Henley Cadell’s ‘Experimental researches in mountain building’: their lessons for interpreting thrust systems and fold–thrust structures

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Abstract: In 1888, inspired by fieldwork in what has become known as the Moine Thrust Belt, NW Scotland, Henry Cadell conducted a pioneering series of analogue deformation experiments to investigate the structural evolution of fold–thrust belts. Some experiments showed that imbricate thrusts build up thrust wedges of variable form, without requiring precursor folding. Others demonstrated a variety of fold–thrust structures and how heterogeneities in basement can localize thrust structures. These experiments are described here and used to draw lessons on how analogue deformation experiments are used to inform the interpretation of fold–thrust structures. Early adopters used Cadell’s results as guides to structural styles when constructing cross-sections in thrust belts. His models and the host of others created since serve to illustrate part of the range of structural geometries in thrust belts. However, as with much subsequent work, Cadell’s use of a deformation apparatus, with a fixed basal slip surface, biases perceptions of fold–thrust belts to be necessarily ‘thin-skinned’ (experimental design bias) and can simply reinforce established interpretations of natural systems (confirmation bias). So analogue deformation experiments may be unreliable guides to the deterministic interpretations of specific fold–thrust structures in the sub surface of the real world.

Deformation experiments using rheologically contrasting materials as analogues for rock are widely used and cited to illustrate the evolution of large-scale geological structures. Their results are used to confirm the viability of interpreted structural geometries illustrated on cross-sections – especially in contractional tectonic regimes. This approach has a long history. An important early pioneer was Henry Moubray Cadell (1860–1934; Fig. 1) and his results were reported in his influential paper on ‘Experimental researches in mountain building’ (Cadell 1889). He was motivated to explain structures that he had mapped out as part of the team from the Geological Survey of Scotland working in what came to be known as the Moine Thrust Belt. One of his experiments, the sequential development of imbricate thrusts, is well known (e.g. Graveleau et al. 2012), and his illustrations were reproduced in some influential publications of the early twentieth century (e.g. Peach et al. 1907; Chamberlin & Miller 1918). Consequently, it might be assumed that he was only concerned with the formation of imbricate thrust systems. However, Cadell conducted a broader array of experiments in contractional tectonics deliberately designed to explore the origins of different structural styles, especially the relationships between folding and thrusting. Although some of his motivations, experimental designs and results are reported in Graveleau et al.’s (2012) excellent review of the development of analogue modelling, and the historical context reported by Oldroyd (1990), it is timely to look more broadly at Cadell’s work. The aim of this paper is to share more fully Cadell’s results and motivations. In doing so, we explore how analogue experiments are used to assist structural interpretation of the real world and how restrictive modelling approaches may introduce bias to these endeavours.

Cadell’s field investigations

Inspection of his notebooks reveals that Cadell was inspired to conduct his deformation experiments by his own fieldwork in NW Scotland (Butler 2004a). In the early 1880s, he was a member of the Geological Survey of Scotland, having joined in 1883. In the early summer of 1884, Cadell was sent north to assist Ben Peach and John Horne in the NW corner of the country. As Oldroyd (1990) extensively documents, Peach and Horne had been sent to Durness and Loch Eriboll districts (Fig. 2) to challenge the validity of
the contentions proposed by Callaway (1883) and Lapworth (1883) that the geological structure was dominated by major low-angle tectonic contacts. Peach and Horne’s director, Archibald Geikie, had held that the region largely consisted of a regular stratigraphic order. Faced with his colleagues’ findings, which confirmed and greatly elaborated upon Callaway and Lapworth’s results, Geikie famously recanted his earlier hypothesis and went on to coin the term ‘thrust’ for the low-angle tectonic contacts (Geikie 1884). He then directed a substantial cohort of his Survey colleagues to map out the region. The Survey team referred to this system, with characteristic understatement, as the ‘zone of complication’ (Oldroyd 1990). We now know it as the Moine Thrust Belt. Accounts of the Survey’s mapping approaches are provided by Butler (2010) and the regional geology is extensively described, including detailed site descriptions, by Mendum et al. (2009).

Even recognizing the talent and numbers that Geikie directed to the mapping, the team made remarkable progress. The northern area, from Eriboll to south of Ullapool (Fig. 2), was largely mapped by the end of 1887. Geikie presented the preliminary results on behalf of the Survey team to a meeting of the Geological Society on 25 April 1888. The written report (Peach et al. 1888) included 15 cross-sections, strongly concentrated on the Assynt district (Fig. 2). The complete report on the NW Highlands had to wait for a further two decades (Peach et al. 1907), although the mapping (and indeed the publication of many of the geological maps) was completed significantly earlier.

A range of structural styles was interpreted by the team and documented in their preliminary account (Peach et al. 1888; Fig. 3). The rock units of NW Scotland are particularly distinctive (Fig. 4) so that the Survey team were readily able to recognize stratigraphic repetitions between which they inferred the presence of steeply dipping reverse faults (‘minor faults’ as designated ‘t’ on Fig. 3a). Along with these steep faults, the team also recognized low-angle thrusts which they generally inferred to have significant subhorizontal displacements (‘major thrusts’, designated ‘T’ on Fig. 3). The ‘minor thrusts’ would, in more modern accounts (e.g. Elliott & Johnson 1980), be termed imbricate thrusts with the ‘major thrusts’ forming the roof and floor thrusts to duplexes. The lowest recognized low-angle thrust was generally designated as the ‘Sole thrust’ (Fig. 4). Some of the structurally higher ‘major thrusts’ carry Lewisian basement (e.g. the Glencoul Thrust, T2; and the Ben More Thrust, T3 on Fig. 3). The basement sheets contain major, broadly westward-facing folds that deform the original basement-cover unconformities.

It was into this team that Cadell was embedded. Geological investigations were facilitated by the newly available topographic survey of Scotland so that the Survey team had access to state-of-the-art...
maps, at a scale of 1:10 560. The geologists did, however, draft their own topographic contours (see Butler 2010, for more details on the mapping strategies and approaches of the Survey team).

Cadell was allocated the mountain wilderness immediately south of Loch Eriboll (Fig. 4). A discussion of his fieldwork is provided in more depth elsewhere (Butler 2004a). The area has over 900 m of relief and is cut by deep valleys. One of these, Strath Dionard (Fig. 4), runs nearly parallel to the regional dip direction of strata and the valley sides provide two natural cross-sections. The deeper parts of these sections, towards the NW, contain metamorphic basement (the Lewisian), overlain
Fig. 3. Selected cross-sections through the Assynt district as published by Peach et al. (1888), and located on Figure 2. Precise localities were not provided in the original publication but correspond as follows: (a) north of Inchnadamph; (b) the ridge between Loch Assynt and Glencoul (c. 4 km north of Fig. 3a); (c) Ben More Assynt. The numbers on the sections identify the various stratigraphic units (see Fig. 4): 1, Lewisian basement; 2, Torridonian; 3, Lower Quartzite; 4, Pipe Rock; 5, Fucoid Beds; 6, Saltarella Grit; 7, Durness Group carbonates. Section a, c. 1.2 km across; section b, 2.4 km across; section c, 3.2 km across.
unconformably by quartz sandstones of Lower Cambrian age (Eriboll Quartzite Formation). These strata are stacked and repeated by thrusts – especially evident on the mountain ridges of Conamheall and Foinaven (Fig. 6a). Cadell recognized these thrust repetitions, although he termed the faults themselves ‘slide planes’ (abbreviated ‘SP’ on Fig. 6b). He also noted that the top of the Lewisian basement passed beneath the repeated Cambrian strata without being offset by faults. He was able to map out the base of the deformed quartz sandstones – later designated as the Sole Thrust (Peach et al. 1907; Fig. 4). He also mapped out the ‘slide planes’.

Throughout his study area, Cadell recognized various thrust geometries (Fig. 6). In many cases these were developed in a single formation, the Pipe Rock Member (Fig. 4), and developed on scales that were too small to be represented on his maps. Where the structures involved more diverse parts of the Cambrian stratigraphy, their internal bed geometries were shown in more detail (Fig. 6f). These representations clearly conform to Peach’s view of imbricate structure (Fig. 5).

The eastern side of Cadell’s study area comprises the ‘Moine Schists’, carried on their eponymous thrust (Fig. 4). Cadell refers to this major structure as ‘the Great Slide Plane’ (‘GSP’ in his notebooks). The Moine Thrust is simply the highest of a series of dislocations, characterized in Cadell’s interpretations (e.g. Fig. 7) as dipping at a low angle, relative
to the smaller thrusts he mapped within the
Cambrian strata.

Cadell’s perception of the characteristic structure
of his study area is shown in Figure 7b, a diagram
from his notebook that is a proof copy destined for
his book on Sutherland’s geology (Cadell 1896). It
shows the structure created by thrusts of different dis-
placement and dip, all repeating stratigraphic units.
Therefore, it was this understanding, built from
field-work, that would inspire Cadell to recreate experi-
mentally the deformation structures that he mapped.

**Cadell’s experiments**

When discoveries are made in various departments of
physical science, it is usual, if possible to try how theo-
ries squares with facts, and in such branches as electricity
and chemistry, the experimental method has produced the most important results

(Cadell 1896, p. 68).

In January 1887, Cadell conducted a series of exper-
iments in the courtyard of his home in Grange, West
Lothian. He was not walking untrodden ground. Deforma-
tion experiments on analogue materials had been carried out at various times in the nine-
teenth century. Of these, Cadell was certainly
aware of those by Hall (1815) and Favre (1878),
who were especially concerned with the origin and
tectonic significance of folding. Daubrée (1879)
had created reverse faults by lateral compression of
a model of layered wax. Therefore, it was not the
experimental concept that was original. The impor-
tance of Cadell’s work lay in his desire to develop
a range of different structures and to investigate
some possible explanations for these differences.

A key issue facing the Geological Survey in their
work in the ‘zone of complication’ was the origin of
the thrust faults. Existing theoretical understanding
of the process largely came from the Swiss Alps,
especially through the influential works of Albert
Heim (1879). In this, thrust faults were considered
to evolve from the progressive development of over-
folds through the attenuation and shearing of the
overturning limbs. Thus, rocks adjacent to the thrust
faults should include strongly sheared and locally
overturned strata. It was an inference that was at
odds with the observations and interpretations that
the Geological Survey team, including Cadell,
were making in the NW Highlands, where thrusts
separated panels of tilted but otherwise largely
undisrupted strata (e.g. Figs 3, 6 & 7). As he subse-
quently noted: ‘it occurred to my colleagues of the
Geological Survey and myself, that our discoveries
and theorizing might, perhaps, be substantiated or
at least illustrated on a small scale by a few simple
experiments at home’ (Cadell 1896, p. 69).

The deformation apparatus (Fig. 1) consisted of
an open-topped rectangular wooden box some six
feet (1.9 m) long of which one end could be driven
in via a hand-turned screw. Thus, the two ends of
the box converged – subjecting any material caught
between these ends to horizontal contraction. Cadell
pressed down on the movable endwall to keep it in
contact with the base of the deformation box. One
of the long sidewalls could be removed during and
after each experiment run so that the structure
could be observed and photographed. These photo-
graphs are the primary records of the experiments,
from which Cadell made careful drawings and
other synoptic diagrams. In the course of the exper-
iments he produced over 60 photographs and associ-
ated sketches, 32 of which he reproduced in his paper
(Cadell 1889). In the account below, some of the
original images, as preserved in his laboratory
book, are reproduced. As he states (Cadell 1889,
p. 339), these ‘images tell their own tale, and require
but little description’.

**Imbricate thrusting**

As Cadell (1896) noted, in order to recreate the types
of imbricate thrusts as interpreted in the NW High-
lands, he needed a deformation medium that was
less prone to buckling than those deployed by Hall
(1815) and Favre (1878). He achieved this by

**Fig. 5.** A scene from Ben Peach’s field notebook
apparently showing his interpretation of imbricate
thrusting. The colours represent stratigraphic units. Note
the schematic restored section, showing that these units
are unbroken and subhorizontal – with the future thrust
trajectories penciled in. In the faulted section pencil
lines indicate different exposure levels through the
structure. Image courtesy of BGS.
entombing layers of dry plaster of Paris within damp sand. By using different colours of sand he created a recognizable stratigraphy for tracking deformation. After a few minutes the plaster had absorbed some water and begun to set: Cadell had created a rheological brittle–ductile multilayer. In other experiments, he found that foundry loam (a paste made from moistened clay and fine sand, primarily used to create moulds for casting iron) could achieve similar results without using plaster of Paris as a brittle layer.

As Cadell pushed the endwall into his multilayer he noted that the surface of the model bulged up. He opened the sidewall to reveal arrays of imbricate thrusts (Fig. 8).

Eureka! said I to myself, not loud but deep. Here was a mountain in embryo newly upheaved, before denudation had ever scratched its brow, full of neat little thrust-planes, a perfect model of some of the heaped-up quartzite bens of Sutherland

(Cadell 1896, p 71; ‘ben’ is a local term for hill or mountain).

Critically for the interpretation of the structure deduced in the NW Highlands, Cadell’s experiments showed that thrusting could occur in a stratigraphic and rheological multilayer without any precursor folding. He further noted that the thrusts all dipped back towards the converging endwall of his deformation apparatus. However, many of Peach et al.’s (1888) cross-sections (e.g. Fig. 3b and c) showed complex thrusting. Cadell went on to create further experiments where he relaxed his downward pressure on the movable endwall so that it rode up across the partly deformed model. In this way he created low-angle thrusts: ‘Hey, Presto! The whole mountain jumped up and slid forwards in a lump, thrust-planes and all, along the top of the strata below, which were also beginning to show distinct signs of thrusting’ (Cadell 1896, p. 72).

The differences in thrust geometry were summarized by Cadell in a series of sketches, clearly derived from photographs of various experimental runs (Fig. 9). In this he describes the stack of imbricate thrusts as ‘wedge structure’, as developed in Figure 8. The other sketches show the variations in the ‘wedge structure’ created in the various experimental runs. He notes that changing the spacing of thrusts and their displacement creates different wedge forms. The lower two diagrams show the results of allowing the endwall to ride up onto the trailing edge of the model – showing how imbricate stacks may be carried forward on underlying structures. In his discussions Cadell clearly recognizes that early formed thrusts can be folded and, as in the third diagram, become downward facing (Fig. 9). However, as the quote above indicates, he was most struck by the creation of thrusts of different sizes as interpreted in the NW Highlands (Fig. 3) – small-displacement imbricate thrusts (which he equates to the ‘minor thrusts’) and larger, low-angle thrusts (that he equates with the ‘major thrusts’).

Fold–thrust structures

In a further experiment, again using encased embrittled layers of plaster of Paris, Cadell created a fold–thrust structure (Fig. 10). From this he deduced that, by changing the layer structure and rheology, folding and thrusting could develop in the same model. The model, in its partly developed form (Fig. 10, upper), has a thrust at depth passing up into an antiform. The forelimb of the fold contains smaller reverse faults, and the back-limb has developed shears. As Cadell (1889, p. 343) notes: ‘Towards the surface this line of shear [the deeper thrust within the model] is seen to split up, till the movement, which was confined to one plane below, has become so distributed through the mass that the underlying thrust plane is lost in a great fold above, and never appears at the surface’. In this fashion Cadell became aware that thrusts, as localized brittle structures, can change structural style up-section. In this case the upward change from thrusting into folding is represented not simply as a fault tip but by a zone of distributed minor thrusting.

After imposing further contraction, in the final state (Fig. 10, bottom), the earlier-formed antiform has elongated upwards, tightening and stretching the limbs. The effect is to largely overprint the back-limb shears. Collectively these deformations record vertical stretching. However, in parallel, a new thrust has developed ahead of the vertically stretched antiform. This thrust has cut cleanly through the multilayer. Thus, the same multilayer can show different structural styles in the same experiment.

The continuity of thrusts to depth

Cadell speculated that brittle thrust structures are unlikely to continue deep in the Earth, arguing that with increased temperatures with depth, ‘rocks must begin to soften, and in such cases rock masses cannot well be expected to behave like rigid bodies’ (Cadell 1896, p. 75). Therefore, he constructed an experiment where the deeper layers were forced to fold rather than fault. To do this he laid the base of his experimental rig with waxed cloth and upon the layer he laid down his rheological multilayer of sand with embrittled plaster of Paris. The expectation was to demonstrate that thrusting in shallow levels could pass downwards into folding. In order to investigate the progressive development of the structure, Cadell removed the side panel of the deformation at various stages of his experiment. These ‘time-lapse’ images are reproduced in Figure 11a.
He noted that the deeper layer of waxed cloth buckled as expected but the shallow levels did indeed fault. The thrust passed downwards so that, with progressive deformation, they became difficult to identify.

Cadell also used this experiment to discuss the symmetry of thrusting relative to the fold – terming the end product a ‘fan structure’ (Fig. 11b). He noted that the thrusts developed progressively as the anticline tightened. The model is interesting because it shows that Cadell was not fixed on simply reproducing Peach’s (Fig. 5) representations of imbricate structures or restricting thrusts to necessarily pass downwards onto a basal detachment or sole thrust. Rather, he was exploring alternative scenarios, forecasting the deep structure of thrust systems in nature that, at the time, lay outside his experience.

**Basement involvement**

Up to this point, Cadell’s experiments, in common with those conducted by previous researchers, used laterally continuous layers of material (sand, clay, foundry loam, plaster of Paris and waxed cloth). This arrangement was appropriate for models that might inform understanding of thrust structures developed in the Cambro-Ordovician strata of NW Scotland – stratigraphy that is remarkably layer-cake over tens of kilometres. However, the arrangement...
of the main rock sequences in the NW Highlands, especially in the Assynt district, was not that simple. The Torridonian strata that underlay the Cambrian rocks formed a wedge shape, tapering eastwards – and this was known to Cadell (see Butler 2010). The gneissic structure of the Lewisian basement that underlaid both the Torridonian and Cambro-Ordovician strata was highly inclined.

To explore the consequences of deformation in a complex, layered system, Cadell constructed a further model that was substantially more elaborate than his other fold–thrust experiments (Fig. 12). The model setup was sketched out in his laboratory notebook (Fig. 12a) and consists of three key layer components. The lowest portion of the model, representing Lewisian basement, was constructed in panels of inclined layers. These are not explicitly described in his notebooks but presumably largely comprise foundry loam and damp sand–clay mixes that were cohesive enough to be built up with significant slopes. In one part of the model Cadell cut in a near-vertical strip of sand, representing a dyke. Above the composite basement layer Cadell created a rightward-tapering wedge (i.e. thinning towards the mobile endwall of the experimental rig) of sand and loam (sequence 1 on Fig. 12b). He then overlaid this wedge with a rightward-dipping sequence of sand, filling the low part of this with a further sand–clay mix (sequence 2 in Fig. 12b). Apparently two thin layers of plaster of Paris are included, one in each of the labelled sequences. Finally, Cadell added a vertical cut in the model, apparently to examine the role of inherited flaws in the layering in localizing subsequent deformation.

Deformation in this model appears to have localized along the layering within the ‘basement’ unit, developing spaced thrusts that cut up into the overlying layers. As with his fold–thrust models,
the trailing edge of this experiment experienced vertical stretching, strongly modifying not only the trajectory of the thrusts but also the thicknesses of layers. The deformation also propagated outwards, away from the moving endwall and into the previously unformed parts of the layers. Regardless of these deformations, angular discordances between the sequences of layers that were built before the experiment ran were still recognizable, although deformed, in the final state.

The ‘basement model’ (Fig. 12) illustrates Cadell’s broader interest in deformation. In their discussion of the structures within the Lewisian gneisses of NW Scotland, Peach et al. (1888) describe localized shear zones – features that they explicitly interpreted as ‘thrusts’. Thus, for these workers, the term ‘thrust’ embraced a range of localized deformation structures. In this sense it is interesting that Cadell included a ‘dyke’ in his model. He noted that the ‘dyke’ was sheared into the thrust – essentially demonstrating the behaviour deduced from outcrop (e.g. Peach et al. 1888, p. 394).

General results

It is evident from the array of experiments that he performed that Cadell was intent not just on recreating simple thrust structures. He deliberately wanted to show how minor and major thrusts were essentially formed in the same way and that, when acting together, could create a wide variety of thrust belt (‘wedge’) structures. However, he went much further, examining the possible relationships between folding and thrusts, relating these to distinct rheological properties and the propensity for brittle failure of layers. He was also intent on upscaling these models to understand the orogenic process, examining how shearing and associated foliations might relate to

Fig. 7. Cadell’s interpretation of the structure at Creag na Faolinn (located on Fig. 4) from diagrams in his field notebook. The profile of the section can be seen in Figure 6d. (a) His interpreted profile with thicknesses of structures (in feet). (b) An etching (subsequently published in Cadell 1896) glued into his field notebook, with additional annotation. The section is oriented WNW–ESE (left to right). The WNW side identifies Cambrian quartzite unconformably overlying ‘undisturbed Archaeon (sic) gneiss’. On the WSE side Moine Schist (sic) overlies a thrust contact (GSP, Great Slide Plane on Fig. 7a, now termed the Moine Thrust) above Archaeon (sic) gneiss. A further thrust plane separates this sheet from ‘Cambrian beds’. Image courtesy of BGS.
localized slip. He drew the following conclusions (as a ‘general summary of results’; Cadell 1889, pp. 356–357):

1. Horizontal pressure applied at one point is not propagated far forward into a mass of strata.
2. The compressed mass tends to find relief along a series of gently inclined thrust-planes, which dip towards the side from which pressure is exerted.
3. After a certain amount of heaping-up along a series of minor thrust-planes, the heaped-up mass tends to rise and ride forward bodily along major thrust-planes.
4. Thrust-planes and reversed faults are not necessarily developed from split overfolds, but

Fig. 8. Cadell’s classic and oft-reproduced record of his imbricate thrusting experiment. He termed this style as ‘wedge structure’; The photographs apparently record two attempts to create imbricate thrusts together with a watercolour painting of the summary structural style. Images courtesy of BGS.
often originate at once on application of horizontal pressure.

(5) A thrust-plane below may pass into an anticline above, and never reach the surface.

(6) A major thrust-plane above may, and probably always does, originate in a fold below.

(7) A thrust-plane may branch into smaller thrust-planes, or pass into an overfold along the strike.

(8) The front portion of a mass of rock being pushed along a thrust-plane tends to bow forward and roll under the back portion.

(9) The more rigid the rock, the better the phenomenon of thrusting will be exhibited.

(10) Fan-structure may be produced by the continued compression of a single anticline.

(11) Thrust-planes have a strong tendency to originate at the sides of the fan.

(12) The same movement which produces the fan renders its core schistose.

(13) The theory of uniformly contracting substratum explains the cleavage often found in the deeper parts of a mountain system, the upper portion of which is simply plicated.

(14) This theory may also explain the origin of fan-structure, thrusting, and its accompanying phenomena, including wedge structure.

Cadell had successfully demonstrated his first hypothesis – that thrusts need not form in a layer that had first to experience over-folding, as envisaged by Heim (1879). He had achieved this by creating a rheological layering that incorporated deliberately embrittled plaster of Paris that would break rather than buckle. In this he confirmed Peach’s (Fig. 5) representation of imbricate thrusts.

Cadell’s experimental apparatus required deformation to be detached from the rigid base. Consequently, the concept of a basal detachment beneath the imbricate thrusts in NW Scotland was reinforced. However, he did consider that this type of thrusting was a relatively shallow phenomenon in the Earth and that, on some larger scale, the deformation passed downwards into folding. In more modern language we might now call this depth-dependent deformation. Cadell illustrated this with watercolour sketches (Fig. 13), possibly used to support his address to the Royal Society of Edinburgh the year after his experiments.

It is evident from the array of experiments that he conducted that Cadell was interested in more than simply establishing that thrusts can form in a layer that had not previously been folded. In doing so he showed that Heim’s (1879) view that thrusts formed rather late in the progressive deformation of strata undergoing contraction was not of universal application. He explored other relationships between thrusting and folding, designing experiments to form structural relationships that, at that time, had not been recognized in the NW Highlands by the Geological Survey team. He documented that thrusts can terminate upwards into folds and pass back down-dip into folds and more distributed deformation. Consequently, he envisaged that deformation can change style, with contrasting behaviours of strain localization, through multilayers and with depth in the Earth. Even though his deformation apparatus was narrow and therefore designed to understand structural evolution in the two-dimensional planes of cross-sections, Cadell was aware that thrusts can pass laterally into folds – and therefore that multilayers can show lateral variations in the ways in which they localize deformation. By creating a ‘fan structure’ he showed that
thrusts can form with opposed dips. Less relevant to the discussions here, Cadell also performed experiments to investigate the relationship between the development of schistosity and deformation kinematics. So, in the space of just a few days, he had greatly expanded knowledge of the structural evolution of fold–thrust systems and raised issues that continue to challenge the community today.

Cadell’s legacy

Cadell presented his experimental results to the Royal Society of Edinburgh on 20 February 1888, using his photographs as illustrations. The written publication appeared in the Society’s Transactions in January of the following year (Cadell 1889). A less formal account is given in his Geology and Scenery of Sutherland (Cadell 1896). Cadell’s father died in January 1888 and that year he resigned from his position in the Geological Survey to manage the family’s extensive business interests (Oldroyd 1990; Mendum 2010). And so, it was for his colleagues in the Geological Survey and others to make use of the experimental results.

The imbrication results (Fig. 9) were used extensively to inspire interpretations in the northern part of the Moine Thrust Belt, so that cross-sections in the NW Highlands memoir (Peach et al. 1907) are broadly similar to those in the preliminary paper (Peach et al. 1888). However, as the Geological Survey team interpreted further south in the thrust belt (Fig. 14), they applied more complex fold–thrust relationships, just as Cadell created in his later experiments (e.g. Figs 11 & 13). In these sectors of the thrust belt the Cambrian quartzites are underlain by thick sandstones of the Torridon Group. Compared with elsewhere in the thrust belt, structures in the south are generally more widely spaced so that thrust sheets incorporate thicker stratigraphic sections. Thrusts are associated with significant folding, especially within Torridon Group rocks. Thus, Cadell’s contention that thrusts can pass downwards into strata that have a greater propensity for folding is
developed by the interpretations of Peach et al. (1907). This willingness to adopt variations in structural style in interpretations along the Moine Thrust Belt has been reflected in subsequent syntheses (e.g. Mendum et al. 2009, fig. 5.2).

The imbrication results were reproduced and discussed by Peach et al. (1907) alongside Cadell’s list of conclusions. The sequence of thrusting in the NW Highlands was a key concern for the Survey team and the issue was fully discussed by John Horne (in Peach et al. 1907). Cadell’s experiments generally showed a forward migration of thrusting. Of course, it is this behaviour that has been assumed to dominate thrust systems, since workers in the foothills of the Canadian cordillera termed the sequence as piggy-back (e.g. Dahlstrom 1970). However, Horne was strongly influenced by the field relationships in the NW Highlands and considered higher thrusts to truncate imbricates that lay in their footwalls (Peach et al. 1907; see discussion in Butler 2010). Horne likened the behaviour to stratigraphic overstep, although in modern parlance the behaviour he invoked might be termed break-back (Butler 1987) or ‘out-of-sequence’ thrusting. Consequently, Horne concluded that interpretations of the real world trumped inferences made from analogue models. Much later, in re-interpreting the Geological Survey’s fieldwork, Elliott & Johnson (1980) proposed that the Moine Thrust Belt behaved exclusively in piggy-back fashion. Subsequent fieldwork has established significantly more complexity in the sequence of thrusts in the NW Highlands (e.g. Coward 1980, 1983, 1988; Butler 1987, 2004b; Holdsworth et al. 2006; Watkins et al. 2014), indeed much of this is presaged by Cadell’s experiments and their inferences. There are generalities concerning the confrontation between model results and the interpretation of real-world structures that are discussed below.

As for the rest of Cadell’s experiments, most of his conclusions are far less well known. Debates as

Fig. 11. (a) Progressive formation of a fold–thrust structure. In modern terminology the structure might be termed a ‘detachment fold’ (e.g. Jamison 1987). Here the lower part of the model is formed by waxed cloth upon which a sand and plaster of Paris multilayer has been laid. The images are displayed in deformation sequence (earliest at the top, latest at the bottom). The waxed cloth and lower sand layer has buckled. However, the shallower layers, within which there are thin seams of embrittled plaster of Paris, develop thrusts. (b) Cadell’s designation of the fold–thrust structure in (a) as a ‘fan structure’. These sketches illustrate the evolution of the structure with thrusts developed as the antiform is progressively tightened. Images courtesy of BGS.
to the downward continuity of thrust structures and changes of structural style are recurrent themes in tectonic research (e.g. Ramsay 1980, fig. 22, and many others since). Cadell recognized these issues yet it is his demonstration of ‘thin-skinned’ thrusting that dominates studies of thrust systems today. Cadell’s fieldwork in the ground south of Loch Eriboll (Fig. 4) was as influential as his experiments. A combination of his experiments and fieldwork features strongly in Seyfert’s (1987, pp. 334–335) encyclopaedia entry on imbricate structure. His cross-section through the Foinaven ridge was reproduced in Read & Watson’s (1962) influential geology primer and again was referenced in Elliott & Johnson’s (1980) reappraisal of the Moine Thrust Belt. It went on to become Boyer & Elliott’s (1982) type example of a hinterland-dipping duplex. Subsequently work has suggested that the duplex model as propounded by Boyer & Elliott is not applicable to the Foinaven sector. The relationships described by Cadell, showing truncation of the imbricate slices by the over-riding Moine Thrust sheet, are correct and the sequential development of thrusting is not simple (Butler 2004b).

Validation, confirmation and structural interpretation

The foundations laid by Cadell experiments in the late nineteenth century have been built upon extensively in the intervening 130 years, as exhaustively documented by Graveleau et al. (2012, see Lacombe et al. 2019 for further references). Many recent studies have used analogue experiments to examine the dynamics of entire thrust wedges, for example the sensitivity of the shape of the overall thrust belt to changes in the strength of the basal detachment, or to patterns of erosion and deposition on the wedge-top. As Graveleau et al. (2012) conclude, analogue modelling has become ‘an indispensable tool for investigating tectonics and relief dynamics’ – that is for investigating the large-scale evolution of thrust systems. Other groups of researchers have sought to use geometric models to limit the range of structural styles they apply to interpretations of real-world examples. The issues that arise from the use of geometric and numerical models in fold–thrust belt interpretations are discussed elsewhere (e.g. Groshong et al. 2012; Butler et al. 2018); here we concentrate on the utility of analogue deformation models in reducing interpretation uncertainty.

Deliberate attempts to mimic individual structures to reduce uncertainty in subsurface interpretation of thrust belts that are prospective for oil and gas were arguably pioneered by Theodore ‘Ted’ Link (1897–1980) in the 1920s and 1930s. Ted Link was an innovative and pioneering exploration geologist who worked in many parts of the world but was a particularly important figure in the discovery of many large hydrocarbon fields in Canada (e.g. Mackenzie 1981; Sikstrom 1996). He started working for Imperial Oil (Exxon) in 1919 but after a few years took leave of absence to complete a PhD at the University of Chicago. There he worked with Rollin Thomas Chamberlin, who’s own work cited Cadell’s experiments (Chamberlin & Miller 1918). Link developed a series of analogue model experiments designed to study thrust structures and orogenic evolution and compared his results to well-documented natural examples of deformed strata.

Fig. 12. Basement structure. (a) Cadell’s design of the experimental setup, based on the ‘double unconformity’ that characterizes the stratigraphic arrangement in the NW Highlands. (b) Traces of the early stages of deformation (XXVII in c), annotating the various model components. (c) The progressive deformation of the model (XXVII–XXIX). Images courtesy of BGS.
On return to Imperial Oil in 1927, Link worked in the foothills of the Canadian Cordillera, including on the rapidly developing Turner Valley Field (Link & Moore 1934). Later, he used a series of analogue deformation experiments based on his cross-sections through the Alberta foothills (Link 1949). In his words: “The logical question for the reader is to ask is: “How does the writer [i.e. Link] know that this is the correct interpretation?” The answer is, the writer made the structure in the laboratory’. Link’s use of analogue modelling in this way was deterministic – the ability to mimic experimentally a particular structural interpretation, even in the poorly, or unconstrained subsurface, confirms the veracity of this interpretation – and therefore that other interpretations are falsified.

The use of analogue models to validate interpretations of subsurface structure in the deterministic manner proposed by Link is increasing. Recent examples include the Dabashan and the eastern Sichuan–Xuefeng fold–thrust belts in South China (Wang et al. 2013; He et al. 2018) within the South China Block (Yan et al. 2016) and the Wupoer fold belt in the NE Pamirs (Wang et al. 2016). These generally impose a structural or stratigraphic template derived from the specific geological case study. Consider the example of the Subandean ranges of southern Bolivia (Moretti et al. 2002 and references therein). The pre-kinematic strata comprise a 10 km succession of siliciclastic units, including significant shaley units (Baby et al. 1989 and others since). The Los Monos Formation (top Devonian) is generally considered to separate two composite packages of siliciclastics. Regional cross-sections (e.g. Moretti et al. 2002; Rocha & Cristallini 2015; Heidmann et al. 2017) all imply that the upper

Fig. 13. Cadell’s watercolour illustrations summarizing the evolution (top to bottom) of thrust structures and their downward passage into folds. Images courtesy of BGS.
and lower competent units deformed semi-independently, decoupled along the Los Monos Formation. Three different series of analogue experiments have been performed (Pichot & Nalpas 2009; Driehaus et al. 2014; Darnault et al. 2016), each using sand (as a proxy for competent units) and silicone (as an incompetent proxy). The array of models is far more elaborate than those conducted by Cadell in the nineteenth century. All pay particular attention to rheology and scaling factors. When applied to the Subandean fold and thrust belt of southern Bolivia, collectively they might appear to provide a good range of scenarios and thus reflect the diversity of viable structural interpretations.

Disharmonic deformation with depth is a well-established expectation for mechanical multilayers where competent layers are separated by thick incompetent horizons, as we discuss elsewhere (Butler et al. 2020). As Darnault et al. (2016) conclude, multiple detachment horizons within the pre-kinematic succession is why the structure within anticlines of the Subandean fold–thrust belt is complex. Yet collectively, the analogue deformations experiments did not lead to better drilling outcomes. The pre- and syn-drill structural models, based on the results of the analogue models, did not survive well penetrations. In order to reach the reservoir, repeated side-tracks were required (Heidmann et al. 2017). The analogue deformation experiments did not

Fig. 14. Peach et al.’s (1907) sections through part of the southern Moine Thrust Belt. Vertical and horizontal scales are equal and each profile is shown in two parts. (a) Beinn Eighe (x on Fig. 2); (b) Beinn Liath Mhor (y on Fig. 2). These illustrate the notion that thrusts (t) in the Cambrian strata (Ca, Cb = Eriboll Sandstone Formation) pass down into folds within the Torridonian (Bb), so that later in their investigations the Geological Survey adopted more diverse structural styles than the thin-skinned imbricate model.
reduce uncertainty in forecasting the probability of specific structural geometries at depth.

Published interpretations of the structure of fold and thrust belts, including the Subandean ranges of southern Bolivia, generally show the fold belt as ‘thin-skinned’ detached upon a basal slip surface. In fact, this is far from certain, lying well below the reach of drilling campaigns. The top of crystalline basement, imaging of which in the foothills of the Canadian Rocky Mountains in the 1960s (e.g. Bally et al. 1966) is commonly seen as the first prima facie evidence of thin-skinned thrusting as a tectonic process (e.g. Hatcher 2007), is very poorly constrained by geophysics in southern Bolivia. Could the anticlines at the surface be ‘thick-skinned’ and root down onto reactivated basement structures? Such a paradigm has not been investigated for southern Bolivia, through either structural interpretation or analogue modelling. Creating an appropriate deformation apparatus to model these ‘thick-skinned’ scenarios is far more complex than for the ‘thin-skinned’ ones.

There have been other attempts to model specific structures using analogue experiments: some have reported a diversity of structural geometries resulting from different experimental setups that explore the impact of inherited structures. For example, Granado et al. (2017) use three different initial model configurations to explore structural evolution in the Höflein high in the western Carpathian fold-thrust belt. Their models incorporate complex half-graben geometries that are deformed above a deep-seated detachment. Note, however, that the complexity of this structure and uncertainty in the pre-tectonic configuration of basins and stratigraphy suggest that significantly more than three different initial configurations would be needed to capture appropriately the range of possible geological interpretations. The work nevertheless illustrates the importance of pre-existing structures in controlling the final structure, just as Link (1931) did some 86 years earlier.

Notwithstanding the work of Granado et al. (2017) and several others (e.g. Del Ventisette et al. 2006 and discussions thereof; Yagupsky et al. 2008; Bonini et al. 2012) to investigate structural inheritance in thrust systems, the array of published analogue models for thrust systems is strongly weighted to ‘thin-skinned’ systems (Graveleau et al. 2012), but is this array representative of the diversity of natural thrust systems, or do the limitations of experimental design bias interpretations of natural thrust belts to conform with those portrayed on analogue models? There is a danger that analogue experiments can anchor structural interpretations of real-world examples in specific subsurface scenarios. Limitations in the design of experiments comprise one of several forms of bias that influence the creation and use of analogue models in interpreting the subsurface. We use the work of Cadell and others to illustrate some of these biases using the narrative to inform commentary on how analogue models of fold-thrust belts may best be used to inform subsurface interpretation.

Experimental biases

During the Vietnam War, Robert McNamara (US Secretary of Defense, 1961–68) used known casualty figures of enemy combatants as a quantitative measure of military success. Other parameters were unmeasurable and thus relegated to having no importance in tracking success – yet ultimately the USA lost the war, while still apparently winning using McNamara’s measure. This is the McNamara Fallacy, also known as the quantitative fallacy (Fischer 1970), in which only information that is readily quantifiable is used to make decisions or inform understanding (Bass 1995). Increasingly it is recognized as a source of cognitive bias across a wide range of disciplines. The deterministic use of analogue deformation experiments risks similar fallacious reasoning. Consider experiments configured to be thin-skinned and scaled using carefully quantified rheological layering (e.g. Schreurs et al. 2006). These may yield structural geometries that can be related explicitly to model input parameters. However, there may be many other combinations of rheology, geometry and deformation setup that can create structural geometries that satisfy observations of real-world examples. The ease of running specific types of experiments, especially for ‘thin-skinned’ models, can influence subsurface interpretation and our perceptions of uncertainties in these interpretations. We term this experimental design bias. This design bias is limited not only by difficulties in engineering deformation rigs but also by our perceptions of the possible structural geometries and evolution.

Confirmation bias (e.g. Nickerson 1998) arises from over-reliance on observations and experimental results that confirm an existing hypothesis or belief. Link’s (1949) words reproduced above are an excellent illustration of unwittingly falling for this. He concluded that being able to mimic in an analogue experiment his prior interpretation of foothill structures demonstrated that his interpretation was correct. The fallacy arises because Link did not attempt to create other subsurface interpretations and so did not try to evaluate the size of the solution space (in the sense of attempting to recognize all possible solutions to the problem and representing that breadth). The same limitations exist in the studies of the fold–thrust belts in south China, Pamirs, Carpathians and Bolivian Subandean chains referenced above. Without assessing the range of possible
structures, it is not possible to evaluate the probability of any one interpretation being correct.

Confirming structural geometries, through analogue model re-creation, falsely gives confidence to a single deterministic model, or narrow range of model realizations. Graveleau et al. (2012) hint at the dangers of this. Experimental design, real-world heterogeneities and the fact that nucleation of structures, in both the real world and analogue models, often arise from minor asperities or heterogeneities; single analogue models are just one realization of many possible geometries (see also Schreurs et al. 2006). This leads to the question as to whether re-creation of known structures in analogue models helps us to predict structural geometries in the unknown subsurface?

Reflections on biases inherent in Cadell’s work

Cadell (1889) adopted a distinctly different philosophy to that of Link (1949) and others. The range of different experiments Cadell ran was limited by the design of his deformation apparatus. His choice of deformable materials and their pre-deformational architectures was also limited. Notwithstanding these limitations, Cadell strove to create a diversity of fold–thrust structures. In modern parlance, he appears intent on limiting experimental design bias. However, in comparing experimental results with interpretations of the real world, was he, along with his colleagues in the Geological Survey, prone to confirmation bias?

For Cadell’s (1889) imbrication models (Figs 8 & 9), thrusts climb from a basal detachment and cut simply through the stratigraphy. The design of the apparatus with its basal detachment was consistent with Cadell’s direct observations that, in the South Eriboll district, deformed Cambrian strata overlay a top-basement surface that retained a simple, gently dipping planar geometry (e.g. Fig. 6b). Thus, his interpretations of a basal detachment beneath imbricate structures were consistent with field observations and not simply anchored by limitations of his experimental setup or narrowness of thought. However, Peach et al. (1907) tended to draw imbricate thrusts as subplanar, steeply inclined faults in their various cross-sections. This representation can be traced back to Peach’s early investigations in NW Scotland (Fig. 5) and, as we have seen, was adopted by Cadell in his field interpretations (Figs 6f & 7). Subsequent remapping in the 1980s established that that imbricate thrusts are folded and have a range of complex dips (e.g. Coward 1988; Mendum et al. 2009). This suggests that Peach et al. (1907) were anchored on Cadell’s imbrication experiments and had used these results to confirm their original interpretations (Peach et al. 1888). Peach et al. (1907) explicitly report Cadell’s (1889) imbrication experiments as confirmation of the structural styles they adopted on their cross-sections for the northern Moine Thrust Belt. The diversity of fold–thrust structures that Cadell (1889) created (Figs 10 & 13) were sparingly adopted by Peach et al. (1907) in their construction of cross-sections.

A basal thrust detachment to arrays of imbricate thrusts is a near-ubiquitous component of cross-sections drawn by Peach et al. (1907) for much of the Moine Thrust Belt. It might therefore seem that the Geological Survey were prone to experimental design bias – as a basal detachment was inherent in Cadell’s experimental apparatus. However, Cadell did attempt to modify his experimental design, by including deep layers where faulting was inhibited in favour of buckling. Of course, these deeper folds detached along the base of his apparatus but the thrusts in the shallower part of the model did not. Perhaps this gave Peach et al. (1907) confidence to interpret thrusts in the southern part of the Moine Thrust Belt as passing down into folds (Fig. 14).

Lessons from Cadell

It was not Cadell’s (1889) intention to mimic directly any specific structure in the NW Highlands. He was interested in demonstrating that particular types of structural geometry could be formed. This began with showing that, given the right conditions and materials, thrusts could form in layers that had not previously undergone folding. These thrusts formed arrays and tended to dip in a single direction, except when associated with folds (his fan structure). Neither Cadell nor his colleagues in the Geological Survey (Peach et al. 1888, 1907) used his experimental geometries to illustrate specific structures in the NW Highlands. Rather, they used the structural style evident in the experiments to draw cross-sections, with imbricate thrusts dipping towards the orogenic interior without any associated folding. However, in order to be consistent with field observations, these sections are considerably more complex than those produced experimentally, by invoking multiple, stacked detachment levels, for example. Note that, as discussed above, Peach et al. (1907) chose to prefer deductions from field observations rather than adopting Cadell’s experimental results when inferring the general sequence of thrusting. Overall then, Cadell (1889) and the early adopters (Peach et al. 1907) were less prone to the risks of over-confidence in their structural interpretations than Link (1949) and others.

Rather than be satisfied with creating a close approximation to a particular geometric interpretation, Peach et al. (1907) embraced a diversity of distinct geometric outputs from an array of different
experiments. This diversity may begin to illustrate the extent of the solution space and therefore show at least part of the uncertainties in the subsurface interpretations. Opting for a single experimental output or outputs based on a single experimental configuration and deformable material is unlikely to limit uncertainty assessment in subsurface interpretation.

Cadell’s (1889) experiments show the virtue of striving for diversity. As such they illustrate a variety of fold–thrust behaviours that can inform subsurface interpretation today – endeavours that are inherently uncertain. Striving for single deterministic solutions without eliminating other alternatives, be these solutions derived from theoretical models or experiments, can engender over-optimistic faith in forecasts of subsurface structure. Deformation apparatuses are much easier to design with simple basal detachments than by mimicking basement-coupled inversion tectonics. Consequently, simple thrust wedges dominate the literature (Graveleau et al. 2012), as they do for interpretations of fold–thrust belts. Similarly, imbricate thrusting is generally inferred to be the dominant structural style in thin-skinned systems while buckle folding is neglected (see Butler et al. 2020 for discussion). Cadell showed that deformation can localize in different ways through a multilayer. It is hoped that these and other structural styles, under-represented in both the interpretation and modelling literature, will be investigated more fully in the future.

Conclusions

Cadell (1889) pioneered the use of analogue deformation models to understand structural evolution in thrust belts. It is an endeavour that continues apace today, with much discussion on the opportunities for technical developments in analogue (and indeed) numerical modelling (see Lacombe et al. 2019, for example). However, there is little discussion of how these insights should be integrated into a workflow to reduce uncertainty in the interpretation of structural geometry in the natural world. The tendency to recreate arrays of imbricates to form thrust wedges, which dominate the modern literature in analogue deformation experiments, may introduce bias by confirming existing subsurface interpretations rather than challenging them.

Cadell was interested in building a range of models to explore what we would now call the ‘solution space’. He created a series of experiments of imbricate thrusting that demonstrated that thrusts could form without precursor folding and that imbricate thrusts could develop in various patterns. Additionally, he investigated how folds and thrusts can form together. Thrusts can lose displacement updip into folds and pass downdip into folding and more distributed strain. Cadell illustrated that basement heterogeneities can localize thrusts. It is unfortunate that, apart from those that produced imbricate thrust arrays (e.g. Graveleau et al. 2012), Cadell’s (1889) results are largely forgotten. His insights into how folding and thrusting can interact during progressive deformation can inform structural interpretation in fold–thrust belts at large.

The selective use of Cadell’s experiments and others since is an illustration of the dangers of cognitive bias inherent in interpretation. Fold–thrust belts need not simply be arrays of imbricate thrusts: they can show a wide range of structural styles (e.g. Butler et al. 2018, 2020 and references therein). Cadell recognized that the localization of deformation, both in his experiments and in nature, can be complex, and that this generates structural variability. We argue that there is more to be learnt from those analogue modelling studies that produce diverse results than those that are concerned with reproducing special structures. Cadell was definitely in the diversity camp. Indeed, it would have been exceptionally difficult to generate identical rheological multilayers for an array of models given his method for generating embrittlement of plaster of Paris. Rather he wanted to explore diversity in the structures that could be produced in his simple deformation apparatus. So, collectively Cadell’s diversity of experiments meant that Peach et al. (1907), as they went on to develop interpretations along the Moine Thrust Belt, were not anchored on one specific structural style. Cadell made no claims of quantification of his models and made only general comparisons between the structures formed in his experiments and those interpreted in nature. This is useful as it shows some of the possible solutions available for structural interpretation in thrust belts.

Expecting analogue modelling to yield single deterministic solutions, and therefore to entirely constrain interpretations of structural geometry is, in our view, over-optimistic. For analogue modelling to achieve this level of utility requires complete understanding of all possible interpretations. Simply being able to mimic in an analogue model the structural geometry displayed on an interpreted cross-section does not demonstrate the veracity of this interpretation, even if it may be reproduced in multiple experiments. Such approaches risk introducing confirmation bias into structural interpretation with the concomitant ignorance of the real uncertainties. There is a thin line between confirmation bias, validation and a void of possible interpretations that reflect our true understanding of subsurface structures in fold–thrust belts. Striving for diversity in analogue models, like those that Cadell created, based on thoughtful experimental design to create a
diversity of structures, can help minimize confirmation bias and help to fill the interpretation void of possibilities.

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