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Editorial

Introduction to the special issue celebrating 200 years of geodynamic modelling

ABSTRACT

Since the first published laboratory models from Sir James Hall in 1815, analogue and numerical geodynamic modelling have become widely used as they provide qualitative and quantitative insights into a broad range of geological processes. To celebrate the 200th anniversary of geodynamic modelling, this special issue gathers review works and recent studies on analogue and numerical modelling of tectonic and geodynamic processes, as an opportunity to present some of the milestones and recent breakthroughs in this field, to discuss potential issues and to highlight possible future developments.

1. Introduction

Analogue and numerical geodynamic modelling have become an essential tool in the Earth Sciences to study the evolution of geological processes. Since the first publication of laboratory experiments by Sir James Hall (Hall, 1815) to model folds observed in geological strata two centuries ago, modelling has seen major advances and breakthroughs. The emergence of new techniques in the laboratory, the advent of the scaling theory (Hubbert, 1937), and the development of numerical algorithms, codes and fast computers have all contributed to create the discipline of geodynamic modelling as we know it today. Resulting studies have provided qualitative and quantitative insights on a wide range of small-scale and large-scale geological processes including boudinage (e.g. Treagus and Lan, 2000; Passchier and Druguet, 2002; Zulauf et al., 2011; Abe and Urai, 2012; Marques et al., 2012), porphyroclast rotation (e.g. Passchier and Sokoutis, 1993; Marques and Coelho, 2001; Schmid and Podladchikov, 2005; Griera et al., 2013), folding (e.g. Abbassi and Mancktelow, 1992; Braun and Sambridge, 1997; Burg and Podladchikov, 1999; Rosas et al., 2002; Schmalholz, 2008), faulting (e.g. Mandl, 1988; McClay, 1990; Sleep and Blanpied, 1992; Donzé et al., 1994; Adam et al., 2005), shear zone formation (e.g. Ildefonse et al., 1992; Tejchman and Bauer, 1996; Grujic and Mancktelow, 1998; Morgan, 1999; Schrank et al., 2008), diapirism (e.g. Vendeville and Jackson, 1992; van Keken et al., 1993; Poliakov et al., 1996; Warsitzka et al., 2013), magma intrusion (e.g. Donnadieu and Merle, 1998; Mériaux and Jaupart, 1998; Gerya and Burg, 2007; Mathieu et al., 2008; Kavanagh et al., 2015), volcanic processes (e.g. Dieterich and Decker, 1975; Armienti et al., 1988; Acocella et al., 2000; Roche et al., 2000), strike-slip tectonics (e.g. Naylor et al., 1986; McClay and Dooley, 1995; Leloup et al., 1999; Finzi et al., 2009; Gerya, 2010; Dooley and Schreurs, 2012), accretionary wedge deformation (e.g. Lallemand et al., 1992; Willett et al., 1993; Koyi, 1995; Burbidge and Braun, 2002; Malavieille, 2010), rifting (e.g. Vendeville et al., 1987; Braun and Beaumont, 1989; Allemand and Brun, 1991; Gupta et al., 1998; Burov and Poliakov, 2001; Lavier and Manatschal, 2006; Huismans and Beaumont, 2011), crustal and lithospheric scale deformation (e.g. England and McKenzie, 1982; Davy and Cobbold, 1991; Bird, 1999; Riller et al., 2010), interaction between tectonics and surface processes (e.g. Willgoose et al., 1991; Braun and Sambridge, 1997; Beaumont et al., 2001; Babault et al., 2005; Graveleau et al., 2015), plume growth (e.g. Whitehead et al., 1975; Griffiths, 1986; Farnetani and Richards, 1994; Ebinger and Sleep, 1998; Davaille et al., 2002; Jellinek et al., 2003; Kerr and Mériaux, 2004; Kumagai et al., 2007; Burov and Gerya, 2014), mantle convection (e.g. Schmidt and Milverton, 1935; Gurnis and Davies, 1986; Tackley et al., 1993; Bunge et al., 1996; van Keken et al., 1997; Moresi and Solomatov, 1998; Davaille, 1999; Zhong et al., 2000; Davaille and Limare, 2007; Davies et al., 2012), subduction (e.g. Jacoby, 1973; Bodri and Bodri, 1978; Garfunkel et al., 1986; Kincaid and Olson, 1987; Gurnis and Hager, 1988; Shemenda, 1993; Zhong and Gurnis, 1995; Funiciello et al., 2003; Kincaid and Griffiths, 2003; Schellart, 2004; Govers and Wortel, 2005; Sobolev and Babeyko, 2005; Stegman et al., 2006; Capitanio et al., 2007; Kneller and van Keken, 2007; Schellart et al., 2007; Schmeling et al., 2008; Jadamec and Billen, 2010; Liu and Stegman, 2012; Duarte et al., 2013; Crameri and Tackley, 2014; Duretz et al., 2014; Moresi et al., 2014; Rodríguez-González et al., 2014; Marques and Kaus, 2016; Chen et al., 2016), and collision (e.g. Tapponnier et al., 1982; Vilotte and Daignières, 1982; England and Houseman, 1988; Peltzer and Tapponnier, 1988; Beaumont et al., 1996; Sokoutis et al., 2005; Schueller and Davy, 2008; Willingshofer and Sokoutis, 2009; Gray and Pysklywec, 2012; Krystopowicz and Currie, 2013; Bajolet et al., 2015).

This special issue builds on two conference sessions that were held at the 2015 General Assembly of the European Geosciences Union in Vienna, in celebration of the 200th anniversary of geodynamic modelling. One regular session (TS8.2) grouped recent studies and focused on their breakthroughs within the framework

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of the state of the art of geodynamic modelling. Another session (US2) gathered six solicited speakers to highlight historical developments and findings in geodynamic modelling and possible future developments in a broad range of disciplines in the Earth Sciences. The special issue aims to gather both review works and new studies on analogue and numerical modelling of tectonic and geodynamic processes from the crustal scale to the planetary scale. The volume provides an opportunity to synthesize some of the historical milestones in the field of geodynamic modelling, to focus on recent breakthroughs and to open a way to possible future progress for a broad range of tectonic and geodynamic processes such as morphotectonic processes, accretionary wedge processes, rifting, crustal deformation, craton margin dynamics, collision, subduction, convection and plume-lid tectonics. An additional special issue is currently under development in the journals Solid Earth and Earth Surface Dynamics (with editors Susanne Buiter and Andreas Lang), primarily based on the EGU2015 session US2 with a focus on two centuries of modelling in the Geosciences across scales.

2. Contributions to this special issue

This special issue of the Journal of Geodynamics gathers thirteen contributions on analogue and numerical geodynamic modelling. These contributions include three review articles and ten research articles that focus on recent state-of-the-art modelling of large-scale geodynamic processes. Among the research articles, four are analogue modelling studies performed in the Earth's gravitational field (Ding and Li, 2016; Malavieille et al., 2016; Saha et al., 2016; Wang et al., 2016) and six are numerical modelling studies (Arredondo and Billen, 2016; Currie and van Wijk, 2016; Feng et al., 2016; Fischer and Gerya, 2016; Rodríguez-González et al., 2016; Sternai et al., 2016). The four papers on analogue geodynamic modelling study crustal to lithospheric deformation. From the six papers on numerical geodynamic modelling, one paper focuses on crustal deformation (Feng et al., 2016), one paper investigates craton margin dynamics (Currie and van Wijk, 2016), two studies focus on subduction (Arredondo and Billen, 2016; Rodríguez-González et al., 2016), one study investigates collision and subduction (Sternai et al., 2016) and one paper studies early Earth plume-lid tectonics (Fischer and Gerya, 2016).

The first contribution to the special issue is a review paper from Schellart and Strak (2016) that discusses the approaches, scaling, materials and quantification techniques used in analogue geodynamic models performed in the Earth's field of gravity, and reviews how these apply to analogue models of subduction. The paper particularly inventories the different fundamental modelling approaches and classifies them in three categories in relation to how energy drives the model (internally, externally, or a combination thereof). A discussion is then proposed on the advantages and limitations of these modelling approaches and on how they are relevant to investigate specific geodynamic problems. The paper also makes a review of the scaling method in the Earth's gravitational field, discusses some scaling issues related to scaling topography in models to nature, and proposes a correction factor for the scaling of topography. Furthermore, the review makes a classification of the various rheological approaches and materials used in laboratory modelling to simulate the horizontal rheological layering of the Earth. It then discusses which methods are appropriate to simulate specific geodynamic processes depending on the modelling approach in use. Finally, the paper also lists the different techniques used to qualitatively and quantitatively analyse the models.

The second contribution is a review paper from King (2016), which discusses how mantle rheology, as constrained from geophysical and experimental observations, can be implemented in geodynamic models. The paper highlights that, depending on which deformation mechanism is considered (i.e. diffusion creep or dislocation creep) and due to uncertainties in the activation energy, activation volume, grain-size and water content, the upper mantle rheology can be set to depth independent or depth dependent with a linear increase of the effective viscosity from the base of the lithosphere to the mantle transition zone. The paper then points out that rheology of the mantle transition zone is highly uncertain despite experimental studies on wadsleyite since water content, which is largely unknown, can have a great weakening effect. Furthermore, constraining the mantle transition zone rheology from observations of slab deformation in numerical subduction models seems difficult because both strong slabs and weak slabs fit the observational data and slab deformation depends on trench migration. The paper also shows that experiments on ferropericlase and bridgmanite strength and geophysical observations allow for a lower mantle rheology with an effective viscosity increase for the upper part and decrease for the lower part.

The third contribution is a review focusing on how numerical modelling studies provide a better understanding of slab-driven mantle flow processes (Jadamec, 2016). The author summarizes and discusses how recent progress in three-dimensional numerical geodynamic modelling has helped investigating particular subduction zone processes related to slab-driven mantle flow. The author puts an emphasis on the importance of simulating the three-dimensional nature of subduction zones and of using relatively high resolution for geodynamic models of subduction. The relatively high resolution is necessary to model the geometric complexities of plate boundaries, and to simulate in combination non-linear mantle flow and slab deformation. The author makes an inventory of the recent progress in advanced computing and then reviews how improvements in numerical models of subduction have allowed to investigate problems such as complex slab geometries and lateral variations in overriding plate thickness, temperature and composition. The review finally focuses on how past and present three-dimensional numerical geodynamic modelling has allowed to gain insights into trench parallel flow, toroidal flow around slab edges, mantle upwelling at lateral slab edges, and small scale convection within the mantle wedge.

In the fourth contribution to the special issue, Ding and Li (2016) present an analogue modelling study that focuses on the mechanism of rift propagation in the Southwest Sub-basin of the South China Sea. The authors performed a total of six experiments, of which four were two-layered crustal models and two were four-layered lithospheric models. The model results are discussed with constraints from geophysical observations. The two and four layered models demonstrate that thermal thinning of the crust and the existence of rigid blocks greatly control rift propagation. The progressively easterly thinned lithosphere seems to control the initiation and rate of rifting, with earlier rift initiation and faster rifting to the east, resulting in a wider rift in the east than in the west. The existence of strong blocks in the middle has an additional effect by localizing rifting early during rift initiation.

The fifth contribution is an analogue modelling study focusing on the formation and evolution of ophiolite blocks in orogenic wedges (Malavieille et al., 2016). The authors simulate the interaction between tectonics, erosion and sedimentation in orogenic wedges using sandbox modelling. The model results provide insights into the mechanisms of incorporation of ophiolite-bearing mélanges in orogenic wedges and into their evolution by exhumation and redeposition during wedge growth. The results have implications for natural ophiolite-bearing mélanges such as those observed in Taiwan (Lichi and Kenting mélanges) and in the northern Apennines (Casanova mélange). The results particularly show that high basal friction promotes the development of steep slopes on the retro wedge, favouring gravitational instabilities that trigger submarine landslides, thereby allowing for exhumation of the