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BOOK REVIEWS

Where thrusts rule the land

Mitra, G. and Wojtal, S. (editors) 1988. *Geometries and Mechanisms of Thrusting, with Special Reference to the Appalachians*. Geological Society of America Special Paper 222. Geological Society of America, Boulder, Colorado, U.S.A. 236 pp. Price $35.

Standing back at the end of the 1980s, as I write this review, it is easy to be overwhelmed by the enormous mass of literature on thrust tectonics produced during the decade. Much of the impetus for this expansion in interest comes from the Appalachians. On the face of it this is rather paradoxical—the mountain belt has inspired more songs about trees than about the size of cliffs and the continuity of outcrop. It is not blessed with a neotectonic setting, being unfashionably old. So the Appalachians would hardly be an attractive proposition to a process-minded research funding council in the financially stringent 1990s. What the region does have in its favour are its economic resources, its proximity to a large geological community and consequently its long history of geological investigation. In this GSA Special Paper, Gautum Mitra and Steve Wojtal, no new-comers to the region, have assembled a strong cast of the main players of Appalachian–Caledonian thrust tectonics. As far as I know the 15 papers do not result from a conference but were invited specifically "to provide, in a single source, new work on thrust geometry and thrust mechanisms, and up-to-date small-scale to regional-scale structural studies to fold-and-thrust belts". I opened the volume with high expectations.

My first impressions were positive. The volume is well laid out, in common with other GSA publications, with large diagrams and generally good reproduction. But as I flicked through there was a strong feeling of *déjà vu*. This is not meant to imply that any of the papers have been reprinted or recut from previous publications, just that the overall treatment seemed similar to that presented elsewhere. For a book billed principally for its thrust geometry, there are no inspirational photographs or seismic sections which clearly show classic geometries. The occasional air-photographs tell more about land usage than the fold–thrust relationships they are designed to show. Rather unenthusiastically I turned to the front to read.

The volume kicks off with an article by Mike Coward on the Moine thrust belt. Although he wasn't to know it, his editors chose to advertise this article in the Preface as a "comprehensive overview". In their time, Peach, Horne and their Survey colleagues produced a 'comprehensive overview' in the classic 1907 Memoir to the northern Highlands of Scotland, taking 668 pages. Expanding the topic to include crustal-scale thrusting and modern geometric interpretations yet keeping the article down to 16 pages suggests a rather interesting definition of "comprehensive". Fortunately the editors remove the hype for their own paper which simply describes the characteristics of selected fault rocks (this time in part from the Appalachians) from which they speculate about how small volumes of rock can accumulate extremely large geological strains. Their conclusions about strain softening, the importance of fluids, displacement localization and deformation mechanisms at different levels in the crust are interesting—certainly deserving a wider audience. The next paper, by Paul Karabinos, has a similar mechanistic flavour. It deals with syntectonic heating in the Taconic klippen of New England comparing *P–T* histories to rates of thrust sheet emplacement. This is highly topical, given modelling strategies published from other mountain belts and current hypotheses.

Peter Geiser weighs in with an informative discussion on balanced section construction, at least in part living up to the Special Paper's title. Critical to his analyses is the idea of 'kinematic admissibility', which can be paraphrased to say that all levels in a geological section must have experienced the same bulk contraction, using available strain data. Coming back to the subplot in this review, it seems difficult to justify building vast amounts of strain data into Appalachian cross-sections when the basic structural architecture is so poorly constrained from geological observations. Following this geometric interlude, the next paper jumps down scale to examine small-scale structures and their relationships to (unseen?) thrust structures. Ed Beutner, Donald Fisher and James Kirkpatrick use synkinematic fibres in pyrite pressure shadows to establish incremental strain histories which are consistent with the movement of rocks up a ramp-flat thrust profile.

The next series of papers deals with thrust belt geometry. Richard Nickelsen presents a detailed study of linked thrusts and detachments from the Valley and Ridge. The eye is drawn to the rather geometric fault-bend folds developed on 4 km high ramps which provide the gross structural underpinnings to the area, at least as illustrated on the cross-sections. Yet the guts of the paper are concerned with a detailed justification for proposing the Antes–Coburn detachment using field photographs and detailed maps—clearly one for the cognescenti. A similarly detailed regional study is made by Byron Kulander and Stuart Dean who examine variations in displacement along the North Mountain–Pulaski fault system, based on 6 km thick cross-sections. Yet again I was left wondering how useful this approach is, given the lack of geological control on cross-sections, but the general lessons concerning lateral section compatibility and displacement tracing are certainly important.

Providing the link to the next mechanistic paper is a contribution by Steve Boyer and Gautam Mitra, relating basement deformation to thrust–fold complexes in the overlying sedimentary cover. Basement–cover relationships are classic topics in Caledonian–Appalachian geology, re-invigorated by the gradual application of thin-skinned thrust concepts to the metamorphic parts of mountain belts. The authors recognize the importance of Alpine studies in examining the different styles of basement shortening, particularly the patterns of high strain zones in crystalline rocks. In this they are to be commended, providing a disappointingly rare reference to areas outside the Appalachians. There are strong European undercurrents in Fred Diegel's description of evaporite-controlled thrusting along the Rome Formation décollement of Tennessee. The debate on the origin of cargneules and significance of their textures is re-enacted with an almost field-guide description supplemented with plenty of detailed outcrop photographs (courtesy of a rare lake drainage operation!).

The rest of the volume, a further six papers, deals with structural geometry. Nick Woodward and Jerry Beets discuss thrust sequences in the southern Appalachian Valley and Ridge. They finally (?) lay the ghost of break-back or overstep thrust sequences in this region by providing a concise case for piggy-back (foreland-migrating) thrusting. It is followed by a much shorter contribution by James Sears which interprets a structural culmination beneath the Blue Ridge in terms of duplex geometry, analogous to the Pine Mountain window developed in the Piedmont thrust sheet. Another regional study is provided by Bob Hatcher, Robert Hooper, Keith McConnell, Teunis Heyn and John Costello, who examine the evolution of thrust geometry in the crystalline southern Appalachians. They build up a view of Alleghanian thrusting developed during the emplacement of the crystalline nappe complex of the Piedmont–Blue Ridge. In contrast to these regional studies, Rick Groshong and Steve Usdansky look at the general patterns of thrusting mimicked by their computer graphics package. Not surprisingly they conclude that the software is unable precisely to construct particular thrust geometries (e.g. flat-topped duplexes). Personally, I remain unconvinced as to the usefulness of programmes such as these, apart from their marketability to appropriate companies, but that's a rather larger debate than can be covered in this review!

Paradoxically, the paper by John Delphia and Ed Bombolakis deals with part of the Wyoming thrust belt, specifically imbricates developed at the Hogsback thrust ramp. They concluded a break-back thrust sequence, in contrast to what has gone before in the Appalachians, starting with the sound premise that "the kinematics of a problem must be understood adequately before the mechanics can be analyzed properly". The last paper, by Atilla Aydin, is a more general discussion of displacement transfer between discontinuous faults. He shows the kinematic similarity between simple frontal ramps, cleavage duplexes and pull-aparts in transferring displacement between stepped fault segments.

Individually then, the separate contributions in this Special Paper are interesting. Yet it is unclear why the individual authors decided to present their material in this way rather than through conventional journals where surely they would have enjoyed a wider readership. Presumably the answer lies in the persuasive powers of the editors. Regrettably, the volume as a whole does not satisfy the need for an overview of thrust tectonics in general, nor Appalachian geology in particular. While it may not inspire another generation of geologists to examine thrust tectonic problems, it does impress the need for solid field work "at all scales from the thin section to the cross-section". This sentiment is most timely, given current fashions towards technological solutions for data collection. The cheery cover photograph shows a party visiting a cutting during a winter field excursion to the Appalachians. The leader has a large geological map, the audience listen attentively (apart from three well-known devotees chatting at the back) and gaze at an asymmetric anticline (what might now be called a fault-bend fold). The debt they owe to the quarrymen and miners is there for all to see.

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Putting laccoliths in their place

Corry, C. E. 1988. *Laccoliths: Mechanics of Emplacement and Growth*. Geological Society of America, Special Paper 220. Geological Society of America, Boulder, Colorado, U.S.A. 110 pp. Price $27.50.

Corry's Special Paper is divisable into four parts. The first consists of a review of work on laccoliths from Gilbert (1877) to the present time. The second part describes the results of gravity and magnetic surveys over laccoliths. The third forms the core of the Special Paper. In it, three chapters deal with the emplacement and growth of laccoliths, and the finite element models Corry uses to investigate the latter. The fourth part includes a glossary and a 23 page list of published references to laccoliths, drawn from the GEOREF database of the American Geological Institute.

Corry defines the laccolith as a floored igneous body, forming through forcible intrusion high in the lithosphere, and fed from below by a dyke. This allows him to include lopoliths in the category. However, throughout the Special Paper he uses the term laccolith in the more familiar restricted sense for an intrusion with a flat floor, and a roof that is either continuous and domed, or fault-bounded and flat. He recognizes four stages in the development of such intrusive bodies, suggesting all except the largest laccoliths take less than a 100 years to form. The first stage involves the necessary rise of magma into the lithosphere. In the second, the change from magma ascent to horizontal spreading begins. In the third stage, spreading ends. It is succeeded in the fourth by thickening of the intrusion, accompanied by the necessary deformation of the roof.

Corry suggests laccoliths vary in character between two extremes. The first is said to preserve the essential features of Gilbert's well-known fault-bounded version. This is Corry's punched model. According to him such laccoliths probably formed at relatively shallow depths within the epizone. The other end member, apparently suggested to Corry by comments and sketches of Gilbert, is named the christmas-tree laccolith. It corresponds with the cedar-tree laccolith of earlier authors. With a domed roof displaying thinning of the country rock, Corry suggests the formation of the second type of laccolith is favoured by the conditions of the mesozone. Gilbert's ideal laccolith (Corry fig. 1a, Fig. 1 here) is placed by Corry between these two extremes.

The growth of these two types of laccolith (stage 4) is investigated by Corry in a series of finite element simulations, including the effects of body forces. All Corry's models are shown at the point of instability. At the next step the solution becomes numerically unstable and the experiment ends. His models provide one horizontal fracture for a laccolith of the punched variety, but a christmas-tree laccolith is developed from a stack of horizontal fractures, centred one above the other and decreasing in length upwards. The members of this stack are considered as inflated one after the other from bottom to top. Here the strong peripheral differential shear stresses of the punched model are absent, a condition regarded by Corry as suitable for the development of the smoothly domed roof shown by this type of laccolith.

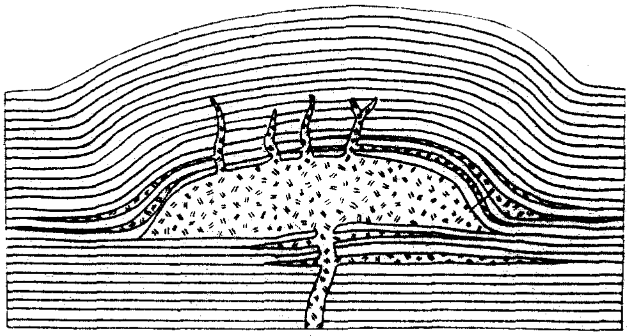

Fig. 1. The ideal form of a laccolith according to Gilbert (1877).

All models share the same boundary conditions. The significance of variations in the latter are outside the scope of the experiments. The models allow the demonstration of what is possible in closely defined circumstances. They do not have the mechanical character which Pollard and Johnson have tried to give to their models of laccolith formation (e.g. Pollard & Johnson 1973, Koch *et al.* 1981).

This then in brief is the scope of Corry's work. What about his conclusions? He says he does not depart in any important way from Gilbert (1877), suggesting that this is remarkable only in that nearly all other investigators have differed substantially from the latter. These opinions surprise me and I do not think that Corry's account of the history of enquiry into laccoliths sustains them. At the same time I think he underestimates the extent to which he himself differs from his mentor Gilbert. Here, of course, I rely on an interpretation of Gilbert's work that Corry presumably would not share.

Bearing in mind this qualification, let us examine Gilbert's sketch (1877) of his ideal laccolith (Corry fig. 1a) (Fig. 1). I find its most interesting feature one not mentioned by Corry. This is the presence of subsidiary sheets with sigmoidal profiles sited on the flanks of the main bell-shaped intrusion. Is it not of interest that these profiles are those appropriate to formation during intrusion at the same time as the main body, and not after it? Corry regards simultaneous intrusion as not usual; does Gilbert here mean to imply the reverse? Is it by chance or design that the latter has placed the subsidiary sheets so that they allow the strata they enclose to be folded while retaining initial thicknesses? Simultaneous intrusion has another advantage: major intrusions are able to grow through rupture of strata separating subsidiary intrusions. Thus the presence of earlier, already-crystallized components is avoided and the country rock is not increasingly stiffened so as to make further developments more and more difficult. We may account through simultaneous intrusion for the common existence of inwardly protruding slabs of country rock, such as shown by Corry from the Wax Factory laccolith (fig. 44). This mode of formation also allows the proportions of country rock and intrusive rock to vary very readily from one laccolith to another, as they evidently do in nature.

I have three more points to make. Firstly, Corry refers with approval to the description of a laccolith (Hyndman & Alt 1987), regarding the example as confirming his own view that laccoliths lie directly above feeder dykes. Hyndman & Alt, however, described in this case a parent dyke as diverted from its course and forming a laccolith only through the effect of a volcanic load above. Here we have a different upper boundary from the horizontal, planar Earth's surface of Corry's models. Moreover, the dyke is described as bodily transforming into a sill by rolling over sideways, before locally thickening into a laccolith. It seems to me that we still have too few data on the anatomy of laccoliths to neglect any well-established field descriptions.

Secondly, I should like to point to an omission from Corry's list of laccoliths. The excluded examples are from Wales, and were described by Jones & Pugh in the *American Journal of Science* in 1949. Anticipating Corry, these authors suggested that the form forced on the country rock bounding a laccolith is determined broadly by the arrangement of places at which the country rock is successively fed with magma. The modifications imposed on the country rock in this way often may be better explained, as I suggest above, by intrusion of magma into several, side-by side fractures at the same time.

Thirdly, I should like to think that Corry's Special Paper will be read widely and that this will help the subject to gain the place in teaching it deserves. The study of laccoliths has the considerable merit of demon-