Physics of the Earth and Planetary Interiors 171 (2008) 265–279

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Episodicity in back-arc tectonic regimes

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ARTICLE INFO

Article history:
Received 31 October 2007
Received in revised form 19 March 2008
Accepted 25 April 2008

Keywords:
Subduction
Back-arc extension
Episodicity
Slab rollback
Hinge-migration
Fluid dynamic modelling
Sea-floor spreading

ABSTRACT

The evolution of back-arc basins is tied to the development of the dynamics of the subduction system they are a part of. We present a study of back-arc basins and model their development by implementing 3D time-dependant computer models of subduction including an overriding plate. We define three types of episodicity: pseudo-, quasi- and hyper-episodicity, and find evidence of these in nature. Observations of back-arc basin ages, histories of spreading, quiescence and compression in the overriding plate give us an understanding of the time-development of these subduction zones and back-arc basins.

Across the globe today, a number of trenches are advancing—the Izu-Bonin Trench, the Mariana Trench, the Japan Trench, the Java-Sunda Trench and the central portion of the Peru-Chile Trench (the Andes subduction zone). The Izu-Bonin, Mariana and Japan all have established back-arc basins, while the others have documented episodes of spreading, quiescence, compression or a combination of these. The combination of advancing and retreating trench motion places these subduction zones in the category of hyper-episodicity.

Quasi-episodicity, in which the back-arc shifts between phases of rifting, spreading and quiescence, is the dominant form of episodic back-arc development in the present. We find this type of episodicity in models for which the system is dynamically consistent—that we have allowed the subducting plate's velocity to be determined by the sinking slabs' buoyancy. Quasi- and hyper-episodicity are only found in subduction zones with relatively high subducting plate velocities, between 6 and 9 cm/year. Finally, those subduction zones for which the subducting plate is moving slowly, such as in the Mediterranean or the Scotia Sea, experience only pseudo-episodicity, where the spreading moves linearly towards the trench but often does so in discrete ridge-jump events.

1. Introduction

The development and evolution of back-arc basins represents a fundamental process of plate tectonics, many aspects of which remain unexplained. Part of the enigmatic nature of back-arc basins is that while they form at convergent plate boundaries, they represent extensional processes which are opposite to the sense of convergence. Even after extensional stresses generated from trench rollback (and retrograde migration of their associated slabs) were identified as the likely origin of back-arc basins (Dvorkin et al., 1993; Faccenna et al., 1996; Jolivet et al., 1994), the exact mechanism as to how subduction dynamics controlled the process was not apparent. Thus, the problem of back-arc basin formation serves as a clear indicator that our understanding of subduction remains inadequate.

Some insight can be gained into these processes by considering the kinematics associated with back-arc basins, which reflect the product of relative motions between the trench, the subducting plate and the overriding plate. A large amount of episodicity can be seen in the recent kinematic synthesis of Sdrolias and Müller (2006), which reports the evolution of back-arc basins in the Pacific ocean during the past 60 Ma. The distribution of sea-floor age suggests extension alternating with phases of tectonic quiescence or compression. Similar arguments can be made for observations related to orogenesis, that the state of mountain building is determined by the trench velocity, and whether it is advancing towards the overriding plate or retreating from it (Lister et al., 2001).

Recent global compilations of the trench motion demonstrate that between 50% and 75% of trenches (depending on choice of absolute reference frame) are currently retreating (Lallemand et al., 2005; Schellart et al., 2007). The remaining trenches are either neutral or advancing, and in the Indo–Atlantic hotspot reference frame there are only a few trenches advancing at present: Japan (1.5 cm/year), Izu-Bonin (2.65 cm/year), Mariana (1.85 cm/year), Sunda (0.7 cm/year), Hikurangi (2.1 cm/year) and

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doi:10.1016/j.pepi.2008.04.012

Bolivia (0.5 cm/year) (Schellart et al., 2007). However, the static view for the present day can be misleading with regards to the motion of trenches because although plate motions may generally be considered smooth and continuous, the motion of plate boundaries is not.

There are other processes besides trench motion which are important in producing back-arc basins, but may also greatly influence the episodicity of basins. Extensional forces may arise from gravitational collapse of regions with thickened crust (Martinod et al., 2000) or from far-field stresses due to changes in plate direction and continent–continent collisions (Silver et al., 1998). These effects have been shown to be important for back-arc basin development in the Aegean and Japan Seas as their contribution likely modulated the more dominant extensional forces from roll-back subduction (Jolivet et al., 1994).

One well-documented case of back-arc basin evolution is that of the Central Mediterranean (Faccenna et al., 2001 and references therein). There, two episodes of extension have occurred since 30 Ma, each beginning with slow rifting and punctuated with fast back-arc spreading. The Liguro-Provençal basin was formed by thinning and rifting for ~8 Myr between 30 and 22 Ma, followed by ~6 Myr of oceanic spreading between 22 and 15 Ma. There is then an apparent 5 Myr hiatus in extension while the ridge jumps to the southeast from 16 to 10 Ma. Extension then resumes for a 5 Myr period of rifting and subsidence, forming the Tyrrhenian basin, followed by new spreading centres within the basin active from 5 Ma to present. These two spreading centres show a linear progression towards the retreating trench (Faccenna et al., 2001; Spadini and Podladchikov, 1996). We classify this as pseudo-episodicity as the overriding plate rheology leads to distinct phases of back-arc spreading although the trench motion is in constant retreat.

The best examples for studying the development of back-arc basin are the large intra-oceanic basins of the Western Pacific. These include the Shikoku, Perace Vela, West Phillipine, Lau, North-Fiji and South Fiji Basins, the Japan, South China and Sulu Seas, as well as the Marianas Trough. We use revised interpretations and compilations of the history of seafloor spreading (Müller et al., 2006) in these regions, as well as a few regions outside the Western Pacific, for example the Scotia Sea. These are combined with recent observations in other nearby marginal basins which together form an ensemble of basins associated with an individual subduction zone. The pattern which emerges from such a synthesis may then be placed into context with the regional dynamics as they are controlled by subduction processes. This regional view of back-arc basin evolution applied worldwide can provide a framework for distinguishing between different types of observed episodicity.

There is a variety of episodicity exhibited in regions with back-arc basins which ultimately reflect the evolution of the stress field. In some cases, extension may be continuously ongoing but an apparent hiatus in extension is either due to a lack of data or a ridge-jump followed by a period of rifting preceding extension, such as the case in the Mediterranean. Either of these cases we term pseudo-episodic. Otherwise, episodic behaviour is observed when extension is interrupted by periods of quiescence (i.e. an actual hiatus of extension) or compression, which we term quasi-episodic and hyper-episodic, respectively.

Various approaches have been adopted for investigating how subduction influences the stress field in the overriding plate. Compilations of subduction related parameters and relevant geologic observations in the overriding plate have been made with the goal to classify tectonic regimes and identify correlations (Heuret and Lallemand, 2005; Jarrad, 1986; Lallemand et al., 2005; Whittaker et al., 2007). Attempts to quantitatively understand how particular parameters affect the dynamics of subduction systems are largely based on analogue and numerical models, however, the full complexity of subduction is difficult to address. Consequently, models typically introduce one or more simplifications such as restricting the dynamics to a 2D geometry, not including an overriding plate or including an overriding plate but in the absence of any interaction with the fluid mantle. Furthermore, many models are not dynamically self-consistent because conditions such as plate speed, trench location or dip angle have been prescribed a priori.

Much of the attention spent on understanding subduction-driven dynamics of the overriding plate has been focused upon the use of 2D numerical models (Buiter et al., 2001; Sobolev and Babeyko, 2005). However, in regard to back-arc basins, the motion of the trench is of primary importance in controlling the time-dependent stress field in the region of the plate boundary. Unfortunately, most 2D models do not achieve self-consistent trench motion because in order to produce one-sided subduction, either the trench location, trench motion or plate motion are prescribed. Models of free subduction are preferable because they treat trench and plate kinematics as emergent features completely driven by the negative buoyancy of the subducting slab (Enns et al., 2005; Funiciello et al., 2003b; Garfunkel et al., 1986). However, one of the limiting factors in models of free subduction has been to include an overriding plate, a plate that interacts strongly with the subducting slab.

Because subduction zones have a finite lateral extent, the mantle flow induced by subducting slabs and the associated subduction dynamics is inherently three-dimensional. A number of analogue and numerical studies have demonstrated that 3D geometry is essential in order to allow mantle flow around slab edges and generate rollback subduction (Dvorkin et al., 1993; Funiciello et al., 2003a; Garfunkel et al., 1986; Schellart, 2004). It was postulated and shown analytically that the corner flow of 2D numerical models is only applicable to 3D models if subducting slabs are sufficiently wide (Dvorkin et al., 1993).

Such wide slabs (infinitely wide in 2D) prevent mantle flow around the edges of the subducting slab, and the entire mantle flow is forced around the tip of the slab. This reduces the ability of the mantle to flow from underneath the slab to the top of the slab, leading to a difference in pressure and a consequent hydrodynamic lift force that supports the slab the slab and inhibits rollback. The mantle flow around the edges of narrow slabs significantly reduces the pressure exerted on the slab, and this reduction is entirely dependent on the finite extent of the slab. The reduced corner suction allows the weight of the slab to exceed the strength of the subducting plate (i.e. the plastic yield stress limit integrated over the plate thickness). This drives an instability expressed as retrograde hinge migration (rollback) in narrow slabs which has been attributed to the origin of back-arc basins and back-arc spreading in the overriding plate (Dvorkin et al., 1993).

This effect is seen quite dramatically in fully dynamic models when the lateral extent of the subducting plate is varied for the full range of plate widths (300–7000 km) that occur on Earth and plate width is a controlling factor for how trenches move and evolve with time (Schellart et al., 2007). Much of the recent work in 3D has been focused on investigating dynamics of a subducting plate and its associated mantle flow in the absence of any overriding plate (Bellahsen et al., 2005; Funiciello et al., 2003a; Morra et al., 2006; Schellart, 2004; Stegman et al., 2006). However, some studies account for the effect of density perturbations due to ridges and plateaus on the subducting plate (Martinod et al., 2005; Royden and Husson, 2006).

Early analogue experiments demonstrated that extension in the overriding plate is a direct consequence of retrograde slab migration (Kincaid and Olson, 1987). Although these models used a free subduction approach which incorporated an overriding plate, no systematic or quantitative investigation of the dynamics of the