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Experimental tectonics: from Sir James Hall to the present

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Abstract

The subject of experimental tectonics is the study of geodynamic processes by means of laboratory scale models. The first roughly scaled experiments were performed by Sir James Hall about two centuries ago, in the intellectual atmosphere generated by the appearance of Hutton's *Theory of the Earth* (Hutton, J., 1795. Theory of the Earth, with Proofs and Illustrations, Vols. I & II. Cadell & Davies, Edinburgh). Their aim was to test the hypothesis that the folding of originally horizontal strata is the result of lateral compression. The idea to test hypotheses by laboratory experiments had already been applied by Hall to petrological problems (crystallization and melting) not involving scaling. Interestingly, however, he constructed a scale model of a Gothic cathedral, using a line of reasoning parallel to that used in his tectonic experiments. From these beginnings, the theory and practice of scale models have grown to become an important part of an integrated approach to the study of geodynamics. One topic which is at present the focus of much attention is the choice of model materials correctly scaling the temperature dependence of lithospheric materials. As an example, a brief discussion is offered of two geodynamic problems where the application of scale models is proving very fruitful: the initiation and time-history of subduction of oceanic and continental lithosphere, and the tectonic evolution of orogenic wedges. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The term *experimental tectonics* is nowadays generally used to denote the study of tectonic processes in nature by means of scale models in the laboratory. The purpose of scale models is not simply to reproduce natural observation, but to test by controlled experiments hypotheses as to the driving mechanisms of tectonic processes. The role of experimental tectonics in the study of geodynamics has been stated effectively by Ramberg (1967):

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> The significance of scale-model work in tectonic studies lies in the fact that a correctly constructed dynamic scale model passes through an evolution which simulates exactly that of the original (the prototype), though on a more convenient geometric scale (smaller) and with a conveniently changed rate (faster).

This statement highlights both the usefulness and the difficulty of work in experimental tectonics. The usefulness lies in the fact that scale models, together with theoretical and numerical models, provide a way to test hypotheses on geodynamic processes, where the only direct observable in nature (the prototype) is the final result. Their main difficulty is the correct scaling of the physical quantities in the prototype and in the model, which requires careful consideration of model materials and experimental design.

Experimental tectonics can be said to have begun with the scale models of folding under compression performed by Sir James Hall (1815). Among milestones in its development, one may mention the treatise by Daubrée (1879); the work by Reyer (1892) on jointing and faulting; that by Willis (1893) on the tectonic style of the Appalachians; the clay models of mountain building and rifting by Cloos (1929, 1939); the development of scale model theory as applied to geology provided by Hubbert (1937); the study of the role of gravity in orogenesis by Bucher (1956); and the monograph on centrifuged scale models by Ramberg (1967), which offers an overview of areas of application, from small-scale structural features to large-scale mantle convection.

In this paper, we first retrace the initial steps of experimental tectonics. The historical and intellectual milieu that led to the original "scale model" experiments of Sir James Hall (Hall, 1815) is outlined first. Then the experiments are recounted, their importance discussed, and an hypothesis offered as to their genesis. We conclude by discussing some significant recent developments, in relation with large-scale geodynamic processes.

2. The Scottish School of Geology: Hall and the Huttonian theory

Some of the ideas that still form the core of geological thought (the principle of actualism and the consequent vastness of geologic time, the igneous origin of granite, the concept of geologic cycle) were formulated by James Hutton more than two centuries ago. Hutton's seminal paper "Theory of the Earth" was read at the Royal Society of Edinburgh in 1785 and published as a 30-page long "Abstract" (Hutton, 1785). It was expanded into an essay (Hutton, 1788), and then followed by an extended treatise in two volumes (Hutton, 1795). Additional material was left in manuscript form at the time of Hutton's death, and an incomplete third volume appeared more than a century later (Geikie, 1899).

While the idea was formerly predominant that there was hardly any geology to speak of before Hutton (Geikie, 1897), now the "Huttonian revolution" has been placed more firmly in its historical context (see e.g. McIntyre, 1963; Porter, 1977; Ranalli, 1982; Dean 1992; Craig and Hull, 1999, among others). In the late eighteenth and early nineteenth centuries, there was in Edinburgh a small group of men interested in matters geological, who formed what has been called the "Scottish School of Geology" (Geikie, 1871). The intellectual atmosphere in which they moved was permeated by the synthetic philosophical ambitions of the Enlightenment. Hutton's "Theory of the Earth" is a child of this atmosphere, in its universalist ambition to construct a theory of the

Earth which, while grounded in empirical observation, would nevertheless express the connecting principles of the science of the Earth in a universal way.

The main exponents of the "Scottish School" were James Hutton (1726–1797), John Playfair (1748–1819), and Sir James Hall of Dunglass (1761–1832). To consider the latter two as merely followers and illustrators of the first would do them less than justice. Hutton's system, as developed in the two 1795 volumes of the *Theory*, is a Janus-like structure: on the one hand, it makes frequent reference to empirical observation, and stresses the importance of never exceeding the bounds of experience; on the other, it organizes the evidence in a theoretical system with a strong teleological flavour. The idea that the Earth is designed to provide a fit habitat for mankind permeates the *Theory*. The Earth is seen as an organism, maintained in a state of healthy equilibrium by the opposing effects of various geological processes. However, there is no trace of teleology in Playfair's *Illustrations of the Huttonian Theory* (1802) or in James Hall's geological writings. It is as if the two younger men had freed the Huttonian theory of a useless skin, while retaining the substance inside. This, and the beautiful clarity of style, is what makes the *Illustrations* one of the classics of science.

James Hall's life (see Eyles, 1961 and Fig. 1 for a portrait in his mature years) was in many ways typical of the "gentleman-of-leisure" approach to science which was not unusual in his days. His father died when he was 15, and thereafter his guardian and granduncle, who was president of the Royal Society of London, supervised his education. Young James attended Christ's College, Cambridge, and the University of Edinburgh, cultivating his interests in chemistry and natural philosophy, but without graduating. In 1783–1786 he went on a grand tour of Europe, which included examination of volcanic activity and products in southern Italy, and led him to a correct interpretation of volcanic dykes. Thereafter, his life was spent between his country estate at Dunglass, East Lothian, and Edinburgh, where he frequented the Royal Society (founded in 1783), of which he became president in 1812. In Edinburgh, he became acquainted with Hutton, Playfair, and their circle of friends (for a description of the intellectual atmosphere in Edinburgh in those days, see McIntyre, 1999). The famous excursion to Siccar Point on the Berwickshire coast in the spring of 1788, when Hutton, accompanied by Playfair and Hall, examined the unconformity between near-vertical Silurian strata and gently dipping Old Red sandstone, started from Hall's house in East Lothian.

Hall's interest in chemistry (he was among the first in the British Isles to accept Lavoisier's views) naturally inclined him towards an experimental approach. Hutton, however, had little faith in experiment, since he thought that the processes of nature were of such a scale as to render futile any attempt to reproduce them in the laboratory. Hall began performing experiments in 1790 but published nothing on the matter until after Hutton's death. His experiments focused on what would now be called experimental petrology, tectonophysics and geodynamics. In experimental petrology, his most important results were the proof that the rate of cooling of a molten rock affects its texture (Hall, 1805), and the demonstration of the stability of limestone at high temperature and pressure (Hall, 1812; see the review by Wyllie, 1999). It should be noted that, although these experiments represented a fundamental step forward in the experimental study of rocks, rudimentary experimental petrology was practised long before Hall (see e.g. the discussion in Yearley, 1984), and that the concept of *scale model* does not come into consideration in their design. On the other hand, it is precisely the introduction of scaling (however qualitative) between natural prototype and model that represents the most important innovation of Hall's tectonics

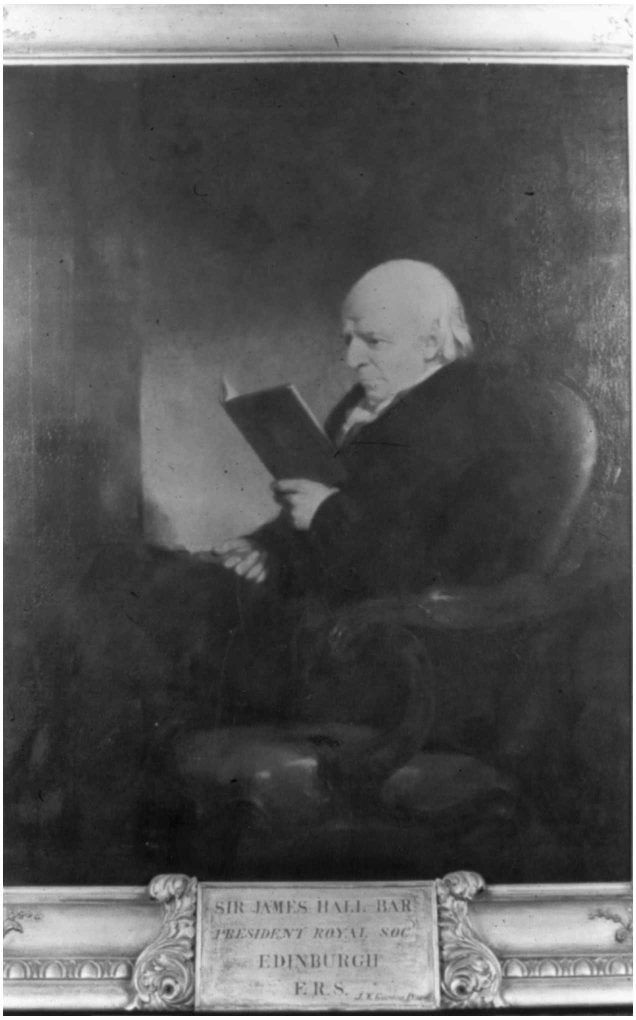

Fig. 1. Portrait of Sir James Hall by Sir John J. Watson-Gordon, R. A. (courtesy of the Royal Society of Edinburgh).

experiments, and that makes his work on "experimental tectonics" the beginning of a radically new line of thought.

3. Folding in nature and in the laboratory: scale models

Hall had examined the belt of deformed Silurian clastic rocks (mainly greywackes, for which he used the Cornish mining term *killas*, and mudstones) that run in an approximately ENE direction across the southern Uplands of Scotland from Galloway to Berwickshire. His observations, together with a report on the experiments performed, are contained in a paper read at the Royal Society of Edinburgh on February 3, 1812 (Hall, 1815, which is the source of all quotations that follow). The strata are everywhere tightly folded, and are well exposed on the Berwickshire coast near Fast Castle (Fig. 2). There, they "exhibit a succession of regular bendings, and powerful undulations, reaching from the top to the bottom of the cliffs, two or three hundred feet in height". Hall correctly interpreted the folded strata as having been originally continuous and horizontal. His schematic cross-section to illustrate the hypothetical continuation of the strata where they had been removed by erosion, or were hidden from view, is shown in Fig. 3.

As to the cause of folding, "this peculiar conformation might be accounted for, by supposing that these strata, originally lying flat, and in positions as nearly level as might be expected to result from the deposition of loose sand at the bottom of the sea, had been urged when in a soft, but tough and ductile state, by a powerful force acting horizontally, . . .[and] at the same time that the whole was held down by a superincumbent weight". The result of the action of this force would be a succession of regular folds to accommodate shortening. Where folds are more complex and irregular, the force must be conceived "most probably to have acted at successive periods" (a suggestion of polyphase deformation).

De Saussure (1796), in the fourth volume of his *Voyages dans les Alpes*, had already spoken of a lateral push ("refoulement") as the agent of shortening and folding; and Playfair (1802) had concluded that, although the primary force causing folding must have been directed vertically (as postulated by the Huttonian theory), it had to be combined with gravity and the resistance of the rocks to generate a lateral push. The specific agent of lateral compression envisaged by Hall was

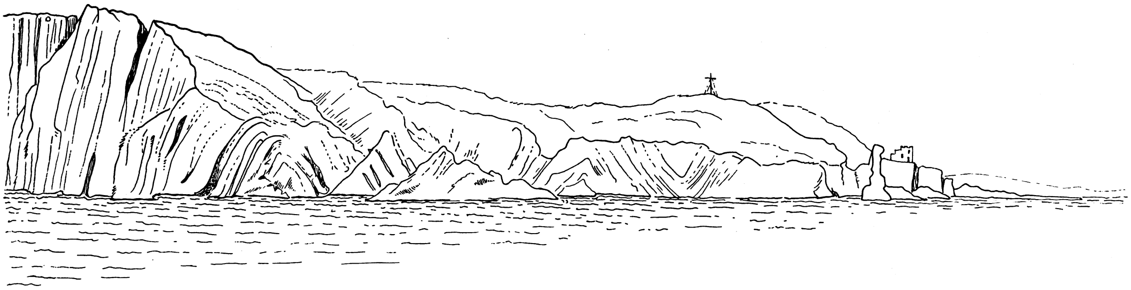

Fig. 2. Folded Silurian strata near Fast Castle, Berwickshire (Figs. 2–5 redrawn from Hall, 1815, Trans. R. Soc. Edin.).

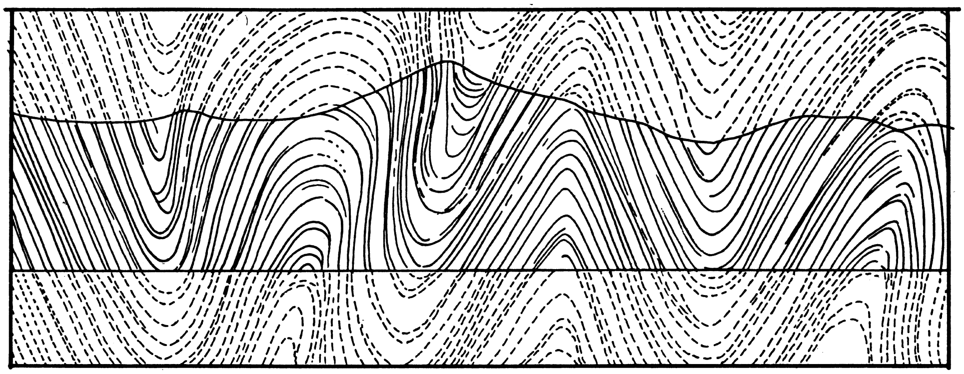

Fig. 3. Folded strata (continuous lines) and their continuation (dashed lines) where eroded or hidden from view.

the intrusion of granite. The novelty of his approach consisted in the experimental verification of the lateral shortening hypothesis by means of a tectonic scale model.

The problem of scaling in experimental tectonics has been the subject of extensive reviews (see e.g. Hubbert, 1937; Ramberg, 1967; Weijermars and Schmeling, 1986; Shemenda, 1994). While geometric similarity is relatively simple to achieve (the model must be a properly scaled-down version of the prototype), physical (kinematic and dynamic) similarity is more complex, and requires proportionality between variables (e.g. length, time, velocity, density, force, stress, strain, strength, viscosity, etc.) characterizing the model and the prototype. A consequence of this requirement is that model materials must be, in a general sense, "softer" than the prototype. In Hall's time, no one was aware of the complexities of scaling. Hall, however, understood in a qualitative manner the need for relatively soft model materials, when he used blankets and layers of clay in his experiments. Hall does not explain how he came to this realization. He did, however, realize that the strata were in a ductile state when deforming, and states simply that he performed a "rude experiment" to illustrate his idea that the observed folds had originated by lateral compression.

The experiments were actually two. In the first one, several pieces of cloth were spread one above the other on a table, to simulate the strata in their original position. They in turn were covered by a door "which happened to be off the hinges", with weights (appropriately, rocks) on it, to simulate overburden pressure. By forcing toward each other two boards applied at the ends of the "strata", folds were generated, roughly resembling those exposed near Fast Castle.

The apparatus for the first experiment—if it deserves such a name—was extremely simple. In the second experiment, however, beds of clay were subjected to lateral pressure in a box with movable ends (Fig. 4), basically of the same type still in use today. The folds generated as a result of lateral shortening were very similar to those observed on the Berwickshire coast (Fig. 5). Hall's second experiment was in principle a fully developed tectonic scale model, involving all three steps necessary in its construction, that is, (i) the accurate interpretation of the geometry observable in nature, and the formulation of an hypothesis concerning the relevant mechanism (in this case, lateral pressure); (ii) the rough scaling of length, time, and strength of model material (although of course the details of quantitative scaling were unknown at the time); and (iii) the use of experimental results to test the validity of the tectonic hypothesis. The idea that geodynamic processes, despite their enormous time and length scales, could be reproduced in the laboratory by suitable scale models, was one of Hall's lasting contribution to the study of the Earth, certainly as important- and in a way more novel- than his work in experimental petrology.

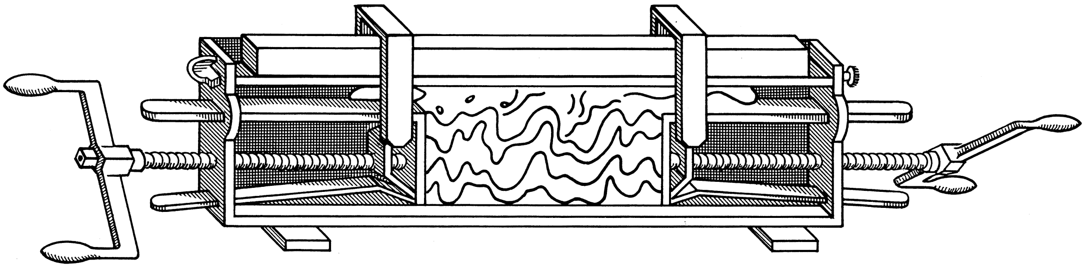

Fig. 4. Machine for scale model of folding by lateral compression, presented by Hall to the Royal Society of Edinburgh in 1812.

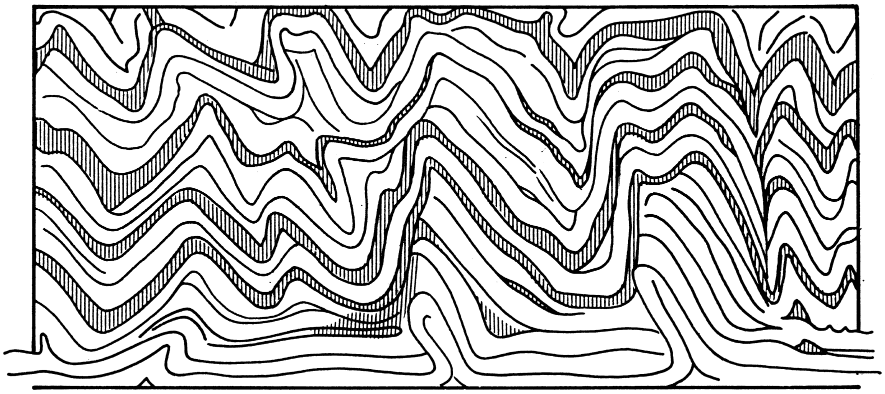

Fig. 5. Model folds resulting from Hall's experiment.

Although necessarily speculative, an hypothesis can be offered on the origin of Hall's ideas on scale models. One of his interests was architecture, and strong analogies can be found between his conception of Earth history and architectural history (see Yearley, 1984). In a paper on the origin of Gothic architecture (Hall, 1798, communicated to the Royal Society of Edinburgh on April 6, 1797 and later expanded in book form), he illustrated the "principle of imitation" and advanced the idea that the Gothic style had evolved from "rustic dwellings" constructed from willow rods. Then he relates how he enlisted the help of a country workman and built a *scale model* of a Gothic building using willow rods: "This little structure exhibits, in miniature, all the characteristic features of the Gothic style... The appearance of the whole, whether seen from within or from without, bears, I flatter myself, no small resemblance to a cathedral" (Hall, 1798). It is worth noting that the study of Gothic architecture and of geology proceeded in parallel in Hall's life (his excursion to the Berwickshire coast, in the company of Hutton and Playfair, took place in 1788; Hall, 1815). In both cases, the idea was to test an hypothesis by the use of a scale model. Hall presents his inquiry into Gothic architecture as an instance of *histoire raisonnée*, "being an attempt to trace, by conjecture, the steps through which an art has passed, in attaining the state in which we observe it", and the building of a model as a way of "*submitting the theory to a kind of experimental test*" (Hall, 1798; my italics). A similar line of reasoning is likely to have guided his studies of folding as a result of lateral compression of strata.

4. Recent developments: subduction, depth-dependent rheology, and orogenic wedges

Experimental tectonics is at present a very active field, with applications ranging from seismology (faulting and fault properties), through structural geology (folding, diapirism, development of small-scale structures), to geodynamics (evolution of orogenic belts, subduction, mantle convection). Here, as an example, two developments of relevance to geodynamics are briefly discussed: models of the subduction process, and models of the tectonic evolution of orogenic wedges (foreland thrust-and-fold belts).

One of the major problems in scale modelling work, as mentioned previously, is the search for suitable model materials. The lithosphere is rheologically layered, consisting of an alternance of brittle (frictional) and ductile (linearly or nonlinearly viscous) materials. This layering is particularly important in the case of continental lithosphere. The depth extent and number of layers depends on composition and temperature (see e.g. Ranalli, 1995).

From the early experiments by Jacoby (1976), there have been many attempts to model plate tectonic processes in the laboratory. Subduction has received particular attention (see e.g. Shemenda, 1994; Faccenna et al., 1996, 1999; Becker et al., 1999). In the experiments by Shemenda (1994), the rheological layering of the lithosphere is modelled by materials consisting, in various amounts, of dispersions of solid hydrocarbons (paraffins and ceresins) and finely ground powders in mineral oils. The asthenosphere is modelled by water. The density of the lithosphere relative to the asthenosphere can be varied by changing the concentration of the powder. The experimental setup is shown in Fig. 6. Different sets of experiments allow the modelling, among other things, of the inititation of subduction of oceanic lithosphere, and of the subduction of continental lithosphere. Interesting conclusions are that subduction initiation requires horizontal compression of the lithosphere, with or without a preexisting zone of weakness; and that continental material can be subducted to 200–300 km of depth (see also Shemenda et al., 1995, 1996). The latter result is in agreement with numerical models of subduction of continental lithosphere (Ranalli et al., 2000).

A different set of subduction models (Faccenna et al., 1996, 1999; Becker et al., 1999) uses a sand mixture and silicone putty to simulate the brittle and ductile parts of the lithosphere, respectively, with glucose syrup as the asthenosphere analogue. The experimental setup is not much different from Shemenda's (1994); however, it allows the study of the evolution of a passive margin separating a continental and an oceanic plate, from the inititiation of subduction to a fully developed sinking slab. The style of subduction is controlled by the convergence velocity, and by the density contrasts between continental plate, oceanic plate, and asthenosphere. An interesting result is that subduction velocity and angle increase with time until the slab reaches the mantle transition zone. This is an instance where scale models are proving an incentive to reexamine observational data.

The problem of the rheological layering of the lithosphere becomes very important when modelling orogenic processes in continental lithosphere. A frequently adopted approach is to simulate the depth-dependence of rheology by using multi-layer models consisting of a super-

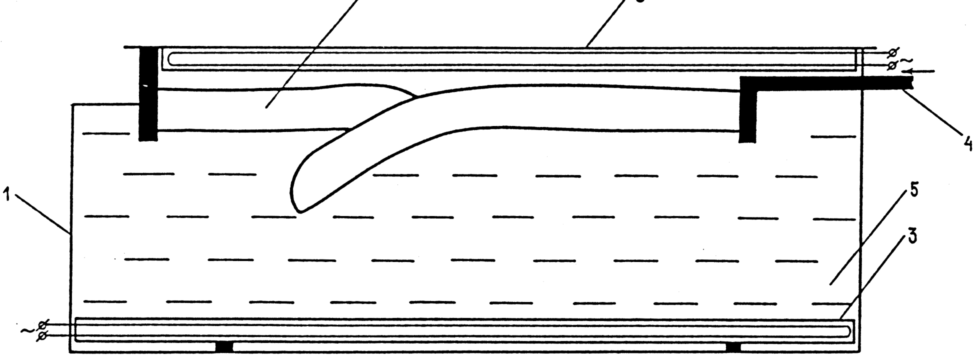

Fig. 6. Schematic view of Shemenda's (1994) experimental setup for modelling of subduction. 1. Tank; 2. model lithosphere; 3. heaters; 4. piston; 5. model asthenosphere (®1994 Kluwer Academic Publishers; reproduced by permission).

position of model materials with different properties (see, among others, Davy and Cobbold, 1991). However, the depth-dependence in nature is a consequence not only of composition but also of the geothermal gradient, and therefore the rheology varies with depth even in cross-sections of approximately homogeneous composition. This need for *thermomechanical modelling* has led to the search for model materials with temperature-dependent rheology and appropriate scaling factors with respect to the prototype (see e.g. Mancktelow, 1988; Cobbold and Jackson, 1992; Rossetti et al., 1999). Paraffin wax is particularly interesting. It behaves as a viscous fluid, with nonlinear viscosity for low homologous temperature ($T/T_m < 0.70$, where T_m is melting temperature), and linear viscosity at high homologous temperature. Its viscosity is a strong function of temperature, which makes it a very suitable material to model the depth dependence of rheology in the crust (Rossetti et al., 1999).

Paraffin is proving very useful in the modelling of orogenic wedges, where a wedge of crustal material, roughly triangular in cross-section, is deformed under the action of shear stress at its base (caused by underthrusting), the resistance of the material at its rear ("backstop"or "hinterland"), and gravity. Wedges can be either thin-skinned, where only supracrustal rocks are affec-

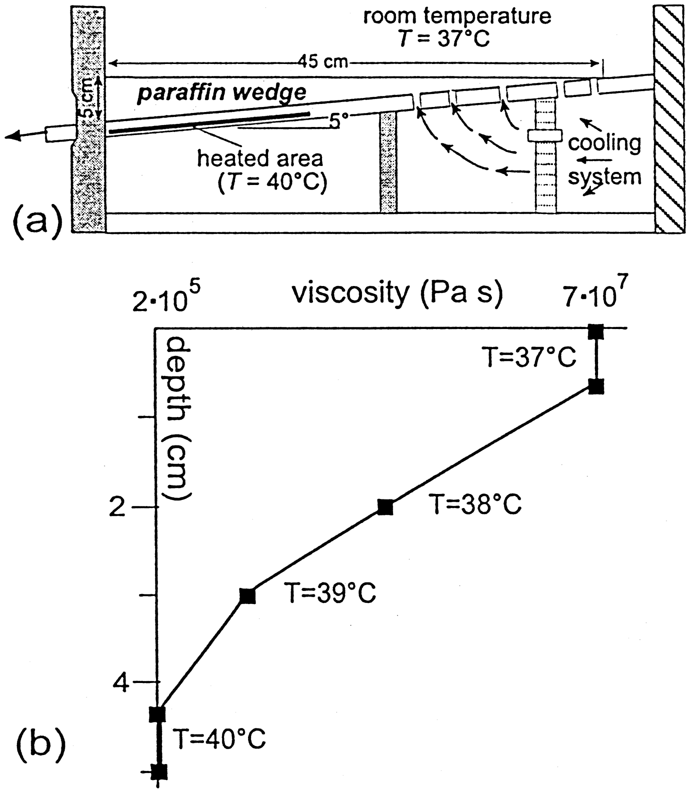

Fig. 7. Schematic drawing of thermomechanical appararatus for scale modelling of orogenic wedges (Rossetti et al., 2000). (a) The model wedge, resting on an inclined mobile basal plate and a rigid backstop, is deformed by steady motion of the basal plate towards the rear of the wedge, simulating underthrusting; (b) vertical viscosity distribution resulting from the temperature gradient near the rear of the paraffin wedge. (®2000 Elsevier Science Publishers; reproduced by permission).

ted (foreland fold-and-thrust belts), or thick-skinned, where deformation involves the basement (cf. Ranalli, 1995 for a brief discussion). The internal deformation is accomplished by thrusting and folding. In the past, these processes have been modelled using various model materials (i.e., sand, plasticine, silicone putty) in either "sandbox" configurations (where deformation is driven by externally imposed shortening), or by the centrifuge technique (where deformation is driven by the gravitational collapse of the "hinterland"; see e.g. Mulugeta, 1988; Dixon and Liu, 1992; Liu et al., 1992, among others). The construction of a thermomechanical apparatus in which a paraffin wedge is subject to a constant and measurable thermal gradient has recently allowed the modelling of orogenic wedges with continuous depth-dependent rheology (Rossetti et al., 2000, 2001 in press; see Fig. 7). This experimental technique has led to a clarification of the relations between shortening rate, equilibrium shape of the wedge, and patterns of deformation within the wedge.

5. Conclusions

It is clear from the above examples that experimental tectonics has come a long way since Hall's time. Its guiding principles, however, are still the same. What Hall (1815) said of the *killas* folds could be equally well said of subduction, orogenic wedges, and other geodynamic features:

> In reducing these irregular forms into system and connection, one object, of no small consequence in geology, seems to be obtained; but it would be desirable, if possible, to go one step farther, and to discover *by what means this peculiar arrangement has been brought about.* For this purpose, it will be necessary to shew, first, that this peculiar conformation may be given to a set of horizontal beds by a mechanical force of sufficient strength; and, secondly, that there are rational grounds for believing, that such a force has been actually exerted in this case. *I have now, and formerly, tried to establish the first point by experiment*; and I shall endeavour to vindicate the second by a train of geological reasoning... [Italics added.]

On the other hand, important changes have occurred, which have given added impetus to experimental tectonics. They can be schematically listed as: (i) the development of a quantitative theory of scaling; (ii) continuous improvement in the knowledge of the rheology of both natural and model materials; and (iii) technological advances which have allowed the construction of more sophisticated experimental apparatus. In the past few decades, a parallel and complementary advance has taken place in the power and flexibility of numerical models. The combination of analogue and numerical models will continue to prove a very useful tool for the advancement of our understanding of geodynamics.

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