The effects of small-scale convection in the shallow lithosphere of the North Atlantic

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Abstract

Curie point depth can be used as a proxy for plate temperatures. Data from the North Atlantic (10° - 50°N) is used here to determine if the observed oscillations and patterns in Curie depths could be a sub product of small-scale thermal instabilities arising at the bottom of the lithospheric plates. Our numerical models suggest that small-scale convection (SSC) cells could produce thermal perturbations at isotherms as low as the Curie point. These results are compatible with North Atlantic observations in terms of wavelengths (150 to 300 km), amplitudes (~ 4 km) and orientations of the instabilities. Observed Curie-point depth oscillations before the onset (70 to 90 Myr) of SSC could also be linked to other different processes. We suggest that, in the case of the North Atlantic lithosphere, the spreading rate variation and the melt and upwelling could be intricately linked and cause a different pattern of SSC.

Keywords: Composition of the mantle, Numerical modelling, Dynamics: gravity and tectonics, Atlantic Ocean, Dynamics of lithosphere and mantle

1. Introduction

The Curie-point depth is known as the depth at which magnetic minerals pass from a ferromagnetic to paramagnetic state under the effect of increasing temperature (Nagata,

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1961). Curie points form a theoretical isotherm of Curie temperatures (e.g., $\sim 580^\circ\text{C}$ for magnetite) at the base of the magnetic layer. Geomagnetic anomalies can be used to study magnetic structures above the Curie point depth. Based on the Earth Magnetic Anomaly Grid (EMAG2; Maus et al., 2009), Li et al. (2013) constrained North Atlantic Curie depths by means of magnetic anomaly inversion with a fractal magnetization model, and showed that Curie depths exhibit a large oscillating and heterogeneous patterns with a wavelength between 200 and 400 km, approximately (Figure 1). They interpret that the oscillations might be a consequence of sublithospheric small scale convection (SSC, Parsons & McKenzie, 1978; Eberle & Forsyth, 1995; Huang & Zhong, 2005).

SSC is one of the proposed mechanisms invoked to explain the divergence between the theoretical cooling predictions and the observables on oceanic plates older than ~ 70 Myr (e.g. Zlotnik et al., 2008). For example, the difference between the observed Pacific seafloor topography over 100 Myr can be 1 km shallower than the predictions, and at 150 Myr the difference could reach 2 km (Stein & Stein, 1992). SSC derives from thermal boundary layer (TBL) instabilities below the oceanic lithosphere. In this scenario, the dripping of cold lithospheric material into the convective mantle is replaced with hot mantle rocks, thus limiting the base of the ocean lithosphere from cooling (Richter, 1973; Parsons & McKenzie, 1978; Davaille & Jaupart, 1994). There have been considerable efforts to understand the physics that rules the thermal instabilities of the SSC (Richter, 1973; Richter & Parsons, 1975; Huang et al., 2003; Afonso et al., 2008; Zlotnik et al., 2008). It is known that the interaction between the large-scale convection and SSC tends to form longitudinal rolls (also called ‘Richter rolls’) and transverse rolls, of which the axis is parallel and perpendicular to the plate motion, respectively. Moreover, van Hunen et al. (2003) concluded that longitudinal rolls may be dominant over transverse rolls if the shearing due to plate motion is significant. The presence of either or both types of rolls is still a matter of debate.

Because Curie points are well within the lithosphere (at depths between 5 and 45 km), it is not clear if SSC could propagate up its thermal anomalies from the Lithosphere–Asthenosphere Boundary (LAB) into the conductive lithosphere until those depths. Moreover, the pattern of the Curie depth oscillations differs slightly between the North Atlantic and the Pacific (Li et al., 2013, 2017; Li & Wang, 2018). In the North Atlantic,

oscillations show an alignment that favors ridge parallel directions, whereas in the Pacific there is not a preferred direction.

In this work we examine the hypothesis that Curie depth anomalies could be a consequence of small-scale convection processes. In addition we provide a possible explanation of the different Curie depth patterns observed in the North Atlantic.

Figure 1: Curie depth map of the North Atlantic based on inversion of magnetic anomalies from EMAG2 (modified from Li et al., 2013), in Albers equal-area conic projection and calculated with a window size of $208.8 \times 208.8 \text{ km}^2$. Thick black lines are fracture zones. Crustal isochrons (white lines) are based on Müller et al. (2008).

2. Model setup

In order to study SSC, we applied the particle-in-cell finite element code Underworld (Moresi et al., 2007). We performed 3D simulations based on the equations of conservation of momentum, mass and energy under the assumptions of incompressibility and

44 using the Boussinesq approximation. Velocity u , pressure P and temperature T are de-
 45 termined by solving the conservation of momentum (Stokes equation), mass, and energy
 46 equations:

$$\nabla \cdot (\eta \nabla^s u) + \nabla P = \rho g \quad (1)$$

$$\nabla \cdot u = 0 \quad (2)$$

$$\rho C_p \left(\frac{\delta T}{\delta t} + u \nabla T \right) = \nabla \cdot (k \nabla T) + \rho f \quad (3)$$

47 where the ∇^s is the symmetrized gradient, η the viscosity, ρ the density, g the gravita-
 48 tional acceleration vector, C_p the isobaric heat capacity, k the thermal conductivity, and
 49 f a heat source (sum of the decay of radioactive elements, adiabatic heating and shear
 50 heating).

51 A general nonlinear rheology is implemented:

$$\varepsilon = A(\sigma' / \mu)^n (b/d)^m \exp \left(- \frac{E + PV}{RT} \right) \quad (4)$$

52 where d is the average grain-size, σ the deviatoric stress second invariant, A the pre-
 53 exponential factor, μ the shear modulus, b the length of the Burgers vector, n the stress
 54 exponent, m the grain-size exponent, E the activation energy, V the activation volume,
 55 and R the gas constant. Table 1 describes the dimensional values used in this study.

56 Deformation in the mantle is governed by two main creep mechanisms: dislocation
 57 creep and diffusion creep (Ranalli, 1995; Kirby, 1983). The first one is present in the
 58 lithospheric mantle samples and the latter may be dominant at depths greater than 250-
 59 300 km. Due to this change in deformation mechanism with depth and given that both
 60 act simultaneously in the mantle, an effective viscosity η_{eff} is computed as the harmonic
 61 mean of two different viscosities (η_{disl} and η_{diff}) from both creep mechanisms:

$$\frac{1}{\eta_{\text{eff}}} = \left(\frac{1}{\eta_{\text{diff}}} + \frac{1}{\eta_{\text{disl}}} \right) \quad (5)$$

62 Calculations are performed in a rectangular box of 4000-6000 km long (depending on
 63 the model), 1000 km wide and 660 km deep using 384×96×96 elements. We impose a

64 velocity boundary condition at the top surface of the box, in the direction of increasing
 65 x coordinate, to control the ocean ridge spreading rate. Inflow material is allowed at the
 66 left wall where the ridge is located, whereas outflow is permitted at the right wall, and
 67 free-slip conditions are set at bottom, back and front walls (Figure 2). Temperature is
 68 fixed at the model surface and bottom at 0°C and 1600°C , respectively. **At starting**
 69 **time t_0 , lithosphere thickness is 80 km with a conductive temperature struc-**
 70 **ture above the base of the lithosphere, where the temperature is set to be**
 71 **1330°C ($16.625^{\circ}\text{C}/\text{km}$).** Below the base of the lithosphere, temperatures are
 72 calculated by linear interpolation between 1330°C and 1600°C ($0.47^{\circ}\text{C}/\text{km}$)
 73 .

Figure 2: Schematic model setup. A constant temperature of 1600°C is defined at the bottom of the model. Left boundary has a constant inflow of young lithosphere, whereas the old lithosphere outflows through the right wall. Bottom and top boundaries are closed and free-slip.

74 3. Curie temperature and Curie depth

75 Assigning a specific temperature to the Curie isotherm is not trivial since Curie point
 76 temperature depends on magnetic minerals. Magnetite has been widely employed to map
 77 Curie isotherm (corresponding to 580°C ; e.g., Bhattacharyya & Leu, 1975), although it
 78 is a rare mineral as stoichiometric Fe_3O_4 . Solid solution of magnetite, depending on
 79 the percentage of maghemite or hematite, may vary Curie temperature between 300 and
 80 680°C . Moreover, Haggerty (1978) reported that serpentinization of mafic and ultramafic
 81 rocks apt to be present in the lower and upper mantle have Curie temperatures between

Table 1: Physical and geometrical model parameters. See Table 2 for models details.

Variables	Symbols	Value	Dimensions
Top temperature	Tt	0	$^{\circ}\text{C}$
Bottom temperature	Tb	1600	$^{\circ}\text{C}$
Box height	H	600	km
Box width	W	4000 - 6000	km
Pre-exponential constant	A	1.5×10^9	MPa
Thermal expansion coefficient	α	3.5×10^{-5}	$1/K$
Thermal diffusivity	κ	10^{-6}	m^2/s
Thermal conductivity	k	3.9	W/mK
Heat capacity	Cp	1200	$\text{Jkg}^{-1}\text{K}^{-1}$
Reference density	ρ	3300	kg/m^3
Gas constant	R	8.314	$\text{Jmol}^{-1}\text{K}^{-1}$
Gravity acceleration	g	9.81	m^2/s

620 $^{\circ}\text{C}$ and 1100 $^{\circ}\text{C}$. Deep magnetic anomaly sources can extend to limits that overpass the conventionally 580 $^{\circ}\text{C}$ and, that if lower crust is indeed largely mafic and partially serpentinized, the Curie isotherm may be controlled by alloy metal systems with Curie temperatures that exceeding 620 $^{\circ}\text{C}$ (Haggerty, 1978).

Furthermore, any method for Curie depth estimation has high intrinsic uncertainty related to the choice of fractal parameter and size of the window used to discretize maps of the magnetic anomaly (Audet & Gosselin, 2019; Mather & Fullea, 2019), and heat flow data are occasionally perturbed by hydrothermal circulation and suffer from low spatial coverage (Mather et al., 2018). For these reasons, Li et al. (2013) and Li & Wang (2016) state that thermal structures can be better constrained through Curie-point depth maps derived from magnetic anomaly data, independent of heat flow measurements.

Table 2: Selected model parameters.

Model run	κ (m^2/s)	Vel (cm/yr)	Dislocation creep			Diffusion creep		
			$E(kJ/mol)$	$V(m^3/mol)$	n	$E(kJ/mol)$	$V(m^3/mol)$	n
1	1.00E-06	1	350	11	3.5	335	4	1
2	1.00E-06	1	120	11	3.5	335	4	1
3	1.00E-06	1	200	11	3.5	335	4	1
4	1.00E-06	1	250	11	3.5	335	4	1
5	1.00E-06	1	300	11	3.5	335	4	1
6	1.00E-06	4	300	11	3.5	335	4	1
7	1.00E-06	1.5	350	11	3.5	335	4	1
8	1.00E-06	2	350	11	3.5	335	4	1
9	1.00E-06	2	400	11	3.5	335	4	1

4. Modelling Results

Our numerical models are designed to study if and how SSC arising at the LAB produces thermal perturbations at Curie point depths. It is well documented (Richter & Parsons, 1975; Huang et al., 2003) that plate velocity and activation energy of dislocation in the lithospheric mantle have a main role on the development and evolution of SSC and therefore, we have tested the influence of the activation energy and plate velocity. Tested rheological parameters and plate velocity are summarized in Table 2. Our reference model has a plate velocity of 1 cm/yr, and rheological activation energy for dislocation and diffusion creep of 350 and 335 kJ/mol, respectively (Karato & Wu, 1993).

All models start with an initial period where thermal diffusion is the main cooling mechanism until the bottom part of the lithosphere becomes unstable and drips develop. This behaviour has been observed previously in many numerical models (e.g., Morency et al., 2005; Huang et al., 2003; Korenaga & Jordan, 2003; van Hunen et al., 2005) where the onset of the instabilities happens at lithospheres older than 70 to 90 Myr. The development of SSC does not produce a perturbation on the Curie isotherm immediately. In Model 1, the sublithospheric convective cells affect the upper mantle, but the Curie-isotherm remains mainly unperturbed and follows a purely diffusive cooling trend (Figure 3a). The maximum downgoing velocity at 200 km depth is ~ 4 cm/yr, whereas on the

Figure 3: Thermal state of model 1 (1 cm/yr spreading rate, $E_{\text{disl}}=350$ kJ/mol). 3-D view of the temperature field and Curie isotherm (**650°C; gray isotherm**) for the top 200 km of the model domain with a 10-fold vertical exaggeration at scaled simulation time of (a) 90 Myr and (b) 170 Myr.

Curie isotherm, the velocities are negligible. This magnitude coincides with previous works (e.g., Morency et al., 2005).

The Curie isotherm begins to develop vertical variations after ~ 90 Myr when the vigour of the small-scale convection cells becomes stronger. From that time on, the models show perturbations in Curie isotherm closely related to the sublithospheric instabilities (Figure 3b). These perturbations are rather small and have amplitudes from 2 to 4 km in the complete Curie-temperature range (from 580 to 850°C). Cross sections of the thermal field from the models show a continuous correlation between the perturbation of the Curie-isotherm and the gravitational instability at the LAB (Figures 4 and 5). This correlation indicates that the perturbation of the shallow temperatures arises from the Rayleigh-Taylor instabilities at the LAB.

The perturbations of the Curie isotherm result not only from the thermal propagation of the temperature variations at depth by diffusion, but also from mechanical deformation that arrives at very shallow layers. The convective velocities acting at Curie depths are much smaller in magnitude than the ridge spreading rate. For visualization purposes, the spreading rate has been subtracted from the corresponding velocity component in the velocity field (Figure 4a).

The initial instabilities in a cell pattern have a wavelength ranging between 150 and 300 km. A competition between longitudinal rolls and transverse rolls is observed. Longitudinal rolls, after 170 Myr model time, seem more stable close to the ridge, and are known to develop preferentially in the presence of a shear flow (e.g., imposed velocity; Richter, 1973). Meanwhile, the ridge-parallel instabilities are observed with greater relevance far from the ridge axis. At old ages, the instability pattern develops transverse rolls ending against longitudinal instabilities (Figure 3b). The onset of the small scale convection is stabilized at ~ 900 km from the ridge (Figure 3b).

We performed models for different activation energy for dislocation creep (Table 2). All cases display similar dynamics for the development of roll structures. The main difference, as previously shown by Huang et al. (2003) and van Hunen et al. (2005), is that the decrease of the activation energy increases thermomechanical erosion of the base of the lithosphere, but it does not change substantially the generation and development of rolls over the

Figure 4: Results obtained for a representative snapshot of the thermal structure for a model ($E = 350$ kJ/mol) with an imposed velocity of 1 cm/yr. 580°C and 800°C isotherm and velocity fields are displayed on a vertical plane located at $y = 500$ km at a scaled simulation time of 170 Myr. (a) Velocity calculated on the first 100 km depth. Here the velocity in the x direction is shown as $V_x - 1$ cm/yr in order to dismiss the influence of the imposed velocity and highlight the vertical one. (b) Velocity calculated on the first 200 km. Dashed line marks the position of the cross section on Figure 5. Maximum velocities are equal to (a) 1.01 and (b) 3.72 cm/yr. The particles illustrated in these figures represent a small fraction (1/3) of the total number of particles used in the numerical calculations.

Figure 5: Results obtained for a representative snapshot of the thermal structure for a model ($E = 350$ kJ/mol) with an imposed velocity of 1 cm/yr. 580°C and 800°C isotherm and temperature are displayed on a vertical plane located at (a) $x = 1500$ km, (b) 2500 km, and (c) 3500 km from the ridge, at a scaled simulation time of 170 Myr.

Curie isotherm. We quantified the maximum amplitude of the roll structure in all models. Figure 6 shows the resulting maximum amplitude of the Curie isotherm (650°C), measured on two cross-sections perpendicular to each other, as a function of elapsed model time for models with an imposed velocity of 1 cm/yr. In general, amplitudes of longitudinal and transverse rolls increase for older lithospheres but it is not possible to observe a direct relationship between maximum amplitudes of rolls and the activation energy values. Which is counterintuitive to the fact that activation energy plays a dominant role in the vigor and amount of small-scale convection (Davaille & Jaupart, 1994; Korenaga & Jordan, 2003; van Hunen et al., 2005). However, it is quite similar to what van Hunen & Zhong (2006) reported in relation to the low dependence of activation energy on the realignment time of rolls. What is worth pointing out is that, as expected for the case $E = 120$ kJ/mol, the amplitudes of the longitudinal and transverse rolls reach their maximum values, 3 km and 4 km, respectively. Figure 6a shows that longitudinal rolls maximum amplitude steadily increase from the onset, while the transverse rolls increase their maximum amplitude markedly between the time of the

Figure 6: Maximum amplitude of roll structures (650°C Curie isotherm) for different activation energy as a function of time for a models with an imposed velocity of 1 cm/yr. Amplitudes measured in two cross sections at (a) $x = 2000$ km and (b) $y = 500$ km.

161 onset and 120 Myr describing an approximately sigmoid curve (Figure 6b).
 162 Models with activation energy of 200, 300 and 350 kJ/mol achieve maximum
 163 amplitude values above 3 km for longitudinal rolls. While, in the transverse
 164 rolls, models with $E = 250$ and 350 kJ/mol are close to 2 km, and between 1
 165 and 2 km for those with $E = 200$ and 300 kJ/mol.

166 Our calculations show a cells with a dominant transversal component for the $E =$
 167 120 kJ/mol (Figure 7a), although it is possible to detect parallel to subparallel trans-
 168 verse rolls and longitudinal rolls developed closer to the ridge and related to the SSC
 169 onset. Curie surfaces for models with $E = 350$ kJ/mol (Figure 7b) shows two belts of
 170 rolls parallel to the ridge axis at 900 km from the ridge associated with the SSC onset.
 171 It is possible to distinguish transverse rolls at ~ 2000 km and a cell with a dominant
 172 transversal component arrangement further from the ridge. In this case, the competition
 173 between transverse and longitudinal rolls is more visible, and there is no clear preferred
 174 orientation. On the contrary, it is more appropriate to point out that the two types of
 175 rolls coexist. Even though Curie surface represents a shallow isotherm, the roll structures
 176 are present and there is no clear evidence of a preferential orientation.

Figure 7: Representative plan view of the Curie isotherm at a scaled simulation time of 90 Myr for (a) $E = 120$ kJ/mol and (b) $E = 350$ kJ/mol. Both models have 1 cm/yr imposed velocity. (c) Curie depth map of the North Atlantic based on inversion of magnetic anomalies from EMAG2 (modified from Li et al., 2013), in Mercator projection and calculated with a window size of 208.8×208.8 km². Thick black line is a fracture zone. Oceanic crust isochrons are based on Müller et al. (2008).

5. Discussion

Previous works have studied the small scale convection process and its consequences for the thermal, mechanical and chemical evolution of the oceanic lithosphere (e.g., Richter, 1973; Richter & Parsons, 1975; van Hunen & Zhong, 2006; Zlotnik et al., 2008; Afonso et al., 2008). These works concentrate on processes happening at the LAB (1250-1330°C) (e.g., Marquart, 2001; Morency et al., 2005; van Hunen et al., 2005) and pay little attention to the shallower and colder part (580-800°C) of the lithosphere at Curie depths.

Li et al. (2013) proposed that the observed perturbation of the Curie-temperature isotherms might be a consequence of the deeper SSC processes, implying a link between the deep instabilities at LAB (90 to 100 km depth) and the shallow perturbations at Curie-depth (40 to 50 km depth). The modification of the Curie isotherm could be a consequence of mechanical and/or thermal perturbations propagated from the LAB to shallow levels. The anomalies observed in the variations of the Curie depths, if being thermal, have to respond to a recent mechanism like the SSC, as otherwise would have been thermally dissipated.

Our numerical results show that i) the Curie-temperature isotherm can be effectively

194 affected by SSC process, and ii) the Curie-depth perturbations resulting from our nu-
 195 merical experiments, for lithospheres older than 80 Myr, are somehow compatible with
 196 the observations of Li et al. (2013) in terms of wavelengths and amplitudes and, to some
 197 degree, with the structure and orientation of the instabilities (e.g. Figure 6). However,
 198 it is not possible to do the same correlation for ages younger than 80 Myr because there
 199 is no thermal perturbation observed before the onset of SSC. Li et al. (2013) suggested
 200 that the onset of SSC is at about 45 Myr.

201 The implications of these results are two folds. The first is that pattern of perturba-
 202 tions of Curie depths observed by Li et al. (2013) in old lithospheres might have been pro-
 203 duced by SSC processes. The second implication deals with the SSC process itself; SSC
 204 has been proposed and studied by many authors from the observations of bathymetry,
 205 surface heat flow and gravity signals at oceanic plates (e.g., Parsons & McKenzie, 1978;
 206 Fleitout & Yuen, 1984; Stein & Stein, 1992; Doin & Fleitout, 1996; Ballmer et al., 2010).
 207 However, there is no direct observation of the process; for example, the current resolution
 208 of oceanic seismic tomography is not enough to observe individual instabilities. The ex-
 209 istence of SSC under the oceanic plates is still under debate (Huang & Zhong, 2005, and
 210 references therein). In this context, the Curie-temperature perturbations might be seen
 211 as a new support for the existence of SSC. Curie-temperature data used here is based
 212 on magnetic field observations, independent from other observables traditionally used to
 213 constrain SSC.

214 *5.1. Curie depth perturbations after onset of SSC*

215 Richter (1973) and Richter & Parsons (1975) concluded that transverse rolls are
 216 gradually suppressed by the large-scale convective flow. Shear forces at the base of the
 217 lithosphere produce a decay in vigor of the transverse rolls that, at some point, are
 218 replaced by longitudinal rolls perpendicular to the trench (Marquart, 2001; van Hunen
 219 et al., 2005). Previous studies (Rabinowicz et al., 1993; Fujimura & Kelly, 1993; Sleep,
 220 2011; Wirth & Korenaga, 2012) show a direct relationship between plate velocity and
 221 the decay time of the transverse rolls: fast moving plates suppress transverse rolls faster
 222 than slow moving plates. Our results are in agreement with these observations. Initially
 223 formed transverse rolls are eventually suppressed and replaced by longitudinal rolls.

224 The SSC developing at the base of the lithosphere modifies the lithosphere itself. The
 225 deformation generated at the LAB by SSC propagates up until Curie depths (Figures 4
 226 and 5) and imprints there the longitudinal and transverse character of the rolls at depth.
 227 The deformation at Curie depth is smaller than at sublithospheric levels, and therefore
 228 perturbations have smaller amplitudes and are smoother (longer wavelengths). However,
 229 all isotherms in the range of Curie-temperatures (580°C to 800°C) are being modified
 230 following the deeper mantle flow (Figures 4 and 5).

231 Numerical results present a similar structure of instabilities at ~ 90 Myr of evolution.
 232 Transverse rolls form closer to the ridge axis linked to the SSC onset. At larger distances
 233 from the ridge instabilities form a cell with a dominant transversal component pattern
 234 mixing rolls types (Figure 7a, b). These observations are similar to those of Rabinowicz
 235 et al. (1993) on a two layer viscosity model, where transverse rolls are found to be
 236 confined within the top low-viscosity layer and located far from the ridge axis. A similar
 237 case, although with different parameter values, is presented by Marquart (2001) for a
 238 plate velocity of 1 cm/yr, in which the 900°C isotherm showed a cell with a dominant
 239 transversal component pattern for the first 25.7 Myr of evolution time.

240 Regarding the depth of the Curie isotherms, numerical results show consistently an
 241 offset of ~ 30 km deeper than those estimated by Li et al. (2013). This difference is
 242 produced by the simplified numerical model that does not include explicitly the oceanic
 243 crust. The lower thermal conductivity of the oceanic crust rocks will produce a steeper
 244 crustal thermal gradient that will move shallow isotherms closer to the surface. In ad-
 245 dition, our results are consistent with previous results that suggest that the lithosphere
 246 thickness beneath ridges increases as the spreading rate decreases, which is generally con-
 247 sistent with the notion that lateral conductive cooling becomes more important at lower
 248 spreading rates (Parmentier & Morgan, 1990). Curie depth from magnetic inversion can
 249 also be underestimated, particularly when using small window sizes (Li et al., 2019).

250 *5.2. Curie depth perturbations before onset of SSC*

251 North Atlantic Curie depths revealed by Li et al. (2013) present shallow belts parallel
 252 to the Mid-Atlantic ridge after the ~ 45 Myr isochron (Figure 7c). At older ages the
 253 pattern is more complex, with a larger component of longitudinal rolls and cells with

254 a dominant transversal component pattern. Unlike these observations in the North At-
 255 lantic, our models do not show oscillations for ages younger than 80 Myr (Figure 7a,b).
 256 Therefore, we suggest that shallow oscillations observed at younger ages between ~ 20
 257 and 80 Myrs could also result from other processes other than the SSC.

258 Mantle melting may also affect the dynamics of the system, via melt and/or depletion
 259 enhanced buoyancy (Buck & Su, 1989; Jha et al., 1994; Parmentier & Morgant, 1990). In
 260 addition, melting may also reduce the viscosity of the lithosphere by creating a chemically
 261 distinct lithosphere that extends to a relatively constant depth (Gaherty et al., 1996).
 262 Many of these processes could be occurring simultaneously, defining the lithosphere at
 263 younger ages. As suggested by Harmon et al. (2020), the presence of partial melt is a
 264 key variable for small-scale convection to occur at ~ 10 Myr seafloor age, and very low
 265 mantle viscosities ($\sim 10^{17}$ Pa.s) are likely required (Buck & Su, 1989). The presence
 266 of partial melt can effectively reduce the mantle viscosity by an order of magnitude or
 267 more (Jackson et al., 2006), and could allow small-scale convection to initiate at young
 268 ages. The melt could potentially alter the thickness of the lithosphere or eventually pond
 269 at its base (Sim et al., 2020; Sparks & Parmentier, 1991). Upwelling at the ridge could
 270 potentially enhance this effect and begin convection at relatively young seafloor ages. As
 271 examined by Raddick et al. (2002), melting occurs in upwellings from perturbations in
 272 melt fraction (eg. variations in the melting temperature), producing small amounts of
 273 melt that can create localized, buoyant upwelling of the mantle. This melting may be
 274 enhanced by instabilities that involve positive feedback between decompression melting
 275 and the subsequent upwelling caused by the presence of this melt (Tackley & Stevenson,
 276 1993; Hernlund et al., 2008). These anomalies, combined with what appears to be a
 277 lithospheric drip, suggest SSC may be active at relatively young ages, and this could be
 278 facilitated by a low - viscosity asthenosphere. In other words, the melt and upwelling
 279 could be linked and cause a different pattern of small-scale convection than that predicted
 280 by this and previous modeling work that have not taken into account this process. Future
 281 models will need to examine the role of melt for enhancing convection and melt migration,
 282 its effects on lithospheric evolution and the driving forces of the plates.

283 Li et al. (2013) and Li & Wang (2018) noted that the base of magnetic sources may
 284 not always correspond to the Curie temperature isotherm but may instead have other

causes, e.g., contact between serpentinized and non-serpentinized mantle, or be biased by compositional variations. In that context, spreading rate variations might be linked to the Curie-point depth structure. At slower spreading rates, lateral conductive cooling is thought to play an important role in creating thicker lithosphere directly beneath the ridge axis (Parmentier & Morgant, 1990). At faster spreading rates, the subridge lithosphere may be thinner or nonexistent with dominant volcanic structures. In addition, the spreading rate may dictate the nature of mantle upwelling beneath the ridge; faster spreading oceanic plates may produce more 2-D sheet-like upwelling, whereas slow spreading may generate more 3-D diapiric upwelling (Parmentier & Morgant, 1990). Spreading rate variations have also a strong influence, on the development of the sub-lithospheric convection (Landuyt & Ierley, 2012), extent of hydrothermal circulation (Zhou et al., 2020), and the serpentinization process (Iyer et al., 2010). Serpentinization occurs in the presence of fluid pathways (e.g. fractures and faults) and is more important at slow spreading ridges (Iyer et al., 2010). This might be the case of the North Atlantic ridge that shows rate variations during the initial 45 Myr (Müller et al., 2008) coinciding with the oscillations of the Curie Depth temperature at younger ages (Figure 8). At ages older than 45 Myr, spreading velocity is nearly constant and therefore variation of the Curie depth cannot be associated.

6. Conclusions

We performed models for different activation energy for dislocation creep. The main difference observed was that the decrease of the activation energy increases thermomechanical erosion of the base of the lithosphere, but it did not substantially change the generation and development of rolls over the Curie isotherm. Even though Curie surface represents a shallow isotherm, the roll structures are present and there is no clear evidence of a preferential orientation. These results show that the Curie-temperature isotherm can be effectively affected by SSC process and are compatible with the observations from the North Atlantic lithosphere in terms of wavelengths (150 to 300 km) and amplitudes (~ 4 km) and, to some degree, with the structure and orientation of the instabilities. Unlike these observations, our models do not show oscillations for ages younger than 80 Myr. Thus, we suggest that shallow oscillations observed at younger ages between ~ 20 and 80

Figure 8: a) Half spreading rate velocity (solid line) and curie depths (red dash line) versus crustal ages through 40° latitude. Half spreading rate velocity (b) and curie depths (c) versus crustal ages for North Atlantic ocean between 50° and 40° latitude. Data from Li et al. (2013) and Müller et al. (2008)

Myrs could also result from other processes other than the SSC. In the case of the North Atlantic lithosphere, the spreading rate variation and the melt and upwelling could be intricately linked and could complicate the dynamics and generation of rolls associated directly with the SSC. Future models will need to examine the role of melt for enhancing convection and melt migration, its effects on lithospheric evolution and the driving forces of the plates

Small-scale convection has been proposed as a possible mechanism to explain the observed flattening of several lithospheric signals (bathymetry, surface heat flow, gravity, etc.), however, in this work, we use curie-depth based on magnetic measurements, which are independent of the other observables used to constrain small-scale convection. Thus, the Curie depth perturbation observed in our numerical models could confirm the existence of SSC at isotherms as low as the Curie point.

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