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COMPUTATIONAL GEODYNAMICS OF THE SOUTH AMERICAN PLATE: CONTRIBUTIONS AND PERSPECTIVES

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ABSTRACT. Computational geodynamics is a key tool in Earth Sciences, enabling the simulation of different geodynamic processes at any time scale in Nature or those which cannot be adequately reproduced by analogue modelling in laboratorial conditions. Specifically, the coupling of surface processes of erosion and sedimentation with the internal dynamics of the lithosphere is a complex problem that involves the solution of a set of differential equations that are only adequately solved by numerical models. During the last three decades, different numerical models were developed to explain the importance of the coupling between the surface and internal dynamics of the Earth, both in active margins and in stable tectonic domains, showing how the coupling leads to counter-intuitive results not observed when each process is analyzed separately. One example of this complex coupling is the feedback mechanism between erosion of the landscape and the regional isostatic response of the lithosphere. In this work, we present simple isostatic and flexural elements that highlight the importance of surface processes on the stress and strain pattern in lithospheric plates. Initially, we present a review on the development of computational geodynamics at University of São Paulo. This review is followed by an analysis of the density structure of the Earth and how the high-density contrast at the Earth's surface creates a major impact on the isostatic equilibrium of the lithosphere when variations on topographic loads are taken into account. Additionally, we show that the wavelength of the denudation of the Earth's surface due to fluvial dynamics corresponds to the characteristic length scale for flexural bending of the lithosphere, maximizing the flexural stresses in the lithosphere. Finally, we present recent works on the coupling between surface and lithospheric processes and future challenges for the development of computational geodynamics, with possible strategies to solve them.

Keywords: numerical models, lithospheric geodynamics, surface processes

INTRODUCTION

Relative to other terms in Geosciences, like "Seismology" and "Geophysics", the word "Geodynamics" is much more recent. This can be attested by the frequency in which this term appears in English literature over the last two centuries, using the Google search tool Ngram Viewer (`https://books.google.com/ngrams`). While the term "Seismology" has been present in English literature since the end of the 19th century, "Geophysics" since the beginning of the 20th century, and the names of some geophysical methods appear during and after the Second World War, the term "Geodynamics" was consolidated in the scientific literature only in the 1960s and 1970s (Figure 1).

In spite of its frequent use in the last decades, a formal definition for "Geodynamics" is not easily found in the academic literature. One of the most used textbooks on the subject, *Geodynamics* (Turcotte and Schubert, 2002), does not present a clear definition of Geodynamics. Only in more recent texts this term is defined:

> *"Geodynamics is the application of the basic principles of physics, chemistry and mathematics to understanding how the internal activity of the Earth results in all the geological phenomena and structures apparent at the surface, including seafloor spreading and continental drift, mountain building, volcanoes, earthquakes, sedimentary basins, faulting, folding, and more. Geodynamics also deals with how the Earth's internal activity and structure reveals itself externally in ways both geophysical, its gravitational and magnetic fields, and geochemical, the mineralogy of its rocks and the isotopic composition of its rocks, atmosphere, and ocean."* (Foreword from Gerald Schubert in Ismail-Zadeh and Tackley, 2010)

From this definition, there are several elements that relate the term Geodynamics to Plate Tectonics. In fact, the two terms are clearly correlated on the timeline, showing that the frequency in which the two terms appear in English literature increased concomitantly between the 1960s and 1970s (Figure 2). While the Theory of Plate Tectonics emerged to present **how** the outermost layers of the Earth, the lithospheric plates, move and interact over geological time scale, Geodynamics had the initial objective of explain **why**, from a physical point of view, the Solid Earth processes occur.

Important advances in the understanding of the solid state physics of the Earth's mantle (Gordon, 1965; McKenzie, 1967) were fundamental to reconcile the elastic behavior of the Earth's interior on the human time scale and the viscous behavior dictated by the Maxwell relaxation time (of the order of thousands of years for the upper mantle), providing the basis for the study of the convective geodynamics of the mantle. Due to the mathematical complexity of the problems related to mantle convection, the use of numerical solutions became a natural step towards the advancement of Geodynamics, giving rise to Computational Geodynamics in the early 1970s (Minear and Toksöz, 1970; Torrance and Turcotte, 1971).

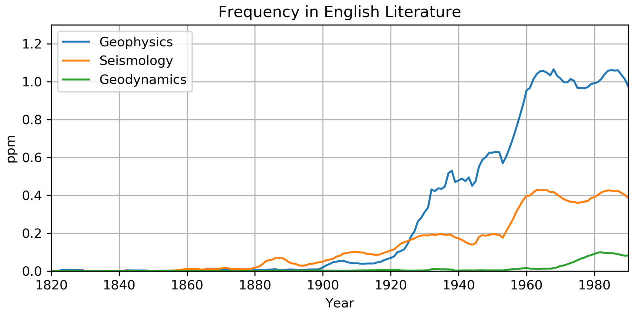

Figure 1: Frequency of the words "Geophysics", "Seismology", and "Geodynamics" in English literature between 1820 and 1990. The frequency is indicated in parts-per-million. Data obtained from the online tool Google Ngram Viewer.

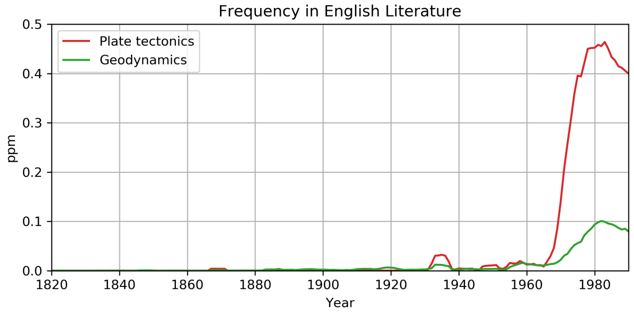

Figure 2: Frequency of the terms "Plate tectonics" and "Geodynamics" in English literature between 1820 and 1990. The frequency is indicated in parts-per-million. Data obtained from the online tool Google Ngram Viewer.

Through Computational Geodynamics it is possible to represent part of the geometric and rheological complexity of the Earth in order to adequately reproduce the behavior of the internal dynamics of the planet, something that is, in most cases, unfeasible through analytical solutions. Similarly, analogue modelling have limitations that, in many cases, prevent the reproduction in the laboratory of the same geodynamic phenomena associated with the evolution of the planet. The use of computational models in Geodynamics makes it possible to verify whether conceptual geological models are valid from a physical point of view, not only for the current terrestrial tectonic regime, but also to probe the geodynamic past of the planet before Plate Tectonics (e.g. Moore and Webb, 2013; Korenaga, 2013) as well as a comparison with tectonism on other planets (e.g. Moresi and Solomatov, 1998; Lenardic et al., 2008).

The development of Computational Geodynamics is sustained on four pillars:

- **Physics:** Through Physics it is possible to identify the constitutive equations that govern some geological phenomenon of interest. In the case of mantle convection, research on fluid dynamics during the 19th and 20th centuries provided the basis for understanding the strength of convection cells in the Earth's mantle in geologic time. Additionally, the theory behind the study of elastic foundations provided the mathematical basis to represent the flexural behavior of the lithosphere over the asthenospheric mantle. Furthermore, the detailed understanding of permanent lithospheric deformation involved the study of non-linear rheological behavior in materials under different stress and temperature conditions.

- **Numerical calculus:** The choice of the mathematical method to obtain the numerical solution of specific differential equations is a crucial step in Computational Geodynamics. The intrinsic particularities of each geodynamic problem can often make it difficult to adapt codes from other areas of science, requiring computational models specially designed for geodynamic problems.

- **Programming:** The degree of difficulty in transcribing numerical solutions into a programming language depends not only on the complexity of the numerical method and/or the original differential equations, but also on the computational tools available. Languages such as Python and Matlab allow algebraic manipulations and solutions of large systems of equations to be easily implemented and solved internally. Similarly, tools like *Portable, Extensible Toolkit for Scientific Computation* (PETSc) for C and Fortran allow the construction of sophisticated numerical codes efficiently, with a high level of abstraction. Other numerical tools (e.g. Libmesh and deal.II) allow the construction of adaptative meshes or unstructured meshes, suitable to better discretize regions of localized deformation, like in non-linear flow or plastic deformation in the crust and lithospheric mantle.

- **Geological and geophysical constraints:** Information from geophysical and geological methods are fundamental observational constraints to reduce the number of solutions of the numerical models. Geophysical methods provide a view of the physical structure (e.g. depth of the lithosphere) and properties (e.g. density and seismic velocity) of the Earth's interior in the **present** (from the surface to the center of the planet). On the other hand, Geology probes the Earth's remote past through samples collected **near the surface of the planet** (Figure 3) and provides information, for example, about their composition, age, and thermobarometric history.

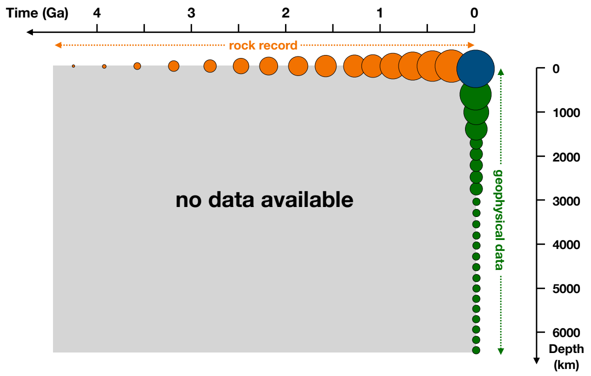

Figure 3: Representation of the different dimensions explored by geophysical and geological methods. The region indicated by "no data available" indicates the geological past of the interior of the planet Earth, where numerical models play a key role in the understanding of the geological evolution of the planet. Modified from Gerya (2014).

In this work we summarize the development of computational geodynamics at *Universidade de São Paulo* (USP), focused exclusively on the link between the evolution of the Earth's surface with the geodynamic evolution of the crust and upper mantle based on the plate tectonics regime. Certainly, computational geodynamics covers many other fields in Geosciences, such as comparative planetology, core-mantle interactions, Archean geodynamics etc., but here we are restricted to modern plate tectonics and the interaction of surface processes with the lithosphere and part of the sublithospheric mantle. Initially, we present a historical overview of the research on computational geodynamics at USP, from the first flexural models of the lithosphere based on elastic rheology to thermomechanical models with non-linear rheology, including the coupling with surface processes of erosion and sedimentation.

DEVELOPMENT OF NUMERICAL GEODYNAMICS AT USP

The onset of geodynamic numerical modelling at IAG/USP can be traced back to the work of Ussami et al. (1999), where a two-dimensional finite difference code was used to study the flexural and isostatic behaviour of the South American lithospheric plate under the load of the Andean Cordillera and associated foreland sedimentary basins, presenting a mechanical explanation for the development of the Pantanal Basin. In this geodynamic problem, the load of the Andean Cordillera induced a downward deflection of the western portion of the South American plate, resulting in the bending of the plate. This bending is called flexure and the wavelength of the lithospheric deflection gives an important constraint about the rigidity of the lithosphere (Figure 4): the larger the lithospheric rigidity, the longer the wavelength of the flexural deflection. The equation numerically solved in this problem was the thin elastic plate approach, representing the flexural behaviour of the lithosphere over a fluid with negligible viscosity, representing the asthenosphere (Watts, 2001). Similarly, Ussami and Molina (1999) modeled the flexural deflection of the lithosphere along the neoproterozoic Araguaia belt, central Brazil, obtaining an estimate for the lithospheric flexural rigidity for this segment of the plate. Also, gravity data was used to constrain the border of the Amazon plate under the São Francisco Craton, suggesting a major suture along the Araguaia belt.

The numerical solution of the thin elastic plate equation was later explored in three dimensions (two horizontal dimensions plus the vertical displacement of the plate), with the development of a finite element code in an irregular triangular mesh (Sacek and Ussami, 2009), aiming to evaluate how the variations of the topographic load of the Andean Cordillera along the orogen impacted the deflection of the lithosphere at different latitudes, considering the variation in flexural rigidity of the plate and the three-dimensional shape of the cordillera. The development of this numerical model opened the opportunity to integrate different geodynamic processes in the same numerical code, such as thermal conduction and advection in the crust and mantle and surface processes of erosion and sedimentation, resulting in the first model to simulate both onshore and offshore parts of rifted margins in an internally consistent manner (Sacek et al., 2012), taking into account the rift and post-rift phases. This work showed how the rifting phase affected the drainage pattern in the continental hinterland, controlling the denudation history of the margin and the influx of sediments to the marginal sedimentary basins.

The application of this coupled numerical model expanded to other geodynamic problems in the following years. Combining surface processes, Andean orogeny and isostatic flexure of the lithosphere, Sacek (2014) presented a mechanical explanation for the development of the Amazon drainage system, connecting the Andes with the equatorial margin, as a consequence of the development of the Andean Cordillera and the asymmetric influx of sediments in the interior of the continent, predicting the sedimentation rate through time in the interior and marginal sedimentary basins. This model was later improved to incorporate the influence of dynamic topography due to the Nazca plate subduction under the South American plate, evaluating the presence of aquatic environments in western Amazonia, also controlling the evolution of habitats and the Amazonian ecosystem (Bicudo et al., 2019, 2020). Additionally, this software was applied to study the denudation history of the Borborema Province, in northeastern Brazil, aiming to understand the exhumation history since the opening of the Atlantic Ocean, probably representing the first coupled geodynamic code to take into account weathering processes in the surface processes model to control the variation of rocks erodibility in space and time (Sacek et al., 2019).

Along with the coupled numerical models of surface processes and the flexural-isostatic response of the lithosphere, other geodynamic models were used or developed at USP, considering other rheological behavior besides the elastic component, exploring in detail how the stress field varies in depth. Using the CitcomCU numerical code (Moresi and Gurnis, 1996; Zhong, 2006) to simulate convection in the upper mantle, Sacek and Ussami (2013) showed how the curvature of the continental lithosphere can affect the contribution of edge-driven convection in the asthenosphere and the lateral thermal conduction along divergent continental margins, showing how these two effects probably affected the subsidence pattern along the Santos Basin in southeastern Brazil. The first model developed at USP that explored non-linear rheologies was the finite element visco-elastic model presented by Assumpção and Sacek (2013), showing how variations in the crustal thickness in the interior of Central Brazil can produce flexural stresses in the lithosphere with amplified effects close to the Earth's surface, explaining the observed seismicity in the upper crust.

In parallel, finite element thermomechanical numerical models were developed to simulate the viscous flow in the asthenosphere and the interaction with the base of the continental lithosphere, quantifying how edge-driven convection affected the evolution of escarpments along divergent continental margins (Sacek, 2017). This research showed that the continuous action of asthenospheric flow under the edge of the continental lithosphere can contribute to erode part of the lithospheric keel, inducing uplift of the continental margin of the order of hundreds of meters during the post-rift phase, possibly explaining the variation of post-rift exhumation rate predicted from thermochronological data along the South Atlantic divergent margins (Gallagher and Brown, 1999a,b).

In the following years, this thermomechanical code was improved, using the *Portable, Extensible Toolkit for Scientific Computation* (PETSc) (Balay et al., 1997, 2021a,b), allowing the code to be fully parallelized using the Message Passing Interface (MPI), and the present version of the code can simulate different rheological behaviour, including Newtonian flow, non-linear viscous flow or visco-plastic deformation (Sacek et al., 2022). This code,

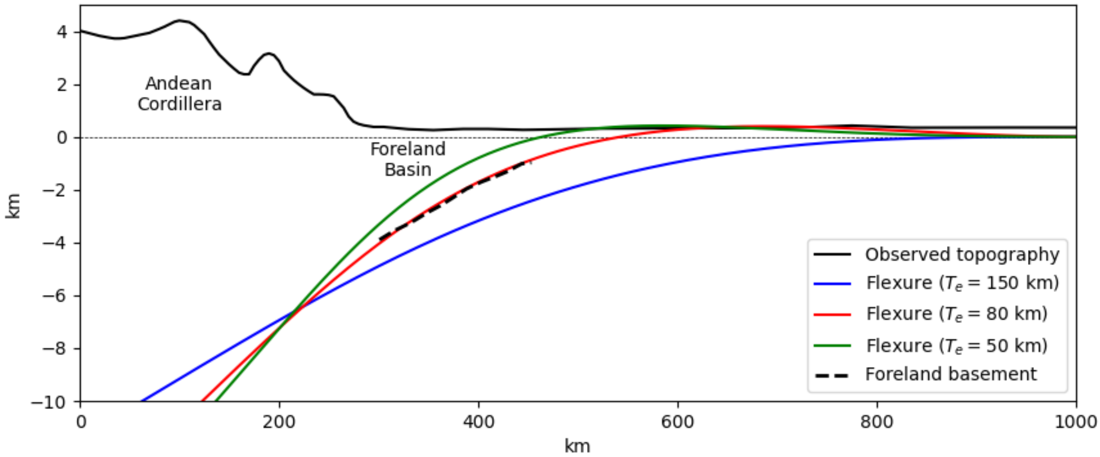

Figure 4: Example of the application of the thin elastic plate model to simulate the flexural behaviour of the lithospheric plate under the load of the Andean Cordillera (black curve). The green, red and blue curves indicate the flexural deflection of the lithospheric plate due to the topographic load of the cordillera for plates with different effective elastic thickness T_e: 50, 80, and 150 km, respectively. The greater the effective elastic thickness, the greater the rigidity. The dashed curve indicates the depth of the foreland basin. The best fit between the flexural models and the observed geometry of the foreland basin is obtained when $T_e \approx 80$ km. For $T_e = 50$ km the wavelength of the adjacent depression is shorter than the observed foreland basin. On the other hand, for $T_e = 150$ the wavelength of the flexural deflection is larger than the observed one.

named Mandyoc, is freely available on Github platform (`https://github.com/ggciag/mandyoc/`) and incorporates free surface, necessary to reproduce the topographic evolution during the numerical simulation. The Mandyoc code was applied to explore complex geodynamic problems that combines the mechanical behaviour of the continental lithosphere and the interaction with surface processes of erosion and sedimentation during and after continental rifting. Based on numerical scenarios with different degrees of coupling between the crust and lithospheric mantle, Silva and Sacek (2022) explored how the differential denudation of the continent along rifted margins affects the stress state of the lithosphere (Figure 5). With these simulations, Silva and Sacek (2022) explored a possible mechanism to explain the evolution of the Serra do Mar and Serra da Mantiqueira escarpments, showing how the denudation along the continental margin induced flexural stresses in the continental crust that contributed to the development of the Continental Rift of Southeastern Brazil (Riccomini, 1989).

THE RELEVANCE OF THE INTEGRATION OF LITHOSPHERIC AND SURFACE PROCESSES IN COUPLED GEODYNAMIC MODELS

The formation of the main features of the Earth's surface can be explained by the internal dynamics of the planet, as a result of the present plate tectonics regime. On the other hand, the direct influence of surface processes in the internal dynamics of the planet is not easily identified from the physical point of view, usually assumed as secondary influence on the internal evolution of the planet. In fact, the redistribution of topographic load due to surface processes of erosion and sedimentation plays an insignificant direct impact on mantle convection (Braun, 2010): the rate of erosion or sedimentation on planet Earth (< 1 cm/year) is too slow to induce feedback on mantle convection velocity in the upper mantle.

However, many numerical experiments that combine surface and lithospheric process show that the internal stress and strain rate pattern in the crust and lithospheric mantle are sensitive to the cumulative influence of surface processes of erosion and sedimentation, specially along active plate boundaries, such as during the development of mountain belts (e.g. Willett, 1999; Beaumont et al., 2004; Chen et al., 2013; Wolf et al., 2022) or divergent continental margins (e.g. Sacek et al., 2012; Andrés-Martínez et al., 2019; Beucher and Huismans, 2020; Silva and Sacek, 2022). This is counter-intuitive because the amplitude of the topographic features observed on the continents (mainly smaller than 2 km) is nearly two orders of magnitude smaller than the thickness of the continental lithosphere (100-200 km). Therefore, how can we explain the relevance of surface processes on the internal stress field of the continental lithosphere, as highlighted by previous numerical models? Based on simple isostatic and flexural analysis, here we will explain why the surface processes have a flexural influence over the lithosphere equivalent to or even greater than the influence induced by mantle dynamics.

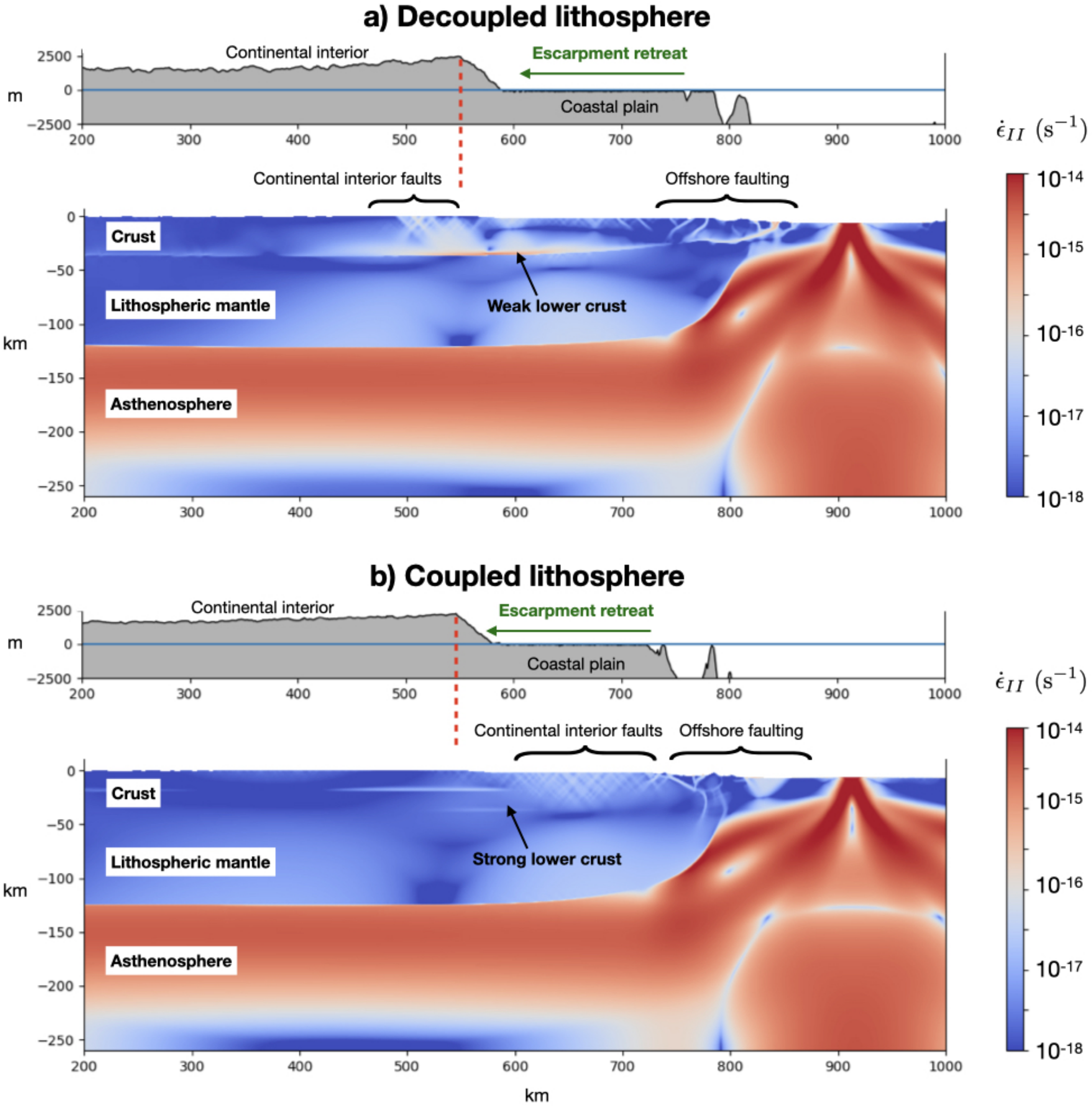

Figure 5: Comparison between two numerical scenarios for the formation and evolution of rifted margins with continental lithospheres with different rheological structure. (a) Decoupled lithosphere, where the lower crust is relatively weak and the upper crust is partially decoupled of the lithospheric mantle. (b) Coupled lithosphere, where the lower crust is rigid and the stresses can be efficiently transmitted between the crust and lithospheric mantle. The color scale indicates the strain rate pattern. Model results from Silva and Sacek (2022).

The first aspect to be analysed is the density structure of the crust and mantle. The free surface represents the largest density contrast interface on planet Earth above the core-mantle boundary (Figure 6): from ∼2700 kg/m^3 of the crust to nearly 1 kg/m^3 of the atmospheric air. In comparison, the density contrast between crust and mantle at the Moho is 400-500 kg/m^3, while the density contrasts in the mantle due to phase transitions are smaller than 400 kg/m^3. Additionally, the convection vigor in the upper mantle is guided by temperature differences of the order of $\Delta T = 100°\text{C}$ (e.g. Petersen et al., 2010), which is equivalent to a density variation $\Delta\rho = \rho_0 \Delta T \alpha$ of nearly 10 kg/m^3, assuming the reference density for the mantle $\rho_0 = 3200$ kg/m^3 and the thermal expansion coefficient $\alpha = 3.28 \times 10^{-5}$ 1/K. Based on these density contrasts, the change of 1 km in crustal thickness due to surface processes is isostatically equivalent to displace the Moho by nearly 6 km or change the mantle temperature by 100°C in a layer 270 km thick. Therefore, any variation in crustal thickness due to erosion has a profound impact on the isostatic equilibrium of the lithosphere, affecting the stress and strain rate of the crust and lithospheric mantle, justifying the incorporation of surface processes on geodynamic models of the lithosphere.

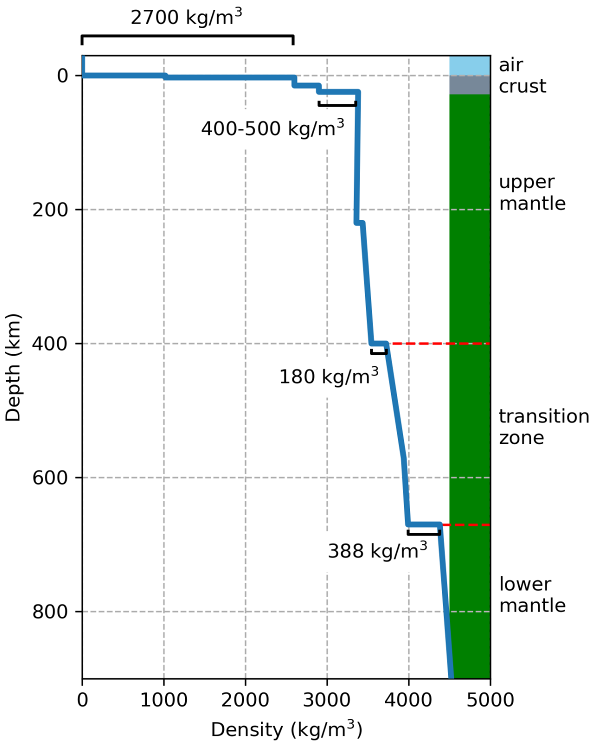

Figure 6: Density profile from the Preliminary Reference Earth Model (PREM, Dziewonski and Anderson, 1981). The density contrasts along the crust-air and mantle-crust interfaces are indicated as 2700 kg/m^3 and 400-500 kg/m^3, respectively. Additionally, the main density contrasts due to phase transitions in the mantle are also indicated.

Furthermore, a second component of our analysis is the wavelength of topographic loads over the lithosphere. The non-uniform denudation pattern observed on the continents mainly due to fluvial dynamics induces the differential erosion of the crust, resulting in abrupt lateral variations of topographic unloading of the lithosphere, which causes flexural stresses that can easily surpass differential stresses induced by long-wavelength stress pattern, like stresses induced by mantle convection under the lithosphere and consequent dynamic topography (Silva and Sacek, 2019). This can be verified by the calculation of the flexural response function ϕ_e of the lithosphere for different flexural rigidities D (Watts, 2001):

$$\phi_e(\lambda) = \left[\frac{D\left(\frac{2\pi}{\lambda}\right)^4}{(\rho_m - \rho_i)g} + 1 \right]^{-1} \tag{1}$$

where λ is the wavelength of the load applied on the lithosphere, ρ_m is the density of the asthenospheric mantle, ρ_i is the density of the medium filling the surface depression (e.g. air, water or sediments). The flexural rigidity D of the lithosphere is given by

$$D = \frac{ET_e^3}{12(1-\nu^2)} \tag{2}$$

where E is the Young's modulus, T_e is the effective elastic thickness of the lithosphere, and ν is the Poisson's ratio.

The flexural response function ϕ_e is a non-dimensional function ranging from 0 to 1. For $\phi_e \to 0$, the wavelength of the vertical load applied over the lithosphere is small enough to be supported exclusively by the flexural rigidity of the lithosphere, and this scenario is called Bouguer response of the lithosphere. For $\phi_e \to 1$, the vertical loads over the lithosphere are compensated exclusively by the buoyancy forces exerted by the asthenosphere under the lithospheric plate, with the wavelength of the vertical load much larger than the characteristic length scale of the flexural response of the lithosphere, and this scenario is called Airy response of the lithosphere. Both end members, the Bouguer and Airy responses, induce small flexural stresses in the lithosphere, with inexpressive internal deformation in the crust and lithospheric mantle.

Flexural stresses are amplified when we have intermediate values for the flexural response function ($0 < \phi_e < 1$). In these cases, the vertical loads are partially supported by the flexural rigidity of the lithosphere and partially by the asthenospheric buoyancy forces. The range of wavelength λ in which the flexural stresses are amplified depends on the flexural rigidity of the lithosphere D, function of the effective elastic thickness T_e. For the continental lithosphere, cratonic domains are mainly represented by T_e values above 50 km (Watts and Burov, 2003). On the other hand, mobile belts and active tectonic domains are mainly characterized by $T_e < 30$ km (e.g. Hartley et al., 1996). For these relatively low T_e values, the curvature of the plate due to flexural behavior is amplified when λ is of the order of 10s to 100s km (Figure 7). These range of λ is compatible with the dimensions of drainage basins with Cenozoic exhumation of the order of hundreds of meters to a few kilometers (e.g. Gallagher et al., 1994). As a comparison, dynamic topography induced by mantle convection under the lithospheric plate presents a wavelength of the order of thousands of kilometers (Braun, 2010). Therefore, in domains with relatively low flexural rigidity ($T_e < 30$ km), the characteristic behavior of the lithosphere is better described by the Airy response, where the lithosphere is vertically displaced with low internal deformation.

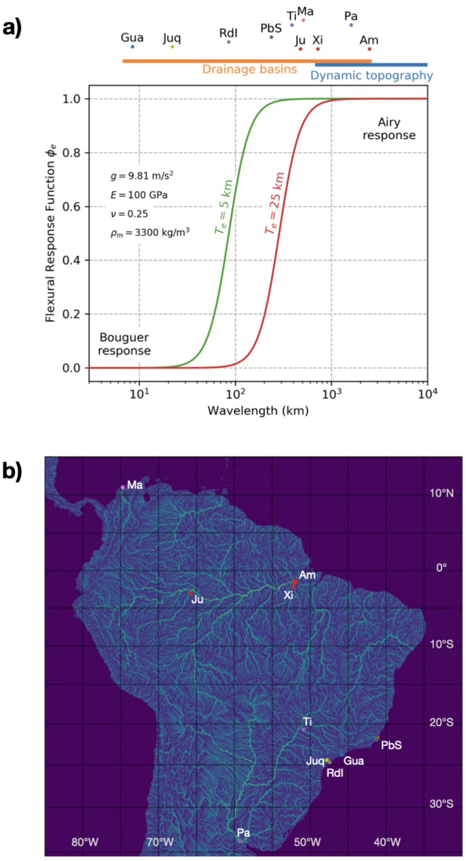

Figure 7: a) Flexural response function ϕ_e for two effective elastic thickness values T_e as a function of the wavelength of the vertical loads applied over the lithosphere. Am = Amazon River and its tributaries: Xi = Xingu and Ju = Juruá; Pa = Paraná River and its tributary Ti = Tietê; PbS = Paraíba do Sul River; Ma = Magdalena River; RdI = Ribeira do Iguape River; Juq = Juquiá River; Gua = Guaratuba River. The wavelength of the large rivers ($\lambda > 100$ km) was estimated by the square root of the drainage area. For small drainage basins ($\lambda < 100$ km) the wavelength was estimated by the distance from the main drainage divide to the Atlantic coast. b) Map indicating the drainage pattern in South America and the location of the river mouth of the respective drainage basin.

Therefore, the combination of large density contrast at the Earth's surface and the characteristic wavelength of erosive exhumation of the crust are key components to understand the relevance of surface processes on the stress pattern observed mainly in the continental lithosphere. The impact of fluvial dynamics on exhumation can affect the lithospheric stress pattern not only in regions with active tectonism, but also in stable continental regions in the long term. Therefore, it is important to improve data coverage on thermochronology and cosmogenic nuclides in regions far from active tectonic domains to better understand erosion rates in continent interiors and their response to changes in rock type and climate variability.

Furthermore, the determination of the timing of fault reactivation and neotectonic activity in the interior of the South American continent is of significant importance for understanding the underlying mechanisms driving tectonic activity. This information can shed light to quantify the relative importance of the feedback mechanisms that exist between surface processes of erosion and sedimentation and the lithospheric stress field, providing insights into the tectonic evolution of the continent, including the formation and deformation of its geological structures and the drivers of uplift and subsidence in different spatial and temporal scales.

COUPLED GEODYNAMIC NUMERICAL MODELS: PAST, PRESENT AND FUTURE PERSPECTIVES

Based on simple isostatic and flexural analyses, in the previous section we highlighted the importance of surface processes on the geodynamic evolution of the lithosphere. Therefore, the incorporation of surface processes is a key ingredient to appropriately simulate the stress and strain rate pattern in the crust and lithospheric mantle through the geological time scale.

In the last five years, different coupled thermomechanical and surface processes models developed by different research groups showed how complex is the feedback mechanism between surface processes and the internal dynamics of the lithosphere along rifted continental margins (e.g. Andrés-Martínez et al., 2019; Silva and Sacek, 2019; Beucher and Huismans, 2020; Pérez-Gussinyé et al., 2020; Silva and Sacek, 2022), affecting the thermal structure of the stretched lithosphere, the creation and preservation of escarpments along the margin, and the onshore/offshore post-rift tectonism. In comparison, the application of these kind of coupled models along convergent margins has a history of application of more than two decades (e.g. Willett, 1999; Beaumont et al., 2004; Wolf et al., 2022), showing how the precipitation pattern and the consequent exhumation of the orogen control the geodynamic evolution of the convergent margin. However, little attention is given to the long-term impact of surface processes in regions of relative tectonic quiescence, far from plate borders. In part, the lack of attention on this problem derives from the monotonous evolution of this kind of tectonic scenario in terms of strain rate magnitude and the timing consuming simulation of the order of 10s to 100s Myr, instead of just a few Myr usually adopted in models applied on active margins. On the other hand, the interplay between surface processes and lithospheric geodynamics on a continental scale can profoundly affect load redistribution and sedimentation rates along continental margins through drainage capture and regional reconfiguration of drainage basins.

The integration of surface processes and the thermomechanical evolution of the lithosphere is an active research topic, and important advances have been made in recent years. One important development was the creation of the *free surface stabilization algorithm* (Kaus et al., 2010), allowing the simulation of thermomechanical models with time steps of thousands of years. Before this algorithm, the stable time steps for models with free surface were of just a few hundreds of years, making the simulation on geological time scale prohibitive. Additionally, efficient surface processes algorithms (Braun and Willett, 2013; Yuan et al., 2019) allowed the simulation of surface processes on regional to continental scale with spatial resolution of just a few kilometers.

The coupling of the thermomechanical and surface processes is challenging because the mesh resolution is usually different and incorrect interpolation techniques can create artefacts on the numerical representation of the landscape. The use of adaptive meshes (Braun and Sambridge, 1997) is a good strategy to overcome this problem but is rarely used, probably due to its implementation complexity. Another challenge for numerical coupled models is the full integration of 3D thermomechanical models with 2D surface processes models. A common approach in recent coupled models is the coupling of 2D thermomechanical models in a vertical section combined with 2D surface processes model in plan view, known as "T models" (e.g. Wolf et al., 2022). This approach is convenient specially when the tectonic evolution of the lithosphere can be adequately represented by two-dimensional geometry. Recent numerical models successfully combined the 3D thermomechanical evolution with surface process models in scenarios with complex three-dimensional geometry (e.g. Koptev et al., 2022).

ONGOING RESEARCH PROJECTS ON COMPUTATIONAL GEODYNAMICS AT USP

The research group on computational geodynamics at USP is working on different lines of geodynamic problems that combine the interaction of surface and lithospheric problems. Here we present some of the research lines developed by the group:

- Influence of rifted margins on the dynamics of collisional orogens over time: this project aims to numerically simulate the formation of orogens from previous rifted continental margins considering a variable initial thermal structure, according to Earth's geological age, to evaluate the role of the upper mantle thermal structure and the geometry of rifted margins on the formation and evolution of Phanerozoic and Neoproterozoic orogens.

- Asthenospheric flow around cratonic keels and its impact on the stress field in the lithospheric mantle and crust: the movement of the continental lithosphere relative to the base of the upper mantle induces stresses at the base of the lithospheric mantle that can be transmitted to the upper crust depending on the degree of coupling between the crust and mantle, affecting the continental stress state in the geological time scale.

- Subduction of aseismic ridges in oceanic plates and the interaction with the continental upper plate: The buoyancy variability of the oceanic lithosphere due to changes in temperature structure and crustal thickness can have an important impact on the angle of subduction, eventually affecting the isostatic and flexural state of the adjacent continental lithosphere. One important example is the development of the Fitzcarrald Arch in western Amazonia due to the subduction of the Nazca Plate under the western margin of South America.

- Fluvial incisions on the Earth's surface and their impact on the flexural stresses in the interior of the continental lithosphere: The local exhumation of rocks due to fluvial erosion can induce flexural stresses in the lithosphere (Silva and Sacek, 2022), inducing bending of the crust and consequently reshaping the landscape. As a natural example, the numerical scenarios explored in this work will be applied to the Vaza-Barris drainage basin in northeastern Brazil, where the flanks of the fluvial valley present an upward deflection probably induced as a flexural response of the crust.

- Fluvial impact of development of arches on the evolution of the Amazon Drainage Basin: the low slope observed in the drainage basin of the Amazon River, connecting the Andean Cordillera with the Equatorial Atlantic margin, is sensitive to the influence of the internal dynamics of the Earth, specially induced by the subduction of the Nazca Plate. Besides the dynamic topography (Bicudo et al., 2019, 2020), the local uplift of the Fitzcarrald and Vaupés Arches shaped the drainage pattern in western Amazonia during the last millions of years, affecting the evolution of the internal and marginal sedimentary basins.

CONCLUSION

In this work we analysed the isostatic and flexural effects of surface processes on the stress field of the lithosphere. We conclude that the characteristic wavelength of denudation along the drainage basins of the order of 10s to 100s of kilometers combined with the high-density contrast between the crust and the atmospheric air can induce flexural stresses in the lithosphere that cannot be reproduced by long-wavelength perturbations induced by dynamic topography, for example. Based on an analysis of the flexural response function for different effective elastic thickness (T_e) values for the lithosphere, we conclude that the flexural stresses induced by localized denudation along drainage basins are especially important for low T_e values ($T_e < 30$ km), corresponding to the effective elastic thickness of mobile belts and active tectonic domains.

These conclusions reinforce the importance of the coupling of surface and lithospheric processes in numerical models to appropriately understand the geodynamic evolution of the lithosphere under different tectonic regimes. Different models were developed in the last years integrating lithospheric and surface processes, resulting in counter-intuitive scenarios that could not be predicted when the geodynamic model neglected the interaction with the surface dynamics, mainly along active continental margins. However, less attention was paid on the geodynamic evolution of continental lithosphere on periods of relative tectonic quiescence, where the long-term influence of surface processes is underestimated. Therefore, a vast range of coupled numerical scenarios can be explored in the future to understand the geodynamic evolution of the lithosphere in domains far from plate boundaries.

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