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# THE SIGNIFICANCE OF HIGH-ANGLE REVERSE FAULTS IN THE CANBERRA REGION.

(Presented to A.N.Z.A.A.S., Dunedin, 1957)

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I feel it is essential to preface my discussion on high-angle faults in the Canberra area with some brief outline of the regional and local environment in which these structures occur.

The Canberra region, some 6,000 square miles, lies on the orogen of the Tasman Geosyncline, or more correctly on the southern of the three clearly defined geanticlines or orogens into which the fold mountains of the Tasman may be divided. To my way of thinking, the most satisfactory interpretation of Tasman tectonics is that in which these three geanticlines are regarded as Palaeozoic island arcs, each with its own slightly differing history of vulcanism and intrusion, with a prominent miogeosyncline behind the southern arc and with a drowned and only partly filled Tasman trough presumably lying east of the geanticlines.

Be that as it may, we are concerned with the southern geanticline and to some extent with the miogeosyncline which lies between it and the craton to the west.

A thick sedimentary sequence conformable from Middle Cambrian to mid-Devonian time is found in the miogeosyncline while on the geanticline a succession of pre-Middle Ordovician sediments, undoubtedly including Cambrian, is followed by comparatively thin sequences of Middle and Upper Ordovician, Silurian and Devonian rocks, interrupted by at least four orogenies, each accompanied by granitic intrusion.

The main point we should note is that records of sedimentation and of tectonics (see Hills and Thomas, 1954) shows that most of the sediments recorded, at least in this part of the Tasman, came not from the craton to the west but from the geanticline or tectonic land which began to rise and to shed toward the end of Cambrian time and which obviously extended farther east than the present mountains. The only time when significant sedimentation could have occurred from the west was in Lower Cambrian time and this may well be the age of the lowest Palaeozoic sediments seen in the geanticline which appear to be slope rather than trough deposits.

We should therefore picture the geanticline as composed of comparatively thin sequences of Palaeozoic rocks mantling a rising Precambrian basement rather than as fold mountains arising from a deep Palaeozoic trough.

Turning now to the Canberra region we see in more detail the composition of part of the geanticline (Noakes, 1954 and Opik, 1954). Low-grade metamorphics of pre-Middle Ordovician age are unconformably overlain by some 4,000 ft. of Middle and Upper Ordovician silts and shales. These were folded and in places intruded by granite in the Benambran orogeny early in Silurian time. Deposition of some 6,000 ft. of Silurian sediments and volcanics followed and these were folded and intruded on a grand scale by granites in the Bowning Orogeny at the end of Silurian time. The Canberra Welt - a meridional ridge - then arose to restrict Devonian sedimentation in the area to two troughs - a western trough in which Middle Devonian sediments were folded and intruded in Tabberabberan time (late Middle Devonian), and the eastern trough in which Upper Devonian rocks were folded and intruded at the end of the period. This final orogeny, the Kanimblan, virtually stabilized this southern geanticline of the Tasman.

We note from this regional study the strong meridional axes of folding, the remarkably high percentage of intrusive granite and the marked meridional lineation of these intrusive bodies - features induced by each of the four major orogenies in turn.

Against this regional background we turn in more detail to the Canberra Welt which is roughly outlined by the distribution of the distinctive Bowning or Silurian granites.

One of the striking structural features of the welt is the occurrence of high angle reverse faults of which six are now known in varying degrees of detail. These are the Lake George Fault, Neronga Fault, Queanbeyan Fault, Murrumbidgee Fault, Cotter Fault and the Goodradigbee Fault.

Although much detail is still required, these faults clearly follow the one pattern. Their characteristics are:

(1) Linear faults roughly following the meridional direction of folding and traceable for distances of 20 to 50 miles.
(2) Marked throw of the order of at least 2,000 to 4,000 ft. with no traceable horizontal movement.
(3) High dips, to either east or west, at angles between 60 and 80 degrees in the direction of the up-throw side.
(4) Close association with Silurian granite, with movement, in some places, before, during and after intrusion.

There is marked variation in the characteristic of the fault zone. In places it is obscure and at others it is marked by a wide zone of brecciation or by crumpling with Alineations impressed. At least some of the faults show evidence of recurrent movement, including possibly Tertiary movement, in the case of the Lake George Fault, but the major shift seems clearly to have taken place about the end of Silurian time.

I should point out at this stage that interest in these faults is heightened by the fact that similar fractures have been noticed in Victoria and New South Wales; indeed the occurrence of high-angle thrusts seems part of the Tasman tectonic pattern.

In the investigation of these faults it is natural to attempt to relate them to the crustal stresses which produced the meridional folding and other faulting in the region, but there is in fact no satisfactory relationship at all as far as I can see. The pattern of broad meridional folding with minor meridional low-angle thrusts; the pattern of sinistral trans-current faults and the normal faults mapped by Dr. Opik in the Canberra area can be related to a comparatively simple stress system in which the principal axes are roughly horizontal and vertical and aligned along meridional and east-west directions.

Such a stress system as illustrated by Anderson (1951, see Fig. 1) provides a satisfactory regional explanation for these structural features but not for the high-angle reverse faults; the recent extension of Anderson's ideas by Moody and Hill (1956) also fails to provide a satisfactory answer.

The high-angle reverse fault has always presented a poser for writers on structural geology and as you all know, text books either gloss over the problem or direct the reader to specific papers in which the problem is discussed. Hafner (1951), Wilson (1948), Anderson (1951), Ewing and Worzel (1954), Willis (1935) and Nevin (1942) postulated specific conditions under which high-angle reverse faults may be induced, but although these explanations may be valid in other areas I feel that none of them can be confidently applied to the Canberra region.

There is time only to mention Nevin's hypothesis which provided some comfort some years ago when I was investigating the first of these high-angle reverse faults - the Lake George Fault, where the structure occurs on the slightly overturned limb of a major fold. Nevin concluded that where cover is thin both low and high-angle thrusts can develop because the easiest relief is likely to be upwards. His type area for this deformation is in the Appalachian Mountains where indeed the explanation may be valid, but in that area, according to Chamberlain (1928), most of the thrusts are low-angle with the occasional thrust at steep inclinations. Nevin's explanation is scarcely satisfactory in the Canberra region where the high-angle thrusts form a group of structures on their own and are not associated to any significant degree with an orthodox pattern of thrusting.

These faults, therefore, appear as structural anomalies and rather than trying to relate them to a stress system to which they appear to be foreign, it is reasonable to investigate the idea that they may be the result of reaction to stresses additional to the perhaps quite different from those responsible for the other structural features (see Fig. 2). Working along these lines and guided by the established mechanics of faulting we see that the simplest explanation would be provided by a near-vertical force working upwards and the first step in this direction brings us face to face with masses of granite - the granite with which the faults are closely associated. At this point, I acknowledge the encouragement I received from Professor Hills of Melbourne University who, I found, was taking the same general line in the study of similar faults in Victoria.

A number of facts about these granites suggest that they may well have provided the force we seek. In the first place, all of these Silurian granites, in fact all the granites in the Canberra region, are unquestionably injected, high level or discordant granites. They have been intruded upward into their present position. Two points are sufficient to prove this contention. The surrounding rocks show only low-grade regional metamorphism so that, to use Walton's (1955) term, granite and metamorphics are not in harmony. Furthermore, granites intrude Silurian rocks, indeed parts of them are found in Upper Silurian strata, so that the cover at best was of the order of one mile; extensive granitization could not be expected at such shallow depth.

In the second place the volume of these high level granites, even on the basis of outcrop, is very large, totalling 25 percent of outcrop on the Canberra Welt and 37 percent on the whole southern geanticline. The proportion occupied by injected granite grows with depth and in fact reaches 60 to 70 percent in the Kosciusko region south of Canberra where the geanticline has been eroded to lower levels.

Thirdly, the injection of such quantities of granite inevitably raises the old "room" problem and recent work in this region is very pertinent.

The large Murrumbidgee batholith has been recently studied by N. Snelling of the Australian National University who finds it composed of a number of large tabular or dyke-like bodies oriented meridionally. These bodies show flow structures and contamination and lie on either side of a central core of massive granodiorite. Snelling has worked out by detailed analysis that in general the composition of the dyke-like bodies is granodiorite plus one-sixth to one-third by weight of stoped and assimilated country rock. Moreover, this assimilation took place at a lower level from which the masses rose as crystal mush. This can only indicate that stoping and assimilation was a minor rather than a major process in granite emplacement in the Canberra Welt at the level exposed.

Taking these facts together we are confronted with the plain fact that these injected granites cannot make room for themselves in the Canberra Welt by the process of stoping alone; we must admit considerable "pushing and shoving", and once we are convinced of that in any area we can no longer afford to ignore, as we tend to do, the injection force of magma in structural studies. Furthermore, granite reaching to within a mile or so of the surface would find it easier to push up than to push sideways.

Of course, the injection force of magma is well known and has never been queried in the classical example of laccoliths doming their roofs in the Henry Mountains, Utah, (Hunt, 1953) because there is no tectonic folding of the country rocks to confuse the issue. Laccoliths have pushed up their roof rocks under a cover of at least one mile. Balk (1951) has pointed out the difficulties in differentiating between the effect of injection forces and those of folding in the neighbourhood of large intrusions where containing strata are normally folded and metamorphosed. But his conviction that deformation does occur, including his "long range effects", provides a timely reminder that so-called pre-granite faults may deserve much closer study.

Literature does provide many examples of deformation apparently due to igneous intrusion. One is reminder of the paired vertical faults which Noble, Harder and Slaughter (1946) attributed to the intrusions in the Black Hills, Dakota; to the thrust with a throw of two miles attributed to intrusive porphyry by Bootwell and Woolsey (1912) in Frog Valley, Utah, and of Eskolas (1948) examples and statement that "diapiric up-swelling and doming is in fact a regular phenomenon in the intrusion of granitic magma".

I therefore suggest that we have found an adequate near-vertical force which not only could be, but must be, taken into account in any structural study of the Canberra region or of the geanticline as a whole.

I suggest that the high-angle reverse faults - in part "paired faults" - are "long range effects" of these elongated injected bodies and were caused by the fracture of Pre-Silurian rocks under the stress of magma making room for itself high in the crust.

In conclusion, I would like to take this idea farther afield and return to the picture of the geanticline as a whole. I see inadequate cover of Palaeozoic rocks on the geanticline to give rise to this flood of injected granite; it more likely comes from a rising Precambrian basement, perhaps by processes of reactivization and granitization and I would suggest that the injection force of magma rising through a comparatively thin Palaeozoic cover has not been taken into proper account in the study of Tasman tectonics.

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