliers in the dataset present a challenge, but their identification and subsequent removal are facilitated by the redundancy of our very large dataset. The outliers are primarily due to errors in the source location and origin time and station timing (e.g., Legendre et al., 2012). To identify outliers, we first compute an initial tomographic model and then, calculate synthetic data from this initial model. The outliers, with the largest data-synthetic misfit, are then removed. This procedure selects the data with the greatest mutual consistency and eliminates the data with the largest errors.

Earthquake source parameters are taken from the Global Centroid-moment-tensor (GCMT) catalogue (Ekström et al., 2012) since 1994, applying a distance-magnitude varying threshold (Schaeffer and Lebedev, 2013).

5.2.1 Resolution Tests

Synthetic resolution tests are the most common method for assessing solution robustness in seismic tomography, and were originally introduced to investigate spatial resolution in inverse problems for which formal resolution cannot be computed due to the large model size (Spakman and Nolet, 1988). They involve the formulation of a heterogeneous synthetic model through which the forward problem is solved using the identical data coverage as the observational data set. The inversion method is then applied to the synthetic data set to recover the synthetic model. Differences between the true and recovered model provide a basis for assessing the reliability of the solution. SACI-24's accuracy has been tested by multiple resolution tests so far, including 1) synthetic spikes at multiple locations (Figure 3.6 and Supplementary Figure 3.5); 2) checkerboard tests (Figure

2.8, Figure 4.3, Figure 4.4 and Figure 4.5); 3) synthetic structures that reconstruct the shape of a known mantle structure such as a craton (Figure 3.7 and Figure 3.8) or vertical mantle plumes (Figure 4.6) and lastly, 4) a modified tomographic model as the input (Figure 4.7 and Figure 4.8).

Checkerboard resolution tests are one of the most common type of synthetic resolution test in seismic tomography studies. The synthetic input model consists of an alternating pattern of fast and slow velocities. These tests have achieved popularity in seismic tomography due to their simple implementation and intuitive insight into the reliability of the recovered model (Rawlinson and Spakman, 2016). To evaluate the model's spatial resolution at the subduction region within the lithospheric depths, we performed additional checkerboard type tests with columns of 250 km width and variable vertical length. In Figure 5.3 and Figure 5.4 we show two tests of similar horizontal geometry and different vertical lengths, spanning three and two depth nodes, respectively. We construct the following input model structures similarly to Figure 2.8, model a). The columns dimensions are two nodes wide a three node separation, approximately, and are input with S-wave velocity anomalies of ± 300 m/s.

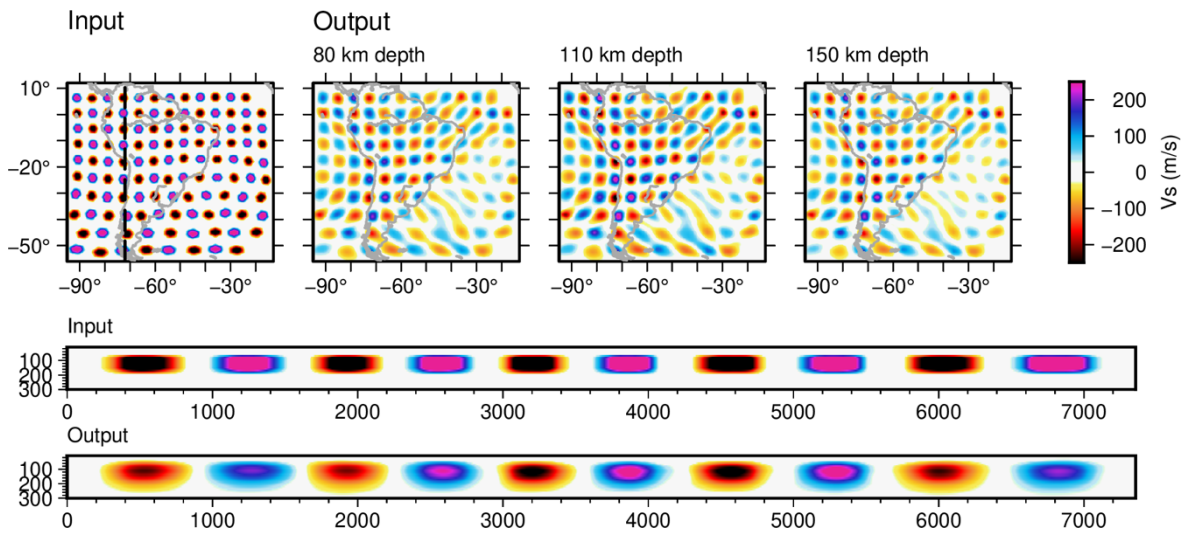


Figure 5.3: Column resolution tests at the depth nodes 80, 110 and 150 km. The input structures are defined with alternating positive and negative columns of 300 m/s. The input and output models are shown as depth slices at the top and vertical cross sections at the bottom. The cross section is shown as a black line in the first plot on the left.

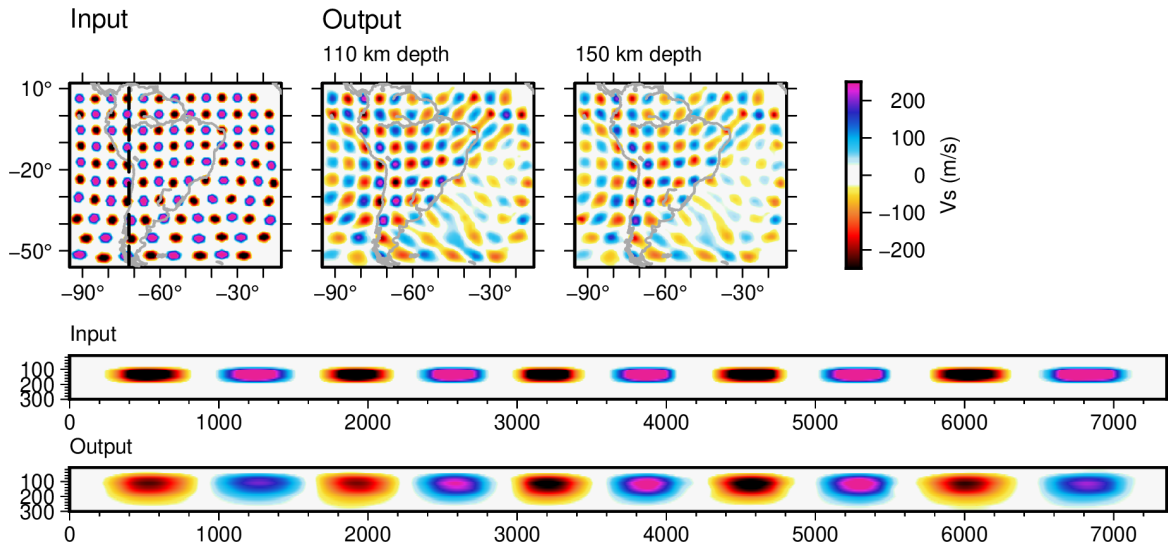


Figure 5.4: Column resolution tests at the depth nodes 110 and 150 km. The input structures are defined with alternating positive and negative columns of 300 m/s. The input and output models are shown as depth slices at the top and vertical cross sections at the bottom. The cross section is shown as a black line in the first plot on the left.

The results from Figure 5.3 and Figure 5.4 confirm the capability of the model to resolve structures of limited length accurately within the lithosphere, especially in the highly sampled subduction region. This test shows the excellent lateral and vertical resolution within the lithosphere, and supports that the model's regularisation does not lead to smearing or shifting of the anomalies between adjacent nodes.

To evaluate how the model performs when sampling the vertically dipping high velocity structure of a subduction slab, we have constructed two subduction geometries as synthetic input in the resolution test. The first consists of narrowed spaced segments that follows the shape of South America's western coastline, from north to south (Figure 5.5). The first segment is defined at the 80 km and 110 km depth nodes. The next "slab-like" segment follows a similar geometry, offset slightly to the east, from 150 km to 260 km depth. We define two more high velocity segments further offset to the east, from 330 km to 410 km and 485 km to 810 km depth. The position of the slab segments is loosely based on the Slab2 model (Hayes et al., 2018). The high velocity segments are input with 300 m/s velocity.

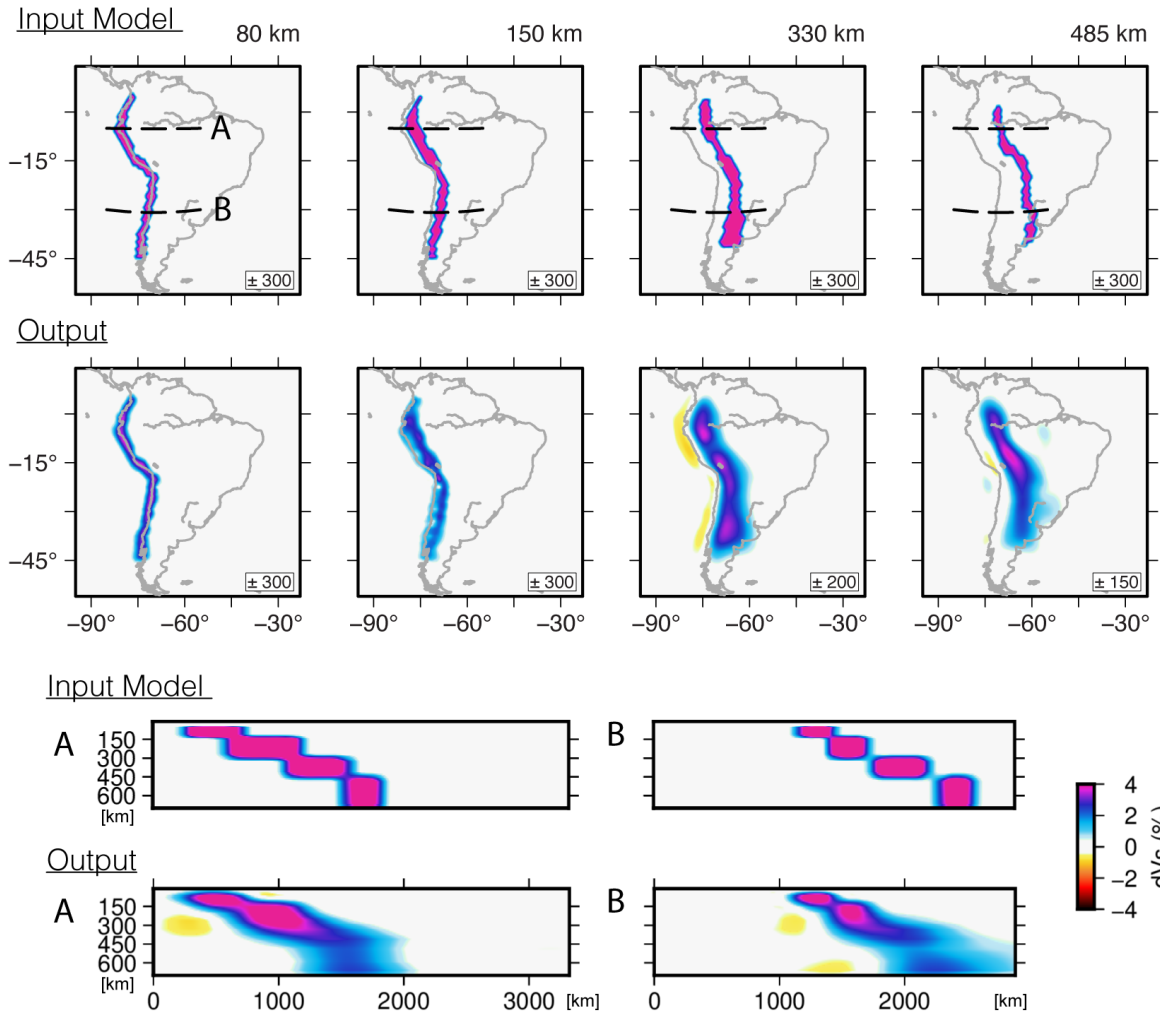


Figure 5.5: The slab segments resolution test is shown at four different depths. The vertical cross sections A and B (shown in the top left panel) show the model geometry with depth (bottom panels). The “slab” segments are input with 300 m/s velocity.

In the second geometry, we add two discontinuities to the synthetic slab geometry (Figure 5.6). The first discontinuity is at 150 km depth, with an approximate 250 km lateral separation. The second discontinuity is defined from 300 km to 485 km depth with no offset from the end of the segment above and the start of the segment below. With this slab geometry, we intend to test how the model resolves slab gaps located at the lithosphere and greater upper mantle depths, whether the gap extends vertically or horizontally.

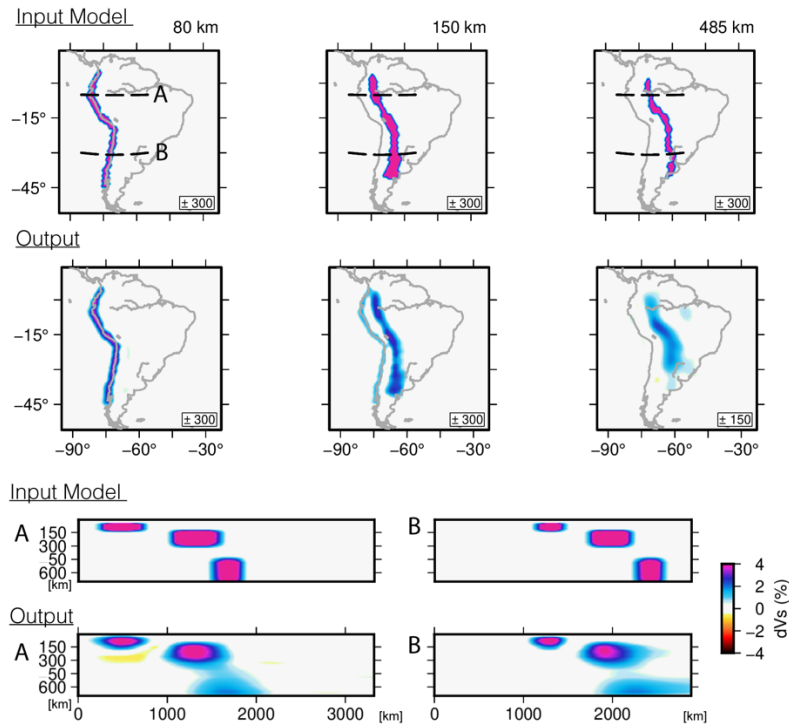


Figure 5.6: Fragmented slab segments resolution test at three different depths. The vertical cross sections A and B (shown in the top left panel) show the model geometry with depth (bottom panels). The “slab” segments are input with 300 m/s velocity.

From the resolution tests shown in Figure 5.5 and Figure 5.6 we confirm the excellent resolution of the model on the top 330 km. SACI-24 accurately resolves the input structures from the continuous and fragmented models, both horizontally and vertically. From 330 km to 485 km depth we observe the slight effect of smearing of the velocities. The block at 330 to 485 km depth appears as connected diagonally with the segment above in the model from Figure 5.5. Nevertheless, the location of the anomaly is still accurate. Similarly, we observe the effect of smearing in the fragmented model, where we observe a velocity anomaly of approximately 1% dVs connecting the two bottom structures in cross section A (Figure 5.6). Despite the observed effect of smearing, the model resolves the two separate segments accurately. The high velocity structure modelled at the greater depths (485-810 km) is also accurately modelled in location, despite some loss in amplitude is observed (~60%). Additionally, we observe the effect of smoothing, with the output geometry appears larger and smoother than the input. Within the transition zone, there is less crossing of seismic paths (as demonstrated in Figure 4.2) when compared to the lithospheric depths. Therefore, the lower density of seismic coverage leads to the smoothing operator to act more intensely in the structures sampled in the mantle transition zone. Additionally, when considering surface waves, the sampling at greater depths is mostly from long wavelengths. The longer

the wavelength, the broader the area over which the seismic energy is distributed (Aki and Richards, 2002). Consequently, surface waves tend to average the seismic properties over larger volumes. This averaging results in a smearing effect, where the distinct boundaries of seismic anomalies become less sharp and more diffused in the resultant seismic images.

5.3 Results and Discussion

Previous seismic studies on the South American subduction zone have primarily focussed on regional-scale models (e.g. Ammirati et al., 2015; Bianchi et al., 2013; Marot et al., 2014; Syracuse et al., 2016). On a continental scale, body wave models often lack adequate seismic sampling at lithospheric depths and have gaps in less sampled regions, such as the Peruvian flat slab (e.g. Portner et al., 2020; Rodríguez et al., 2020). The new continental-scale model, SACI-24, offers the advantage of incorporating both surface and body waves from a global dataset, allowing for detailed imaging of the full extension of the subduction slab, from the crust to the mantle transition zone. The dense sampling at lithospheric depths reveals the complex interaction between the Nazca and Caribbean subduction and the South American continental lithosphere.

In this chapter, we will discuss the small-scale structures identified by our model and also aim to provide a broader perspective on the subduction process as a whole, by comparing different subduction segments and their correlations over varying time scales, as evidenced by geodynamic models (Hu and Liu, 2016), kinematic evolution models (Schepers et al., 2017), time dependent modelling (Taramón et al., 2015) and geochemical data (DeCelles et al., 2009).

High-velocity anomalies along the northern and eastern coasts of South America (Figure 5.7) indicate the subducting oceanic lithosphere of the Caribbean and Nazca Plates, situated to the north and east of South America, respectively. The subduction structures delineated by our model exhibit marked variability, both latitudinally from north to south and vertically, as they descend into the upper mantle. Based on the subduction morphology described by previous and inferred from our own observations, we divide the discussion on five different segments of the subduction zone: Northwest South America, Peruvian flat slab segment, Central Andes, Chile-Pampean segment and Patagonia.

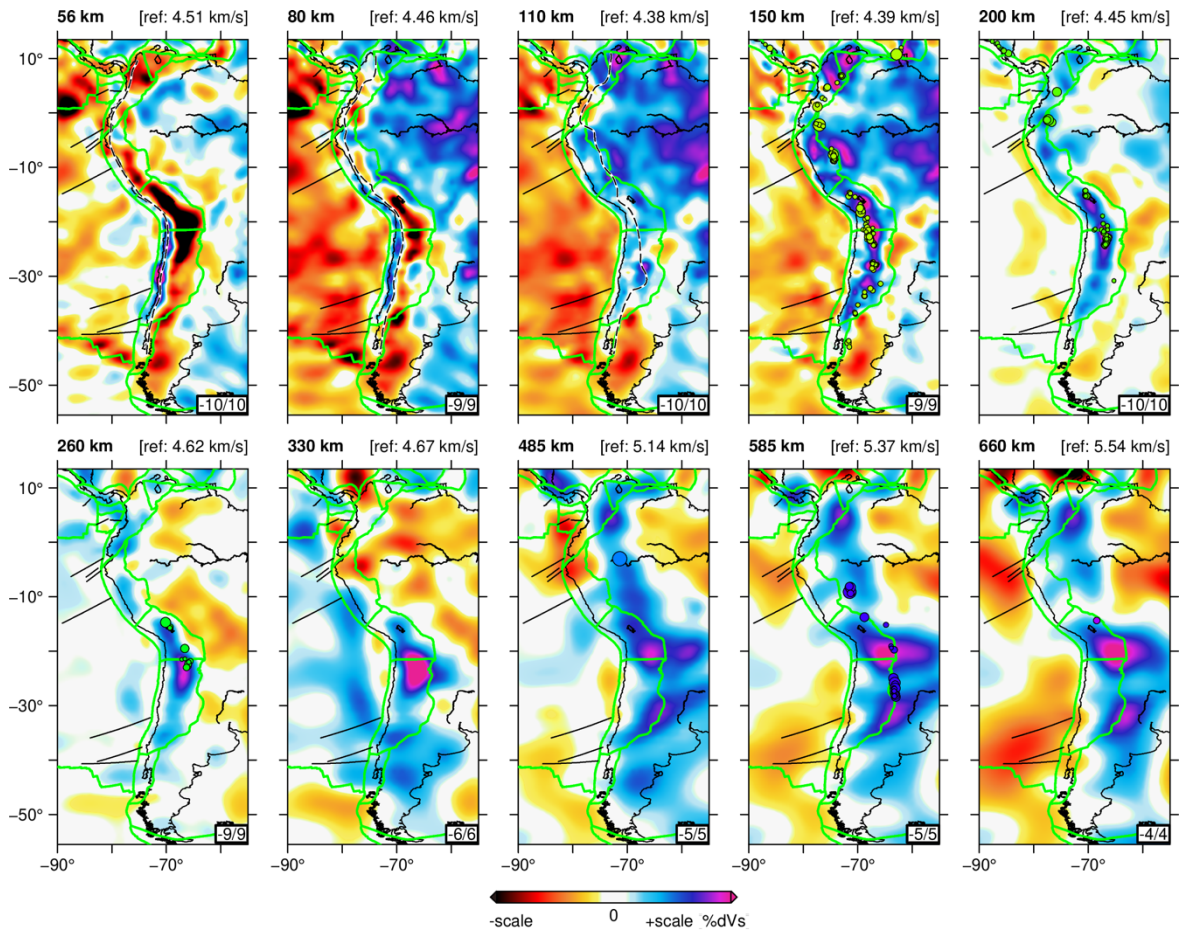


Figure 5.7: S-wave velocities according to SACI-24 at ten different depths (56, 80, 110, 150, 200, 260, 330, 485, 585, 660 km). Velocity variations are plotted in percentage with respect to the reference velocity at the depth, indicated at the top of each map. The subduction depth contours from Slab2 (Hayes et al., 2018) are plotted as dashed lines at 56, 80 and 100 km depths. From 150 km to 660 km, circles indicate the seismicity at the depth (± 10 km) from the USGS catalogue (Geological Survey).

5.3.1 Northwestern South America

Beneath the northwestern region of South America (NW SA) (Figure 5.7, Figure 5.8), we identify multiple areas of fast seismic velocities, mainly in the upper mantle above 300 km depth. We interpret these anomalies as cold lithosphere from the subduction of the different plates surrounding the region.

In Figure 5.8, we identify the likely origin of the major anomalies. To complement the structures delimited by seismic tomography, we add information from tectonic boundaries from Hasterok et al. (2022), seismicity from the USGS earthquake catalogue (Geological Survey) and slab depths from Slab2 (Hayes et al., 2018). We also include the

locations of the Bucaramanga nest and Cauca cluster (Pennington, 1981), as these may represent changes in the subduction behaviour.

We have showed the model's accuracy in resolving small scale anomalies (~ 250 km) within the lithosphere in the resolution tests in Figure 5.3 and Figure 5.4. The small slab fragments we identify in this portion of the subduction range from ~ 300 km (segment N0 in Figure 5.8) to up to 700 km long. Vertically these fragments appear as having approximately 100-200 km thickness. Based on the results from the resolution tests showed in Section 5.2.1, we can confirm that the dimensions of the slab fragments we discuss in this region is well within the resolving limitations of the model.

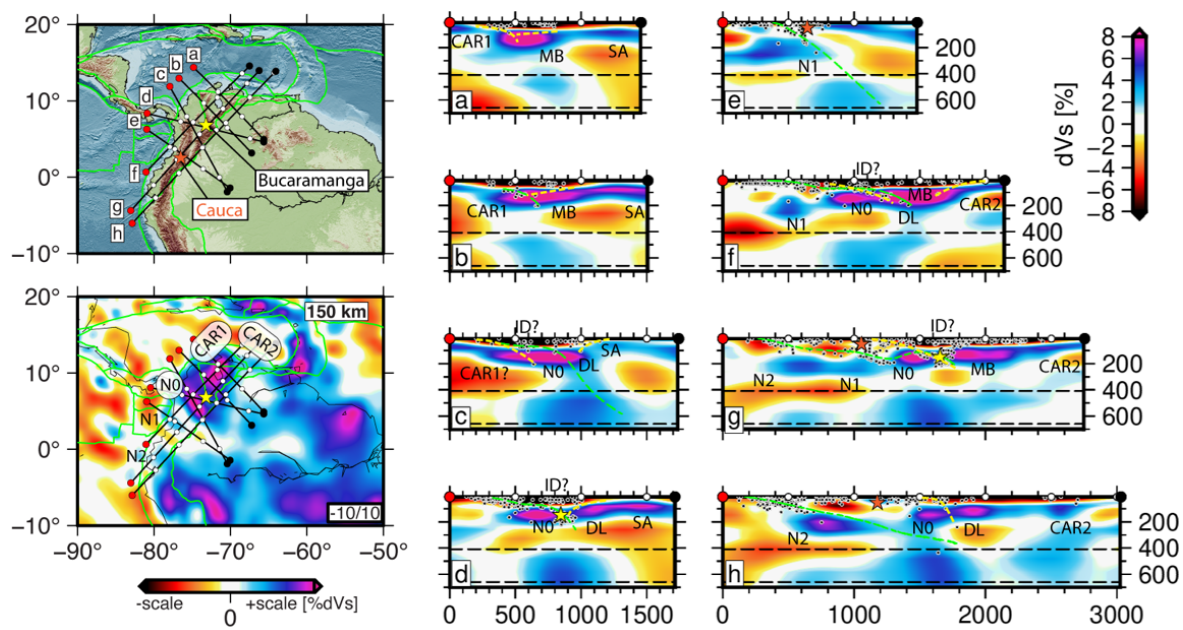


Figure 5.8: Cross sections through SACI-24 in northwestern South America. Stars on the location maps and the cross-sections indicate the Bucaramanga (yellow) and Cauca (orange) seismic nests. Green dashed lines on the cross-sections are from Slab2, and black circles indicate earthquakes. Yellow dashed lines are our interpreted plate boundaries discussed in the main text. The different slab segments observed are labelled: CAR1 and CAR2 from the Caribbean Plate; N0, N1, N2 from the Nazca Plate. MB, Maracaibo Block; SA, South America; DL, Delaminated lithosphere; ID?, Unidentified segment.

5.3.1.1 Identification of Multiple Slab Segments

The map views (Figure 5.7) and the cross-sections (Figure 5.8a-h) indicate at least five separate slab segments beneath the northwestern region of South America. Due to the complex configuration of the possibly overlapping Caribbean and Nazca plates under South

America, several slab configurations have been proposed for this region from regional tomography models (Syracuse et al., 2016; Taboada et al., 2000; González et al., 2023) and other geophysical information (González et al., 2023; Mojica Boada et al., 2022). Our model brings additional details in the identification each slab segment, either supporting existing models or by adding seismic information on a not yet modelled hypothetical structure. To the west of the Panamá Block and the Eastern Cordillera, we attribute the high seismic velocity anomalies to the subduction of the Nazca plate. This is based on the slab's closeness to the Nazca plate and its backtracking to a Nazca plate origin, as shown in Figure 5.8f-h. Additionally, there is a general agreement that this segment originates from the Nazca plate from kinematic reconstruction (González et al., 2023), seismicity and velocity models (Syracuse et al., 2016; Taboada et al., 2000). We label these segments as N0, N1, and N2 in Figure 5.8 for clarity.

The main question that remains is the plate configuration east of this area (Mojica Boada et al., 2022; Sun et al., 2022; Syracuse et al., 2016). We have identified two new structures in this area, ID? above the Bucaramanga seismic nest and DL. Based on results from Mojica Boada et al., (2022), we interpret the low seismic anomaly ID? as the result of delamination of the local lowermost lithosphere from the flat subduction of the Nazca plate. East of ID?, the high seismic velocity structure DL would be displaced lithospheric material from ID?, supported by geodynamic modelling results (Axen et al., 2018).

To the east of the Bucaramanga nest, we identify two more slab segments, as shown in Figure 5.8-f, g, h. These easternmost segments can be backtracked to the Caribbean plate, which is thought to subduct towards the southwest and south (Taboada et al., 2000). We label these CAR1 and CAR2. Multiple studies agree on the shallow subduction of the Caribbean plate in this region (Pennington, 1981; Taboada et al., 2000; Vargas and Mann, 2013).

For a better understanding of the observed slab segments in our tomography model, we now discuss each cross section of Figure 5.8.

Cross Sections a-b. These sections reveal the upper mantle structure beneath the Maracaibo Block, showing the shallow high-velocity anomalies of CAR1 subduction near the trench. A deeper high-velocity anomaly is also evident under the Maracaibo Block, flanked by the mountain ranges of the Sierra Nevada de Santa Marta to the north and the Merida Andes to the south. We propose that this fast anomaly originates from the underthrusting of the thick South American continental lithosphere. In this context, the Caribbean plate's subduction is linked to the mountain building process of the Sierra Nevada

de Santa Marta, while the underthrusting of the South American lithosphere is tied to the Merida Andes.

The origin of the lower crust of the Maracaibo Block has been suggested to be related to the northeast underthrusting of the South American platform under the El Pilar fault system (Cediel et al., 2003). A direct connection between the South American lithosphere and the fast anomaly under the Maracaibo Block is seen in cross section b. In Figure 5.8 we attempt to add the proposed boundaries of each plate in yellow dashed lines. For simplification, in Figure 5.8 we will denominate this fast anomaly as the Maracaibo Block (MB). Additionally, a second high-velocity segment is visible, lower into the mantle. We attribute this feature to an older subduction slab, corroborating previous interpretations that suggest it is a detached, broken segment of the Caribbean slab (Cornthwaite et al., 2021).

Cross Section c: This section is parallel to the high-velocity anomaly we observe at 150 km depth. We attribute this fast anomaly mainly to the Nazca plate. The plate appears to dip east under South America, roughly parallel to the trench west of Panamá and the Eastern Cordillera. This suggests that the Eastern Cordillera system is a direct result of the subduction of the Nazca plate. In this region, it is possible that the Nazca subduction underlies the Caribbean shallow subduction as proposed by different models (González et al., 2023; Mojica Boada et al., 2022; Taboada et al., 2000; Van Der Hilst et al., 1994). Our model, however, does not separate these two closely spaced structures. This segment of the slab is the only part of the subduction in NW SA where we observe continuity of the slab down to 700 km (also seen in f).

Cross Section d: This section crosses multiple mountain ranges and includes the Bucaramanga seismic nest. We identify that the nest sits at the boundary between two slab segments. The Nazca plate (N1) is subducting at a shallow angle, and to the east of it, we identify another fast anomaly, which we attribute to thick lithosphere of the South American platform.

In cross section g, we have a perpendicular view of the intersection of the slab segments. There, we see that the thick lithosphere of the Maracaibo Block intercepts this location together with N1 and the lithosphere on the South American side. The seismicity on the edge of the MB suggests that the compression forces are causing the MB to underthrust west under the lithosphere of Colombia. Above the location of the Bucaramanga nest, we also observe an area marked by low seismic velocities (see Figure 5.7- 56 km depth) and upper crustal seismicity. We can identify this in additional cross sections (Figure 5.8-c,g), and we will denominate this anomaly ID?. We interpret ID? as a possible result of the flat subduction of the Nazca plate in this area, which lead to delamination of the local

lowermost lithosphere (Mojica Boada et al., 2022). Geodynamic modelling shows that in this scenario, the lithospheric material could be displaced eastward if buoyant (Axen et al., 2018). Accordingly, we identify a high seismic velocity structure east of this region, visible in Figure 5.7 at 56 and 80 km depth, which we will denominate DL. We do not have enough evidence, however, to classify whether the origin of this fast anomaly is lithospheric delamination, as previously proposed (Mojica Boada et al., 2022), or underthrust South American platform.

Cross Section e: Here, we find an additional Nazca slab segment, denoted as N0. This segment is overlaid by the Cauca cluster and is thought to be bounded by the Caldas Tear to the north (Vargas and Mann, 2013) and the subducted Malpelo rift to the south (Sun et al., 2022; Vargas and Mann, 2013). The lower seismic velocities in this segment could be due to the young and warm lithosphere of the subducted Sandra rift.

Cross Sections f, g, h: These sections run parallel to the main tectonic trends in NW SA and serve as additional evidence for identifying the seismic anomalies discussed earlier.

5.3.2 Peruvian flat-slab segment

We define the Peruvian flat slab segment as the area between the subduction of the Carnegie ridge and the subduction of the Nazca ridge (Figure 5.1). In this region, intermediate depth seismicity is scarce, with seismicity resuming in the mantle transition zone in some areas at depths of 500-700 km. In this section, we will discuss the structural variations of the subduction showed by our model SACI-24.

From Figure 5.7, we observe a highly heterogeneous upper mantle in this area. High seismic velocities, indicative of the Nazca plate's subduction, are evident from depths of 56 km to 200 km. Interestingly, there is an absence of fast anomalies between depths of 260 km and 330 km. At a depth of 485 km, both seismicity and high seismic velocities re-emerge.

In Figure 5.9 we present vertical cross-sections of seismic velocities in the Peruvian region, supplementing this with seismicity data from the USGS earthquake catalogue (Geological Survey) and slab depths from Slab2 (Hayes et al., 2018). The observed heterogeneity in upper mantle seismic velocities appears to stem from the irregular dipping angles of the Nazca subduction oceanic slab under the South American platform.

We have tested the robustness of the model in resolving continuous versus fragmented slab subduction in Figure 5.5 and Figure 5.6. The results validate the model accuracy in resolving continuous and/or fragmented subduction segments across all depths. Within the top 300 km, the model resolves seismic anomalies with great precision, in

amplitude, location, and shape. At the mantle depths greater than 300 km we observe small scale smearing of the anomalies, which could lead to make fragmented blocks of slab appear as continuous. We show that despite this observed the smearing effect in Figure 5.6-A, the amplitude of the smearing anomaly between blocks ($\sim 1\%$ dVs) is smaller than the amplitude of the continuous structures ($\sim 3\text{--}4\%$ dVs) in Figure 5.5. In the mantle transition zone, the model correctly resolves the location of the input structure. However, we observe that the resulting structure appears less sharp and more diffused due to the effect of smearing. In the following discussion we will consider the model limitations observed from the resolution tests from Figure 5.5 and Figure 5.6 when making inferences about the geometry and behaviour of the subduction slab.

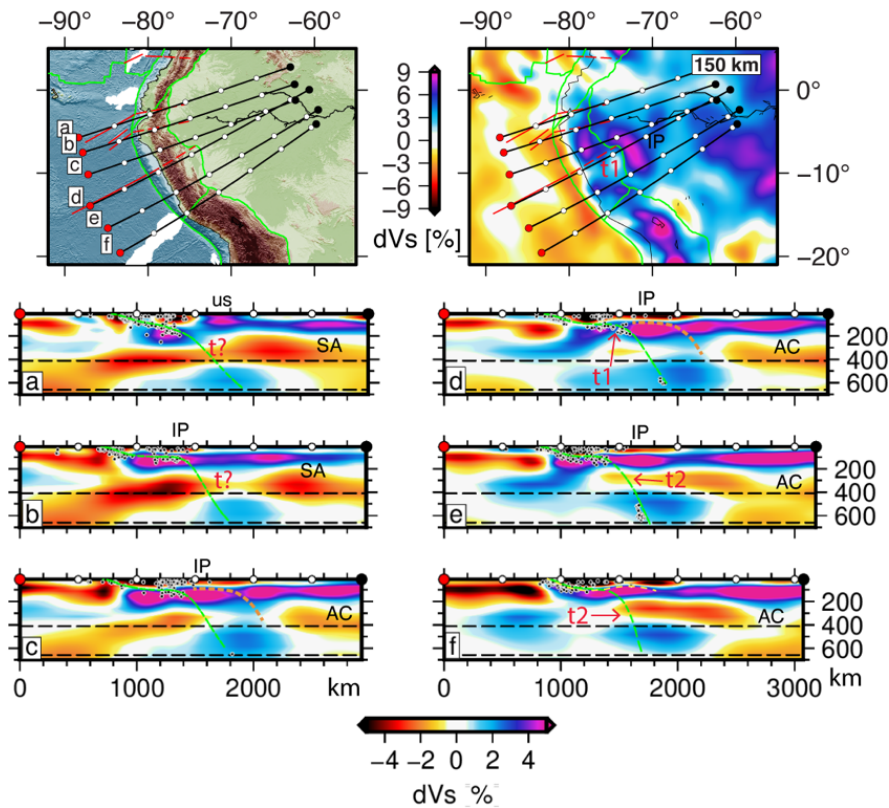


Figure 5.9: Vertical cross sections on the Peruvian region indicating the distribution of seismic velocities within the upper mantle. Cross section locations are indicated as labelled lines on the top figures. Cross sections on the bottom: Green dashed lines are from Slab2 and black circles are seismicity locations. Orange dashed lines are the subduction boundaries we interpret in the text. We label the different slab tears observed as $t?$, $t1$ and $t2$. Additional labels on the cross sections are explained on the main text: us, underplated slab; SA, South America; IP, Inca Plateau; AC, Amazon Craton.

5.3.2.1 Geometry of the flat slab

Flat subduction is believed to initiate in the northern Peruvian segment, and the formation of the flat slab has been associated with the subduction of the "lost" Inca Plateau. This plateau is considered to be the conjugate feature of the Marquesas Plateau in the western Pacific (Gutscher et al., 1999).

We observe multiple fast seismic anomalies in the shallow upper mantle depths (110-150 km) and the full extent of the Peruvian flat slab. This anomaly aligns well with prior suggestions of the subducted oceanic lithosphere of the Inca Plateau, and we will refer to it as IP (Figure 5.9). The IP fast anomaly is noticeable due to its great dimension (600 km length) and is clearly visible in the cross sections of Figure 5.9b-e.

We notice, however, that the location of IP does not correspond exactly with the present shallow seismicity. What we observe seems to correspond with the behaviour of slab flattening and tearing previously described by geodynamic modelling (Hu and Liu, 2016) and kinematic reconstruction (Schepers et al., 2017), and only now revealed by seismic tomography.

Upon examining the various cross-sections in Figure 5.9, we propose that IP originates from the Nazca plate and represents the furthest extent of the flat slab (Figure 5.9-b,c,e). However, in Figure 5.9-d IP appears to be entirely detached from the remaining slab, and seismicity data suggest that the current subduction is occurring on its western edge, indicating the presence of a slab tear. This observation aligns well with predictions from geodynamic modelling and is consistent with the slab curvature indicated by seismicity (Hu and Liu, 2016). We therefore propose the existence of a tear in what was once a continuous flat segment that included IP. The location of this tear, which we will designate as t1, may be influenced by the subduction of the Mendaña Fracture Zone. We mark the location of t1 in Figure 5.9 for clarity.

We also observe a second tear, corroborated by both seismic tomography (Antonijevic et al., 2015) and geodynamic modelling (Hu and Liu, 2016). This tear, which we label as t2, is commonly ascribed to the slab flattening induced by the subduction of the Nazca ridge. In our model, t2 vertically bisects the slab at depths ranging from 200 km to 400 km, as seen in Figure 5.9e, f. Additionally, we identify a third tear, denoted as t?, in Figure 5.9a, b. While not explicitly detailed in their study, the modelling work by Hu and Liu, (2016) predicts tearing in this area when using alternative geotherms values. The presence of slab tears in the upper 400 km of the model have been validated by resolution models in Figure 5.5 and Figure 5.6. We have showed the model's accuracy in resolving

separate seismic structures of dimensions similar to those of a subduction slab, and the corresponding separation between them.

Slab tearing in flat slab subduction settings can be explained by the differential sinking rates between the subducting aseismic ridges and the surrounding slab portions. Aseismic ridges, being less dense than the surrounding slab (Gutscher et al., 1999), exhibit slower sinking rates, leading to the accumulation of extensional strain at their down-dip extremities (Hu and Liu, 2016). As the tear manifests within the slab hinge, the high-pressure mantle beneath it ascends. This behaviour is evident in Figure 5.9-d where the slab's upper surface displays an apparent upward dip, corroborated by seismicity. This local mantle upwelling induces thermal weakening in the adjacent slab, thereby facilitating the expansion of the tear (Hu and Liu, 2016).

Slab tearing has been additionally confirmed by seismic anisotropy measurements within the Peruvian slab (Eakin et al., 2016). The upwelling asthenosphere beneath the torn slabs creates favourable conditions for slab melting, particularly of its crust, potentially giving rise to adakitic magmatism (Gutscher et al., 2000; Hu and Liu, 2016). In Peru, adakitic eruptions occurred along a ~300 km N–S distance range (-8° to -10° latitude) during 10–4 Ma (Gutscher et al., 2000). The locations of adakitic volcanism coincide with our proposed tear location t1 and provide additional evidence for our observations.

The geometries we observe within the Peruvian slab segment can be interpreted as representing various phases of slab flattening, tearing, and a return to conventional subduction. This cyclical behaviour aligns with the tectonic reconstruction of the Andes presented by Schepers et al., (2017). The main driver for flat slab formation, according to their model, is the South American plate advancing over the Nazca slab bend, that remained stationary in the mantle. In this scenario, in concert with other drivers, an overpressured sub-slab mantle is supporting the weight of the slab in an advancing upper plate-motion setting can locally impede rollback and maintain flat slabs until slab tearing releases the excess pressure. Tear subduction re-establishes a continuous slab and allows the process to recur.

The first stage of flat slab formation and maintenance is observed in Figure 5.9-b and Figure 5.9-f, where we observe continuous horizontal slabs ranging from 600 km to 800 km in length. Despite evidence of slab tearing at greater depths (200–400 km), these slabs appear to be supported by an overpressured, thermally elevated asthenospheric mantle. This is true specially for Figure 5.9-b, where the strong low velocity anomaly has been observed by many models (Antonijevic et al., 2015; Bishop et al., 2017; Scire et al., 2016). The relationship between this slow seismic anomaly and the Galápagos plume was explored in Chapter 4.

In cross sections c and e of Figure 5.9 we may be witnessing an intermediate stage of slab tearing and pressure release. The observed seismicity within the slab could be a response to the thinning and extensional stress exerted by the overpressured sub-slab mantle. As noted earlier, Figure 5.9-d shows evidence of slab tearing, while the segmented slab in Figure 5.9-a could indicate a more advanced stage of tearing and a resumption of normal subduction.

Taramón et al., (2015) predicted in their geodynamic modelling that seismic imaging would reveal a highly contorted slab shape in the upper mantle shortly after the cessation of a flat slab episode. Over time, the slab would regain a more homogeneous shape in the upper mantle, although the imprint of the previous flat slab episode might persist in its deeper structure. We believe that the heterogeneous slab geometry revealed by our model aligns precisely with the outcomes predicted by Taramón et al., (2015). Current observations in the Peruvian slab segment, including tearing and a return to normal subduction (Antonijevic et al., 2015), suggest the likely conclusion of this flat slab episode. Just as seismic imaging allows us to delineate current processes in slab dynamics, it may also enable us to identify regions where the signatures of past slab flattening and tearing events are preserved.

5.3.2.2 Underplating of subducted lithosphere

As a subduction slab encounters the continental overriding plate, variations in the continental lithosphere thickness can cause flattening of the slab through flow-induced reduction in pressure within the mantle wedge (Stevenson and Turner, 1977). Narrowing of the mantle wedge or increased wedge viscosity both act to increase negative pressure and pull the slab upward. The upward pull by the hydrodynamic stresses is often termed ‘hydrodynamic suction’ (Manea et al., 2012; O’Driscoll et al., 2012; Taramón et al., 2015).

Hydrodynamic suction exerted by a thick overriding plate has been proposed as one of the main mechanisms for the formation of flat slabs (Ma and Clayton, 2015; Manea et al., 2017). Taramón et al., (2015) delineate two modes of slab flattening in their 3D geodynamic simulation: permanent underplating and transient flattening. In the case of permanent underplating, the suction force is sufficient to fully couple the subducting plate to the overriding lithosphere. Transient flattening occurs when the negative buoyancy of the slab is strong enough to overcome the suction force exerted by the overriding craton.

While both transient flattening and permanent underplating have generally been attributed to the subduction of buoyant oceanic plateaus or episodes of rapid trench rollback, underplating tends to occur preferentially beneath cratons (Taramón et al., 2015). This

distinction highlights the role of the overriding plate's characteristics, particularly its thickness and buoyancy, in determining the mode of slab flattening.

Despite the presence of slab tearing, we note that the IP segment of the flat slab remains coupled beneath South America. We attribute this underplating of the buoyant oceanic plateau to the hydrodynamic suction effect exerted by the thick lithosphere of the Amazon Craton. In Figure 5.9, we can observe the Amazon Craton's thick, fast lithosphere in proximity to the flat slab segments, particularly in cross sections c to f.

In the cross sections c and d of Figure 5.9, we identify fast seismic velocities below the IP segment extending to the mantle transition zone, indicated by orange dashed lines. We propose two potential origins for this fast anomaly, in line with the models described by Taramón et al., (2015).

Firstly, permanent underplating of the IP segment could have occurred, facilitated by its proximity to the Amazon Craton's thick lithosphere, as suggested by Wells et al., (2014). In this scenario, a slab gap forms beneath the craton, leading to tearing in adjacent sections of the subducting plate and the initiation of a new subduction zone. The fast anomaly we observe beneath the IP segment would then represent the dipping portion of the previously flat slab, now fully detached and sinking into the lower mantle.

Secondly, in the case of a transient slab flattening episode, the IP segment remains attached to the adjacent slab section and will eventually be pulled into the mantle. Given our earlier discussion regarding Figure 5.9-a, where we suggest that this section might represent a more advanced stage of flat subduction and detachment, the fast seismic velocities observed ahead of the subduction could be remnants of a previously underplated slab segment, denoted as "us" in Figure 5.9-a).

5.3.3 Central Andes and Chile-Pampean flat slab

South of the Peruvian flat subduction zone lies the Central Andes, characterised by the elevated topography of the Andean Plateau (Figure 5.1). This plateau represents the Earth's largest orogenic feature formed through ocean-continent convergence. In this section, we turn our attention to the seismic velocities observed beneath the Central Andes to shed light on the underlying geodynamic processes.

In Figure 5.7, distinct features are evident beneath the Central Andes compared to other subduction zones along the western margin of South America. Within the crustal depths (56-80 km), a band of positive seismic velocities is observed at the continent's margin, while strong low seismic velocities underlie the mountain range. At a depth of 80 km, a band

of positive seismic velocities is discernible northeast of the Central Andes orogenic boundary. At 150 km depth, strong positive seismic velocities are present beneath the Central Andes with varying lateral extents from north to south. Between depths of 200 km and 330 km, a more homogeneous band of fast seismic anomalies is observed, with slightly higher amplitudes in the central region. Within the mantle transition zone (485-660 km), the fast anomalies appear to bifurcate at approximately 25°S latitude, and a new fast anomaly emerges east of the subduction zone at 20°S.

Figure 5.10 shows multiple cross-sections of the seismic velocities beneath the Central Andes, the Chile-Pampean flat slab, and the adjacent South American platform. Based on the integration of new insights from our tomography model with recent geological and geodynamic research the main findings from SACI-24 discussed in this section include:

- The identification of continental underthrusting over multiple areas of the Central Andes, previously observed only at smaller scale by seismic tomography (Beck and Zandt, (2002) and refs within);
- Several stages of Cordillera lithospheric root growth and delamination, proposed as a large scale Cordillera event (Decelles et al., 2015; Ducea et al., 2013; Kay and Coira, 2009) but only observed in local scale by seismic tomography (Andersen et al., 2022; Beck and Zandt, 2002; Tassara and Echaurren, 2012; Ward et al., 2016; Whitman et al., 1996);
- The identification of broad region of fast seismic velocities within the mantle transition zone as possible delaminated lithospheric material from past lithospheric root foundering events.

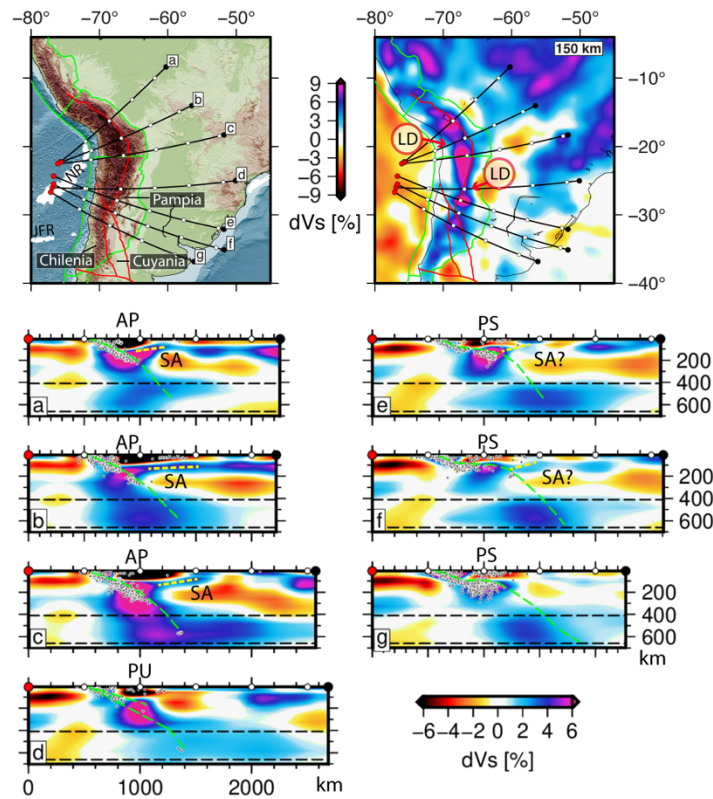


Figure 5.10: Vertical S-wave velocity cross sections on the Central Andes and Chile-Pampean region. Cross section locations are indicated as labelled lines on the top figures. Red lines indicate the boundaries between the Pampia, Chilenia and Cuyania terranes. Cross sections on the bottom: Green dashed lines are from Slab2 and black circles are seismicity locations. Yellow dashed lines are the subduction boundaries we interpret in the text. NR, Nazca Ridge; JFR, Juan Fernandez Ridge; LD, Lithospheric delamination; AP, Altiplano; PU, Puna; SA, South America; PS, Pampean segment.

5.3.3.1 Dynamics of the crust

In Figure 5.10, we observe a spatial variation in the extent of low seismic velocities within the crust beneath the Cordillera, ranging from 13°S to 30°S. These low crustal velocities, particularly under the Altiplano, are commonly attributed to a weak, felsic composition (Beck and Zandt, 2002). The extent of this low-velocity crustal zone varies latitudinally. In Figure 5.10-a the zone spans approximately 400 km, but it expands southward, reaching a breadth of about 600 km in Figure 5.10-c.

The recent lithospheric modelling by Wang and Currie, (2023) highlights the significance of a ductile, weak lower crust in the Altiplano's dynamics. As the orogen grows upward, this weak lower crust flows laterally, contributing to a stepwise expansion of the orogenic belt. Over time, this process can induce deformation that propagates into the

continental crust. The weak lower crust serves as a crust-mantle décollement, facilitating the decoupling of the continental mantle lithosphere from the crust and enabling it to underthrust the plateau.

In alignment with this model, our observations from Figure 5.10-a, b, c suggest an eastward migration of the weak lower crust towards the South American platform. We also identify westward-dipping high-velocity anomalies extending from the platform towards the subduction zone. We interpret these anomalies as indicative of continental underthrusting, corroborating the model's assertion that the weak lower crust acts as a décollement, allowing for lithospheric interactions that contribute to the plateau's uplift and expansion.

5.3.3.2 Cordillera Cyclicity

A recurrent question in geodynamics is the role of the mantle lithosphere in mountain building. When the crust undergoes shortening, the underlying mantle lithosphere must shorten and thicken too. Estimates of shortening in the Andean Cordilleran range up to ~400 km (Kley and Monaldi, 1998; McQuarrie, 2002). As the orogenic belt consist almost exclusively of upper-crustal rocks that were detached from the lower crust (Boyer and Elliott, 1982), a slab of lower crust and lithosphere equal in length to the total upper-crustal shortening must underlie the region (Oldow et al., 1990). In the central Andes, the volume of lithosphere underthrust beneath the magmatic arc since early Cenozoic time is proposed to be on the order of 10^7 km (Allmendinger et al., 1997). Surprisingly, thin lithosphere is often found beneath plateaus (e.g. northern Tibet) (Schurr et al., 2006).

In the central Andes, multiple mechanisms have been proposed as the cause for lithospheric removal. For example, underthrusting of the continental lithosphere under the mountain range may lead to decoupling and consequent delamination or subduction of the orogen's subcrustal lithosphere (Beck and Zandt, 2002). In contrast, DeCelles et al., (2009) advocate for a model of localized delamination, driven by density instabilities arising from the eclogitization of the mafic lower crust.

Recent studies have also attributed rapid and transient geological phenomena in the Altiplano and Puna regions to lithospheric drips into the sub-lithospheric mantle (Andersen et al., 2022; Ducea et al., 2013; Göğüş et al., 2022; Ward et al., 2016). It has been proposed the Altiplano has a significantly deeper lithospheric root at 80 km depth than the more southern Puna, with 60 km depth (Kay and Coira, 2009; Tassara and Echaurren, 2012). The change in lithospheric structure is accompanied by a major change in morphology: at around

22°S, the relatively flat Altiplano gives way to the more rugged, almost 1km higher, Puna (Whitman et al., 1996).

Seismic tomography models consistently reveal anomalously fast lithospheric mantle velocities beneath the Central Andes, generally attributed to foundered lithosphere (Beck and Zandt, 2002; Tassara and Echaurren, 2012; Ward et al., 2016; Whitman et al., 1996). Our data corroborate these findings, showing high seismic velocities east of the subduction slab, extending from the Altiplano to the northern reaches of the Pampean slab area (Figure 5.10a-e). Resolution tests showed that the model defines with excellent spatial accuracy seismic structures in the top 150 km of the model (Figure 5.3, Figure 5.4, Figure 5.5 and Figure 5.6). Despite the small-scale heterogeneities found in the lithosphere of this region, these are within the sampling accuracy of our high-resolution model SACI-24.

In the cross sections underlying the Altiplano (Figure 5.10a-c), we identify a high-velocity seismic band extending from the South American platform to beneath the mountain range. This is interpreted as evidence of the underthrusting of continental lithosphere, as indicated by dashed yellow lines. Multiple data sources, including seismic tomography, shear wave anisotropy, and gravimetry, converge to suggest that continental lithosphere has underthrust to approximately 65.5°W beneath the Eastern Cordillera's elevated regions (Beck and Zandt, (2002) and references within). Continental lithosphere underthrusting is the first evidence of the influx of lithospheric material under a cordillera system (DeCelles et al., 2009).

As the continental lithosphere—and potentially the lower crust—underthrusts and thickens beneath the Cordillera, melting processes differentiate the material into a dense eclogitic root (DeCelles et al., 2009). Upon reaching a critical mass, this eclogitic root triggers a foundering event (Andersen et al., 2022; Decelles et al., 2015; Ducea et al., 2013; Kay and Coira, 2009). Removal of large volumes of dense lithosphere and influx of asthenosphere will cause a rapid isostatic increase in surface elevation and ignimbrite eruptions (Silva et al., 2006). In the Bolivian Altiplano rapid surface uplift has been documented in the Late Miocene (~10-6 Ma; Garzione et al., (2008)) and widespread voluminous ignimbrites of 10-1 Ma are found in the southern Altiplano/ northern Puna Plateau (Silva et al., 2006). With the lithospheric foundering event the cycle may begin again (DeCelles et al., 2009).

In Figure 5.7, we observe alternating regions of thick and thin fast seismic anomalies beneath the Central Andes, specifically within the 150 km depth range. These variations are further corroborated by the cross-sectional data presented in Figure 5.10, which reveal notable north-to-south structural changes beneath the Cordillera. While seismic imaging

primarily captures the present-day lithospheric architecture, we propose that the cross sections a-d in Figure 5.10 represent the Cordillera's lithospheric root at varying stages of growth and delamination, progressing from south to north. Areas where lithospheric root delamination may have occurred are denoted by the label "LD" in Figure 5.10.

In the northernmost cross-section depicted in Figure 5.10-a, we find a strong fast anomaly east of the subduction reaching to 200 km depth. We propose that this section shows a thick Cordillera root structure, possibly prior to delamination time. In the southern Altiplano, the cross sections Figure 5.10-b,c show a high velocity structure of smaller dimension when compared to Figure 5.10-a. Crowding of material from the underthrusting of continental lithosphere is less evident, suggesting these structures represent different stages in the growth of the lithospheric root. The rapid uplift documented for the Altiplano around 10-6 Ma (Garzzone et al., 2008) may serve as evidence for a prior delamination event, marking the resumption of underthrusting and root growth (Figure 5.10-b).

In the cross-section beneath the northern Puna Plateau (Figure 5.10-d), we no longer observe high seismic velocities from the South American platform towards the base of the Cordillera root. Under the mountain belt, the distinction between subducted oceanic lithosphere and lithospheric root is not straightforward. Based on the seismicity and Slab2 contour, it is possible that part of the observed fast seismic anomaly is the Cordillera lithospheric root. Given these observations, we propose a more advanced stage of lithospheric delamination for the northern Puna Plateau. This interpretation aligns with the observed widespread, non-subduction-related volcanism (Ducea et al., 2013; Murray et al., 2015; Silva et al., 2006) and the region's elevated topography compared to the Altiplano Plateau (Allmendinger et al., 1997). The removal of lithospheric material would have facilitated uplift as the lower-density asthenosphere supplanted the higher-density mantle lithosphere.

Within the transition zone depths, we find a broad region of fast seismic velocities east of the subduction (as indicated by the deep seismicity) on the Central Andes region at ~20°S (Figure 5.7: 485-585 km depth and Figure 5.10-c). We propose that this fast seismic anomaly might be the delaminated lithospheric material from past lithospheric root foundering events, such as the 17-16 Ma and 10-6 Ma events proposed for the Altiplano (Garzzone et al., 2008, 2017). This anomaly is also observed by several large scale tomography models (Amaru, 2007; Fukao and Obayashi, 2013; Romanowicz, 2008; Simmons et al., 2021).

5.3.3.3 Chile-Pampean segment

In the southern Puna, the subduction transitions to the Chile-Pampean flat slab segment. Figure 5.10-e reveals a shift from steep to flat subduction over a span of 400 km, as further evidenced in Figure 5.10-g. Similar to the northern Central Andes, we observe a variable extent of high seismic velocities beneath the Cordillera. Intriguingly, these seismic velocities align with the delineated structures of the accreted Pampia, Chilenia, and Cuyania terranes. For instance, in Figure 5.10-e a high-velocity block at 150 km depth is demarcated on the west by the Pampia terrane, while in Figure 5.10-g, a distinct high-velocity structure is confined within the Cuyania terrane boundaries.

The agreement between the fast seismic anomalies beneath the Pampean segment and the boundaries of the accreted terranes suggests that continental lithospheric factors exert a significant influence on both orogenesis and subduction dynamics in this region. Geological observations suggest that the regional crustal structure is inherited from the accretion of the different terranes (Davis et al., 1999). Seismological data further corroborate this, indicating that these fault structures extend to considerable depths and currently accommodate crustal shortening in the region (Ammirati et al., 2015, 2015).

Contrary to the proposal of flat slab formation due to the buoyancy of the Juan Fernandez Ridge (e.g. Gans et al., 2011; Gao et al., 2021), Marot et al., (2014) find seismic velocities that do not support the presence of a buoyant material in the flat slab area. Their model indicate a thin, high density subduction oceanic crust, consistent with the concentration of seismic activity, high mantle conductivity (Booker et al., 2004) and recent volcanism further east (Kay and Gordillo, 1994).

In the northern Chile-Pampean segment (Figure 5.10-e, f) we observe positive seismic velocities to the east of the subduction zone. Although these velocities are less pronounced compared to those in Figure 5.10-a, b, c they may signify the underthrusting of a weaker South American lithosphere. Considering the presence of a thick lithospheric block related to the Pampia terrane on the continental lithosphere, the compression of this lithospheric material could be driving root growth and delamination episodes, similar to our interpretation of the Central Andean region.

Between latitudes 31°S and 32°S, the dense seismicity delineates a shallower subduction angle, as shown in Figure 5.10-g. In this cross section, we find two high seismic velocity blocks underlying the slab, largely overlain by the region's seismicity. The western block, adjacent to the coast, has a thickness of 100 km and is demarcated to the east by the boundary between the Chilenia and Cuyania terranes. The second block, situated beneath

the Cuyania terrane, extends from a depth of 100 km to nearly 300 km. The demarcation between these two blocks aligns with previous receiver function studies, which identify a major structure separating the Chilenia and Cuyania terranes (Ammirati et al., 2016). This structure, constrained by reverse focal mechanisms, likely represents a reactivation of the collision between the two terranes (Ammirati et al., 2015). Under compressional forces, both terranes would maintain rigidity, while their deep lower crust and lithosphere would likely undergo eclogitization (Ammirati et al., 2016; Marot et al., 2014). Subduction erosion would then drive material east, contributing to the anomalous thick crust (Ammirati et al., 2015; Gans et al., 2011) and lithosphere we observe.

We propose an alternative mechanism for the shallow subduction of the Chile-Pampean ridge. Instead of cratonic lithosphere induced hydrodynamic suction, as previously proposed (Manea et al., 2012), we suggest that the thick lithosphere of the Cuyania terrane may be instrumental in slab flattening. Supporting this hypothesis, samples from the Pocho volcanic field, located at the easternmost segment of the flat slab, indicate the incorporation of depleted Proterozoic components (Kay and Gordillo, 1994). A Proterozoic formation age for the Cuyania terrane would account for the anomalously thick lithosphere observed in our seismic data. The dense seismicity in this region does not clearly indicate the subduction interface, making it challenging to distinguish fast seismic anomalies associated with subduction from those originating from the Andean lithospheric root.

At the Chile-Pampean segment, no deep seismicity is observed. In a similar manner, we observe a gap in the subduction related fast seismic anomalies from ~300 km to 400 km depth. This observation aligns with our earlier discussion regarding the Peruvian flat slab: the underplated flat slab material beneath the Chile-Pampean segment could be strongly coupled to the continental lithosphere, leading to the detachment of the slab's edges. The presence of a slab gap in this region is also consistent with the slab gap configurations predicted by 3D geodynamic modelling (Hu and Liu, 2016).

5.3.4 Payenia and Patagonia Segment

5.3.4.1 Payenia Segment

South of the flat subduction of the Chile-Pampean region, we find high seismic velocities indicating the sudden re-steepening of the Nazca plate (Figure 5.11-a). We observe low seismic velocities on the east of the subduction, related to a thin continental lithosphere

of this region. There is indication of continental underthrusting under the cordillera region, evidenced by positive seismic velocities extending from the continental platform towards beneath the mountain range from 100 km to 200 km depth.

In the previous sections, we described the Andean cordillera cycle as primary controlled by the absolute motion of the South American continent (DeCelles et al., 2009; Schepers et al., 2017). On the Central Andes regions, the thick continental crust and lithosphere (Isacks, 1988) favoured generalized delamination during steepening of the slab and associated with voluminous rhyolitic ignimbrite eruptions as the Altiplano-Puna Volcanic Complex (Kay and Coira, 2009; Ramos, 2009). Similarly, cycles of shallowing and steepening were recognized to have occurred in the Payenia segment (Folguera et al., 2011). However, the Payenia paleoflat-slab segment is the only one characterized by intense basaltic flooding associated with the steepening of the subducted slab (Ramos et al., 2014). In contrast to the Central Andes region, it is proposed that an original normal-to-thin crust of the continent is controlling the formation of large basaltic flooding in the foreland.

The seismic velocities we find for this region agree with the proposal of a thin lithosphere controlling the mountain building and volcanism of the Payenia segment. Additionally, by showing current underthrusting of continental lithosphere is taking place, we have evidence that a new cordillera cycle has initiated since the last flat subduction at ~5 Ma (Folguera et al., 2011; Ramos and Folguera, 2009). Our model shows the high seismic velocities associated to the subduction extending to the transition zone. As observed for the Central Andes, we find high seismic velocities east of the subduction on the transition zone. Similarly, we propose this material could have originated from the previous lithospheric delamination events recorded by past flat slab subduction.

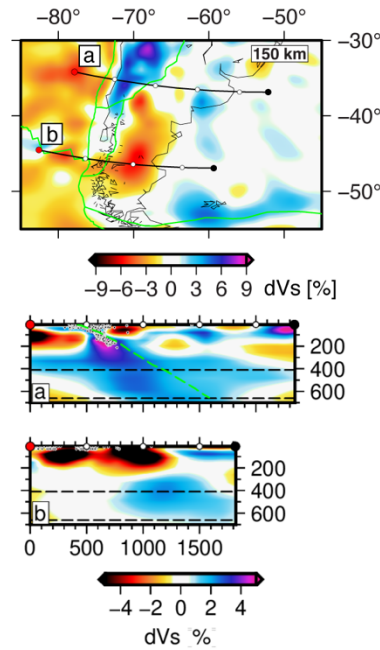


Figure 5.11: Seismic velocity distribution of the Payena and Patagonia subduction segments. Cross section locations are indicated as labelled lines on the top figures. Green dashed lines are from Slab2 and black circles are seismicity locations.

5.3.4.2 Patagonia Segment

In Figure 5.11, we show a vertical cross section through the subduction of the Chilean spreading ridge. We observe anomalously slow mantle throughout this region, with fast velocities only present in the transition zone and offshore on the lithosphere of the Argentine Basin. The absence of fast seismic anomalies related to the subduction indicate the formation of a slab window. Slab windows form when a spreading ridge subducts and the plates continue to diverge, opening a gap in the subducting plate interface. The Patagonian slab window began forming ~ 18 Ma, when the Chile Ridge started subducting beneath South America (Breitsprecher and Thorkelson, 2009).

Under Patagonia, we observe seismic velocities much lower than the expected for continental lithosphere ($<3\%$ dVs). Such low seismic velocities indicate that within the shallow depths (<80 km), continental lithosphere is missing and has been replaced by hot asthenospheric mantle (Figure 5.7). The absence of lithospheric mantle suggests that hot mantle material from the subduction of the slab window have eroded the base of the South American lithosphere. Thermal erosion of the overriding plate is predicted by thermo-mechanical models of ridge subduction (Groome and Thorkelson, 2009). This observation is supported by previous studies based on regional heat flow data (Ávila and Dávila, 2018),

crustal thickness measurements (Robertson Maurice et al., 2003), regional seismic tomography (Mark et al., 2022) and glacial isostatic adjustment models fit to observed uplift rates (Lange et al., 2014; Richter et al., 2016).

5.4 Conclusions

The increasingly dense seismic station distribution across South America, in particular in the Andes, enables tomographic imaging of the upper mantle at a new level of detail. The new, high-resolution, plate-scale model SACI-24 offers important new insights into the subduction dynamics. Consequently, we can delineate the various stages of Cordillera cyclicity associated with subduction geometry and orogenesis.

- **Slab Segments in Northwestern South America.** SACI-24 illuminates the presence of several slab segments originating from the Nazca and Caribbean plates. We identify two segments of the Nazca plate separated by the Caldas tear. The western segment is characterized by warmer lithosphere, attributed to the subduction of the Sandra Ridge, while the eastern segment subducts at a shallow angle for approximately 300 km. Additionally, the Caribbean plate subducts under South America in two directions. From the northeast, it underthrusts the South American lithosphere from north to south, and from the north it subducts to the southeast.
- **Bucaramanga Seismic Cluster.** Our model locates the Bucaramanga seismic cluster as the intersection between different lithospheric segments: the Nazca slab, the lithospheric root of the Maracaibo Block, and, possibly, a layer of delaminated lithosphere.
- **Active Underthrusting Regions.** Our model shows the structure of the regions of the active underthrusting of continental lithosphere beneath the Andean Cordillera system. These regions include northwestern South America adjacent to the Maracaibo Block, as well as segments of the Central Andes, Pampean, and Payenia regions.
- **Peruvian Flat Slab Segment.** Our model maps structures that correspond to multiple stages of the slab flattening and tearing, likely driven by the subduction of anomalously buoyant lithosphere and the interaction of subduction with the thick lithosphere of the Amazon Craton. A segment of the flat slab of dimensions similar to those of the “lost” Inca Plateau appears to be coupled to the continental

lithosphere. As a result, the slab is torn in at least two locations. We identify a segment of the flat slab where, after tearing, normal subduction appears to have restarted.

- **Cordillera Cyclicity.** In the Central Andes, Pampia and Payenia segments, we identify the multiple stages of the Cordillera cyclicity. These include underthrusting of continental lithosphere, which leads to root growth. The continuous lithospheric growth eventually reaches a point of instability, resulting in lithospheric foundering. We identify regions under the Altiplano and Puna Plateaus where lithospheric delamination lead to uplift and volcanism.
- **Pampia Segment:** In the Pampia segment, our model reveals thick lithosphere corresponding to the accreted terranes of Pampia, Chilenia, and Cuyania. We propose that the inherited lithospheric structure from these terranes exerts a controlling influence on subduction dynamics, including slab flattening.
- **Transition Zone Depths:** Lastly, we suggest that the cold mantle material east of the slab within the transition zone depths likely originates from continental lithosphere displaced during root foundering events.

In summary, new observations provided by SACI-24 improve our understanding of the complex geodynamics of subduction beneath South America, from slab segmentation to lithospheric underthrusting and foundering.

6 Conclusions

In this study, we built a high resolution seismic tomography model of South America and the surrounding regions using more than 970,000 seismic waveforms. As a first step, we constructed the dataset constraining the model by retrieving earthquake records from all freely available global seismic data, with particular focus on the seismic deployments on the South American Continent. The waveform dataset was then complemented by the temporary FAPESP “3-Basins Thematic Project”. After performing the three step inversion utilizing the Automated Multimode Inversion method, we carefully selected the model regularisation parameters that optimize the seismic coverage in the South American continent.

In Chapter 1, we introduce the reader to the general concepts of seismology. In Chapter 2 we provide a in-depth explanation of the full process involved in the model calculation, including: data collection and pre-processing, detailed description of the methods used to calculate the final tomographic model and a analysis on the model optimization by the choice of regularisation parameters. In Chapter 3 we detailed the computation of the new S-wave model SACI-24. In Chapters 3, 4 and 5 we compared our model SACI-24 to the current state of the art in seismic tomography and discuss what features can now be considered well established, where our new tomography achieved improvements in resolution, and what the main remaining open questions are. Moreover, we compiled a comprehensive review of the upper mantle structure under South America and its surroundings.

6.1 Cratonic Lithosphere and Tectonic Processes

In Chapter 3, we used our model SACI-24 to identify the detailed boundaries of cratonic lithosphere. We find that the structure of the cratonic lithosphere is much more complex than previously proposed from seismic tomography and other geophysical methods. This is due to the significant improvements in the resolution of the shear-wave velocity structure within the lithospheric depths that SACI-24 offers when compared to previous regional and global models. The lithospheric structure variations indicated by the seismic velocities show clear relationships with the locations of the deformation and rifting, basin formation and magmatism.

Our improved mapping of cratonic boundaries allows us to identify the small-scale heterogeneity within each craton. We separate two distinct cratonic blocks within the

Amazon Craton boundaries that we denominate Guiana and Central Brazil Blocks. The São Francisco Craton extends beyond previously proposed limits and shows internal variability with thinner lithosphere beneath the Paramirim and Pirapora aulacogens. Under the Paraná Basin, we separate multiple fragments of cratonic lithosphere. The newly identified thin lithosphere within the Amazon and São Francisco Cratons and Paraná Block correlates well with areas of recurrent magmatism, failed rifting and basin formation. These findings highlight the importance of lithospheric control in mantle dynamics and tectonic evolution.

6.2 Intraplate Magmatism and Mantle Plumes

In Chapters 3 and 4, we reveal that lithospheric thickness is the main control on intraplate magmatism distribution. We find that by juxtaposing the newly revealed lithospheric structure from seismic tomography with plate motion reconstructions, we can relate most of the complex, intraplate magmatism in South America to present-day hotspots. This applies also to the well-known, but widely discussed, Central Atlantic Magmatic Province (CAMP) and Paraná Magmatic Province (PMP). We find that the Fernando hotspot was located under the thick lithosphere of the Amazon Craton at the emplacement time of CAMP. As evidenced by the maximum thickness of sills and basalt floods from CAMP and PMP, the hot mantle material from the Fernando and Tristan hotspots erupted at the surface on top of thin lithospheric channels we map with our model. We propose that the existing thick cratonic lithosphere lead the igneous material from the Fernando and Tristan hotspots to deviate towards the surrounding thinner and weaker lithosphere, travelling laterally for 100s of kilometres following the lithospheric gradient.

Within the mantle transition zone, SACI-24 reveals anomalously low seismic velocities under most of the South American platform. The low seismic velocities are located on the east of the Nazca plate subduction and are strongest under SE Brazil. From the comparison between our model and full mantle tomography models, we identify this anomaly as an upwelling of hot material from the deep lower mantle originating from at least 2000 km deep. On the upper mantle under the South Atlantic we find broad areas of fast seismic velocities. We propose these fast anomalies indicate the presence of delaminated lithosphere from the continental South American lithosphere, similar to the cratonic erosion shown to have occurred in Africa by Celli et al., (2020a). The lithospheric delamination process would have occurred due to plume(s) impact prior to the opening of the South

Atlantic. The presence of lithospheric material derived from continental delamination and subduction of the Nazca plate within the upper mantle, combined with the absence of deep-seated mantle plumes under recognised hotspots, leads us to believe in a “super” plume origin. We propose that this plume under SE Brazil is likely the primary source of all observed intraplate magmatism since the Mesozoic. The lithospheric material in the upper mantle would have deflected the path of the main plume conduit, dividing it into several branches and giving rise to multiple hotspot locations. In the shallow asthenosphere, the hot material follows horizontally towards thin oceanic lithosphere, causing the current complex distribution of hotspot volcanism.

6.3 Slab Geometry

In Chapter 5, the enhanced resolution of our plate-scale model SACI-24 has provided a nuanced understanding of subduction dynamics beneath South America. SACI-24 illuminates several slab segments originating from the Nazca and Caribbean plates. In northwest South America, the Caribbean plate exhibits bidirectional subduction beneath South America, moving under South American lithosphere from both the northeast and the north. From north to south, the Nazca plate subduction is observed as fragmented segments with distinct dipping angles. In the northwest, it flattens where it meets the Caribbean slab and the continental lithosphere of the Maracaíbo Block.

Under the Peruvian region, hydrodynamic suction from the thick lithosphere of the Amazon Craton leads to flattening of the slab. Our new images of the slab reveal a large slab segment coupled with the continental lithosphere, resulting in multiple slab tears. In one of the segments, we identify the resumption of subduction after slab tearing.

Thanks to the new insights from our model, we observe that the continental lithosphere appears to play a major role in the subduction dynamics under the Central Andes, Pampia, Payenia and Patagonia. Cycles of slab flattening, tearing and return to normal subduction are related to the underthrusting of the South American lithosphere under the Andean Cordillera. Current flat slab subduction is also observed at the Pampian segment, where we observe correlation between fast seismic anomalies and the boundaries of previous accreted terranes. After resuming normal subduction at the Payenia segment, subduction of the Nazca plate ends at the Chilean Rise Ridge. At this location, hot asthenosphere is displaced towards the slab gap, leading to lithospheric delamination of the southernmost portion of the continent.

6.4 Cordillera Cyclicity

In Chapter 5, we describe the observations from our tomography model in terms of Cordillera cyclicity models (e.g. DeCelles et al., 2009; Schepers et al., 2017; Taramón et al., 2015). We are able to map regions of active underthrusting of the South American lithosphere under the root of the Andean Cordillera in northwestern South America, and the Central Andes, Pampia and Payenia regions. In the known locations of underthrusting of continental material, we find segments of the Andean belt where thick lithosphere is present as a result of root growth, alternating with other portions of the Cordillera where the lithospheric root is absent or thinner, especially in the northern Puna Plateau. In these segments, the lack of a thick lithospheric root evidenced by our images is consistent with lithospheric removal proposed to occur due to density instabilities of the thickened mountain root (Decelles et al., 2015).

Within the transition zone, we identify regions of fast seismic anomalies east of the subduction of the Peruvian, Central Andes and Payenia slab segments. In the case of previous lithospheric foundering events, portions of lithosphere are expected to have sunk into the deeper mantle. We suggest that these fast seismic anomalies are, therefore, the colder material from the continental lithosphere displaced during root foundering events.

6.5 Final Considerations and Future Work

The work developed for this thesis unveils an unexpectedly complex Earth structure beneath South America, opening numerous possibilities for further investigation. In the continental lithosphere, additional work from geodynamic modelling could help in the understanding of the dynamics between cratonic lithosphere, rifting and basin formation. Seismic tomography provides a snapshot of the current lithospheric state. Therefore, we cannot discern on whether the South American cratons initially formed as a continuous, homogeneous structure, modified since then by geodynamic processes, or they were formed as a multitude of smaller, fragmented cores with varying lithospheric thickness as we observe at present day in our tomographic images. Further supporting information from techniques that can infer the past states of the lithosphere is needed, such as petrology and geodynamic modelling. The accurate mapping of the lithosphere throughout geologic time would lead to improvement understanding of the tectonic evolution processes such as plate

reconstruction, and its reflection on surface dynamics, including the distribution of magmatism, basin formation and continental rifting. This historical perspective is crucial for advancing our understanding of tectonic evolution, plate reconstruction, and surface dynamics. Additionally, given the high-resolution seismic tomography model developed in this study, future work could focus on incorporating additional data types, such as seismic receiver functions, to further detail the thickness of the lithosphere and transition zone and confirm our inferences on the subducting slabs, delaminated lithosphere, and mantle plumes.

The large scope of this work enables a broad view of the coexisting mantle processes and their potential interactions. Multidisciplinary studies are essential to comprehend how Earth's different segments interact. In Chapter 4, we highlighted the importance of lithosphere thickness in the distribution of intraplate magmatism, and in Chapter 5 how the continental lithosphere affects subduction dynamics. Further work should focus on the long-term effects of Nazca subduction on the distribution of plume material beneath the continent. Additional research on the understanding of the interaction between the slow-seismic anomaly associated with the Galápagos plume and the Peruvian flat subduction could include mantle anisotropy measurements and geochemical characterisation of the hotspot lavas. Geodynamic modelling and plate reconstructions could be applied to further investigate the interaction between a “super” plume and the long-lived Nazca subduction.

The underthrusting of the South American platform, as indicated by the models of Cordillera cyclicity, raises questions about the recycling of continental material induced by oceanic lithosphere subduction. This process has been largely described and debated (e.g. Beck & Zandt, 2002), and its large-scale implications have only started to be explored. Detailed comparison with other continents with a similar subduction history, such as North America, could help provide the context for future implications and questions such as: Can cratonic lithosphere be destroyed in this way? How can this process affect the long-term stability and evolution of the lithosphere? Plate evolution models may need to be updated to account for the loss of continental material during different stages of subduction.

In summary, while this thesis provides a detailed snapshot of the current geodynamic setting of South America, it also sets the stage for future work aimed at understanding how these geodynamic processes interact through time. Future research could focus on the role of mantle dynamics in lithospheric processes, the long-term stability of the lithosphere, and the implications of these for seismic hazards and mineral exploration.

7 Bibliography

- Affonso, G.M.P.C., Rocha, M.P., Costa, I.S.L.L., Assumpção, M., Fuck, R.A., Albuquerque, D.F., Portner, D.E., Rodríguez, E.E., Beck, S.L., 2021. Lithospheric Architecture of the Paranapanema Block and Adjacent Nuclei Using Multiple-Frequency P -Wave Seismic Tomography. *Journal of Geophysical Research: Solid Earth* 126. <https://doi.org/10.1029/2020jb021183>
- Aki, K., Richards, P.G., 2002. *Quantitative Seismology*.
- Alkmim, F.F., Martins-Neto, M.A., 2012. Proterozoic first-order sedimentary sequences of the São Francisco craton, eastern Brazil. *Marine and Petroleum Geology* 33, 127–139. <https://doi.org/10.1016/j.marpetgeo.2011.08.011>
- Alkmim, F.F., Neves, B.B.B., Alves, J.A.C., 1993. Arcabouço Tectônico do Cráton do São Francisco—Uma Revisão. O Cráton do São Francisco. II Simpósio sobre o Cráton do São Francisco, Salvador, Bahia.
- Allmendinger, R., Jordan, T.E., Kay, S., Isacks, B., 1997. The evolution of the Altiplano-Puna Plateau of the Central Andes, *Annual Reviews of Earth and Planetary Sciences*, v. 25, 139–174. *Annual Review of Earth and Planetary Sciences* 25, 139–174.
- Almeida, F.F.M., 1977. O Craton Do São Francisco. *Revista Brasileira de Geociências* 7, 349–364.
- Almeida, F.F.M., Hasui, Y., Brito Neves, B.B., Fuck, R.A., 1981. Brazilian structural provinces: An introduction. *Earth Science Reviews* 17, 1–29. [https://doi.org/10.1016/0012-8252\(81\)90003-9](https://doi.org/10.1016/0012-8252(81)90003-9)
- Almeida, F.F.M.D., 1987. Distribuição Regional E Relações Tectônicas Do Magmatismo Pós-Paleozoico No Brasil. *Revista Brasileira de Geociências* 17, 325–349. <https://doi.org/10.25249/0375-7536.1986325349>
- Almeida, F.F.M.D., Brito Neves, B.B.D., Dal Ré Carneiro, C., 2000. The origin and evolution of the South American platform. *Earth Science Reviews* 50, 77–111. [https://doi.org/10.1016/S0012-8252\(99\)00072-0](https://doi.org/10.1016/S0012-8252(99)00072-0)
- Almeida, F.F.M.D., Carneiro, C.D.R., Mizusaki, A.M.P., 1996. Correlação do Magmatismo das Bacias da Margem Continental Brasileira com o das áreas Emersas Adjacentes. *RBG* 26, 125–138. <https://doi.org/10.25249/0375-7536.19963125138>
- Amaru, M., 2007. Global travel time tomography with 3-D reference models, *Geologica Ultraiectina*.
- Ammirati, J.B., Alvarado, P., Beck, S., 2015. A lithospheric velocity model for the flat slab region of Argentina from joint inversion of Rayleigh wave phase velocity dispersion and teleseismic receiver functions. *Geophysical Journal International*. <https://doi.org/10.1093/gji/ggv140>
- Ammirati, J.-B., Pérez Luján, S., Alvarado, P., Beck, S., Rocher, S., Zandt, G., 2016. High-resolution images above the Pampean flat slab of Argentina (31–32°S) from local receiver functions: Implications on regional tectonics. *Earth and Planetary Science Letters* 450, 29–39. <https://doi.org/10.1016/j.epsl.2016.06.018>
- Andersen, J., Göğüş, O.H., Pysklywec, R.N., Santimano, T., Şengül Uluocak, E., 2022. Symptomatic lithospheric drips triggering fast topographic rise and crustal deformation in the Central Andes. *Commun Earth Environ* 3, 150. <https://doi.org/10.1038/s43247-022-00470-1>
- Anderson, Don L., Dziewonski, A.M., 1984. Seismic Tomography. *SCIENTIFIC AMERICAN* 251, 60–71.
- Anderson, Don L., Dziewonski, A.M., 1984. Seismic tomography. *Scientific American* 251, 60–71.

- Antonijevic, S.K., Wagner, L.S., Kumar, A., Beck, S.L., Long, M.D., Zandt, G., Tavera, H., Condori, C., 2015. The role of ridges in the formation and longevity of flat slabs. *Nature* 524, 212–215. <https://doi.org/10.1038/nature14648>
- Assumpção, M., An, M., Bianchi, M., França, G.S.L., Rocha, M., Barbosa, J.R., Berrocal, J., 2004a. Seismic studies of the Brasília fold belt at the western border of the São Francisco Craton, Central Brazil, using receiver function, surface-wave dispersion and teleseismic tomography. *Tectonophysics* 388, 173–185. <https://doi.org/10.1016/j.tecto.2004.04.029>
- Assumpção, M., Bianchi, M.B., 2016. Pantanal, Chaco and Paraná (PCPB) structural studies network. <https://doi.org/10.7914/8SCF-YD39>
- Assumpção, M., Schimmel, M., Escalante, C., Roberto Barbosa, J., Rocha, M., Barros, L.V., 2004b. Intraplate seismicity in SE Brazil: stress concentration in lithospheric thin spots. *Geophysical Journal International* 159, 390–399. <https://doi.org/10.1111/j.1365-246X.2004.02357.x>
- Ávila, P., Dávila, F.M., 2018. Heat flow and lithospheric thickness analysis in the Patagonian asthenospheric windows, southern South America. *Tectonophysics* 747–748, 99–107. <https://doi.org/10.1016/j.tecto.2018.10.006>
- Axen, G.J., Van Wijk, J.W., Currie, C.A., 2018. Basal continental mantle lithosphere displaced by flat-slab subduction. *Nature Geosci* 11, 961–964. <https://doi.org/10.1038/s41561-018-0263-9>
- Bahia, R.B.C., Martins-Neto, M.A., Barbosa, M.S.C., Pedreira, A.J., 2007. Análise da evolução tectonossedimentar da Bacia dos Parecis através de métodos potenciais. *Revista Brasileira de Geociências* 37, 639–649. <https://doi.org/10.25249/0375-7536.2007374639649>
- Bahia, R.R., Abreu, F.A.M., 1985. O rift do Amazonas—sistema aulacogênico na plataforma amazônica, in: 2nd Simpósio de Geologia Da Amazônia, Belém-PA, Anai. pp. 222–241.
- Ball, P.W., White, N.J., MacLennan, J., Stephenson, S.N., 2021. Global influence of mantle temperature and plate thickness on intraplate volcanism. *Nature Communications* 12, 1–13. <https://doi.org/10.1038/s41467-021-22323-9>
- Ballmer, M.D., Ito, G., Wolfe, C.J., Solomon, S.C., 2013. Double layering of a thermochemical plume in the upper mantle beneath Hawaii. *Earth and Planetary Science Letters* 376, 155–164. <https://doi.org/10.1016/j.epsl.2013.06.022>
- Barbosa, J.S.F., Cruz, S.C.P., Souza, J.S. de, 2012. Terrenos metamórficos do embasamento. *Geologia da Bahia: pesquisa e atualização*, CBPM 1, 101–201.
- Barbosa, J.S.F., Sabaté, P., 2002. Geological features and the Paleoproterozoic collision of four Archean crustal segments of the São Francisco Craton, Bahia, Brazil. A synthesis. *Anais da Academia Brasileira de Ciências* 74, 343–359. <https://doi.org/10.1590/S0001-37652002000200009>
- Basile, C., Girault, I., Paquette, J.-L., Agranier, A., Loncke, L., Heuret, A., Poetisi, E., 2020. The Jurassic magmatism of the Demerara Plateau (offshore French Guiana) as a remnant of the Sierra Leone hotspot during the Atlantic rifting. *Scientific Reports* 10, 7486. <https://doi.org/10.1038/s41598-020-64333-5>
- Bassin, C., Laske, Gabi, Masters, G., 2000. The current limits of resolution for surface wave tomography in North America. *Eos Trans. AGU* 81, F897.
- Beck, S.L., Zandt, G., 2002. The nature of orogenic crust in the central Andes. *JOURNAL OF GEOPHYSICAL RESEARCH* 107, ESE 7-1-ESE 7-16. <https://doi.org/10.1029/2000JB000124>
- Bedle, H., Van Der Lee, S., 2006. Fossil flat-slab subduction beneath the Illinois basin, USA. *Tectonophysics* 424, 53–68. <https://doi.org/10.1016/j.tecto.2006.06.003>
- Bellieni, G., Comin-Chiaramonti, P., Marques, L.S., Melfi, A.J., Piccirillo, E.M., Nardy, A.J.R., Roisenberg, A., 1984. High- and low- TiO₂ flood basalts from the Parana

- plateau (Brazil): petrology and geochemical aspects bearing on their mantle origin. *Neues Jahrbuch für Mineralogie Abhandlungen* 150, 273–306.
- Bertrand, H., Fornari, M., Marzoli, A., García-Duarte, R., Sempere, T., 2014. The Central Atlantic Magmatic Province extends into Bolivia. *Lithos* 188, 33–43. <https://doi.org/10.1016/j.lithos.2013.10.019>
- Beyreuther, M., Barsch, R., Krischer, L., Megies, T., Behr, Y., Wassermann, J., 2010. ObsPy: A Python toolbox for seismology. *Seismological Research Letters* 81, 530–533.
- Bezerra Maia de Hollanda, M., Pimentel, M., Oliveira, D., Sá, E., 2006. Lithosphere–asthenosphere interaction and the origin of Cretaceous tholeiitic magmatism in Northeastern Brazil: Sr–Nd–Pb isotopic evidence. *Lithos* 86, 34–49. <https://doi.org/10.1016/j.lithos.2005.04.004>
- Bianchi, M., Heit, B., Jakovlev, A., Yuan, X., Kay, S.M., Sandvol, E., Alonso, R.N., Coira, B., Brown, L., Kind, R., Comte, D., 2013. Teleseismic tomography of the southern Puna plateau in Argentina and adjacent regions. *Tectonophysics* 586, 65–83. <https://doi.org/10.1016/j.tecto.2012.11.016>
- Bianchi, M.B., Assumpção, M., Rocha, M.P., Carvalho, J.M., Azevedo, P.A., Fontes, S.L., Dias, F.L., Ferreira, J.M., Nascimento, A.F., Ferreira, M.V., Costa, I.S.L., 2018a. The Brazilian Seismographic Network (RSBR): Improving Seismic Monitoring in Brazil. *Seismological Research Letters* 89, 452–457. <https://doi.org/10.1785/0220170227>
- Bianchi, M.B., Assumpção, M., Rocha, M.P., Carvalho, J.M., Azevedo, P.A., Fontes, S.L., Dias, F.L., Ferreira, J.M., Nascimento, A.F., Ferreira, M. V., Costa, I.S.L., 2018b. The Brazilian seismographic network (RSBR): Improving seismic monitoring in Brazil. *Seismological Research Letters* 89, 452–457. <https://doi.org/10.1785/0220170227>
- Bird, P., 2003. An updated digital model of plate boundaries. *Geochemistry, Geophysics, Geosystems* 4. <https://doi.org/10.1029/2001GC000252>
- Bishop, B.T., Beck, S.L., Zandt, G., Wagner, L., Long, M., Antonijevic, S.K., Kumar, A., Tavera, H., 2017. Causes and consequences of flat-slab subduction in southern Peru. *Geosphere* 13. <https://doi.org/10.1130/GES01440.1>
- Bizzi, L. a., De Wit, M.J., Smith, C.B., McDonald, I., R.a., A., 1995. Heterogeneous enriched mantle materials and dupal-type magmatism along the SW margin of the São Francisco craton, Brazil. *Journal of Geodynamics, Proceedings of the International Symposium on the Physics and Chemistry of the Upper Mantle* 20, 469–491. [https://doi.org/10.1016/0264-3707\(95\)00028-8](https://doi.org/10.1016/0264-3707(95)00028-8)
- Bloch, E., Ibañez-Mejia, M., Murray, K., Vervoort, J., Müntener, O., 2017. Recent crustal foundering in the Northern Volcanic Zone of the Andean arc: Petrological insights from the roots of a modern subduction zone. *Earth and Planetary Science Letters* 476, 47–58. <https://doi.org/10.1016/j.epsl.2017.07.041>
- Booker, J.R., Favetto, A., Pomposiello, M.C., 2004. Low electrical resistivity associated with plunging of the Nazca flat slab beneath Argentina. *Nature* 429, 399–403. <https://doi.org/10.1038/nature02565>
- Boscaini, A., Marzoli, A., Bertrand, H., Chiaradia, M., Jourdan, F., Faccenda, M., Meyzen, C.M., Callegaro, S., Serrano Durán, L., 2022. Cratonic keels controlled the emplacement of the Central Atlantic Magmatic Province (CAMP). *Earth and Planetary Science Letters* 584, 117480. <https://doi.org/10.1016/j.epsl.2022.117480>
- Boyd, F.R., Gurney, J.J., Richardson, S.H., 1985. Evidence for a 150–200-km thick Archaean lithosphere from diamond inclusion thermobarometry. *Nature* 315, 387–389. <https://doi.org/10.1038/315387a0>
- Boyer, S.E., Elliott, D., 1982. Thrust Systems1. *AAPG Bulletin* 66, 1196–1230. <https://doi.org/10.1306/03B5A77D-16D1-11D7-8645000102C1865D>

- Breitsprecher, K., Thorkelson, D.J., 2009. Neogene kinematic history of Nazca–Antarctic–Phoenix slab windows beneath Patagonia and the Antarctic Peninsula. *Tectonophysics* 464, 10–20. <https://doi.org/10.1016/j.tecto.2008.02.013>
- Brito Neves, B.B., 2003. A saga dos descendentes de Rodínia na construção de Gondwana. *Revista Brasileira de Geociências* 33, 77–88.
- Brito Neves, B.B., Fuck, R.A., 2013. Neoproterozoic evolution of the basement of the South American platform. *Journal of South American Earth Sciences* 2 47, 72–89.
- Brito Neves, B.B. de, Fuck, R.A., 2014. The basement of the South American platform: Half Laurentian (N-NW)+half Gondwanan (E-SE) domains. *Precambrian Research* 244, 75–86. <https://doi.org/10.1016/j.precamres.2013.09.020>
- Bulanova, G.P., Walter, M.J., Smith, C.B., Kohn, S.C., Armstrong, L.S., Blundy, J., Gobbo, L., 2010. Mineral inclusions in sublithospheric diamonds from Collier 4 kimberlite pipe, Juina, Brazil: subducted protoliths, carbonated melts and primary kimberlite magmatism. *Contrib Mineral Petrol* 160, 489–510. <https://doi.org/10.1007/s00410-010-0490-6>
- Bullen, K.E., 1942. The density variation of the earth's central core*. *Bulletin of the Seismological Society of America* 32, 19–29. <https://doi.org/10.1785/BSSA0320010019>
- Burke, K.C., Lytwyn, J., 1993. Origin of the rift under the amazon basin as a result of continental collision during pan-african time. *International Geology Review* 35, 881–897. <https://doi.org/10.1080/00206819309465563>
- Burnham, A.D., Bulanova, G.P., Smith, C.B., Whitehead, S.C., Kohn, S.C., Gobbo, L., Walter, M.J., 2016. Diamonds from the Machado River alluvial deposit, Rondônia, Brazil, derived from both lithospheric and sublithospheric mantle. *Lithos* 265, 199–213. <https://doi.org/10.1016/j.lithos.2016.05.022>
- Cahill, T., Isacks, B.L., 1992. Seismicity and shape of the subducted Nazca Plate. *Journal of Geophysical Research* 97.
- Callegaro, S., Marzoli, A., Bertrand, H., Chiaradia, M., Reisberg, L., Meyzen, C., Bellieni, G., Weems, R.E., Merle, R., 2013. Upper and lower crust recycling in the source of CAMP basaltic dykes from southeastern North America. *Earth and Planetary Science Letters* 376, 186–199. <https://doi.org/10.1016/j.epsl.2013.06.023>
- Cediel, F., Shaw, R.P., Cáceres, C., 2003. Tectonic Assembly of the Northern Andean Block, in: *The Circum-Gulf of Mexico and the Caribbean Hydrocarbon Habitats, Basin Formation and Plate Tectonics*. American Association of Petroleum Geologists. <https://doi.org/10.1306/M79877C37>
- Celli, N., Lebedev, S., Schaeffer, A.J., Gaina, C., 2020a. African cratonic lithosphere carved by mantle plumes. *Nature Communications* 11. <https://doi.org/10.1038/s41467-019-13871-2>
- Celli, N., Lebedev, S., Schaeffer, A.J., Ravenna, M., Gaina, C., 2020b. The upper mantle beneath the South Atlantic Ocean, South America and Africa from waveform tomography with massive data sets. *Geophysical Journal International* 221, 178–204.
- Celli, N.L., 2020. Regional-scale structure and dynamics of the crust, upper mantle and transition zone from waveform tomography with massive datasets.
- Chang, S., Ferreira, A.M.G., Ritsema, J., van Heijst, H.J., Woodhouse, J.H., 2015. Joint inversion for global isotropic and radially anisotropic mantle structure including crustal thickness perturbations. *Journal of Geophysical Research: Solid Earth* 120, 4278–4300.
- Chantel, J., Manthilake, G., Andrault, D., Novella, D., Yu, T., Wang, Y., 2016. Experimental evidence supports mantle partial melting in the asthenosphere. *Science Advances* 2. <https://doi.org/10.1126/sciadv.1600246>
- Chaves, C., Ussami, N., Ritsema, J., 2016. Density and P-wave velocity structure beneath the Paraná Magmatic Province: Refertilization of an ancient lithospheric mantle.

- Geochemistry, Geophysics, Geosystems 17, 3054–3074.
<https://doi.org/10.1002/2016GC006369>
- Chiarabba, C., De Gori, P., Faccenna, C., Speranza, F., Seccia, D., Dionicio, V., Prieto, G.A., 2016. Subduction system and flat slab beneath the Eastern Cordillera of Colombia. *Geochemistry, Geophysics, Geosystems* 17, 16–27.
<https://doi.org/10.1002/2015GC006048>
- Ciardelli, C., Assumpção, M., Bozdağ, E., van der Lee, S., 2022. Adjoint Waveform Tomography of South America. *Journal of Geophysical Research: Solid Earth* 127, e2021JB022575.
- Civiero, C., Lebedev, S., Celli, N.L., 2022. A Complex Mantle Plume Head Below East Africa-Arabia Shaped by the Lithosphere-Asthenosphere Boundary Topography. *Geochem Geophys Geosyst* 23, e2022GC010610.
<https://doi.org/10.1029/2022GC010610>
- Colletta, B., Hebrard, F., Letouzey, J., Werner, P., Rudkiewicz, J., 1990. Tectonic style and crustal structure of the Eastern Cordillera (Colombia) from a balanced cross-section. *Petroleum and tectonics in mobile belts* 47, 81–100.
- Comin-Chiaramonti, P., de Barros Gomes, C., 2005. Mesozoic to Cenozoic Alkaline Magmatism in the Brazilian Platform.
- Contreras-Reyes, E., Carrizo, D., 2011. Control of high oceanic features and subduction channel on earthquake ruptures along the Chile-Peru subduction zone. *Physics of the Earth and Planetary Interiors* 186, 49–58. <https://doi.org/10.1016/j.pepi.2011.03.002>
- Cordani, U.G., de Brito Neves, B.B., Fuck, R.A., Porto, R., Thomaz Filho, A., Cunha, F.M.B., 1984. Estudo preliminar de integração do pré-cambriano com os eventos tectônicos das bacias sedimentares brasileiras. *Ciência. Técnica. Petróleo. Seção: exploração de petróleo* 14, 1–70.
- Cordani, U.G., Ramos, V.A., Fraga, L.M., CEGARRA, M., DELGADO, I., SOUZA, K.G. de, GOMES, F.E.M., SCHOBENHAUS, C., 2016. Tectonic map of South America=Mapa tectônico da América do Sul.
- Cordani, U.G., Sato, K., 2000. Crustal evolution of the South American platform, based on Nd isotopic systematics on granitoid rocks. *Episodes* 22, 167–173.
<https://doi.org/10.18814/epiiugs/1999/v22i3/003>
- Cordani, U.G., Tassinari, C.C.G., Teixeira, W., Basei, M.A.S., Kawashita, K., 1979. Evolução tectônica da Amazônia com base nos dados geocronológicos, in: *Actas. Instituto de Investigaciones Geologicas, Ciudad de Aurica*.
- Cordani, U.G., Teixeira, W., D'Agrella-Filho, M.S., Trindade, R.I., 2009. The position of the Amazonian Craton in supercontinents. *Gondwana Research* 15, 396–407.
<https://doi.org/10.1016/j.gr.2008.12.005>
- Cordani, U.G., Teixeira, W., Tassinari, C.C.G., Coutinho, J.M.V., Ruiz, A.S., 2010. The rio apa craton in mato grosso do sul (brazil) and northern paraguay: Geochronological evolution, correlations and tectonic implications for rodinia and gondwana. *American Journal of Science* 310, 981–1023. <https://doi.org/10.2475/09.2010.09>
- Cornthwaite, J., Bezada, M.J., Miao, W., Schmitz, M., Prieto, G.A., Dionicio, V., Niu, F., Levander, A., 2021. Caribbean Slab Segmentation Beneath Northwest South America Revealed by 3-D Finite Frequency Teleseismic P-Wave Tomography. *Geochemistry, Geophysics, Geosystems* 22, e2020GC009431.
<https://doi.org/10.1029/2020GC009431>
- Cortés, M., Angelier, J., 2005. Current states of stress in the northern Andes as indicated by focal mechanisms of earthquakes. *Tectonophysics* 403, 29–58.
<https://doi.org/10.1016/j.tecto.2005.03.020>
- Costa dos Santos, A., Mata, J., Jourdan, F., de Oliveira Rodrigues, S.W., Pereira Monteiro, L.G., Guedes, E., Benedini, L., Geraldés, M.C., 2021. Martin Vaz island geochronology: Constraint on the Trindade Mantle Plume track from the youngest

- and easternmost volcanic episodes. *Journal of South American Earth Sciences* 106, 103090. <https://doi.org/10.1016/j.jsames.2020.103090>
- Courtillot, V., Davaille, A., Besse, J., Stock, J., 2003. Three distinct types of hotspots in the Earth's mantle. *Earth and Planetary Science Letters* 205, 295–308. [https://doi.org/10.1016/S0012-821X\(02\)01048-8](https://doi.org/10.1016/S0012-821X(02)01048-8)
- Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P., Besse, J., 1999. On causal links between flood basalts and continental breakup. *Earth and Planetary Science Letters*.
- Crosby, A.G., McKenzie, D., Sclater, J.G., 2006. The relationship between depth, age and gravity in the oceans. *Geophysical Journal International* 166, 553–573. <https://doi.org/10.1111/j.1365-246X.2006.03015.x>
- Cruz, S.C.P., Alkmim, F.F., 2017. The Paramirim Aulacogen, in: São Francisco Craton, Eastern Brazil. pp. 97–115. https://doi.org/10.1007/978-3-319-01715-0_6
- da Silva, C.C., Poveda, E., da Silva Dantas, R.R., Julià, J., 2021. Ambient Noise Tomography with Short-Period Stations: Case Study in the Borborema Province. *Pure and Applied Geophysics* 178, 1709–1730. <https://doi.org/10.1007/s00024-021-02718-x>
- Dahlen, F.A., Tromp, J., 1998. *Theoretical Global Seismology*.
- Daly, M.C., Andrade, V., Barousse, C.A., Costa, R., McDowell, K., Piggott, N., Poole, A.J., 2014. Brasiliano crustal structure and the tectonic setting of the Parnaíba basin of NE Brazil: Results of a deep seismic reflection profile. *Tectonics* 33, 2102–2120. <https://doi.org/10.1002/2014TC003632>
- Danderfer Filho, A., Lana, C.C., Nalini Júnior, H.A., Costa, A.F.O., 2015. Constraints on the Statherian evolution of the intraplate rifting in a Paleo-Mesoproterozoic paleocontinent: New stratigraphic and geochronology record from the eastern São Francisco craton. *Gondwana Research* 28, 668–688. <https://doi.org/10.1016/j.gr.2014.06.012>
- Darros de Matos, R.M., 2021. Magmatism and hotspot trails during and after continental break-up in the South Atlantic. *Marine and Petroleum Geology* 129, 105077. <https://doi.org/10.1016/j.marpetgeo.2021.105077>
- Davies, J.H.F.L., Marzoli, A., Bertrand, H., Youbi, N., Ernesto, M., Schaltegger, U., 2017. End-Triassic mass extinction started by intrusive CAMP activity. *Nature Communications* 8, 1–8. <https://doi.org/10.1038/ncomms15596>
- Davis, J., Roeske, S., McClelland, W., Snee, L., 1999. Closing the ocean between the Precordillera terrane and Chilenia: Early Devonian ophiolite emplacement and deformation in the southwest Precordillera. *Special Paper of the Geological Society of America* 336, 115–138. <https://doi.org/10.1130/0-8137-2336-1.115>
- de Azevedo, P.A., Rocha, M.P., Soares, J.E.P., Fuck, R.A., 2015. Thin lithosphere between the Amazonian and São Francisco cratons, in central Brazil, revealed by seismic P-wave tomography. *Geophysical Journal International* 201, 61–69. <https://doi.org/10.1093/gji/ggv003>
- De Barros Gomes, C., Comin-Chiaramonti, P., Velázquez, V.F., 2013. A synthesis on the alkaline magmatism of Eastern Paraguay. *Brazilian Journal of Geology* 43, 745–761. <https://doi.org/10.5327/Z2317-488920130004000012>
- De Brito Neves, B.B., 2002. Main Stages of the Development of the Sedimentary Basins of South America and their Relationship with the Tectonics of Supercontinents. *Gondwana Research* 5, 175–196. [https://doi.org/10.1016/s1342-937x\(05\)70901-1](https://doi.org/10.1016/s1342-937x(05)70901-1)
- de Laat, J.I., Lebedev, S., Celli, N.L., Bonadio, R., de Melo, B.C., Rawlinson, N., 2023. Structure and evolution of the Australian plate and underlying upper mantle from waveform tomography with massive data sets. *Geophysical Journal International* 234, 1806. <https://doi.org/10.1093/gji/ggad120>
- de Min, A., Piccirillo, E.M., Marzoli, A., Bellieni, G., Renne, P.R., Ernesto, M., Marques, L.S., 2003. The central atlantic magmatic province (CAMP) in Brazil: Petrology,

- geochemistry, $^{40}\text{Ar}/^{39}\text{Ar}$ ages, paleomagnetism and geodynamic implications. *Geophysical Monograph Series* 136, 91–128. <https://doi.org/10.1029/136GM06>
- Debayle, E., Dubuffet, F., Durand, S., 2016. An automatically updated S-wave model of the upper mantle and the depth extent of azimuthal anisotropy. *Geophysical Research Letters* 43, 674–682. <https://doi.org/10.1002/2015GL067329>
- Decelles, P., Carrapa, B., Horton, B., McNabb, J., Gehrels, G., Boyd, J., 2015. The Miocene Arizaro Basin, central Andean hinterland: Response to partial lithosphere removal? *Memoir of the Geological Society of America* 212, 359–386. [https://doi.org/10.1130/2015.1212\(18\)](https://doi.org/10.1130/2015.1212(18))
- DeCelles, P.G., Ducea, M.N., Kapp, P., Zandt, G., 2009. Cyclicity in Cordilleran orogenic systems. *Nature Geosci* 2, 251–257. <https://doi.org/10.1038/ngeo469>
- Deckart, K., Bertrand, H., Liégeois, J.P., 2005. Geochemistry and Sr, Nd, Pb isotopic composition of the Central Atlantic Magmatic Province (CAMP) in Guyana and Guinea. *Lithos* 82, 289–314. <https://doi.org/10.1016/j.lithos.2004.09.023>
- De Laat, J.I., Lebedev, S., Celli, N.L., Bonadio, R., Chagas de Melo, B., Rawlinson, N., 2023. Structure and evolution of the Australian plate and underlying upper mantle from waveform tomography with massive data sets. *Geophysical Journal International* 234, 153–189. <https://doi.org/10.1093/gji/ggad062>
- Delor, C., Lahondère, D., Rossi, P., Cocherie, A., Guerrot, C., Potrel, A., 2003. The Bakhuis ultra-high temperature granulite belt: II. Implications for late Transamazonian crustal stretching in a revised Guiana Shield framework. *Géologie de la France* 2–4, 207–30.
- Dias, R.C., Julià, J., Schimmel, M., 2015. Rayleigh-Wave, Group-Velocity Tomography of the Borborema Province, NE Brazil, from Ambient Seismic Noise. *Pure and Applied Geophysics* 172, 1429–1449. <https://doi.org/10.1007/s00024-014-0982-9>
- DIGIS Team, 2022. GEOROC Compilation: Continental Flood Basalts. <https://doi.org/10.25625/WSTPOX>
- Donatti-Filho, J.P., Tappe, S., Oliveira, E.P., Heaman, L.M., 2013. Age and origin of the Neoproterozoic Brauna kimberlites: Melt generation within the metasomatized base of the São Francisco craton, Brazil. *Chemical Geology* 353, 19–35. <https://doi.org/10.1016/j.chemgeo.2012.06.004>
- Ducea, M., Seclaman, A., Murray, K., Jianu, D., Schoenbohm, L., 2013. Mantle-drip magmatism beneath the Altiplano-Puna Plateau, central Andes. *Geology* 41, 915–918. <https://doi.org/10.1130/G34509.1>
- Duvernay, T., Davies, D.R., Mathews, C.R., Gibson, A.H., Kramer, S.C., 2022. Continental Magmatism: The Surface Manifestation of Dynamic Interactions Between Cratonic Lithosphere, Mantle Plumes and Edge-Driven Convection. *Geochemistry, Geophysics, Geosystems* 23. <https://doi.org/10.1029/2022GC010363>
- Dziewonski, A.M., 1977. Large-scale heterogeneities in the lower mantle. *Journal of Geophysical Research*.
- Dziewonski, A.M., Anderson, D.L., 1981. Preliminary reference Earth model. *Physics of the Earth and Planetary Interiors* 25, 297–356. [https://doi.org/10.1016/0031-9201\(81\)90046-7](https://doi.org/10.1016/0031-9201(81)90046-7)
- Eakin, C.M., Long, M.D., Scire, A., Beck, S.L., Wagner, L.S., Zandt, G., Tavera, H., 2016. Internal deformation of the subducted Nazca slab inferred from seismic anisotropy. *Nature Geoscience* 9, 56–59. <https://doi.org/10.1038/ngeo2592>
- Ekström, G., Nettles, M., Dziewoński, A.M., 2012. The global CMT project 2004-2010: Centroid-moment tensors for 13,017 earthquakes. *Physics of the Earth and Planetary Interiors* 200–201, 1–9. <https://doi.org/10.1016/j.pepi.2012.04.002>
- El-Sharkawy, A., Hansteen, T.H., Clemente-Gomez, C., Fulla, J., Lebedev, S., Meier, T., 2023. Shallow Asthenospheric Volumes Beneath Cenozoic Volcanic Provinces in the Circum-Mediterranean: Evidence From Seismic Tomography And Integrated

Geophysical-Petrological Thermochemical Modelling (No. EGU23-8412). Presented at the EGU23, Copernicus Meetings. <https://doi.org/10.5194/egusphere-egu23-8412>

- Engdahl, E.R., Van der Hilst, R.D., Berrocal, J., 1995. Imaging of subducted lithosphere beneath South America. *Geophysical Research Letters* 22, 2317–2320.
- Ernesto, M., Marques, L.S., Piccirillo, E.M., Molina, E.C., Ussami, N., Comin-Chiaramonti, P., Bellieni, G., 2002. Paraná Magmatic Province-Tristan da Cunha plume system: Fixed versus mobile plume, petrogenetic considerations and alternative heat sources. *Journal of Volcanology and Geothermal Research* 118, 15–36. [https://doi.org/10.1016/S0377-0273\(02\)00248-2](https://doi.org/10.1016/S0377-0273(02)00248-2)
- Fairhead, J.D., Wilson, M., 2005. Plate tectonic processes in the South Atlantic Ocean: Do we need deep mantle plumes? Special Paper of the Geological Society of America 388, 537–553. <https://doi.org/10.1130/0-8137-2388-4.537>
- Faleiros, F.M., Pavan, M., Remédio, M.J., Rodrigues, J.B., Almeida, V.V., Caltabeloti, F.P., Pinto, L.G.R., Oliveira, A.A., Pinto De Azevedo, E.J., Costa, V.S., 2016. Zircon U–Pb ages of rocks from the Rio Apa Cratonic Terrane (Mato Grosso do Sul, Brazil): New insights for its connection with the Amazonian Craton in pre-Gondwana times. *Gondwana Research* 34, 187–204. <https://doi.org/10.1016/j.gr.2015.02.018>
- Faria, H.P.A., 2015. Caracterização De Domínios Tectono-Geofísicos Na Bacia dos Parecis com Base em Dados de Métodos Potenciais. Universidade de Brasília.
- Faure, S., Godey, S., Fallara, F., Trépanier, S., 2011. Seismic Architecture of the Archean North American Mantle and Its Relationship to Diamondiferous Kimberlite Fields. *Economic Geology* 106, 223–240.
- Feng, M., van der Lee, S., Assumpção, M., 2007. Upper mantle structure of South America from joint inversion of waveforms and fundamental mode group velocities of Rayleigh waves. *Journal of Geophysical Research: Solid Earth*. <https://doi.org/10.1029/2006JB004449>
- Fernandes, P.R., Tommasi, A., Vauchez, A., Neves, S.P., Nannini, F., 2021. The São Francisco cratonic root beneath the Neoproterozoic Brasília belt (Brazil): Petrophysical data from kimberlite xenoliths. *Tectonophysics* 816, 229011. <https://doi.org/10.1016/j.tecto.2021.229011>
- Fichtner, A., Kennett, B.L.N., Igel, H., Bunge, H.-P., 2009. Full seismic waveform tomography for upper-mantle structure in the Australasian region using adjoint methods. *Geophysical Journal International* 179, 1703–1725. <https://doi.org/10.1111/j.1365-246X.2009.04368.x>
- Finger, N.-P., Kaban, M.K., Tesauero, M., Haeger, C., Mooney, W.D., Thomas, M., 2021. A Thermo-Compositional Model of the Cratonic Lithosphere of South America. *Geochemistry, Geophysics, Geosystems* 22, e2020GC009307. <https://doi.org/10.1029/2020GC009307>
- Fodor, R.V., Hanan, B.B., 2000. Geochemical evidence for the Trindade hotspot trace: Columbia seamount ankaramite. *Lithos* 51, 293–304. [https://doi.org/10.1016/S0024-4937\(00\)00002-5](https://doi.org/10.1016/S0024-4937(00)00002-5)
- Fodor, R.V., Mukasa, S.B., Sial, A.N., 1998. Isotopic and trace-element indications of lithospheric and asthenospheric components in Tertiary alkalic basalts, northeastern Brazil. *Lithos* 43, 197–217. [https://doi.org/10.1016/S0024-4937\(98\)00012-7](https://doi.org/10.1016/S0024-4937(98)00012-7)
- Folguera, A., Orts, D., Spagnuolo, M., Vera, E.R., Litvak, V., Sagripanti, L., Ramos, M.E., Ramos, V.A., 2011. A review of Late Cretaceous to Quaternary palaeogeography of the southern Andes. *Biological Journal of the Linnean Society* 103, 250–268. <https://doi.org/10.1111/j.1095-8312.2011.01687.x>
- Forsythe, R., 1982. The late Palaeozoic to early Mesozoic evolution of southern South America: a plate tectonic interpretation. *Journal of the Geological Society* 139, 671–682.

- Foulger, G.R., 2018. Origin of the South Atlantic igneous province. *Journal of Volcanology and Geothermal Research* 355, 2–20. <https://doi.org/10.1016/j.jvolgeores.2017.09.004>
- Fowler, C.M.R., 2005. *The solid earth: an introduction to global geophysics*, 2nd ed. ed. Cambridge University Press, Cambridge, UK ; New York.
- Fraga, L.M., Reis, N.J., Agnol, R.D., 2009. Cauarane - Coeroeni Belt – the Main Tectonic Feature of the Central Guyana Shield , Northern Amazonian Craton. XI Simpósio de Geologia da Amazônia 2–5.
- Fraga, L.M., Reis, N.J., Dall’Agnol, R., Armstrong, R., 2008. Cauarane--Coeroene belt--the tectonic southern limit of the preserved rhyacian crustal domain in the Guyana shield, northern Amazonian craton, in: *International Geological Congress*.
- French, S.W., Romanowicz, B., 2015. Broad plumes rooted at the base of the Earth’s mantle beneath major hotspots. *Nature* 525, 95–99. <https://doi.org/10.1038/nature14876>
- French, S.W., Romanowicz, B.A., 2014. Whole-mantle radially anisotropic shear velocity structure from spectral-element waveform tomography. *Geophysical Journal International* 199, 1303–1327. <https://doi.org/10.1093/gji/ggu334>
- Fuck, R.A., Brito Neves, B.B., Schobbenhaus, C., 2008. Rodinia descendants in South America. *Precambrian Research* 160, 108–126. <https://doi.org/10.1016/j.precamres.2007.04.018>
- Fukao, Y., Obayashi, M., 2013. Subducted slabs stagnant above, penetrating through, and trapped below the 660 km discontinuity. *Journal of Geophysical Research: Solid Earth* 118, 5920–5938. <https://doi.org/10.1002/2013JB010466>
- Fullea, J., Lebedev, S., Martinec, Z., Celli, N.L., 2021. WINTERC-G: mapping the upper mantle thermochemical heterogeneity from coupled geophysical-petrological inversion of seismic waveforms, heat flow, surface elevation and gravity satellite data. *Geophysical Journal International*.
- Gans, C.R., Beck, S.L., Zandt, G., Gilbert, H., Alvarado, P., Anderson, M., Linkimer, L., 2011. Continental and oceanic crustal structure of the Pampean flat slab region, western Argentina, using receiver function analysis: new high-resolution results. *Geophysical Journal International* 186, 45–58. <https://doi.org/10.1111/j.1365-246X.2011.05023.x>
- Gao, Y., Yuan, X., Heit, B., Tilmann, F., Herwaarden, D.V., Thrastarson, S., Fichtner, A., n.d. Impact of the Juan Fernandez ridge on the Pampean flat subduction inferred from full waveform inversion 1–23.
- Garzione, C., Hoke, G., Libarkin, J., Withers, S., MacFadden, B., Eiler, J., Ghosh, P., Mulch, A., 2008. The Rise of the Andes. *Science (New York, N.Y.)* 320, 1304–7. <https://doi.org/10.1126/science.1148615>
- Garzione, C.N., McQuarrie, N., Perez, N.D., Ehlers, T.A., Beck, S.L., Kar, N., Eichelberger, N., Chapman, A.D., Ward, K.M., Ducea, M.N., Lease, R.O., Poulsen, C.J., Wagner, L.S., Saylor, J.E., Zandt, G., Horton, B.K., 2017. Tectonic Evolution of the Central Andean Plateau and Implications for the Growth of Plateaus. *Annual Review of Earth and Planetary Sciences* 45, 529–559. <https://doi.org/10.1146/annurev-earth-063016-020612>
- Geological Survey, U.S., n.d. Earthquake Lists, Maps, and Statistics.
- Geraldes, M.C., Motoki, A., Costa, A., Mota, C.E., Mohriak, W.U., 2013. Geochronology (Ar/Ar and K-Ar) of the south Atlantic post-break-up magmatism. *Geological Society Special Publication* 369, 41–74. <https://doi.org/10.1144/SP369.21>
- Gibson, S.A., Mckenzie, D., 2023. On the role of Earth ’ s lithospheric mantle in global volatile cycles. *Earth and Planetary Science Letters* 602, 117946. <https://doi.org/10.1016/j.epsl.2022.117946>
- Gibson, S.A., Rooks, E.E., Day, J.A., Petrone, C.M., Leat, P.T., 2020. The role of sub-continental mantle as both “sink” and “source” in deep Earth volatile cycles.

Geochimica et Cosmochimica Acta 275, 140–162.
<https://doi.org/10.1016/j.gca.2020.02.018>

- Gibson, S.A., Thompson, R.N., Day, J.A., 2006. Timescales and mechanisms of plume–lithosphere interactions: $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology and geochemistry of alkaline igneous rocks from the Paraná–Etendeka large igneous province. *Earth and Planetary Science Letters* 251, 1–17. <https://doi.org/10.1016/j.epsl.2006.08.004>
- Gibson, S.A., Thompson, R.N., Leonardos, O.H., Dickin, A.P., Mitchell, J.G., 1995. The Late Cretaceous Impact of the Trindade Mantle Plume: Evidence from Large-volume, Mafic, Potassic Magmatism in SE Brazil. *Journal of Petrology* 36, 189–229. <https://doi.org/10.1093/petrology/36.1.189>
- Gibson, S.A., Thompson, R.N., Weska, R.K., Dickin, A.P., Leonardos, O.H., 1997. Late Cretaceous rift-related upwelling and melting of the Trindade starting mantle plume head beneath western Brazil. *Contributions to Mineralogy and Petrology* 126, 303–314. <https://doi.org/10.1007/s004100050252>
- Góes, A.M.O., Feijó, F.J., 1994. Parnaíba Basin; Bacia do Parnaíba. *Boletim de Geociências da PETROBRAS* 8.
- Göğüş, O.H., Sundell, K., Uluocak, E.Ş., Saylor, J., Çetiner, U., 2022. Rapid surface uplift and crustal flow in the Central Andes (southern Peru) controlled by lithospheric drip dynamics. *Sci Rep* 12, 5500. <https://doi.org/10.1038/s41598-022-08629-8>
- González, R., Oncken, O., Faccenna, C., Le Breton, E., Bezada, M., Mora, A., 2023. Kinematics and Convergent Tectonics of the Northwestern South American Plate During the Cenozoic. *Geochem Geophys Geosyst* 24, e2022GC010827. <https://doi.org/10.1029/2022GC010827>
- Gorczyk, W., Mole, D.R., Barnes, S.J., 2018. Plume-lithosphere interaction at craton margins throughout Earth history. *Tectonophysics* 746, 678–694. <https://doi.org/10.1016/j.tecto.2017.04.002>
- Goutorbe, B., de Oliveira Coelho, D.L., Drouet, S., 2015. Rayleigh wave group velocities at periods of 6–23 s across Brazil from ambient noise tomography. *Geophysical Journal International* 203, 869–882. <https://doi.org/10.1093/gji/ggv343>
- Greenwood, J., Gibson, S., Thompson, R., Weska, R., Dickin, A., 1999. Cretaceous kimberlites from the Paranatinga-Batovi region, central Brazil: geochemical evidence for subcratonic lithospheric mantle heterogeneity. Presented at the Proc. 7th Kimberlite Conf, pp. 291–298.
- Griffin, W.L., O'Reilly, S.Y., Afonso, J.C., Begg, G.C., 2009. The composition and evolution of lithospheric mantle: A re-evaluation and its tectonic implications. *Journal of Petrology* 50, 1185–1204. <https://doi.org/10.1093/petrology/egn033>
- Groome, W.G., Thorkelson, D.J., 2009. The three-dimensional thermo-mechanical signature of ridge subduction and slab window migration. *Tectonophysics* 464, 70–83.
- Guarino, V., Bonazzi, M., Nimis, P., Guitarrari Azzone, R., Cariddi, B., Zanetti, A., 2024. Stabilization and evolution of the Brazilian subcontinental lithospheric mantle: Insights from garnet xenocrysts and peridotite xenoliths of Três Ranchos kimberlite (APIP, Brazil). *Gondwana Research* 130, 18–35. <https://doi.org/10.1016/j.gr.2024.01.005>
- Guarino, V., Wu, F.Y., Lustrino, M., Melluso, L., Brotzu, P., Gomes, C. de B., Ruberti, E., Tassinari, C.C.G., Svisero, D.P., 2013. U-Pb ages, Sr-Nd- isotope geochemistry, and petrogenesis of kimberlites, kamafugites and phlogopite-picrites of the Alto Paranaíba Igneous Province, Brazil. *Chemical Geology* 353, 65–82. <https://doi.org/10.1016/j.chemgeo.2012.06.016>
- Gutscher, M.A., Maury, R., Eissen, J.P., Bourdon, E., 2000. Can slab melting be caused by flat subduction? *Geology* 28, 535–538.

- Gutscher, M.A., Olivet, J.L., Aslanian, D., Eissen, J.P., Maury, R., 1999. The “lost Inca Plateau”: Cause of flat subduction beneath Peru? *Earth and Planetary Science Letters* 171, 335–341. [https://doi.org/10.1016/S0012-821X\(99\)00153-3](https://doi.org/10.1016/S0012-821X(99)00153-3)
- Hartmann, L.A., Campal, N., Santos, J.O.S., McNaughton, N.J., Bossi, J., Schipilov, A., Lafon, J.M., 2001. Archean crust in the Rio de la Plata Craton, Uruguay - SHRIMP U-Pb zircon reconnaissance geochronology. *Journal of South American Earth Sciences* 14, 557–570. [https://doi.org/10.1016/S0895-9811\(01\)00055-4](https://doi.org/10.1016/S0895-9811(01)00055-4)
- Hartmann, L.A., Santos, J.O.S., Cingolani, C.A., McNaughton, N.J., 2002. Two Paleoproterozoic Orogenies in the Evolution of the Tandilia Belt, Buenos Aires, as Evidenced by Zircon U-Pb SHRIMP Geochronology. *International Geology Review* 44, 528–543.
- Haschke, M., Siebel, W., Günther, A., Scheuber, E., 2002. Repeated crustal thickening and recycling during the Andean orogeny in north Chile (21°-26°S). *Journal of Geophysical Research: Solid Earth* 107, ECV 6-1-ECV 6-18. <https://doi.org/10.1029/2001jb000328>
- Hasterok, D., Halpin, J.A., Collins, A.S., Hand, M., Kreemer, C., Gard, M.G., Glorie, S., 2022. New Maps of Global Geological Provinces and Tectonic Plates. *Earth-Science Reviews* 231, 104069. <https://doi.org/10.1016/j.earscirev.2022.104069>
- Hayes, G.P., Moore, G.L., Portner, D.E., Hearne, M., Flamme, H., Furtney, M., Smoczyk, G.M., 2018. Slab2, a comprehensive subduction zone geometry model. *Science* 362, 58–61. <https://doi.org/10.1126/science.aat4723>
- Heilbron, M., Alkmim, F.F., Cordani, U.G., 2017. The São Francisco Craton and Its Margins, in: *São Francisco Craton, Eastern Brazil*. Springer, pp. 321–331. <https://doi.org/10.1007/978-3-319-01715-0>
- Heimdal, T.H., Svensen, H.H., Ramezani, J., Iyer, K., Pereira, E., Rodrigues, R., Jones, M.T., Callegaro, S., 2018. Large-scale sill emplacement in Brazil as a trigger for the end-Triassic crisis. *Scientific Reports* 8, 1–12. <https://doi.org/10.1038/s41598-017-18629-8>
- Heintz, M., Debayle, E., Vauchez, A., 2005. Upper mantle structure of the South American continent and neighboring oceans from surface wave tomography. *Tectonophysics* 406, 115–139. <https://doi.org/10.1016/j.tecto.2005.05.006>
- Ho, T., Priestley, K., Debayle, E., 2016. A global horizontal shear velocity model of the upper mantle from multimode Love wave measurements. *Geophysical journal international* 207, 542–561.
- Hoernle, K., Hauff, F., Kokfelt, T.F., Haase, K., Garbe-Schönberg, D., Werner, R., 2011. On- and off-axis chemical heterogeneities along the South Atlantic Mid-Ocean-Ridge (5–11°S): Shallow or deep recycling of ocean crust and/or intraplate volcanism? *Earth and Planetary Science Letters* 306, 86–97. <https://doi.org/10.1016/j.epsl.2011.03.032>
- Hoggard, M.J., Czarnota, K., Richards, F.D., Huston, D.L., Jaques, A.L., Ghelichkhan, S., 2020. Global distribution of sediment-hosted metals controlled by craton edge stability. *Nature Geoscience* 13, 504–510. <https://doi.org/10.1038/s41561-020-0593-2>
- Hooper, P.R., 1997. The Columbia River Flood Basalt Province: Current Status, in: *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. American Geophysical Union (AGU), pp. 1–27. <https://doi.org/10.1029/GM100p0001>
- Horton, B.K., 2018. Tectonic Regimes of the Central and Southern Andes: Responses to Variations in Plate Coupling During Subduction. *Tectonics* 37, 402–429. <https://doi.org/10.1002/2017TC004624>
- Hosseini, K., Matthews, K.J., Sigloch, K., Shephard, G.E., Domeier, M., Tsekhmistrenko, M., 2018. SubMachine: Web-Based Tools for Exploring Seismic Tomography and

- Other Models of Earth's Deep Interior. *Geochemistry, Geophysics, Geosystems* 19, 1464–1483. <https://doi.org/10.1029/2018GC007431>
- Hosseini, K., Sigloch, K., Tsekhmistrenko, M., Zaheri, A., Nissen-Meyer, T., Igel, H., 2020. Global mantle structure from multifrequency tomography using P, PP and P-diffracted waves. *Geophysical Journal International* 220, 96–141. <https://doi.org/10.1093/gji/ggz394>
- Houser, C., Masters, G., Shearer, P., Laske, G., 2008. Shear and compressional velocity models of the mantle from cluster analysis of long-period waveforms. *Geophysical Journal International* 174, 195–212. <https://doi.org/10.1111/j.1365-246X.2008.03763.x>
- Hu, J., Liu, L., 2016. Abnormal seismological and magmatic processes controlled by the tearing South American flat slabs. *Earth and Planetary Science Letters* 450, 40–51. <https://doi.org/10.1016/j.epsl.2016.06.019>
- Hu, J., Liu, L., Faccenda, M., Zhou, Q., Fischer, K.M., Marshak, S., Lundstrom, C., 2018. Modification of the Western Gondwana craton by plume-lithosphere interaction. *Nature Geoscience* 11, 203–210. <https://doi.org/10.1038/s41561-018-0064-1>
- Hunt, L., Stachel, T., Morton, R., Grütter, H., Creaser, R.A., 2009. The Carolina kimberlite, Brazil - Insights into an unconventional diamond deposit. *Lithos* 112, 843–851. <https://doi.org/10.1016/j.lithos.2009.04.018>
- Isacks, B.L., 1988. Uplift of the Central Andean Plateau and bending of the Bolivian Orocline. *J. Geophys. Res.* 93, 3211–3231. <https://doi.org/10.1029/JB093iB04p03211>
- Julia, J., Assumpção, M., Rocha, M.P., 2008. Deep crustal structure of the Paraná Basin from receiver functions and Rayleigh-wave dispersion: Evidence for a fragmented cratonic root. *Journal of Geophysical Research: Solid Earth* 113, 1–23. <https://doi.org/10.1029/2007JB005374>
- Kaminsky, F.V., Khachatryan, G.K., Andreazza, P., Araujo, D., Griffin, W.L., 2009. Super-deep diamonds from kimberlites in the Juina area, Mato Grosso State, Brazil. *Lithos* 112, 833–842. <https://doi.org/10.1016/j.lithos.2009.03.036>
- Kaminsky, F.V., Sablukov, S.M., Belousova, E.A., Andreazza, P., Tremblay, M., Griffin, W.L., 2010. Kimberlitic sources of super-deep diamonds in the Juina area, Mato Grosso State, Brazil. *Lithos* 114, 16–29. <https://doi.org/10.1016/j.lithos.2009.07.012>
- Kaminsky, F.V., Zakharchenko, O.D., Davies, R., Griffin, W.L., Khachatryan-Blinova, G.K., Shiryayev, A.A., 2001. Superdeep diamonds from the Juina area, Mato Grosso State, Brazil. *Contributions to Mineralogy and Petrology* 140, 734–753. <https://doi.org/10.1007/s004100000221>
- Karato, S.-I., 1995. Effects of water on seismic wave velocities in the upper mantle. *Proceedings of the Japan Academy, Series B* 71, 61–66.
- Karato, S.I., 1986. Does partial melting reduce the creep strength of the upper mantle? *Nature* 319, 309–310.
- Kawabata, H., Hanyu, T., Chang, Q., Kimura, J.-I., Nichols, A.R.L., Tatsumi, Y., 2011. The Petrology and Geochemistry of St. Helena Alkali Basalts: Evaluation of the Oceanic Crust-recycling Model for HIMU OIB. *Journal of Petrology* 52, 791–838. <https://doi.org/10.1093/petrology/egr003>
- Kay, S., Gordillo, C., 1994. Pocho volcanic rocks and the melting of depleted continental lithosphere above a shallowly dipping subduction zone in the Central Andes. *Contributions to Mineralogy and Petrology* 117, 25–44. <https://doi.org/10.1007/BF00307727>
- Kay, S.M., Ardolino, A.A., Gorrington, M.L., Ramos, V.A., 2007. The somuncura large igneous province in Patagonia: Interaction of a transient mantle thermal anomaly with a subducting slab. *Journal of Petrology* 48, 43–77. <https://doi.org/10.1093/petrology/egl053>

- Kay, S.M., Coira, B.L., 2009. Shallowing and steepening subduction zones, continental lithospheric loss, magmatism, and crustal flow under the Central Andean Altiplano-Puna Plateau. *Memoir of the Geological Society of America* 204, 229–259. [https://doi.org/10.1130/2009.1204\(11\)](https://doi.org/10.1130/2009.1204(11))
- Kendrick, E., Bevis, M., Smalley, R., Brooks, B., Vargas, R.B., Lauría, E., Fortes, L.P.S., 2003. The Nazca–South America Euler vector and its rate of change. *Journal of South American Earth Sciences* 16, 125–131. [https://doi.org/10.1016/S0895-9811\(03\)00028-2](https://doi.org/10.1016/S0895-9811(03)00028-2)
- Kennett, B.L.N., Engdahl, E.R., Buland, R., 1995. Constraints on seismic velocities in the Earth from traveltimes. *Geophysical Journal International* 122, 108–124. <https://doi.org/10.1111/j.1365-246X.1995.tb03540.x>
- Kincaid, C., Druken, K.A., Griffiths, R.W., Stegman, D.R., 2013. Bifurcation of the Yellowstone plume driven by subduction-induced mantle flow. *Nature Geoscience* 6, 395–399. <https://doi.org/10.1038/ngeo1774>
- King, S.D., Ritsema, J., 2000. African Hot Spot Volcanism: Small-Scale Convection in the Upper Mantle Beneath Cratons. *Science* 290, 1137–1140. <https://doi.org/10.1126/science.290.5494.1137>
- Klein, E.L., Almeida, M.E., Rosa-Costa, L.T., 2012. The 1.89–1.87 Ga Uatumã Silicic Large Igneous Province, northern South America. *Large Igneous Provinces Commission* 1–14.
- Klein, E.L., Moura, C.A.V., 2008. São Luís Craton and Gurupi Belt (Brazil): possible links with the West African Craton and surrounding Pan-African belts. *Geological Society, London, Special Publications* 294, 137–151. <https://doi.org/10.1144/SP294.8>
- Kley, J., Monaldi, C.R., 1998. Tectonic shortening and crustal thickness in the Central Andes: How good is the correlation? *Geology* 26, 723–726. [https://doi.org/10.1130/0091-7613\(1998\)026<0723:TSACTI>2.3.CO;2](https://doi.org/10.1130/0091-7613(1998)026<0723:TSACTI>2.3.CO;2)
- Klöcking, M., Hoggard, M.J., Rodríguez Tribaldos, V., Richards, F.D., Guimarães, A.R., MacLennan, J., White, N.J., 2020. A tale of two domes: Neogene to recent volcanism and dynamic uplift of northeast Brazil and southwest Africa. *Earth and Planetary Science Letters* 547, 116464. <https://doi.org/10.1016/j.epsl.2020.116464>
- Klöcking, M., White, N., MacLennan, J., 2018. Role of basaltic magmatism within the Parnaíba cratonic basin, NE Brazil. *Geological Society Special Publication* 472, 309–319. <https://doi.org/10.1144/SP472.4>
- Knesel, K.M., Souza, Z.S., Vasconcelos, P.M., Cohen, B.E., Silveira, F.V., 2011. Young volcanism in the Borborema Province, NE Brazil, shows no evidence for a trace of the Fernando de Noronha plume on the continent. *Earth and Planetary Science Letters* 302, 38–50. <https://doi.org/10.1016/j.epsl.2010.11.036>
- Kroonenberg, S.B., 2014. Geological Evolution of the Amazonian Craton: forget about geological provinces!, in: *Geological Map of South America Workshop*. pp. 109–131. <https://doi.org/10.1002/9781444306408.ch2>
- Kroonenberg, S.B., de Roeper, E., 2010. Geological Evolution of the Amazonian Craton, in: *Amazonia: Landscape and Species Evolution: A Look into the Past*.
- Kroonenberg, S.B., De Roeper, E.W.F., Fraga, L.M., Reis, N.J., Faraco, T., Lafon, J.M., Cordani, U., Wong, T.E., 2016. Paleoproterozoic evolution of the Guiana Shield in Suriname: A revised model. *Geologie en Mijnbouw/Netherlands Journal of Geosciences* 95, 491–522. <https://doi.org/10.1017/njg.2016.10>
- Lafon, J.M., DELOR, C., GUERROT, C., LAHONDERE, D., 2003. Archean crustal remnants in the easternmost part of the Guiana Shield: Pb-Pb and Sm-Nd geochronological evidence for Mesoarchean versus Neoarchean signatures. *Géologie de la France* 83–99.

- Lana, C., Alkmim, F.F., Armstrong, R., Scholz, R., Romano, R., Nalini, H.A., 2013. The ancestry and magmatic evolution of Archaean TTG rocks of the Quadrilátero Ferrífero province, southeast Brazil. *Precambrian Research* 231, 157–173. <https://doi.org/10.1016/j.precamres.2013.03.008>
- Lange, H., Casassa, G., Ivins, E.R., Schröder, L., Fritsche, M., Richter, A., Groh, A., Dietrich, R., 2014. Observed crustal uplift near the Southern Patagonian Icefield constrains improved viscoelastic Earth models. *Geophysical Research Letters* 41, 805–812. <https://doi.org/10.1002/2013GL058419>
- Lebedev, S., Boonen, J., Trampert, J., 2009. Seismic structure of Precambrian lithosphere: New constraints from broad-band surface-wave dispersion. *Lithos* 109, 96–111. <https://doi.org/10.1016/j.lithos.2008.06.010>
- Lebedev, S., Nolet, G., 2003. Upper mantle beneath Southeast Asia from S velocity tomography. *J. Geophys. Res.* 108, 2048. <https://doi.org/10.1029/2000jb000073>
- Lebedev, S., Nolet, G., Meier, T., van der Hilst, R.D., 2005. Automated multimode inversion of surface and S waveforms. *Geophysical Journal International* 162, 951–964. <https://doi.org/10.1111/j.1365-246X.2005.02708.x>
- Lebedev, S., Van Der Hilst, R.D., 2008. Global upper-mantle tomography with the automated multimode inversion of surface and S-wave forms. *Geophysical Journal International* 173, 505–518. <https://doi.org/10.1111/j.1365-246X.2008.03721.x>
- Legendre, C.P., Meier, T., Lebedev, S., Friederich, W., Viereck-Götte, L., 2012. A shear wave velocity model of the European upper mantle from automated inversion of seismic shear and surface waveforms. *Geophysical Journal International* 191, 282–304. <https://doi.org/10.1111/j.1365-246X.2012.05613.x>
- Lei, W., Ruan, Y., Bozdağ, E., Peter, D., Lefebvre, M., Komatitsch, D., Tromp, J., Hill, J., Podhorszki, N., Pugmire, D., 2020. Global adjoint tomography—model GLAD-M25. *Geophysical Journal International* 223, 1–21. <https://doi.org/10.1093/gji/ggaa253>
- Leitch, A M, Davies, G.F., Wells, M., 1998. A plume head melting under a rifting margin. *Earth and Planetary Science Letters* 161, 161–177.
- Leitch, A.M., Davies, G.F., Wells, M., 1998. A plume head melting under a rifting margin. *Earth and Planetary Science Letters* 161, 161–177. [https://doi.org/10.1016/S0012-821X\(98\)00147-2](https://doi.org/10.1016/S0012-821X(98)00147-2)
- Leonardos, O.H., Carvalho, J+B, Tallarico, F. H. B., Gibson, S.A., Thompson, R.N., Meyer, H. O. A., Dickinson, A.P., 1993. O xenólito de granada lherzolito de Tres Ranchos 4: urea rocha matriz do diamante na provincia magmatica cretácica do Alto Paranaíba, Goiás. Presented at the Simp. Bras. Geol. Diamante, Cuiabá, pp. 129–140.
- Leonardos, O.H., Gibson, S.A., Thompson, R.N., 1995. First evidence of thick sub-cratonic lithospheric mantle forming a Cretaceous diamond source beneath SE Brazil. *The National Academy of Sciences of India WS Fyfe Sp.*
- Lima, I.F. de, Rubert, R.R., Pierosan, R., Barros, M.A. de S., Sommer, C.A., Okuno, D.I. de A., 2021. The 1.88 Ga Uatuma Magmatism in the Serra dos Magalhães region: petrology and implications to the extension of the south-eastern edge of the Amazonian Craton. *Brazilian Journal of Geology* 51.
- Liu, M., Gao, H., 2022. Three-Dimensional Variation of the Slab Geometry Within the South American Subduction System. *Geophysical Research Letters* 49, e2021GL095924. <https://doi.org/10.1029/2021GL095924>
- Lopes De Castro, D., Hilario Bezerra, F., Adolfo Fuck, R., Mary Vidotti, R., 2016. Geophysical evidence of pre-sag rifting and post-rifting fault reactivation in the Parnaíba basin, Brazil. *Solid Earth* 7, 529–548. <https://doi.org/10.5194/se-7-529-2016>

- Loris, I., Nolet, G., Daubechies, I., Dahlen, F.A., 2007. Tomographic inversion using ℓ_1 - norm regularization of wavelet coefficients. *Geophysical Journal International* 170, 359–370. <https://doi.org/10.1111/j.1365-246X.2007.03409.x>
- Lowrie, W., 2018. *Geophysics: A Very Short Introduction*. Oxford University Press.
- Ma, Y., Clayton, R.W., 2015. Flat slab deformation caused by interplate suction force. *Geophysical Research Letters* 42, 7064–7072. <https://doi.org/10.1002/2015GL065195>
- Mabesoone, J.M., Fúlfaro, V.J., Suguio, K., 1981. Phanerozoic sedimentary sequences of the South American platform. *Earth Science Reviews* 17, 49–67. [https://doi.org/10.1016/0012-8252\(81\)90005-2](https://doi.org/10.1016/0012-8252(81)90005-2)
- Manea, vlad constantin, Perez-Gussinye, M., Manea, M., 2012. Chilean flat slab subduction controlled by overriding plate thickness and trench rollback. *Geology* 40, 35–38. <https://doi.org/10.1130/G32543.1>
- Manea, V.C., Manea, M., Ferrari, L., Orozco, T., Valenzuela, R.W., Husker, A., Kostoglodov, V., 2017. A review of the geodynamic evolution of flat slab subduction in Mexico, Peru, and Chile. *Tectonophysics* 695, 27–52. <https://doi.org/10.1016/j.tecto.2016.11.037>
- Mantovani, M.S.M., Quintas, M.C.L., Shukowsky, W., de Brito Neves, B.B., 2005. Delimitation of the Paranapanema proterozoic block: A geophysical contribution. *Episodes* 28, 18–22. <https://doi.org/10.18814/epiiugs/2005/v28i1/002>
- Mark, H.F., Wiens, D.A., Ivins, E.R., Richter, A., Ben Mansour, W., Magnani, M.B., Marderwald, E., Adaros, R., Barrientos, S., 2022. Lithospheric Erosion in the Patagonian Slab Window, and Implications for Glacial Isostasy. *Geophysical Research Letters* 49, 1–10. <https://doi.org/10.1029/2021GL096863>
- Marot, M., Monfret, T., Gerbault, M., Nolet, G., Ranalli, G., Pardo, M., 2014. Flat versus normal subduction zones: a comparison based on 3-D regional traveltime tomography and petrological modelling of central Chile and western Argentina (29°–35°S). *Geophysical Journal International* 199, 1633–1654. <https://doi.org/10.1093/gji/ggu355>
- Marques, A., Zanotto, O.A., França, A.B., Astolfi, M.A.M., Paula, O.B., 1993. Compartimentação tectônica da Bacia do Paraná. Relatório Interno PETROBRAS, Núcleo de Exploração da Bacia do Paraná.
- Marques, L.S., Dupré, B., Piccirillo, E.M., 1999. Mantle source compositions of the Parana Magmatic Province (southern Brazil): Evidence from trace element and Sr-Nd-Pb isotope geochemistry. *Journal of Geodynamics* 28, 439–458. [https://doi.org/10.1016/S0264-3707\(99\)00020-4](https://doi.org/10.1016/S0264-3707(99)00020-4)
- Marzoli, A., Callegaro, S., Dal Corso, J., Davies, J., Chiaradia, M., Youbi, N., Bertrand, H., Reisberg, L., Merle, R., Jourdan, F., 2018. The Central Atlantic Magmatic Province (CAMP): A Review. pp. 91–125. https://doi.org/10.1007/978-3-319-68009-5_4
- Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, G., Min, A.D., 1999a. Extensive 200-Million-Year-Old Continental Flood Basalts of the Central Atlantic Magmatic Province. *Science* 284, 616–618. <https://doi.org/10.1126/science.284.5414.616>
- Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, G., Min, A. De, 1999b. Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province. *Science* 284, 616–618.
- Masters, G., Jordan, T.H., Silver, P.G., Gilbert, F., 1982. Aspherical Earth structure from fundamental spheroidal-mode data. *Nature* 298, 609–613. <https://doi.org/10.1038/298609a0>
- Masun, K.M., Scott Smith, B.H., 2008. The Pimenta Bueno kimberlite field, Rondônia, Brazil: Tuffisitic kimberlite and transitional textures. *Journal of Volcanology and Geothermal Research* 174, 81–89. <https://doi.org/10.1016/j.jvolgeores.2007.12.043>

- Mather, B.R., Müller, R.D., Seton, M., Ruttor, S., Nebel, O., Mortimer, N., 2020. Intraplate volcanism triggered by bursts in slab flux. *Sci. Adv.* 6, eabd0953. <https://doi.org/10.1126/sciadv.abd0953>
- Matos Cunha, L., Neto, I.C., Silveira, F.V., Nannini, F., 2017. Projeto Diamante, in: APRESENTAÇÃO DOS RESULTADOS DO PROJETO DIAMANTE BRASIL. CPRM, Brasília.
- Matthews, K.J., Maloney, K.T., Zahirovic, S., Williams, S.E., Seton, M., Müller, R.D., 2016. Global plate boundary evolution and kinematics since the late Paleozoic. *Global and Planetary Change* 146, 226–250. <https://doi.org/10.1016/j.gloplacha.2016.10.002>
- McHone, J.G., 2000. Non-plume magmatism and rifting during the opening of the central Atlantic Ocean. *Tectonophysics* 316, 287–296. [https://doi.org/10.1016/S0040-1951\(99\)00260-7](https://doi.org/10.1016/S0040-1951(99)00260-7)
- McKenzie, D., Bickle, M.J., 1988. The volume and composition of melt generated by extension of the lithosphere. *Journal of Petrology* 29, 625–679. <https://doi.org/10.1093/petrology/29.3.625>
- McKenzie, D., Priestley, K., 2008. The influence of lithospheric thickness variations on continental evolution. *Lithos* 102, 1–11. <https://doi.org/10.1016/j.lithos.2007.05.005>
- McQuarrie, N., 2002. The kinematic history of the central Andean fold-thrust belt, Bolivia: Implications for building a high plateau. *Geological Society of America Bulletin* 114, 950–963. [https://doi.org/10.1130/0016-7606\(2002\)114<0950:TKHOTC>2.0.CO;2](https://doi.org/10.1130/0016-7606(2002)114<0950:TKHOTC>2.0.CO;2)
- Mégnin, C., Romanowicz, B., 2000. The three-dimensional shear velocity structure of the mantle from the inversion of body, surface and higher-mode waveforms. *Geophysical Journal International* 143, 709–728. <https://doi.org/10.1046/j.1365-246X.2000.00298.x>
- Meier, T., Soomro, R.A., Viereck, L., Lebedev, S., Behrmann, J.H., Weidle, C., Cristiano, L., Hanemann, R., 2016. Mesozoic and Cenozoic evolution of the Central European lithosphere. *Tectonophysics* 692, 58–73. <https://doi.org/10.1016/j.tecto.2016.09.016>
- Merle, R., Marzoli, A., Bertrand, H., Reisberg, L., Verati, C., Zimmermann, C., Chiaradia, M., Bellieni, G., Ernesto, M., 2011. ⁴⁰Ar/³⁹Ar ages and Sr-Nd-Pb-Os geochemistry of CAMP tholeiites from Western Maranhão basin (NE Brazil). *Lithos* 122, 137–151. <https://doi.org/10.1016/j.lithos.2010.12.010>
- Merle, R., Marzoli, A., Reisberg, L., Bertrand, H., Nemchin, A., Chiaradia, M., Callegaro, S., Jourdan, F., Bellieni, G., Kontak, D., Puffer, J., McHone, J.G., 2014. Sr, Nd, Pb and Os Isotope Systematics of CAMP Tholeiites from Eastern North America (ENA): Evidence of a Subduction-enriched Mantle Source. *Journal of Petrology* 55, 133–180. <https://doi.org/10.1093/petrology/egt063>
- Milani, E.J., 2004. Comentários sobre a origem e a evolução tectônica da bacia do paraná. *Geologia do Continente Sul-Americano: Evolução da Obra de Fernando Flávio Marques de Almeida* 265–279.
- Milani, E.J., Ramos, V.A., 1998. Paleozoic orogenies in southwestern Gondwana and the subsidence cycles of the Parana Basin. *Orogenias paleozoicas no domínio sul-ocidental do Gondwana e os ciclos de subsidência da bacia do Parana*. *Revista Brasileira de Geociências* 28, 473–484. <https://doi.org/10.5327/rbg.v28i4.651>
- Milani, E.J., Zalán, P.V., 1999. An outline of the geology and petroleum systems of the Paleozoic interior basins of South America. *Episodes-Newsmagazine of the International Union of Geological Sciences* 22, 199–205.
- Miller, M.S., Levander, A., Niu, F., Li, A., 2009. Upper mantle structure beneath the Caribbean-South American plate boundary from surface wave tomography. *Journal of Geophysical Research: Solid Earth* 114, 1–13. <https://doi.org/10.1029/2007JB005507>
- Mizusaki, A.M.P., Thomaz-Filho, A., Milani, E.J., De Césaro, P., 2002. Mesozoic and Cenozoic igneous activity and its tectonic control in northeastern Brazil. *Journal of*

- South American Earth Sciences 15, 183–198. [https://doi.org/10.1016/S0895-9811\(02\)00014-7](https://doi.org/10.1016/S0895-9811(02)00014-7)
- Mohriak, W.U., Nóbrega, M., Odegard, M.E., Gomes, B.S., Dickson, W.G., 2010. Geological and geophysical interpretation of the Rio Grande Rise, south-eastern Brazilian margin: extensional tectonics and rifting of continental and oceanic crusts. *PG 16*, 231–245. <https://doi.org/10.1144/1354-079309-910>
- Mojica Boada, M.J., Poveda, E., Tary, J.B., 2022. Lithospheric and Slab Configurations From Receiver Function Imaging in Northwestern South America, Colombia. *JGR Solid Earth* 127, e2022JB024475. <https://doi.org/10.1029/2022JB024475>
- Monsalve, G., Jaramillo, J.S., Cardona, A., Schulte-Pelkum, V., Posada, G., Valencia, V., Poveda, E., 2019. Deep Crustal Faults, Shear Zones, and Magmatism in the Eastern Cordillera of Colombia: Growth of a Plateau From Teleseismic Receiver Function and Geochemical Mio-Pliocene Volcanism Constraints. *Journal of Geophysical Research: Solid Earth* 124, 9833–9851. <https://doi.org/10.1029/2019JB017835>
- Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., 2006. A catalogue of deep mantle plumes: New results from finitefrequency tomography. *Geochemistry, Geophysics, Geosystems* 7. <https://doi.org/10.1029/2006GC001248>
- Moraes Neto, J.M., Hegarty, K.A., Karner, G.D., Alkmim, F.F., 2009. Timing and mechanisms for the generation and modification of the anomalous topography of the Borborema Province, northeastern Brazil. *Marine and Petroleum Geology* 26, 1070–1086. <https://doi.org/10.1016/j.marpetgeo.2008.07.002>
- Motta, J.G., Souza Filho, C.R. de, Carranza, E.J.M., Braitenberg, C., 2019. Archean crust and metallogenic zones in the Amazonian Craton sensed by satellite gravity data. *Scientific Reports* 9. <https://doi.org/10.1038/s41598-019-39171-9>
- Mpodozis, C., Ramos, V., 1989. The Andes of Chile and Argentina, in: *Geology of the Andes and its Relation to Hydrocarbon and Mineral Resources*. Earth Sciences Series 11, 59–90.
- Müller, R.D., Seton, M., Zahirovic, S., Williams, S.E., Matthews, K.J., Wright, N.M., Shephard, G.E., Maloney, K.T., Barnett-Moore, N., Hosseinpour, M., Bower, D.J., Cannon, J., 2016. Ocean Basin Evolution and Global-Scale Plate Reorganization Events Since Pangea Breakup. *Annual Review of Earth and Planetary Sciences* 44, 107–138. <https://doi.org/10.1146/annurev-earth-060115-012211>
- Murray, K.E., Ducea, M.N., Schoenbohm, L., 2015. Foundering-driven lithospheric melting: The source of central Andean mafic lavas on the Puna Plateau (22°S–27°S), in: *Geodynamics of a Cordilleran Orogenic System: The Central Andes of Argentina and Northern Chile*. Geological Society of America. [https://doi.org/10.1130/2015.1212\(08\)](https://doi.org/10.1130/2015.1212(08))
- Nadeau, S., Chen, W., Reece, J., Lachhman, D., Ault, R., Faraco, M.T.L., Fraga, L.M., Reis, N.J., Betiollo, L.M., 2013. Guyana: The lost hadean crust of South America? *Brazilian Journal of Geology* 43, 601–606. <https://doi.org/10.5327/Z2317-48892013000400002>
- Nannini, F., Neto, I.C., Silveira, F.V., Matos Cunha, L., Gusmão de Oliveira, R., Weska, R.K., 2017. Áreas kimberlíticas e diamantíferas do estado do Mato Grosso. CPRM Serviço Geológico do Brasil, Brasília.
- Neto, F.L.S., Juliã, J., Schimmel, M., 2019. Upper-mantle structure of the Borborema Province, NE Brazil, from P-wave tomography: Implications for rheology and volcanism. *Geophysical Journal International* 216, 231–250. <https://doi.org/10.1093/gji/ggy421>
- Neto, I.C., Costa e Castro, C., Silveira, F.V., Matos Cunha, L., Weska, R.K., Saraiva de Souza, Weldom, 2014. INTRUSÕES KIMBERLÍTICAS DE RONDÔNIA: UMA SÍNTESE COM BASE NO CONHECIMENTO ATUAL. Presented at the 6 Simpósio Brasileiro de Geologia do Diamante, Patos de Minas.

- Neves, S.P., Teixeira, C.M.L., Bruguier, O., 2020. Long-lived localized magmatism in central-eastern part of the Pernambuco-Alagoas Domain, Borborema Province (NE Brazil): Implications for tectonic setting, heat sources, and lithospheric reworking. *Precambrian Research* 337, 105559. <https://doi.org/10.1016/j.precamres.2019.105559>
- Nimis, P., Grütter, H., 2010. Internally consistent geothermometers for garnet peridotites and pyroxenites. *Contrib Mineral Petrol* 159, 411–427. <https://doi.org/10.1007/s00410-009-0455-9>
- Nolet, G., 2008. A Breviary of Seismic Tomography, A Breviary of Seismic Tomography.
- Nolet, G., 1990. Partitioned waveform inversion and two-dimensional structure under the network of autonomously recording seismographs. *J. Geophys. Res.* 95, 8499–8512. <https://doi.org/10.1029/JB095iB06p08499>
- Nunn, J.A., Aires, J.R., 1988. Gravity anomalies and flexure of the lithosphere at the Middle Amazon Basin, Brazil. *Journal of Geophysical Research* 93, 415–428. <https://doi.org/10.1029/JB093iB01p00415>
- O'Connor, J.M., Duncan, R. a., 1990. Evolution of the Walvis Ridge-Rio Grande Rise Hot Spot System: Implications for African and South American Plate motions over plumes. *Journal of Geophysical Research* 95, 17475. <https://doi.org/10.1029/JB095iB11p17475>
- O'Driscoll, L.J., Richards, M.A., Humphreys, E.D., 2012. Nazca–South America interactions and the late Eocene–late Oligocene flat-slab episode in the central Andes. *Tectonics* 31. <https://doi.org/10.1029/2011TC003036>
- Oldow, J.S., Bally, A.W., Avé Lallemant, H.G., 1990. Transpression, orogenic float, and lithospheric balance. *Geology* 18, 991–994. [https://doi.org/10.1130/0091-7613\(1990\)018<0991:TOFALB>2.3.CO;2](https://doi.org/10.1130/0091-7613(1990)018<0991:TOFALB>2.3.CO;2)
- Oyhantçabal, P., Siegesmund, S., Wemmer, K., 2011. The Río de la Plata Craton: A review of units, boundaries, ages and isotopic signature. *International Journal of Earth Sciences* 100, 201–220. <https://doi.org/10.1007/s00531-010-0580-8>
- P. R., V., 1973. Subduction and Aseismic Ridges. *Nature* 241. <https://doi.org/10.1017/CBO9781107415324.004>
- Padilha, A.L., Vitorello, Í., Antunes, C.E., Pádua, M.B., 2015. Imaging three-dimensional crustal conductivity structures reflecting continental flood basalt effects hidden beneath thick intracratonic sedimentary basin. *Journal of Geophysical Research: Solid Earth* 120, 4702–4719. <https://doi.org/10.1002/2014JB011657>
- Paes de Barros, A.J., 2007. GRANITOS DA REGIÃO DE PEIXOTO DE AZEVEDO - NOVO MUNDO E MINERALIZAÇÕES AURÍFERAS RELACIONADAS - PROVÍNCIA AURÍFERA ALTA FLORESTA (MT). Roberto Perez Xavier.
- Paige, C.C., Saunders, M.A., 1982. LSQR: An algorithm for sparse linear equations and sparse least squares. *ACM Transactions on Mathematical Software (TOMS)* 8, 43–71.
- Pankhurst, R.J., Ramos, A., Linares, E., 2003. Antiquity of the Río de la Plata craton in Tandilia, southern Buenos Aires province, Argentina. *Journal of South American Earth Sciences* 16, 5–13. [https://doi.org/10.1016/S0895-9811\(03\)00015-4](https://doi.org/10.1016/S0895-9811(03)00015-4)
- Pankhurst, R.J., Rapela, C.W., Fanning, C.M., Márquez, M., 2006. Gondwanide continental collision and the origin of Patagonia. *Earth-Science Reviews* 76, 235–257. <https://doi.org/10.1016/j.earscirev.2006.02.001>
- Panning, M.P., Lekić, V., Romanowicz, B.A., 2010. Importance of crustal corrections in the development of a new global model of radial anisotropy. *Journal of Geophysical Research: Solid Earth* 115. <https://doi.org/10.1029/2010JB007520>
- Paulick, H., Münker, C., Schuth, S., 2010. The influence of small-scale mantle heterogeneities on Mid-Ocean Ridge volcanism: Evidence from the southern Mid-

- Atlantic Ridge (7°30'S to 11°30'S) and Ascension Island. *Earth and Planetary Science Letters* 296, 299–310. <https://doi.org/10.1016/j.epsl.2010.05.009>
- Pearson, D.G., Canil, D., Shirey, S.B., 2003. Mantle samples included in volcanic rocks: xenoliths and diamonds. *Treatise on geochemistry* 2, 568.
- Peate, D.W., Hawkesworth, C.J., Mantovani, M.S.M., 1992. Chemical stratigraphy of the Paraná lavas (South America): classification of magma types and their spatial distribution. *Bulletin of Volcanology* 55, 119–139. <https://doi.org/10.1007/BF00301125>
- Pedrosa-Soares, A.C., Alkmim, F.F. de, 2011. How Many Rifting Events Preceded the Development of the Araçuaí-West Congo Orogen? *Geonomos* 19, 244–251. <https://doi.org/10.18285/geonomos.v19i2.56>
- Pennington, W.D., 1981. Subduction of the Eastern Panama Basin and seismotectonics of northwestern South America. *J. Geophys. Res.* 86, 10753–10770. <https://doi.org/10.1029/JB086iB11p10753>
- Pereira, R.S., Fuck, R.A., 2005. Archean Nucleii and the Distribution of Kimberlite and Related Rocks in the São Francisco Craton, Brazil. *Revista Brasileira de Geociências* 35, 93–104. <https://doi.org/10.25249/0375-7536.200535s493104>
- Pessano, P.C., Ganade, C.E., Tupinambá, M., Teixeira, W., 2021. Updated map of the mafic dike swarms of Brazil based on airborne geophysical data. *Journal of South American Earth Sciences* 107. <https://doi.org/10.1016/j.jsames.2020.103076>
- Piccirillo, E.M., Melfi, A.J.P.P.-S.P., 1988. Mesozoic flood volcanism of the parana basin: petrogenetic and geophysical aspects.
- Pinto, M.L., Vidotti, R.M., 2019. Tectonic framework of the Paraná basin unveiled from gravity and magnetic data. *Journal of South American Earth Sciences* 90, 216–232. <https://doi.org/10.1016/j.jsames.2018.12.006>
- Pires, G.L.C., Bongioio, E.M., Geraldies, M.C., Renac, C., Santos, A.C., Jourdan, F., Neumann, R., 2016. New 40Ar/39Ar ages and revised 40K/40Ar* data from nephelinitic–phonolitic volcanic successions of the Trindade Island (South Atlantic Ocean). *Journal of Volcanology and Geothermal Research* 327, 531–538. <https://doi.org/10.1016/j.jvolgeores.2016.09.020>
- Portner, D.E., Rodríguez, E.E., Beck, S., Zandt, G., Scire, A., Rocha, M.P., Bianchi, M.B., Ruiz, M., França, G.S., Condori, C., Alvarado, P., 2020. Detailed Structure of the Subducted Nazca Slab into the Lower Mantle Derived From Continent-Scale Teleseismic P Wave Tomography. *Journal of Geophysical Research: Solid Earth* 125, 1–26. <https://doi.org/10.1029/2019JB017884>
- Porto, A., Carvalho, C., Lima, C., Heilbron, M., Caxito, F., La Terra, E., Fontes, S.L., 2022. The Neoproterozoic basement of the Parnaíba Basin (NE Brazil) from combined geophysical-geological analysis: A missing piece of the western Gondwana puzzle. *Precambrian Research* 379, 106784. <https://doi.org/10.1016/j.precamres.2022.106784>
- Presser Baez, L.J., 2016. Diamantes En Paraguay, Cincuenta Años De Ocurrencia. *BOLETÍN del Museo Nacional de Historia Natural del Paraguay* 20, 154–187.
- Priestley, K., Ho, T., Takei, Y., McKenzie, D., 2024. The thermal and anisotropic structure of the top 300 km of the mantle. *Earth and Planetary Science Letters* 626, 118525. <https://doi.org/10.1016/j.epsl.2023.118525>
- Priestley, K., McKenzie, D., 2006. The thermal structure of the lithosphere from shear wave velocities. *Earth and Planetary Science Letters* 244, 285–301. <https://doi.org/10.1016/j.epsl.2006.01.008>
- Prieto, G.A., Beroza, G.C., Barrett, S.A., López, G.A., Florez, M., 2012. Earthquake nests as natural laboratories for the study of intermediate-depth earthquake mechanics. *Tectonophysics* 570–571, 42–56. <https://doi.org/10.1016/j.tecto.2012.07.019>

- Qin, Y., Capdeville, Y., Maupin, V., Montagner, J.P., Lebedev, S., Beucler, E., 2008. SPICE benchmark for global tomographic methods. *Geophysical Journal International* 175, 598–616. <https://doi.org/10.1111/j.1365-246X.2008.03904.x>
- Ramos, V.A., 2008. Patagonia: A paleozoic continent adrift? *Journal of South American Earth Sciences* 26, 235–251. <https://doi.org/10.1016/j.jsames.2008.06.002>
- Ramos, V.A., 1999. Plate tectonic setting of the Andean Cordillera. *Episodes* 22, 183–190. <https://doi.org/10.18814/epiiugs/1999/v22i3/005>
- Ramos, V.A., 1988. Late Proterozoic-Early Paleozoic of South America - a Collisional History. *Episodes* 11, 168–174.
- Ramos, V.A., 1984. Patagonia: un continente paleozoico a la deriva?, in: 9° Congreso Geológico Argentino, SC Bariloche, Buenos Aires, 1984. pp. 311–325.
- Ramos, V.A., Cristallini, E.O., Pérez, D.J., 2002. The Pampean flat-slab of the Central Andes. *Journal of South American Earth Sciences* 15, 59–78. [https://doi.org/10.1016/S0895-9811\(02\)00006-8](https://doi.org/10.1016/S0895-9811(02)00006-8)
- Ramos, V.A., Folguera, A., 2009. Andean flat-slab subduction through time. *Geological Society Special Publication* 327, 31–54. <https://doi.org/10.1144/SP327.3>
- Ramos, V.A., Litvak, V.D., Folguera, A., Spagnuolo, M., 2014. An Andean tectonic cycle: From crustal thickening to extension in a thin crust (34°–37°SL). *Geoscience Frontiers* 5, 351–367. <https://doi.org/10.1016/j.gsf.2013.12.009>
- Ramos, V.A., Vujovich, G., Martino, R., Otamendi, J., 2010. Pampia: A large cratonic block missing in the Rodinia supercontinent. *Journal of Geodynamics*. <https://doi.org/10.1016/j.jog.2010.01.019>
- Rapela, C.W., Pankhurst, R.J., Casquet, C., Fanning, C.M., Baldo, E.G., González-Casado, J.M., Galindo, C., Dahlquist, J., 2007. The Río de la Plata craton and the assembly of SW Gondwana. *Earth-Science Reviews* 83, 49–82. <https://doi.org/10.1016/j.earscirev.2007.03.004>
- Rawlinson, N., Pozgay, S., Fishwick, S., 2010. Seismic tomography: A window into deep Earth. *Physics of the Earth and Planetary Interiors* 178, 101–135. <https://doi.org/10.1016/j.pepi.2009.10.002>
- Rawlinson, N., Spakman, W., 2016. On the use of sensitivity tests in seismic tomography. *Geophys. J. Int.* 205, 1221–1243. <https://doi.org/10.1093/gji/ggw084>
- Reid, F.J.L., Woodhouse, J.H., Van Heijst, H.J., 2001. Upper mantle attenuation and velocity structure from measurements of differential S phases. *Geophysical Journal International* 145, 615–630. <https://doi.org/10.1046/j.1365-246X.2001.01395.x>
- Reis, H.L.S., Alkmim, F.F., 2015. Anatomy of a basin-controlled foreland fold-thrust belt curve: The Três Marias salient, São Francisco basin, Brazil. *Marine and Petroleum Geology* 66, 711–731. <https://doi.org/10.1016/j.marpetgeo.2015.07.013>
- Reis, H.L.S., Alkmim, F.F., Fonseca, R.C.S., Nascimento, T.C., Suss, J.F., Prevatti, L.D., 2017. The São Francisco Basin, in: São Francisco Craton, Eastern Brazil: Tectonic Genealogy of a Miniature Continent. pp. 117–143. https://doi.org/10.1007/978-3-319-01715-0_7
- Renne, P.R., Deckart, K., Ernesto, M., Féraud, G., Piccirillo, E.M., 1996. Age of the Ponta Grossa dike swarm (Brazil), and implications to Paraná flood volcanism. *Earth and Planetary Science Letters* 144, 199–211. [https://doi.org/10.1016/0012-821x\(96\)00155-0](https://doi.org/10.1016/0012-821x(96)00155-0)
- Ribeiro, A.C., Riccomini, C., Leite, J.A.D., 2018. Origin of the largest South American transcontinental water divide. *Scientific Reports* 8, 1–8. <https://doi.org/10.1038/s41598-018-35554-6>
- Ribeiro, B.V., Finch, M.A., Cawood, P.A., Faleiros, F.M., Murphy, T.D., Simpson, A., Glorie, S., Tedeschi, M., Armit, R., Barrote, V.R., 2022. From microanalysis to supercontinents: Insights from the Rio Apa Terrane into the Mesoproterozoic SW

- Amazonian Craton evolution during Rodinia assembly. *Journal Metamorphic Geology* 40, 631–663. <https://doi.org/10.1111/jmg.12641>
- Richter, A., Ivins, E., Lange, H., Mendoza, L., Schröder, L., Hormaechea, J.L., Casassa, G., Marderwald, E., Fritsche, M., Perdomo, R., Horwath, M., Dietrich, R., 2016. Crustal deformation across the Southern Patagonian Icefield observed by GNSS. *Earth and Planetary Science Letters* 452, 206–215. <https://doi.org/10.1016/j.epsl.2016.07.042>
- Rickers, F., Fichtner, A., Trampert, J., 2013. The Iceland-Jan Mayen plume system and its impact on mantle dynamics in the North Atlantic region: Evidence from full-waveform inversion. *Earth and Planetary Science Letters* 367, 39–51. <https://doi.org/10.1016/j.epsl.2013.02.022>
- Ritsema, J., Deuss, A., Van Heijst, H.J., Woodhouse, J.H., 2011. S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltime and normal-mode splitting function measurements: S40RTS. *Geophysical Journal International* 184, 1223–1236. <https://doi.org/10.1111/j.1365-246X.2010.04884.x>
- Rivadeneira-Vera, J.C., Bianchi, M.B., Assumpção, M., Cedraz, V., Julià, J., Rodríguez, M., Sánchez, L., Sánchez, G., Lopez-Murua, L., Fernandez, G., Fugarazzo, R., 2019. An updated crustal thickness map of central South America based on receiver function measurements in the region of the Chaco, Pantanal and Paraná Basins, southwestern Brazil. *Journal of Geophysical Research: Solid Earth* 2018JB016811. <https://doi.org/10.1029/2018JB016811>
- Robertson Maurice, S.D., Wiens, D.A., Koper, K.D., Vera, E., 2003. Crustal and upper mantle structure of southernmost South America inferred from regional waveform inversion. *Journal of Geophysical Research: Solid Earth* 108. <https://doi.org/10.1029/2002JB001828>
- Rocha, M.P., Azevedo, P.A. de, Assumpção, M., Pedrosa-Soares, A.C., Fuck, R., Von Huelsen, M.G., Von Huelsen, M.G., 2019. Delimiting the Neoproterozoic São Francisco Palecontinental Block with P-wave traveltime tomography. *Geophysical Journal International* 219, 633–644. <https://doi.org/10.1093/gji/ggz323>
- Rocha, M.P., Schimmel, M., Assumpção, M., 2011. Upper-mantle seismic structure beneath SE and Central Brazil from P- and S-wave regional traveltime tomography. *Geophysical Journal International* 184, 268–286. <https://doi.org/10.1111/j.1365-246X.2010.04831.x>
- Rocha-Júnior, E.R.V., Marques, L.S., Babinski, M., Machado, F.B., Petronilho, L.A., Nardy, A.J.R., 2020. A telltale signature of Archean lithospheric mantle in the Paraná continental flood basalts genesis. *Lithos* 364–365, 105519. <https://doi.org/10.1016/j.lithos.2020.105519>
- Rodríguez, E.E., Portner, D.E., Beck, S.L., Rocha, M.P., Bianchi, M.B., Assumpção, M., Ruiz, M., Alvarado, P., 2020. Mantle dynamics of the Andean Subduction Zone from continent-scale teleseismic S-wave tomography. *Geophysical Journal International*.
- Rogers, A., Flanigan, M., Nebel, O., Nebel-Jacobsen, Y., Wang, X., Arculus, R.J., Miller, L., Smith, I., Mather, B.R., Kendrick, M., O'Neill, H.St.C., 2023. The isotopic origin of Lord Howe Island reveals secondary mantle plume twinning in the Tasman Sea. *Chemical Geology* 622, 121374. <https://doi.org/10.1016/j.chemgeo.2023.121374>
- Romanowicz, B., 2008. Using seismic waves to image Earth's internal structure. *Nature* 451, 266–268. <https://doi.org/10.1038/nature06583>
- Romanowicz, B., 1995a. A global tomographic model of shear attenuation in the upper mantle. *J. Geophys. Res.* 100, 12375–12394. <https://doi.org/10.1029/95JB00957>
- Romanowicz, B., 1995b. A global tomographic model of shear attenuation in the upper mantle. *Journal of Geophysical Research* 100. <https://doi.org/10.1029/95jb00957>
- Santos, J.O.S., 2003a. Geotectônica dos Escudos das Guianas e Brasil-Central, in: *Geologia, Tectônica e Recursos Minerais Do Brasil*. Brasília, pp. 169–195.

- Santos, J.O.S., 2003b. Geotectonics of the Guyana and Central Brazilian Shields, Geology, tectonics and mineral resources of Brazil. Serviço Geológico–CPRM, Brasília.
- Santos, J.O.S., Chernicoff, C.J., Zappettini, E.O., McNaughton, N.J., Hartmann, L.A., 2019. Large geographic and temporal extensions of the Río de la Plata Craton, South America, and its metacratonic eastern margin. *International Geology Review* 61, 56–85. <https://doi.org/10.1080/00206814.2017.1405747>
- Santos, J.O.S., Hartmann, L.A., Gaudette, H.E., Groves, D.I., Mcnaughton, N.J., Fletcher, I.R., 2000. A New Understanding of the Provinces of the Amazon Craton Based on Integration of Field Mapping and U-Pb and Sm-Nd Geochronology. *Gondwana Research* 3, 453–488. [https://doi.org/10.1016/S1342-937X\(05\)70755-3](https://doi.org/10.1016/S1342-937X(05)70755-3)
- Santos, J.O.S., Hartmann, L.A., McNaughton, N.J., Fletcher, I.R., 2002. Timing of mafic magmatism in the Tapajós Province (Brazil) and implications for the evolution of the Amazon Craton: Evidence from baddeleyite and zircon U-Pb SHRIMP geochronology. *Journal of South American Earth Sciences* 15, 409–429. [https://doi.org/10.1016/S0895-9811\(02\)00061-5](https://doi.org/10.1016/S0895-9811(02)00061-5)
- Schaeffer, A., Lebedev, S., 2013. Global shear speed structure of the upper mantle and transition zone. *Geophysical Journal International* 194, 417–449. <https://doi.org/10.1093/gji/ggt095>
- Schaeffer, A.J., 2014. Imaging The Structure and Dynamics of the Earth's Upper Mantle and Crust Using Multimode Waveform Tomography.
- Schaeffer, A.J., Lebedev, S., 2014. Imaging the North American continent using waveform inversion of global and USArray data. *Earth and Planetary Science Letters* 402, 26–41. <https://doi.org/10.1016/j.epsl.2014.05.014>
- Schepers, G., Van Hinsbergen, D.J.J., Spakman, W., Kesters, M.E., Boschman, L.M., McQuarrie, N., 2017. South-American plate advance and forced Andean trench retreat as drivers for transient flat subduction episodes. *Nature Communications*. <https://doi.org/10.1038/ncomms15249>
- Schilling, F.R., Trumbull, R.B., Brasse, H., Haberland, C., Asch, G., Bruhn, D., Mai, K., Haak, V., Giese, P., Muñoz, M., Ramelow, J., Rietbrock, A., Ricaldi, E., Vietor, T., 2006. Partial Melting in the Central Andean Crust: a Review of Geophysical, Petrophysical, and Petrologic Evidence. *The Andes* 459–474. https://doi.org/10.1007/978-3-540-48684-8_22
- Schilling, M.E., Carlson, R.W., Tassara, A., Conceição, R.V., Bertotto, G.W., Vásquez, M., Muñoz, D., Jalowitzki, T., Gervasoni, F., Morata, D., 2017. The origin of Patagonia revealed by Re-Os systematics of mantle xenoliths. *Precambrian Research* 294, 15–32. <https://doi.org/10.1016/j.precamres.2017.03.008>
- Schimmel, M., Marcelo Assumpção, 2003. Seismic velocity anomalies beneath SE Brazil from P and S wave travel time inversions. *Journal of Geophysical Research* 18.
- Schmitz, M., Heinsohn, W.D., Schilling, F.R., 1997. Seismic, gravity and petrological evidence for partial melt beneath the thickened Central Andean crust (21–23°S). *Tectonophysics* 270, 313–326. [https://doi.org/10.1016/S0040-1951\(96\)00217-X](https://doi.org/10.1016/S0040-1951(96)00217-X)
- Schobbenhaus, C., Neves, B.B.B., Brito Neves, B.B. de, 2003. A geologia do Brasil no contexto da Plataforma Sul-Americana. *Geologia, Tectônica e Recursos Minerais do Brasil*. Brasília, CPRM 5–25.
- Schurr, B., Asch, G., Rietbrock, A., Trumbull, R., Haberland, C., 2003. Complex patterns of fluid and melt transport in the central Andean subduction zone revealed by attenuation tomography. *Earth and Planetary Science Letters* 215, 105–119. [https://doi.org/10.1016/S0012-821X\(03\)00441-2](https://doi.org/10.1016/S0012-821X(03)00441-2)
- Schurr, B., Rietbrock, A., Asch, G., Kind, R., Oncken, O., 2006. Evidence for lithospheric detachment in the central Andes from local earthquake tomography. *Tectonophysics* 415, 203–223. <https://doi.org/10.1016/j.tecto.2005.12.007>

- Schutt, D.L., Leshner, C.E., 2006. Effects of melt depletion on the density and seismic velocity of garnet and spinel lherzolite. *Journal of Geophysical Research: Solid Earth* 111, 1–24. <https://doi.org/10.1029/2003JB002950>
- Scire, A., Zandt, G., Beck, S., Long, M., Wagner, L., Minaya, E., Tavera, H., 2016. Imaging the transition from flat to normal subduction: Variations in the structure of the Nazca slab and upper mantle under southern Peru and northwestern Bolivia. *Geophysical Journal International* 204, 457–479. <https://doi.org/10.1093/gji/ggv452>
- Self, S., Jay, A.E., Widdowson, M., Keszthelyi, L.P., 2008. Correlation of the Deccan and Rajahmundry Trap lavas: Are these the longest and largest lava flows on Earth? *Journal of Volcanology and Geothermal Research* 172, 3–19. <https://doi.org/10.1016/j.jvolgeores.2006.11.012>
- Sella, G.F., Dixon, T.H., Mao, A., 2002. REVEL: A model for Recent plate velocities from space geodesy. *Journal of Geophysical Research: Solid Earth* 107, ETG 11-1-ETG 11-30. <https://doi.org/10.1029/2000JB000033>
- Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T.H., Shephard, G.E., Talsma, A., Gurnis, M., Turner, M., Maus, S., Chandler, M., 2012. Global continental and ocean basin reconstructions since 200Ma. *Earth-Science Reviews* 113, 212–270. <https://doi.org/10.1016/j.earscirev.2012.03.002>
- Shirzad, T., Assumpcao, M., Bianchi, M., 2020. Ambient seismic noise tomography in west-central and Southern Brazil, characterizing the crustal structure of the Chaco-Paraná, Pantanal and Paraná basins. *Geophysical Journal International* 220, 2074–2085. <https://doi.org/10.1093/gji/ggz548>
- Silva, S.D., Zandt, G., Trumbull, R., Salas, G., Jiménez, N., 2006. Large ignimbrite eruptions and volcano-tectonic depressions in the Central Andes: a thermomechanical perspective. *Geological Society of London Special Publications* 269, 47–63. <https://doi.org/10.1144/GSL.SP.2006.269.01.04>
- Simmons, N. A., Myers, S.C., Morency, C., Chiang, A., Knapp, D.R., 2021. SPiRaL: A multiresolution global tomography model of seismic wave speeds and radial anisotropy variations in the crust and mantle. *Geophysical Journal International* 227, 1366–1391. <https://doi.org/10.1093/gji/ggab277>
- Simmons, N. A., Myers, S.C., Morency, C., Chiang, A., Knapp, D.R., 2021. SPiRaL: a multiresolution global tomography model of seismic wave speeds and radial anisotropy variations in the crust and mantle. *Geophysical Journal International* 227, 1366–1391. <https://doi.org/10.1093/gji/ggab277>
- Skolotnev, S.G., Bylinskaya, M.E., Golovina, L.A., Ipat'eva, I.S., 2012a. The origin of Bahia seamounts (Brazil Basin, South Atlantic) in connection to new data on their age. *Dokl. Earth Sc.* 443, 444–450. <https://doi.org/10.1134/S1028334X12040162>
- Skolotnev, S.G., Peyve, A.A., Ivanova, E.V., Murdmaa, I.O., Levchenko, O.V., Bylinskaya, M.E., 2012b. New data on composition and structure of the Pernambuco Seamounts, Brazil basin, south Atlantic region. *Dokl. Earth Sc.* 443, 330–336. <https://doi.org/10.1134/S1028334X12030294>
- Sleep, N.H., 2003. Fate of mantle plume material trapped within a lithospheric catchment with reference to Brazil. *Geochemistry, Geophysics, Geosystems* 4, 1–18. <https://doi.org/10.1029/2002GC000464>
- Sleep, N.H., 1997. Lateral flow and ponding of starting plume material. *Journal of Geophysical Research: Solid Earth* 102, 10001–10012. <https://doi.org/10.1029/97jb00551>
- Smith, M.L., Dahlen, F.A., 1973. The azimuthal dependence of Love and Rayleigh wave propagation in a slightly anisotropic medium. *Journal of Geophysical Research*. <https://doi.org/10.1029/JB078i017p03321>
- Soares, J.E., Berrocal, J., Fuck, R.A., Mooney, W.D., Ventura, D.B.R., 2006. Seismic characteristics of central Brazil crust and upper mantle: A deep seismic refraction

- study. *Journal of Geophysical Research: Solid Earth* 111, 1–31. <https://doi.org/10.1029/2005JB003769>
- Sobolev, S.V., Zeyen, H., Stoll, G., Werling, F., Altherr, R., Fuchs, K., 1996. Upper mantle temperatures from teleseismic tomography of French Massif Central including effects of composition, mineral reactions, anharmonicity, anelasticity and partial melt. *Earth and Planetary Science Letters* 139, 147–163. [https://doi.org/10.1016/0012-821x\(95\)00238-8](https://doi.org/10.1016/0012-821x(95)00238-8)
- Spakman, W., Nolet, G., 1988. Imaging algorithms, accuracy and resolution in delay time tomography, in: Vlaar, N.J., Nolet, G., Wortel, M.J.R., Cloetingh, S.A.P.L. (Eds.), *Mathematical Geophysics: A Survey of Recent Developments in Seismology and Geodynamics*. Springer Netherlands, Dordrecht, pp. 155–187. https://doi.org/10.1007/978-94-009-2857-2_8
- Stanton, N., Gordon, A., Cardozo, C., Kusznir, N., 2021. Morphostructure, emplacement and duration of the Abrolhos Magmatic Province: A geophysical analysis of the largest post-breakup magmatism of the South-Eastern Brazilian margin. *Marine and Petroleum Geology* 133, 105230. <https://doi.org/10.1016/j.marpetgeo.2021.105230>
- Steinberger, B., 2000. Plumes in a convecting mantle ' Models and observations for individual hotspots. *Journal of Geophysical Research* 105.
- Stevenson, D.J., Turner, J.S., 1977. Angle of subduction. *Nature* 270, 334–336. <https://doi.org/10.1038/270334a0>
- Sun, M., Bezada, M.J., Cornthwaite, J., Prieto, G.A., Niu, F., Levander, A., 2022. Overlapping slabs: Untangling subduction in NW South America through finite-frequency teleseismic tomography. *Earth and Planetary Science Letters* 577, 117253. <https://doi.org/10.1016/j.epsl.2021.117253>
- Syracuse, E.M., Maceira, M., Prieto, G.A., Zhang, H., Ammon, C.J., 2016. Multiple plates subducting beneath Colombia, as illuminated by seismicity and velocity from the joint inversion of seismic and gravity data. *Earth and Planetary Science Letters* 444, 139–149. <https://doi.org/10.1016/j.epsl.2016.03.050>
- Taboada, A., Rivera, L.A., Fuenzalida, A., Cisternas, A., Philip, H., Bijwaard, H., Olaya, J., Rivera, C., 2000. Geodynamics of the northern Andes. *Tectonics* 19, 787–813.
- Taramón, J.M., Rodríguez-González, J., Negredo, A.M., Billen, M.I., 2015. Influence of cratonic lithosphere on the formation and evolution of flat slabs: Insights from 3-D time-dependent modeling: CRATONS INFLUENCE ON SUBDUCTION DYNAMICS. *Geochem. Geophys. Geosyst.* 16, 2933–2948. <https://doi.org/10.1002/2015GC005940>
- Tassara, A., Echaurren, A., 2012. Anatomy of the Andean subduction zone: three-dimensional density model upgraded and compared against global-scale models: Anatomy of the Andean subduction zone. *Geophysical Journal International* 189, 161–168. <https://doi.org/10.1111/j.1365-246X.2012.05397.x>
- Tassinari, C.C.G., 1996. O mapa geocronológico do Cráton Amazônico no Brasil: revisão dos dados isotópicos (null em Geologia isotópica). Universidade de São Paulo, São Paulo. <https://doi.org/10.11606/T.44.2013.tde-22082013-163642>
- Tassinari, C.C.G., 1981. Evolução Geotectônica da Província Rio Negro Juruema na Região Amazônica. Universidade de São Paulo.
- Tassinari, C.C.G., Macambira, M.J.B., 2004. A evolução tectônica do Cráton Amazônico. *Geologia do continente sul-americano: evolução da obra de Fernando Flávio Marques de Almeida*.
- Tassinari, C.C.G., Macambira, M.J.B., 1999. Geochronological provinces of the Amazonian Craton. *Episodes* 22, 174–182. <https://doi.org/10.18814/epiiugs/1999/v22i3/004>
- Teixeira, N.A., Campos, L.D., Paula, R.R.D., Lacasse, C.M., Ganade, C.E., Monteiro, C.F., Lopes, L.B.L., Oliveira, C.G.D., 2021. Carajás Mineral Province - Example of

- metallogeology of a rift above a cratonic lithospheric keel. *Journal of South American Earth Sciences* 108, 103091. <https://doi.org/10.1016/j.jsames.2020.103091>
- Teixeira, W., Cordani, U.G., Faleiros, F.M., Sato, K., Maurer, V.C., Ruiz, A.S., Azevedo, E.J.P., 2020. The Rio Apa Terrane reviewed: U Pb zircon geochronology and provenance studies provide paleotectonic links with a growing Proterozoic Amazonia. *Earth-Science Reviews* 202, 103089. <https://doi.org/10.1016/j.earscirev.2020.103089>
- Teixeira, W., Cordani, U.G., Nutman, A.P., Sato, K., 1998. Polyphase Archean evolution in the Campo Belo metamorphic complex, Southern São Francisco Craton, Brazil: SHRIMP U-Pb zircon evidence. *Journal of South American Earth Sciences* 11, 279–289. [https://doi.org/10.1016/S0895-9811\(98\)00011-X](https://doi.org/10.1016/S0895-9811(98)00011-X)
- Teixeira, W., Hamilton, M.A., Girardi, V.A.V.V., Faleiros, F.M., Ernst, R.E., 2019. U-Pb baddeleyite ages of key dyke swarms in the Amazonian Craton (Carajás/Rio Maria and Rio Apa areas): Tectonic implications for events at 1880, 1110 Ma, 535 Ma and 200 Ma. *Precambrian Research* 329, 138–155. <https://doi.org/10.1016/j.precamres.2018.02.008>
- Teixeira, W., Oliveira, E.P., Marques, L.S., 2017. Nature and Evolution of the Archean Crust of the São Francisco Craton, in: *São Francisco Craton, Eastern Brazil*. Springer, pp. 29–56. https://doi.org/10.1007/978-3-319-01715-0_3
- Teixeira, W., Tassinari, C.C.G., Cordani, U.G., Kawashita, K., 1989. A review of the geochronology of the Amazonian Craton: Tectonic implications. *Precambrian Research* 42, 213–227. [https://doi.org/10.1016/0301-9268\(89\)90012-0](https://doi.org/10.1016/0301-9268(89)90012-0)
- Thiede, D.S., Vasconcelos, P.M., 2010. Paraná flood basalts: Rapid extrusion hypothesis confirmed by new $^{40}\text{Ar}/^{39}\text{Ar}$ results. *Geology* 38, 747–750. <https://doi.org/10.1130/G30919.1>
- Thompson, R.N., Gibson, S.A., 1991. Subcontinental mantle plumes, hotspots and pre-existing thinspots. *Journal of the Geological Society* 148, 973–977. <https://doi.org/10.1144/gsjgs.148.6.0973>
- Thompson, R.N.N., Gibson, S.A.A., Mitghell, J.G., Dickin, A.P.P., Leonardos, O.H., Brod, J.A., Greenwood, J.G., Mitchell, J.G., Dickin, A.P.P., Leonardos, O.H., Brod, J.A., Greenwood, J.G., 1998. Migrating Cretaceous-Eocene magmatism in the Serra do Mar Alkaline Province, SE Brazil: melts from the deflected Trindade mantle plume? *Journal of Petrology* 39, 1493–1526. <https://doi.org/10.1093/petroj/39.8.1493>
- Tozer, B., Watts, A.B., Daly, M.C., 2017. Crustal structure, gravity anomalies, and subsidence history of the Parnaíba cratonic basin, Northeast Brazil. *Journal of Geophysical Research: Solid Earth* 122, 5591–5621. <https://doi.org/10.1002/2017JB014348>
- Turner, S., Regelous, M., Kelley, S., Hawkesworth, C., Mantovani, M., 1994. Magmatism and continental break-up in the South Atlantic: high precision $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. *Earth and Planetary Science Letters* 121, 333–348. [https://doi.org/10.1016/0012-821X\(94\)90076-0](https://doi.org/10.1016/0012-821X(94)90076-0)
- Ultiana, M.A., Welsink, H.J., Ramos, V.A., Turic, M., Milani, A.B.F.E.J., de Brito Neves, B.B., Eyles, N., Skarmeta, J., Santa Ana, H., 1995. Structural and tectonic controls of basin evolution in southwestern Gondwana during the Phanerozoic.
- Van Der Hilst, R.D., Mann, W.P., Mann, P., 1994. Tectonic implications of tomographic images of subducted lithosphere beneath northwestern South America. *Geology* 22, 451–454. [https://doi.org/10.1130/0091-7613\(1994\)022<0451](https://doi.org/10.1130/0091-7613(1994)022<0451)
- van der Lee, S., James, D., Silver, P., 2001. Upper mantle S velocity structure of central and western South America 106, 30821–30834.
- van der Lee, S., Nolet, G., 1997. Upper mantle S velocity structure of North America. *Journal of Geophysical Research: Solid Earth* 102, 22815–22838. <https://doi.org/10.1029/97JB01168>

- Van Der Lee, S., Wiens, D.A., 2006. Seismological Constraints on Earth's Deep Water Cycle. *Earth's Deep Water Cycle* 168, 13–28.
- Van der Meijde, M., Julià, J., Assumpção, M., 2013. Gravity derived Moho for South America. *Tectonophysics* 609, 456–467. <https://doi.org/10.1016/j.tecto.2013.03.023>
- Vandecar, J.C., James, D.E., Assumpção, M., 1995. Seismic Evidence for a Fossil Mantle Plume beneath South-America and Implications for Plate Driving Forces. *Nature* 378, 25–31. <https://doi.org/10.1038/378025a0>
- Vargas, C., 2019. Subduction geometries in northwestern South America.
- Vargas, C.A., Mann, P., 2013. Tearing and breaking off of subducted slabs as the result of collision of the panama arc-indenter with Northwestern South America. *Bulletin of the Seismological Society of America* 103, 2025–2046. <https://doi.org/10.1785/0120120328>
- Vargas, C.A., Pujades, L.G., Montes, L., 2007. Seismic structure of South-Central Andes of Colombia by tomographic inversion. *GeofInt* 46, 117–127. <https://doi.org/10.22201/igeof.00167169p.2007.46.2.21>
- Vasquez, M.L., Rosa-Costa, L.T., 2008. Geologia e Recursos Minerais do Pará. Belém.
- Vdovin, O., Rial, J.A., Levshin, A.L., Ritzwoller, M.H., 1999. Group-velocity tomography of South America and the surrounding oceans. *Geophysical Journal International* 136, 324–340. <https://doi.org/10.1046/j.1365-246X.1999.00727.x>
- Wagner, L.S., Jaramillo, J.S., Ramírez-Hoyos, L.F., Monsalve, G., Cardona, A., Becker, T.W., 2017. Transient slab flattening beneath Colombia. *Geophysical Research Letters* 44, 6616–6623. <https://doi.org/10.1002/2017GL073981>
- Wang, H., Currie, C.A., 2023. Stepwise Widening of the Central Andes—The Role of the Lower Crust. *Geophysical Research Letters* 50, e2023GL103969. <https://doi.org/10.1029/2023GL103969>
- Wang, L.H., van Hunen, J., Pearson, D.G., 2015. The thinning of subcontinental lithosphere: The roles of plume impact and metasomatic weakening. *Geochemistry Geophysics Geosystems* 16, 1156–1171. <https://doi.org/10.1002/2015GC005784>
- Wang, Z., Dahlen, F.A., 1995. Spherical-spline parameterization of three-dimensional Earth models. *Geophysical Research Letters* 22, 3099–3102.
- Ward, K.M., Zandt, G., Beck, S.L., Wagner, L.S., Tavera, H., 2016. Lithospheric structure beneath the northern Central Andean Plateau from the joint inversion of ambient noise and earthquake-generated surface waves. *Journal of Geophysical Research: Solid Earth* 121, 8217–8238. <https://doi.org/10.1002/2016JB013237>
- Wells, R., Bukry, D., Friedman, R., Pyle, D., Duncan, R., Haeussler, P., Wooden, J., 2014. Geologic history of Siletzia, a large igneous province in the Oregon and Washington Coast Range: Correlation to the geomagnetic polarity time scale and implications for a long-lived Yellowstone hotspot. *Geosphere* 10, 692–719. <https://doi.org/10.1130/GES01018.1>
- Whalen, L., Gazel, E., Vidito, C., Puffer, J., Bizimis, M., Henika, W., Caddick, M.J., 2015. Supercontinental inheritance and its influence on supercontinental breakup: The Central Atlantic Magmatic Province and the breakup of Pangea. *Geochemistry, Geophysics, Geosystems* 16, 3532–3554. <https://doi.org/10.1002/2015GC005885>
- Whitman, D., Isacks, B.L., Kay, S.M., 1996. Lithospheric structure and along-strike segmentation of the Central Andean Plateau: seismic Q, magmatism, flexure, topography and tectonics. *Tectonophysics* 259, 29–40. [https://doi.org/10.1016/0040-1951\(95\)00130-1](https://doi.org/10.1016/0040-1951(95)00130-1)
- Whittaker, J.M., Afonso, J.C., Masterton, S., Müller, R.D., Wessel, P., Williams, S.E., Seton, M., 2015. Long-term interaction between mid-ocean ridges and mantle plumes. *Nature Geoscience* 8, 1–6. <https://doi.org/10.1038/NGEO2437>

- Will, T.M., Frimmel, H.E., 2018. Where does a continent prefer to break up? Some lessons from the South Atlantic margins. *Gondwana Research* 53, 9–19. <https://doi.org/10.1016/j.gr.2017.04.014>
- Wilson, M., 1997a. Thermal evolution of the Central Atlantic passive margins: continental break-up above a Mesozoic super-plume. *Journal of the Geological Society* 154, 491–495.
- Wilson, M., 1997b. Thermal evolution of the Central Atlantic passive margins: continental break-up above a Mesozoic super-plume. *JGS* 154, 491–495. <https://doi.org/10.1144/gsjgs.154.3.0491>
- Woodhouse, John H., Dziewonski, A.M., 1984. Mapping the upper mantle: Three-dimensional modeling of earth structure by inversion of seismic waveforms. *J. Geophys. Res.* 89, 5953–5986. <https://doi.org/10.1029/JB089iB07p05953>
- Woodhouse, J. H., Dziewonski, A.M., 1984. Mapping the upper mantle: three-dimensional modeling of Earth structure by inversion of seismic waveforms. *Journal of Geophysical Research* 89, 5953–5986. <https://doi.org/10.1029/JB089iB07p05953>
- Woolley, A.R., 1987. Alkaline rocks and carbonatites of the world. Geological Society of London.
- Yáñez, G., Cembrano, J., Pardo, M., Ranero, C., Selles, D., 2002. The Challenger–Juan Fernández–Maipo major tectonic transition of the Nazca–Andean subduction system at 33–34°S: geodynamic evidence and implications. *Journal of South American Earth Sciences, Flat-Slab Subduction in the Andes* 15, 23–38. [https://doi.org/10.1016/S0895-9811\(02\)00004-4](https://doi.org/10.1016/S0895-9811(02)00004-4)
- Yarce, J., Monsalve, G., Becker, T.W., Cardona, A., Poveda, E., Alvira, D., Ordoñez-Carmona, O., 2014. Seismological observations in Northwestern South America: Evidence for two subduction segments, contrasting crustal thicknesses and upper mantle flow. *Tectonophysics* 637, 57–67. <https://doi.org/10.1016/j.tecto.2014.09.006>
- Zalán, P.V., Wolff, S., Conceição, J.C. de J., Marques, A., Astolfi, M.A.M., Vieira, I.S., Appi, V.T., Zanotto, O.A., 1990. Bacia do Paraná. Origem e evolução das bacias sedimentares 135–168.
- Zarifi, Z., Havskov, J., Hanyga, A., 2007. An insight into the Bucaramanga nest. *Tectonophysics* 443, 93–105. <https://doi.org/10.1016/j.tecto.2007.06.004>
- Zhang, Haitao, Yan, Q., Li, C., Shi, X., Yang, Y., Wang, G., Hua, Q., Zhu, Z., Zhang, Hui, Zhao, R., 2021. Tracing material contributions from Saint Helena plume to the South Mid-Atlantic ridge system. *Earth and Planetary Science Letters* 572, 117130. <https://doi.org/10.1016/j.epsl.2021.117130>
- Zhang, Y., Tanimoto, T., 1993. High-resolution global upper mantle structure and plate tectonics. *Journal of Geophysical Research: Solid Earth* 98, 9793–9823.
- Zhao, D., 2001. Seismic structure and origin of hotspots and mantle plumes. *Earth and Planetary Science Letters* 192, 251–265. [https://doi.org/10.1016/S0012-821X\(01\)00465-4](https://doi.org/10.1016/S0012-821X(01)00465-4)
- Zheng, J., Griffin, W.L., O'Reilly, S.Y., Zhang, M., Pearson, N., Pan, Y., 2006. Widespread Archean basement beneath the Yangtze craton. *Geology* 34, 417–420. <https://doi.org/10.1130/G22282.1>
- Zhu, F., Li, J., Liu, J., Lai, X., Chen, B., Meng, Y., 2019. Kinetic Control on the Depth Distribution of Superdeep Diamonds. *Geophysical Research Letters* 46, 1984–1992. <https://doi.org/10.1029/2018GL080740>
- Zielhuis, A., Nolet, G., 1994. Shear-wave velocity variations in the upper mantle beneath central Europe. *Geophysical Journal International* 117, 695–715. <https://doi.org/10.1111/j.1365-246X.1994.tb02463.x>
- Zolinger, I.T., 2005. As Intrusões de Afinidade Kimberlítica E1 e Es1 da Região Colorado do Oeste, Rondônia. Universidade de São Paulo.

