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Heat flow and lithospheric thickness analysis in the Patagonian asthenospheric windows, southern South America

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ABSTRACT

The lithosphere–asthenosphere boundary (LAB) is a first-order discontinuity, essential to understand the Earth composition and evolution. However, its detection has been critical and several regions still lack of coverage. Southern Patagonia, in southern most South America, is one such area, which has been affected by the subduction of a seismic oceanic ridge (South Chile Ridge) and formation of an extensive slab window since ~12 Ma. We calculate the LAB position by defining the thermal lithospheric thickness of the southernmost Patagonia using the thermal conductivity equation to estimate the surface heat flow. We used data from seventy-five hydrocarbon wells of two from the most productive petroleum basins in Argentina: the Golfo de San Jorge and Magallanes-Austral basins. Our results show the highest heat flow values in the southernmost region, over the Austral basin and core of the slab window (~70–90 mW/m^2). These values are twice as hot as global average. To the north, over de Golfo de San Jorge basin and northern margin of the slab window, heat flows are "normal" (~50–60 mW/m^2). These thermal contrasts, from south to north, agree with the kinematic reconstructions of the Chile ridge and northward widening of the slab window. These heat flows values evidence an attenuated lithospheres, which thickens eastward from between 25 km (to the west, trench region) to 50 km (to the east, foreland region).

1. Introduction

The lithosphere is the upper rigid mechanical boundary layer of the Earth's surface that moves mechanically coherently with plate motions due to its stronger rheology, and high viscosity (Artemieva, 2009; Priestley and McKenzie, 2013; Steinberger and Becker, 2016). It is underlain by a weak asthenosphere, characterized by pervasive plastic deformation on time scales of tens of thousands of years. The lithosphere–asthenosphere boundary (LAB) is a first-order tectonic discontinuity, critical in understanding the geodynamic and geochemical evolution of Earth. However, its detection, physical state, and controlling mechanisms are still controversial. This is because the LAB can be defined by a multiplicity of geophysical and geochemical parameters and methods (e.g., seismic tomography, gravity, bottom borehole temperature, etc.). In addition, this information is not available in many regions (e.g., our study area, see below).

The LAB depth, which can be characterized by the thickness of the lithosphere, is conditioned (among others) by thermal and compositional effects (see Artemieva, 2009), which change with depth. Four "types" of lithosphere have been widely used for different geophysical studies: the elastic, thermal, electrical, and seismic (Artemieva, 2009). Independently of its definition, most works agree the LAB is strongly temperature-dependent and is represented by the isotherm of ~1300 °C (McKenzie, 1967). The lithosphere thicknesses and LAB location are based on global, regional and local approaches as well as diverse and contrasting methodologies. Among them, seismic tomography (e.g., Bird et al., 2008; Conrad and Lithgow-Bertelloni, 2006; Pasyanos et al., 2014; Priestley and McKenzie, 2013; Steinberger and Becker, 2016) receiver function (e.g., Rychert et al., 2010) and borehole heat flow studies (Artemieva, 2006; Davies, 2013; Hamza and Vieira, 2012; Tassara and Echaurren, 2012). Particularly, the heat flow approaches have demonstrated to be accurate and widely used (Artemieva and Mooney, 2001; Hamza and Vieira, 2012).

Southernmost South America, particularly southern Patagonia, lacks of reliable LAB models. This region (see Fig. 1), however, is an interesting place to study not only because of the lack of geophysical surveys and LAB data but also because it is an attractive geodynamic setting. Southern Patagonia has been affected by the subduction of a seismic ridge (the South Chile spreading Ridge, Fig. 1), which began to affect the southwestern most margin of South America at ~14 Ma. From this event, thermal anomalies and consequent changes in the LAB depth could be expected. The subduction of seismic ridges leads to the

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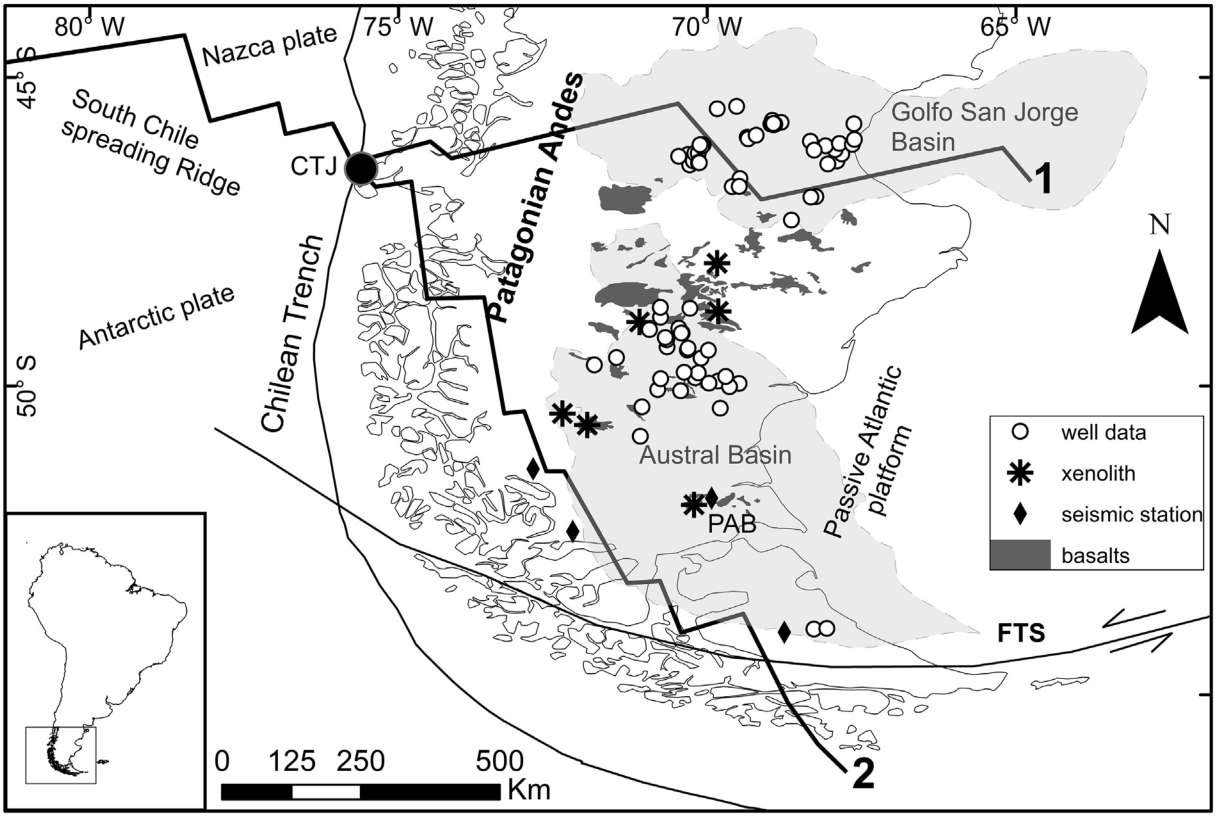

Fig. 1. Map showing the main tectonic features of Southern Patagonia. White dots show the location of our well data. Austral and Golfo de San Jorge basins are in light grey. The location of the xenolith are shown as asterisks (Bjerg et al., 2005; Stern, 1989; Stern et al., 1990; Zaffarana et al., 2014); cenozoic basalts of the Patagonian plateau lavas are shown in dark grey (Boutonnet et al., 2010; Espinoza et al., 2010; Gorring et al., 1997, 2003) seismic stations location are shown as diamonds (Robertson Maurice et al., 2003). CTJ: Chile Triple Junction. 1 and 2 are the northern and southern margins of the slab window, (taken form Breitsprecher and Thorkelson, 2009). FTS: Fagnano transform system. PAB: Pali Aike basalt.

formation of asthenospheric or slab windows (Groome and Thorkelson, 2009; Thorkelson, 1996), where hot buoyant asthenospheric mantle rises up the isotherm of ~1300 °C. Therefore, the LAB in these regions should be shallower than in areas unaffected by heat anomalies.

Most of the global LAB depth databases show information in southern Patagonia derived by extrapolating records collected hundreds to thousands of kilometers away (Bird et al., 2008; Conrad and Lithgow-Bertelloni, 2006; Pasyanos et al., 2014; Priestley and McKenzie, 2013; Steinberger and Becker, 2016). These global data, over the slab window region, show remarkable differences of locally > 50 km between them (Artemieva and Mooney, 2001; Conrad and Lithgow-Bertelloni, 2006; Pasyanos et al., 2014; Priestley and McKenzie, 2013; Rychert et al., 2010). This is not only due to the different geophysical methods used but also because of the lack of data in the region. Although some of these studies have been useful for analyzing the LAB at global scales (long wavelengths), regional approaches (to analyze shorter wavelength topographic features or basins, for example) require of better LAB depth resolution.

The regional and local lithosphere thickness databases are also very scarce. Robertson Maurice et al. (2003) used seismic waveform inversion to estimate the depths of the LAB. This study reported low seismic velocities at relatively shallow depths (60 km) in southeast Patagonia (located to hundreds of kilometers away from the trench, see location in Fig. 1), evidencing a "thin" lithosphere. These authors also interpreted crustal thicknesses between 26 and 34 km, which agree with other global databases (CRUST 1.0 and LITHOS 1.0). On the base of thermobarometry on xenoliths, different studies have calculated geothermal gradients between 10 and 14 °C/km. While the lowest gradients (Zaffarana et al., 2014) would reach the ~1300 °C at 100 km depth, suggesting (in contrast to the seismic studies) an "average" lithosphere, the highest values (*c.* 13.8 °C/km, cf. Bjerg et al., 2005) would generate the same temperature at ~60 km depth. In summary, everything indicates not only a lack of lithosphere thickness data in southern Patagonia but also that the few reported data (global, regional and local) show great differences between them.

In order to contribute to the understanding of the geodynamic evolution in South America and improvement of the LAB global databases, in this work we calculate the lithospheric thickness of southern Patagonia using heat flow estimations from 75 hydrocarbon well data. These wells come from two of the most productive petroleum basins of South America, the Golfo de San Jorge and Magallanes-Austral basins (Fitzgerald et al., 1990; Hechem and Strelkov, 2002; Sylwan, 2001). Our results are interpolated with other scattered heat flow data supplied from other sources to enlarge the covered area by boreholes. With this information, we expect to reconstruct the thermal structure and lithospheric thicknesses in southern Patagonia, as well as their spatial variations likely associated with the Chile seismic ridge and slab window dynamics. On the base of the seismic ridge and slab window reconstructions, we will also analyze the influences of the thermal time factor on heat-controlled geodynamic processes.

2. Geological and tectonic setting

The study region is located in the southernmost Patagonia, between 45° and 50° S, ranging from the southern Patagonian Andes, to the west, to the extra-Andean foreland (also known as the Patagonian plateau) and passive Atlantic platform, to the east (Fig. 1). Patagonia, including our study region, has been interpreted as a Paleozoic exotic terrane that collided with Gondwana in the Early–Middle Permian (Ramos, 2008). Since then, four major tectonic stages occurred (Ghiglione, 2016): (1)

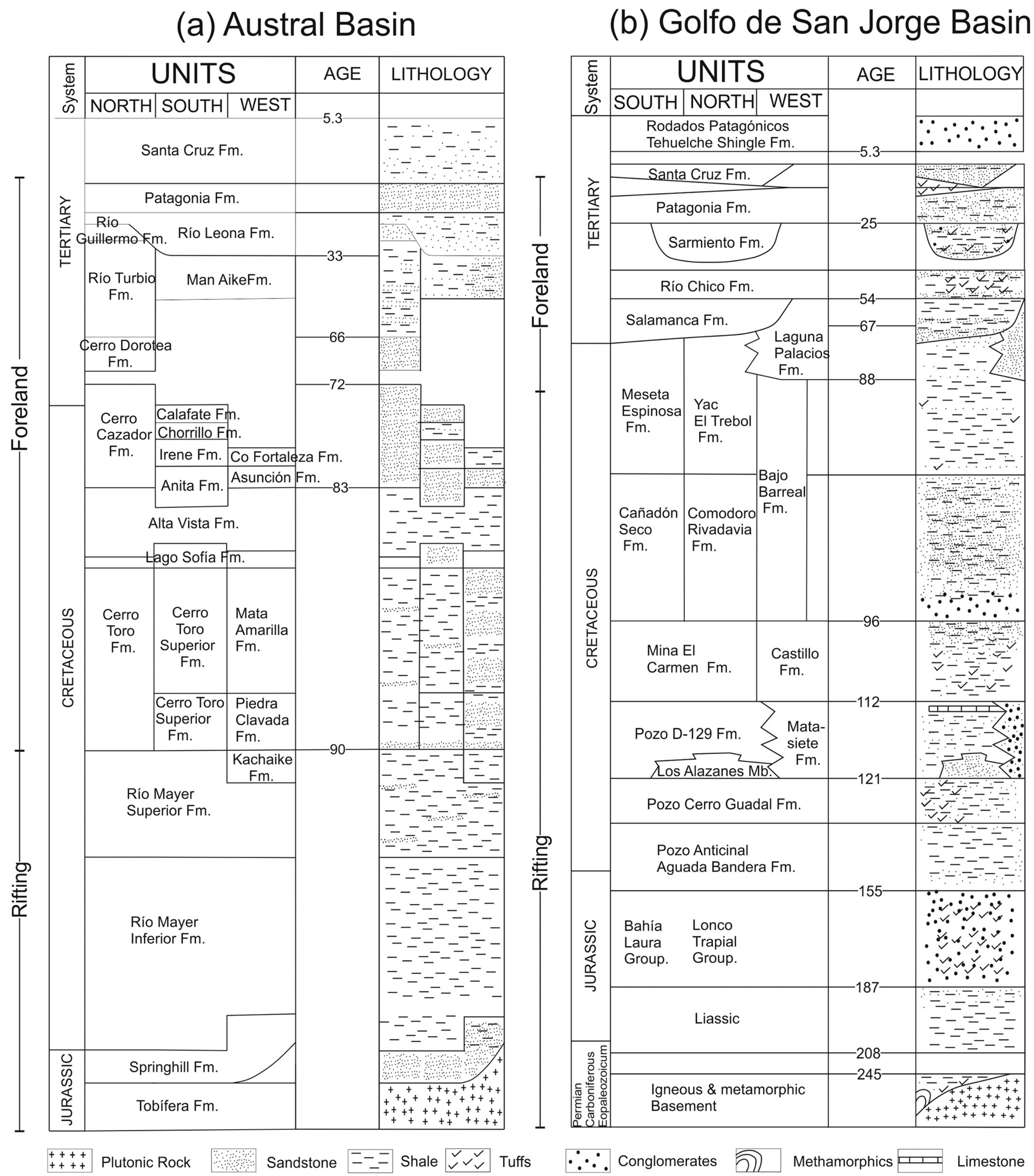

Fig. 2. Stratigraphic chart showing sedimentary units, ages and lithology of the (a) Austral and (After Fitzgerald et al., 1990; Hechem and Strelkov, 2002). (b) Golfo de San Jorge basins (After Sylwan, 2001).

Jurassic crustal extension and rhyolitic magmatism, followed by (2) rifting associated with the opening of the South Atlantic in the Cretaceous, the (3) formation and uplift of the Southern Andes in the Paleogene to middle Miocene and finally the (4) development of an asthenospheric windows since late Miocene to Present day. The first three events developed sedimentary basins related with the breakup of Gondwana (rift basins, Uliana et al., 1989) and shortening along the Patagonian Cordillera (Ghiglione et al., 2010). The last stage has been responsible for the extrusion of extensive plateau basalts (Gorring et al., 2003) and regional foreland uplift (dynamic uplift, Dávila et al., 2018 and reference therein). The latter stage is likely related with sedimentation along the platform and abyssal basins (Dávila et al., 2018).

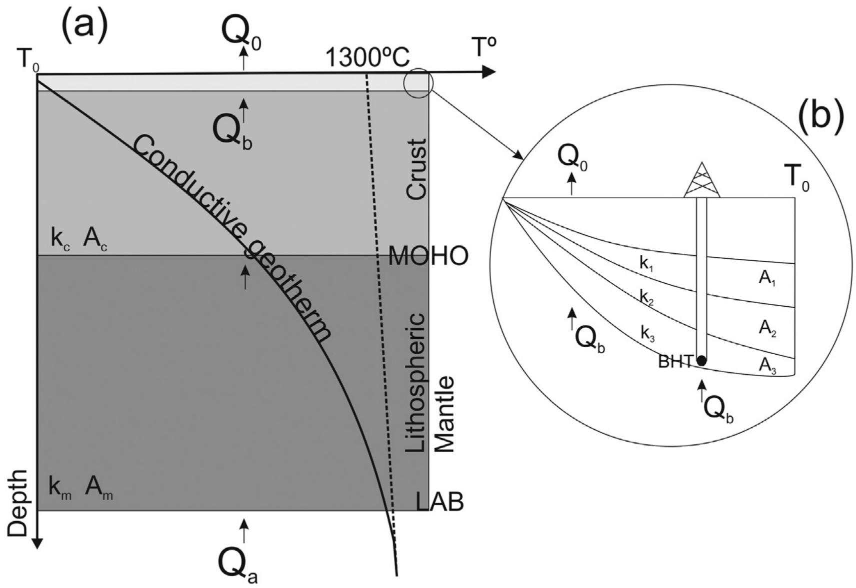

Fig. 3. Thermal structure and parameters to estimate lithospheric thickness. (a) Notice that the LAB is the intersection between the theoretical conductive geotherm (solid line) and mantle adiabat (dashed line) at 1300 °C. K_c and K_m are thermal conductivity and Ac and Am are radiogenic heat productions for the crust and mantle respectively (After Artemieva, 2011). Q_a, Q_b, and Q_0 are asthenospheric, basal, and surface heat flows, respectively. T0 is surface temperature (see methodology). The circle shows the location of the basin depicted in (b). (b) Thermal parameters to estimate surface heat flow (Q_0) in a sedimentary basin using Petromod (see methodology). K1–3 are thermal conductivities for different sedimentary layers; A1–3 are the radiogenic heat productions for the same layers. BHT: bottom hole temperature.

The Austral (or Magallanes) and Golfo de San Jorge basins record most of this history (see Fig. 2). Both depocenters are over a thousand meters thick and comprise different stratigraphic units, which are shown and correlated in Fig. 2, and are the main stratigraphic source for our studies (see methodology below).

The last stage of asthenospheric window formation in southern Patagonia is particularly important for our analysis given that it is largely considered a major heat flow driving mechanism (McCrory et al., 2009) and major control for the LAB position. It has been associated with the collision of the South Chile Ridge, an active oceanic spreading center, with the South American continent (Gorring et al., 2003). At the plate margin, this setting conducted to the formation of the Chile Triple Junction (CTJ), located since ~4 Ma at Present-day at 46°S (Breitsprecher and Thorkelson, 2009).

However, the CTJ would have migrated almost 1000 km northward, from 54°S latitude, since 16 Ma (Middle Miocene), as ridge segments subparallel to the trench collided with the subduction margin (Breitsprecher and Thorkelson, 2009). The CTJ along the Chilean margin is characterized by a large negative Bouguer anomaly (Murdie et al., 2000), negative velocity anomalies in both surface- and body-wave travel-time tomography models (Russo et al., 2010). In this context, toward the Patagonian foreland, extensive plateau basalts developed from 12 Ma to modern days (e.g. Boutonnet et al., 2010; Espinoza et al., 2010; Gorring et al., 1997, 2003) These basalts cover most of southern Patagonia, on gently eastward-sloping erosional surface from the easternmost Southern Patagonian Andean thrust front (Lagabrielle et al., 2004) to the Atlantic domains. These record a geochemical signature with variable OIB (oceanic island basalt)-like character that has been related to the input of hot asthenospheric mantle underlying the subducting slab below the continental lithosphere of the South American Plate. However, beyond the basalt studies, there is sparse additional evidence to justify the presence and development of an asthenospheric window across the Patagonian foreland. Here we present new heat flow data and lithospheric thickness estimations along the Magallanes and Golfo de San Jorge basins (see Fig. 1), covering areas from the foreland to the Atlantic margin, which will allow contributing to the understanding of the Patagonian slab window evolution from a different data source.

3. Methods

Variations on Earth surface heat flow can be interpreted in terms of the thermal structure of the lithosphere (Artemieva, 2011). In stable areas of continents, where no tectonic activity has been experienced for several million years (like the Siberian Platform and Canadian shield, among others), the thermal structure has been approximated by the steady state solution of the thermal conductivity equation (see Artemieva and Mooney, 2001). In contrast, in tectonically young and active regions, the lithosphere is characterized by transient thermal regimes (Artemieva, 2011). How "thermally stable" the lithosphere is (steady or transient states), depends on the characteristic time of thermal equilibration that defines the time delay for a thermal front associated with a thermal perturbation at depth z to reach the surface and become reflected in the surface heat flow (Turcotte and Schubert, 2002). Groome and Thorkelson (2009), studied the thermal and mechanical effects of ridge subduction and slab window migration, suggesting that a near-surface steady state is generated after ~10 Myr. On the other hand, based on kinematic reconstructions. Breitsprecher and Thorkelson (2009) showed that the slab windows were below the Austral (or Magallanes) basin since ~12 Ma. If the latter is the case, southernmost Patagonia could be in (or near) a thermal steady state, which allows us to simplify our computations to calculate the lithospheric thickness using the thermal conductivity equation.

The thermal conductivity equation is given by:

$$\frac{d^2T}{dz^2} = \frac{A(z)}{k(T)} \tag{1}$$

with boundary conditions at surface:

$$T|_{z=0} = T_0 \tag{2}$$

$$Q_0 = -k\frac{dT}{dz} \tag{3}$$

where Q_0 is the near surface heat flow, T_0 is surface temperature, T is temperature a function of depth, k is thermal conductivity, and $A = A(z)$ is the heat production as a function of depth. The solution of Eq. (1) allows determining the distribution of temperature with depths (Fig. 3). The 1300 °C isotherm corresponds to the LAB depth. These calculations require to define: (a) the surface heat flow and (b) the distribution of thermal parameters (thermal conductivity and heat production) within the crust and lithospheric mantle (Fig. 3, see details below).

3.1. Surface heat flow

The sedimentary basins preserve valuable information on the spatial and temporal variations of heat flow. Under steady state conditions, the surface heat flux is composed of the heat flow at the base of the lithosphere and the radiogenic heat production of the lithospheric mantle and crust (Fig. 3). Any change of these conditions might conduct to transient states (disequilibrium). In a sedimentary basin, processes as diverse as sedimentation and/or erosion, surface temperature variations, groundwater circulation, hydrothermal fluids, igneous activity and tectonic activity can also produce these changes. Basins with faster sediment accumulation results in lower geothermal gradients (blanketing effect) and heat flow values decreasing toward the surface by diffusion and advection (Hantschel and Kauerauf, 2009). In contrast, increasing erosion rates might contribute to rise the geothermal gradients. After the sedimentation or erosional processes end, the thermal state starts gradually to return to equilibrium (characteristic time).

We use PetroMod, basin modelling software package, to calculate the surface heat flow as a function of depth in 75 hydrocarbon wells from the Golfo de San Jorge and Magallanes-Austral basins (see Figs. 1 and 2), which reached > 1000 and up to 5000 m below the surface. Those wells shorter than 1000 m were disregarded to avoid heat flow data potentially affected by surficial process like water circulation. The software needs a) two boundary conditions, b) rock types and c) ages of the wells stratigraphy (Fig. 2b). The upper thermal boundary corresponds to the average surface temperature through time, compiled by PetroMod from literature (see Hantschel and Kauerauf, 2009). The lower thermal boundary is the basal heat flow of the basin (generated at lithospheric scales), constrained in our model by the bottom hole temperature (BHT) data. Given that the BHT at the time of drilling is 10–20 °C lower than pre-drilling BHT (Beardsmore and Cull, 2001), we corrected drilling temperatures using the Harrison et al. (1983) approximation. The Harrison correction is a second order polynomial function. It is based on empirically adjusting that provide a correction factor that can be added to the BHT from a geophysical log header to yield an estimated equilibrium temperature. Although other methods allow better corrections, like the Horner method (Horner, 1951), they requires data not presented in the well log headers.

The rock types (from log headers, simplified in Fig. 2) provide the heat flow model with the radiogenic heat contribution and the thermal conductivity for each stratigraphic unit. The unit ages allow estimating the sedimentation rates and magnitudes of the erosional episodes (blanketing effect).

Other factors like fluid migration and volcanism are not considered in our model. Firstly, no hydrothermal activity has been described in borehole reports or surface geology. Second, although magmatic activity might alter the rock maturation and paleo-thermal history of the basins (Hantschel and Kauerauf, 2009), the igneous intrusions in Patagonia are > 10^5 yr old. Peace et al. (2017b) shown that after approximately 15,000 yr the thermal perturbation by magmatism are indistinguishable from the background geothermal gradient.

3.2. Lithospheric thermal parameters

We solve Eq. (1) (see above) for a continental lithosphere, considering vertical variations in thermal conductivity and radiogenic heat production with depth. This model considered three layers: upper and lower crust and lithospheric mantle. The crustal thicknesses was taken from CRUST 1.0 (Laske et al., 2013), which shows remarkable correlations with values estimated from available regional and local seismic studies in Patagonia (Alcacer et al., 2017; Chulick et al., 2013). We used the upper crust thickness model from Chulick et al. (2013), which presents the seismic structure of South America and the seismic velocity of the uppermost mantle (Pn and Sn).

In the upper continental crust, the conductivity of most rocks decreases when the temperature increases (e.g., Wang et al., 2010). We followed for this upper layer the Cermak and Rybach (1982) model:

$$k(T) = \frac{k_0}{(1 + cT)} \tag{4}$$

where k_0 is the thermal conductivity at 0 °C and near-surface pressure conditions and c is a material constant (in the range 0 to 0.003 °C^{-1}). In the present study c, was assumed to be 0.001 °C^{-1} and k_0 2.5 (Artemieva and Mooney, 2001). We consider the thermal conductivities of the lower crust as well as lithospheric mantle as constant (Artemieva and Mooney, 2001).

Another important factor in our modelling is the depth distribution of the radioactive heat production within the lithosphere. We assume that the heat production decreases exponentially with depth (Turcotte and Schubert, 2002), following

$$A(z) = A_0 e^{\frac{-z}{h_r}} \tag{5}$$

where A_0 is the surface (y = 0) radiogenic heat production rate per unit mass, and hr is a length scale for the decrease in A with depth. At depth $y = hr$, A is 1/e of its surface value and h_r = 10 km. We used a radiogenic heat productions for the lithospheric mantle and lower crust of 0.02 and 0.4 μW/m^3, respectively (cf. Hasterok and Chapman, 2011). From the lower crust to the asthenospheric mantle, these values were considered constant in depth as the exponential decreasing model used for the upper crust (see Eq. (5)) may underestimate the heat production in the two lowers layers (see Artemieva and Mooney, 2001).

4. Results

The changes of heat flow with depth in the San Jorge and Austral basins (see Fig. 1) show variations of < 10^{-4} mWm/m^2, suggesting that the sedimentation-erosion thermal effects would not have affected the modern surface heat flows. This supports the hypothesis that the major thermal changes are driven by large-scale variations and, particularly, by changes in the lithospheric thicknesses (e.g., Peace et al., 2017a).

Figs. 4 and 5 synthesize the heat flow data and lithospheric thicknesses of southern Patagonia calculated in this work. The averaged heat flow data plotted on a grid of 1° × 1° (Fig. 4) (see Supplementary Material: Surface heat flow database) allow us to recognize two contrasting heat flow zones: 1) The Patagonian foreland and 2) surrounding the CTJ area (Fig. 4). While in the foreland region the highest values are approximately 88 mW/m^2 in the Austral basin, to the south and within the core of the asthenospheric window, the lowest values are 51 mW/m^2 in the Golfo de San Jorge basin to the north, in the northern margin of the window. The values reported in the Austral basin are anomalously high respect to the global continental average (Artemieva, 2011). The highest heat flow data are between the CTJ zone, with values exceeding 400 mW/m^2.

We calculated lithospheric thicknesses between 35 and 50 km for the thermally-equilibrated Patagonian foreland region (Austral basin) (see Figs. 1 and 5). These values resulted (see Eq. (1)) from considering (see Fig. 5a) heat flows between ~90 and ~70 mW/m^2, mean upper and lower crustal thicknesses of 10 and 20 km, respectively and a LAB temperature of 1300 °C. This indicates Patagonia lithosphere is thin with respect to the average or “normal” lithospheric thickness of ~100 km (Artemieva, 2009).

Using the same method described above (see also Fig. 5a) and available heat flow values from southern Patagonia (Fig. 4a), we calculated and interpolated areal lithospheric thicknesses in a 1° × 1° equal area grid for the Austral basin (Fig. 5b). This map shows thicknesses of ~25 km near the trench, suggesting not only an extremely shallow LAB but also the lack of a lithospheric mantle. This attenuated lithosphere extends toward ~200 km from the trench into the Chilean forearc region (Fig. 5b). From here and toward the foreland, the lithosphere becomes gradually thicker, with values up to ~50 km, evidencing a clear eastward lithospheric thickness thickening.

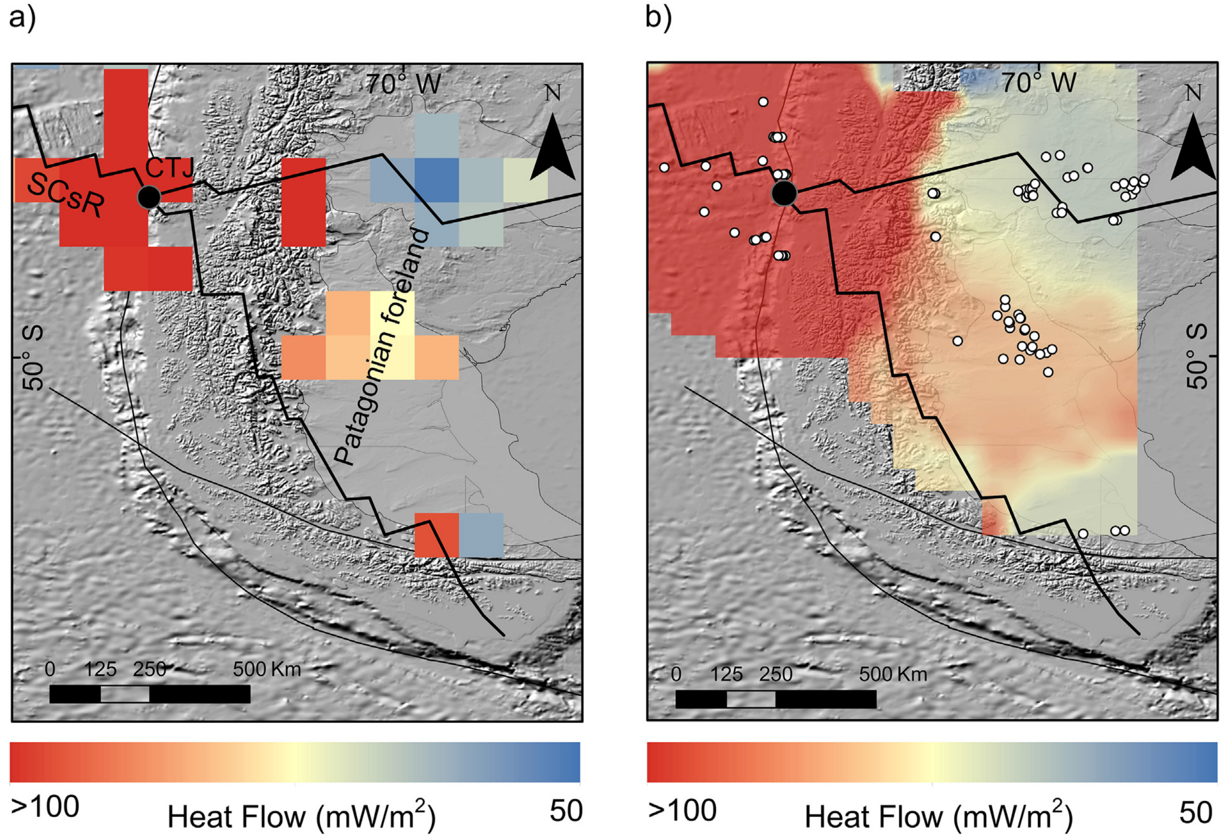

Fig. 4. Surface heat flow map of southern Patagonia in mW/m^2. (a) Mean areal heat flow in 1° × 1° equal area grids from global databases (black dots) and our calculations (no dots). (b) Interpolated heat flow data on an equal area grid of 1° × 1° using IDW interpolation. White dots show the location of our well data. SCsR: South Chile seismic Ridge; CTJ: Chile Triple Junction.

5. Discussion

In this contribution we provide regional distribution of heat flow data in southern Patagonia. Our values are spatially coincident with the location of the Nazca–Antarctica slab window beneath the southernmost South America (Fig. 4), suggesting a causative relationship. The heat flows, in turn, are twice as hot as global average values, supporting the development of an attenuated lithosphere (Figs. 4 and 5). Thermal conditions in areas affected by slab windows are generally high (Thorkelson, 1996) because of mantle upwelling (e.g., Johnston and Thorkelson, 1997) and absence of subducting slabs, which refrigerate the mantle (Curie and Hyndman, 2006). Together with kinematic plate reconstructions (Breitsprecher and Thorkelson, 2009) and basalt geochemical signatures (Gorring et al., 1997), our data validate the episodic northward widening of the slab window from the late Miocene to present proposed by several authors (Gorring et al., 1997; Lagabrielle et al., 2004).

As mentioned previously, the highest heat flow values are on the South Chile spreading ridge, showing super-elevated thermal conditions up to 400 mW/m^2 (Fig. 4). The trench and forearc zones, in the nearby regions along the boundary between the Antarctic and South American plates, report also high values (Fig. 3b), likely associated with the northward shifting of the oceanic ridge. To the north of the CTJ, along the Chilean oceanic trench and forearc, values are an order the magnitude lower, between 40 and 70 mW/m^2; evidencing a cool and refrigerated belt (Curie and Hyndman, 2006). In contrast, toward the southern Patagonian foreland, the heat flow data reduce significantly from west to east and, more importantly, from south to north (Fig. 4). While the eastward reduction might be related to the depth of the heat source, shallower to the trench (Murdie and Russo, 1999), the northward cooling could be related with the opening direction of the slab window. Fig. 6 shows a map overlapping the kinematics of the slab windows from 14 Ma to present (Breitsprecher and Thorkelson, 2009) and the modern heat flows reported in this work (Fig. 4). The northward decreasing of heat flow is consistent with the northward widening of the asthenospheric window in southern Patagonia. The relatively low heat flows in the north of the slab window (Golfo San Jorge basin), where we should expect higher values, are likely evidencing a disequilibrated or transient state. The kinematic reconstructions show the asthenospheric window would have reached the Golfo de San Jorge basin approximately at 2 Ma (Fig. 6). Under these conditions, a transitional thermal state would be expected to the north. Consequently, the heat flows from the northern areas of the asthenospheric windows might be responding to an ancient geodynamic stage (thermal memory > 15 my), when the region was dominated by normal thermal conditions generated by a "normal" subduction like further north (~50 mW/m^2, Fig. 4).

It is important to notice that, in our analysis, even considering high radiogenic heat productions and end-member thermal conductivities (most sensitive parameters in Eqs. (3), (4) and (5)), the lithospheric thicknesses would not increase > 5–7 km. These values still represent thin lithospheres.

Our reported lithospheric thicknesses are in good agreement with the Robertson Maurice et al. (2003) studies, which determined the crustal and upper mantle structure of the southernmost South America by inverting four local seismograms (recorded for the SEPA, Seismic Experiment in Patagonia and Antarctica, www.gcmd.nasa.gov). These average velocity models evidence a relatively thin lithosphere of ~60 km. It is important to mention that this study estimated crustal thicknesses of 26–36 km, similar to the values used in our computations (from CRUST 1.0 and LITHOS 1.0). Most thermobarometric studies using xenolith samples (e.g., Bjerg et al., 2005) arrived at similar

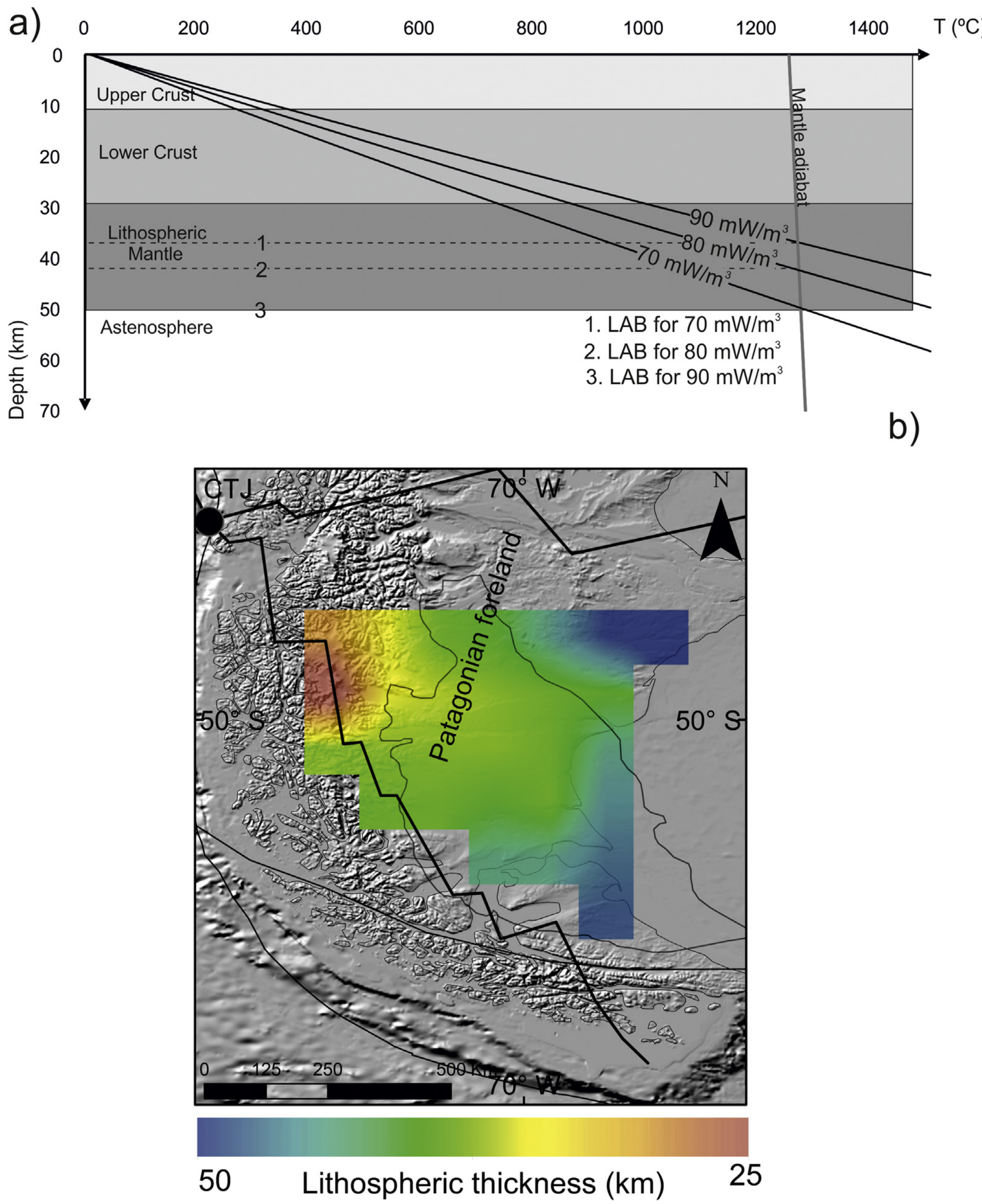

Fig. 5. Lithospheric thicknesses estimated from surface heat flows of south Patagonia. (a) Estimation of the lithospheric thicknesses using the interceptions between the geotherms for different heat flow values (70 to 90 mW/m^2) calculated using the steady-state thermal conductivity equation and considering an upper crustal thickness of 10 km and lower crustal thickness of 20 km (from CRUST 1.0) and the mantle adiabat (grey line). (b) Map of the lithospheric thermal thickness of southern Patagonia using a 1° × 1° IDW interpolation. CTJ: Chile Triple Junction.

values. These works calculated pressure and temperature of equilibration using the pyroxene as thermometer and the Ca exchange between coexisting olivine and clinopyroxene as barometer. In the southeastern Patagonia, in the Pali Aike basalt (PAB in Fig. 1), temperatures are high, suggesting a geothermal model gradient of approximately 13.8 °C/km, and pressures coherent with depths ~60 km. It is important to notice that only a few studies on xenoliths (e.g., Zaffarana et al., 2014) have suggested larger lithospheric thicknesses of ~100 km. However, such hypothetical results do not agree with our heat flow records. Averaged lithospheric thicknesses show lower heat flows, < 50 mW/m^2, like those reported in northern Patagonia or Sierras Pampeanas (Tassara and Echaurren, 2012). It is important to mention that in our model the lithospheric thickness depends strongly on surface heat flow values, which are strongly controlled by the BHT obtained from hydrocarbon wells. No thermal data were low enough to reproduce such a thicker lithosphere.

Toward the north of the study area the average heat flows (~60 mW/m^2, with maximum and minimum of 67 mW/m^2 and 50 mW/m^2, respectively, Fig. 4) are similar to those reported in regions affected by "normal" subduction, out of the asthenospheric windows (Curie and Hyndman, 2006). The lithospheric thickness obtained from using the steady state equation for these areas with lower heat flow data indicate a deeper LAB. For a heat flow of 60 mW/m^2, and considering the thermal parameters described in the methodology, the LAB would be 75 km depth. This lithospheric thickness across the northernmost asthenospheric window boundary is similar to those obtained immediately to the north and out of the slab window (Tassara and Echaurren, 2012). Considering this regions would be in transient thermal state (see above), we suggest this region would be still recording a previous thermal setting governed by continuous subduction.

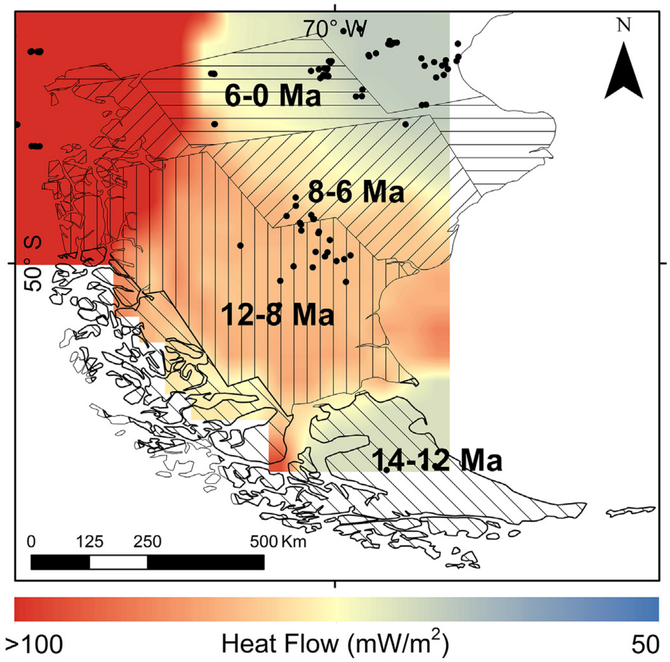

Fig. 6. Kinematics of the slab windows from 14 Ma to Present day (After Breitsprecher and Thorkelson, 2009) overlapping the distribution of modern heat flows estimated in this study (Fig. 4). Notice the higher heat flows develops where the slab windows started to widening and the anomalous thermal state stay longer.

Therefore, we would expect to have a LAB similar to that calculated further south, on the Austral basin, where we assumed a thermal steady state.

6. Conclusions

In this contribution we provide the first regional-scale distribution of heat flow data and lithospheric thickness of southern Patagonia. Calculations are regional, based on surface heat flows estimated from 75 hydrocarbon well data (drilled between 1000 and 6500 m depths), from two sedimentary basins (Golfo de San Jorge and Austral basins). While heat flow data obtained to the south of the study region, in the Austral basin, indicate abnormally high values (~90 mW/m^2), in the Golfo de San Jorge basin, to the north, heat flows are "normal" (~50 mW/m^2) compared to the average reported in continental regions. Our data distribution is consistent with the kinematic evolution and northward migration of the seismic ridge and slab window formation (Breitsprecher and Thorkelson, 2009).

Our heat flow results, in turn, evidence an eastward increasing of the lithospheric thicknesses between 25 and 50 km in the Austral basin region. The lack of thermal equilibrium in the Golfo de San Jorge basin, to the north, does not allow the thermal LAB to be calculated using the steady-state equation. Nonetheless, we propose lithospheric thicknesses similar to those reported to the south, in the Austral basin, given that the Golfo de San Jorge area would have been embraced by the asthenospheric window since 2 Ma (Breitsprecher and Thorkelson, 2009).

Our calculation of present-day heat flow data and thermal lithospheric thickness in southern Patagonia support the existence of a slab windows as well as northward widening through time, as shown by plate kinematic reconstructions (Breitsprecher and Thorkelson, 2009) and Cenozoic volcanism models (Gorring et al., 1997).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tecto.2018.10.006.

References

Alcacer, J.M., Onorato, M.R., Perucca, L.P., Miranda, S., 2017. Preliminary study of gravimetric anomalies in the Magallanes-Fagnano fault system, South America. Geod. Geodyn. 9, 42–49. https://doi.org/10.1016/j.geog.2017.10.002.

Artemieva, I.M., 2006. Global 1° × 1° thermal model TC1 for the continental lithosphere: implications for lithosphere secular evolution. Tectonophysics 416, 245–277. https://doi.org/10.1016/j.tecto.2005.11.022.

Artemieva, I.M., 2009. The continental lithosphere: reconciling thermal, seismic, and petrologic data. Lithos 109, 23–46. https://doi.org/10.1016/j.lithos.2008.09.015.

Artemieva, I.M., 2011. The Lithosphere: An Interdisciplinary Approach. https://doi.org/10.1017/CBO9780511975417.

Artemieva, I.M., Mooney, W.D., 2001. Thermal thickness and evolution of Precambrian lithosphere: a global study. J. Geophys. Res. Solid Earth 106, 16387–16414. https://doi.org/10.1029/2000JB900439.

Beardsmore, G.R., Cull, J.P., 2001. Crustal Heat Flow: A Guide to Measurement and Modelling. Cambridge University Press.

Bird, P., Liu, Z., Rucker, W.K., 2008. Stresses that drive the plates from below: definitions, computational path, model optimization, and error analysis. J. Geophys. Res. Solid Earth 113. https://doi.org/10.1029/2007JB005460.

Bjerg, E.A., Ntaflos, T., Kurat, G., Dobosi, G., Labudía, C.H., 2005. The upper mantle beneath Patagonia, Argentina, documented by xenoliths from alkali basalts. J. S. Am. Earth Sci. 18, 125–145. https://doi.org/10.1016/j.jsames.2004.09.002.

Boutonnet, E., Arnaud, N., Guivel, C., Lagabrielle, Y., Scalabrino, B., Espinoza, F., 2010. Subduction of the South Chile active spreading ridge: a 17 Ma to 3 Ma magmatic record in central Patagonia (western edge of Meseta del Lago Buenos Aires, Argentina). J. Volcanol. Geotherm. Res. 189, 319–339. https://doi.org/10.1016/j.jvolgeores.2009.11.022.

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.

Cermak, V., Rybach, L., 1982. Thermal conductivity and specific heat of minerals and rocks. In: Angenheister, G. (Ed.), Landolt-Bornstein Numerical Data and Functional Relationships in Science and Technology. 16. Springer, New Ser., Group V, Berlin, pp. 213–256.

Chulick, G.S., Detweiler, S., Mooney, W.D., 2013. Seismic structure of the crust and uppermost mantle of South America and surrounding oceanic basins. J. S. Am. Earth Sci. 42, 260–276. https://doi.org/10.1016/j.jsames.2012.06.002.

Conrad, C.P., Lithgow-Bertelloni, C., 2006. Influence of continental roots and asthenosphere on plate-mantle coupling. Geophys. Res. Lett. 33, 2–5. https://doi.org/10.1029/2005GL025621.

Curie, C.A., Hyndman, R.D., 2006. The thermal structure of subduction zone back arcs. J. Geophys. Res. Solid Earth 111, 1–22. https://doi.org/10.1029/2005JB004024.

Davies, J.H., 2013. Global map of solid Earth surface heat flow. Geochem. Geophys. Geosyst. 14, 4608–4622. https://doi.org/10.1002/ggge.20271.

Dávila, F., Lithgow-Bertelloni, C., Martina, F., Ávila, P., Nóbile, J., Collo, G., Ezpeleta, M., Canelo, H., Sánchez, F., 2018. Mantle influence on andean and pre-andean topography. In: The Evolution of the Chilean-Argentinean Andes. Springer, pp. 363–385.

Espinoza, F., Morata, D., Polve, M., Lagabrielle, Y., Maury, R.C., de la Rupelle, A., Guivel, C., Cotten, J., Bellon, H., Suarez, M., 2010. Middle Miocene calc-alkaline volcanism in Central Patagonia (47°S): petrogenesis and implications for slab dynamics. Andean Geol. 37.

Fitzgerald, M.G., Mitchum, R.M., Uliana, M.A., Biddle, K.T., 1990. Evolution of the San Jorge Basin, Argentina. Am. Assoc. Pet. Geol. Bull. 74 (6), 879–920.

Ghiglione, M., 2016. Geodynamic Evolution of the Southernmost Andes. Connections With Scotia Arc. https://doi.org/10.1007/978-3-319-39727-6.

Ghiglione, M., Quinteros, J., Yagupsky, D., Bonillo-Martínez, P., Hlebszevtich, J., Ramos, V.A., Vergani, G., Figueroa, D., Quesada, S., Zapata, T., 2010. Structure and tectonic history of the foreland basins of southernmost South America. J. S. Am. Earth Sci. 29, 262–277. https://doi.org/10.1016/j.jsames.2009.07.006.

Gorring, M., Kay, S.M., Zeitler, P.K., Ramos, V.A., Rubiolo, D., Fernandez, M.I., Panza, J.L., 1997. Neogene Patagonian plateau lavas: continental magmas associated with ridge collision at the Chile Triple Junction. Tectonics 16 (1). https://doi.org/10.1029/96TC03368.

Gorring, M., Singer, B., Gowers, J., Kay, S.M., 2003. Plio-Pleistocene basalts from the Meseta del Lago Buenos Aires, Argentina: evidence for asthenosphere-lithosphere interactions during slab window magmatism. Chem. Geol. 193, 215–235. https://doi.org/10.1016/S0009-2541(02)00249-8.

Groome, W.G., Thorkelson, D.J., 2009. The three-dimensional thermo-mechanical signature of ridge subduction and slab window migration. Tectonophysics 464, 70–83. https://doi.org/10.1016/j.tecto.2008.07.003.

Hamza, V.M., Vieira, F.P., 2012. Global distribution of the lithosphere-asthenosphere boundary: a new look. Solid Earth Discuss. 3, 199–212. https://doi.org/10.5194/se-3-199-2012.

Hantschel, T., Kauerauf, A.I., 2009. Fundamentals of Basin and Petroleum Systems Modeling. Springer Science & Business Media.

Harrison, W.E., Luza, K.V., Prater, M.L., Chueng, P.K., 1983. Geothermal Resource Assessment of Oklahoma (Special Publication 83-1). Geol. Surv, Okla.

Hasterok, D., Chapman, D.S., 2011. Heat production and geotherms for the continental lithosphere. Earth Planet. Sci. Lett. 307, 59–70.

Hechem, J.J., Strelkov, E., 2002. Secuencia sedimentaria mesozoica del Golfo San Jorge. In: Geología y Recursos Naturales de Santa Cruz. Relatorio Del XV Congreso Geológico Argentino, pp. 1–9.

Horner, D.R., 1951. Pressure build-up in wells. In: 3rd World Petroleum Congress.

Johnston, S.T., Thorkelson, D.J., 1997. Cocos-Nazca slab window beneath central America. Earth Planet. Sci. Lett. 146, 465–474.

Lagabrielle, Y., Suárez, M., Rossello, E.A., Hérail, G., Martinod, J., Régnier, M., de la Cruz, R., 2004. Neogene to Quaternary tectonic evolution of the Patagonian Andes at the latitude of the Chile Triple Junction. Tectonophysics 385, 211–241. https://doi.org/10.1016/j.tecto.2004.04.023.

Laske, G., Masters, G., Ma, Z., Pasyanos, M., 2013. Update on CRUST1. 0—a 1-degree global model of Earth's crust. Geophys. Res. Abstr. 2658.

McCrory, P.A., Wilson, D.S., Stanley, R.G., 2009. Continuing evolution of the Pacific-Juan de Fuca-North America slab window system-a trench-ridge-transform example from the Pacific Rim. Tectonophysics 464, 30–42. https://doi.org/10.1016/j.tecto.2008.01.018.

McKenzie, D.P., 1967. Some remarks on heat flow and gravity anomalies. J. Geophys. Res. 72, 6261–6273.

Murdie, R.E., Russo, R.M., 1999. Seismic anisotropy in the region of the Chile margin triple junction. J. S. Am. Earth Sci. 12, 261–270.

Murdie, R.E., Styles, P., Prior, D.J., Daniel, A.J., 2000. A new gravity map of southern Chile and its preliminary interpretation. Rev. Geol. Chile 27, 49–63.

Pasyanos, M.E., Masters, T.G., Laske, G., Ma, Z., 2014. LITHO1. 0: an updated crust and lithospheric model of the Earth. J. Geophys. Res. Solid Earth 119, 2153–2173.

Peace, A., Foulger, G.R., Schiffer, C., McCaffrey, K.J.W., 2017a. Evolution of labrador Sea-Baffin Bay: plate or plume processes? Geosci. Can. 44, 91–102. https://doi.org/10.12789/geocanj.2017.44.120.

Peace, A., McCaffrey, K., Imber, J., Hobbs, R., van Hunen, J., Gerdes, K., 2017b. Quantifying the influence of sill intrusion on the thermal evolution of organic-rich sedimentary rocks in nonvolcanic passive margins: an example from ODP 210-1276, offshore Newfoundland, Canada. Basin Res. 29, 249–265. https://doi.org/10.1111/bre.12131.

Priestley, K., McKenzie, D., 2013. The relationship between shear wave velocity, temperature, attenuation and viscosity in the shallow part of the mantle. Earth Planet. Sci. Lett. 381, 78–91. https://doi.org/10.1016/j.epsl.2013.08.022.

Ramos, V.A., 2008. Patagonia: a paleozoic continent adrift? J. S. Am. Earth Sci. 26, 235–251. https://doi.org/10.1016/j.jsames.2008.06.002.

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. J. Geophys. Res. Solid Earth 108. https://doi.org/10.1029/2002JB001828.

Russo, R.M., Gallego, A., Comte, D., Mocanu, V.I., Murdie, R.E., Vandecar, J.C., 2010. Source-side shear wave splitting and upper mantle flow in the Chile Ridge subduction region. Geology 38, 707–710. https://doi.org/10.1130/G30920.1.

Rychert, C.A., Shearer, P.M., Fischer, K.M., 2010. Scattered wave imaging of the lithosphere-asthenosphere boundary. Lithos 120, 173–185. https://doi.org/10.1016/j.lithos.2009.12.006.

Steinberger, B., Becker, T.W., 2016. A comparison of lithospheric thickness models. Tectonophysics 1–14. https://doi.org/10.1016/j.tecto.2016.08.001.

Stern, C.R., 1989. Garnet peridotite xenoliths from the Pali Aike basalts of southernmost South America. In: Kimberlites Relat. Rocks, pp. 735–744.

Stern, C.R., Frey, F.A., Futa, K., Zartman, R.E., Peng, Z., Kyser, T.K., 1990. Trace-element and Sr, Nd, Pb, and O isotopic composition of Pliocene and Quaternary alkali basalts of the Patagonian Plateau lavas of southernmost South America. Contrib. Mineral. Petrol. 104, 294–308.

Sylwan, C.A., 2001. Geology of the Golfo San Jorge Basin, Argentina (Geologia de la Cuenca del Golfo San Jorge, Argentina). J. Iber. Geol. 27, 123–158.

Tassara, A., Echaurren, A., 2012. Anatomy of the Andean subduction zone: three-dimensional density model upgraded and compared against global-scale models. Geophys. J. Int. 189, 161–168. https://doi.org/10.1111/j.1365-246X.2012.05397.x.

Thorkelson, D.J., 1996. Subduction of diverging plates and the principles of slab window formation. Tectonophysics 255, 47–63. https://doi.org/10.1016/0040-1951(95)00106-9.

Turcotte, D., Schubert, G., 2002. Geodynamics (472 pp.). https://doi.org/10.1017/CBO9780511807442.

Uliana, M.A., Biddle, K.T., Cerdan, J., 1989. Mesozoic extension and the formation of Argentine sedimentary basins. In: Extensional Tectonics and Stratigraphy of the North Atlantic Margins. American Association of Petroleum Geologists Tulsa, Memoir, pp. 599–614.

Wang, D., Lu, X., Song, Y., Shao, R., Qi, T., 2010. Influence of the temperature dependence of thermal parameters of heat conduction models on the reconstruction of thermal history of igneous-intrusion-bearing basins. Comput. Geosci. 36, 1339–1344. https://doi.org/10.1016/j.cageo.2010.03.014.

Zaffarana, C., Tommasi, A., Vauchez, A., Grégoire, M., 2014. Microstructures and seismic properties of south Patagonian mantle xenoliths (Gobernador Gregores and Pali Aike). Tectonophysics 621, 175–197. https://doi.org/10.1016/j.tecto.2014.02.017.