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Tectonics is a Hologram

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Tectonics is a hologram

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Abstract

A hologram is an image in which each area contains almost all the information about the entire system. It is a metaphor commonly used for complex systems in which the whole is bigger than the sum of the parts because of self-organization. And also the whole is smaller than the sum of the parts, since the collective organization limits the behavior of dynamic features. The tectonic evolution of the Earth is an emergent behavior of the lithosphere-mantle system, a witness of a program defined at the scale of rocks. Modeling the physics behind tectonics at a global scale became a reachable goal entering the 21st century. Geodynamicists developed numerical models of solid-sate convection with yielding, and reproduced some fundamentals of planetary tectonics. In the past 15 years, several groups in the world have used these models to investigate how continents drift, seafloor spreads and

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plates evolve. These emergent characteristics tell that the whole is bigger than the sum of the parts. Slabs, plumes, ridges, plates are interdependent and constrain each other. The whole is smaller than the sum of the parts. In this context, searching for causality relationships between tectonic features seems vain. In this chapter, I consider this point of view to describe how convection models with yielding have changed and still change our views on how tectonics shape the Earth. I finally propose an outlook about this window that remains half-opened.

Keywords: Mantle convection, plate tectonics, numerical modelling, subduction, complex systems

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1. Introduction

On every planet there is active tectonics, and there has been active tectonics. Even if it is extremely weak, macroscopic finite strain patterns shape their surface and draw their uniqueness. These structures are the way we identify them, traits of their identity and keys to their history. On Mercury, hundreds of kilometers long fault scarps cutting impact craters witness recent activity at planetary scale (Watters et al., 2016). Venus displays tectonic and volcanic structures, being rift systems (Olapa Chasma) interacting with volcanic eruptions (Idunn Mons), which have been identified as geologically recent (D'Incecco et al., 2020). The first months of seismic recording on Mars have evidenced tectonically active faults (Banerdt et al., 2020). Planetary-scale structures, as the Valles Marineris, show active deformation in the form of faults, landslides and possibly mud volcanoes (Kumar et al., 2019). Titan, Enceladus, Europa and Pluto each have their scars. And of course, the Earth that we can observe more closely and connect the surface to its interior. Our planet shows organized tectonics at a global scale, such that plate tectonics has been developed as a successful framework Morgan (1968) to describe its self-organization, linking together faults, volcanoes, deformed belts, sedimentary deposits, remanent magnetism and even more, within a geometrical and geodynamic logic. It can extend to climate and life. This extraordinary organization of the surface of the Earth is the expression of a cascade of interactions operating over a diversity of scales. At the microscopic scale, relevant processes are the production of heat by unstable atomic nuclei, diffusion of atoms and heat, chemical reactions, phase transformation in solids and fluids, dislocation propagation in crystals and more. These small scale processes interact with each other everywhere in the globe with a variety of intensity and directions. They define a complex system, impossible to describe fully, highly non-linear, from which emerges a self-organization with an apparent macroscopic behavior. Plate tectonics is a geometric theory to describe this behavior.

In 1999, I started to work on the deep structure of the Earth's mantle looking for relationships between dynamics and the geochemical diversity of mantle-derived rocks (Coltice and Ricard, 1999). After studying the effects of convective mixing on geochemical heterogeneity (Coltice and Schmalzl, 2006), I was convinced that the geochemical picture of the Earth was mostly inherited from the early differentiation history of our planet, and I focused on the formation of continents and the Earth's core (Labrosse et al., 2007; Monteux et al., 2007; Rey and Coltice, 2008; Coltice et al., 2009, for example). I enjoy fieldwork and observations so more and more, I looked at continents, and started to make numerical models of convection with continental lithosphere (Coltice et al., 2007). The temperature dependence of viscosity was a major factor for my conclusions. The problem was that a convection model with temperature-dependent viscosity alone generates a sluggish surface at best, and a one-plate planet at worst. Therefore, plate-like behavior was necessary to model a mobile surface. I was lucky that Paul Tackley and Tobias Rolf opened their door and allowed me to work with them. The first time I watched movies of the models of Tobias, I was shocked. I could see plate tectonics in operation. Dynamically. And in a second my mind switched. I had the vision that these models would take us to a new description of tectonics. I could see that the lithosphere dynamics and mantle convection communities could reach their hands in terms of modeling and targets. Since that time I have been working with these models and diving into complex systems and self-organization. I could not consider anymore simple causal links, but a systemic approach to the deformation over the whole globe.

Self-organization for tectonics is widely discussed, leading to abstract models of interacting processes. For instance Miltenberger et al. (1993) have created models where elasticity, threshold dynamics, and small-scale heterogeneity interact to produce relevant spatio-temporal patterns of faults. At larger scale, Anderson (2002) proposed a vision where the interactions between stresses and temperature within the mantle-crust system generate the emergent pattern of plate tectonics. The integrative work of Bird (2003) was a step forward in the identification of self-organization at plate-scale by describing a plate area distribution that can be modeled by a power law typical of fragmentation models (Sornette and Pisarenko, 2003). When there is self-organization, it often becomes useless to separate a part from the whole. For instance, questions like 'do plates make the mantle move, or does the mantle make plates move ?' separate plates from the mantle, although they form a single complex system. It can be rephrased: how can we link the motion of the plates and the motion of the mantle? It is a hologramic principle (Morin, 1990): the parts are in whole, and information on the whole is inscribed within the parts. Tectonics is then like a hologram: it is an image in which each area contains almost the full information about the mantle-lithosphere system. With such approach, causality becomes a fuzzy way to tackle problems. For instance, the westward drift of the lithosphere is not caused by the Pacific slabs. Westward drift and the Pacific slabs coexist at the same instant and cannot be isolated to each other. They are the result of a program, which could be compared to the genetic code in life sciences, and a series of interactions at all scales. In this context, the whole is bigger than the sum of the part: there is emergence. And also, the whole is smaller than the parts: the system-specific constraints inhibit some behavior specific to the parts.

In practice, geodynamicists studying the lithosphere design numerical models with local equations and material properties defined at microscopic scale. They look for the generation of macroscopic tectonic and magmatic structures. Mantle convection models are a step forward in tackling the self-organization question at a global scale, necessary to treat the lithosphere-mantle system as a whole. The first models generating plate-tectonic like patterns were published more than 20 years ago (Tackley, 1998; Trompert and Hansen, 1998a; Moresi and Solomatov, 1998). The key to producing plate-like behavior was to combine temperature-dependent viscosity and a threshold model for the stress-strain rate relationship (Bercovici, 1993). Recently, a similar step has been started for laboratory experiments using natural colloidal solutions (Davaille et al., 2017).

In this chapter, I will first explore some aspects of mantle convection models producing tectonics to identify the program behind self-organization. I will then focus on the emergent properties like subduction, remaining the big fundamental for our planet. It leads to the relationships between the parts and the whole. I finish with an outlook and final thoughts given the promises of this approach.

2. The program of plate-like tectonic emergence in convection models: pseudo-plasticty

2.1. Context

Tectonics has been a driver of mantle convection concepts. Holmes (1931) built his model towards a description of the mechanics of continental drift. With the advent of seafloor spreading, Turcotte and Oxburgh (1967) introduced a semi-analytical model of mantle convection providing a framework to the heat-flow-age relationship in the ocean floor. Plate tectonics imposed a new concept of rigid blocks moving in pieces (Morgan, 1968), which was followed by two types of modeling. First, to push the initiative on mantle convection, McKenzie et al. (1974) conducted the first time-dependent numerical models of convection. Alongside, Richter and McKenzie (1978) studied arising forces in viscous flow models (convection without the time-dependent heat conservation equation) with plates, inspired by the approach of Forsyth and Uyeda (1975). From these roots, time-dependent convection models diversified, following the development of computers and parallel supercomputers, and viscous flow models as well. The first family of models reached a limit by the end of the 1990's: they were useful to study global properties (average surface heat flow, velocity etc...), physics of the deep mantle and geochemistry varying parameterizations but by no means they could generate predictions for geological observations. The second family of models started with rooted limits: they could help characterize the Earth today, but they could not do so for a fully dynamical perspective (time-dependent). Therefore, at the end of the 1990's geoscientists took two different paths: (1) working on the non-linear rheology of rocks (Bercovici, 1993) and numerical methods (Tackley, 1998; Trompert and Hansen, 1998a; Moresi and Solomatov, 1998) to build numerical models of mantle convection generating self-consistently plate-like behavior, (2) working on convection models with imposed plates at the surface (Gable et al., 1991; Bunge et al., 1998; Monnereau and Quéré, 2001; McNamara and Zhong, 2005).

By definition, imposing plates means imposing rigidity at the surface and precluding modeling tectonics. I, therefore, focus on the models taking the rheology path, pointing the reader to review articles for more comprehensive work on both families of models(Lowman, 2011; Coltice et al., 2017a). In 1998, three numerical modeling studies were published with convection models generating plate-like behavior (Tackley, 1998; Trompert and Hansen, 1998a; Moresi and Solomatov, 1998). These models integrated the work of Bercovici (1993), formulating the hypothesis to keep the viscous approach to the problem, meaning that plate-like behavior is a viscous response.

The author tests the power of a variety of viscosity laws to generate plate-like characters, being localization of the deformation and equipartitioning of poloidal/toroidal kinetic energy (Olson and Bercovici, 1991). After disqualifying power laws, Dave Bercovici points to pseudo-plastic laws that succeed in generating localized low viscosity pseudo-plate boundaries circling very viscous pseudo-plates, and producing substantial toroidal flow. This seminal work created the foundations of the convection models producing plate-like tectonics since.

To start the process, the three publications cited above introduced a yield stress parameterization, leading to an expression of the viscosity at the strength limit σ_y being

$$\sigma_y = \mu_y \dot{\varepsilon_{II}},$$

with μ_y the viscosity at the pseudo-plastic limit and $\dot{\varepsilon_{II}}$ the second invariant of the strain rate. This formulation is combined with a temperature dependence of viscosity, making it high when cold, and low when hot. It launched the race to identify the conditions of existence of plate-tectonics. At low yield stress a convective flow will produce a soft and deformed surface, at high yield stress a stagnant lid forms, and in between is the land of a range of plate-like regimes. The issue lies in the quest for yield stress values, most models pointing to below 150 MPa (O'neill and Lenardic, 2007; Richards et al., 2001; van Heck and Tackley, 2008; Rolf and Tackley, 2011; Arnould et al., 2018). Solomatov (2004) noted that the lower end values for the yield stress (10-30 MPa) are similar to the "stress drop during earthquakes (Kanamori, 1994), and the stresses which produce the observed trench topography (Zhong and Gurnis, 1994)". The yield stress values have been a new parameter to expand our vision of super-Earths, setting the question of the existence of plate-tectonics at a central position (Valencia et al., 2007; O'neill and Lenardic, 2007; van Heck and Tackley, 2011). However, subtleties in initial conditions and melting history may be more critical than the yield stress value itself (Seales and Lenardic, 2021; Lourenço et al., 2018).

Obtaining a range of yield stress values for plate-like behavior was a fundamental step, but also one leading to confusion. The value obtained in models is mostly taken out of its context to be compared directly to experiments and observations without awareness. As a matter of fact, what is called a yield stress in mechanics of solids has substantially higher values for mantle rocks than what is needed in geodynamic models (Demouchy et al., 2013; Zhong and Watts, 2013; Hansen et al., 2019). This has been a criticism of convection models with yielding since. However, such quick comparison is not appropriate for several reasons:

- evaluation of dynamical models rely on force (or time) ratios being dimensionless numbers. One specific dimensional value in a model can be compared to a natural value only if all other dimensional model values are appropriate for the Earth, which is impossible to know and achieve.

- In pseudo-plasticity the "pseudo" word matters. It is a viscous model parameterizing a rheology that is not only viscous. Therefore, comparing the stress/strength enveloppes of viscous models with stress/strength enveloppes for the Earth's lithosphere is not appropriate. The latter combines elasticity, brittle failure, plasticity and viscosity, showing different domains for the relevant rheological behavior (it is more like a phase diagram). The former is just a curve for a given viscosity law. This said, comparison with awareness is relevant. It means that one has to find a physical domain in which both approaches can meet. It is also relevant to work with dimensionless numbers in convection models. I will propose an approach in section 3.

2.2. Without and with pseudo-plasticity

Pseudo-plasticity impacts convection in all its dimensions. The most obvious is kinematics at the surface. As shown in Fig.1, the kinematics of convection without pseudo-plasticity can be fully described by a flow diverging from a plume and converging to downwellings that can be either circular or slightly planar when a viscosity jump is imposed (Bunge et al., 1997). The theoretical ridge, trench and transform structure of plate tectonics is not produced. The apparent long wavelength of thermal heterogeneity in the mantle, imaged by seismic tomography (Su and Dziewonski, 1991) and consistent with the geoid Cazenave et al. (1989), does not emerge from every convection model. Without pseudo-plasticity, three parameterizations produce long-wavelength thermal heterogeneity: a viscous jump within the mantle (Bunge et al., 1997; Zhong et al., 2007), the presence of continental rafts at the surface (Gurnis, 1988; Guillou and Jaupart, 1995) and the presence of rigid plates (Gurnis and Zhong, 1991). In terms of flow beneath the thermal boundary layer, convection models without lateral viscosity contrasts do not generate mantle drag, i.e. velocity at the surface is always faster in its direction than below the boundary layer (Coltice et al., 2019), and toroidal motion does not exist (Chandrasekhar, 1961). Regions of divergence correspond exactly to upwellings.

With pseudo-plasticity, the planform of convection involves sheet-like downwellings with properties consistent with subduction on Earth (Crameri and Tackley, 2014; Coltice et al., 2019) and cylindrical plumes (Arnould et al., 2020). The surface pattern is a network of divergent, convergent and possibly transform boundaries (Langemeyer et al., 2021). These boundaries are sharp or diffuse, making them sometimes hard to automatically identify (Mallard et al., 2017). In such models, large viscosity gradients come into play. A viscosity value imposes its flow scale. With variable viscosity, a diversity of flow wavelengths interact (Arnould et al., 2018). Viscosity gradients allow decoupling and, therefore, the interior flow and the surface can differ strongly, especially above upwellings. The dominant wavelength of convection is directly connected to the value of the yield stress. In the plate-like regime, the wavelength is long, being degree 2 in a sphere (van Heck and Tackley, 2008; Yoshida, 2008; Rolf et al., 2012; Mallard et al., 2016). The surface expression of the long-wavelength flow pattern is the distribution of large plates of similar sizes, comparable to those of the North American plate and up to that of the Pacific plate (Mallard et al., 2016). The presence of a viscosity jump is not a prerequisite for the long wavelength. A stiff surface produces long wavelength as expected. The viscosity gradients at the base of plates are strong, 5 to 7 orders of magnitude over tens of kilometers in numerical models. They generate small-scale flow beneath old seafloor as instabilities (Coltice et al., 2017c), but also short and intermediate scales around sinking slabs (Király et al., 2017; Arnould et al., 2018). Toroidal flow represents the motion of lower viscosity (and generally faster) material around more viscous (and generally slower) material. The decoupling caused by viscosity gradients produces contrasts in kinematics between the surface and the shallow mantle. The plates smaller than the larger ones are produced by fragmentation forced by subduction tractions (Mallard et al., 2016), hence ridges are most of the time not the places of mantle upwellings but passive structures. Therefore, with pseudo-plasticity, surface patterns do not reflect deep structures, contrarily to convection models without strain localization. This observation is consistent with the fact that mantle drag becomes a force to be considered in such models (Coltice et al., 2019).

2.3. On temperature-dependent viscosity

Temperature dependent viscosity is a fundamental ingredient in generating plate-like behavior: it produces the lid structure, as long as the viscosity contrast over the thermal boundary layer is larger than 10^4 (King, 2009), the slab strength impulsing toroidal flow around it, and decoupling between hot upwellings and plates. The dependence of viscosity upon temperature is extreme in rocks. In the cold boundary layer, viscosity values are so high that it ultimately means that viscosity is not the relevant rheological approximation to use. Instead, elasticity and brittle behavior would be more appropriate. Viscosity drops quickly towards the base of the upper thermal boundary layer. The viscosity contrast between the colder and hotter region of the mantle, or within a model is a fundamental parameter to examine. The magnitude is fundamental, but also its gradients are to be scrutinize with a lot of care (King, 2009; Stein and Hansen, 2013).

Hence tackling the numerical problem to obtain stable and reliable solutions is a challenge. To take that challenge, the first step is to develop appropriate numerical methods (Yoshida and Ogawa, 2004; Choblet et al., 2007; Tackley, 2008; May and Moresi, 2008; Kronbichler et al., 2012), and the second step is to choose parameterizations that can be reliably solved. In the recent literature, there are two types of temperature-dependent parameterizations for plate-like behavior models. The first one is based on controlling the viscosity contrast between the values of temperature being temperature at the surface T_s and temperature at the base $T_s+\Delta T$, ΔT being the temperature jump of reference:

$$\mu \propto \exp\left(\frac{A}{(T-T_s)/\Delta T+1} - \frac{A}{2}\right), \qquad (1)$$

in which T is the temperature variable and A the factor that controls the maximum viscosity contrast in the model. This type of parameterization is ideal when working with dimensionless numbers, which makes sense since reaching an Earth-like regime with these models is a big challenge in terms of computation. The viscosity dependence relies on relative temperature (being $T-T_s$). Trompert and Hansen (1998b); Tackley (1998); van Heck and Tackley (2008); Yoshida (2008); Foley and Becker (2009); Rolf and Tackley (2011); Mallard et al. (2016); Langemeyer et al. (2021) use that type of parameterization to study convection with plate-like behavior.

The second type is built on an experimental parameterization:

$$\mu \propto \exp\left(\frac{E_a}{RT} - \frac{E_a}{RT_0}\right), \qquad (2)$$

in which T_0 is a reference temperature which determines the viscosity of reference in the model, and E_a the activation energy. This law explicitly uses the absolute value of temperature. This makes it less useful when exploring dimensionless numbers. However, the viscosity gradients between hot and cold are stronger than in equation (1), which is the basis of modelling plates:

close to rigid pieces over soft flowing mantle. Crameri and Tackley (2014, 2016); Zhang and O?Neill (2016); Coltice et al. (2017a); Coltice and Shephard (2018); Arnould et al. (2019); Coltice et al. (2019); Arnould et al. (2020) use that type of parameterization in 3D models.

These two laws produce plate-like behavior when combined with a yield stress formulation. The mean emergent properties (tectonic regimes, heat flow, root mean square velocity) are weakly dependent on the temperature-dependent formulation (Stein and Hansen, 2013). However, the tectonic and convective structures are slightly different, especially when it comes to trenches and subduction. The comparison of published models shows that subduction with law 2 initiates from small 3D structures and develops arcuate trenches that most of the time retreat (Crameri and Tackley, 2014; Coltice et al., 2019), while they are linear and stable features with law 1 (Rolf et al., 2012; Mallard et al., 2016). For instance, in published work and from my experience with both viscosity laws, plume induced subduction only exists using law 2, highlighting the role of viscosity contrasts at the base of the thermal boundary layer, around slabs and plumes. The viscosity laws are still to explore and should not be neglected. As I will suggest in subsection 3.4, they can drive different mechanisms for subduction initiation and plume-lithosphere interaction.

3. The whole is bigger than the sum of the parts parts. The whole is smaller than the sum of the parts

Solving the local equations of 3D convection with a pseudo-plastic approximation leads, with the adequate parameters, to emergent tectonic features.

As for any complex system, there is no way to predict the existence of these features from the local equations. Self-organization is an intrinsic property of these models. I describe here some of the emergent features that could be relevant for our planet today.

3.1. Continental drift

Continental drift in convection models has been extensively studied since Gurnis (1988), but mostly without plate-like behavior. This seminal work confirmed the idea that continents and convection interact leading to a self-organization that is characterized by long wavelength convection and moving continents. The latter drift towards downwellings (being pressure lows in the boundary layer). Once it lies above it, because it is buoyant and viscous, it shuts down the downwelling and another one initiates elsewhere. This view guided Zhong et al. (2007) to propose that supercontinent cycles (Nance et al., 2014; Mitchell et al., 2021, for reviews on supercontinent cycles), are organized by an assembly phase when mantle convection is dominated by a single subduction system in one hemisphere attracting all continents, and a dispersion phase when two new systems of subduction dominate away from the supercontinent. Convection models with viscous continental rafts produced supercontinent cycles with relevant time scales (Trubitsyn and Rykov, 1995; Lowman and Jarvis, 1999; Phillips and Bunge, 2007, among others). Would the fact that supercontinent cycles could be produced without accounting for plates (with the exception of Lowman and Jarvis, 1999) and strong slabs suggest that continental drift is independent of plate tectonics?

Adding plate-like behavior to models with continents show it is not the case. A major conclusion in the previous convection studies is that the long wavelength structure of the flow is the dominating feature for continental drift and supercontinent cyclicity. In convection models without plate-like tectonics, long wavelength is produced by the existence of continental rafts (Gurnis, 1988; Guillou and Jaupart, 1995; Phillips and Coltice, 2010), or by the viscosity jump within the mantle (Bunge et al., 1996; Zhong et al., 2007). However, when plate-like behavior is accounted for the long wavelength, the flow is generated primarily by the existence of strong plates (van Heck and Tackley, 2008; Yoshida, 2008; Rolf et al., 2012, 2018; Mallard et al., 2016) (long wavelengths already exist without viscous jump and continents). Therefore, the initial reasoning could stand, but the physics changes. Irregularities in supercontinent cycles become more connected to the non-linearity of the rheological response in the lithosphere (Rolf et al., 2014, 2018) than the hypothetical existence of strong plumes (Phillips and Bunge, 2007). The details of continent aggregation and breakup also differ. For example, in models without plate-like behavior, supercontinent formation always happen by extroversion, meaning that following the breakup, continent pieces collide on the exterior margins. However, this is not always the case on Earth. The formation of Pangea happened by introversion, continent pieces having collided on the interior margins (Murphy and Nance, 2003). Such behavior is not often observed in models with plate-like behavior, but has been observed in Coltice et al. (2019). More work is needed to evaluate if introversion happens for specific convection parameterisations. Also, in this numerical model, continental collision happens synchronously with rifting in distant regions, which is typical of the Earth (Himalayas growing synchronously with the opening of the African rift).

3.2. Seafloor spreading

Within ”ocean” basins (oceans do not explicitly exist in the models), the numerical solutions of convection with yielding generate seafloor spreading characteristics. The basins are fragmented into pieces that behave like plates, 90 % of active strain being restricted to 1-10 % of the surface depending on model parameters. Fragmentation is represented by divergent boundaries, sometimes with vorticity component, which have similarities with mid-ocean ridges. They are long linear features with no clear connection with the underlying velocity and temperature fields. They appear as passive structures of fragmentation emerging to accommodate forces imposed by slabs, plumes and viscous stresses between the boundary layer and the interior. The connections between ridge systems correspond to triple junctions (Figure 1C). In convection models with a viscous law 2, quadruple junctions also exist, but only temporarily and related to plume-ridge configurations (Arnould et al., 2020). Ridges are a fundamental example of the assertion ”the whole is smaller than the sum of the parts” because the fragmentation pattern in such models is forced fully by the collective interactions over the whole surface. It forms a network that adapts constantly to global changes in mechanical stresses. Only the thermal dimension involves some memory, meaning some sort of independence of a ridge from its surroundings. A ridge is a hotter area, a thinner boundary layer. Hence, a locally weaker area. This acts as a restoring force on a system, contributing to keep the ridge where it has been.

The fragmentation pattern varies with the yield stress value. The plate’s area distribution is a convenient way to explore the fragmentation pattern. For the Earth, the distribution can be divided into several large plates of a similar size (being of the order of the Pacific plate size for instance), and a distribution of smaller plates that follow a power law (Bird, 2003). A discussion about the possibility of using one single density function or 3 different ones (one for small plates, one for intermediate and one for large) could be relevant (Sornette and Pisarenko, 2003; Vallianatos and Sammonds, 2010). Whatever the mathematical interpretation, 3D spherical convection models with yielding generate such distributions innately (Mallard et al., 2016). It is a typical emergent pattern of convection with such rheology. A lower yield stress shifts the distribution to smaller and hence more numerous plates, while a larger yield stress pushes the distribution towards a smaller number of larger plates. Fragmentation is more localized in areas where subduction is active, which represents the main driver of fragmentation.

Plumes influence the localization of ridges by weakening thermally the boundary layer in their vicinity. Because they are several 100 K hotter than their surroundings, plumes reduce the thickness of the boundary layer they are in contact with, and over areas extending several 100 km. Therefore, the impact of a plume close to a ridge can lead to a ridge jump (Fig. 2A), to the localization of the fragmentation of a whole ocean basin (Fig.2B), or to nothing at all. Sometimes, it is even the hot wake of a plume, which is like a thermal scar in the boundary layer, that focuses the fragmentation of a plate (Fig.2C). This type of tectonic event depends on too many interactions (local and long-distance) to be predicted, unfortunately.

Textbooks often represents seafloor spreading with the typical symmetric magnetic stripe patterns. They represent the distribution of ages on the seafloor, from which so many properties are correlated: bathymetry, heat flow, hydrothermal activity among others. The seafloor age-area distribution on Earth today is called triangular: the youngest seafloor dominate and a very limited amount of >100 My seafloor exists. One can interpret that the age of subduction is equally distributed. This is surprising for a convective system for which a critical age determines, in principle, the onset of cold instabilities. I will come back to it in subsection 3.4. Indeed, Labrosse and Jaupart (2007) showed that simple convection models generate distributions of seafloor ages that are rectangular: the area of a given age is constant up to a critical age beyond which the area is 0. In a 3D spherical geometry, convection with yielding produce a variety of age-area distributions, and when continents are added, the triangular one dominates (Coltice et al., 2012, 2013). Continental margins impose a geometrical forcing. They also generate stronger time-dependence of convection, which translates into strong fluctuations of the production of new seafloor. Both lead to triangular-like age-area distributions. The interpretation is that the present-day age-area distribution of the Earth represents "forced" subduction below continents and changes in seafloor production. Hence, depending on the continental configuration (Coltice et al., 2014) and timing, the age-area distribution evolves between rectangular and exponential decay, going through triangular shapes.

3.3. Transform zones

Transform faults were a key feature to demonstrate the occurence of seafloor spreading (Wilson, 1965) and build a plate tectonic theory (Morgan, 1968). Their existence is not for granted. Indeed, a plate boundary showing pure rotational behavior is a very special configuration. Boundaries combining divergence with rotation could be the rule. It actually is in most models of convection with yielding, in which transform shear zones (faults do not exist in viscous models) are replaced by ridges with strong rotational components. Overall, the toroidal component of the velocity, which corresponds to vorticity and potentially transform motion, is comparable between convection models with plate-like behavior and the Earth (van Heck and Tackley, 2008). But the tectonic features expressing it are somewhat different. Therefore two major questions arise: what physical parameters are needed to allow pure transform motion to emerge ; what does the transform offset expresses in terms of regional and global dynamical evolution?

Transform motion has been observed in 3D spherical models of convection with yielding (Coltice et al., 2017b, 2019), but as a feature which is not as dominant as on Earth today, except at specific times during a calculation. Exploring the parameter space of these models is extremely difficult: computations require weeks to months, the non-linearities imply that changing one parameter redefines the whole flow regime. The number of parameters to vary is larger than 10. However, global and regional lithospheric models already define the scope of the generation of transform motion. Langemeyer et al. (2021) reproduced large and distinct transform offsets in a series of 3D spherical models of convection with yielding. When the yield stress is constant with depth and close to the yield stress that sets the transition to the stagnant lid regime, transform motion emerges within elongated ridge systems. In these models, the offsets develops with time and grow, starting from a corrugated ridge system. The models that produce these transform motions only develop a small number of very large plates, which differs from the Earth plate size distribution. This study shows that transform motion emerges in global models when plates are stiff (the yield stress value is large). When they are not, transform motion exists and develops, but quickly derive into transpressive-transtensive motion. Weakening is an issue, because if a slight divergence onsets in the weak areas, it grows at the expanse of transforms, which seem to require some degree of strength. Fig. 3 shows the transient evolution of a transform offset I obtained in a calculation I conducted for parameter exploration, which has similarities with those of Langemeyer et al. (2021), since plates are large and not many. The offsets develop through time and are not set from the start of the model.

Regional models of the lithosphere that are pulled from the sides can provide complementary views on transform systems. Gerya (2010) proposes that strain weakening is a major ingredient to nucleate and develop transform segments, which acts as instabilities in asymmetric ridges. 3D lithospheric models including grain size reduction initiate transforms when reaching extreme weakening (Schierjott et al., 2020). However, the results of global models and regional models seem to conflict at first sight. The missing connections come from: (1) weakening mechanisms have not been explored in 3D spherical models of convection yet, but attention is brought up and work is in progress (Fuchs and Becker, 2019; Rolf and Arnould, 2021) (modeling weakening is a big issue in terms of numerical methods, especially at a global scale (Duretz et al., 2020)) and (2) regional models show transform onset over <3-4 Myrs while global models have shown that the difficulty is to keep these structures stable for long periods if they are weak.

3.4. Subduction

Subduction appears as the essence of tectonics on Earth. When looking for the onset of plate tectonics, scientists search for clues of subduction within the oldest crustal minerals (Turner et al., 2020, for instance). In classical convection models, without strongly varying viscosity, the surface boundary layer is unstable and drips form and sink into the interior. Making the connection with subduction is another story since other characteristics are required. Among them, subduction on Earth is one-sided, with sheet-like structures dipping with a variety of angles, migrating and deforming the upper plate (Schellart, 2007; Husson, 2012).

3.4.1. Downwellings or subduction?

In 3D spherical models of convection with yielding, convergent boundaries are linear features, mostly arcuate depending on their width, and downwellings are sheet-like structures. Therefore, they have a lot in common with subduction zones on Earth. However, most models display two-sided subduction, with both sides of the boundary layer sinking into the interior. As a result, the cold downwellings are mostly vertical until they reach a rheological/phase boundary where their geometry can change (Yanagisawa et al., 2010). One-sided subduction is the extreme configuration of asymmetric subduction (Gerya et al., 2008). It is observed in convection models with yielding when a thin weak layer is continuously formed at the surface of the models (Crameri et al., 2012; Coltice et al., 2017b, 2019) and reinforced by the incorporation of a free-surface (Crameri et al., 2012; Crameri and Tackley, 2015). It can also be observed in models with strong viscosity gradients, which typically employ the viscosity law 2 (Coltice et al., 2017a; Arnould et al., 2018; Rodriguez et al., 2021; Coltice et al., 2019).

For the models with asymmetric to one-sided subduction, the more narrow the trench, the more arcuate and the faster their retreat, as predicted by regional models (Stegman et al., 2006). However, no systematic study has been made yet. Subduction is the singular dynamic feature for convection with plate-like tectonics. In a global model, no subducting slab remains isolated from the information in the whole system. It is typically a feature influenced by the systemic contraints, the collective interactions. They certainly inhibit some of the behaviors that can been studied in models and experiments involving the sinking of one or two isolated slabs into a box. For instance, the type of regime diagram found in state-of-the-art slab models (Garel et al., 2014) could be explored in the a large-scale context. For now, looking for situations in which the whole is smaller than the sum of the parts has not yet been done.

Another point to raise is the termination of trenches. While geological and seismological observation could favor the tearing of slabs on their sides (Jolivet et al., 2015), convection models display slab sides that are rolling-up (Fig. 4: Line 2). That difference may suggest again the importance of weakening mechanisms to complete the picture of an Earth-like tectonics in global models.

Slabs produced by convection models are very stiff in the upper mantle, generating strong toroidal motion around them, and buckle and fold within a more viscous lower mantle where they reside for long times and sink slowly. Therefore, the shape of slabs contrasts between upper and lower mantle structure, being well defined and in continuity with the surface in the former, and diffuse and folded around in the latter. Part of it comes from the viscosity jump, as in Strak and Schellart (2021) for instance, part of it comes from the existence of other slabs, plumes and dynamic features.

3.4.2. Onset of subduction

On Earth, most subduction zones initiated in the past 65 My (Gurnis et al., 2004) within oceans, and are fully active at present. The detection of incipient subduction is a very difficult task because it requires it exists today and we have enough observations to document it. Some examples are proposed (Duarte et al., 2021), but research is ongoing for definitive data to validate such hypothesis. In the literature, the variety of subduction initiation mechanisms comes from combinations of observations and regional modeling in which the initial configuration is imposed (Stern and Gerya, 2018, for a review). Again, the collective interactions are fundamental here to inhibit ranges of possibilities that can be found in models where onset of subduction is studied in isolation. Indeed, reviewing subduction initiation points to the impact of external contributors to the process on Earth (Lallemand and Arcay, 2021).

Little attention has been addressed to subduction initiation in convection models with yielding, except Crameri and Tackley (2016) and Ulvrova et al. (2019), the latter being in 2D. Subduction initiation is a result of self-organization. There is no weak zone placed initially to favor it in these models. Therefore, they appear where a dense instability can develop and where the local stress exceeds the yield stress. Crameri and Tackley (2016) observed that the impact of hot plumes favor subduction initiation by thinning locally the boundary layer (weakenning) and generating a lateral buoyancy contrast. Modeling of a free surface helps because the lateral pressure gradients caused by topography changes can be accounted in a better way than free slip boundary conditions. The existence of continental margins can focus a fraction of subduction initiation (Rolf and Tackley, 2011; Ulvrova et al., 2019). This can happen because continents are lighter, imposing a buoyancy gradient at the ocean-continent boundary (Nikolaeva et al., 2010; Lévy and Jaupart, 2012; Rey et al., 2014).

Digging into 3D spherical models of convection with plate-like behavior shows that subduction initiation and growth differs depending on the type of temperature dependence of the viscosity discussed before. The models with law 1 initiate subduction by boundary layer yielding that can operate at the scale of an ocean: subduction can initiate has a shear zone extending over thousands of kilometers (Fig. 4: Line 1). It never happens that way in models with law 2 (both Crameri and Tackley, 2016 and Ulvrová et al. 2019 uses that law). Subduction initiation starts on a very confined region and develops by extending the trench on both sides, in a growing arc fashion. In Coltice et al. (2019), subduction initiates where a local buoyancy contrast can grow, like a boundary between two basins of differing ages (Fig. 4: Line 2), or under the effect of a plume impinging on relatively young seafloor (Rodriguez et al., 2021).

The onset of subduction in convection models with yielding brings to the table the balance between stresses and buoyancy. The growth of a cold instability from the boundary layer happens for a critical nondimensional number in convection models without yielding, being a local critical Rayleigh number Ra_{cr}:

$$Ra_{cr} = \frac{\rho_0 g \alpha \Delta T \delta_{cr}^3}{\kappa \mu},$$

ρ_0 being the reference density, g the gravity acceleration, α the thermal expansion, ΔT the temperature contrast over the layer, δ_{cr} the critical thickness of the layer, κ the thermal diffusivity and μ the viscosity of the layer. Therefore, the fundamental value is the thickness of the layer, which is mostly determined by its thermal age. Without yielding, subduction happens when the boundary layer is locally old enough, thick enough.

When yielding comes into the story, two critical nondimensional numbers come into play, because the growth of the instability at the boundary layer scale (not small scale convection) imposes that the local stress exceeds the yield stress. Therefore, the first nondimentional number is the ratio between the yield stress and buoyancy:

$$S_b = \frac{\sigma_y}{\rho_0 g \alpha \Delta T \delta},$$

δ being here the local thickness of the layer. And the second nondimensional number is the ratio between the yield stress and viscous stresses:

$$S_t = \frac{\sigma_y \delta}{\mu \kappa},$$

which corresponds to the nondimensional yield stress often expressed in publications. The ratio of S_t/S_b is by definition the Rayleigh number. Therefore, to characterize the system, one needs either the Rayleigh number and one among S_b and S_t, or just S_b and S_t.

Because of a new condition on the stress to reach, the local Ra_{cr} can be exceeded. The lithosphere is unstable but strong enough not to yield and sink. Therefore small scale convection at the base of the boundary layer initiates, buffering the thickness of the boundary layer for seafloor ages exceeding the critical age. If not, the boundary layer can become even more thick and hence old modeled seafloor becomes extremely stiff because of the temperature dependence of the viscosity. As a consequence, initiating subduction on old seafloor is difficult because the local S_t is very large. Solomatov (2004) proposed that small scale convection could initiate subduction in convection models with yielding, bridging a theory and 2D numerical models using a Frank-Kamenetskii law for the temperature-dependence of the viscosity. 3D models using law 2 do not produce subduction initiation from small-scale convection. A reason is certainly related to the fact that small-scale instabilities have temperature contrasts proportional to the inverse of the local viscosity contrast ($\Delta\mu/\mu$) (Davaille and Jaupart, 1994). In the models using law 2, the viscosity gradients are so large at the base of the boundary layer that the buoyancy of small scale instabilities is not strong enough to generate yielding. Therefore, stronger buoyancy effect are required as plumes, continent-ocean boundaries or boundaries between basins of contrasting ages (transform motion, or a scarred plate boundary).

The published models of convection with yielding in 3D are not yet able to take into account some relevant physics for subduction initiation on Earth: weakening, viscous anisotropy or melting among others. For now, they can only account for the feedbacks between instantaneous stresses and buoyancy.

4. Outlook

20 years of modeling mantle convection with plate-like behavior have opened the gates between lithospheric modeling and convection modeling. The tools are now similar for many research groups: Stokes solvers with variable material properties and rheologies that are projected in the viscous space, pseudo-plasticity being one of them. Parallel supercomputers provide the computational power to determine the numerical solutions in 3D. These models, as any model, are imperfect. Therefore, it is useful to carry experiments and compute other kinds of numerical models (Morra et al., 2007; Bonnardot et al., 2008; Combes et al., 2012; Gerardi et al., 2019, for instance) to identify the areas of progress and increase awareness on their use. The convergence of modeling approaches between communities that tackle tectonics from 2 sides is very promising. Communities already gather in common science meetings. However, it will still take time for both approaches to reach their prime: mantle convection models are requested to account for the essential rheological behaviors identified by microphysics and lithospheric modeling (Burov and Watts, 2006; Bercovici and Ricard, 2014, among others), and lithosphere models are requested to initiate the regional models with temperature and chemical fields consistent with self-organized convection.

Yet, convection models with yielding can be used to study the underlying mechanisms of plate tectonics in a way geological observations come into play (Mallard et al., 2016; Rolf and Pesonen, 2018; Rolf et al., 2018; Ulvrova et al., 2019; Coltice et al., 2019; Rodriguez et al., 2021; Langemeyer et al., 2021). How plate boundaries initiate, evolve and cease, how the tectonic jigsaw reorganizes, how continents break and mountains build in details, and so many other questions. These models provide a systemic approach to core questions that have remained unanswered since the birth of plate tectonic theory.

I focus then on 4 major points to deal with:

- **Rheology vs. initial conditions.** The answer to a tectonic problem is often searched within rheological parameters, especially in regional models. It is natural because these models specify thermal initial conditions built on assumptions. However, the consistency between rheology and initial conditions is harshly and rarely met. Ideally, the initial set up with the physical parameters used should correspond to a solution, obtained from solving the equations, being a self-organized state. For instance, the initial conditions (boundary layer temperature distribution, temperature at depth) for a subduction model is supposed to be built on a convection model with the chosen parameterization. The forces applied on a lithospheric model are supposed to be consistent with what a 3D model that self-organizes would produce. Taking Earth-like conditions is not consistent with a choice of parameters which, by essence, cannot match exactly and comprehensively with the Earth (material properties but also physics). As a consequence, varying the rheology of the model tells that what is observed comes from feedbacks between the initial conditions and the parameterization. These are non-linear feedbacks. The question is then: does the result express consequences of uncertainties or relevant mechanisms? And in a complex system, it is very hard to separate both possibilities. Additionally, the whole is smaller than the parts, which leads to the question: does the observed behavior express when interactions exist?

- **Memory.** Localization with memory is a step to make for 3D spherical convection models. For now, yielding in these models mean instantaneous yielding and healing. Although, there is already a strong effect of thermal and chemical memory. Indeed, 100 My is a typical time scale for a thermal anomaly to die out, and even more for a chemical anomaly (a continental block for instance). A plume, a ridge, or a subduction imposes a thermal anomaly which in turn produces a rheological anomaly that persists for a long time. Wether memory driven by grain size reduction and growth dominates over thermal/chemical memory is a relevant question and depends on the time and space scales of the process studied. Coltice and Shephard (2018) and Bello et al. (2015) highlighted this issue: differences in initial conditions produce quick differences in terms of tectonics and thermal state, that are larger or comparable to differences in rheological parameters. Also, buoyancy is the driving force of the system, rheology is a filter to its expression. In a system that self-organizes, thermal anomalies develop on their own depending on the full organization of the flow, not necessarily where a weak zone exists (Fuchs and Becker, 2019). A classical property in a complex system is that although emergence implies that the whole is more than the sum of the pieces, the sum of the pieces is also more than the whole. Indeed, the interactions between the pieces are constraining the global structures. Therefore, while memory (being a local property) in an isolated regional model is dominant and can express, the interactions between dynamic regions of a global model (producing self-organization) may inhibit that effect in the final structuration.

- **Automatic analysis of tectonics.** Analyzing the tectonics of 3D spherical models with fine resolution that generate billions of years of geological histories is a challenge. Tectonics is in the details of the structure. On Earth, plates are a first way to map global structures, before zooming into them and their boundaries. It is primordial that computers can identify automatically discrete structures in 3D, or at least give some help. Computer vision and machine learning strategies are promising and will give a boost to studying tectonics in 3D global models (Bremer et al., 2010; Mallard et al., 2017; Duclaux et al., 2020; Wrona and Brune, 2021; Tierny et al., 2017).

- **Inverse methods.** 3D spherical models of convection with plate-like behavior can already be predictive enough to be used for inverse modeling (Coltice and Shephard, 2018; Coltice et al., 2019), depending of course on what the inverse problem is. Using these models to inverse geological and geophysical observations, without making assumption on the tectonic history, would open a way to make reconstructions without the plate tectonic assumptions. Data assimilation tests on simple models are promising (Bocher et al., 2016; Li et al., 2017; Bocher et al., 2018), but there is still a step to make to push these inverse models towards 3D sphericity and time-dependence. The leap forward that oceanography has made for circulation reconstructions could be in reach in the next years, with the promise to bring together tectonic and deep flow reconstructions.

5. Final thoughts

Models of global convection with yielding generate emergent tectonics at the surface within a range of parameters. The patterns observed within the top cold boundary layer rarely simply mirror the flow structure in the weaker hot mantle beneath it. The models which have been developed in the past 20 years are computationally demanding in 3D, but provide unique ways to investigate how deformation at the surface of planets evolve, how lithospheric shear zones of any kind initiate, develop, cease, interact with each other and deep flow. For now, these models have barely been employed to study the physics at play for emerging tectonic features like ridges, transform, subduction, collision, continent cycles... But the bridge with lithospheric models is close to be built, pushing the modeling towards a synergistic approach. In convection models with plate-like behavior, the systemic complexity precludes simple causal links, such as "subduction triggers a rift", "this plume breaks this continent", "plate velocity accelerates thanks to this subduction initiation", because a full set of interactions at a variety of scales generate a single self-organized state, that can substantially alter if a small perturbation is added. It is easy to end up in the chicken or egg question, and difficult to work looking for simplicity or Occam's razor principles. An illustration of the causality blindness is given by Lorenz (1972) when discussing the butterfly effect in complex chaotic systems:

"1. If a single flap of a butterfly's wing can be instrumental in generating a tornado, so all the previous and subsequent flaps of its wings, as can the flaps of the wings of the millions of other butterflies, not to mention the activities of innumerable more powerful creatures, including our own species.

2. If a flap of a butterfly's wing can be instrumental in generating a tornado, it can equally well be instrumental in preventing a tornado."

Change tornado to subduction, and the flap of a butterfly's wing to an earthquake and it would fit the convection-tectonics system. Even though looking for causal links between slabs, plumes, plates and other dynamic features seems vain, convection models with yielding provide a full description of the fields involved (temperature, velocity, rheology), helping to investigate systematics, and how tectonics rely on the physical parameters being the underlying program of the emerging diversity. The physics of these models is relevant to the Earth, but also to the planets of our solar system, allowing to investigate the intrinsic properties leading to their unique identity. The hologram metaphor suggests tectonic structures contain information about the whole history of planetary interiors. Geodynamic models are a source of light to reveal it.

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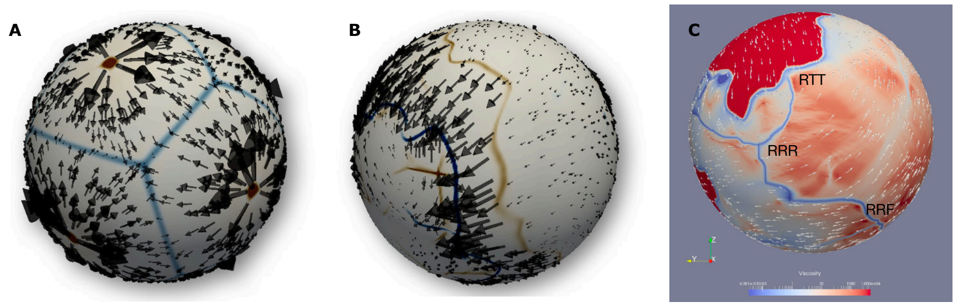

Figure 1: A: Surface velocities, diverging area in blue and convergent area in red in a convection model with viscosity varying only radially (model "Radial viscosity - basal heating" in Coltice et al., 2019). B: Surface velocities, diverging area in blue and convergent area in red in a convection model with viscosity varying only radially (model "Reference model" in Coltice et al., 2019). C: 3D snapshot of the viscosity at 10km depth on the hemisphere of a convection model, showing triple junctions (RRR=ridge-ridge-ridge, RTT=ridge-trench-trench and RRF=ridge-ridge-transform). Arrows show the direction of the velocity at the surface. The convection model has the same parameterization as that of Coltice et al. (2017), but with continental rafts initially positioned as Pangea. Thermal initial conditions are obtained running the code fixing the tracers until a statistical state is reached.

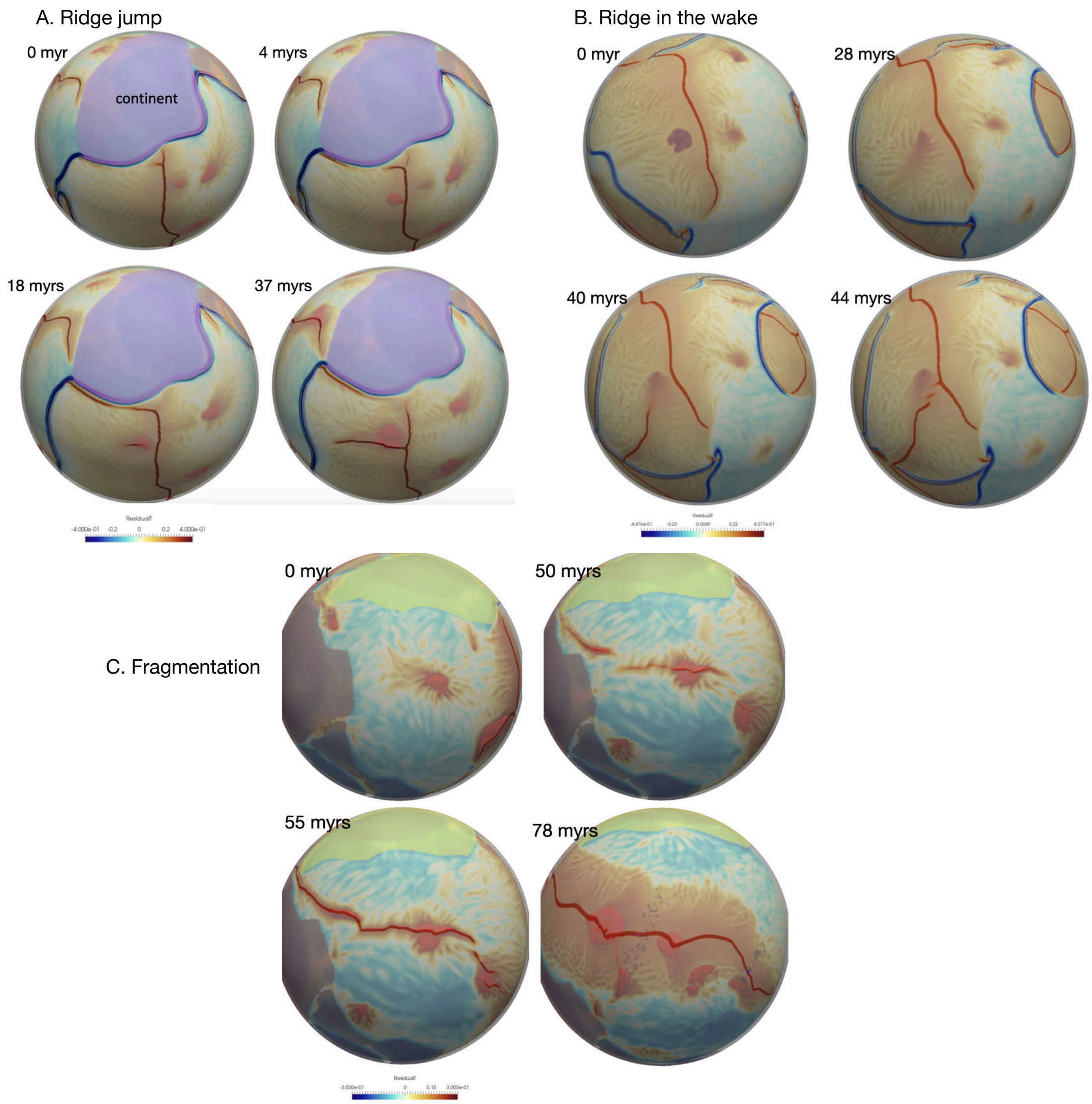

Figure 2: 3D snapshot of plate fragmentation styles involving plumes. Convection model corresponds to running the model of Coltice and Shephard (2018) without imposing plate motions. Color is the non-dimensional residual temperature (temperature difference with the lateral mean) at depth 50km. Red isotherm of non-dimensional temperature 0.9 highlight plume position (except in B). Continental rafts are shaded areas (except in B). A. corresponds to a ridge switching direction under the influence of a plume. B. corresponds to fragmentation occuring within the wake of the plume. C. corresponds to the fragmentation of a large ocean basin.

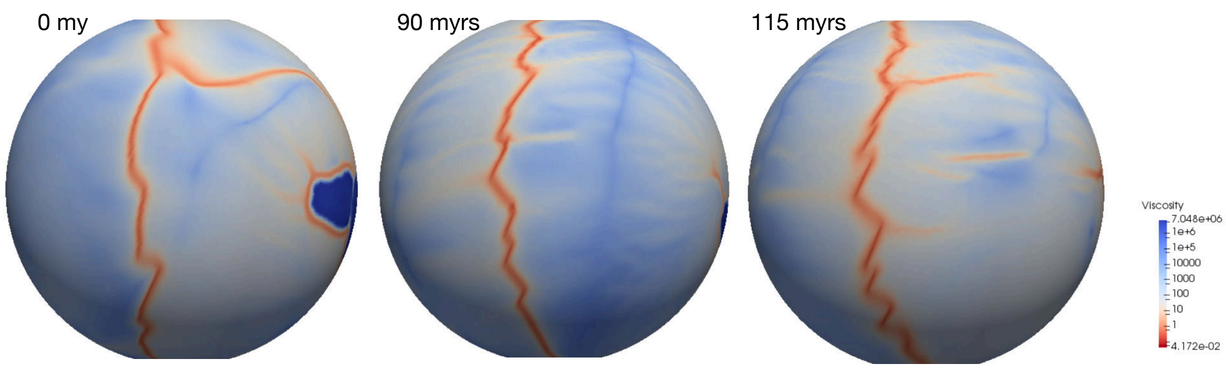

Figure 3: 3D snapshots of the development of transform-like shear zones in a convection model built on Earth's continent model in Coltice et al. (2017) but with weaker continental lithosphere on their edges. Weaker means viscosity and yield stress are both 10 times lower than that of the mantle. These edges get easily recycled and stretched within the convective system and can reach the surface again.

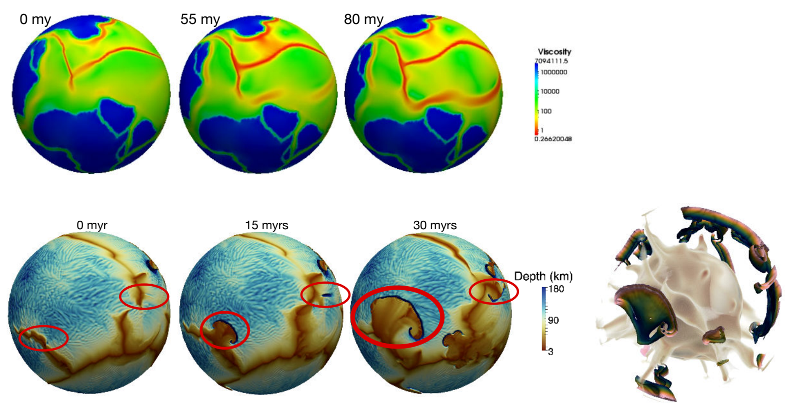

Figure 4: Line 1: 3D snapshots of model PLC1 in Bello et al. (2014) showing the initiation of a linear subduction zone close to the equator. Line 2: 3D snapshots of the fine resolution model in Coltice et al. (2019), showing initiation of subduction. In the southern hemisphere, subduction initiates around a plume. In the East side of the northern hemisphere, a subduction initiates close to a ridge at a smooth boundary between to basin of slightly different ages. On the left: Corresponding interior structure of the 30 Myr snapshot. Hot isotherm shows the presence of plumes. Cold isotherm is colored by depth and represents the sinking slabs in the upper mantle of the model. The sides of the slabs in such model are rolling up.