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Analogue modelling of large-scale tectonic processes: An introduction

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Introduction

Analogue modelling has been applied to study geological processes since the beginning of the 19th century to provide qualitative and quantitative insights into specific geological problems. The advantage of analogue models is that they offer the opportunity to investigate the individual influence of different parameters on geological processes. Furthermore, boundary conditions can be set according to the needs of the experimenter. Also, they offer the opportunity to study the 3D structural evolution of a specific model, thus supplying a clear coherent kinematic picture, which can help with the interpretation of natural prototypes. Since the modelling technique can be readily applied to offer solutions for three-dimensional problems involving large strains, it can offer invaluable new insights into geological problems, which are intrinsically three-dimensional and often involve large amounts of strain.

Analogue models are representative of a natural prototype if they are properly scaled and if the materials used show a similar rheological behaviour as the natural prototype. In analogue or physical modelling of geological processes certain scaling rules should be followed in order to make the model a good analogue of the natural prototype. The theory of these rules was first introduced by Hubbert (1937) and was later discussed by Hubbert (1951), Horsfield (1977), Shemenda (1983), Richard (1991), Davy and Cobbold (1991) and Cobbold and Jackson (1992).

According to Hubbert (1937), a model is properly scaled to its natural counterpart if it is geometrically, kinematically and dynamically similar. An analogue model and a natural prototype are geometrically similar if all the corresponding lengths are proportional and all the corresponding angles within the bodies are equal. For kinematic similarity, the geometrically similar model and prototype have to undergo similar changes of shape and/or position, where the time required for any change in the model is proportional for the corresponding change in the prototype (Ramberg, 1967). Finally, for dynamical similarity between a geometrically and kinematically similar model and prototype, the two bodies have to have similar ratios and distributions of different kinds of driving and resistive forces (gravitational, frictional and viscous) acting on the different particles of the body.

History of analogue modelling

Probably the first documentation of an analogue experiment to simulate a geological process was presented in the Transactions of the Royal Society of Edinburgh by Sir James Hall (Hall, 1815). Here, he described his first attempts to model folds observed in geological strata. Two experiments were performed. In the first experiment, several pieces of cloth, linen and woollen fabric were spread out on a table, one above the other. A flat door was put on top of the layered stack, being loaded with weights, to confine the stack. Next, two boards were applied to the sides of the stratified mass and were subsequently forced towards each other. This resulted in the gradual uplift of the heavy door, while the strata were constrained and adopted upward and downward bending folds. In the second experiment, beds of clay confined in a box were subjected to lateral compression due to movement of movable ends driven by screw jacks, which is basically the same experimental design as is still in use today for fold and thrust type experiments. This experiment resulted in the generation of folds in the strata. The similarity between the folds reproduced in the experiments and folds observed in natural strata led the author to conclude that folds observed in nature must have a similar origin as in the experiment and therefore are the result of horizontal compression. This hypothesis had already been proposed by de Saussure (1796), where he spoke of a lateral push as the cause for shortening and folding of rocks in the Alps. This experiment illustrated over almost two centuries ago the potential of analogue modelling techniques to understand geological structures.

Since the pioneering experiments in the early 1800’s, several other modellers followed in the late 1800’s studying fractures, folds and thrusts (e.g. Favre, 1878; Daubre, 1879; Schardt, 1884; Cadell, 1889; Willis, 1893). In the 20th century, analogue modellers started to investigate a wider range of geological problems with similar modelling techniques (Mead, 1920; Link, 1930; Escher and Kuenen, 1929; Kuenen and de Sitter, 1938; Nettleton and Elkins, 1947; Hubbert, 1951; Cloos, 1955; Parker and McDowell, 1955; Ramberg, 1955; Oertel, 1962).

A major step forward in analogue modelling came with the advent of a well-founded scaling theory for analogue modelling of geological processes, provided by Hubbert

(1937). This theory revolutionised analogue modelling by changing it from a descriptive tool to a quantitative technique, thus making it an efficient and reliable tool to study geological processes at various scales (e.g. from microstructure analysis to large scale tectonic processes) (Koyi, 1997). According to Hubbert (1937) an analogue model is a good representative of a natural prototype, if it follows the three aspects of similarity: geometric, kinematic and dynamic. Since Hubbert (1937) several other papers have been published on scaling of analogue models applied to geological processes (Hubbert, 1951; Horsfield, 1977; Shemenda, 1983; Richard, 1991; Davy and cobbold, 1991, Cobbold and Jackson, 1992).

Another major step forward in analogue modelling, especially for modelling of large-scale tectonic processes, came in the 1980's, when realistic models were built to simulate crustal and lithospheric scale processes (Faugere and Brun, 1984; Davy and Cobbold, 1988). Here, different types of material (brittle and viscous) were combined in one model to simulate a rheologically stratified crust and mantle, e.g. conform to the predicted strength profiles for the Earth's crust and lithospheric mantle (Davy and Cobbold, 1988, 1991). In these experiments, the materials were chosen as such, that the experiments were properly scaled when executed in the normal field of gravity. However, one limitation of such models is that they are unable to take into account the rheological modifications due to temperature variations during crustal or lithospheric scale deformation (Brun, 1999), such as occur during subduction and rifting. Some attempts have been made to find appropriate analogue materials to be used in thermomechanical modelling (Cobbold and Jackson, 1992; Rossetti et al., 1999) and has, for instance, proven to be useful in modelling the thermomechanical development of orogenic wedges (Rossetti et al., 2000). In this special issue of the Journal of the Virtual Explorer, two papers are presented which also deal with thermomechanical analogue modelling of geological processes.

Analogue modelling techniques

Several different techniques have been used to construct analogue models of large-scale tectonic processes, such as subduction, rifting, gravity spreading, indenter tectonics, escape tectonics and convection. A first division can be made between models, which are designed as such to be used in the normal field of gravity and models constructed for the usage in an artificially high field of gravity.

The latter of these two groups are performed in a centrifuge, where the centrifugal force plays the same role in the models as the force of gravity does in geological processes. The advantage of this technique is that the analogue materials used for centrifuge experiments have a relatively high strength and are therefore relatively easy to work with during construction and analysis of the model. The obvious disadvantage is that an entire (expensive) centrifuge is needed to conduct an experiment. Furthermore, every time an intermittent stage in the structural evolution of an experiment needs to be examined, the machine has to be turned of. Centrifuge modelling was first introduced to analogue modelling of geological processes by Bucky (1931). The centrifuge modelling technique took a great step forward in the early 1960's due to the work of Hans Ramberg, who build an entire analogue lab around a centrifuge at the University of Uppsala in Sweden. His work led to a better understanding of the role of gravity in deformation of the Earth's crust and lithosphere (Ramberg, 1967, 1981). From this time onwards, centrifuge modelling has been widely used to investigate geological processes (Ramberg, 1970; Dixon, 1974, 1975; Talbot, 1977; Dixon and Summers, 1985; Koyi, 1988; Liu and Dixon, 1991; Koyi and Skelton, 2001). The centrifuge technique has dominated analogue modelling for some three decades, but has now largely been replaced by analogue models deformed in the normal field of gravity, in which much weaker materials are used (Koyi, 1997).

Experiments performed in the normal field of gravity should be made of extremely weak materials, in order to be properly scaled for gravity. The advantage of this approach is that it does not require an (expensive) centrifuge in order to run an experiment and that the evolution of an experiment can be recorded continuously. Furthermore, most materials used in these type of experiments (such as granular material and syrups) are relatively cheap and easy to obtain (except for silicone putties). A disadvantage of this approach is that the construction of models is more difficult, especially for experiments with inverted density profiles (e.g. a dense oceanic lithosphere overlying a less dense asthenosphere). Several different modelling approaches exist, which are mainly related to the rheological approximation of the lithosphere and sub-lithospheric mantle.

(1) The first approach has been developed by the analogue modelling group in Rennes (France). In this approach, analogue models are constructed of materials with different rheologies (brittle and viscous), to incorporate the different behaviour of rocks at different depths in the crust and mantle. Brittle behaviour in rocks is modelled by granular material (such as sand), which deforms conform a Mohr-Coulomb type behaviour (Mandl, 1977; Krantz, 1991; Schellart, 2000). The viscous behaviour of rocks is simulated with viscous material such as silicone putty, honey and glucose syrup. These models have been used to investigate a wide variety of geological phenomena, including extrusion tectonics, subduction, rollback, back-arc extension, gravity spreading and continental collision (Faugere and Brun, 1984; Davy and Cobbold, 1988, 1991; Ratschbacher et al., 1991; Brun et al., 1994; Faccenna et al., 1996, 1999; Hatzfeld et al., 1997; Brun, 1999; Diraison et al., 2000; Keep, 2000; Martinod et al., 2000; Schellart et al., 2002a,b; Burg et al., 2002).

(2) In a second approach, plastic materials are used to model the deformation of rocks. This approach has been used to model the India-Eurasia collision (Tapponnier et al., 1982). This approach has also been applied by Alexander Chemenda, with models primarily constructed

of plastic and viscoplastic hydrocarbon waxes to simulate the lithosphere and water to simulate the asthenosphere. These models have been build to investigate processes such as subduction, extension, slab rollback and back-arc deformation (Shemenda, 1992, 1993, 1994; Shemenda and Grocholsky, 1992, 1994; Chemenda et al., 1995, 1996, 1997, 2000, 2001).

(3) In a third approach, the lithosphere and sub-lithospheric mantle are modelled with viscous rheologies only. Each layer is represented by a material with a homogeneous viscous rheology. Thus, these experimental designs are effectively the same as those used in numerical models using the thin viscous sheet approximation to simulate the lithosphere (e.g. Bird and Piper, 1980; England and McKenzie, 1982, 1983; Vilotte et al., 1982; Houseman and England, 1986). With such an analogue set-up, modellers have investigated slab kinematics and dynamics during subduction (Kincaid and Olson, 1987; Olson and Kincaid, 1991; Griffiths et al., 1995; Guillou-Frottier et al., 1995; Funiciello et al., 2000, 2002; Faccenna et al., 2001b).

(4) In a fourth approach, the lithosphere and sub-lithospheric mantle are modelled with temperature dependent viscous or plastic rheologies. An appropriate vertical temperature gradient is applied to the experiment, simulating the geothermal gradient in the Earth's lithosphere and sub-lithospheric mantle, thus influencing the rheological behaviour of the analogue materials during deformation. These models have been build to investigate various geological processes such as rifting (Brune and Ellis, 1997) and the thermomechanical development of orogenic wedges (Rossetti et al., 2000).

Contents of this volume

This special volume of the Journal of the Virtual Explorer is dedicated to analogue modelling of large-scale tectonic processes and comprises nine papers. The contributions cover a wide range of tectonic settings, including strike-slip deformation, fold and thrust deformation, transpression, back-arc extension, rifting, diapir emplacement and subduction. Two papers present results of analogue experiments performed in a centrifuge (**Mulugeta; Dietl and Koyi**), while the remainder of the papers describe experiments performed in the Earth's gravitational field. From these seven papers, two papers present results of thermomechanical analogue models (**Boutelier and Chemenda; Wosnitza**), while the other five papers present results of mechanical analogue models build with stratified brittle-viscous rheologies (**Le Calvez and Vendeville; Schellart et al.; Schreurs et al.; Schreurs and Colletta; Schreurs et al.**). From this last group of papers, three papers present results of analogue experiments recorded in a CT-scanner, with which three-dimensional images of the analogue models were obtained (**Schreurs et al.; Schreurs and Colletta; Schreurs et al.**).

The first paper by **Calvez and Vendeville** reviews results of previous analogue models simulating the along-strike interaction between laterally offset faults, such as the formation of pull-apart basins in between strike-slip faults and relay zones in between laterally offset normal faults. A new model design is presented in which faults can freely propagate along strike after they have nucleated at a predetermined model-controlled location. The new design provides much more freedom for fault interaction within the relay zone and for fault-block rotation than previous models, and therefore, results significantly differ from those of previous models.

Schellart et al. present the results of 3-dimensional analogue modelling of asymmetric back-arc extension of an overriding lithosphere with a varying initial rheology. The results show that with increasing lithospheric brittle to viscous strength (BS/VS), the fault density decreases in magnitude, while the asymmetry in deformation pattern in the back-arc region increases. The extent of deformation is mainly dependent on the ratio of brittle strength to buoyancy force (BS/BF), i.e. the larger the ratio, the smaller the area of deformation. The experimental results have been compared with several arc - back-arc systems to explain the asymmetric structures observed in these systems.

The third paper by **Schreurs et al.** presents results of analogue experiments to investigate the development and evolution of transfer zones in fold and thrust belts, which were recorded in a CT-scanner to generate 3-D volumetric images. Models were build to investigate the difference in evolution between thrust domains that were underlain or not underlain by a thin viscous layer. In the brittle domain, closely spaced and dominantly forward propagating thrusts formed a narrow and high fold-and-thrust belt. In the brittle-viscous domain, the thrust belt was wider and lower, and there was no consistent vergence of thrusting and folding. Transfer zones formed in the transition zone between the two domains. The authors conclude that the location and orientation of these transfer zones are directly related to the geometry of the boundary between basal viscous layer and adjacent brittle layers.

Mulugeta discusses results of centrifuge experiments to investigate the interactive development of ramp-flat thrust styles for various rheological stratifications. The models exhibit various fault-fold geometries (e.g. fault bend folds, footwall synclines, wedge faults) as structural expressions of ductile ramp-flat accommodation. Depending on the rheological stratification, the ramps change shape and length as slip accumulates along the fault surfaces in flowing surroundings.

In the following paper by **Boutelier and Chemenda**, results of thermo-mechanical physical modelling of continental subduction are presented using new temperature sensitive analogue materials to model the lithospheric layers. The authors found that during subduction, the model crustal layer subducted to considerable depth before it underwent large and complex deformation including upward ductile flow of the deeply subducted portions, localised failure of the model upper crust at shallow depths and possible delamination of the model crust and mantle layer.

In the sixth paper, **Schreurs and Coletta** present analogue modelling results of continental transpression, which were recorded in a CT-scanner to generate 3-D volumetric images. The experiments were performed to investigate the control of the applied ratio of shear strain rate and shortening strain rate on the initial fault evolution. This ratio proved to be critical for the geometry of the fault zone and fault types (strike-slip faults, oblique-slip faults, thrust faults) that developed in such a fault zone.

In the paper from **Dietl and Koyi** results of analogue centrifuge models are presented to study the kinematics and dynamics of concentrically expanded plutons. From the modelling results, the authors conclude that concentrically expanded plutons can result from combined initial diapirism and subsequent ”ductile dyking“ and that multiple diapirs can form only when the overburden units deform in a ductile fashion during the different stages of diapirism.

In the eighth paper, **Schreurs et al.** present results of analogue experiments to study the influence of brittle-viscous multilayers on faulting during rifting. It was found that the presence of an interbedded viscous layer in between two brittle layers can lead to the development of two independent, decoupled conjugate normal fault systems in the upper and lower brittle layer, where the initial width between conjugate faults depends on the thickness of the brittle layers. It was also found that location and orientation of extensional transfer zones can be directly linked to the geometry of the interbedded viscous layer.

In the ninth and final paper, **Wosnitza** discusses a new recording technique to reconstruct the stress field in thermomechanical analogue models. The technique makes use of an infrared camera to allow the thermal field of the temperature dependent materials used in the experiment to be analysed during deformation. The viscosity distribution is then obtained from the temperature field and from rheological material properties. Combining the viscosity field with the strain rate field, it is then possible to calculate the stress field in the model. The author discusses the application of the new recording technique to experimental modelling of orogenic processes.

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