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A review of analogue modelling of geodynamic processes: Approaches, scaling, materials and quantification, with an application to subduction experiments

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ABSTRACT

We present a review of the analogue modelling method, which has been used for 200 years, and continues to be used, to investigate geological phenomena and geodynamic processes. We particularly focus on the following four components: (1) the different fundamental modelling approaches that exist in analogue modelling; (2) the scaling theory and scaling of topography; (3) the different materials and rheologies that are used to simulate the complex behaviour of rocks; and (4) a range of recording techniques that are used for qualitative and quantitative analyses and interpretations of analogue models. Furthermore, we apply these four components to laboratory-based subduction models and describe some of the issues at hand with modelling such systems. Over the last 200 years, a wide variety of analogue materials have been used with different rheologies, including viscous materials (e.g. syrups, silicones, water), brittle materials (e.g. granular materials such as sand, microspheres and sugar), plastic materials (e.g. plasticine), visco-plastic materials (e.g. paraffin, waxes, petrolatum) and visco-elasto-plastic materials (e.g. hydrocarbon compounds and gelatins). These materials have been used in many different set-ups to study processes from the microscale, such as porphyroclast rotation, to the mantle scale, such as subduction and mantle convection. Despite the wide variety of modelling materials and great diversity in model set-ups and processes investigated, all laboratory experiments can be classified into one of three different categories based on three fundamental modelling approaches that have been used in analogue modelling: (1) The external approach, (2) the combined (external + internal) approach, and (3) the internal approach. In the external approach and combined approach, energy is added to the experimental system through the external application of a velocity, temperature gradient or a material influx (or a combination thereof), and so the system is open. In the external approach, all deformation in the system is driven by the externally imposed condition, while in the combined approach, part of the deformation is driven by buoyancy forces internal to the system. In the internal approach, all deformation is driven by buoyancy forces internal to the system and so the system is closed and no energy is added during an experimental run. In the combined approach, the externally imposed force or added energy is generally not quantified nor compared to the internal buoyancy force or potential energy of the system, and so it is not known if these experiments are properly scaled with respect to nature. The scaling theory requires that analogue models are geometrically, kinematically and dynamically similar to the natural prototype. Direct scaling of topography in laboratory models indicates that it is often significantly exaggerated. This can be ascribed to (1) The lack of isostatic compensation, which causes topography to be too high. (2) The lack of erosion, which causes topography to be too high. (3) The incorrect scaling of topography when density contrasts are scaled (rather than densities); In isostatically supported models, scaling of density contrasts requires an adjustment of the scaled topography by applying a topographic correction factor. (4) The incorrect scaling of

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externally imposed boundary conditions in isostatically supported experiments using the combined approach; When externally imposed forces are too high, this creates topography that is too high. Other processes that also affect surface topography in laboratory models but not in nature (or only in a negligible way) include surface tension (for models using fluids) and shear zone dilatation (for models using granular material), but these will generally only affect the model surface topography on relatively short horizontal length scales of the order of several mm across material boundaries and shear zones, respectively.

1. Introduction

Analogue modelling (also referred to as laboratory modelling or physical modelling) is an experimental approach that is used in the Earth Sciences to investigate geological phenomena and geodynamic processes in a laboratory at convenient time scales and length scales. Analogue models are simplified representations of a particular component of the Earth's system (the natural prototype) using simplified geometries, rheologies and boundary conditions. Analogue models are useful because they overcome some inherent limitations that exist when studying the Earth directly. In particular, the study of geodynamic processes in nature is difficult because: (1) only the present state of the Earth is known; (2) Many geodynamic processes occur at geological time scales of millions of years, which far exceed the human life span; (3) Many geodynamic processes occur at large spatial scales and deep inside the Earth, making direct observation difficult or impossible. Analogue models allow one to investigate the progressive development of a particular geodynamic process or geological phenomenon from start to finish, providing a complete evolutionary picture of the process under investigation. Furthermore, such processes can be investigated in a controlled environment of the laboratory at convenient time scales (seconds to hours) and length scales (millimetres to meters). Additionally, analogue models allow the experimenter to systematically investigate and quantify the influence of a particular physical parameter on a particular geodynamic process. Finally, in case the model is properly scaled, then the experimental results can be directly applied to the natural prototype, providing insight into the natural system.

Analogue modelling has a long history, starting 200 years ago with the first analogue experiments conducted by Sir James Hall (Hall, 1815), who developed models to investigate the folding of layered sedimentary rocks. Other modellers followed in the late 1800s studying geological structures such as fractures, folds and thrust faults (e.g. Favre, 1878a,b; Daubre, 1879; Schardt, 1884; Cadell, 1889; Willis, 1893). An increase in analogue modelling studies occurred in the 1900s, as a larger diversity of geodynamic processes and geological phenomena were investigated, including salt dome formation (e.g. Escher and Kuenen, 1929; Link, 1930; Parker and McDowell, 1955), folding (e.g. Mead, 1920; Kuenen and de Sitter, 1938), thrust faulting (Hubbert, 1951), normal faulting (e.g. Hubbert, 1951), fracturing (e.g. Mead, 1920; Cloos, 1955; Oertel, 1962), proto-subduction (Kuenen, 1936), mantle flow (e.g. Griggs, 1939), orogeny (e.g. Kuenen, 1936; Griggs, 1939), boudinage (e.g. Ramberg, 1955), plutonism (e.g. Ramberg, 1970) and plume formation (e.g. Whitehead and Luther, 1975). As the theory of plate tectonics was developed in the 1960s, analogue models of plate tectonic processes followed, including the first analogue models of subduction (e.g. Jacoby, 1973, 1976; Kincaid and Olson, 1987), lithospheric rifting (e.g. Shemenda and Grocholsky, 1994; Benes and Davy, 1996; Brune and Ellis, 1997), collision-indenter tectonics (e.g. Tapponnier et al., 1982; Davy and Cobbold, 1988; Ratschbacher et al., 1991), and lithospheric shortening (e.g. Davy and Cobbold, 1991).

During the 1900s, analogue modelling changed from being a qualitative and descriptive tool to a quantitative technique due to the formulation of the scaling theory, which was first introduced by Hubbert (1937) and further developed by many others (e.g. Hubbert, 1951; Ramberg, 1967, 1981; Horsfield, 1977; Shemenda, 1983; Weijermars and Schmeling, 1986; Richard, 1991; Davy and Cobbold, 1991; Ribe and Davaille, 2013). The scaling theory, which requires geometric, kinematic and dynamic similarity between analogue model and natural prototype, allows the experimenter to scale quantitative model results such as lengths, geometries, velocities, forces, stresses and strains to values in nature, allowing for a quantitative and deeper understanding of the geological phenomenon or geodynamic process under investigation.

The analogue modelling technique has come a long way in the last 200 years, and has provided many novel insights into a wide variety of geological phenomena and geodynamic processes. In the last decade, the reproducibility of analogue models has been under investigation with benchmark studies of upper crustal shortening and extension (Schreurs et al., 2006), and upper crustal shortening (Schreurs et al., 2016). Such studies provide new insight into the influence of a variety of conditions (e.g. lab environment, experimental apparatus, analogue materials, model preparation techniques, the human factor) on the experimental outcomes and reproducibility of analogue experiments.

In the last three decades a number of reviews have been written on analogue modelling of particular geodynamic settings and processes, including extensional fault systems (McClay, 1990), continental extension (Corti et al., 2003), accretionary wedges (Graveleau et al., 2012), strike-slip zones (Dooley and Schreurs, 2012) and mantle convection (Davaille and Limare, 2007). In addition, a number of reviews exist on the history of analogue modelling (e.g. Koyi, 1997; Ranalli, 2001; Schellart, 2002).

This review work on analogue modelling is more general than the above-mentioned reviews, although it does provide an application to analogue modelling of subduction. Note that this review will only focus on analogue modelling performed in the normal field of gravity. So far, most analogue models have been performed in the normal (Earth's) field of gravity, although a considerable number of models have also been performed in an artificial gravity field, such as induced by a centrifuge (e.g. Ramberg, 1967; Dixon and Summers, 1985; Peltzer, 1988; Bonini et al., 2001; Harris and Koyi, 2002; Mart et al., 2005; Corti et al., 2010; Dietl and Koyi, 2011; Noble and Dixon, 2011; Godin et al., 2011).

The review has four main aims. The first is to provide a fundamental physical classification scheme for the three different analogue modelling approaches that exist, to discuss for which geodynamic problem each of these approaches might be justified or not, and to discuss potential problems and limitations with these different approaches. The second aim is to provide a discussion and new insight into the scaling of topography in analogue models. It will be shown, using the scaling theory, that topography in analogue experiments needs to be scaled differently in case the experiments are scaled for density contrasts instead of densities. The third aim is to provide an overview of the different rheological approaches that have been used in analogue modelling to represent