# Henry 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 structural evolution of fold and 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 localise thrust structures. These experiments are described here and used to draw lessons in 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. But, 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.

Key-words: Moine Thrust belt, analogue experiments, interpretation uncertainty, cognitive bias

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 20th 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, that 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 recognising 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 25th 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 recognise 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 recognised low-angle thrusts which they generally inferred to have significant sub-horizontal 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 recognised 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 is generally assumed that Ben Peach was the chief innovator of structural interpretation (e.g. Oldroyd 1990; Mendum & Burgess 2015). His field notebooks from the time show repeated sketches of a theoretical nature illustrating his ideas on the formation of imbricate thrusts (Fig. 5). These have the appearance of communication tools, perhaps drawn to share knowledge with Cadell and other members of the Survey team (Butler 2010). In these sketches, imbricate thrusts are considered to be arrays of reverse faults that acted upon originally horizontally-bedded strata. The effect is that the cross-sectional representations of thrust structures produced by the Survey team, not only in the preliminary report (Peach *et al.* 1888) but also in the main memoir (Peach *et al.* 1907), have a remarkably uniform quality.

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 900m 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 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 recognised these thrust repetitions, though he termed the structures “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 in his study area, Cadell recognised 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, characterised 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 Fig. 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 displacement and dip, all repeating stratigraphic units. And so, it was this understanding, built from fieldwork, that would inspire Cadell to recreate experimentally 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 theories 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 experiments in the courtyard of his home in Grange, West Lothian. He was not walking untrodden ground. Deformation experiments on analogue materials had been carried out at various times in the 19th 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. So, it was not the experimental concept that was original. The importance 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 overfolds 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 subsequently noted: “it occurred to my colleagues of the Geological Survey and myself, that our discoveries and theorising 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 into 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 end-wall 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 photographs are the primary records of the experiments, from which Cadell made careful drawings and other synoptic diagrams. In the course of the experiments he produced over 60 photographs and associated 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 Highlands, he needed a deformation medium that was less prone to buckling than those deployed by Hall (1815) and Favre (1878). He achieved this by entombing layers of dry plaster of Paris within damp sand. By using different colours of sand he created a recognisable stratigraphy for tracking deformation. And 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 of 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 end-wall 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).

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 end wall of his deformation apparatus. However, many of Peach *et al*.'s (1888) cross sections (e.g. Fig. 3b, c) showed complex thrusting. Cadell went on to create further experiments where he relaxed his downward pressure on the movable end-wall so that it rode up across the partly deformed model. In this way he created low-angle thrusts:

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Local term for hills or mountains.[*]

"Hey, Presto I 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 Fig. 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 end-wall 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 down-ward facing (Fig. 9). But, 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 Fig. 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 to restrict 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 km. 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). And 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 set-up 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 end-wall 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 localising 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 end-wall 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 recognisable, 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 localised shear zones – features that they explicitly interpreted as “thrusts”. Thus, for these workers, the term “thrust” embraced a range of localised 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 thrusts 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. And he was intent on upscaling these models to understand orogenic process, examining how shearing and associated foliations might relate to localized slip. He drew the following conclusions (as a "general summary of results": Cadell 1889, p.356-7):

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 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 will the phenomenon of thrusting 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, 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 recognised in the NW Highlands by the geological Survey team. He documented that thrusts can terminate upwards into folds and pass back downdip into folds and more distributed deformation. Consequently, he envisaged that deformation can change style, with contrasting behaviours of strain localisation, through multilayers and with depth in the Earth. And 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 localise 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 20th 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 managed 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, though 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 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 recognised 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 feature strongly in Seyfert's (1987, p 334-5) 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 19th 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 "to be 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 1995). 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 (e.g. Link 1928, 1931). 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) 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 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 19th 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.* 2019). 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 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, either through 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 set-ups 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, the complexity of this structure and uncertainty in the pre-tectonic configuration of basins and stratigraphy suggests 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. Ventisette et al. 2006 and discussions thereof; Yagupsky *et al.* 2006; Bonini *et al.* 2012) to investigate structural inheritance in thrust systems, the array of published analogue models for thrust systems are 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 sub-surface scenarios. Limitations in the design of experiments is one of several forms of bias that influence the creation and use of analogue models in interpreting the sub-surface. 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 sub-surface interpretation.

### *Experimental Biases*

During the Vietnam War, Robert McNamara (US Secretary of Defense, 1961-1968) used known casualty figures of enemy combatants as a quantitative measure of military success. Other parameters were unmeasurable and thus relegated to have 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 recognised 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. But there may be many other combinations of rheology, geometry and deformation set-up 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 foothills structures, demonstrated that his interpretation was correct. The fallacy arises because Link did not attempt to create other subsurface interpretations so did not try to evaluate the size of the *solution space* (in the sense of attempting to recognise 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 realisations. 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 realisation 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 were also limited. Notwithstanding these limitations, Cadell strove to create a diversity of fold-thrust structures. In modern parlance, he appears intent to limit experimental design bias. But, in comparing experimental results with interpretations of the real-world, was he and his colleagues in the Geological Survey prone to confirmation bias?

For Cadell's (1889) imbrication models (Figs. 8 and 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 set-up or narrowness of thought. But Peach *et al.* (1907) tended to draw imbricate thrusts as sub-planar, 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, were 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. But 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, 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 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 sub-surface structure. Deformation apparatuses are much easier to design with simple basal detachments than mimic 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.* 2019 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, are investigated more fully in the future.

## Discussion

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 in 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 up-dip into folds and pass down dip into folding and more distributed strain. He illustrated that basement heterogeneities can localise 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 on 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, 2019 and references therein). Cadell recognised 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 for 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's a thin line between confirmation bias, validation and a void of possible interpretations that reflect our true understanding of sub surface 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 minimise confirmation bias and help to fill the interpretation void of possibilities.

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## Figure captions

Figure 1. a) Henry Cadell posing with his deformation apparatus, surrounded by the materials he used to conduct the experiments. Note the sieve for ensuring equality of sand grade. b) sketch from Cadell's field notebook in which he lays out the design for his experiments. Images courtesy of BGS.

Figure 2. Simplified geological map of the northern Moine Thrust Belt, showing localities discussed in the text. The selected section lines from Peach *et al.* (1888) reproduced in Fig. 3 are indicated a-c. The boxed area locates Fig. 4. The inset shows the location of Fig. 3 in NW Scotland and the cross-sections of Fig 14 (x, y).

Figure 3. Selected  cross-sections through the Assynt district as published by Peach *et al.* (1888), and located on Fig. 2. Precise localities were not provided in the original publication. 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 – approximately 1.2 km across; section b – 2.4 km across; section c – 3.2 km across.

Figure 4. Simplified geological map of the Loch Eriboll district of the Moine Thrust Belt (located on Fig. 2). X – viewpoint for Fig. 6a; Y – viewpoint for Fig. 6c; Z – viewpoint for Fig. 6e; v – section location for Fig. 6f; w – section-line for Fig. 7. The inset shows the stratigraphic units involved in this part of the thrust belt (note that Torridonian rocks are not present here). The numbers on the column relate to the numerals on the sections of Fig. 3.

Figure 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 these units are unbroken and sub-horizontal – with the future thrust trajectories penciled in. In the faulted section pencil lines indicate different exposure levels through the structure. Image courtesy of BGS

Figure 6. Cadell country – the ground south of Loch Eriboll with some of his field sketches portraying the structure. Images are located on Fig. 4. a) shows the Conamheall ridge,

viewed from the eastern slopes of Srath Beag, with the Foinaven ridge in the background. Conamheall comprises imbricated Cambrian quartzites (almost exclusively the Pipe Rock Member of the Eriboll Sandstone Formation, with an original stratigraphic thickness of c 75m). The thrusting direction is inferred to be to the WNW (i.e. from L to R). b) Cadell's field sketch (dated 8th July 1885) showing his interpretation of imbricated Pipe Rock on Conamheall, viewed from the slopes of the Foinaven ridge (spelled "Foinnebheinn" here) , looking broadly NE-wards. SP = slide plane. c) view onto the Conamheall ridge from the summit area of Foinaven (near point 914m), giving a broadly equivalent perspective as for Fig. 6b. These structures were illustrated by Peach *et al.* (1907) and used by Boyer & Elliott (1982) as their type-example of a hinterland-dipping duplex. d) Cadell's field sketch looking northward down Srath Beag from the Conamheall ridge towards Loch Eriboll. The foreground captures part of the imbricated Pipe Rock that lies adjacent to Creag Shomhairle (called Creag Choral by Cadell). e) shows this structure more clearly, with increasing eastward dip in bedding in more eastern (internal) thrust slices. This structure is illustrated by Butler 1987 as a clear example of an antiformal stack duplex. f) Cadell's field interpretation of imbrication of Cambrian strata on the northern cliffs of Creagan Meall Horn. Images (b, d, f) courtesy of BGS

Figure 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 Fig. 6 d. a) shows his interpreted profile with thicknesses of structures (in feet). b) is 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 Archaean (sic) gneiss". On the ESE side Moine Schist (sic) overlies a thrust contact (GSP = Great Slide Plane on Fig 7a, now termed the Moine Thrust) above Archaean (sic) gneiss. A further thrust plane separates this sheet from "Cambrian beds". Image courtesy of BGS.

Figure 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.

Figure 9. Cadell’s summary diagrams that illustrate four contrasting experimental results to create thrusts. Images courtesy of BGS.

Figure 10. Progressive formation of a fold-thrust structure developed in Cadell’s rheological multilayer. In modern terminology this structure might be termed a “fault-propagation fold” (e.g. Jamison 1987). The bright white layer is embrittled plaster of Paris. This experiment has been photographed twice. The top image shows an intermediate deformation state. After acquiring the photograph Cadell will have replaced the side panel of the deformation rig, continued pushing in the end-wall. After a further contraction (estimated here to be about 5 cm), the side-wall was removed and the model re-photographed (lower image) to reveal that a new thrust has formed below the former fold-thrust structure. Note that the tape measure (graded in inches) is repositioned between photographs and is designed simply to provide a scale rather than a reference frame for tracking displacements. Images courtesy of BGS.

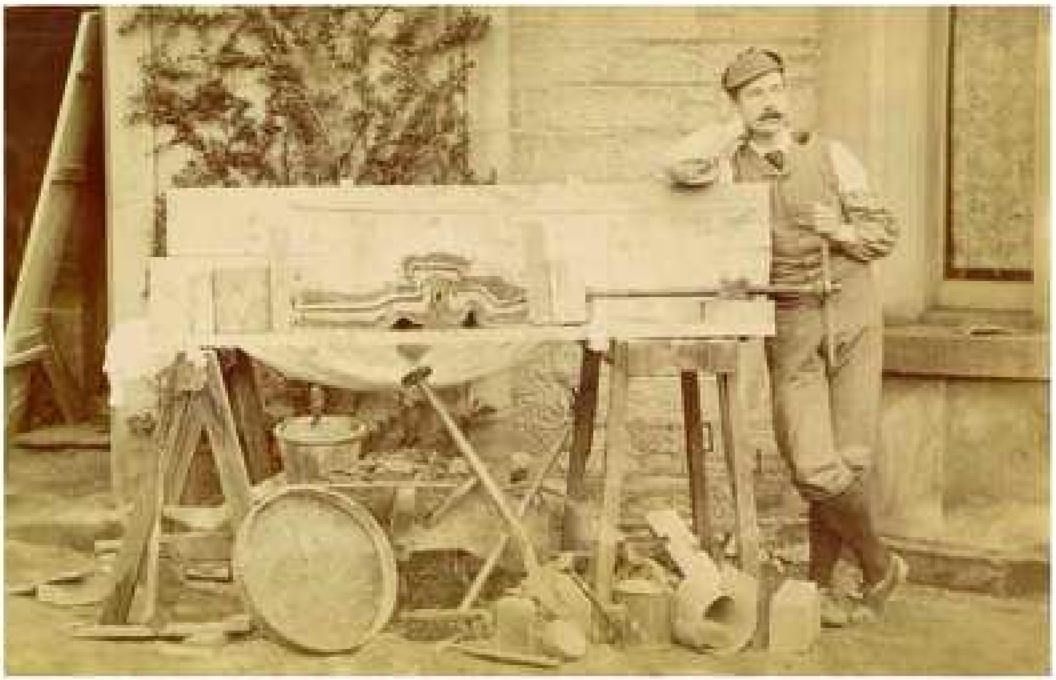
Figure 11. a) Progressive formation of a fold-thrust structure. In modern terminology the structure might be termed a “detachment fold” (e.g. Jamison 1987). Here the lower part of the model is formed by waxed cloth upon which sand and plaster of Paris multilayer has been laid. The images are displayed 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, develops thrusts. b) Cadell’s designation of the fold-thrust structure in (a) as “fan structure”. These sketches illustrate the evolution of the structure with thrusts developed as the antiform is progressively tightened. Images courtesy of BGS.

Figure 12. Basement structure. a) is his design of the experimental set up, based on the “double unconformity” that characterizes the stratigraphic arrangement in the NW Highlands. b) traces the early stages of deformation (XXVII in c), annotating the various model components. c) shows the progressive deformation of model (XXVII – XXIX). Images courtesy of BGS.

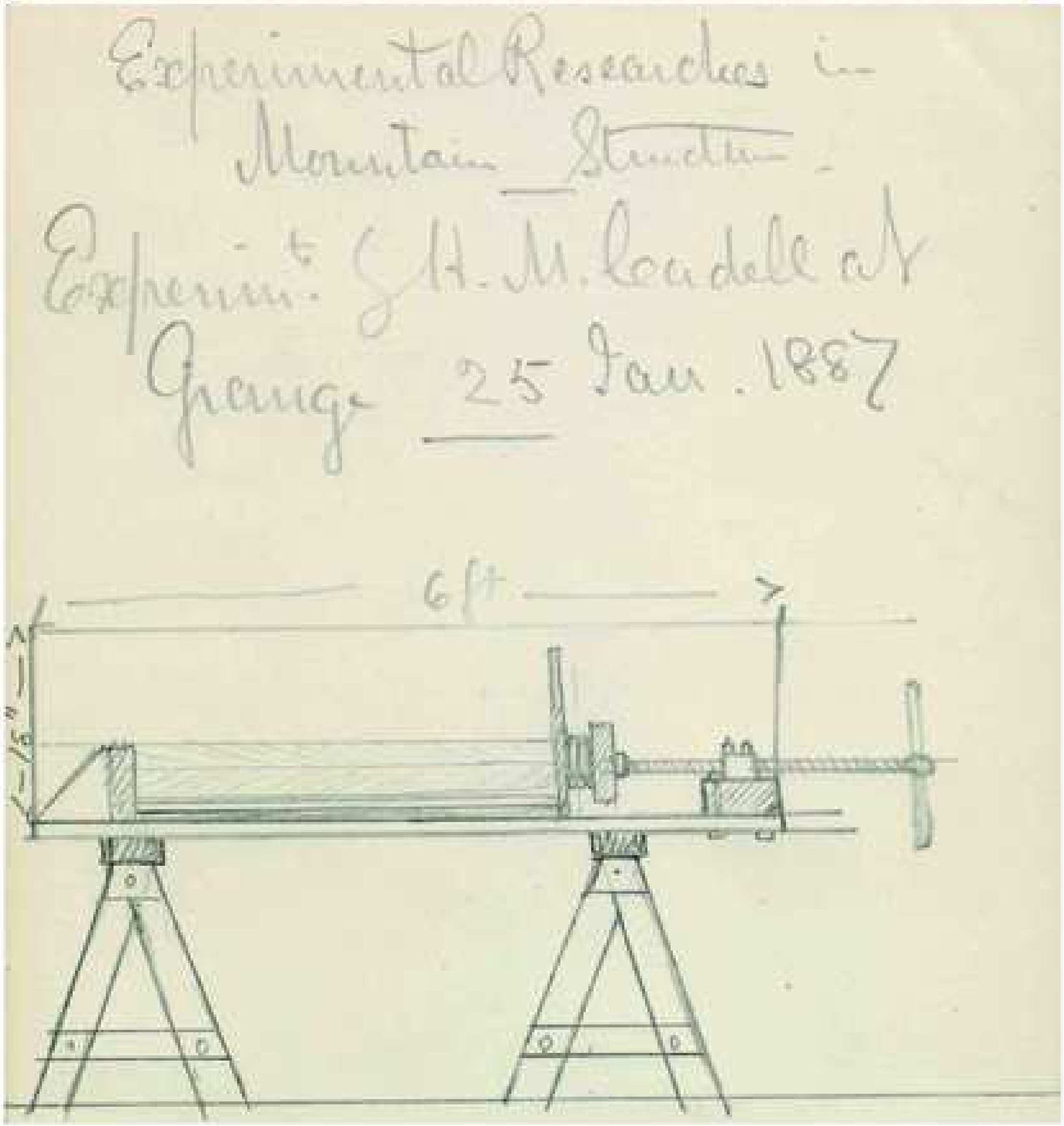
Figure 13. Cadell’s watercolour illustrations summarising the evolution (top to bottom) of thrust structures and their downward passage into folds. Images courtesy of BGS.

Figure 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) passing 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.

Fig 1

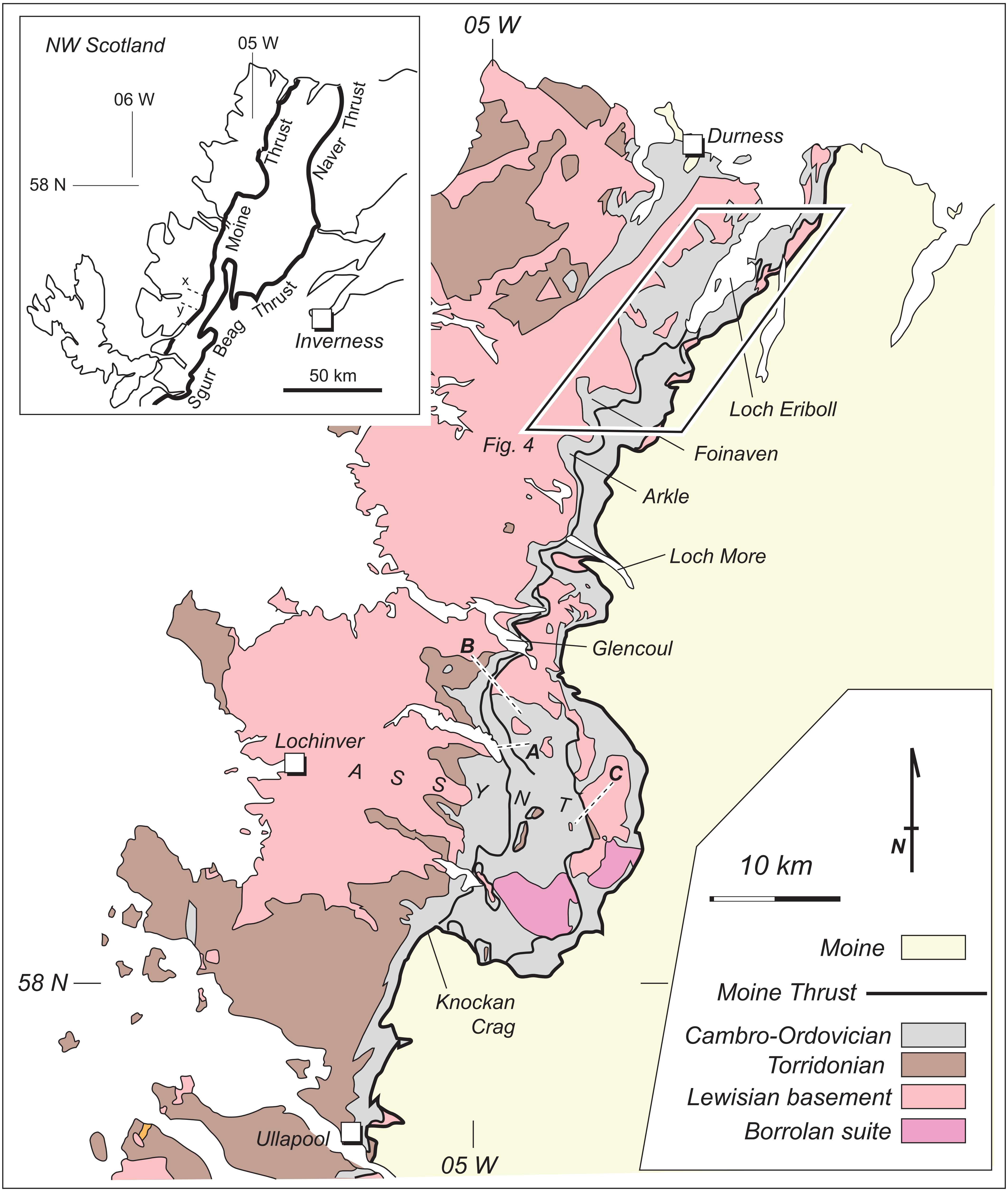


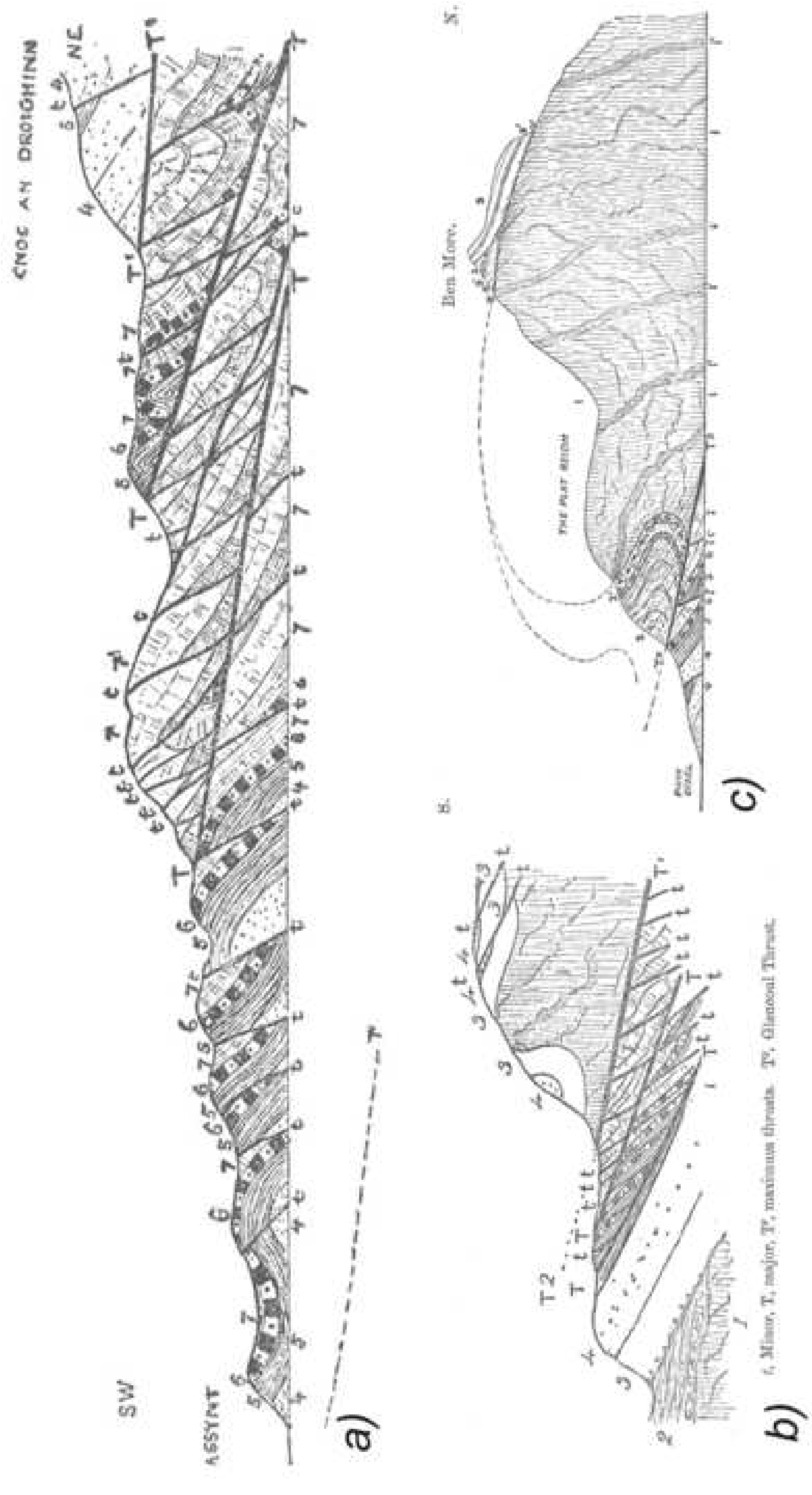
a


Experimental Researches in
Mountain Structure.
Experimt G.H.M. Cadell at
Grange 25 Jan. 1887
6 ft

b

Fig 2


05 W
NW Scotland
05 W
06 W
58 N
Moine Thrust
Naver Thrust
Sgurr Beag Thrust
x
y
Inverness
50 km
Durness
Fig. 4
Loch Eriboll
Foinaven
Arkle
Loch More
Glencoul
B
A
C
Lochinver
A S S Y N T
58 N
Knockan Crag
Ullapool
05 W
10 km
N
Moine
Moine Thrust
Cambro-Ordovician
Torridonian
Lewisian basement
Borrolan suite



t, Minor, T, major, T', maximum thrusts. T', Glencoul Thrust.

Fig 4

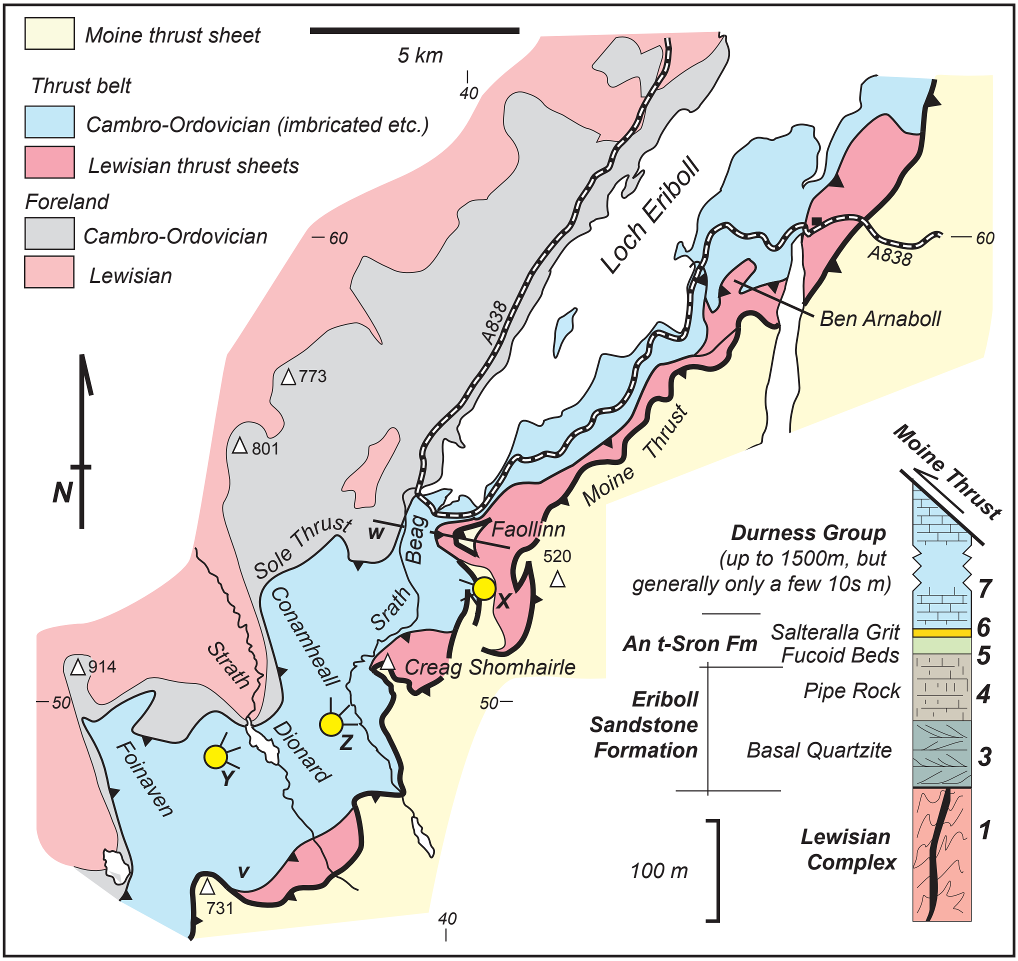
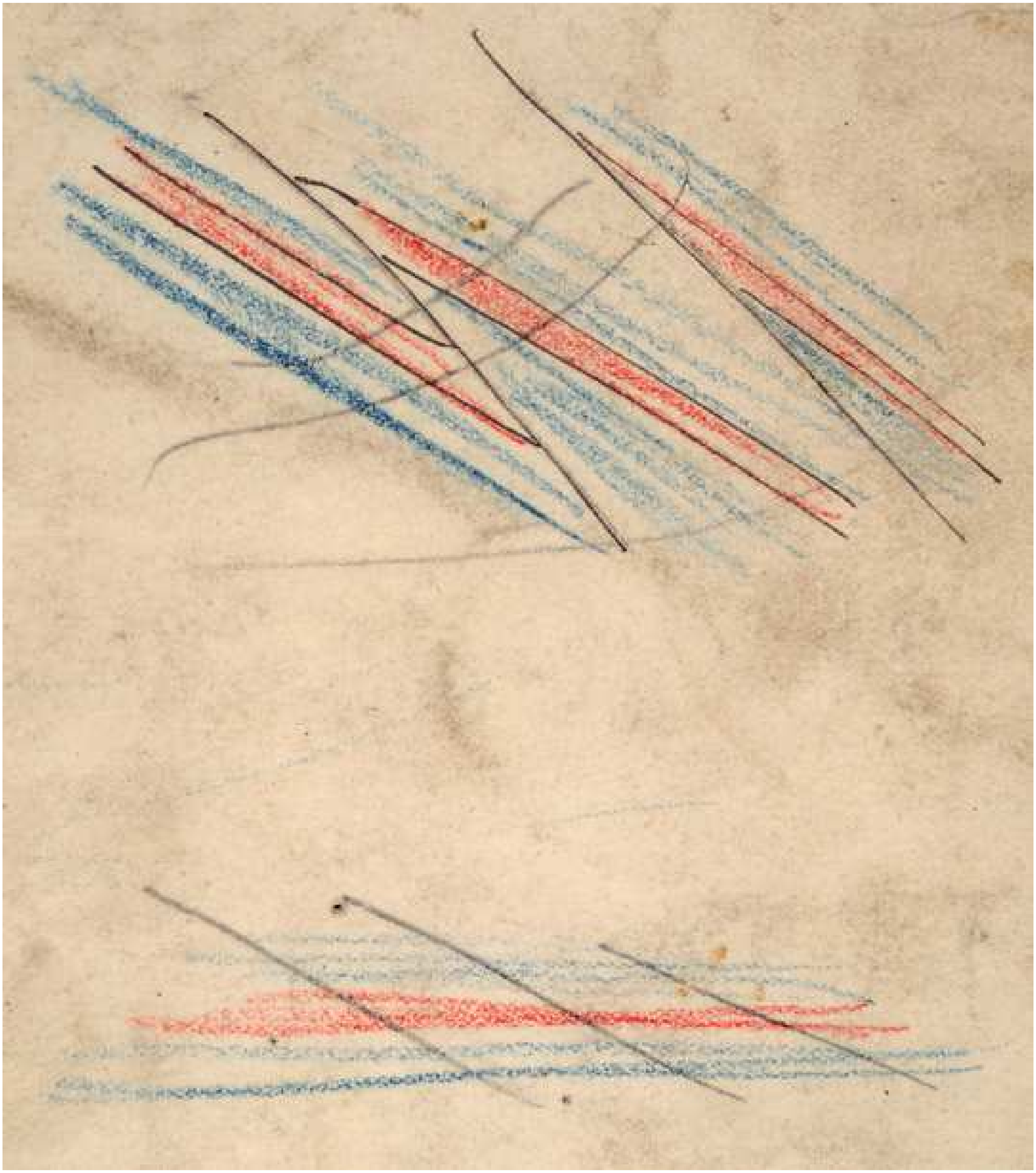

Moine thrust sheet
5 km
Thrust belt
Cambro-Ordovician (imbricated etc.)
Lewisian thrust sheets
Foreland
Cambro-Ordovician
Lewisian
N
40
60
60
50
50
40
Loch Eriboll
A838
A838
Ben Arnaboll
773
801
914
731
520
Moine Thrust
Sole Thrust
W
V
X
Y
Z
Faollinn
Creag Shomhairle
Strath Beag
Strath Conamheall
Strath Dionard
Foinaven
Moine Thrust
Durness Group
(up to 1500m, but
generally only a few 10s m)
7
6
5
4
3
1
An t-Sron Fm
Salteralla Grit
Fucoid Beds
Eriboll
Sandstone
Formation
Pipe Rock
Basal Quartzite
Lewisian
Complex
100 m

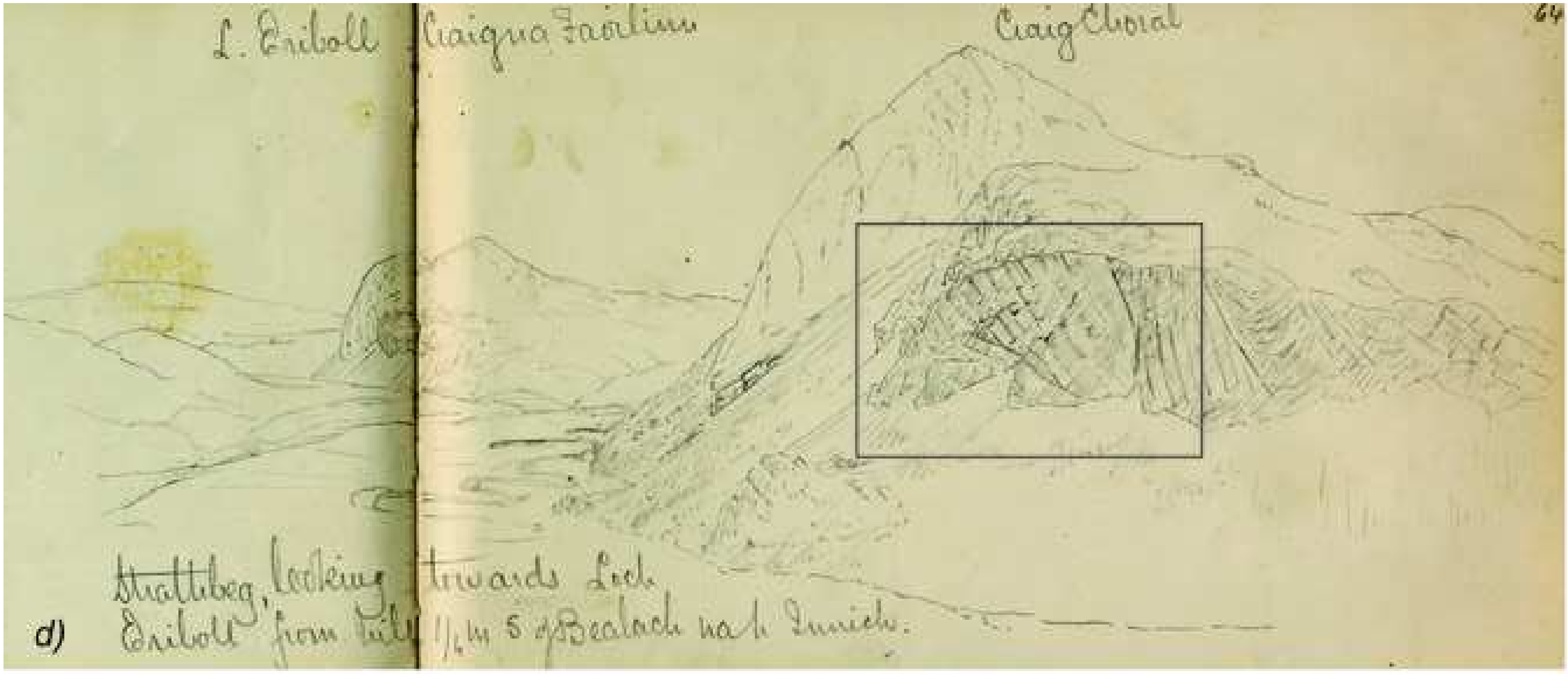
figure 5 Click here to access/download;figure;Fig 5 Peach imbs.jpg




SW
FOINAVEN RIDGE
CONAMHEALL
914m
W
FORELAND DIP-SLOPE
imbricated Pipe Rock
IMBRICATED CAMBRIAN QUARTZITES (chiefly Pipe Rock)
SRATH BEAG
a)
Conamheall
from
hummocky gneiss
b)
NE
E
Ben Hope
Conamheall top
Loch Eriboll
C Shomhairle
Fig. 6e
foreland quartzites
Lewisian of foreland
Strath Dionard
c)

figure 6b

Click here to access/download;figure;Fig 6blo.jpg



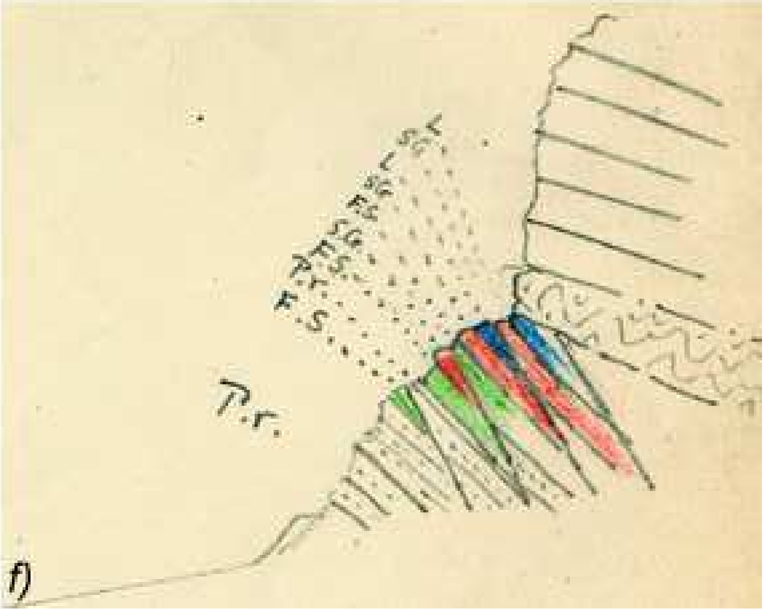
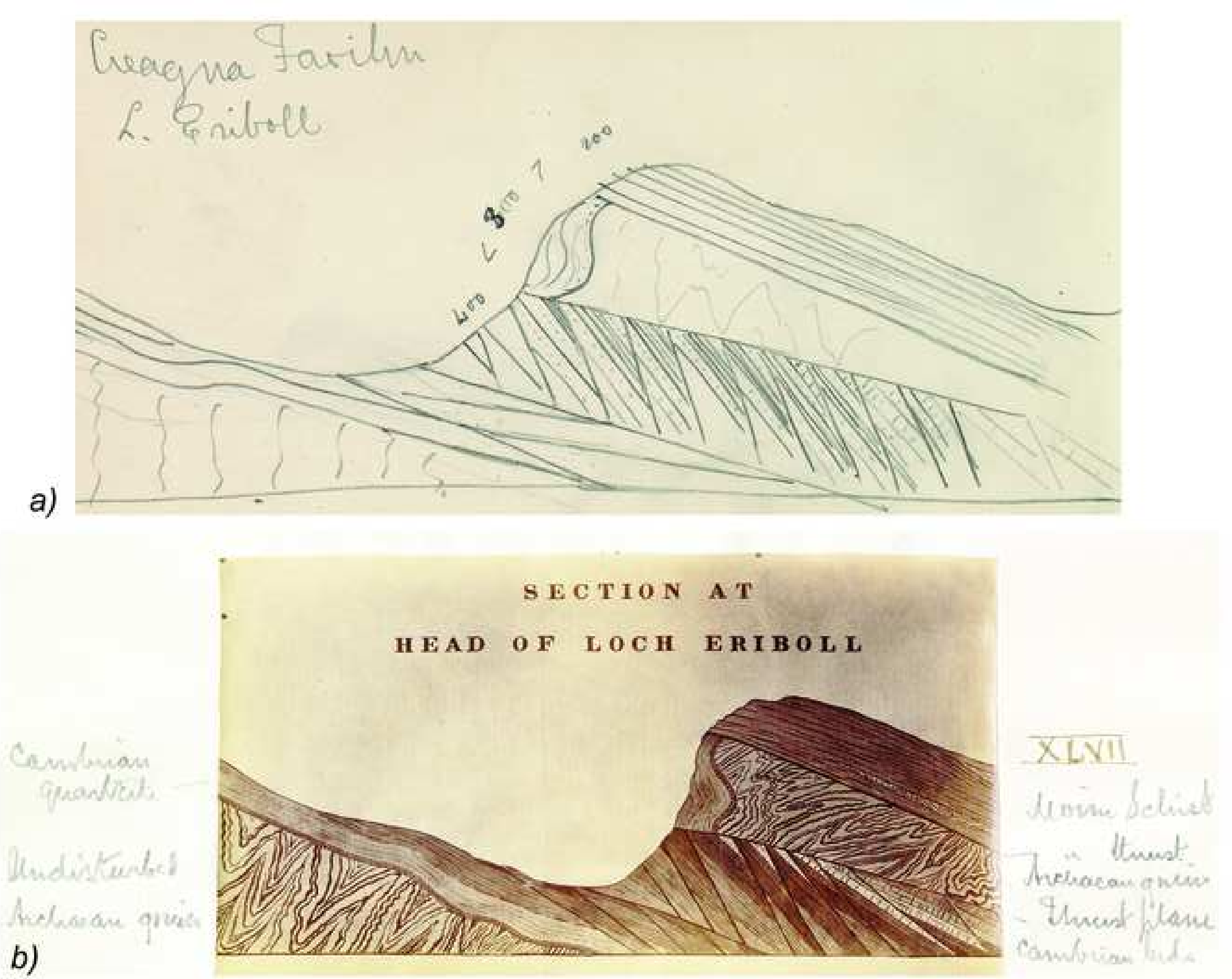


figure 7


Creagna Faoilin
L. Eriboll
200
7
300
L
400
a)
SECTION AT
HEAD OF LOCH ERIBOLL
Cambrian quartzite
Undisturbed Archaean gneiss
XLVII
Moine Schist
" thrust
Archaean gneiss
Thrust plane
Cambrian beds
b)

Strata originally 3' 5" long 1 3/4" deep.
Squeezed in 20"

a

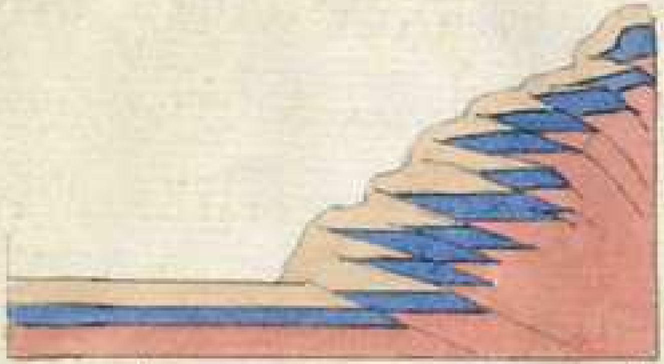
I*

4

II

5

IIa



Diagram

* The numbers on the photos in this book correspond to the Nos in arabic figures on the plates in Imbricate box

figure 9

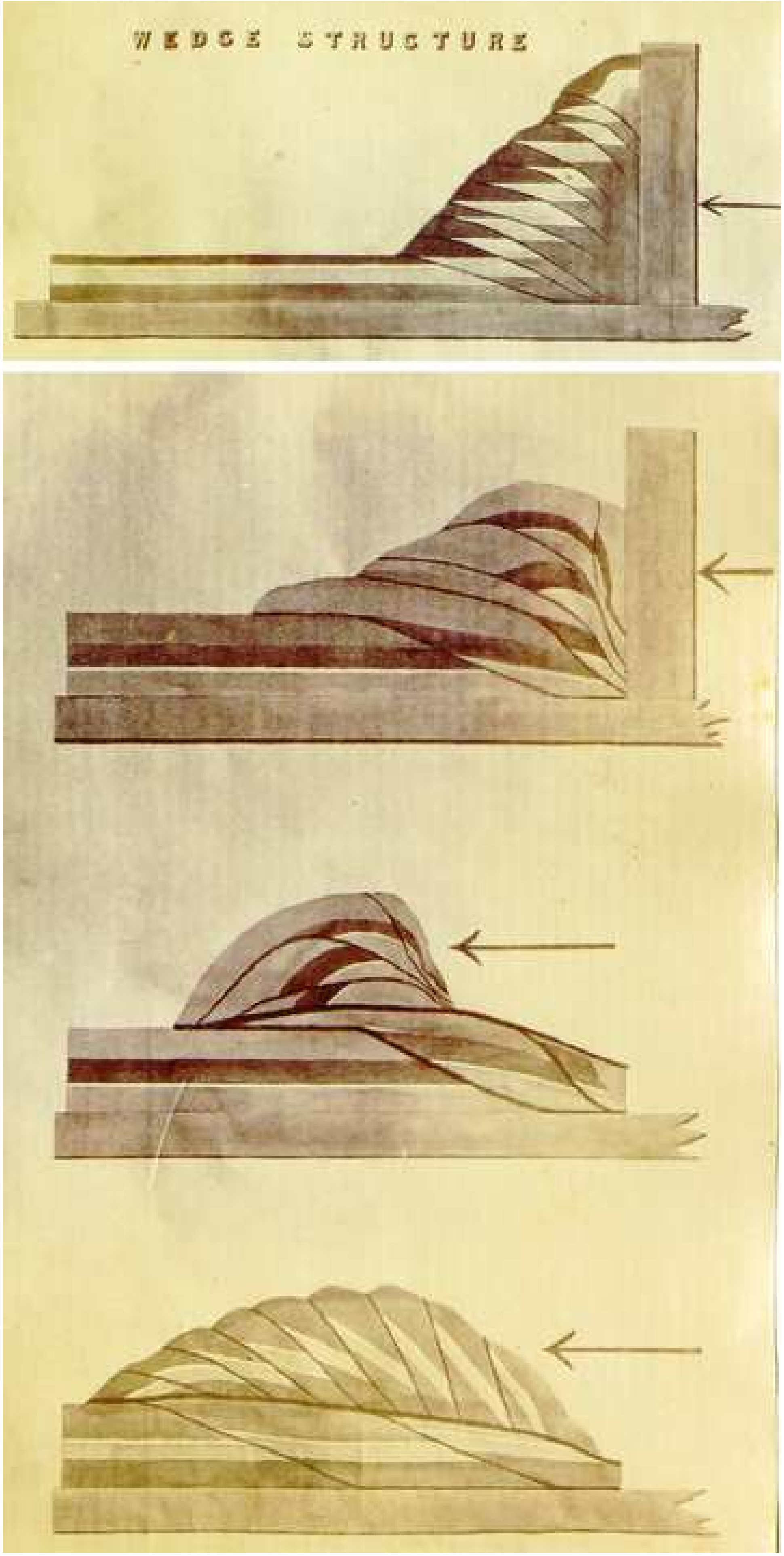


Fig 10

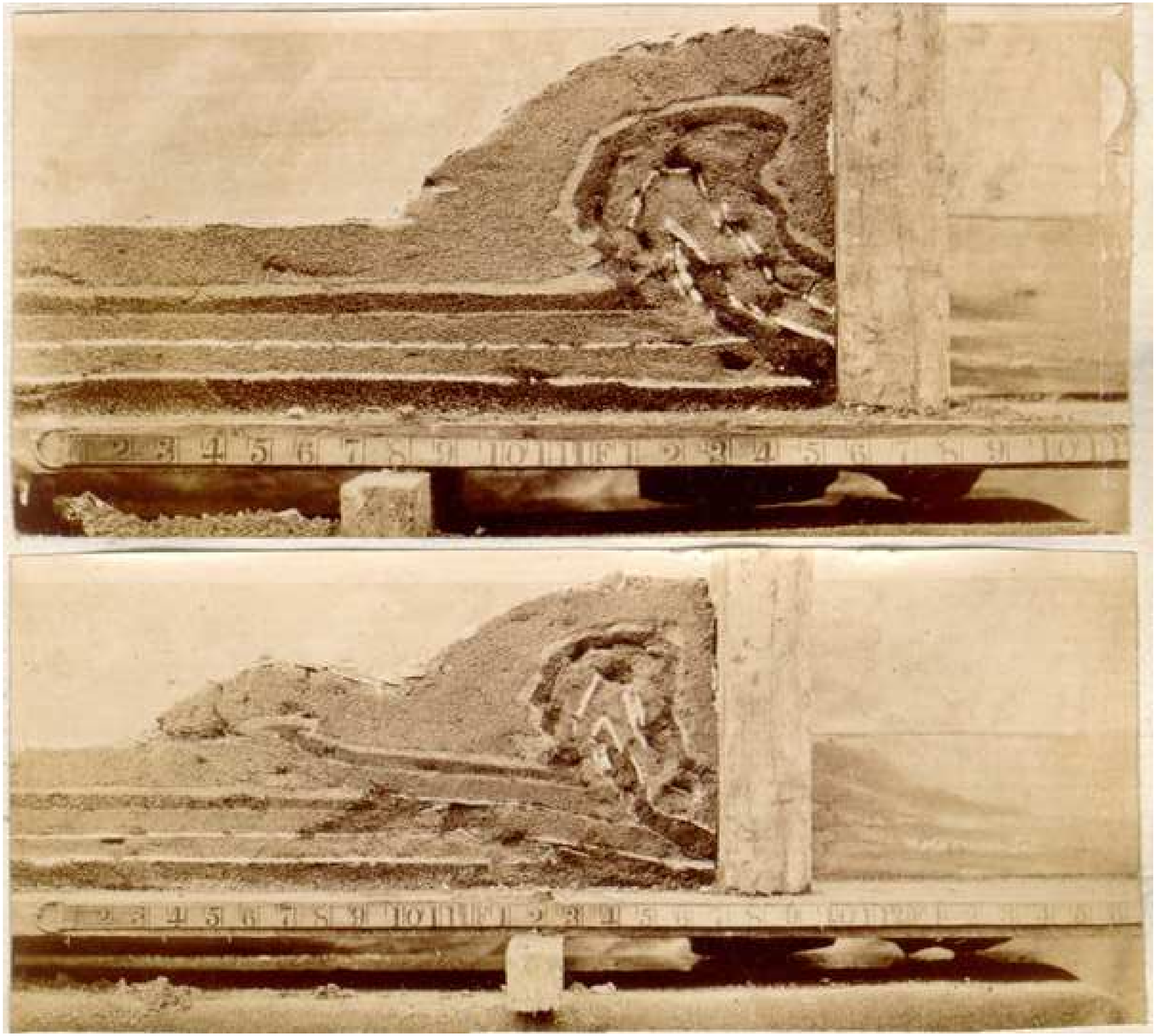


figure 11

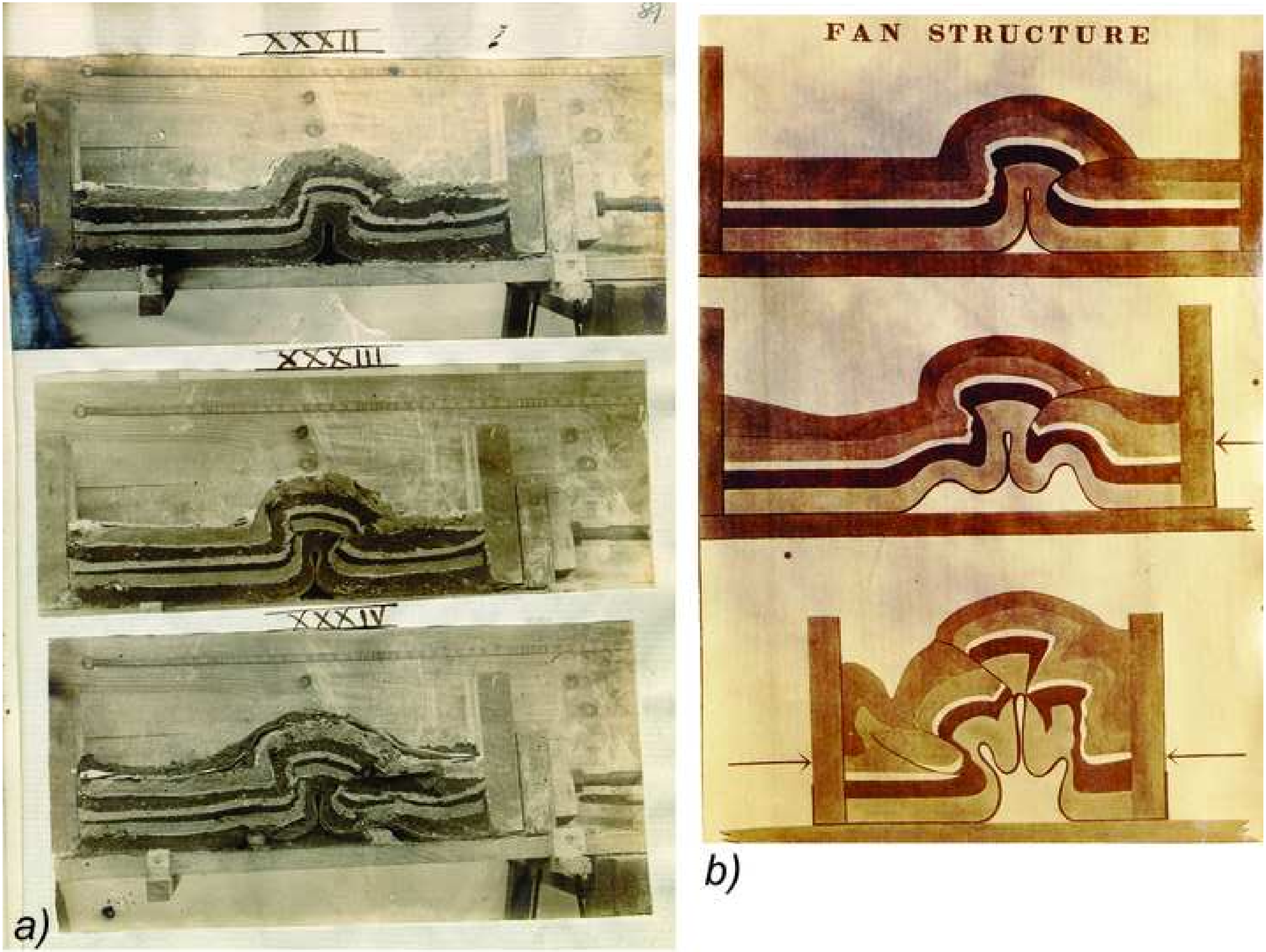


figure 12

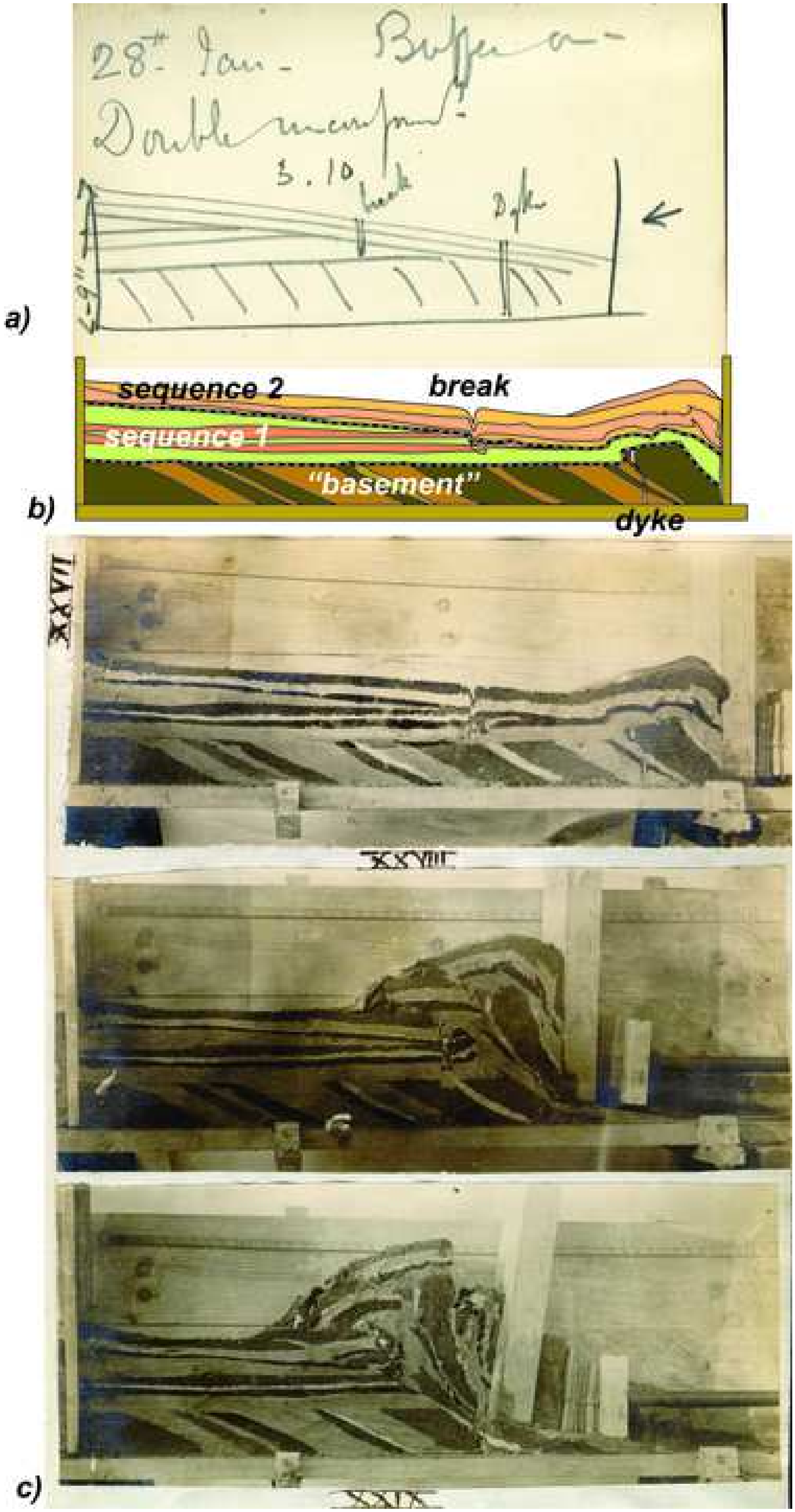

28th Jan. – Buffer a –
Double unconform!
3.10
break
Dyke
a)
sequence 2
break
sequence 1
"basement"
b)
dyke
XXVII
XXVIII
c)
XXIX

figure 13

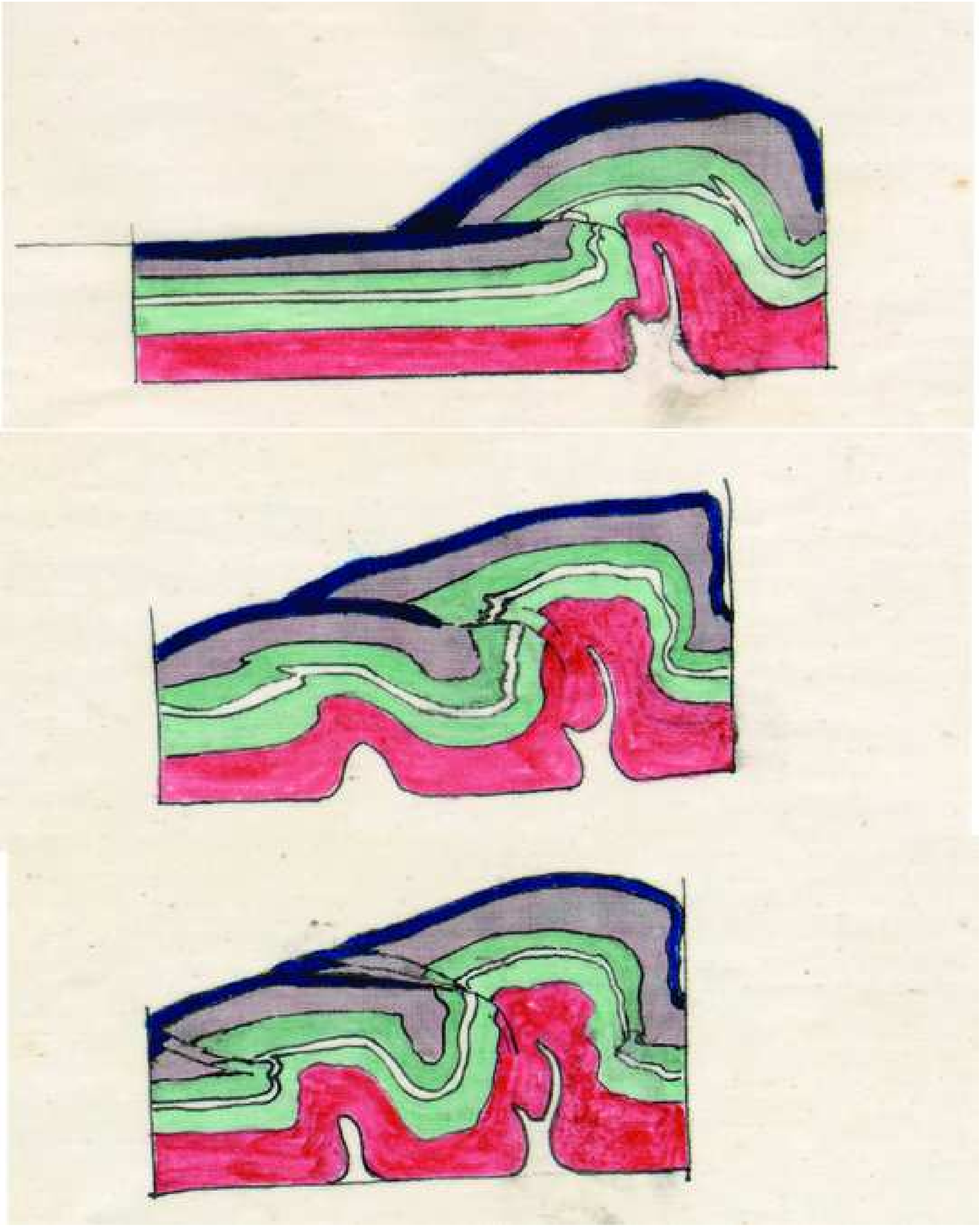
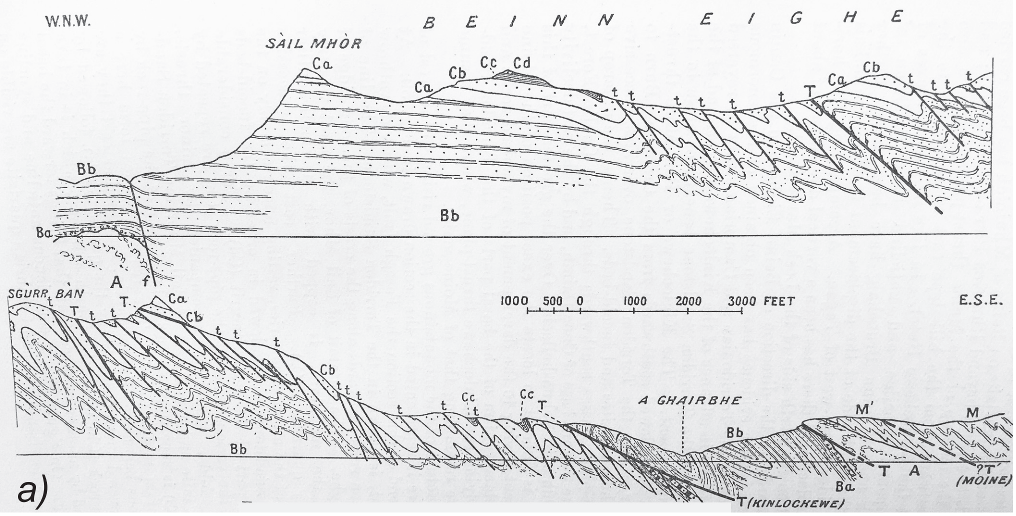


figure 14


W.N.W.
B E I N N E I G H E
SÀIL MHÒR
Ca
Cb
Cc
Cd
T
t
Bb
Ba
A
f
SGURR BÀN
1000 500 0 1000 2000 3000 FEET
E.S.E.
A GHAIRBHE
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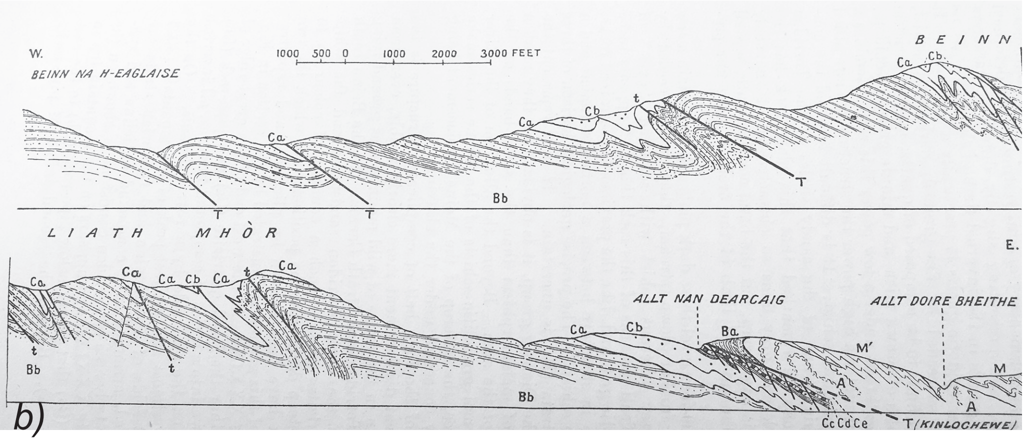
(MOINE)
T(KINLOCHEWE)
a)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Ca
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ALLT DOIRE BHEITHE
Ba
M'
M
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T(KINLOCHEWE)
b)