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Ultraslow, slow, or fast spreading ridges: Arm wrestling between mantle convection and far-field tectonics

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ABSTRACT

Oceanic spreading rates are highly variable, and these variations are known to correlate to a variety of surface observables, like magmatic production, heat flow or bathymetry. This correlation lead to classify ridges into *fast* and *slow* spreading ridges, but also into the more peculiar *ultraslow* spreading regime. Here we explore the dynamic relationships between spreading ridges, plate tectonics and mantle flow. We first focus on the thermal signature of the mantle, that we infer from the global S-wave seismic tomography model of Debayle and Ricard (2012). We show that the thermal structure of ridges gradually departs from the half-space cooling model for slow, and above all ultraslow spreading ridges. We also infer that the sublithospheric mantle temperature decreases by more than 150 °C from fast to ultraslow spreading regimes. Both observations overall indicate that the mantle convection pattern is increasingly chaotic underneath slow and ultraslow spreading ridges. We suggest that this is due to far-field tectonics at the other ends of lithospheric plates: not only it modulates the spreading rates but it also alters the convection regime by obstructing the circulation of plates, which in turn modifies the surface kinematic conditions for the convecting mantle. We test this hypothesis using a thermo-mechanical model that represents a convection cell carrying a continental lithosphere atop. The continent gradually drifts away from the spreading ridge, from which the oceanic lithosphere grows and cools while the continent eventually collides at the opposite side. In turn, this event drastically modifies the upper kinematic condition for the convecting mantle that evolves from a *mobile* lid regime to an almost *stagnant* lid regime. Implications on spreading ridges are prominent: heat advection decreases with respect to thermal conduction, which causes the oceanic lithosphere to thicken faster; the oceanic plates get compressed and destabilized by a growing number of small scale transient plumes, which disrupt the structure of the oceanic lithospheres, lower the heat flow and may even starve ultraslow ridges from partial melting. It follows that the spreading rate of a modern ridge mirrors its status in the global plate tectonics framework within a unique breakup, drift, collision scenario, within the transition from mobile to stagnant lid, and that it is the same mechanism that build mountains at converging boundaries and control spreading rates. Oceanic ridges thus can be regarded as a sensor of the resisting rather than driving forces. Both the model and the seismic structure of the mantle underneath ridges reveal that the temperature variations are largest at shallow depths in the upper mantle, i.e. at the critical depth where the melt supply to the above ridges can be modulated, thereby also explaining why slow and ultraslow ridges are almost exclusively associated to cold mantle. It follows that the chemistry of oceanic ridge basalts may not strictly reveal the mantle potential temperature, but the variations in the sublithospheric temperature field.

1. Introduction

Mid-oceanic ridges display a wide range of tectonic velocities. Similarly to subduction rates, spreading rates have been tentatively correlated to a variety of physical, geochemical, and morphological characteristics of spreading ridges (e.g., Chen and Morgan, 1990; Bown and White, 1994; Shen and Forsyth, 1995; Klein and Langmuir, 1987). The most striking results is the remarkably uniform crustal thickness for ridges with spreading rate above 15 mm/yr (∼7 km; Chen, 1992; White et al., 1992), excepted near hotspots and fracture zones. However, this monotonic rule breaks down for

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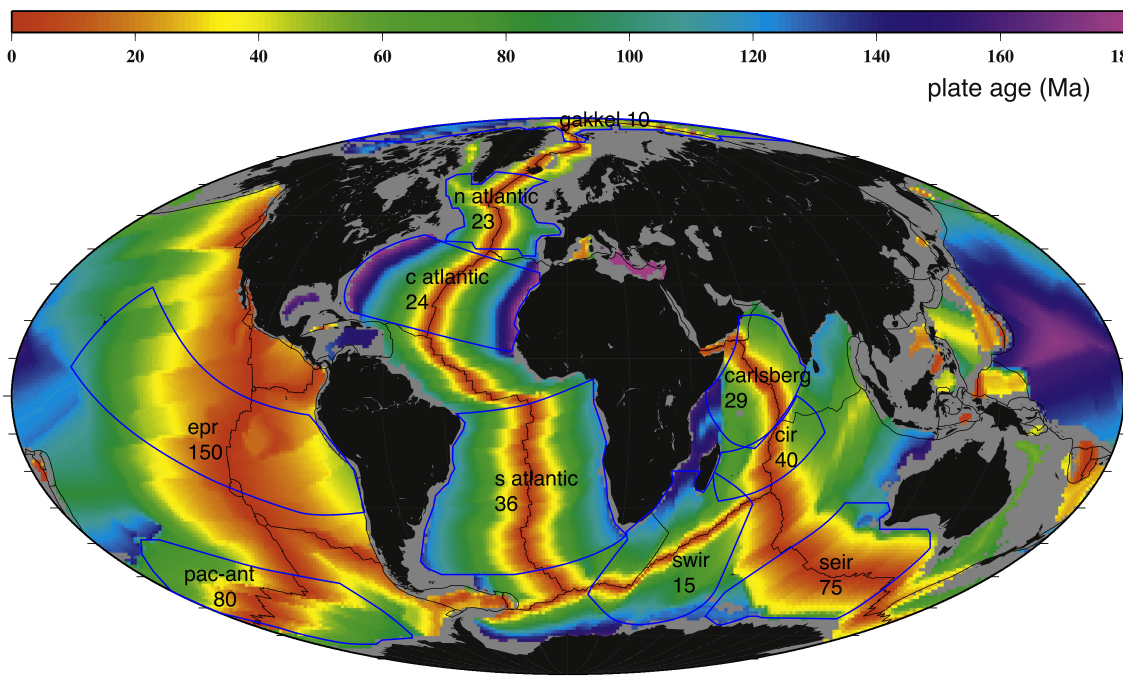

Fig. 1. a) Seafloor age map (Müller et al., 2008). Ridge labels and maximum spreading rates (mm/yr). *epr*: East Pacific Rise (Nazca/Pacific); *pac-ant*: Pacific–Antarctic ridge (Pacific/Antarctic); *seir*: South East Indian Ridge (Australia/Antarctic); *s atlantic*: South Atlantic ridge (Africa/South America); *carlsberg*: Carlsberg ridge (Africa/India); *c atlantic*: Central Atlantic ridge (North America/Africa); *n atlantic*: North Atlantic ridge (Eurasia/North America); *swir*: South West Indian Ridge (Antarctic/Africa); *gakkel*: Gakkel ridge (Eurasia/North America). Blue contours delineate the location of the oceanic domains considered for oceanic plate pairs across ridges. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

very low spreading rates (i.e. at *ultraslow* spreading ridges, below the threshold value of 15 mm/yr), where thinner crusts are systematically observed (Reid and Jackson, 1981). The observation that the ultraslow South West Indian Ridge (*SWIR*) and Gakkel ridges (Fig. 1) are *a*-volcanic, and possibly *a*-magmatic (Cannat, 1993; Dick et al., 2003; Cannat et al., 2008), eventually attests for a low melt supply that do not fulfills the demand for a ∼7 km thick crustal layer. This property has been interpreted as resulting from a variety of processes, including mantle composition (Zhou and Dick, 2013), melt focusing within the mantle (Dick et al., 2003; Chen, 1992), along axis melt redistribution (Fox et al., 1995; Curewitz and Karson, 1998; Chen, 1992; Sauter et al., 2011), shortening of the melting column within a thicker conductive thermal lid (Reid and Jackson, 1981), ridge obliquity relative to plate motion (Dick et al., 2003), or simply by overall lower mantle temperature (Cannat, 1993). Hydrothermal cooling within the variable fracture networks at slow and fast ridges is also often invoked (Phipps Morgan and Chen, 1993). However, the cause of this lower thermal regime remains unclear at the ridge scale, for departure from a mean spreading rate is also interpreted as depending on the deep thermal regime, implying that buoyancy driven mantle flow controls the behavior of ridges (e.g. Sotin and Parmentier, 1989; Su et al., 1994). Ultraslow ridges would correspond to a cool enough mantle to starve ridges from the magmatic supply.

Here, we explore the possibility that plate tectonics and continental drift not only modify plate velocities – including spreading rates – but may also alter the pattern of the long-wavelength thermal regime of the mantle, in particular at shallow depths where it may disturb oceanic accretion. We suggest that spreading rates are not modulated by the vigor of the underlying mantle convection but instead by the tectonics acting at the opposite plate boundaries. This reasoning is driven by kinematic clues: spreading of the *SWIR* was twice faster before the Late Eocene onset of the Alpine collision between the African and Eurasian plates, and gradually decreased from that time onwards (see for instance the reconstructions of Müller et al., 2008), reflecting the declining northward absolute velocity of the African plate (e.g. Dewey et al., 1989; Silver et al., 1998). To the North, the Alpine collision increased the resistance to plate motion and impedes further northward motion of Africa; to the South, the Antarctic plate, being circumscribed by ridges, also opposes any motion. Overall, we hypothesize that this change in the dynamics of the Tethyan margin modulated the spreading rates of the *SWIR* down to its current value. The second modern example, *viz.* the Gakkel ridge, always spread at low rates, due to the resistance at the opposed plate boundaries of the massive Eurasian and North American continents that systematically precluded fast spreading. Overall, we suggest that the effect of continental aggregation or slab anchoring at active margins is to prevent plate motion and alter mantle flow by changing the surface boundary condition from mobile lid to sluggish or stagnant lid (Yamato et al., 2013). This mechanism would in turn decrease the heat supply to the mantle underneath ridges in particular, thereby modulating primordial features such as magmatic productivity and crustal thickness, heat flow, ridge bathymetry, and lithospheric aging. In the following, we investigate the intricate relationships between plate tectonics, mantle convection and ridge spreading, first by means of an analysis of the seismic geometry of the spreading lithospheres near their ridges, and secondly thanks to a thermo-mechanical model designed to test our hypothesis on the dynamics of the system and to predict the thermal evolution of the spreading lithosphere.

2. Seismic structure of spreading lithospheres and mantle temperature variations

The common understanding that the thermal structure of the lithosphere obeys a first-order dependence on the square root of age has been inferred for long (e.g. Parsons and Sclater, 1977; Turcotte and Schubert, 2002). Seismic tomography independently validated this theory wherein oceanic plates are thermal boundary layers cooling over the convecting mantle (Ritzwoller et al., 2004;