THE GEOLOGY OF THE WEST COAST RANGE OF TASMANIA

PART II

STRUCTURE AND ORE DEPOSITS

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(WITH 13 FIGURES AND 2 PLATES)

(Communicated by Professor S. Warren Carey)

VI. STRUCTURE.

Four major periods of earth movement have been recognised in Tasmania; these have been set out by Carey (1953) as Upper Cambrian, post-Lower Devonian and pre-Middle Carboniferous, Jurassic(?), and early Tertiary. The first two of these, the Tyennan and Tabberabberan orogenies, were characterised by compression and folding of geosynclinal sediments, and the last two by block faulting and epeirogenic movements of the crystalline massif of Tasmania. The post-Permian structures (which will be treated briefly) are of interest here only insofar as they may complicate the picture of the Palaeozoic orogenies.

Post-Permian Faults.

The presence of "post-dolerite" faulting in the West Coast area has been deduced by several workers, and the basis for their deductions has been set out by Edwards (1940). One of these faults is that which runs N.N.W. from Mt. Sorell past the Sisters Hills towards Dundas (see Strahan, Queen River and Yolande map sheets); Carey (1953, p. 1123) shows this fault in a general map of the region, and in the Zeehan area has called it the Long Fault. Although it follows the strike of Devonian faults or flexures the fault is anomalous in that it has a westerly downthrow and cuts some Devonian structures. On the other hand, it readily fits into the pattern of the Tertiary faulting which produced the Macquarie Harbour depression (see map by Fairbridge, 1949, p. 150), and as it follows the boundary between the Range and the Howards Peneplain it can be interpreted as having down-faulted an old land surface.

More or less aligned with the fault in the Queenstown area is a Devonian flexure which separates two pieces of country of different structural pattern and which in depth must be a major Devonian fault;

it may be that the younger fault represents a revival of movement of the older structure but with a reversed direction. In any case, it is very difficult to interpret either of the coinciding structures, and all that need be said is that the later fault which cuts out the Gordon Limestone at the King River must have a throw of at least 1,000 ft., and is probably Tertiary in age.

In view of the widespread Jurassic and Tertiary faulting of Tasmania it is possible that other north-westerly faults cut the region, but so far as the West Coast Range is concerned this is improbable. Any faults which might cut the area would dislocate the old Carboniferous peneplain and upset the general concordance of summits in the range. It is possible that faults with throws up to 300 ft. might pass undetected but such small faults would not materially affect the much coarser Devonian structures.

Cambro-Devonian Structures.

The Dundas Geanticline.

It was shown in Part I of this work (Bradley, 1954) that the Dundas Trough of sedimentation deepened sharply to the west of the Tyennan Block and that at least 10,000 ft. of sediments were laid down before the end of the Upper Cambrian. Then the Tyennan Orogeny raised the Dundas Ridge and created the Jukes Trough between the ridge and the block (fig. 4).*

The trough was a sharply angular depression shelving to the east and bounded on its western and deeper side, throughout the period of deposition of the Dora Conglomerate, by what was probably an active fault; it may be considered as having been similar to the present-day "fault angle depressions" of New Zealand. For our immediate purpose the depression can be regarded as an asymmetric syncline and the Dundas Ridge can be interpreted as an asymmetric anticline thrust against this syncline. It has been shown that the Dundas Ridge was probably emergent during the deposition of the Dora Conglomerate. It was also shown that the Jukes Trough must have been subsiding continually during the Tremadocian and that in a relative sense the Dundas Ridge was rising. It will be shown that the position of the main anticlinal uplift of the Devonian orogeny coincided with that of the Cambrian movements and it follows that the Dundas Ridge was merely one aspect, the late Cambrian geomorphic aspect, of an evolving and long enduring anticlinal structure. In this wider aspect the structure will be called the Dundas Geanticline; following Carey's (1953) usage the structure resulting from the late Cambrian orogeny will be called the Porphyroid Anticlinorium and that resulting from the Devonian orogeny will be called the West Coast Range Anticlinorium.

After the major uplift of the geanticline in late Cambrian times it is probable that the Porphyroid Anticlinorium was bent round the north-west corner of the Tyennan Block, being widest near Mt. Bischoff, and that it plunged and died out to the south near Macquarie Harbour.

* Figures 1-4 are to be found in Part I of this work.

There, sedimentation was probably continuous from Middle Cambrian to Silurian times, but to the north and east the land was only submerged after Tremadocian times. During the Devonian orogeny there was renewed movement of the geanticline, and the sediments of the Jukes Trough were compressed along with the Porphyroid Anticlinorium and the covering Gordon Limestone and Eldon Group sandstones; the resulting complex structure forms the West Coast Range Anticlinorium, and the last structural relic of the Jukes Trough forms the King-Sophia Synclinorium. The West Coast Range Anticlinorium (plate I) is made up of a number of echeloned smaller folds and these consist of yet smaller folds so that if the anticlinorium is described as a first order fold the others are conveniently termed second and third order folds.

Because of the asymmetry of the geanticline and the 5,000 ft. of sediments which were deposited between the orogenies the Porphyroid and West Coast Range Anticlinoria are not quite coincident, and the Devonian fold axis lies perhaps half a mile to the east of the Cambrian axis. The present state of erosion is such that post-Cambrian sediments have been entirely stripped from the crest of the West Coast Range Anticlinorium and only the strata of the anticlinal limbs remain. The

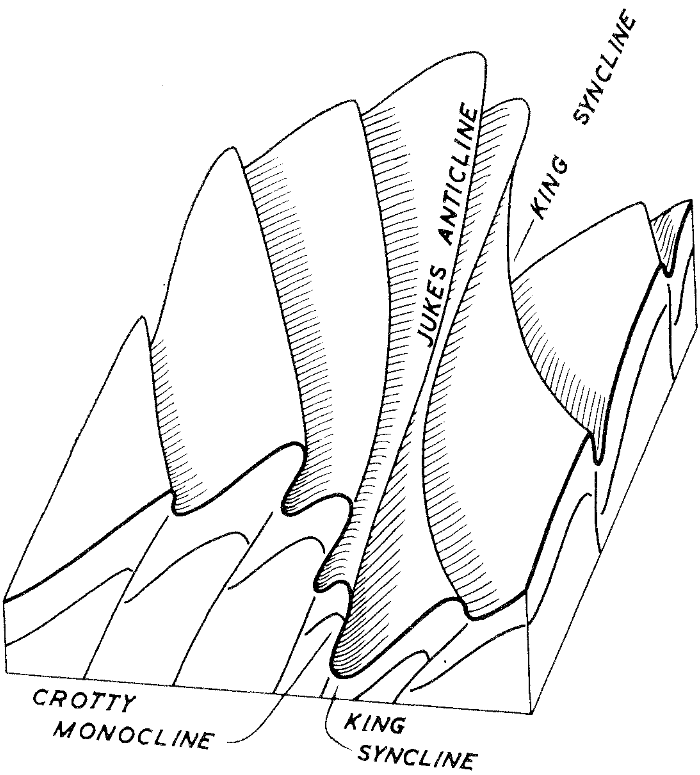

FIG. 5.—The idealised structure of the Jukes Anticline, Crotty Monocline and King Syncline and their relations to the north-west folds.

eastern and steeper limb built of the thick Owen and Dora Conglomerates is the more prominent, and this forms the bulk of the West Coast Range.

What follows is a detailed study of the structure of this limb of the West Coast Range Anticlinorium together with a broad study of the anticlinorium and synclinorium as a whole.

Second Order Folds.

Although it is convenient to speak of the vertical limb in the singular as the " Main Monocline " it is a compound structure like the anticlinorium, and just as that first order fold is made up of second and third order folds, so the monocline is made up of echelonned second and third order monoclines. Reading from south to north on plate I the second order folds are the Sorell, Jukes, Thureau, Read, Tyndall and Farrell; and the best defined of the monoclines, thrusts or overfolds are the Sorell Overfold, Crotty Monocline, Tyndall Fault, and Farrell Monocline. The second order structures are simplest, and best typified by the Jukes Anticline and the Crotty Monocline (fig. 5).

The Jukes Fold is asymmetric, and its eastern limb, which is vertical or slightly overturned, results from the upturning of the thickest conglomerates of the Jukes Trough. Consequently the vertical part of the limb of Owen Conglomerate is wide and the top of the formation does not quite coincide with the westward margin of the Tremadocian subsidence but lies some five furlongs to the east. The faulted margin should, theoretically, be marked by the westward limit of the thick conglomerates, and is so marked within a few chains at Mt. Owen, but irregularities caused by step faulting and uneven subsidence, by overstepping of the Owen Conglomerate on to the uneven surface of the Dundas Ridge, and by metamorphism of the Owen Conglomerate, mask the line.

Because the Owen Conglomerate is silicified and is resistant to erosion, the western margin of the thickest conglomerates is more or less the western margin of the crest of the quartzite hills, and this line is also marked by the presence of a remarkable mineralised tear fault, the Lyell Shear. The shear represents, with qualification, the actual fault line of the Cambrian subsidence and the eastern margin of the Dundas Geanticline. The origin of the shear, which is a transcurrent fault, is related to the fact that when the Dundas Geanticline was rejuvenated in the Devonian it moved northwards and carried the overlying strata with it. The country on the eastern side of the fault was left behind and a transcurrent fault was formed in the strata overlying the older fault line. The vertical movement on the west side of the fault was to a slight extent localised immediately over the fault line so that the shear is locally monoclinal, but in general the vertical movement was distributed through the 5,000 ft. of overlying strata and formed the larger Main Monocline of the range.

The anticlinorium as a whole is thought to be made of several echelonned units like the Jukes Anticline which have had very similar histories and which are probably structures inherited to some extent from the Tyennan orogeny. Although it would be possible to have had a simple Jukes Trough with a continuous western wall, and for the whole to have been folded *en echelon* in the Devonian, this would not quite explain the

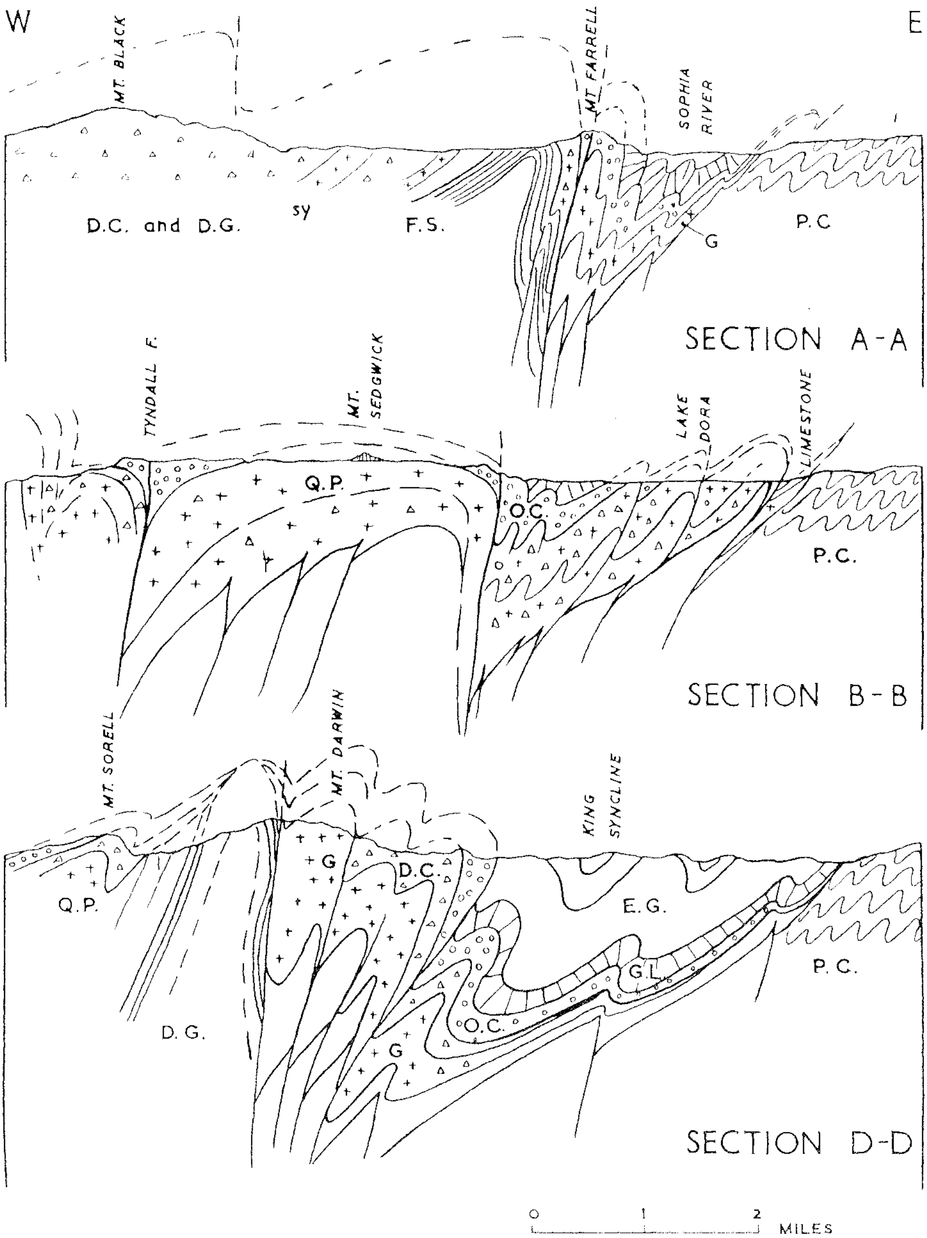

FIG. 6.—Sections across the King-Sophia Synclinorium (see Plate I). D.G.—Dundas Group; E.G.—Eldon Group; P.C.—Precambrian; O.C.—Owen Conglomerate; D.C.—Dora Conglomerate; G.L.—Gordon Limestone; G.—Granite; Q.P.—Quartz Porphyry.

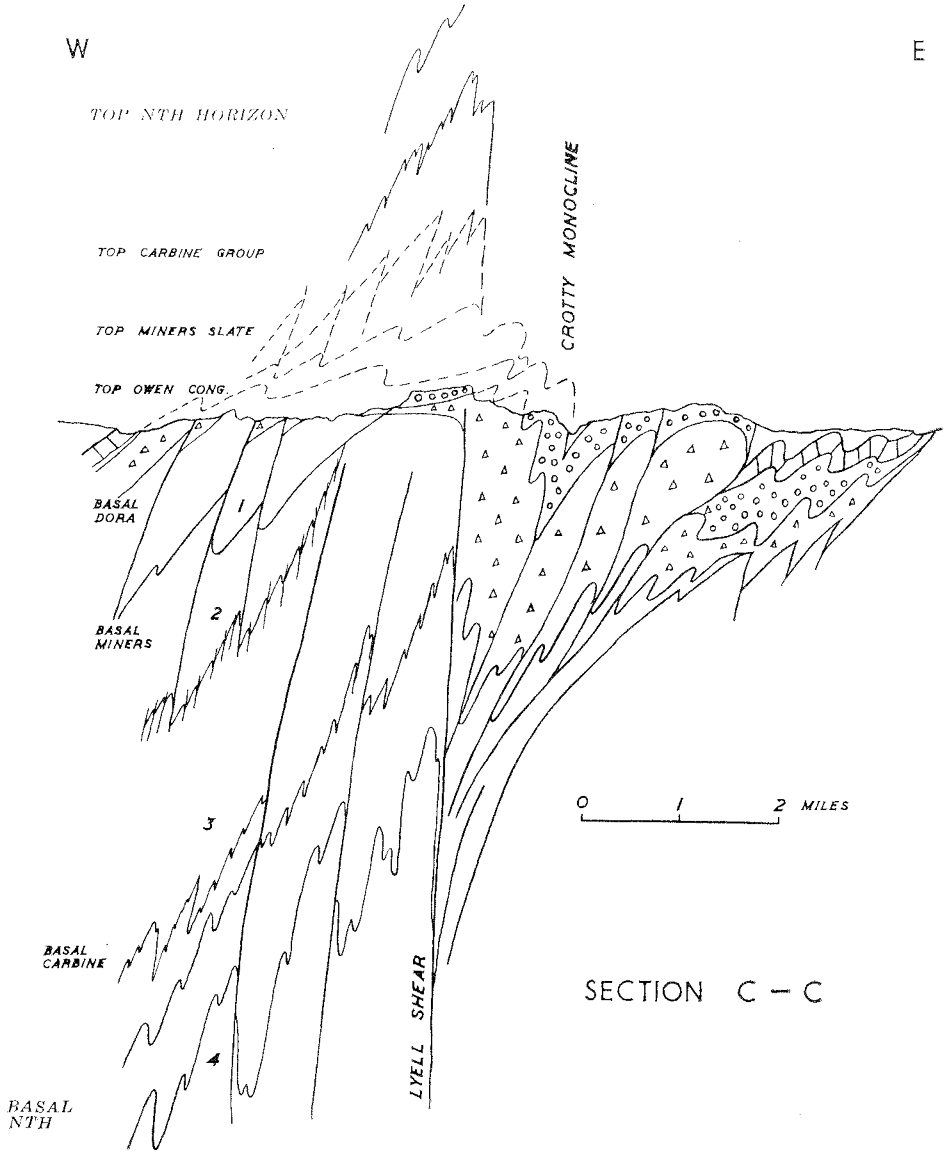

FIG. 7.—Section across Mt. Huxley (see Plate I). The section is extrapolated in depth in accord with the text, page 71 of this article, by projection of folds along plunge lines. The figures indicate zones of 1. massive shears; 2. slaty cleavages; 3. plication and schisting; 4. plastic flow. The latter should be scaled off to a depth several miles lower than the page allows.

observed pattern of outcrops. It is preferable to visualise the Porphyroid Anticlinorium as an echelonned structure and to imagine the Jukes Trough as subsiding along three echelonned faults during the Tremadocian. Then, when rejuvenation occurred, the thickest conglomerates would always form the western and steeper limb of each subsidiary basin. In this way we can explain the parallel variation in thickness of sediments seen across the folds of Mt. Sorell, Mt. Jukes and Mt. Farrell.

The comparison of structure and stratigraphy between one second order fold and another is complicated considerably by the fact that in the central section of the range, near Mt. Tyndall, the anticlinorium and synclinorium rise to a culmination, and we see a more deeply eroded section than at either Mt. Jukes or Mt. Farrell. Had the structures not been echelonned it would have been possible to take direct advantage of the culmination and to use an axial view along the plunge of the synclinorium to visualise the nature of the bottom of the King Syncline. As it is, none of the second order folds are quite comparable with another, and it is difficult to use the "axial plunge" method. It is even difficult to make simple comparisons of folds by name because the echelonned second order folds usually plunge, and the section through any one must be compared only with a carefully chosen section through any other fold.

With this caution in mind it is possible to compare both the Tyndall Fault and the Dora Shear with the Crotty Monocline in depth, and, in a general way, to project a series of sections at different depths across the King-Sophia Synclinorium. In the region of culmination the deep synclines of the Sophia and King Rivers are represented by the elevated Tyndall Range, which, although 1,200 ft. above those synclines and, despite its being a broad anticline, is a structural low between the Sticht Range (Tyennan Block) and Mt. Read (the anticlinorium). Thus, the sediments, general structure and metamorphism of the east-west section in this area must be somewhat similar to that in depth in the King Syncline at Crotty. A comparison of the Tyndall Fault and the Crotty Monocline (figs. 6B and 7) shows that, whereas the Crotty Monocline rears and thrusts vertical Owen Conglomerate against Eldon strata of the King Syncline, the Tyndall Fault thrusts vertically bedded quartz porphyries (Dora Conglomerate) against the westerly dipping Owen Conglomerate of the low Tyndall Anticline; in both cases a sharp fault angle is formed.

THIRD ORDER STRUCTURES.

For convenience in the account which follows, the West Coast Range Anticlinorium will often be called the anticlinorium, and the Porphyroid Anticlinorium will always be given its full title. The anticlinorium has already been divided into second order folds, and on examination of the map (plate I) it is seen that these are made up of a large number of small overfolds or thrust masses which strike in north-westerly directions; these third order folds, which are thrust towards the north-east, will be called North-West Folds. The Main Monocline is also cut by a large number of north-east trending third order fault structures which are expressed as monoclines or faults; these will be called North-East Faults. All of these structures, along with the north-south tear faults of the Lyell Shear type, are shown on the map.

On examination of the structural pattern it is immediately apparent that a transverse east-west structure, the Linda Disturbance, separates the Range into two structural units. Ignoring this for the moment, the pattern is immediately recognisable as typical of areas which have been subjected to north-east—south-east dextral shearing couples. There are very close similarities between this area and the Livermore Region of transcurrent faulting in California (Vickery, 1925), and even closer analogies between it and the highly sheared and mineralised copper belt of the Front Range of Colorado (Lovering and Goddard, 1950). In the active orogenic belt of New Zealand this pattern appears to the writer to be dominant in some late Tertiary foldings, and it is commonly associated with present-day transcurrent movement. Quite apart from these analogies, or by argument from more direct field evidence, it is possible by the inspection of the pattern to deduce that the region has suffered north-east—south-west compression and north-south shearing. The fault pattern can then be interpreted by use of the parallelogram of forces to show the lines on which this compression has been resolved and the probable directions of movement on most faults can be qualitatively assessed as follows:—

1. N.-S. faults are dextral transcurrent faults (dextral and transcurrent in the sense of Anderson, 1942, p. 54).
2. N.E.-S.W. faults are tensional.
3. N.W.-S.E. structures are compressional.
4. E.-W. faults are sinistral transcurrent faults

Because of our lack of knowledge of the orientation of the shearing stresses and of the shearing strengths of the rocks little more can be deduced, but it might be suspected by analogy with the branch faults of the Livermore Region that the north-west faults are sometimes dextral tears; this would apply particularly to those with a more northerly trend. The field occurrence of each of these structural types may be examined next.

The North-West Folds.

The North-West Folds vary in trend from N. 60° W. to N. 20° W, and they are rarely simple folds but are commonly asymmetrical or overthrust towards the north-east; despite their variation in form and trend the general terms north-west fold, thrust, or fault will be applied to these structures. They rise in the Zeehan Basin as simple folds of Eldon strata, and as they pass into the older rocks in the core of the anticlinorium they change into asymmetric folds and then into thrusts; at the same time, they swing in gentle arcs and pass into a north-south line along the crest of the Main Monocline. There, all minor folds become thrusts, but still further east they appear to pass out of the monocline into the King Syncline, and beyond that the folds pass again into north-west thrusts as they rise to the Tyennan Block.

It appears that the folds can be seen as folds only in the structural lows where they occur above the middle of the Owen Conglomerate, and that below that horizon they are steep thrusts or shears. This is clearly shown by the broken structures in the Lynch Slates which are folded a few points (e.g., north of Mt. Murchison) and by the intense brecciation of the Cambrian lavas. Where the lavas contain slate bands the slate is sheared, comminuted and mixed with all kinds of fragments, and it is the porphyritising of this mixture which has produced many of the inclusion-crammed porphyries of the region.

Quite apart from variation with stratigraphic depth, the north-west structures become more intensely thrust along the crest of the anticlinorium and some of the thrusts, on Mt. Jukes for example, show a forwards displacement of 150 yards. The thrust planes also vary in dip, for the thrusts in the Queen River Valley are steeper than 70°, those on the western face of Mt. Owen are about 50°, and those of Mt. Jukes are as low as 40°.

The passage of the north-west thrusts into the Main Monocline is best seen on the eastern side of Mt. Jukes where the vertical or slightly overturned quartzites stand as an almost continuous ridge for several miles. This ridge is seen to be cut obliquely and to be slightly offset by vertical shear planes which trend a little west of north. Aligned, but not demonstrably related to any particular one of these shears, are the long, more or less synclinal ridges which run up the flank of Mt. Jukes and pass with a small break into thrust synclines of the mountain top. The merging of the north-west structures, which is probably more perfect than field evidence indicates, is shown in figure 5, which also illustrates how the composite Crotty Monocline passes into the King Syncline as a series of tight folds which gradually open out. A glance at the Jukes and Darwin map sheets (published with Part I) shows how this happens—how the north-west structures are repeated by the north-east faults and how these faults are compensated by the tilting of blocks. The tilting results in many apparent anomalies, such as that at 366/793, Darwin Sheet, for it obscures the simple mergence of folds and often appears to set anticlines in line with synclines. An appreciation of the tilting effects is pre-requisite to the understanding of the north-west folds as they are seen in the field, for otherwise they appear hopelessly jumbled.

The field appearance of the north-west folds is worth a special note for, considering the complexity of the structure and the difficulty of the country, the evidence for them is very clear and is fully adequate to the purpose of a structural study. The excellent geomorphic expression of structures involving Eldon strata and Gordon Limestone has already been mentioned, but there are also numerous river gorge and scarp sections in which folds and thrusts are admirably displayed. In the older strata reverse faults are marked by sharp gullies in the hogback of the Miners Slate, but it is difficult to follow faults through the breccias and porphyroids, and some uncertain interpolations of faults have had to be made there. On the other hand, the great thrusts in the quartzite cappings of the range and the distinctive red and white thrust sheets of Mt. Owen and Mt. Jukes can be seen from a distance of ten miles away in the north-west. The traces of these faults are difficult to map for the thrust surfaces and topographic surfaces coincide and both are exceedingly complex; the same difficulty applies to the mapping of the Owen Conglomerate, for erosion is usually halted at its upper surface and a direct plan of outcrops, even if contours could be supplied, would be unintelligible on anything less than a 25-inch scale. These difficulties are partially resolved by using a smoothed surface of projection for the one-inch maps, and by showing traces and outcrops much simpler than they are in fact.

The Linda Disturbance.

As already noted and illustrated in Plate I this structure occupies an east—west zone which cuts across the range. The southern margin of the zone runs through Mt. Owen while the northern limit is marked by the east—west faults which run just south of Lake Margaret and along the North Eldon River. The axis of the structure runs east—west through Mt. Lyell and against it the north-west folds from both sides are deflected and thrust. The zone as a whole is seen as a structural low crossing the anticlinorium and lowering it by about 2,000 ft., and as a zone of intense shattering and faulting which extends for many miles to both east and west. Towards the west the faulting downthrows to the south, and against the zone the north-west folds are deflected, compressed and thrust, while the country is pneumatolised and the faults are mineralised with galena. Towards the east the Linda Disturbance follows the Nelson Valley and continues ten miles or more past Bubb's Hill, sometimes as a trough-like system of faults but at others as a stepwise system downthrowing northward. The Gordon Limestone at Bubb's Hill is mineralised with galena, and the east-west faults further east carry arsenopyrite; as the block faulting of Tasmania is not accompanied by mineralisation the structure must be pre-Permian and, in view of the fact that the structure downthrows Silurian strata, it is probably of Devonian age.

The Linda Disturbance is an important regional structure which has first order dimensions and affects the Precambrian Block and West Coast Range alike. Near Mt. Lyell the deflection of folds and their overturning suggests that the disturbance is a zone of tearing; it is far too complex to be a single tear fault, but in plan it looks as if the north-west folds have been folded normal to the horizontal plane and dragged against the axis of the disturbance.

The North Lyell Fault which closely follows the axis presents the only known direct evidence of strike slip and this has been described to the writer by Dr. C. Loftus Hills as taking the form of large horizontal channels and striations which slickenside the walls of the fault in the workings of the old North Lyell Mine. Other east-west faults, such as those on the south side of Lake Margaret, show such a contortion of the rocks to either side that the folds are visible on aerial photographs, and this degree of contortion in the absence of great throw may be attributed to tear movement.

There are two possible explanations of the Devonian structures of the Linda Disturbance; the first assumes the existence of a faulted depression across the site of the range before the Devonian orogeny, and it supposes that the north-west folds were not so much dragged against as compressed northwards against a pre-existing fault. If this were so, the amount of east—west tear movement on the North Lyell

Fault need be only small, of the order of one mile, and no great offset of the Jukes Trough deposits would result. This fits the facts quite well, but so does the second theory which supposes that the structure reulted from a straightforward tearing of about three miles; it ignores the rather obvious correlation of the Crotty Monocline with the Tyndall Fault and requires that the latter was originally echelonned with and lay almost three miles to the east of the former. Then a movement of this distance would align the two echeloned faults and the two basins of the Jukes Trough and give an impression of no movement. There is some evidence in the lithology of the Owen Conglomerate of differing conditions of deposition to the north and south of Lake Margaret, but this could equally well be attributed to the presence in the Tremadocian Epoch of an east—west trough or of a pair of echelonned basins.

Further in favour of a large movement are the regional aspects of the structure; if folds are traced round the Disturbance it seems that the line of the Tyndall Fault should pass into the Comstock Valley and thence into the King Valley, and it would certainly be echelonned with the Crotty Monocline. Again, while it is apparent that the thrust sheets of Mt. Owen have been thrust towards the north-east, and those of Mt. Lyell and Mt. Sedgwick have been thrust in a complementary fashion to the south-west: it is also true, though not so apparent, that this complementary relation extends on a regional scale into the surrounding country. To the east of Mt. Owen the Raglan Range is elevated, while to the west of Mt. Lyell and Mt. Sedgwick there is an elevation of the Howards Plain mass. These uplifts suggest some strong relative tear movement of the country on either side of the disturbance.

Before leaving the Linda Disturbance some comment is required on the locally intense metasomatism which occurs in this zone about a mile north of the Lyell Highway and along the Balaclava and Collingwood Rivers. This metasomatism characteristically converts thick limestones into enormous masses of felted but unschisted actinolite rock, and is associated with sericitisation and sulphide deposition. The metasomatism and mineralisation is Devonian and its significance may be important, for it occurs fifteen miles from Mt. Lyell, and it appears that the zone is mineralised independently of the West Coast Range mineralisation. In particular it may mean that not only does the Lyell mining field lie at the juncture of two major structures, but that it also lies at the intersection of two mineralising structures.

The North-East Faults.

These faults are not analogous nor are they complementary, in a simple fashion, to the north-west structures. They show the following features:—

1. They cut all other structures without deflection.
2. They are vertical faults, sometimes expressed as monoclines, are smooth and arcuate in plan, and sometimes appear to be overthrust.

3. Whereas the north-west striking structures are all low angled thrusts directed to the north-east, the north-east faults are vertical and have a variable direction of throw; there is, however, a very common direction of throw which is to the south-east.
4. The amount and direction of throw on individual faults varies, some faults tend to die out westwards, but the few that persist possibly increase in throw.
5. The faults, even when they have little throw, are lines along which the blocks to either side are tilted, and they appear to coincide with abrupt anticlinal or synclinal axes.
6. The rocks forming the margins of the faults are often intensely buckled and brecciated.
7. The faults are the most consistently mineralised minor faults.
8. The faults are later than any period during which granitising took place.

There are some apparent inconsistencies connected with these faults; if they are tensional, why are they so late and so little related to the other structures? what is the reason for their regional and arcuate pattern, and why do they show apparent compressional features? The age of the faults is not in doubt for their crosscutting relations to the north-west folds are clear at Zeehan as well as in the range, and they clearly post-date the silicification of the Owen Conglomerate, for they are often the site of intense brecciation of the Formation—e.g., at North Lyell and Comstock. At Queenstown they cut porphyry bodies and acted as feeders for pneumatolising solutions which hydrolised and kaolinised the same bodies.

Now, the faults mapped have been observed because they are conspicuous by reason of their size, their pneumatolytic effects, or their mineralisation. There are hundreds of unmapped small faults and joints which have much the same trend but which are unmineralised and inconspicuous. It is probable that many of these were contemporaneous with, and were truly complementary to, the north-west folds, but the fact remains that the larger faults were later than any other tectonic event and were coincident with the final stages of metamorphism; they were not contemporaneous with nor complementary to the greater part of the north-west folding which occurred before silicification of the Owen Conglomerate.

It is difficult to explain the fundamental cause of the lateness of these faults and a partial answer must suffice; it seems that the later stages of orogeny were marked by a decrease in the compressional component of the shearing couple and that this allowed the development of a few large, instead of many small, tensional faults. It will be shown below that the north-south tear faults of the Lyell Shear type were probably little earlier than the north-east faults, and as the former are closely related to the granitising processes of the region it may be that there is a genetic relation between metamorphism and structure. If this is so it becomes possible that the change in the nature of the stresses in the Lower Palaeozoic rocks was not the result of changing forces but of a changing constitution of the crust.

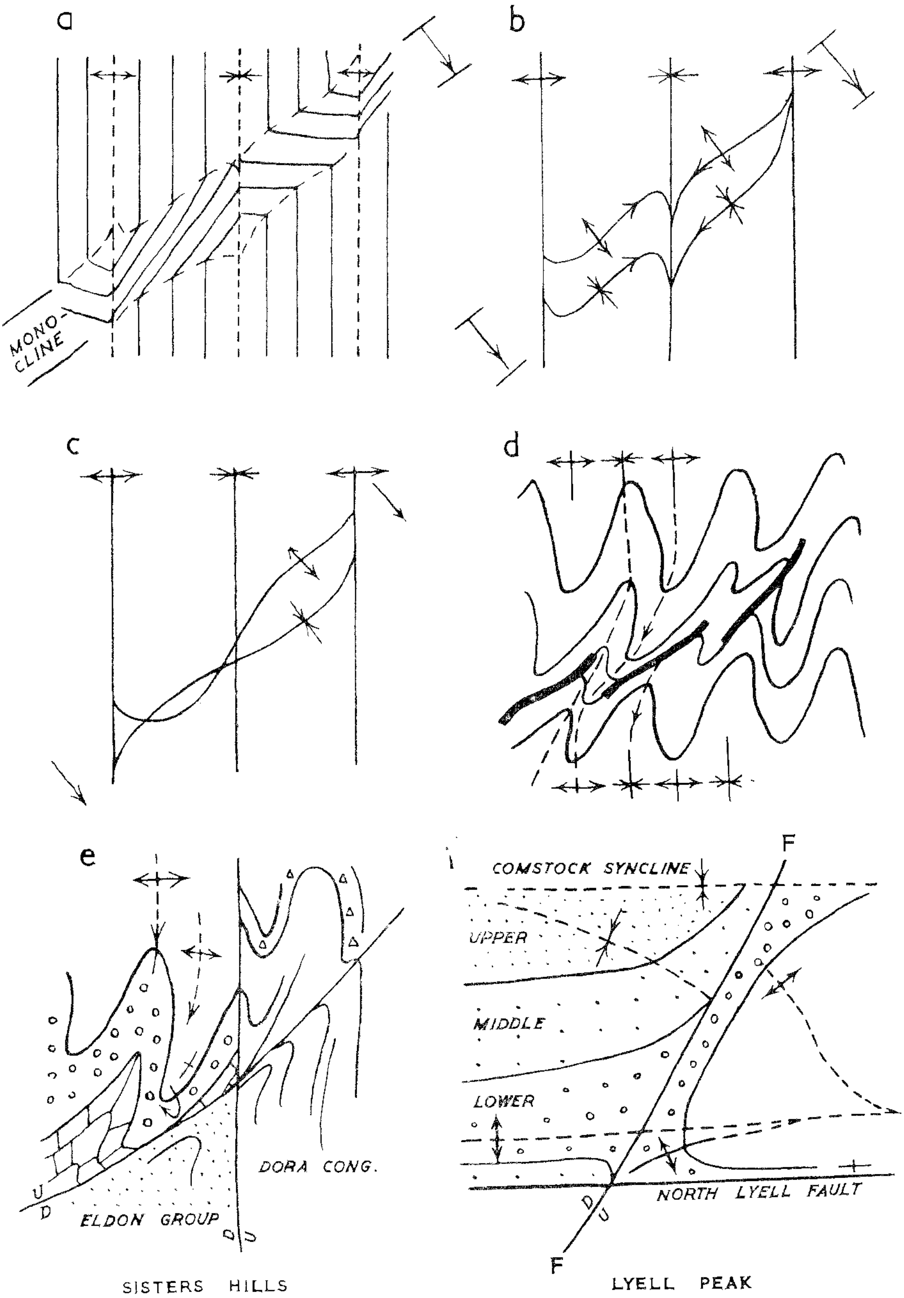

FIG. 8.—To show the effects of oblique superimposition of monoclines on minor folds: (*a*) shows bed traces affected by an artificially angular monocline after peneplanation; (*b*) fold axes set up by a smooth monocline; (*c*) effect of a vertical monocline; (*d*) as for (*c*) but showing bed traces; (*e*) the Sisters Fault; (*f*) east end of Mt. Lyell (diagrammatic).

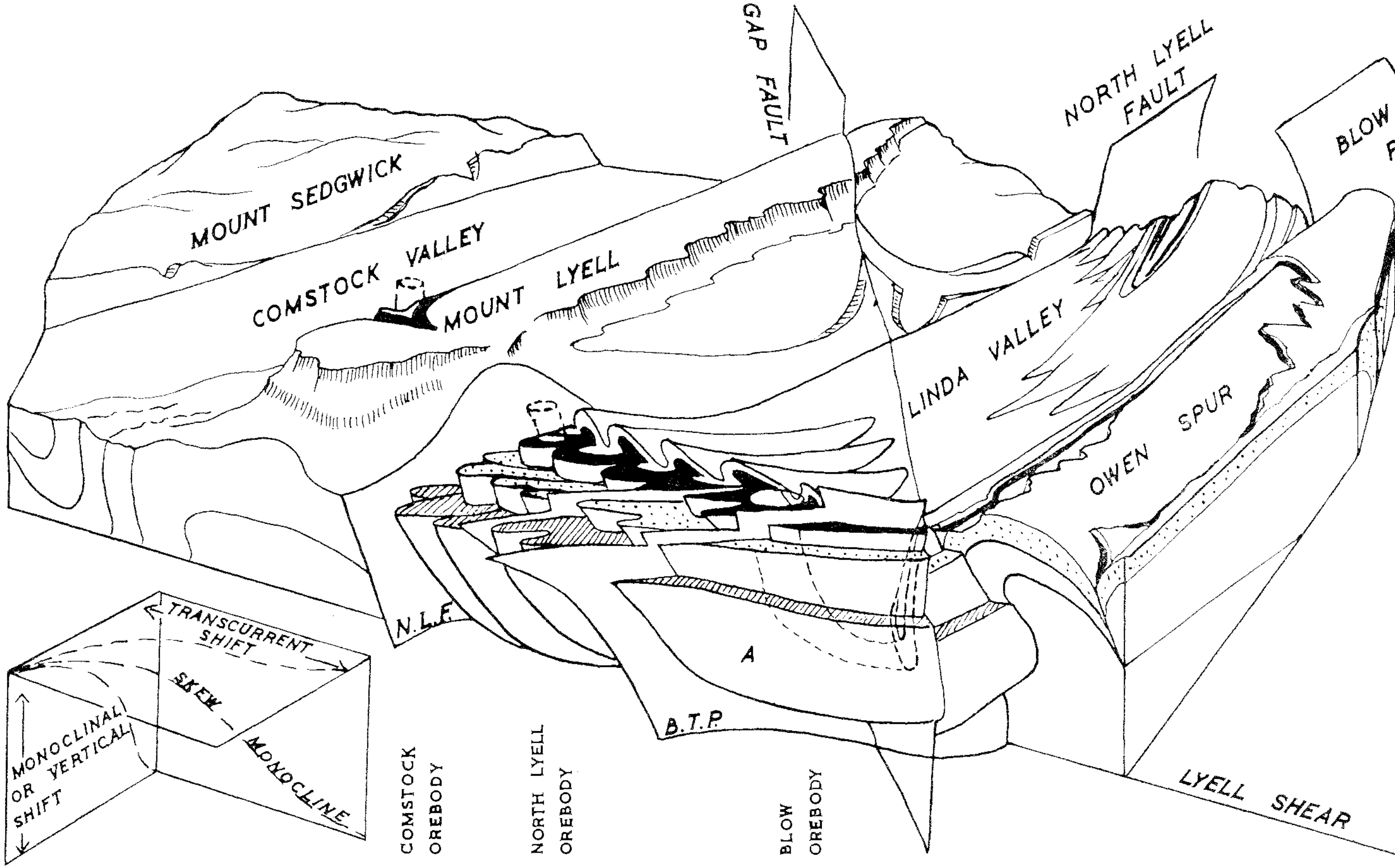

FIG. 9.—To show the effect of the Lyell Shear and the Gap Fault. In ascending succession:—shaded—Low grade ore horizon; dots—Middle Conglomerate; black—Chocolate Shale; overlying the black—Tubicolar Sandstone. The structures shaped like the bows of boats are synclines whose axial planes lean away from the viewer; thus the dips at A are inverted and are apparently towards the viewer.

Apart from the general problem there is the related problem of the regional change of trends of the north-east faults; there is a striking relation between the strike of the faults and the distance from the Tyennan Block. Thus, the faults on the block have a strong tendency to run north-north-east while they swing into an east-north-east direction in the Zeehan Basin. This may be explained by supposing that the old basement was more deeply buried towards the west, i.e., in the deeper part of the geosyncline, and that at greater depths it became more plastic. With rocks which had a low shearing strength, the angle between the shearing force and the tensional cracks would increase and the faults would become more and more westerly in the deeper part of the syncline.

The intense buckling and brecciation which often accompanies the north-east faults are sometimes present on faults like that at the south-east end of Mt. Owen which have no throw; these effects may be attributed to small tear movements but they are more probably due to oscillatory or accommodation movements on the faults.

The occasional overturning of beds along the faults, particularly along the Sisters Fault, is another matter. This fault (plate I), which is probably continuous with the Margaret Fault, is a fault only in depth, for in shallower and less competent strata it is often expressed as a monocline. The cross cutting relation of this and similar faults to the earlier structures is often very complex, for when the monoclinal drag structures are obliquely superimposed on the north-west folds they often create an impression of thrusting and overturning (figs. 8A to 8D). The result of this superimposition is that the dips of the folds and the monocline are vectorially combined, so that the dips with common components are increased while those with opposing components are reduced. This is shown in figure 8A by the deflection of bed traces and in the common case it means that a vertical flexure imposed obliquely on other folds will always cause some overturning of one limb and the reduction of dip in the other (fig. 8C). The overturning creates wholly enclosed structures in which one limb must be squeezed and sheared (fig. 8D) while the flattening of alternate limbs allows a smooth unbroken passage across the monocline. Thus, along the length of the monocline a very slightly echelonned series of thrusts is formed and this gives the effect of a discontinuous fault. Such structures are not uncommon in the region, and somewhat similar faults have been observed by other workers at Lyell, but they are very difficult to visualise and quite impossible to depict without many diagrams; it is for this reason that the example shown in figure 8E is a simplified version of the occurrence at Sisters Hills. It will be noticed that the north—south folds of the diagram are not offset and the fault is not transcurrent, but it may also be observed that the immediate effects are identical with those caused by tear movement.

One of the most interesting of the north-east faults is illustrated in figures 8F and 9. This scissors fault has a westerly downthrow on Mt. Lyell and an easterly downthrow in the Linda Valley. Figure 9 shows how the blocks to either side of the fault have been tilted and figure 8F shows the effects of the pronounced drag on the fault on Mt. Lyell. The throw of the fault must be about 1,500 ft. or more, and it is almost wholly distributed as a monoclinal effect in the adjoining strata so that plunging folds are formed to either side of the axis of the Mt. Lyell Anticline. On the south side the diagonal folds are clearly drag structures on a fault plane, but in the Comstock Valley the fault, though distinct, is relatively insignificant beside the broad plunging folds. It is assumed that these are the structures which Conolly (1947) shows in his figure 2 and which he has extrapolated to join up with the Comstock Syncline and a Sedgwick Anticline. The writer disagrees with this interpretation and considers that both folds pass into the vastly larger Comstock Syncline. In the succeeding paragraphs it will be shown that Conolly's Sedgwick Anticline is possibly the continuation of the western end of the Mt. Lyell Anticline. In passing, it is noted that the amount of drag on this particular fault is not consistent with the idea that north—east faulting post-dates the silicification of the Owen Conglomerate. It must be allowed that some north-east faulting occurred before silicification, and it may be that the lateness of the tensional north-east faults is due to lateness of the induration of the rocks rather than to a lateness of a particular kind of stress.

The Lyell Shear.

The location of the Lyell Shear is indicated in plate 1; it is a complex dextral tear fault with a variable upthrow to the west and with a highly variable surface expression. Conolly (1947) regards it at Lyell as a 2,000 ft. high monocline, while at South Darwin it is, as first seen by the writer, a sharp syncline; at intermediate points it appears to be a simple tear, and at some places (this is extraordinary for a tear fault) it begins or ceases abruptly. Parts of this fault have been identified by other workers and have been given various names and interpretation, so it is here called the Lyell Shear to avoid confusion. Economically the shear is important, for along its length occur all of the important ore bodies south of Comstock, and it appears that it has not only controlled ore deposition, but has to an appreciable extent commanded the passage of porphyritising and granitising solutions. Fortunately, the structure can be readily dated relative to other processes; it pre-dates mineralisation and granitisation which are always particularly evident along its course; it pre-dates the silicification of the Owen Conglomerate, for it causes rotation of pebbles without their deformation and rarely causes brecciation of that formation; it post-dates the formation of the north-west folds and the Linda Disturbance, both of which it cuts; and by inference it is also later than the main uplift of the anticlinorium. The most intriguing features of the shear are the interplays it makes by combining with the north-west folds, particularly those at Mt. Lyell. These interplays which give the Shear its most specific character are often expressed as intermittent faults similar to those just described for the Sisters Fault, but they are present on a larger scale and are developed to a much greater degree of perfection.

A broad view of the Shear is given in the simplified diagram of figure 10; the north-west folds and the anticlinorium have been flattened out from east to west and the structures formalised. Thus, only one of the several folds between Mt. Lyell and Mt. Owen is shown, and the dragging of those folds is drawn in terms of planes rather than of curved surfaces. The Shear runs as a simple tear from South Darwin

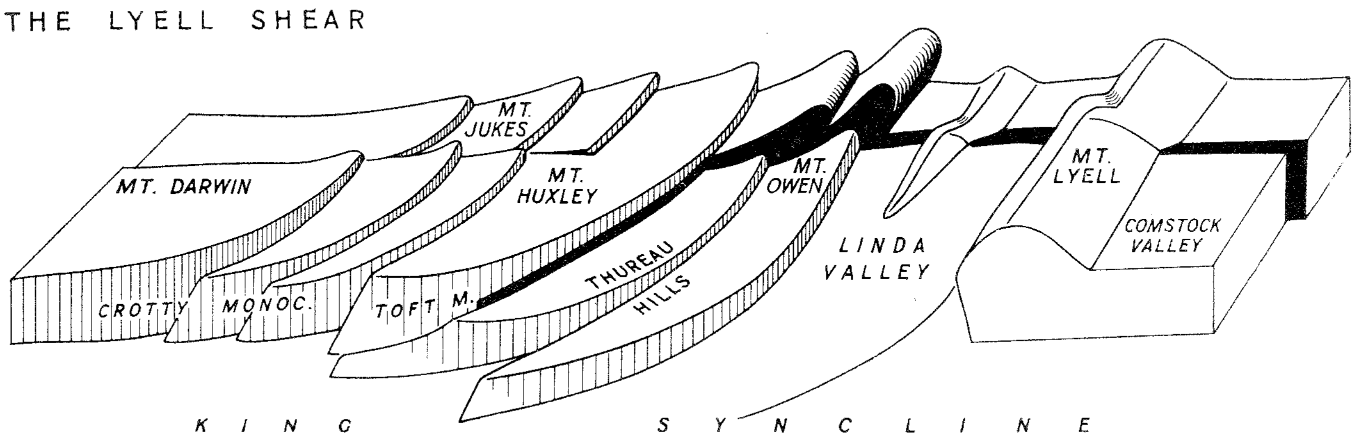

FIG. 10.—The Lyell Shear; the figure is not to scale and the small deflected fold in Linda Valley is only one of several and its west side uplift is four times that shown.

Peak to Mt. Huxley where it passes under the sheet of Owen Conglomerate capping that bluff. At that point it seems that the sheet and a considerable depth of basement has remained unbroken and has moved forward on both sides of the fault. This requires the explanation that the tear movement has been transferred from the Shear to a parallel position, and this is most likely to have been along the Toft Monocline; it also requires that the sheet on the eastern side has been thrust northwards across its immediate neighbour.

To the north the shear is very evident along the face of Mt. Owen but it does not appear to cut Owen Spur; from there it runs intermittently across Linda Valley and at the North Lyell Mine is again interrupted by the great fold of Mt. Lyell. On the northern side of that fold the shear comes in as strong as ever at the Comstock Mine, and from there it may pass on to Mt. Sedgwick and be continuous with the Tyndall Fault, but it has not been clearly recognised north of the mine. It appears that in some way the tear movement has been halted by the Linda Disturbance or by the mass of Mt. Sedgwick and has been partly resolved into a pile of folds; it can be imagined that the block on the west side of the shear has encountered a rigid obstacle and that the north—west folds on that side have been further compressed and thus raised, so that the fault in the vicinity of Mt. Lyell has acquired a considerable west side upthrow. It is, however, impossible to resolve any more than superficial tear movements into uplift of this kind, and the transcurrent movement of the deeper seated Precambrian strata must somehow have persisted northward across the Comstock Valley. It seems probable that the tear movement on the Lyell Shear has been transferred to the Dora Shear (plate I) by the same kind of sidestepping which has already been deduced for the Mt. Huxley area. In this case, however, the sidestepping has been deeper seated and has been permanent, and it is suspected that the new line of movement was determined by an already existing fault.

The local effects of the fault are of great interest and at Lyell Mines the west-side uplift is resolved by dragging of the Owen Conglomerate into the monoclinal effect described by Conolly. A small amount of northward movement was suspected by that writer, but the differential compression of folds on the western side of the shear has not hitherto been considered. It is clear from figure 10 that dextral movement along the fault will cause the north facing thrust folds of Mt. Owen to be compressed and thrust even more to the north. On the other hand it seems that the south facing asymmetric Mt. Lyell Fold will tend to be rotated against itself. Ignoring any drag effects the tendency will be for the Mt. Lyell Fold to be inverted in exactly the opposite sense to what it is on the eastern side of the shear; its northern limb will be inverted, its steep southern limb will be raised to the horizontal, and its north dipping thrust plane will be rotated so that it dips south—i.e., is inverted. This is substantially what seems to happen, but a large part of this effect is due to the uplift on the western side of the fault, and to the remarkable dragging effects which convert the uplift into a vertical monocline; these effects are described in the following detailed accounts.

The Lyell Shear at Lyell Mines.

The ability of the Owen Conglomerate to accommodate itself to every kind of flexing is remarkable, and this undoubtedly accounts for the perfection of the structures seen at Lyell. In that context of intense folding a highly competent body, e.g., the Conglomerate in a silicified condition, would have been completely brecciated, and a less competent bed would have been smeared out, but there was, in the Owen Conglomerate, an unconsolidated formation of pebbles which was relatively competent yet which did not fracture readily. The fine structures of the Linda Valley and at the Lyell Mines have already been described by Conolly (1947), but this treatment is slightly different.

Linda Valley is, as shown in figure 9, a folded trough between the inward facing Owen Spur and the Lyell Folds; the trough is tilted from both ends towards the north-east fault which cuts through the centre and is terminated at its western end by the Lyell Shear. In the example of the Sisters Fault the effect of a monocline cutting obliquely through other folds was to invert and unroll alternate limbs, and on the Lyell Shear we have the same result. At the western end of the valley occur a number of east plunging folds which are exposed as the stripped rock surface of the Tubicolar Sandstone; on the line of the Lyell Shear the sandstones of the northern limbs of the folds are seen to twist to a vertical position, sometimes within a yard and sometimes more gradually, while those of the southern limbs are not at all contorted and may even be re-tilted towards the horizontal. It is stressed that the exposures are in all cases bare rock, and in many cases the structural surfaces are topographic. The upturns are very apparent, for they usually follow a line of haematite metasomatism, but the line of the shear is generally masked because it is also the contact of schist against quartzites. Even so, the bedding and relict beds of the quartzites can sometimes be traced across the contact, and near the North Lyell Mine the bedding in the schists can be observed to swing in an arc, and dips can be seen to pass through the vertical and become inverted. Just as at the Sisters Hills, this effect can be attributed to a monoclinal upturning, but in this case the angle of intersection of the structures is rather obtuse (70°) and because of this the argument of simple upturning just fails to be convincing; in addition, the argument, although it largely explains the observed structures at the mines, is quite inadequate when applied to the large north-west folds of Owen Spur and Mt. Lyell.

On Mt. Lyell the structure is that depicted in figures 11 and 12, and is similar to that drawn by Conolly but with this difference—Conolly continues the axis of the Lyell Fold in a straight line towards the west whereas the writer has swung it through almost 90° towards the Comstock Mine. This may seem to be quite different but it is purely a matter of interpretation, for Conolly's dip observations are much the same as those used here. In effect, it is as if the axis of the Mt. Lyell Fold has been turned clockwise through 90° in a horizontal plane, and the fold has been rotated on its axis through 90° in a vertical plane. Something of this kind has already been attributed to monoclinal warping, but in this case a stereographic study of the angles of dip of the north-west folds along with the angle of intersection of those folds and the monocline, reveals that no amount of rotation on a north-south axis can result in the near horizontallity of the beds at the western end of Mt. Lyell.

It becomes necessary, then, to advocate an additional mechanism, that a transcurrent element of movement has taken part in the folding. If the dextral strike slip of the Lyell Shear is considered to have been distributed over a wide zone just as the dip slip has been, we should have the effect of a monocline in plan just as we have a monocline in section, and if we consider only the effect of this structure on the original north-west folds it is obvious that those folds would be deflected northwards into the line of the monocline. If we impose the monoclinal rotation on these deflected folds, which are now parallel to the monoclinal axis, it is possible to account for horizontal as well as overturned limbs and so to solve the problems we see in the field.

Before proceeding, however, it should be made clear that the distributed strike shift and dip shift and rotational effects are not separable in fact, but are all attributes of one process. Monoclines are usually regarded as due to movement in a vertical plane normal to the axis, but the process here is one of movement in an inclined plane normal to the fold. The process of warping in an inclined plane, which is probably

FIG. 11.

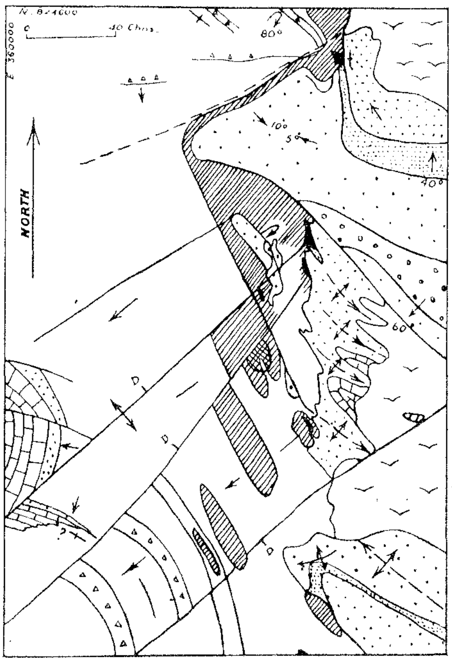

FIG. 12.

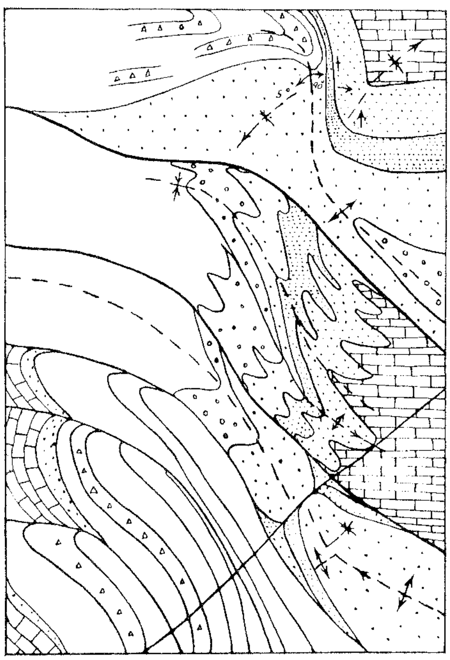

FIG. 11.—Map of the Lyell Mines. The exact shape of the low grade ore is not definable and that shown is in part after Nye *et al.* (1934) and in part interpretative.

FIG. 12.—Reconstruction of the area shown in figure 11 without metamorphism or minor north-east faults.

as common as oblique slip on faults, is here called *skew warping*, and its product is named a *skew monocline*; where recognisable the latter will be a composite structure made of simpler elements, but commonly the skew monocline will be indistinguishable from an ordinary monocline.

The effects of skew warping near the Mt. Lyell Mines is shown in the figures 11 and 12. The second of these shows a reconstruction of the geology without the metamorphic effects or the north-east faults. To avoid too great a departure of bed traces from the present forms of outcrops, the map projection surface is not a horizontal surface but a plane which has been bent along a north-south axis to conform roughly with the surface profile of an east-west cross section through the Lyell Mines. The map is purely interpretative of the information given on the adjacent map, figure 11, of field observations, of strikes and occasional dips in the schists, of the known variation in lithologies and thickness of the Owen Conglomerate, and of the known propensity of the low grade ore to replace beds. On the latter point, the fold forms of the low grade ores are conjectured from the shape of their outcrops in relation to the throws of the north-east faults.

The maps should explain themselves except for some enlargement on the following points:—On examination of figure 12, it should be remembered that the Owen Conglomerate changes in thickness from 1,600 ft. at the mines to less than 100 ft. at the Smelters, and that structurally and on the western side of the area the Dora Conglomerate takes its place (included with the Dora Conglomerate on this map are some Dundas rocks).

In explanation of figure 11 the Owen Conglomerate appears to have been porphyritised or ' eaten back " to its present outline by metamorphism which, along with mineralisation, appears to have been particularly intense along the contact and less intense westward. The residual masses at the Blow and near North Lyell are the most significant features of the map, and the former mass can be projected below ground to where it appeared at the bottom of the Blow Open Cut, while the second mass has been followed extensively in the underground workings of the Tharsis Mine (Conolly, 1947, and Alexander, 1953).

In the block diagram (fig. 9) the development of the topography needs explanation; looking at the southern face of Mt. Lyell it is readily seen that the bedding of the red and white conglomerates passes as a horizontal trace along the length of the escarpment, with only a slight deflection as it crosses the shear, and it is this continuity that suggests that the shear does not continue through Mt. Lyell. With the explanation offered above, it appears to be a special pleading to suggest that erosion has picked the one section line (the present escarpment) which provides the most nearly horizontal beds running across the shear. The reason is simple, for the quartzites when disposed horizontally are highly stable and almost imperishable, whereas when they are inclined they present their greatest weakness to mechanical erosion; they are then reduced or cut back, leaving only the stably disposed horizontal or nearly horizontal beds.

It will be seen that a study of the structure is inextricably involved with this type of geomorphic problem, with metamorphic effects, mineralisation, sedimentary history and regional geology, and that in order to proceed further at Lyell the larger structural picture must be filled in. Before leaving figure 12 attention must be drawn to the close similarity between upturned and blended folds at Lyell, and those of the Main Monocline and north-west folds (fig. 5); since the former upturning was post north-west folding, it may be considered whether the uplifting of the Main Monocline was also late. In view of the earlier history of the geanticline this is most unlikely, but it is noted that any late uplift and dextral movement along the Crotty Monocline would be undetectable.

The Lyell Shear at Mt. Jukes.

To the south of Mt. Lyell Mines the Lyell Shear can be followed for two miles as a line of upturning and of intense metasomatism, but it is not clearly seen again until Lake Jukes is reached. There the Jukes Cirque has been eroded back to a fault plane which now forms its rear wall and the Lake conceals the fault line. To the north and south of the tarn small bornite and chalcopyrite prospects have been opened on the fault line and a westerly downthrow of some 50 ft. is observed. The angle of dip of the fault is within 10° of vertical, but it is not possible to tell its direction. There are no signs of the dragging which occurs at Lyell and there are no other signs of tear movement, but the continuity of the line of haematitic and pyritic deposits to the south and north of this point may signify that only one structure is involved and it seems reasonable to suppose that this would be the Lyell Shear.

The Lyell Shear at South Darwin.

Just west of South Darwin Peak the shear (fig. 13) runs parallel but some distance to the east of the axis of the south plunging anticlinorium, so that a dextral shift on the fault, where there is pronounced drag, creates a sharp anticline and syncline. By itself this arrangement is not conclusive evidence of tearing, for it could be the result of a fault downthrowing to the west. Fortunately, more evidence is available; it happens that to the north of the last structure the adinoles of the Darwin Plateau dip steeply west, and where they are intersected by the shear they are dragged in the same sense as before, forming a synform or synclinal structure in line with the previous anticline and an antiform in line with the previous syncline. This parallel offsetting of beds with opposing dips can be produced by tear or hinge movement but not by simple faulting, so that the fault is clearly a tear or a hinge fault, and in view of the regional setting it is accepted as a tear. The fault has some interesting implications in this particular locality; traversing Mt. Darwin from east to west one passes from the eastern limb of the Main Anticline on to a granitic metamorphic complex which is structurally still conformable, and then one continues on to westerly dipping adinoles which are at least broadly concordant with the granite. These adinoles are probably in their correct sequence, and they are most probably Dundas Group slates overturned. If they are overturned the antiform and synform structures in these beds can be readily explained as inverted syncline and inverted anticline respectively, and their apparently anomalous alignment with the first mentioned folds is seen to be a normal one.

This zone of contortions, of shearing and of mineralisation is the crucial area of the earlier argument on the metamorphic "unconformity", it is the sharp syncline at South Darwin which preserves the controversial unconformity, and it is the inverted anticline in the adinoles which carries the wholly inadequate amount of haematite and magnetite which might conceivably contribute to the "unconformable" breccia. In the Owen Conglomerate there are some pyritic and haematitic veins which are clearly Devonian and which, along with the magnetite pebbles of the breccia and magnetite veins of the adinoles, are immediately associated with the Lyell Shear; because of the restricted occurrences of the iron ores it is economical of hypotheses to suppose that they were introduced at only one time, i.e., in the Devonian. There is, however, another argument to be considered; it is that if the Lyell Shear has been a line of continuous movement in two orogenies it would be not at all unreasonable to suppose that the same metasomatic phenomena might accompany each set of movements and that the closely associated magnetite and haematite ores do in fact represent the two periods of mineralisation proposed by Hills (1914).

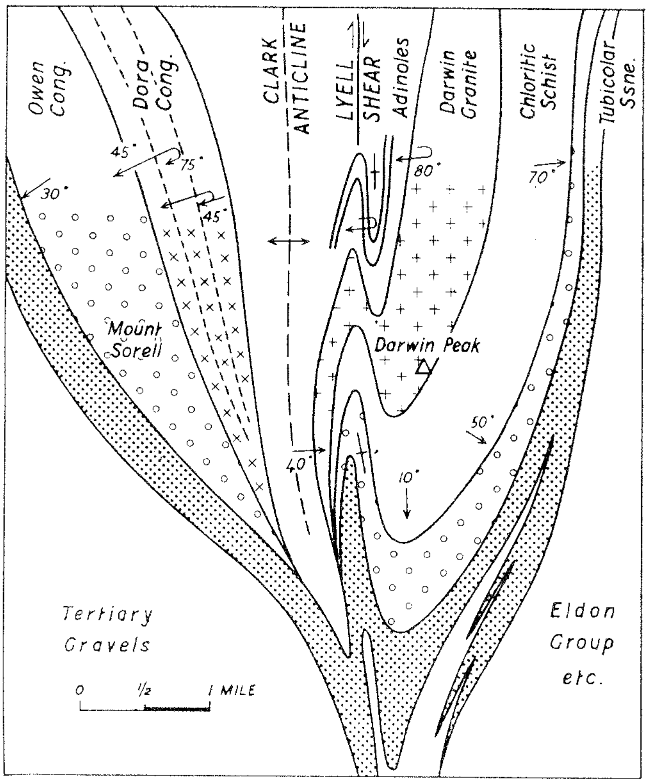

FIG. 13.—Reconstruction, without north-east faults, of the area at the south end of Mt. Darwin and Mt. Sorell.

Finally, although it is difficult to give a reliable estimate of the tear movement on the shear, this tearing may be of the order of 1,000 ft.; any vertical shift on either side of the fault would be difficult to observe and would radically upset this figure.

The Sorell and Clark Anticlines.

Now that the effects of the north-east faults and the Lyell Shear can be allowed for, the major structures and the sedimentary history of the area west of Mt. Darwin can be approached. In the reconstructed area presented in figure 13; the Owen Conglomerate of Mts. Sorell and Darwin thins out markedly towards the nose of the Clark Anticline and on each mountain this conglomerate is underlain by formations which thin out in the same direction. On Mt. Sorell the underlying formation is the Sorell Conglomerate which is composed of granite and magnetite pebbles and on Mt. Darwin there are two formations, a fine grained conglomeratic greywacke and the stratified and conglomeratic Darwin Granite. At the nose of the Clark Anticline only the Tubicolar Sandstone continues round the end of the fold, and it is the lower and conglomeratic portion of the Owen Conglomerate which thins out. In view of the general tendency of the Owen and Dora Conglomerates to have sympathetic variation in thickness it is thus wholly reasonable from a structural standpoint to suppose that the Sorell Conglomerate and Darwin Granite were both originally Dora Conglomerate.

It is now structurally and historically consistent to regard the Clark Anticline as the old Dundas Ridge against which these two formations thinned. The rocks of the core of the Clark Anticline tell very little of their origin, for they consist of thoroughly mixed slates, adinoles, quartz porphyries and quartz sericite schist which cannot be mapped separately or recognised except in the broadest terms. From the large content of slaty and hornfelsic rocks involved, the complex is almost certainly made up of the Dundas Group strata, and the observed strikes of the slates are consistent with the presence of a south plunging anticlinal axis running along the Clark River. From the attitudes of the Mt. Darwin adinoles it may be inferred that the major anticline has an overturned eastern limb but this must be largely due to the Devonian folding and the Cambrian structure must have been a less acute fold. The unconformity at the base of the Dora Conglomerate must, in accord with this thesis, have been less than 60°.

The Sorell Anticline (fig. 6C) follows the general pattern of folds in the region, in that it is an asymmetric fold overturned to the east, but the degree of overturn is greater than usual and the exposure of the structure in the eastern face of Mt. Sorell is also unusual. In that face the three limbs of an overturned anticline and syncline are seen; the horizontal trace of a synclinal axial plane occurs near the base of the cliff or is buried by scree and the trace of the anticlinal axial plane occurs 500 ft. to 600 ft. above. The resultant triplication of the Sorell Conglomerate is not at all obvious as the formation is uniform, and it led Hills to estimate the thickness of the conglomerate as much greater than is thought here. The 45° and 75° dips given by Hills (1914) show the true situation quite clearly if one interprets his 75° dip as the overturned dip of the central limb.

There is a small anomaly in the thickness of the Owen Conglomerate on Mt. Sorell, for it is found that the formation thins out or becomes sandier in every direction and it must be concluded that the site of the Devonian fold was also the site of a thick accumulation of detritus in Tremadocian time. In brief, the Sorell Overfold is the surface expression of a rejuvenated Cambrian fault in the same way as is the Crotty Monocline, but by comparison it was only a small structure of the Porphyroid Anticlinorium and not a much larger part of the West Coast Range Anticlinorium. It is readily conceived that the Sorell Fault of Cambrian age was echelonned with the ancestral thrust of the Jukes Block and that it was prolonged far to the south as the eastern margin of the Porphyroid Anticlinorium.

The Mt. Read Anticline.

Having discussed the type structures of the southern area it is possible to turn to the less dramatic foldings to the north of the Linda Depression. In this area the third order north-west folds are everywhere, except on Mt. Murchison, very subordinate to the second order folds, and the broad structure is simple. Passing from west to east (plate I) the large folds are the Mt. Read Anticline, Tyndall Fault, Tyndall Anticline, Dora Syncline, Murchison Anticline, Farrell Anticline and Sophia Syncline. Of the first of these very little is known; the others strike 20° west of north except for the last which swings from that bearing to a north-easterly trend.

Mount Read fold, which probably includes several large folds, is known only as an elevated block of porphyroid rocks which extends west from Mt. Read to Mt. Dundas where it includes highly folded Cambrian and Precambrian strata. Where stratification is recognisable the strike of the strata is, in general, north-south and dips are usually in excess of 45°; immediately west of Mt. Tyndall, bedding is clearly displayed in the vertical and north striking conglomeratic quartz porphyries, and though exposures are fair they are so much interrupted by moraine that they lead to no consecutive structural picture. Descending to the Henty River and ascending the slopes leading to Mt. Dundas the country is forest covered, exposures are disconnected and only the rock types can be observed. These are predominantly the breccia and flysch types of South Queenstown; they are locally lightly feldspathised but are generally highly chloritised and do not lend themselves to any system of precise identification or structural mapping. The strata west of the Henty River are probably of the Dundas Group, while those to the east are more strongly conglomeratic or molassic and are probably Dora Conglomerate.

Further north between Red Hills and Mt. Read a section parallel to the last runs for most of the way in quartz and feldspar porphyries which are on the whole massive and give no structural information. On the eastern side of the Henty River the porphyries are again bedded and in the Red Hills area some structures can be followed for 100 yards or more.

The Tyndall Anticline.

This, one of the largest folds of the region, has been mapped for a distance of nine miles from Mt. Sedgwick to Red Hills and consists of a low, almost flat-topped anticline which, along with the neighbouring and similar sized Dora Syncline, forms a full fold with a wavelength of five miles and an amplitude of about 4,000 ft. The fold, which is bordered on its western side by the Tyndall Fault and the upthrust mass of Mt. Read, tends to be thrust to the east and is slightly asymmetric. It is divided by two systems of north-east faults, one at Lake Margaret and another near Lake Julia, into the central horizontal part which forms the Tyndall Range, a north plunging part at Mt. Sedgwick, and a south plunging part at Red Hills. The central part of the fold, built of Owen Conglomerate, has been stripped of its softer cover and the topography generally conforms to its surface, but locally this surface has been deeply carved into cirques which expose the core of the fold and the base of the Owen Conglomerate. The Red Hills and Sedgwick parts of the fold have such plunges that their original protective cover of quartzite passed above the present 4,000 ft. contour and was removed during the Carboniferous peneplanation; the old pre-Permian surface exposed at Mt. Sedgwick still has scattered relics of Permian deposits, but as a rule the Dora Conglomerate and porphyries which form the core of the fold are eroded to well below the level of the adjacent quartzites.

The north-east fault systems which dislocate the anticline are not well defined, for that at Lake Margaret passes below the lake and that at Lake Julia is not easily recognised, for it consists of many branches cutting uniform conglomerate. In a broad view the combined effect of faulting and tilting is clear and is similar at both ends of the anticline. Thus, at Lake Margaret the Gordon Limestone is downthrown about 2,000 ft. below its mean position in the crest of the anticline and two miles to the south, at Sedwick Peak, it must have been raised by at least 2,000 ft. and the tilting must have been of the order of 25°. Similarly, at Red Hills the tilting, though masked by a sub-parallel topography, can be directly observed in the 6° plunge of the fold and at Lake Julia the tilting at the south end of the block may be deduced from the 30° dips in the axial plane of the fold.

The particular interest of the anticline lies in the character of its third order folds which correspond to the north-west folds of the Jukes Anticline. Here the folds trend north 20° west and are not oblique but parallel to the axis of the large anticline. They are best seen in the eastern limb of the anticline on the south-east slopes of Mt. Murchison where they are revealed in stripped surfaces of the Tubicolar Sandstone and are shown to be asymmetric folds with a wavelength of 200 yards and an amplitude of 100 ft. The folds do not thrust towards the north-east as do the north-west folds elsewhere, but face in the opposite direction. This facing is easily rationalised by regarding the folds as drag folds facing towards the axis of the anticline, but this raises the question—are the other north-west folds drag folds also? Those folds are generally rather large to be regarded thus, but this is not a critical objection, and as they are only displayed clearly in the western limb of the anticlinorium their north-east direction of thrust is consistent with their being drag folds. There are, however, good reasons why they are not typical: their obliquity to the larger fold axes and the fact that they pass downwards into deeper seated strata as thrusts. Although it is conventional to regard drag folds as parallel to their parent fold axes there is no mechanical difficulty to prevent drag folds being formed in an oblique fashion. Convention also allows that the direction of shortening of strata is normal to the fold axis, but this is not necessarily the direction of movement of beds. In the Jukes Anticline and in other folds formed by shearing couples the real direction of shortening of beds may be oblique to the fold axis and the slip of beds will also be in that direction (north-east—south-west for the West Coast Range). Any drag folds will consequently be formed by rotation in that direction and will trend north-west.

The problem is best set out now by asking—are the north-west folds drag folds belonging to a larger fold or is the anticlinorium made up of a large number of smaller echeloned folds? These questions present their own answers. Both large and small folds are integral to each other; they are one compound result of one system of stresses. As far as the Tyndall Range is concerned the reason for parallelism and normality of the "drag" folds is simply that the fold has suffered little compression; its eastern limb has not been overturned to invert the drag folds and the anticline has not been subject to any great shearing stress to upset their parallelism. Why this should be the case as we pass away from the Lyell District is not debated.

The Tyndall Fault.

The Tyndall Fault is best expressed and least equivocal along the foot of the western flank of Mt. Tyndall where it upthrows the vertically bedded conglomeratic quartz porphyries of the Mt. Read Anticline against the west dipping Owen Conglomerate of the Tyndall Anticline. Although the fault line has been excavated and refilled with peat and moraine and the fault is not seen it can best be interpreted in the regional structure as a vertical or slightly thrust fault similar to that which occurs in depth on the Crotty Monocline. The quartz porphyries must, then, represent the monoclinal limb and the quartzites the eastern limb of a sharp asymmetric syncline; this is the "Tyndall Syncline", and the Tyndall Fault is the break along its axial plane.

The downthrowing and tilting effects caused by the north-east faults have already been described in relation to the Tyndall Anticline and these faults must now be considered in relation to the Tyndall Fault. At Lake Julia there are several of these faults, but they may be treated here as one and their effects attributed to the largest of the group. This fault follows Newton Creek, crosses the Tyndall Range and passes on to the Sticht Range. Because the line of the fault has been broadly eroded by ice or weather the fracture is never seen and it is not at first obvious, but the effects of the fault, which must have a throw of more than 1,000 ft., are very conspicuous in the broader view. In the dry lake flat in the core of the Tyndall Anticline, the beds in the south wall of the cirque are seen to be arched and some 300 ft. of the sub-greywacke beds are exposed below the Owen Conglomerate. On the northern side of the cirque the base of the Owen Conglomerate is not seen, and the formation has a general southward dip, so that there must be a fault running across the lake flat, and it must downthrow to the north for at least 300 ft.

On Newton Creek the field evidence for the fault is quite clear, for the line of the creek is a line of abruptly changing formations; on the north side the Owen Conglomerate and the underlying greywackes of the Julia Hills have a general dip to the south-west and they are folded on axes striking north-west, but on the south side the stratigraphically lower quartz porphyries are vertical and strike north and south.

The effect of the north-east fault on the Tyndall Fault is perplexing, for all of the obvious signs of that major fault disappear. It may pass along the eastern side of the Julia Hills, it may continue northwards past Lake Julia or may continue as an apparently small fault which passes to the north-north-east. This last fault, which is favoured as the continuation of the Tyndall Fault, creates a monoclinal effect in the conglomerates—it downthrows to the east and it dies out rapidly to the north. In accepting this fault as the continuation of the Tyndall Fault one must accept that the latter has the same monoclinal character and is an almost vertical upthrust. If this is so, then the Julia Hills are made of the conglomeratic western or upper side of the monoclinal fold and they owe their existence to the downthrow of the north-east fault on Newton Creek. The Tyndall Syncline is thus a purely superficial effect due to the upthrust and when the fault dies out northwards the syncline must also die out. The Tyndall Fault is now revealed as cutting at a very low angle across the Tyndall Anticline and as being somewhat similar to the Lyell Shear at Lyell.

To the south of the Tyndall Range the course of the Tyndall Fault is uncertain, but if it is to continue in line with its known extent it must cross the track to the Lake Margaret Dam. That it does so is shown by the vertical Owen Conglomerate in the last half mile of the track, but the further southward course of the fault can only be extrapolated. It appears that the north-east fault at Lake Margaret has downthrown the monoclinal structure to the south so that its western and upper limb is again preserved as at the Julia Hills, but this time as the west end of Mt. Sedgwick.

The interpretation which may now be given to the Tyndall Fault is that it has the same origin as the Lyell Shear; it represents a major line of upthrusting of the Porphyroid Anticlinorium and the Tyndall Range consists of deposits of the adjacent trough. The Cambrian fault died out northwards and the Trough must also have shallowed towards Mt. Murchison. At the same time an echelonned fault, the Dora Shear, took up the throw of the Tyndall Fault and became progressively greater towards the north so that a new deep basin was formed on the site of Mt. Farrell.

The southward termination of the Tyndall Fault is as mysterious as the northward continuation of the Lyell Shear, and it is thought that the two may originally have been one. If it is assumed that the Comstock

Syncline, whose trough is never exposed, is an east-west tear fault, then the simple correlation might be made that the two faults represent the rejuvenated upthrust of the Porphyroid Anticlinorium. There is a possible difference between the two, for it seems that the transcurrent movement on the Lyell Shear was not transmitted to the Tyndall Fault, nor was there any great mineralisation along the fault.

The Dora Syncline.

The Dora Syncline must once have been as open and simple as the Tyndall Anticline, but it has been so distorted by late folding and faulting that it is now very obscure. The syncline is most clearly seen to the south of Lake Dora where a ring of inward dipping Owen Conglomerate outlines the core of the fold. The softer Junee strata which formed this core have been removed by a south flowing glacier and have been replaced by tills, but the structure is quite clear. This closed basin owes its existence to the northward tilting which is effective south of the Lake Margaret Fault, and to the monoclinal uplift of the Dora Shear which cuts north—south across the syncline and closes it on its western side. For the moment the Dora Shear may be regarded as a monocline with effects intermediate between those of the Lyell Shear and the Crotty Monocline, or as a zone of mineralised shears, faults and monoclines which downthrow to the east. It is in the contorted central portion of the Dora Syncline that its synclinal structure is vaguest, but further to the north the fold once more becomes apparent in the Owen Conglomerate of Mt. Murchison where it was noted by Reid (1925). The fold is complicated by the small drag folds already discussed, but after allowing for these it appears to be a syncline with limbs dipping at about 45°.

The Murchison Anticline.

Like the Dora Syncline the Murchison Anticline is divided into two parts by the Dora Shear, a northern part of which lies between Mt. Murchison and Mt. Farrell, and a southern part of which occurs at Lake Dora. The fold is highly asymmetric and is thrust to the east on to the Farrell Anticline and the Precambrian massif. In the southern area the thrust plane, which is shown in figure 6B may be regarded as a south-west branch of the Dora Shear and as springing from the shear in the vicinity of Anthony Creek. The minor branch faults shown in the section are not wholly hypothetical, but at least one may be deduced from the map, figure 16C, and it appears to be mineralised with pyrite and copper.

At Lake Dora the anticline is formed of Dora Conglomerate which dips to the west; these dips show a progressive flattening from the west side of the lake, where they are 70°, to the eastern side of the lake, where they are only 20°. This evidence is sufficient to show that the beds in this locality form the western limb of an anticlinal structure and the steeper westerly dips still further to the east are consistent with the presence of an overturned limb there. Along the boundary between the Dora Conglomerate and the Precambrian quartzites of the Sticht Range occurs a narrow strip of pure quartzose conglomerates which are regarded by the writer as Owen Conglomerate and which dip west at an angle of 50°. These conglomerates lie unconformably on the underlying plicated quartz schists of the range, and as there is no Dora Conglomerate intervening it is concluded that the latter formation thinned and has been overstepped from west to east by the Owen Conglomerate. It is considered that there has been thrusting along the line of overstep and thinning, and that the thick pile of Dora Conglomerates of the Jukes Trough has been thrust on to the old land mass to the east (fig. 6B). Thus the Dora Conglomerate now lies against, and apparently overlies, Owen Conglomerate which rests immediately on the Precambrian. Passing south from the Sticht Range to the Lake Dora area the Owen Conglomerate, which can be traced as a bed overlying the Precambrian schist, has an increasing admixture of non-quartzose detritus and becomes thinner and of finer grade so that it is no longer quite typical of the formation. This is the situation to the east of the lake where a group of disconnected and alternating beds of quartzite and quartzose greywacke lie against the Precambrian quartz schists, and it is at this juncture that a narrow strip of limestone lies between the quartzose beds. The exact relations of the beds are not decipherable, but the limestone is interpreted here as being Gordon Limestone and it is considered as lying in the thrust syncline between the thrust and over-thrust masses (fig. 6B).

Towards the north the anticline is represented by a narrowing strip of schisted and mineralised Dora Conglomerate; at Walfords Peak and alongside Lake Rolleston the western limb and parts of the Owen Conglomerate capping of the anticline is preserved in the third order synclines of the fold. Further north, on Anthony Creek, the anticline is downfaulted to the north by the same Newton fault that is so important in the Tyndall Anticline. At that point the western limb of the fold is brought down so as to expose the Owen Conglomerate once more and the anticlinal strip of Dora beds (schist) is narrowed.

The inaccessible country east of Mt. Murchison was not examined except from a distance of two miles, but it appears to consist exclusively of bare white quartzite hills with none of the low rusty-coloured terrain of the Dora or pyritic schist formations; the structure given in plate I for that area is based on this broad information but is largely extrapolated from the structures to the north and south.

The Murchison Anticline (plate II) is next encountered in the area to the north-east of Mt. Murchison as a block of porphyries and Dundas Slate; the latter dips west at 70° and is apparently isoclinally folded for the outcrop traces the shape of the nose of a large fold. This must be an anticline, for upstream from the Suspension Bridge on the Murchison River there is an inverted sequence which rises to the east until the Owen Conglomerate is met in the gorge. There the structure is well exposed in the cliffs on the south side of the river and the inverted eastern limb of the Murchison Anticline is thrust at an agle of 80° on to the western limb of the Farrell Anticline; there is only a suggestion of a sharp syncline on the thrust between the folds. Downstream from the Suspension Bridge the sequence appears to be upright and the beds dip west at about 45° so that the anticlinal axis must lie just upriver from that point. The anticline presumably runs across the Tullah Flats, but the evidence for it is restricted to strikes and a few unreliable dips. The steeper limb is, however, clear and it can be traced along the length of Mt. Farrell and it appears that the west dipping beds on the west side of Mt. Farrell must all be uplifted and slightly overturned.

The Farrell Anticline.

This fold is well revealed in the cliffs on the north side of the Murchison Gorge, where its quartzite limbs dip east at 70° and west at 50°. The core of the anticline has been eroded by the Murchison River which has exposed a clean section of the contact zone between the granite and the conglomerate. The contact which, along with the anticlinal axis has been followed for three miles upstream, is seen to be concordant and the trend of the fold is observed to swing from a north 20° west to a north-west direction.

Mapping reveals that the axis of the fold traverses the length of the Murchison River and that it passes into the monocline of Mt. Farrell. This is reminiscent of the passage of the north-west folds of the King Syncline into the Crotty Monocline, but this is the only place where such a passage can be observed and mapped. The map, plate II, shows a number of form lines taken from aerial photographs, and as the beds are nearly vertical these can be regarded as strikes. As the Farrell Anticline plunges to the north the map thus presents an exaggeration of the vertical section across the fold, and it will be seen that the anticline passes into the monocline by the tightening up and diminution of its western limb.

The Sophia Syncline.

The Sophia Syncline is a sharp asymmetric downwarp of the same type as the King Syncline, having at Mt. Farrell the same asymmetry of character of its deposits, the same kind of vertical western limb and the same kind of history. Like the King Syncline it lies between the West Coast Range Anticlinorium and the Tyennan Block, and its Owen and Dora Conglomerates are thick to the west and thin to the east. The fold is for the greater part of its length a horizontal fold which extends for many miles to the north along the Mackintosh River, and is some two miles across at its Owen Conglomerate outcrops. In the Sophia Valley, however, the fold plunges north and as its floor of quartzites rises to the south the axis of the fold swings from a northerly to a north-westerly trend; the syncline then passes out into complex thrusts on the Tyennan Block in the same way as do the minor folds of the King Syncline.

At Mt. Farrell the Owen Conglomerate is of the normal coarse and thick facies encountered elsewhere and it is suggested that it was deposited in a contemporaneously subsiding fault angle depression. Towards the north there is a rapid facies change and the formation, which commonly forms mountains elsewhere, is just shown as a ridge on aerial photographs. There is little doubt that the Jukes Trough existed in the sense of a synclinal structure along the Mackintosh Valley during Tremadocian times and the probable reason for the non-deposition of the quartzites was that the ancient syncline was already filled with Dora Conglomerate and was not actively subsiding. It is likely that there was an adequate supply of quartzitic fill, for this material was supplied in vast amounts to the same structural basin. It is improbable that in the region to the north the geanticline was actively rising, for the Owen Conglomerate of the Sophia Syncline is uncontaminated by greywacke detritus. It seems probable that the ancestral Sophia Syncline, *i.e.*, the Jukes Trough, shallowed towards the north and any subsidence or uplift had ceased there before Tremadocian time.

Turning now to the south end of the Sophia Syncline, there is again a facies change towards thinner and finer Owen Conglomerate; this is best observed at the south-eastern extremity of Mt. Farrell, where the Formation consists largely of Tubicolar Sandstone which is 400 ft. thick and is interbedded with conglomerate only towards its base. The facies changes suggest that the Sophia Basin was to some extent separate from the rest of the Jukes Trough, perhaps as an isolated deep basin within the trough; this would be consistent with the idea that there was east side subsidence on a fault line beneath the present Farrell Monocline. It will be noted that there is no evidence that the Owen Conglomerate did not exist to the west of Mt. Farrell but it is likely that if the Formation existed in any thickness in that direction some traces of it would remain as synclinal remnants capping hills. These are not found and in the Huskisson Valley where the Gordon Limestone is next encountered to the west no conspicuous signs of the conglomerate can be detected on aerial photographs.

The King-Sophia Synclinorium.

Although they are disconnected the King and Sophia Synclines are continuous in a general sense, for they form the extremities of a much larger synclinorium; this is the King-Sophia Synclinorium which is like the West Coast Range Anticlinorium in that it consists of a series of second and third order folds. The ends of the synclinorium plunge to the north and south away from the centre which is arched along its length in a broad culmination centred near Mt. Murchison. The line of maximum uplift lies along the axis of the Farrell Anticline and this causes the break between the Sophia Syncline and the rest of the major structures.

As previously shown there is some evidence that this break was present in an incipient form during the Tremadocian and it seems probable that the larger second order folds were also in existence then. It is difficult to distinguish the lowest part of the synclinorium in the area of culmination, for the echelonned and thrust nature of the second order synclines means that the lowest part of the synclinorium steps from one depression to the next; in the north the deepest part lies in the Sophia Syncline, but in the south it probably lies along the Tyndall Fault. It is probable, but not certain, that the deepest parts of the Jukes Trough coincided with the structurally lowest parts of the Synclinorium.

The Dora Shear.

The Dora Shear is in many ways analogous to the Lyell Shear; it consists of a number of echelonned faults which run in a fairly straight line from Mt. Sedgwick past Lake Rolleston, along the eastern side of Mt. Murchison and into the monocline of Mt. Farrell. The orientation of this fault system in the wider fault pattern of the country has been indicated (plate I), and from this the system may reasonably be interpreted as transcurrent; because the faults are almost strike structures it is not possible to demonstrate any tear movements along their length, but there are commonly signs of intense shearing, and the shear pattern, round Lake Dora is so coarse and distinct that it can be easily observed in aerial photographs. The contortion of beds and the common occurrence of monoclinal structures along the line of the shear are readily attributable to overthrusting, but the intense mineralisation and feldspathisation along the length of the line are, in the writer's opinion, strongly suggestive of a transcurrent rather than of a simple thrust fault.

The one important difference between the Dora and Lyell Shears is that while the latter cuts the north-west folds at a high angle and does not branch along them, the former cuts the north 20° west folds at a low angle and tends to run into them. Thus, on Anthony Creek the thrust plane of the Murchison Anticline passes into and becomes indistinguishable from the shear. The shear is best displayed at this point, and on the south end of Mt. Farrell where it has already been described in broad outline, but there are several features of additional interest. The actual fault is difficult to place as there are many sub-parallel faults in a zone; these are easily distinguished for they are mineralised with pyrite and chalcopyrite and have attracted the attention of prospectors. From the Murchison Gorge southwards the line of the shear is almost continuously feldspathised and where the Owen Conglomerate is present there is intense haematisation. The latter is true at Little Farrell and for three miles south and again along Anthony Creek, and many small prospect trenches and adits have been made in both places. In the Dora area there is a widespread dissemination of chalcopyrite in chloritic schists, but this is not strictly localised on the fault line. It may, however, reflect the broadness of the shearing zone in that neighbourhood.

The southward continuation of the more prominent of the Dora group of shears requires mention; from Anthony Creek there are two branches of the shear, one, already discussed, passes to the south-east and the other and main branch passes due south. The latter probably continues under the moraine of Lake Rolleston and runs along the west side of the lake. It is seen to create a sharp synclinal effect in the Owen Conglomerate at the south-west corner of the lake and it continues south to create a vertical monocline (downthrowing east) south-east of Lake Huntley. Aerial photographs show the structure as continuing south again but breaking up into a number of south-east branches. The most southerly and largest of these branches was examined in the area east of Sedgwick Peak and it proves to be a fault which downthrows to the east and sets haematitised Owen Conglomerate against quartz porphyry.

The Mackintosh Shear.

The structure to the north and west of Mt. Farrell is complicated by the entrance of a new factor which cannot be discussed at length, and which forms a convenient limit for this study. On reference to figure 1 or, for preference, to Cary's (1953) figure 3 it will be seen that Mt. Farrell lies at a point where the West Coast Range Anticlinorium bends round the north-western corner of the Tyennan Block. At one stage the writer was under the impression that the minor structures of the anticlinorium also followed gradually round the bend, but it is not so and the structures proceed in a series of jerks. It has been seen that the movement and mineralisation of the Lyell Shear passes from one echeloned fault to its neighbour and in the end passes to the Dora Shear. The Dora Shear also consists of branches, and so far these have all had much the same trend but now, at Mt. Farrell, the characters of the Dora Shear are transferred to a fault with a different trend. This is the Mackintosh Shear which runs from the sterling Valley Mine for about ten miles in a north 10° east direction. The fault clearly upthrusts the strata on its western side and this motion is responsible for the cutting out of the Owen Conglomerate at the north end of Mt. Farrell. It is obvious that it requires a strike, or near strike, fault to cut out that vertically disposed formation there and this can only happen by the thrusting of the Porphyroid rocks against the much younger strata. As there are no exposures in the alluvium on the east side of the fault it is deduced that the Owen Conglomerate is missing and that the beds there are the Gordon Limestone or even younger Formations.

The convergence of strikes which occurs along the Mackintosh Fault to the north of Mt. Farrell is also found along the southward continuation of the fault on the west side of Mt. Farrell, and at the same time the line is marked by a series of ore bodies. Hall *et al.* (1953, p. 1157) have claimed that the convergence is due to an unconformity which has also controlled faulting and mineralisation, but this does not seem probable to the writer. The continuation of the Mackintosh Fault south of the Sterling Valley Mine is in some doubt and it may continue into the line of the Dora Syncline on Mt. Murchison or continue along the eastern side of that mountain to join up with a known fault with a similar trend at the Gooseneck. The first of these alternatives is preferred and the map is drawn accordingly, but both may be true as shown by dashes on plate I.

Now it can be seen that the Murchison Anticline disappears into the Mackintosh Shear just as the Farrell Anticline disappears into monoclinal limb of the Murchison Anticline, and that the throw of the Mackintosh Shear is compounded of the throws of the two previous folds. Along the Mackintosh River the uplift on the west is considerable and the Owen Conglomerate is not again encountered on the west side of the fault for many miles, and then it is very thin. Instead, and according to Ward (1908), porphyroid, quartz porphyry and granite are encountered along with much the same mineralisation phenomena which are met on the Murchison River.

In the area to the north of Mt. Murchison there is not only the swing of the northerly shears to be considered but also the possible swing of the north-east faults. In this area there is a marked absence of north-east faults but there is a development of west-north-west faults which have much of the characters of north-east faults elsewhere. These are prominent in the lower Murchison Gorge and on Mt. Farrell, and that at the former locality is marked by ore deposition at the Murchison Mine. At the other localities the writer's mapping is inadequate to show definitely that the faults affect ore deposition at the Mt. Farrell Mines, but there are marked indications in the haematitisation along the faults on the mountain that they may do so.

There is some hesitation in calling these faults simple tension faults for they may be faults with a sinistral movement similar to that which occurs on the North Lyell Fault. In this connection it is possible that there is a weak development of the Linda Disturbance type of structure across the northern end of Mt. Murchison through Rosebery and along the Pieman River. This " Pieman Disturbance " finds support in the map of Carey (1953, p. 1123) which shows that the Pieman River follows a line of east-west trending flexures which have resulted in two instances from the deflection of northerly folds, the Huskisson Syncline and perhaps the Zeehan Basin.

Despite all this the west-north-west faults will be provisionally regarded as tensional and as equivalent to the north-east faults in the Queenstown area. Whether this interpretation applies to the north-east faults crossing the Sophia Syncline is yet another matter and this cannot be decided without further regional information.

The Red Hills Shear.

This is, in reality, not one but a widely spaced group of faults which can be most readily spoken of by reference to the largest member, which is the fault that runs north-north-west from Lake Dora to the Red Hills and beyond. This fault has a north-east downthrow which at the most is of the order of 500 ft. and creates a monocline of this size at its southern end. Near the Red Hills the fault has no downthrow but it is marked by a zone of intense brecciation and resilicification of the Owen Conglomerate and by sporadic pyritisation of the adjacent schists. Some movement on the fault clearly post-dates the first silicification of the Owen Conglomerate and this post-dates the Dora Shear. (The Dora Shear is dated by analogy with the Lyell Shear as pre-silicification.) This dating merely indicates that there was some late movement on the fault and does not exclude the possibility of earlier movement. The late movement does, however, relate the shear to the other late shears and faults of the region and it may be structurally significant. On examination of the structural map of the area the fault is seen to be unrelated to the north 20° west folds, for it is oblique to them and it may well be a branch fault of the Dora Shear. It is analogous to the branch faults of the Livermore area, and like them it may have had a very small dextral tear movement.

The shear may be important in the mineralisation of the area, for although it is not immediately responsible for the Red Hills low grade ore body it is directly associated with the shearing and alteration of the porphyries subjacent to the ore. The line of shearing and chloritisation can be identified at several points along the power line toward Rosebery, where the orientation of the ore body is consistent with the shear being continuous up to that point. This alignment is probably quite fortuitous and it can, at the best, have only a tentative significance in such a highly faulted country.

Structures of the Dundas Orogeny.

Within the area studied there is no direct evidence of the angular relations of the Dundas and Junee strata; what is probably more reliable information than an actual exposure of an unconformable contact is the broad discordance of the two formations as seen in a regional mapping. The east-west cross section (fig. 7) through Mt. Huxley is the best section for showing this relationship, for there the detail of the normally confusing minor structure is well known and can be allowed for. When this is done there is little doubt that the Junee Group lies on the Dundas strata with a discordance of 35° or more.

A second line of evidence is that the Dundas strata rarely present more than one limb, the western, of an anticline. Had the Miners Slate, which is extremely resistant to erosion and metamorphism, been conformable below the Owen Conglomerate and had it not already been indurated it would have been folded with the Owen Conglomerate and should be traceable across the anticlinorium. Of course, the cutting out of the eastern limb of the Porphyroid Anticlinorium may well be attributed to the Devonian upthrusting, but this pre-supposes that the Dundas strata were indurated at that time, and had been folded previously.

The asymmetry of structure which is found in the older rocks is similar to, but more exaggerated than, that of the younger strata, and both are consistent with there having been a vertical upthrusting on the east side of the anticlinoria. In the rocks themselves there are no differences of minor features such as shearing patterns which would indicate that there had been a different direction of compression in Cambrian and Devonian times, and the fact that the Dundas and Junee strata usually dip steeply in the same direction means that the mapping of outcrops can rarely lead to the detection of unconformity.

The real strength of the case for a Tyennan orogeny in this area lies in the palaeogeographic reconstruction which can be made with this orogeny as its basis; the inclusion in the palaeogeographic history of the concept of evolving folds increases the complexity of the reconstruction but makes its critical examination much easier.

Palaeogeography and Evolution of Structure.

The traditional procedure in palaeogeographic reconstruction is to rely on analogies with present day geomorphic expression, but when the reconstruction is of a dynamically altering scene this is obviously difficult. The nearest approach to seeing processes of folding in operation can perhaps be made in the active orogenic belt of New Zealand, where the writer has not only examined late Tertiary and Pleistocene structures of the same type as the Dundas Anticlinorium, but has had the advantage of the experience in this field of Professor C. A. Cotton and other New Zealand geologists. The present-day faulting in New Zealand is well known, but as the extreme recency of pronounced folding and tilting is only now being appreciated even by local workers, some enlargement is made on this point.

The southern shore of the North Island of New Zealand is made up of three peninsulas with intervening bays; reading from west to east the peninsulas correspond to three greywacke anticlinal uplifts, blocks, or masses, of the Wellington District, the Rimatuka Range and the Haurangi Mountains, and the bays are respectively parts of the Hutt and Wairarapa synclinal depressions. The uplifted units have the appearance of asymmetric anticlines with the east limb faulted out and accordingly they appear to be thrust to the east. The fault lines of the Wellington and Rimatuka uplifts are marked at the surface by the scarps of faults which geomorphological studies show to be dextrally transcurrent (Cotton, 1951), and there are many smaller north-west branch faults which are interpreted by the writer as diverging from the main faults into the uplifted blocks. These branch, splinter, or splay faults are the direct analogues of the north-west folds of the West Coast Range Anticlinorium; related splinter faults of the synclinal depressions are naturally obscured by recent deposits, but in the Wairarapa depression some of them are still apparent.

The recency of the uplift of the anticlines is shown by the facts that on the eastern side of the Wairarapa depression the Nukumaruan (possibly Pleistocene) marine limestones and clays dip west at 30° on a wide scale and that, at the Manawatu Gorge on the Wellington uplift similar Pleistocene strata occur to the west and east of the fold and dip at angles of 30° and 80° respectively. In the writer's opinion the late Pleistocene and Recent folding of these strata is similar to, and only slightly less severe than, that of the Owen Conglomerate.

The pre-Cretaceous histories of the greywacke anticlines of New Zealand are generally similar to the earlier history of the Dundas Ridge, and that of the Dun Mountain (Marlborough) Block is comparable in many details. It has the same greywacke strata and slates of a flysch facies, the same lavas, breccias and coarse pyroxenites, and along its boundary thrust at Pepins Island there is an intense feldspathisation and epidotisation which results in syenites very similar to those occurring on the Dora Shear on the Murchison River; the scanty copper mineralisation which is common in the district presents yet another analogy. The Dun Mountain structure, although already ancient, is now only at the stage of the Porphyroid Anticlinorium, and the Pleistocene greywacke conglomerates of the Moutere depression at Nelson are in every detail of context and texture identical with the Dora Conglomerate.

To call the raised blocks of New Zealand asymmetric anticlines is, perhaps, misleading for the most striking feature is not the attenuation but the complete absence of eastern anticlinal limbs. In addition, the western limb is often only gently flexed and the name of "tilted fault block" is quite apt for these structures; the name "fault angle depression" as applied to the lower or synform angle between the vertical ? faults and the surface of the blocks is also apt, but for the corresponding upper or antiform angle which is worn away a name has yet to be invented. The fault blocks are easily visualised as 10-20 miles wide slivers of country divided by major transcurrent faults and continually tilting across their length and in one direction from age to age. Such an image is readily construed when the block is tilted by about 5°, but when the tilting is 30° in one phase of uplift, as in the Wairarapa, and it is clear that there have been several such uplifts in the Tertiary, or when late Tertiary beds of the synclines are vertical, as sometimes happens, it is very difficult to imagine the tilting as the result of rotation alone. The combined effects of the larger faults and small faults parallel to them, along with the tilting of blocks, results in the kind of isoclinal structure of the Porphyroid Anticlinorium. It must not be imagined that the fault planes have been rotating in this process of tilting, for they are probably nearly vertical, and it cannot be supposed that the beds in the core of the " fold " have been compressed into a smaller bulk. The only possible answer to the problem of tilting is that the core rocks, although of hard greywacke and although shallow-seated, have been squeezed out of their position and it seems that they must have been squeezed upward along the faults in the same way as a piercement sheet of serpentine may have been. Apart from New Zealand there are distinct parallels between the fault angle foldings of the Basin Ranges of the Cordilleran region of North America, the Tertiary folding of California and Colorado, and the Tasmanian structures. Hills (1914, p. 46) first drew attention to the similarity of the sedimentation in the Western American environments and those of the Cambrian of Western Tasmania. The Basin Range structures are discussed by Eardley (1951) who gives an account of the observations which have been made on them, and of the theories which have been put forward to explain them. There is, it seems, much evidence that the faulting is " normal " and that tilting is not due to overthrusting, and Eardley (p. 479) attributes to Nolan the idea that the tilting of blocks is impossible unless accompanied either by widespread shearing or plastic flow at relatively slight depths. Nolan's reasoning appears to be much the same as the writer's, for he considers that the faults of fault angle structures were not normal in the tensional sense but were formed during compression.

In Colorado a structure analogous to that of the West Coast Range is extremely well displayed by the Front Range (Lovering and Goddard, 1947, p. 3). This is shown by figure 14 and by the writing of the authors, who described the eastern margin of the range, which has a north-south trend, as " the locus of many echelon north-westerly folds and persistent steep north-westerly faults. Its structure is dominantly that of a steep monoclinal fold . . . The period of overthrusting (*of north-west folds*) * was followed by north-easterly and east-north-easterly faulting on a large scale throughout the mineral belt during and after the intrusion of the porphyrites that dot it. Many of the mineral deposits are localised at the intersection of the easterly and north-easterly faults with the earlier persistent north-westerly faults where they cross the mineral belt ". There are some interesting differences between the Front and West Coast Range structures, which merely serve to emphasise their similarities. The former is greater than the latter but this is, in part, a matter of depth of erosion and the writer has examined only one side and one end of a structure which extends west for 20 miles to Carey's (1953, p. 1115) Rocky Cape Geanticline. The great low angled and sub-horizontal thrust sheets and klippe which lie to the west and south of the Front Range structures are nappe structures which this writer supposes have slid from the rising geanticline and have no correlatives

* Writer's insertion.

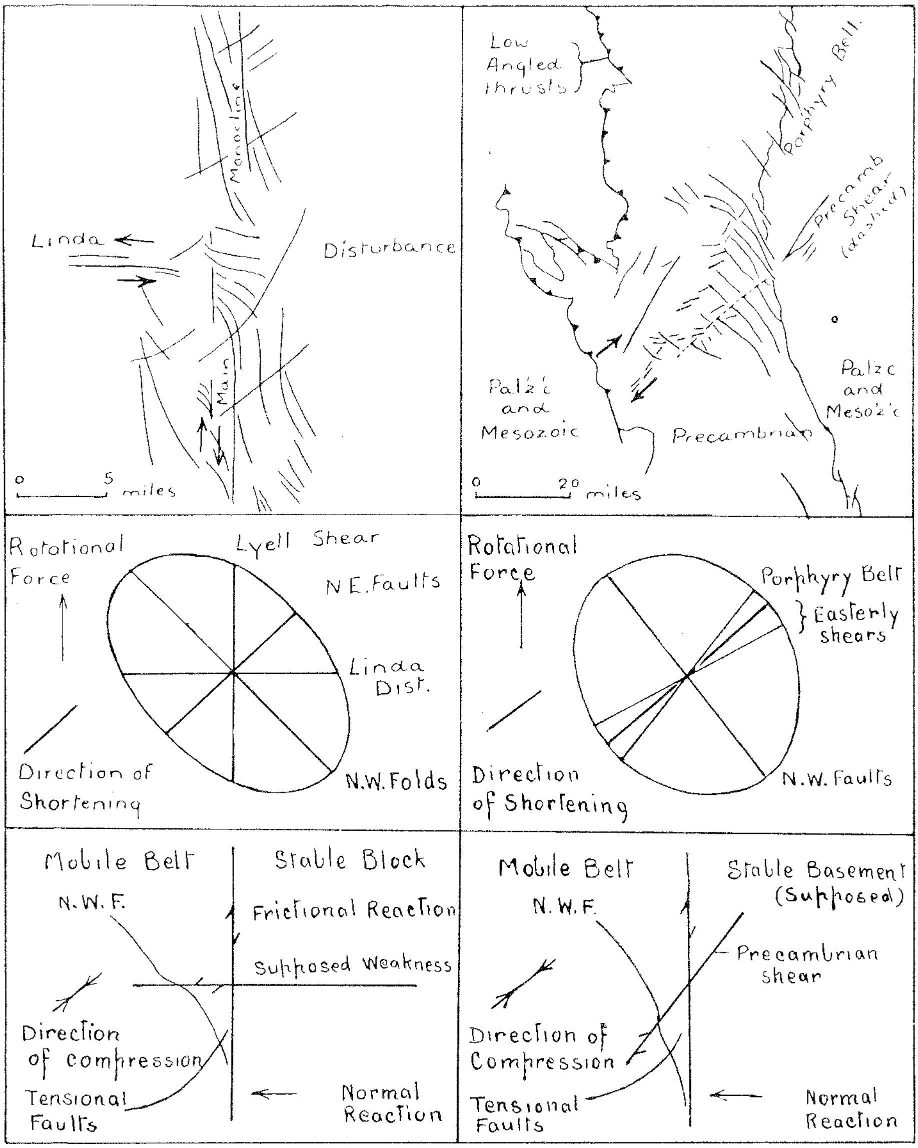

FIG. 14.—To compare the structural patterns and stress environments of (left) the West Coast Range and (right) the Front Range (after Lovering, 1950).

The middle row shows interpretations based on the assumptions that stress is inhomogeneous (rotational) and the crust homogeneous.

The lower diagrams show the compressive force as homogeneous and the crust as inhomogeneous. The compressive force is resolved by weakness in the crust into frictional reaction along the line of weakness and normal reaction perpendicular to that line.

in Tasmania. Figure 14 compares the fault patterns of the two ranges in terms of their stress environments and reveals that the "porphyry" or "mineral" belt of the Front Range is directly comparable in a structural sense with the Lyell-Dora shear system. Lovering and Goddard refer (loc. cit., p. 63) to the easterly faults having been formed in a zone of shearing and tension, and it is probable that the two sets of faults suggested by the diagram are grouped together by the authors. The lower diagrams of figure 14 show a different kind of analysis and that there are some grounds for supposing that the stress system was in part determined by weaknesses in the crust.

The comparison outlined above is valid not only in a spatial sense but also in a time sense, for the Front Range has been a positive element and anticlinorial axis from Cambrian to early Tertiary times. Similarly, the timing of the faulting and metasomatic phenomena are parallel to a degree.

In California the example of Mt. Diablo (Taff, 1935, p. 1098) shows that the idea of solid piercements of ordinary rocks is not new nor without good evidence. The piercing body in the Mt. Diablo region consisted of precisely the same kind of rock assemblage as has already been described for Dun Mountain and the Porphyroid Anticlinorium, and it lies in a similar context of fault angle structures.

In Taff's words "a mass of the Franciscan, subcircular in outline and approximately four miles in diameter, was forced upwards as a fault plug into or through the apex of the structure . . . the upward movement of the Franciscan plug may have been facilitated by erosion from the axial belt of the uplift.". Taff visualises the uplift as the result of a long process of vertical uplifting and tilting of a slice of country and shows (loc. cit., p. 1083) that this resulted in no less than eleven unconformities.

This kind of situation is very similar to that which, in the writer's opinion, exists in New Zealand today and existed in both of the Tasmanian anticlinoria. The main difference between the picture presented by Taff and that held by the writer is that the writer imagines the whole length (not a part) of the core of the anticlinorium as being a piercement structure.

Structural Synthesis.

Carey (1954) has described a rheid or laminar flow mechanism of formation of anticlinal structures at great depths in the more plastic zone of the crust. He supposes that under certain circumstances rocks may flow upwards in a laminar fashion somewhat similar to that of the flow of salt in salt plugs. In his case, however, the flow surfaces are not cylindrical as with salt plugs, but are planar, and the resultant deformation of strata is not domal but anticlinal. Allowing that this thesis is correct, Carey's anticlines are really vast piercement structures of metamorphic rock and they must have had some expression at shallower depths. Such anticlines may even have some showing at the surface of the earth in those regions where orogeny is occurring today.

Carey's type example of a rheid anticline is the Broken Hill Anticlinorium, a complex asymmetric fold (Gustafson, 1950) which bears many resemblances to the West Coast Range Anticlinorium and which may be likened to a vertically attenuated version of that structure. The folding in both regions is of the same order of size and has the same kind of obliquity of minor and major folds; there is a clear parallel between the Main Shear structure of Broken Hill and the Lyell and Dora Shears, and in each case there is the same kind of intense metasomatism and mineralisation. The only material differences of structure which the writer can see are wholly attributable to the deep-seated origin, plasticity, and more attenuated character of the folds at Broken Hill as compared with the West Coast Range, and it is a reasonable extrapolation to assume that the "Range" is underlain by the "Hill" type of structure. If this is accepted and Carey's thesis is adopted, as it will be here, the Porphyroid and West Coast Range Anticlinoria represent the shallow-seated expression of a piercement anticline.

Rheid flow of the more perfect kind exhibited by once deeply buried rocks cannot be expected among shallow-seated rocks with their thin cover and low retaining pressures, and if flow, comparable in any way with rheid flow, exists at shallow depths it must be expressed in the form of numerous shears and faults. The surface expression of piercements of solid rock might be expected to take the form of an exuded heap of structureless rubble, but that idea is presumptive that the process of exudation is rapid; if the piercing were as slow as erosion may be fast then a rock piercement might be no more prominent at the surface than are many salt plugs.

The nature of the shallow-seated "flow planes" can be better understood by reference to figure 7, which shows the passage from plastic rheid folds towards the surface. The deepest of the very highly deformed rocks passes up into a zone of highly plicated or foliated and isoclinally folded strata and that passes into a zone where flowage is along cleavage surfaces. The latter passes up into a near-surface zone where the units of movement are still larger and where small shears and many thrusts carry movement to the surface. In the natural course of events the uppermost zone would not be preserved, for it would commonly form an emergent anticlinal crest and a zone of mechanical weakness which would be rapidly eroded. Alternatively, the hard rocks, which occur in the crests of anticlines and which are capable of being brecciated, must sometimes be buried below some thousands of feet of soft sediments (this was the case in the West Coast Range Anticlinorium) and then the retaining pressures would be sufficient to preclude brecciation of the harder strata which would yield by cleaving.

In accounting for rheid phenomena Carey is not concerned with the ultimate cause of flow, and points out that flow need not be the result of compression; indeed, he demonstrates that some rheid type folds may form in the complete absence of compression. Without disagreeing with this as a general possibility the view adopted here is that upward flow is commonly the result of compression, and that a small part of the arching of very large folds or anticlinoria is the direct result of shortening of strata under horizontal compression; the remainder and biggest part of folding is indirectly due to compression which operates through a hydrostatic rheid mechanism. The mechanism by which this process might occur merits further discussion.

For the purpose of argument the sialic crust is considered as a more or less rigid layer ten miles thick lying on a heavier and more plastic substratum. In the same sense sialic rocks at a depth of about ten miles generally begin to become plastic, and at a depth of about twenty miles they have no long term strength. If the crust is considered to be folded into anticlines and synclines (no matter how) any small anticlinal loads will be borne by the rigid crust acting as a slab does in engineering practice, and they will be distributed through the isostatically balanced mass by the shearing strength of the rocks. There is patently a limit to the size of anticlinal load or synclinal relief of load which the crust can distribute in this manner, and let us assume that the largest fold that can be supported by the shearing strength of the sial is twenty miles in full wavelength. It would seem that no folds larger than this could exist unless the anticline and syncline were compensated at the base of the sial by a corresponding and respective thickening or thinning of the sial.

This may not be true, for large parts of the crust may be uncompensated by an appreciable, though unknown, amount in excess of the load which the crust can bear when acting as a slab; that is, providing the crust has the structure of an arch or of an anticline measured between two adjacent synclinal troughs (fig. 15). Then a portion, no matter how small, of the anticlinal load may be distributed by thrust on to the synclinal area, and as the syncline has a negative load it will support this thrust. In other words, the compensation of an outsize anticline, anticlinorium or geanticline may, in part, be made by a depression of the sial layer below the neighbouring syncline and not below the anticline.

Because of the strength and thickness of the sial it is probable that there is a lowest possible size for such folds and it is fairly obvious that there must be a maximum size also. That is because the limiting strengths of rocks put a term to the thrusts which arches can bear, and decide the size of folds. Much depends here upon how one regards the strength of the crust; if it is thought to be high then the size of a possible fold increases accordingly but if it is regarded as low then the largest fold can only be a trifle larger than the 20 miles suggested. One might expect variations of both limits depending on a number of unknown factors such as sub-surface temperature and thickness of the crust, but in the writer's opinion the probable limits lie near 15 and 50 miles, which are figures which seem to apply to many of the larger folded or tilted units of the active orogenic belts.

A second qualification of our hypothetical folds concerns the regional stress system in which the folds occur, for it is apparent that the continued existence of an anticline as an arch is dependent on the maintenance of

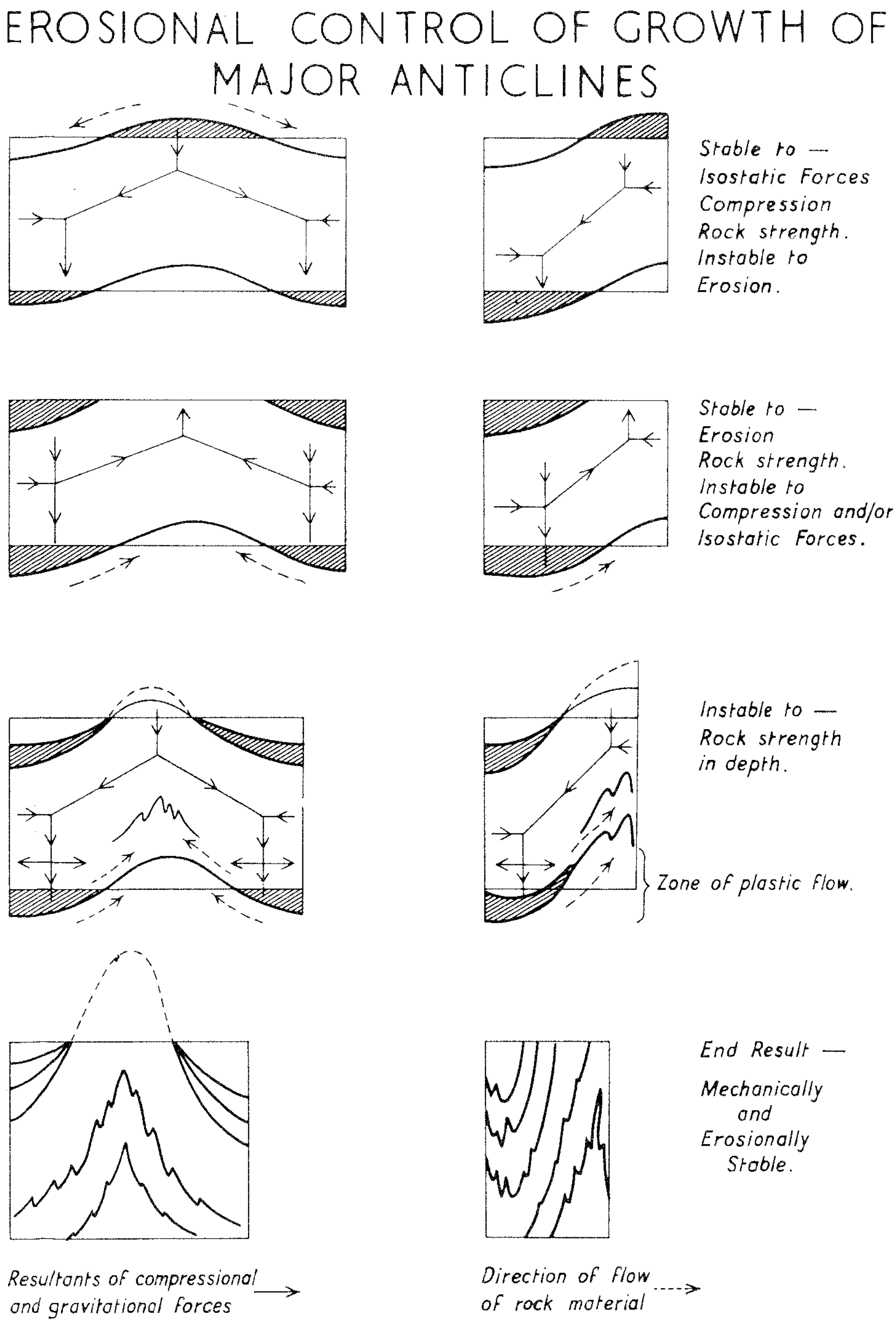

Fig. 15.—The horizontal lines towards the top and bottom of each small diagram represent the mean equilibrium position (of isostatic equilibrium) of the top and bottom of the rigid crust. The thicknesses are not precise but may be taken as 15 to 25 miles and it is assumed that this crust is floating. Shaded parts show the departure from equilibrium caused by arching of the crust.

its buttresses, i.e., of a state of compression. If, for example, it happened that the fold were to be tensed across its axis the anticlinal arch would subside, the syncline would rise, and each would return to its own independent isostatic equilibrium. This second qualification does not mean that the fold must be kept under a state of dynamic compression in order to exist, but it does mean that a static pressure must be maintained once an anticline is raised.

Finally, the arguments which have hitherto been applied to anticlines and synclines are taken to apply equally to fault angle structures. These are sufficiently akin to asymmetric anticlines for most workers to regard them as the same, so there should be no difficulty here, and it may be (it seems empirically probable) that the single limbed structure is more capable than the normal fold in spreading its load from crest to trough.

Now we can consider the history of one of these large faulted anticlines after its inception by compression. Our picture to start with is of an asymmetric fold of, say, 20 miles across and 100 miles long, and with an amplitude of 10,000 ft. and a mean altitude at sea-level; the surface profile is in equilibrium by the interaction of the inherent strength of the structure and isostatic balance. This situation is, of course, not a static one and is dependent on subaerial erosive processes, so that eventually the anticlinal crest must be destroyed and the synclinal trough will be filled. It is easy to see that the syncline will be loaded but it is not obvious that there will be an upward relief of pressure in the anticlinal core. This will be so because erosion will not have materially affected the capacity of the arch to bear load and the effect of erosion is simply to relieve pressure below the anticline. The result of the transference of load must be to cause a differential pressure in the plastic layer in depth, and to allow material to flow from below the syncline into the core of the anticline. If the juncture between the sial and sima is sharp the displaced material will be basic, or if it is gradational the material might be dioritic, but the result will be the same; the land surface over the anticline will rise and the surface over the syncline will fall to their original profiles. In the absence of dynamic compression this process might happen once or perhaps twice but it would cease as soon as the strain on the arch were relieved; i.e., as soon as the sedimentary loading on the syncline began to effect a material subsidence there. With a continued dynamic compression and continued erosion and flow the process would also be continuous and would result in an isoclinal fold or a vertically tilted fault block. It seems probable that in the final stages of tilting the synclinal root would become as plastic as the substratum into which it was depressed and it would tend to flow into the adjacent anticlinal high. Such a flowage would, in a sense, be complementary to the sedimentary loading of the synclinal area and would also tend to halt the process. It could not do so as long as compression was applied and the arch or tilt block had the strength and disposition which would allow an unequal distribution of load. In the final result a region subjected to this kind of folding would consist of large deep asymmetric synclines of lightly metamorphosed rock alternating with sharp anticlines of metamorphosed rocks. Assuming that the fault on which rotation occurred were to tap the solutions available from the heated rocks in the core of the fold it would follow that the attenuated limb would be a locus of metasomatic activity and mineralisation.

This folding process is essentially one which applies to rocks above or near sea level, and the theory as it is set out above cannot interpret the earlier folding of eugeosynclinal sediments. It does not set out to do so for so far as the West Coast Range and Porphyroid Anticlinoria are concerned neither were folded by the compression and crumpling of soft sediments but were both the result of lifting and tilting, and it is believed that both had a hard basement at no vast depth.

Looking at the process in its surface aspects, what seems to happen is that the tilted block rotates into a vertical position in much the same manner as has already been described for actual cases. On the uplift side there is an upward flow of material adjacent to the fault plane and the crest of the anticline is pushed up again and again. The limb is pushed further out into the syncline and as each cycle of erosion, deposition and uplift occurs, an angular unconformity forms parallel to the strike; as the latest deposits of each cycle are tilted the angles of several unconformities could theoretically add up over a dozen movements to the absurd figure of 180°. At the same time the young deposits of the trough are compressed between the closing fault angle and are squeezed upward and outward on to the low side of the depression. This could explain on the one hand the remarkable occurrence (Hutton, 1939) of a narrow strip of vertical Tertiary deposits caught in the schists of Otago, and show on the other hand (fig. 6B) how the Dora Conglomerate thrusts far over the limestone east of Lake Dora. It shows, too, why the beds along the Dora Shear are indeed sheared, for they lie close in to the fault angle. If it is allowed that the fault plane passes down for, say, 20 miles it is not surprising that the Dundas Geanticline should at one time have been the scene of basic vulcanism and ultrabasic intrusion, or the Dora Shear, Main Shear at Broken Hill and the Nelson Fault, N.Z., be the scene of metasomatic activity.

The process contrasts with the more widely known folding of the Hercynian Appalachians, for that folding occurred only after an ancient basement had been buried for a vast time under a great thickness of young sediments. The folding which eventuated in that instance was more or less plastic and gave rise to smooth fold forms, but in examples where the rigid crust has only a shallow or very young cover the tilt block structure results. This does not mean that thick sediments may not occur in the tilt block setting, but that they must be folded soon after their deposition or at short intervals during their deposition. The tilt block fold may thus be characteristic of orogenic belts subject to relatively continuous movement.

The distinction of the above two fold types was made long since by Gilbert who, according to Willis (1934), described the prevailing fault angle structures of Nevada as "Basin Range" structures, i.e., tilted blocks with vertical faults, and attributed their tilting to a force acting vertically from a source immediately beneath the displaced masses. The Geological Map of North America (Stose, 1946) shows the Basin Range fault blocks to have a mean width of the order of 20 miles, and been almost stripped from its crestal surface. If such anticlines have sustained histories it will always happen that the record of any temporary regional subsidence will be removed from the top of the fold and the record of piercement will be obliterated. On the other hand, one might expect that on proceeding across a tilted block he should encounter older and older strata: on the whole this is true, but it is even more probable that he will encounter more and more metamorphosed rocks and that instead of finding recognisable ancient cores he should, if erosion is deep, find granites. Our investigator need not expect to find a gradual metamorphic change, for, apart from strike faulting, it seems most probable that the major fault on which movement has occurred has also been a feeder for solutions which concentrated metamorphism along their length; this may have happened several times.

In view of the erosion of the structures at the crests of anticlines it is unlikely that one could guess at their form were it not for examples such as the West Coast Range where the ultimate stage of uplift was delayed and thick deposits were laid down. Where such formations have been preserved we may look at one phase of movement only and see what can happen to the rocks at the crests of folds. The West Coast Range Anticlinorium shows none of the longitudinal tensional faults which one might expect with a piercement structure, but rather it appears to be a highly compressed fold. If we think only in terms of an east-west cross section the problem is immediately settled, the fold must be the result of compression above and cannot be a piercement. With the additional factor of shearing (strike slip) movement on the north-west faults the opposite solution can be shown to be possible. The same kind of shearing force which caused the formation of the Lyell Shear also caused the north-west fault blocks to rotate in a clockwise direction so that they became more nearly parallel to the main north-south axis, and were stretched along their lengths; this resulted in the development of north-east tensional faults more or less normal to the length of the blocks. The rotation of the blocks out of an oblique line into one more nearly parallel to the main fold must have compressed them across their widths. Although this compression probably added to the already existing north-east thrust component of the north-west folds it does not necessarily mean that the anticlinorium grew in height or narrowed in width at this stage, for the N.-W.—S.E. stretching could conceivably have caused the diminution of the volume and altitude of the fold, and the general effect in the zone of shearing would be that the zone would retain its width.

At the level of the Owen Conglomerate, i.e., at about 5,000 ft. deep, there is no record of deformational stretching, and the tensional movement which is recorded was taken up entirely by the separation of beds. This separation, although very considerable, did not take the form of numerous tensional faults, as it might in weaker or deeper-seated rocks, but was resolved on the relatively few known north-east faults. The extension across these major faults was possibly of the order of 50 yards, but it could not be expressed as gaps of that width; instead, the blocks to either side of the north-east faults tilted to the north-west or south-east to present wider sections and to take up the "want" in those directions. The amount of tilting of these blocks is thus a direct measure of the amount of separation on faults and, as the mean dip of fault blocks is about 6°, the amount of separation which occurred in the length of the range must add up to about 700 yards.

It is to be observed that this opening on the north-east tensional faults does not necessarily represent all of the stretching which occurred, for it is highly probable that it represents only the stretching which occurred after the silicification of the Owen Conglomerate. Any stretching which was prior to that, and strictly contemporaneous with the Lyell Shear, must have been in unsilicified Owen Conglomerate and would be expressed as distortion, perhaps as monoclines, but not as faulting. This partly explains the lateness of the north-east faults in the Owen and overlying formations, but for the underlying formations it must be assumed that it was feldspathisation, &c., which rendered the rocks rigid. Allowing that the timing of these faults was partly controlled by metamorphism, the fact remains that the north-east faults and the Lyell Shear were the result of a phase of movement different from that which went before. Why this was so is not known, but it is just as probable that it was due to the changing strengths of rocks in depth as that it was due to changing directions of the causal force: it is impossible to disentangle the two.

Now that several structures and aspects of structures have been described, they can be assessed in terms of their relative importance. In the first instance is the question of the strength of the transcurrent component of the regional shearing couple. It is simple to postulate that the couple was applied in a north east-south west direction, but that does not say what was the north-south friction of the crust in a vertical plane (this sets a limit to the shearing couple) nor tell the amount of actual movement which occurred. There was, in fact, relatively little movement in the Tabberabberan orogeny; it cannot have amounted to more than a few hundred or very few thousand feet in a north-south direction. Again, the actual amount of shift tells us little about the shearing force. Relative to the strength of the rocks or the rapidity with which they healed after fracture, the force was slight and barely adequate to cause fracture. This probably accounts for some of the less usual features of the range and, in particular, for the pronounced obliquity of major and minor folds. The degree of obliquity is unusual, but is known elsewhere and is fully as great in a very similar context in the Front Range (Lovering and Goddard, 1950).

This brings us to the next assessment, of the relative importance of drag, tear and thrust movements on the north-west faults; drag in the conventional sense can be ignored, but the other two are difficult to assess. At Mt. Owen, thrusting is due to squeezing rather than over-riding and there may be some strike shift on the fault planes. The thrusts on Mt. Jukes are the surface expression of steep and deep shears and they probably have considerable dextral strike shift. They may, for convenience, be thought of as deep drag shears but are not restricted to a stratum or formation.

The Linda Disturbance is the obstacle which defeats almost any kind of attack; there are classic analogies to this kind of cross structure in the de Bavay Fault at Broken Hill (Gustafson, 1950, p. 1419) and the "porphyry belt" near Denver in the Front Range (Lovering and Goddard, 1950, p. 61). All three are tear structures with shifts of the order of some thousands of feet and are the scene of intense porphyritisation or intensified mineralisation, or perhaps of late phase leaching of porphyries (kaolinisation) and ores (impoverishment). The amount of drag of the north-west folds against the Disturbance is the best index of the shift, but it is much exaggerated by the north-south compression and can be discounted by about half, so that, taken in a general view with relation to other structures, the east shift on the south side is about one mile. The origin of the Disturbance is still obscure but it is certainly as old as any of the Devonian structures.

The best explanation which the writer can devise for the cessation of the Lyell Shear as it crosses the disturbance is as follows:—It is assumed that the geanticline was offset along the line of the Comstock Valley and that any renewed movement along the line of the shear was interrupted in depth by the unbroken mass of Mt. Sedgwick to the north. This tended to halt the shear but it probably did not do so completely, for a fault which may be due to movement on the shear continues on to Mt. Sedgwick. This accounts for a part of the movement and another part must have been resolved into the monoclinal uplift at Lyell, but even together these parts are still very small. The main part of the movement was probably transferred to the whole of the Sedgwick mass, which proceeded to move along the Dora Shear. In between the two shears there must have been a zone of relative north-south tension and this may be reflected in the east-west faults of Mt. Sedgwick, and maybe in the Lake Margaret Fault, but is not otherwise apparent.

If the Lyell Shear, which is not at all deflected in the zone of the Linda Disturbance, actually represents the basement structure, then the twisted folds of Mts. Owen and Lyell must be relatively superficial. As the latter are formed of deposits of the Jukes Trough this is a reasonable conclusion, but a distinction must be drawn between these folds and those which occur on Mt. Jukes and which lie over the shallow-seated bed-rock.

Conclusion.

To avoid confusion, the writer is at some pains to point out that the structures described are not the structures made familiar by text books. They are not the thrust and fold structures known in the Scottish Highlands, the nappes of the Alps nor the folds of the Younger Appalachians, nor are they typical of all of the structures of the mineralised areas of the Canadian, Australian and Baltic Shields. While all of those areas may have been considered at one time or another as typical of present day folded regions at different depths, that is not the writer's opinion. The fault angle type of folding seems to be characteristic of eugeosynclinal environments and to be typical of the Circum-Pacific belt where we can examine it today. It is possible that it is only representative of the later phases of the eugeosynclinal cycle and that an earlier phase of folding exists, but what that might be is not conjectured. It is considered that this specific type of folding has the following characteristic associations. Its earlier phases are marked by eugeosynclinal sedimentation (greywacke flysch) and basic and ultrabasic intrusion. Its later phases are marked by transcurrent faulting and long continued orogeny with repeated wearing down and rejuvenation. Economically, such mountain belts are metalliferous provinces, and petrologically they may be described as the provinces of porphyries, and pneumatolytic injection. Thus, among older mountain belts of Europe they are typified by the Hercynides rather than by the Caledonides or Alps proper. Neither the rules of tectonics nor of metamorphism of the Alps, Highlands or Appalachians can be simply applied to these belts.

What may be the most important contribution here is not the account of the structure of the West Coast Range Anticlinorium, but the extrapolated structure of the Porphyroid Anticlinorium. This extrapolation is one of structure in time and is comparable to the extrapolation of a section or map into a third dimension. The latter activity can result in satisfying results even where there is only a plan, and is much helped by a few spot heights or dip arrows. The field of this extrapolation has much more than that. Working on the theory that the Devonian and Tyennan orogenies followed the same lines, the structures of the post-Tyennan sediments must represent a subdued version of the present structure of a given horizon in the Cambrian sediments. Accordingly, if the vertical scale of the present structure of figure 5 is exaggerated by, say, two and one half times we should get a picture of the shape of the Cambrian strata. The section showing this (fig. 7) may cause some surprise, particularly when it is advocated as of general application to large parts of the world, but it is claimed that there is as yet no acceptable substitute to this view to explain large scale isoclinal folding in terms of the whole thickness of the crust.

PALAEOGEOGRAPHY.

From late Proterozoic to Upper Cambrian time there existed to the west of the Tyennan Block the Dundas Trough or Geosyncline into which many thousands of feet of typical redeposited greywacke sediments were poured. The source of the greywacke detritus may have been distant, but it is possible that some of it was derived from the non-metamorphosed cover of the Tyennan Block, and it may be that some was derived from an island chain to the west. As is common with the deposition of greywackes, there was intermittent spilitic vulcanism and there was at least one phase in the late Cambrian of intrusion of irregular but sill-like pyroxenites. The story of the greywackes, which are monotonous and without good marker beds, cannot be traced in detail, but the very presence of graded beds indicates some earth movement of the country from which the sediments were derived and the vulcanism can be reasonably supposed to have been associated with movement in the geosyncline.

The first folding of the greywackes into a geanticline may have occurred as far back as in the lower Cambrian, but the first definite dating comes from fossil evidence from Dundas (Elliston, 1954) that greywacke deposits there are of upper Mid-Cambrian age and that they were folded in a pre-Tremadocian orogeny. This folding resulted in the emergence of the Dundas Geanticline to form the Dundas Ridge which was at first only a chain of basaltic and trachytic volcanoes, but which gradually grew to form an echelonned chain of hills. The rise of the geanticline was continuous though punctuated by faulting along its eastern side and it was sufficiently fast to maintain the ridge in a youthful geomorphic condition. The coarse detritus derived from the ridge during this phase of uplift was fed into the Zeehan Basin to the west and into the Jukes Trough to the east, and it is probable that periodic faulting and uplift of the geanticline gave rise to many breccias such as those of the Lynch Conglomerates. As the cycle drew to its close it is probable that the low island chain was overstepped at several places like Mt. Sedgwick, but it is probable that further north the ridge was not covered until it was overlapped by the Gordon Limestone.

The existence of the Dundas Ridge was not ended by a cessation of movement of the geanticline but by a regional warping which caused a subsidence of the geosynclinal region, and an emergence of the Tyennan Block. Under these conditions the ridge remained more or less static at or about sea level and the troughs on either side were deepened to receive the quartzose detritus from the Tyennan Block.

The coarseness and sudden appearance of the breccias at the base of the Owen Conglomerate must mean that the regional warping was accompanied by faulting. As the breccias are in part of greywacke origin it is probable that there were still low fault scarps in the Dundas Ridge, but the absence of any great quantity of greywacke means that there was no mountainous country there. In the Queenstown district the supply of detritus was adequate to keep the subsiding Jukes Trough filled to sea level, but it was not so to the south of Darwin Peak where deeper water existed and limestones were laid down. North of Mt. Murchison conditions were different again and it seems probable that there was neither uplift of the geanticline nor subsidence of the Jukes Trough during the deposition of the Owen Conglomerate, and the country there must have been senile and incapable of supplying coarse detritus to the adjacent basins. The end of the Owen cycle of sedimentation was marked by the cessation of relative movement of the geanticline and trough and by a regional subsidence and a marine transgression which allowed the deposition of the Tubicolar Sandstone across the entire region.

Unfortunately, contemporary movement of the geanticline is usually unrecognisable in the Owen Conglomerate but there is clear evidence of some movement during the deposition of the Tubicolar Sandstone, and it is possible that there were small movements during the deposition of the limestone and later deposits. The transgression of the limestone seas was cyclic in that it resulted in the deposition of several calcareous bands in the Tubicolar Sandstone and in a rhythmic banding of the lower part of the limestone, but otherwise stable conditions appear to have prevailed until the deep sea regressed towards the south in the lower

Silurian. Then the region was once more raised to near sea level and the Crotty Sandstone was deposited under conditions very similar to those prevailing during the deposition of the Tubicolar Sandstone. It is possible that the Crotty Sandstone passes out to the south as does the Tubicolar Sandstone, and that the limestone seas to the south of Mt. Darwin were in existence long after the seas to the north had shallowed. It is difficult to guess at the origin of the material of the Crotty Quartzites but the small unconformity at the base of the formation in the Zeehan district suggests two possible sources. It is possible that the regional uplift caused contemporaneous erosion of the limestone over the Tyennan Block and that the Crotty Sandstone consists of reworked Tubicolar Sandstone and new basement detritus, and it is also possible that there was some uplift of the geanticline and again reworking of the earlier deposits. A third possibility is that somewhere to the east of the Range the limestone thins out altogether, so that the Crotty and Tubicolar quartzites are in juxtaposition. It is possible that all of these conditions prevailed, but there was certainly no great movement of any kind during this period.

The lithology and ecology of the Eldon sediments indicates the kind of movement and conditions which must have prevailed during Siluro-Devonian times; these were gentle oscillations of sea level and alternating deposition of silts, muds and calcareous sandstones. The detail of the Eldon environment and the timing of the Devonian fold movements are a matter for the palaeontologist, but the general story seems to be a simple one of shelf sea sedimentation at no vast distance from a low-lying land.

STRUCTURAL RELATIONS OF ORE BODIES.

Accounts of individual ore bodies of the region have already been given by Ward (1908), Hills (1914), Nye, Blake, Henderson (1934) and Conolly (1947), and the writer is not in a position to add to these. This account does not seek to describe ore bodies nor to evaluate them, but rather to relate them to each other and to their broad structural environment. As ores are only special rock types it is convenient to describe certain rocks in the same relation at the same time. Apart from a few suggestions, the detailed description of rocks and ores and an account of their origins will be delayed to Part 3.

The distribution of some selected but representative and significant prospects in the West Coast Range is shown by the figures on Plate I and a catalogue of these (largely drawn from the authors quoted) reads from north to south as follows:—

1. *Mackintosh Copper* (Ward, 1908, p. 86). This deposit lies off the map but is included for completeness. It lies 5 miles north of Tullah. The deposit of copper and lead sulphides occurs in north-south shears and consists of diffuse veins in partly silicified chloritic schist and slate and has been worked to a limited extent.
2. *The Mt. Farrell Mining Company* (Ward, 1908, p. 73). These extensive deposits of silver lead are continuous with the last through a series of minor deposits. They occupy a number of sheared veins at the juncture of chloritised greywacke (Dora Conglomerate) and slates.

3. *The Murchison River Silver and Lead Company* (Ward, 1908, p. 79). In the general zone of the Mackintosh Shear this deposit is continuous with the last, but it strikes rather more east of north, 25° east instead of 10° east. The deposit of galena, blende and pyrite, which was worked for some time, occurs in feldspathised Dora Conglomerate, and as the replacement of these beds is preferential it gives the impression of irregular sills of syenite as noted by Ward (loc. cit.). The syenite is not at all sericitised but is fresh and translucent like many trachytes. The mine is situated at the intersection of a tensional fault with the main shear zone (plate II); the fault, which is of great throw, is marked by the line of the Lower Murchison Gorge, and is typical of the north-east tensional faults further south. The map shows that it has a broad monoclinal effect which influences the Farrell folds. As the zone downthrows to the north the Sophia Syncline consequently widens and the Farrell Anticline narrows, and it also happens that the blocks of country to the north and south of the fault are differentially tilted.
4. *Miscellaneous.* Continuing south from the last is a system of north-west trending veins of galena which lie in Dora Conglomerate and Farrell Slate around the boundary of the porphyritised and granitised mass of the Murchison River. This system, which is still on the Mackintosh Shear, terminates in the Sterling Valley Mine (Ward, p. 197). The line is one of intense silicification of the slates and chloritic schists and this results in a quartz blow sometimes a chain or more wide. None of the mineral deposits have proved to be more than prospects.
5. *Murchison River Copper and Iron Prospects.* Along the Murchison River and around the granite there are a number of poor prospects which are contact veins of pyrite and chalcopyrite and massive replacements of haematite. On the contact small baryte stringers run into the haematitised rock and a two foot vein of baryte is recorded by Ward as running north 20° west; this occurs in quartz porphyries.
6. *Miscellaneous.* Small galena shows occur in the limestone of the Sophia Valley, at the bridge in the centre of the valley, and near the contact between the granite and Owen Conglomerate along the eastern side of the valley. Particular prospects occur in the limestone at White Hawk Creek just to the north of the map and on the Sophia River.

It is to be observed that the district north of Mt. Murchison is characterised by galena with some zinc and a little copper and by granite rather than quartz porphyries. There is a very clear relation between the incoming of the quartz porphyries and granite of the Murchison River and the incoming of copper and haematite there and this arrangement shows an excellent example of zoning. In general, the lead ores are richest along the line of the Mackintosh Shear but are not confined to it, and they are usually associated with relatively unsericitised feldspar porphyries. So far as the character of the veins is concerned there does not seem to be any great preference for ore deposition on easterly tension faults, and most veins are on northerly shears. To the south of the Farrell Mining Field the situation changes completely and the feldspar porphyries are usually highly sericitised or give way to quartz porphyries. The ores are, with few exceptions, of copper, pyrite is abundant, and it is to be observed that granite is never the contact rock of disseminated copper ores.

7. *The Red Hills Prospect.* Figure 16A shows the mode of occurrence at this deposit which is clearly stratiform and in the field is a massive chlorite rock. It is almost certainly a chlorite pyrite replacement of an argillaceous rock but so uniform is it that no trace of its origin remains. Its relation to the overlying and underlying sericitised nodular feldspar porphyries was described in Part I and seeds no amplification. The ore, according to Blake (1939) contains less than 0·5 per cent Cu, and apart from that is of too scanty an amount to warrant low grade working. The usual copper mineral is chalcopyrite and the only other is bornite which occurs in small quartz veins some distance away from the main body alongside the Red Hills Shear.

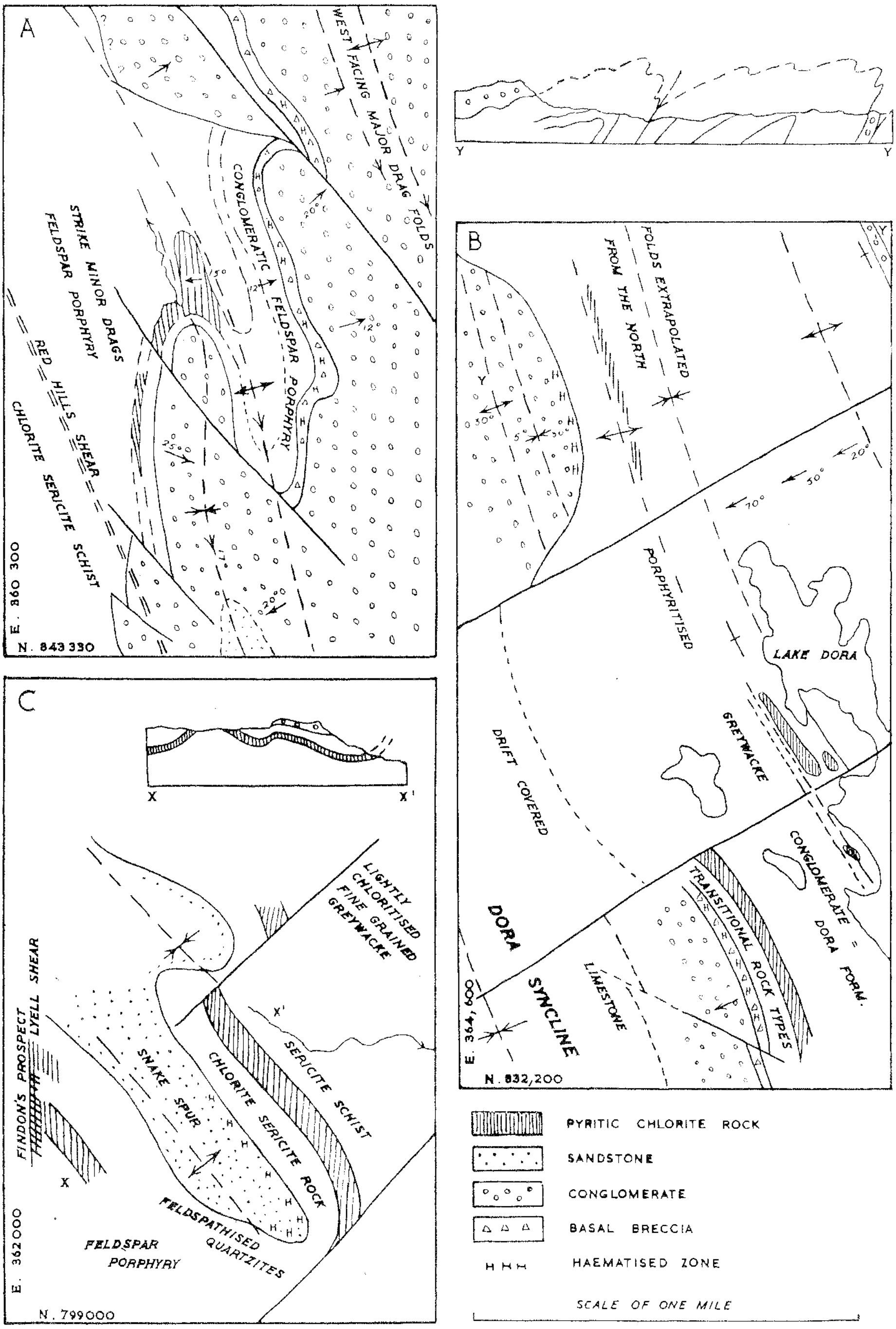

FIG. 16.—To show the disposition of concordant low grade ore deposits at (*a*) Red Hills; (*b*) Darwin; (*c*) Lake Dora. The grids are for reference to Plate I and are approximate.

8. *Miscellaneous.* These prospects occur in sericite chlorite schists running along the Dora Shear and none are large enough to have justified more than trenching or the driving of small adits. The zone is long and continuous and consists of a weak dissemination of pyrite and chalcopyrite in sericite and chlorite rock. It is generally impossible to tell what the parent rock was and the best estimate in view of the environment is that the country was originally greywacke.
9. *Tyndall copper.* Prospects in this vicinity are poor and so far as could be seen consist of very thin pyritic disseminations in a narrow zone along the contact of the quartz porphyries and basal strata of the Owen Conglomerate. In this vicinity the latter are quartzose greywackes and are transitional between the Owen and Dora Conglomerates, and the metamorphism also tends to be transitional so that no sharp contacts are seen. While in this neighbourhood it is worthy of notice that the Tyndall Fault which brings quartz porphyry in contact with Owen Conglomerate marks the only such juncture known to the writer where there is no trace of blue haematite staining of the conglomerate.
10. *Lake Dora Copper Prospects.* Figure 16B shows that these deposits are very similar to the Red Hills bodies, and though there is some doubt as to the structure in the central part of the area there is a strong suggestion that all of the deposits are " bedded ", and perhaps all occur below a contact.

The known contact ore is again probably a replacement of an argillite or may be of a tuff and again consists almost exclusively of massive chlorite and pyrite. Blake (1939) gives the copper content of the richest portions beside the lake as less than 0·5 per cent Cu. The associated country rock of this locality is a fresh and highly conglomeratic quartz porphyry and no feldspar porphyries are to be seen anywhere around. The most massive, or least conglomeratic looking, of the porphyries occurs along the southernmost of the north-east faults, and the most intensively prospected of the ores and the most highly haematitised part of the Owen Conglomerate also occur there. There is a strong suggestion that the north-east fault, which is one of the Lake Margaret system, has to some extent controlled the deposition of ore and the formation of quartz porphyry as well; this seems to contradict the view already expressed that the north-east faults are later than granitising processes. The Dora deposits do not lie on the Dora Shear but at a small distance from it, and like the Red Hills deposits they lie quite close to a north-west fault which can be construed as a branch fault of the shear.

11. *Zeehan Road Barytes Prospects.* These two deposits are north-east trending veins of barren barytes which vary in thickness from two to ten feet. The filling is on the whole of massive spar but is in a small part of clear crystal in vughs. The walls of the veins are sharp and the country is of feldspathised and unsericitised Dora Conglomerate. It is concluded that the fissure is tensional and that the deposits are low temperature formations of late origin.
12. *Sisters Hills.* The Sisters Fault is another north-east fault mineralised with galena which is reported by prospectors from the limestone on the Henty River and which has been seen as linings of small vughs alongside the fault at Sisters Hills.

At the time of the drawing up of the Yolande Sheet the writer was unaware of the full significance of the Sisters structures and of the existence of the Lake Margaret Fault, and he continued the Sisters Fault along one of the echeloned shears (see Yolande Map Sheet, Bradley, 1954). With the new knowledge, the Sisters Fault can now be re-interpreted as continuous with the Lake Margaret Fault as shown in Plate I, and this also serves to explain the outcrops mapped on the Yolande Sheet.

Passing now to the prospects associated with the Lyell Shear, a reverse procedure to that adopted so far will be used and prospects will be enumerated from the south northwards, so that we can finish up at Lyell.

13. *South Darwin Prospects.* Along the Lyell Shear at South Darwin Peak occurs a large number of very indifferent haematite and copper prospects. About a mile to the south-west of the peak a typical concordant pyritised contact occurs between the Darwin Granite and the Owen Conglomerate and the rocks over the contact are haematitised. Proceeding north along the shear and passing down below the contact the haematite gives way to magnetite in the adinoles of figure 13; at that point the amount of sulphides visible to the writer was very small and appeared to be located in small irregular stringers of blue-green chlorite and quartz. To the south-east of Darwin Peak some lead sulphides are reported to occur in the limestones there (Hills, pers. comm.) and there are some faint showings of galena in the railway track cuttings near the nine mile post.

On the broad plateau of Mt. Darwin, which consists largely of feldspar porphyry, there are many sporadic and irregular veins of haematite, and if these can be used as a guide to the nearness of contacts it appears that the Owen Conglomerate has only recently been removed from the top of the mountain. The veins carry some copper sulphide but are very irregular and, in these days of dear labour and relatively cheap open cut working of low grade ores, they have lost the importance given to them by earlier workers.

14. *Darwin Low Grade Ore.* From the modern point of view the first really promising prospects in the southern half of the range are the low grade bodies around Snake Spur near Darwin (fig. 16B). These tabular bodies are similar again to the Dora and Red Hills bodies, but with the slight difference that they are not of massive chlorite but are in part sericitic. In this case the bodies are closely related to the Lyell Shear and there seems to be some relation of ore deposition to a north-east fault across the end of the spur. This fault is only inferred from the differing degree of alteration to either side and is doubtful. Snake Spur is the only locality in the area where a gradual process of feldspathisation of the quartzites is visible and the relict structures, which Waller (1903) called laminations and attributed to schistosity, probably indicate that replacement was preferential. The same effect was noticed by Hills (1914, p. 131) who states, " A wonderful variety of these rock types are here shown in the relatively short distance of five chains, varying from green chloritic schist to a rock having the appearance of a fissile sandstone. These bands merge imperceptibly one into the other at right angles to their strike".

Waller described the formation as a lode but he was quite clear that Findon's Lode followed as a tabular body under the capping of the spur to join up with the Darwin low grade ore, and it is surprising that he did not identify it as a stratum. It is difficult to see which is the horizon replaced at Darwin and, despite the fact that the quartzite overlying the ore is probably the Tubicolar Sandstone it is not possible to say that the ore replaces a horizon in the Owen Conglomerate. The beds below the ore horizon are chloritised and fine-grained conglomerates, they are hardly contorted at all and are quite unschisted, so that they appear to be altered greywacke. On seeing what can happen to the quartzites of the spur which are first replaced by feldspar and then by chlorite it is impossible to be definite in the matter. Judging by experience at Lake Dora and Red Hills it is probable that the ore lies fairly close below the Owen Conglomerate which must accordingly be thin at this point.

15. *Barytes Prospect* (Hills, 1914, p. 121). This is an east-west vein of barytes some 3 ft. wide which appears to belong to the north-east tensional fault system and as it occurs in feldspar porphyries it appears to be later than these rocks.

16. *Lake Jukes* (Hills, 1914, p. 117). Between the last occurrence and Lake Jukes several haematitic and pyritic prospects lie close to the line of the Lyell Shear, but it seems that the prospectors who took up the claims were more than ordinarily optimistic even for those days. Even at Lake Jukes, where some thousands of pounds were invested, the showings of ore are, according to Hills, very limited, and he described the ore as sporadic irregular veinlets of bornite. These occur in the quartz feldspar porphyry adjacent to and below the contact with the Owen Conglomerate.

17. *Proprietary Peak* (Hills, 1914, p. 100). This prospect is, like the last, an irregular network of veins too scattered to make a mine and too thin to justify large scale operation; it lies on the line of the Lyell Shear and below the base of the Owen Conglomerate, but it is not a contact body for it is narrow, trends north-south and, according to Hills, it extends in depth; the ore is chalcopyrite and it appears to have been formed in a shear zone.

18. *Mt. Huxley.* Along the eastern side of Mt. Huxley and extending to the Mt. Lyell Mines is a wide sheared zone of feldspathised and chloritised greywacke conglomerate. These are mainly Dora Conglomerate, they are lightly pyritised, and they are indistinguishable from some of the Mt. Lyell schists derived from quartzitic conglomerate. The pyrite in this zone is not associated with the Owen Conglomerate contact, for the present surface must lie below that horizon and the pyrite seems to be a wide dissemination around shear fissures.

19. *Strahan Road Gold Mine.* This prospect is probably typical of many gold bearing veins of the region but it is the only one which can be traced for any distance. The vein can be traced in a south-west direction as a ridge of silicified greywacke from a knoll (361700/815400) to the Strahan road (see Queen River and Owen Map Sheets, Bradley, 1954). Gold prospectors have driven short adits at several points apparently without much success and alongside the road some fairly extensive workings were made. The writer has no reports on this mine, but it was apparently a marginal prospect. The "quartz" from the ridge is a creamy chert and on the whole the quartz of the veins appears to be fine. The vein is obviously one of the north-east faults and looking at prospects generally, there is a fair case for supposing that this orientation of gold veins is common. Hills (1914, p. 121) cites one example on Mt. Darwin which seems to belong to this category and which bears free gold, but in most cases no gold is visible, and in the whole history of the region no gold veins have been mined with success.

20. *Burkes Show.* This is a small galena prospect lying on a north-east fault which can be followed some way toward the West Lyell Mine. The evidence for the fault is very clear, for the quartz porphyry in Queenstown is upthrown in a straight line against the Gordon Limestone and the Crotty Sandstone. This portion of the fault is mineralised with galena for about one mile. As the fault cuts out the limestone at the Sandhill, its throw must be about 1,000 ft., and it is apparent that it must continue across the town for the limestone does not appear between the Eldon Group and the Dora Conglomerate in any east-west section. Near Conglomerate Creek the continuation of the fault is again marked by the cutting off of the limestone and the fault has been extrapolated with few checks from that point to the mines.

21. *Mt. Lyell Mines.* The account which follows is an interpretation of the work of all those who have contributed to the Lyell problem and it is the application of the writer's broad picture to the detailed problem. To make this quite clear a summary will be made of the findings to be drawn from the region. At this stage it will hardly be questioned that the Lyell, Dora and Mackintosh Shears have controlled ore deposition and much silicate metasomatism. Ore is found in the shears of the system and disseminations are associated with both shears and their branch faults. Rather than the shears forming passages for ore solutions rising from the "igneous" bodies, they appear to have provided the solutions which have produced the rocks as well as the ores. Because of its transcurrent character, the Lyell Shear must extend to a great depth and it seems likely that the Dora Shear did likewise and that the solutions they transported were also of deep-seated origin; in the writer's opinion they may rise from 30 miles deep, but there is no need to explore this point here.

The second great control on ore deposition and rock alteration appears to have been stratigraphic and to have been a function of the differing compositions and constitutions of formations. In general, the ores are zoned from copper to lead outward and probably upwards from the lines of the shears, and as these coincide with the attenuated limb of the geanticline the migrating ore solutions tend to accumulate in anticlinal highs. The spreading of metasomatising solutions along porous horizons in chemically uniform rocks tends to produce sill-like bodies of the syenite type at Tullah, and the subsequent upward migration of the solutions must tend to produce fronts of alteration. There seems to be no reason why the same kind of sequence should not occur several times in a vertical succession, but this has not been observed. In the West Coast Range the lateral spread of solutions in the Dora Conglomerate seems to have been general and the formation of upward migrating fronts seems to have resulted. The fronts have apparently been halted by gross changes in the permeability or composition of beds and the front of feldspathising and chloritising appears to have been stopped by the highly permeable and siliceous Owen formation. It may be conceived that the Owen formation was of open texture and that any high temperature and pressure solutions entering it would suffer a change of pressure, and just as geysers deposit their load on meeting the air, they also would deposit their burden of silica. In a chemical sense it is natural that a halt would be caused at the juncture of the formations, for the greywackes are so near in composition to feldspar and quartz porphyry that they would be made over very readily. It is thought that the physico-chemical equilibrium at the contact would influence the precipitation of sulphides and of haematite and so cause the contact ore bodies. There appears to be some tendency for sulphides to replace argillaceous bands, but there is only one example where the original beds can be identifid. That is at the Lyell Mines, and the bed is the Chocolate Shale member of the Owen Conglomerate. The above argument of the growth of fronts applies to the deposition of ore at formation boundaries and along the contacts of concordant porphyries, but it does not exclude the possibility that porphyries might be discordant and ore bodies transgressive.

The role of the north-west folds and faults is our next consideration, and it is apparent that any upward migration of solutions would tend to be controlled by them. Such a canalisation of ore solutions might cause the localising of rich ores, but where the thickness of the ore horizon is greater than the amplitude of the folds the effects will not be quite so marked. In regard to canalisation there is, however, the additional possibility that any deep-seated fault or shear which is expressed toward the surface as a monocline and which cuts minor folds will be expressed as a number of echeloned shears. The location of these will be controlled as at the Sisters Hills, and if the deep-seated fault is a feeder the shears will canalise ore solutions and localise ore deposits.

It has been shown that the north-east faults have some importance in ore deposition; they are tensional, are late, and carry leaching solutions, probably steam under pressure. These solutions have sericitised and kaolinised the feldspars of the porphyries and have deposited the resultant colloidal silica in chalcedonic or cherty veins; they have probably derived their baryte content from the same source, the feldspars, and they have probably taken their gold from the leached ubiquitous pyrite. The deposition of the separate products at different levels in the vein system is another matter. Apart from structural arguments it is evident that leaching is a process subsequent to the formation of low grade ores. The latter are closely associated with feldspathisation and they are therefore regarded as products of anamorphism. When the feldspar porphyries surrounding the low grade bodies are sericitised (they are very nearly kaolinised at times) it is apparent that the ores as well as the rocks have been subjected to a hydrolising process. When one finds in conjunction with such ore bodies, other and richer ore concentrations which have no associated feldspathisation but are accompanied only by sericitisation it is reasonable to suppose that they have a different origin. There are two possible and related modes of origin of these rich ores, one, which will not be treated here, where stringers of ore moved ahead of the pyritic front (this is the case of the Murchison River copper prospects), and the other where the ore is the result of leaching of low grade bodies; this is the case of the richer bodies at Lyell. The process is the same as has already been detailed—that the solutions emanating from depth during the later phase of metamorphism have leached the ore mineral and have re-deposited it higher in the tensional fault system. The transport of solutions at this stage is a different matter from that during granitisation; it is by channels rather than by diffusion. In this environment solutions are more sensitive to changes of pressure, temperature, and reactive wall rocks than in the granitising stage, so that ores are differentiated and replacement is selective.

The process sketched above is similar to the well-known process of secondary enrichment of ores, except that it occurs at higher temperatures and it must be expected that its products, like the secondary ores, will be characteristic and will be distinguishable from the truly primary ores. In general there must be a wide variation among possible conditions of deposition and the following criteria apply specifically to the circumstances surrounding the genesis of ore in the West Coast Range. The terms primary and secondary have already been pre-empted, so that for convenience and to distinguish the late phase ores from true contact, anamorphic or "frontal" ores, they will be called tele-frontal.

The following guides have been used by the writer to distinguish tele-frontal phenomena:—

1. All quartz or siliceous veins below the quartz haematite front are regarded as tele-frontal.
2. All mass sericitisation or kaolinisation except when very close to or above the haematite front is late; the latter cannot be distinguished as early or late.
3. All bornite which occurs inside the haematite front is late. This is because bornite never appears in dissemination and is, presumably, not a frontal product.

For ore bodies outside the haematite front it is not possible to be quite so definite, but the following are general guides:—

4. Siliceous sulphide bodies are late. Non-siliceous ores may be contemporaneous with granitisation or late.
5. Highly differentiated ores, i.e., large pure masses, are late. Complex ores are possibly early.
6. Gold veins and ores with high gold content are late. Any ore with a concentration of rarer minerals is late.
7. Baryte probably indicates lateness particularly when the veins occur in porphyries.
8. Ores fed by the tensional faults are late—this is probably specific to this locality.
9. Any ore with magnetite is an early product of granitisation.

Now to turn to the Lyell ore bodies; figure 9 shows the writer's picture of the main structure at Mt. Lyell Mines without the confusing north-east faults. The low grade ore is shown as a replacement of the lower portion of the Owen Conglomerate, and though the picture given is thought to be correct in principle it is almost certainly wrong in detail. The illustration is a straight-out extrapolation of known factors but it cannot allow for unpredictable changes which might occur after leaving the known ground of Mt. Owen and Linda Valley. Principle among these factors are the facies changes in the Owen Conglomerate, for it is known that the formation changes thickness abruptly and it is just possible that there are interdigitations of Dora Conglomerate with the Owen Conglomerate at this juncture. Thus, although the structure of a conglomerate bed can be traced across the contact, there is no absolute guarantee that the Lyell schists are necessarily metamorphosed Owen Conglomerate. On the upper side of the contact it is also possible that an interdigitation of greywacke beds into the Owen Conglomerate would be unrecognisable, because the greywacke would be silicified beyond recognition. These fantastic complexities are the inevitable working out of the theory of origin of the West Coast Range structure, and it happens that at one point or another the writer has seen all of these variations. Making allowances for these factors, and apart from Conolly's findings, there is little doubt that the diagram represents the true situation and the low grade ore is a replacement of the Owen Conglomerate.

The Middle Conglomerate member of the formation, which is sandy in parts, has resisted alteration to a sufficient degree to leave substantial relics which are shown in figure 11, and it is the presence of this member which allows the working out of the structure. The Chocolate Shales have been most susceptible to change and it is largely because of the ready schisting of these fine argillaceous beds that the residuals of the Middle Conglomerate have been isolated. The shale has also been particularly favourable to replacement by sulphides and the rich ores at North Lyell, the Blow, and Comstock occurred in it.

Now, it is conceivable that the ore solutions found their way to this horizon through channels along the Blow Thrust Plane, the North Lyell Thrust Plane and along the faulted Comstock Syncline, and it may be that the bodies are wholly the result of a granitising wave of mineralisation. It is possible, however, that the bodies which are all aptly situated with regard to north-east faults are due to late phase leaching and concentration of ore. The importance recently attributed to the north-east folds by Conolly (see Alexander, 1953) suggests that this is so. The brecciation of the Owen Conglomerate at Comstock and North Lyell indicates late movement and there has been much cherty re-silicification of the breccias. At the Blow and at other localities the presence of barytes is suggestive of late activity and the presence of many varied and rare sulphides tends to support the idea. As far as the north-east faults are concerned there is a slight difference of nomenclature between the Mt. Lyell geologists, who call them flexures, and the writer, who calls them faults. This difference is not significant.

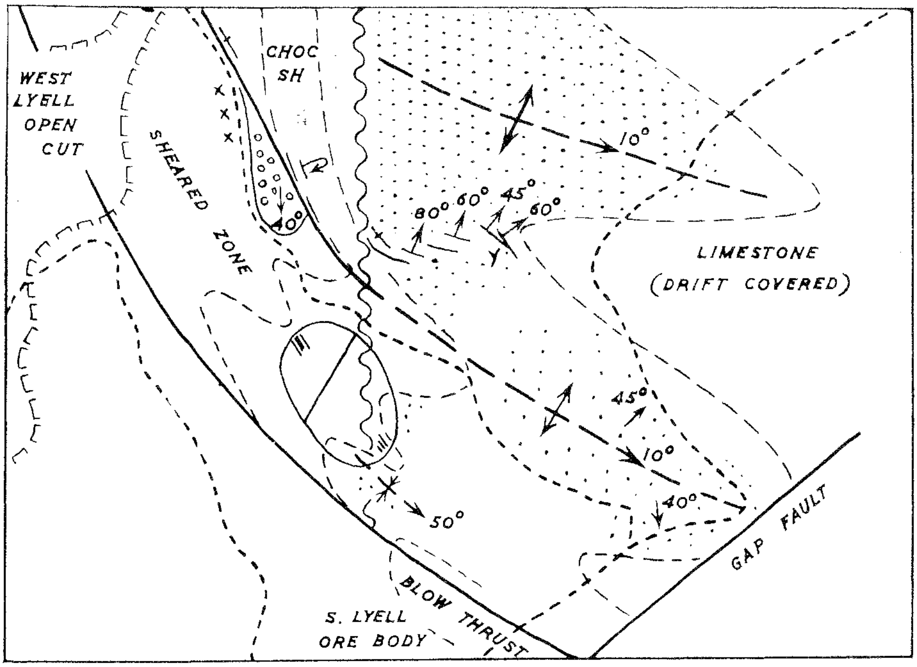

FIG. 17.—To illustrate the geology at the Blow Open Cut. Undulating line—boundary between schists (left) and non-schists (right); shortest dashes—roads; heaviest dashes—fold axes; heavy lines—faults; medium dashes—projected formation boundaries x denotes locality of sandstone dykes and y the position of a minor unconformity.

With these ideas in mind, and figures 9, 11 and 12 before us, the richer bodies may be examined, taking the Blow deposit as a type. This ore formation, which is now completely excavated, once formed a pipe-like body tapering downwards and the pipe, in the writer's opinion, can be seen to lie in the trough of a steeply plunging syncline which is divided by a smaller anticline. The ore was predominantly of chalcopyrite and pyrite with some bornite and was a replacement of the Chocolate Shales. Immediately to the south-west of the pipe the Blow thrust plane passes close by and provides a possible feeding channel, and on the north side of the body another shear occurs. A slight difference in the interpretation of the structure at the Blow is given by the writer as compared with Conolly (see Alexander, 1953) who carries the Blow thrust plane with a sharp twist through the Blow deposit. Here it is thought that there are two faults, the first being the Blow or Owen Spur thrust plane, and the second being a shear which begins only alongside the Blow (fig. 17). The Blow lies on the southern side and partly on the flank of a minor north-west fold, and as this fold is upturned at the Lyell Shear it breaks along its crest line and the southern limb is thrust over the northern. At the same time, intense alteration occurs along the break, and so we have the vertical limb in a very altered condition. The progressive overturning of this northern limb is beautifully displayed along the old haulage line near the Blow and the more nearly horizontal southern limb is seen in the smaller Razor Back mass. It is just possible that this fault, as well as the Blow thrust plane, has been a feeder, but there are two more faults, both tensional north-east faults, which might serve in that role. The smaller of these can be seen in the south-west and north-east faces of the Open Cut. The latter exposure is poor but the former is clear, and it shows a clean cut fault plane with marked contortion to either side and with intense sericitisation along its length. The large fault is the Gap Fault, a fault which has not been proved in this immediate vicinity but which has been deduced as crossing Linda Valley. There are so many conflicting foci of alteration at the Gap that it is unlikely that the Gap Fault can ever be demonstrated except indirectly. The evidence for it is good—it can be observed on Mt. Lyell and on aerial photographs of that mountain—it has been drawn between the tilted ends of Linda Valley and there is evidence that it downthrows to the east. The latter consists of an exposure of a fine white loose sanlstone in the old railway cuttings south of Linda. This sandstone closely resembles, and is taken to be, the Crotty Quartzite—it is most unlikely that it has been confused with the Tubicolar Sandstone which in this vicinity is much different. If the folds at the western end of the valley are projected along their axial line they could hardly result in the exposure of the quartzite, and it is assumed that a fault has downthrown this formation to the east.

Figure 17 shows how the Gap Fault might serve as a feeder to the Blow deposit, i.e., by canalising along the syncline itself or along the Blow thrust plane. It is probable that there is no one answer to the problem of feeding channels, and it would be very difficult to choose between the north-east fault in the Blow or the Gap Fault, but there is perhaps some significance in the fact that the South Lyell body lay in depth (600 ft.) some 600 to 800 ft. to the south-west of the Blow (Alexander, 1953). Within the limits of the size of the body it seems probable that the ore lay at the intersection of the Blow and Gap Faults, and would, of course, coincide with the projection of the Chocolate Shales of the Blow Syncline, as shown in figure 9.

So far, as the details of other ore bodies are concerned the reader is recommended to Conolly's (1947) and Alexander's (1953) accounts but for the general reader the following general structural notes are made:—

The Comstock Ore Bodies.

The pyritic ore is located as irregular lenses in the monoclinal axis of the deflected North Lyell fold. The fold is readily traced in the bedded porphyries to the north and west of the mine and the porphyries appear underground with ore showing at the contact with the Owen Conglomerate. The steep monoclinal limb appears to have controlled the location of ore, but perhaps just as important is a north-east fault which the writer has inserted on figure 11. There is little direct evidence for this fault except in the presence of pronounced north-east joints and faces in the mine open cut. There must have been some late movement nearby for the rocks around are highly brecciated and re-cemented by cherty silica and the writer would attribute these phenomena to a north-east fault. The ores near the surface are accompanied by much sericite and replace the Chocolate Shales and these replacements are similar to those at the Blow and North Lyell. A particular interest of the Comstock locality lies in the presence of a galena vein which occurs to the north-east of the open cut and which presumably lies on the north-east tension fault. As the vein is stratigraphically higher than the pyrite ores this provides another example of the zoning previously mentioned. Tensional faults seem to be a more natural home for lead ores than are shears but Broken Hill provides an excellent example to the contrary and so do the deposits at Tullah. It should have been mentioned earlier that the latter provide an example of frontal lead deposits and here at Comstock is an example of a tele-frontal deposit. It is of interest that slugs of galena have been found in the limestone near Linda and these are regarded as having an origin similar to the vein at Comstock and as having been deposited along the Gap Fault.

The North Lyell Mine.

This is the remaining rich ore body of the Lyell vicinity. It is again an irregular pipe lying in Chocolate Shales under an overhang of Tubicolar Sandstone. The ore is chalcopyrite with bornite and it lies close to the North Lyell Fault. There is little doubt that this fault has influenced deposition but according to Conolly north-east faulting has been equally if not more important.

West Lyell and Tharsis Mines.

The position of these bodies is indicated on figure 11 along with the trace of the relevant north-east faults, and taken together these tell their own story.

Conclusion

In environments like the West Coast Range it is not enough to make a separate study of rocks to arrive at their genesis or of ores to trace their origins. It is not enough to study sediments to guess at their environment of deposition nor to study structure as geometry. All of these must be studied as one, for they are like the parts of an organism, they have a common evolution and a fundamental unity.

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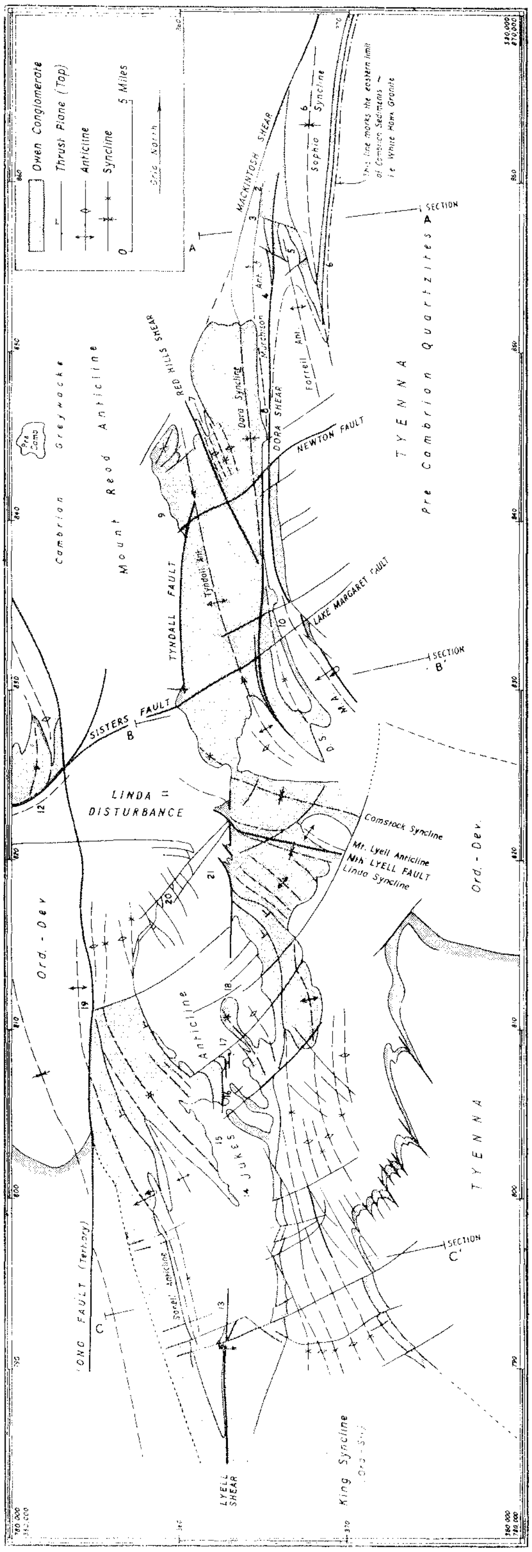

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