GEOLOGY OF THE WEST COAST RANGE OF TASMANIA, PART III

Porphyroid Metasomatism

By

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(With 6 Figures and 4 Plates)

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ABSTRACT

Quartz and felspar porphyries and associated greenschists of the West Coast Range are described. Felspar porphyries are considered to have originated by the felspathising of spilitic lavas, lava breccias and related greywackes during a period of progressive metamorphism. Metamorphic mineral assemblages of the greenschist and albite-epidote-amphibolite facies are recognized in the porphyries and are identified with increasing degrees of porphyritising of host rocks. Sharp contacts between chlorite-sericite schists and quartzites are regarded as metamorphic in origin and as indicating the replacing action of a chloritising and sericitising front. Haematite rich rocks and low grade pyritic ores which respectively occupy narrow zones above and below the schist quartzite contact are regarded as representing minor haematising and pyritising fronts.

Sulphide and silicate metasomatism are closely related to the structure of the range and it appears that the advance of fronts has been engendered and controlled by the upward flow of heated waters through fault fissures and pore spaces. Metasomatic replacement was effected by diffusion and exchange through intergranular films. This mechanism is thermodynamically efficient and allows adequate explanations of growth, and also of corrosion structures, of quartz and felspar crystals in the porphyries. During the advance of fronts there was extensive transport of material; metamorphism was not merely an adjustment to changed isogradial conditions. In particular, migrating solutions leached iron, copper and sulphur from the basic rocks and precipitated them in specific zones where they now form low grade ores.

After a period of rising temperatures and progressive metamorphism there followed an interval of cooling and retreat of thermal zones. Because of the presence of abundant water there was during this cooling phase an intense retrograde metamorphism of the recently formed felspathic rocks. Hydration of these rocks resulted in the liberation of silica and thus gave rise to quartz porphyries and quartz sericite schists. Extreme pneumatolysis and leaching of silica from the porphyries gave rise to kaolinised rocks and to veins of quartz and chert. A similar kind of leaching of sulphides from the low grade ores, and of selective precipitation of sulphides in pipes and veins, gave rise to rich ore bodies.

INTRODUCTION

On Magmatism

Given all the information accumulated from the study of igneous rocks over the past hundred years one might expect that petrologists would be able to reach agreement on the mode or modes of origin of granites. It seems that differences of opinion probably stem in the first instance from the geographic isolation and consequent different geological environments and approaches of schools. A cursory examination of geological maps of Brittany (War Office, 1942) shows that the environment of the French school is one of stratiform or concordant "granites porphyroides" which readily lend themselves to stratigraphic and structural mapping, and whose study might readily lead to metasomatic hypotheses. The setting is the same in parts of Canada, Fennoscandia and Australia, and probably in Cornwall. In Scotland and in the Atlantic states of North America occur entirely different phenomena of dynamothermal metamorphism and cauldron subsidence complexes which respectively indicate certain limitations of diffusional metamorphism in the production of granites and point to magmatic origins. As a result much of the study of granites in those countries has centred round processes of crystallization and differentiation of fusion and assimilation, and metasomatism has until recently been ignored.

Considering the problem on a world-wide scale there is convincing evidence of both magmatic and metasomatic processes and the writer, in common with others, has no difficulty in believing that there are "granites and granites". That this account deals with phenomena typical of the Hercynian terrain of France must not, therefore, be taken to mean that the writer belongs to the "French school", nor that magmatic origins have been ignored. That it deals solely with metasomatic origins of porphyries must be taken to mean, instead, that the West Coast Range region constitutes a province which once suffered a particular kind of metamorphism.

Gradational Metamorphism

"Les considérations structurales l'étude des structures pre-existantes sont donc a la base des recherches sur la metasomatose". Wegmann (1948, p. 46).

An attempt has been made by the writer (Parts I and II, 1954 and 1956) to demonstrate that large bedding structures of sediments at Mount Lyell can be traced into metamorphic rocks and granites. Wegmann's statement applies to the finer bedding and particle (conglomeratic) structures of rocks also. Using these characters, independently of gross structures, many rocks which superficially appear to have been of magmatic origin can be demonstrated to be sedimentary and metamorphic. So far as the existence of such relict structures are concerned there is, for the writer, no problem of fact remaining. There are such rocks. They do show a gradational metamorphism, and the only problem concerning them is—what were the processes of metamorphism which brought them to their present state? There is no doubt, either, that such rocks exist in many parts of the world. From Vermont, Hitchcock (quoted by Winchell, 1888, p. 334) states " We define this rock as a conglomerate with a cement of syenite or granite, or as a syenite or granite with pebbles in it ". From Canada, Brown (1948, p. 438) states " Contacts between sediments and porphyry are gradational and as the sediments are highly altered or ' porphyritised ', it is often difficult to differentiate sediments from porphyry ". From Minnesota, Winchell (1888, p. 219) says " Here is a real conglomerate . . . A real conglomerate . . . in a groundmass of typical syenite is certainly an extraordinary occurrence; I have never seen it before . . . never read of it " Emmons *et al* (1953, p. 116) . . . " The Wisconsin rapakivi granites . . . may be traced into rocks which we regard as metamorphosed greenstones ".

Apart from the example cited here and in Part I of this work there are numerous other examples of such transitional rocks characterised by relict pebbles.

Metamorphic Contacts

There is also, for the writer, no problem of fact remaining as to the existence of sharp metamorphic contacts. The contacts at Mount Lyell between schist and quartzite, and on the Lynchford-Crotty track between porphyry and haematitic conglomerates are, from a structural viewpoint, indisputably metamorphic. (The writer would in these contexts allow no interpretations which did not explain the overall structures.)

Apart from the examples of Part I (*loc. cit.*) there are numerous cases described from many parts of the world. At one such sharp contact, below the unconformable Goodrich Quartzite of Michigan, Van Hise and Bailey (1897, p. 442) find a granite conglomerate in which " the matrix is completely crystalline . . . if it were not for the conglomeratic character of the rocks their sedimentary origin could not be asserted from the evidence shown by thin section ". Below each of a succession of related overstepping unconformities (or transgressive contacts) associated with haematite, Van Hise finds much the same thing, e.i., below the Mesnard Quartzite (p. 224) and the Wewe Slate (p. 271). These and similar unconformities in America have been debated for sixty years (Lamey, 1937), and were debated even by Van Hise.

. . . The apparent transition of the Mesnard quartzite into granite noted by Romminger, says Van Hise (1897, p. 239), is only due to mashing at the juncture of the two formations. " The mashing has transformed the clastic rock into a crystalline schist and metamorphosed the granite into a similar looking rock ".

The sub-Bottnian unconformity, one of many in Fennoscandia (von Eckermann, 1936), has a similar lengthy history of debate. Sederholm (1934, p. 35) feels obliged to point out that " the occurrence of a conglomerate containing pebbles of gneiss is evidence of age that cannot be gainsaid ", but he expresses his underlying doubt and reasons for saying this (p. 47) when he relates how, at contacts, granite " occasionally fills rounded cavities in the basic rock which have probably originated by the corroding action of the magma ". Further reason is found in the writing of McCallien (1932, p. 271) on the sub-Bottnian unconformity. He quotes Sederholm thus, " Nobody who has any respect for facts could, standing before this contact, explain it by assuming that the diorite was younger than the schists ". In face of this and of derived pebbles of diorite in the conglomerate McCallien (*loc. cit.*, p. 271) prefers to rely on intrusive stringers from the diorite; " the diorite " he says, " is younger, i.e., intrusive into the sediments ".

Faced with the same kind of anomaly Wahl (1947), in an area he himself describes as granitised, overcomes the problem by supposing that quartz porphyry has been intruded along an unconformable contact and injected between the pebbles. He says (p. 190) that " the porphyry contains numerous xenoliths of older country rocks . . . often to a certain extent digested by the lava " and continues (p. 291), " it is, however, remarkable that these xenoliths only seem to occur as a fairly limited horizontal streak in the lava " (i.e., apparently retain an original bedded character).

According to Wegmann (1948, p. 46) Keilhau has it that " one must recognize the existence of phenomena before one attempts to explain them ". In the works cited above is the recognition of the porphyroid problem. It is world-wide. We may now ask: what is porphyritising, how is it effected, why should it be associated with conglomerates and follow sedimentary boundaries, why should it result in sharp contacts, what is the meaning of the association spilite, porphyry, pyrite, haematite, and finally what is the relation of all these to major earth structures?

THE PORPHYROID CYCLE OF METAMORPHISM
Comparisons

The idea of metamorphic zones in regional metamorphism has long been established and the work of Becke, Grubenmann, Barrow, Van Hise and others has been broadened into a theory of metamorphic facies by Eskola (1920). This last concept treats metamorphism in terms of zones of chemical equilibrium at different temperatures and pressures in the earth, and defines a facies as all those rocks crystallizing with perfect equilibrium between minerals under one set of pressure-temperature conditions. In Harker's sense of regional

(dynamo-thermal) metamorphism the minerals which occur at a given depth are determined by pressure-temperature conditions in relation to the composition of the source rocks, and with little reference to transfer of material. In that view it is also considered that there has been little retrograde metamorphism and minerals now seen at the surface are metastable phases of minerals formed at the peak of anamorphism. These ideas of restricted metamorphism have tended to be attached to Eskola's (1920, p. 146) much broader concept which considers "minerals, quite regardless of their mode of crystallization, whether from magma or aqueous solution or gas . . . or by gradual change of earlier minerals". Porphyroid metamorphism fits into Eskola's scheme quite readily, and while it is similar to dynamothermal metamorphism in respect of broad causes, principles and facies, it is different in respect of the completeness of recrystallization, in the sharpness and brevity of zones and in the characteristic development of highly porphyritic rocks and sulphide ores. Also different is its close association with intense pneumatolysis and retrograde (largely hydrolytic) metamorphism. These differences are related to an environment where there was abundant water, where solutions were particularly free to migrate, and where geothermal and pressure gradients were steep. In this context the minerals of any one facies are not primarily dependent on the original composition of the rocks, but, because of the addition or subtraction of material from the parent rock, may be quite different.

The greatest single problem of the porphyroids is that of distinguishing between the earlier phases of metamorphism and the later phases of pneumatolytic and retrograde metamorphism which followed. To assist discussion the writer has adapted two terms "anamorphism" and "katamorphism" which have largely fallen out of use and which very conveniently fit the two stages of porphyroid metamorphism. Anamorphism as defined by Van Hise (1904, p. 43) is the process of rock alteration which results in the production of complex compounds from simpler ones. It is a process of dehydration and compaction usually occurring at some depth and pressure, and is the process usually referred to in the ordinary use of the word metamorphism. Katamorphism as defined by Van Hise (1904, p. 43) is the production of simple compounds from more complex ones, and includes processes of weathering and hydration at atmospheric temperatures and pressures.

Anamorphism will here be used to mean the process of progressive metamorphism, i.e., Van Hise's meaning. Katamorphism will be extended in meaning to include processes of hydration at relatively high temperatures and to include retrograde processes generally. This modification is considered reasonable since hydrothermal alteration produces sericitic and clay rocks somewhat similar to weathering products and because Van Hise's definition refers expressly to such processes of simplification of composition.
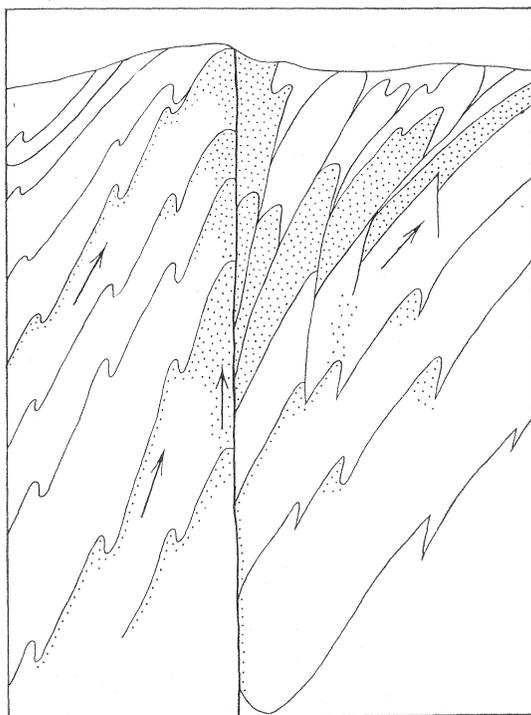

FIG. 18 a.—Cross section of the West Coast Range showing probable directions of flow and regions of accumulation of heated waters.
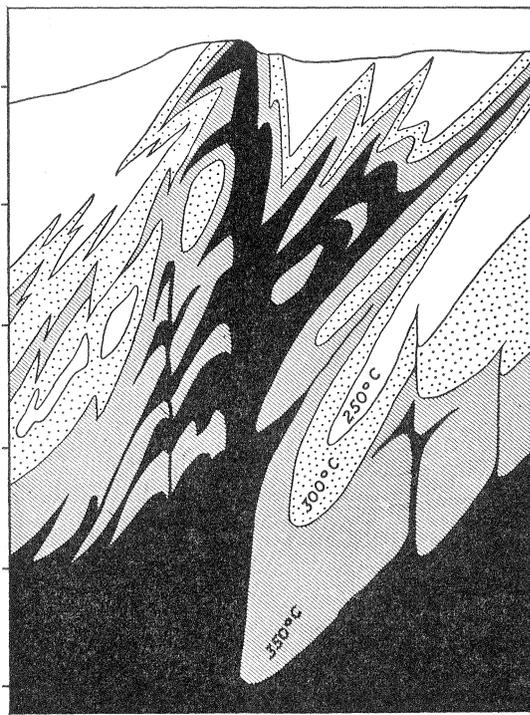
FIG. 18 b.—Showing general form of isogeotherms resulting from the distribution of heated waters in fig. 18 a.

Fluid and Heat Transfer

It is supposed that in the West Coast Range at the beginning of the porphyroid cycle of metamorphism there was an access of heat from depth along the Lyell Shear which formed a deep-rooted line of weakness in the crust (fig. 18).

Heat was transmitted by fluid transfer, i.e., through the bodily migration of intensely superheated water. Migration was fostered and controlled by shatter zones along the Lyell Shear and Linda Disturbance and by aquifers such as the Owen and Dora Conglomerates. Fuilds were further controlled by major structures such as the West Coast Range anticlinorium and travelled into anticlinal crests.

Barth (1951, p. 301) contends that migration is an old and rather obvious idea and it does not apply to metamorphic rocks in general. " By burial and orogenic pressure . . . all fissures and cavities close completely . . . Only in sheared rocks and in loosely packed sediments and their low metamorphic equivalents is permeability good enough to allow migration." The porphyroids may have been formed at relatively shallow depths: the rocks from which they were formed were particularly pervious and there was some shearing associated with their metamorphism but one would only reluctantly call the Murchison granite a low grade metamorphic product. The porphyroid rocks though in fact common are simply different from what Barth describes as " metamorphic rocks in general ".

The idea of Barth (loc. cit.) and others that there might be no migration of fluids in deep-seated rocks is based to some extent on the assumption that the " solutions we are discussing here behave like ground water ". After Gillingham's (1948) experiments it seems most improbable that water above 400°C behaves anything like ground water. Having little or no surface tension the fluid, even without volatiles and though dense, is more likely to act like a chemically active gas under very high pressures. Apart from this, cavities do not close up at the depth of formation of all granites. The tourmaline nodules of the Heemskirk granite (Waterhouse, 1916) were undoubtedly formed at the same depth as the granite was formed, yet a large proportion of them are hollow and were probably once filled with fluids. If cavities are filled with fluids at the same pressure as their surroundings there is no reason why they should close up and further, if solutions are generated by heat from hydrous minerals within the rocks, they might even attain a higher pressure than their surroundings and themselves be a primary cause of opening of fissures.

Even at great depths (10 miles or more) there is no reason why solutions should not migrate upwards any more than why basalts should not. The only difficulty is to get water down to such depths in the first instance. The continued depression of the Zeehan Syncline must have caused the deep burial of large amounts of water and the compaction of its sediments must at some stage have resulted in the migration of that water towards the Lyell Shear (fig. 18a). The presence of stratigraphic traps below unconformities along the flank of the growing anticlinorium must have materially assisted in the trapping of connate water and its passage to great depths.

The only problem is how deep might the rocks have been depressed before losing all their connate and combined water. This is dependent very much on the nature of the rocks concerned (the porphyroid parent rocks were essentially conglomeratic and were not " normal " sediments, cf. Yoder (1955, p. 509) and is largely a matter of opinion. The writer imagines that reconstitution under load would only become important in sealing a coarse aquifer of indurated pebbles, to the passage of ordinary water at depths approaching five miles, and that gas phase water would travel through pore spaces and self-created openings and shear fissures to depths of 10 miles or more. Possible directions of flow of heated fluids and the consequent warping of isogeotherms towards the surface are shown in fig. 18b. In view of the recorded 200°C temperatures in steam bores 1000 feet deep along wide fault zones at Wairakei, New Zealand (Steiner, 1953), the suggestion that the 400° isotherm might reach to within 10,000 feet of the surface does not seem unreasonable.

From an empiric viewpoint the penetration of the Cambrian strata by fluids even down to a molecular scale is evident everywhere. Innumerable veins of albite, quartz, and epidote indicate that rocks were permeable along fractures, and the kaolinization of the porphyry at Queenstown shows that the whole of that formation was intimately permeated by water. Where greywackes have been wholly replaced by chert, as on the track above the Comstock mine, it is absurd to say that silicon ions or silica ions cannot migrate, and where, as at the mines, there is ample evidence that quartzites have been replaced by felspar and sericite it is futile to maintain that large aluminium ions cannot be exchanged in large quantities.

The writer would not, however, advocate the diffusion of elements through crystal lattices for the porphyroids. In keeping with the broad hypothesis of gross movement of solutions in fissures and pore spaces he would advocate a detailed transmission of solutes by diffusion through immobile intergranular films of water.

Shape of Isograds

Returning to the broader picture, solutions migrating upwards established a series of pressure-temperature zones (isograds of Tilley), and as they passed through the rocks there was a mutual chemical adjustment of both rocks and solutions. In this way new mineral facies were formed and as time passed isogeotherms moved upwards so that there was formed a series of advancing waves of alteration. This idea, essentially the " front concept " of Reynolds (1946) applied in a " wet " context, is also similar to the views of Goodspeed (1952) and Backlund (1946).

As migration was controlled by fractures and sedimentary structures, the isogradal surfaces must have been most complex and the form of successive zones must have resembled a series of concentric cedar-tree laccoliths. That is in contrast to dry metamorphism where heat transport may be assumed to be by conduction and where isograds must have much simpler profiles. During an interval of time, shapes of surfaces were probably still more complex, for repeated earth movements during metamorphism must have altered the size and shape of fractures, and one must visualize a series of " cedar-trees laccoliths " superimposed on, but slightly offset from, each other. Because of periodic intense faulting and the resultant intermittent release of steam, gas pressures even to depths of miles must have varied and isograds must have fluctuated to and fro in response. Again, this is different from " dry " metamorphism where gas pressure and structural controls are much less important. The structural picture is generally complex; there must be few places in the world where everything is as simple as at Mount Lyell.

Ignoring complexities of form, and thinking only of simple shells of metamorphism, the relations between anamorphic zones must have been as follows: Individual minerals or groups of minerals may be regarded as critical and others as noncritical to specific isograds. Some, like the higher plagioclases and chlorites, might extend over wide zones, while others, like albite and epidote, were restricted to moderate temperature zones of hydrothermal alteration. Haematite was also specific, being restricted to the lowest temperature zone and pyrite was confined to the next warmer zone. This is all according to the dry concept, but because of freedom to migrate there is with porphyroid metasomatism a much smaller tendency for the original rocks to dominate the composition of the reconstituted ones. Instead, there is a strong tendency for components to migrate into zones of their optimum stability and there form concentrated zones of critical minerals. Zones thus tend to be zones composed largely of index minerals, rather than zones with index minerals, or even without index minerals as is often the case in the Scottish Highlands. Zones may, however, be diluted with less critical minerals like chlorite, and this appears to be the case of the chlorite-pyrite ore zone at Mt. Lyell.

Metamorphic Diffusion Zones

The mechanism by which " metasomatic diffusion zoning " might be effected has been treated in some detail by Korzhinsky (1948) who describes how solutions may ascend open fissures and permeate wall rocks, and how ions might further migrate by diffusing through immobile pore solutions.

This writer sees the process as one where solutions act as both collectors and precipitants. Compounds are dissolved from one zone where they are unstable and, as solutions move outwards, are precipitated in the next cooler zone. As isograds themselves move upwards so minerals like pyrite may be repeatedly leached from the rocks and precipitated, again and again, and be carried forward in a cumulative manner.

The range of conditions over which a mineral might remain stable is one factor determining the width of the zone in which it occurs. Less critical minerals may be precipitated far in advance of the isograd where they are resorbed; transport of these minerals proceeds in giant leaps. With more critical minerals, leaps are small, zones are narrow and minerals are concentrated. Where fault fissures allow easy upward travel, solutions (and isogeotherms) might migrate far ahead of their respective zone. Thus we may visualize some veining of the country rock as part of the process of anamorphism, not of late phase cooling of magmas. Such veins may be associated with all zones and isograds.

Stability ranges of minerals are not the only factors determining width of zones, for introduced chemical factors may affect equilibria. Thus reactive beds like limestones may cause the formation of new insoluble minerals like datolite at Colebrook Hill and scheelite at King Island, Tasmania, and so restrict the distribution of boron and tungsten into narrow zones. Here the freedom to migrate by diffusion in solution is determined by the affinity of the freely migrating ions for others like those of calcium which do not migrate so freely.

A discussion of the collection of water, carbon dioxide, chlorine, fluorine, &c., into a " cloud of volatiles " (Backlund, 1946) illustrates the general principle of advance of fronts and shows how the physical properties of sediments may influence width of zones. In most rocks even at great depths some water occurs either in the free state or with varying degrees of combination in clays which contain something of the order of 10 per cent water. Apart from the effects of pressure already described, the effect of heat is to reconstitute clay minerals into less hydrous species, and upward migration of heat must tend to drive the liberated water upward through any available channels. The further isogeotherms migrate, the greater the cumulative total of migrating water and its associated volatile compounds must be.

Contacts Between Zones

With increasing depth in the earth there must be everywhere, and in particular above this cloud of volatiles, some isogeotherm corresponding to the critical temperature of water. Whether or not this temperature is affected by dissolved solids as suggested by Smith (1953), and whether or not water at this temperature resembles a gas, the surface tension of water gradually diminishes with increasing temperature and normally vanishes at critical temperatures. Assuming that water in the earth similarly loses its surface tension at temperatures approaching 400°C, capillarity must cease to affect its passage through fine pores. It may further be assumed (by extrapolation from the laboratory behaviour of water) that this change of fluidity of water is in the final instance relatively sudden.

If these assumptions are correct there must, then, be some isothermal surface or narrow zone in the earth above which given rocks behave as relatively impervious to superheated water, and below which the same kind of rocks are relatively pervious to the more fluid " near gas " phase. Ignoring for the

moment the chemical activity of water at 400°C, there must be a sudden pressure (and temperature) drop across the boundary, a sudden change in the prevailing chemical equilibria, and a corresponding break in the mineral facies developed.

Alternatively, variation in the permeability of rocks may produce much the same result. Thus a wave of volatiles passing through moderately permeable strata will be held back on encountering a nearly impermeable stratum and a steep pressure gradient may develop across the contact of the two. Other factors being constant critical minerals might be deposited or resorbed at the contact and the two formations might develop separate facies. The two factors of permeability and fluidity tend to be complementary and their effects to coincide. Thus, if an impervious barrier such as the Farrell Slate or the silicified Owen Conglomerate were to impede migration, there would be an increase of fluids and pressures below the contact and temperatures would rise. This would continue until higher temperatures were reached and the barrier were resolved by the increased chemical activity of solutions. Alternatively, temperatures and pressures would rise until the barrier was resolved by explosion. The knife-edge contacts of the Owen Conglomerate at Lyell and of the hornfels "pendants" in the Darwin Granite may have been much influenced by such permeability and fluidity factors.

The passage of solutions from less permeable rocks into vast and highly permeable formations (such as the Owen Conglomerate must have been before silicification) would also be accompanied by a very sudden drop in pressure. Any broad upward migration across bedding must, as in the previous cases, result in the deposition of critical minerals at the lower contacts of such formations. Permeable beds must, however, allow the spread of relatively uniform pressures throughout their thickness and favour the development within them of one mineral facies rather than of gradation of facies. It would be possible in this interpretation for two formations like the Owen and Dora which originally had different constitutions and, presumably, different permeabilities to have developed two separate facies of metamorphism. This separation of facies along with the different original compositions of the two formations could account for their very different reactions to metamorphism, and for the deposition of ores at their contact. It seems unlikely, however, that such contacts would be sharp or transgressive like the Lyell contacts; on the contrary, relatively diffuse and conformable contacts as at Lake Dora and Red Hills would be expected.

Late Phase Metamorphism

Porphyroid metamorphism, as distinct from "dry" metamorphism is particularly characterized by its late, retrograde or katamorphic stages of pneumatolysis and hydrothermal alteration. With the cooling of a region after it has reached a peak of anamorphism there is necessarily a retreat of isograds and the possibility of retrograde metamorphism. During this phase of cooling late fracturing of the West Coast Range Anticlinorium allowed a large scale release of water over a wide area. Around these faults there was a superposition of low temperature facies on high, i.e., the kaolinization and sericitization of porphyries and

granite. Migration of solutions in these processes was not guided by any regionally impelling force such as existed in the earlier advance of fronts, so one cannot properly speak of a retreat of fronts but simply of retrograde metamorphism.

The source of the water in this phase is probably the same as in the first half of the cycle. The cloud of volatiles of that early phase does not represent all of the water originally present in the rocks, but only that portion most readily detached. It seems probable that during all of the anamorphic phase, water is driven off from the rocks at all depths by rising temperatures and that this water continually migrates upwards to maintain the thermal gradient.

With rocks of fairly uniform conductivity such as occur with dry metamorphism, geothermal gradients are probably straight-line or gentle curves (fig. 19 a) but with fluid transfer of heat gradients are variable. The zone in which there is the greatest concentration of water is that with the greatest conductivity (fig. 19 b), and not only may this conductivity be some orders greater than that of dry rocks, but with time this conductive zone migrates towards the surface. This movement continues until at the peak of anamorphism the zone of conductivity reaches an optimum level as in fig. 19 c.
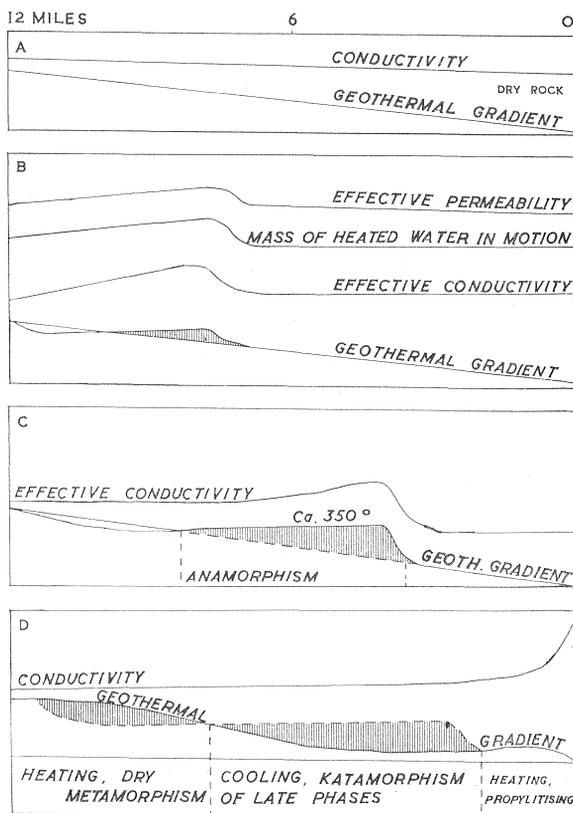

FIG. 19.—Showing the effect on the geothermal gradient of accumulating and upward migrating body of water. B, C and D represent successive stages of upward migration of isogeotherms. The dashed line in each figure indicates the state of the geothermal gradient in the previous figure.

Migration beyond this level must cause heat to be rapidly dissipated to the surface by conductivity of rocks, by eruption or by hot springs. Then although there is still a flow of heat from depth and isogeotherms at a depth of several miles are still rising and driving a little water before them, the rocks at intermediate depths may be cooling (fig. 19 *d*). It is the water driven off at this last stage which causes the late phase metamorphism of the porphyroids. This does not mean that metamorphism may not go further for isogeotherms may still rise slowly by conductivity of the rocks and if the region under consideration were depressed into the crust it would be possible to have intense dry high temperature metamorphism of rocks which had just passed through a wet porphyroid stage. There are some appearances of this having happened at Broken Hill, but not in the West Coast Range.

Mineral Facies of the Porphyroids

Reviewing in terms of metamorphic facies the Cambrian rocks which might originally have been present in the West Coast Range together with those resulting from metamorphism we have the following categories:—

(1) The original sediments and lavas. These are divisible into:

   (*a*) Hydrated rocks of the weathering or N.T.P. facies (argillites and quartz arenites).

   (*b*) Anhydrous or partly hydrated lavas of the sanidinite facies and fragments of similar rocks in the tuffs and greywackes.

(2) Rocks of successive stages of metamorphism.

   (*a*) First katamorphic stage of the outermost hydrothermal front in which anhydrous remnants of lavas (augite and plagioclase) were hydrated at low temperatures to chlorite, sericite and kaolin rocks like those of 1(*a*).

   (*b*) Anamorphic stages in which rocks of 1(*a*) and 2(*a*) were rebuilt into

   (i) greenschist rocks with pyrite,

   (ii) rocks of the albite epidote amphibolite facies.

   (*c*) Second katamorphic stage of retrograde metamorphism in which any of the preceding rocks might be sericitized and leached of silica or quartzified. These effects tend to be irregular and localized.

(3) Vein rocks.

   (*a*) Those resulting from the leaching of sediments and lavas in stage 2(*a*) and 2(*b*). These veins are composed of rocks belonging to several facies (frontal deposits of Bradley, 1956), and include quartz-haematite, pyrite, quartz-epidote and felspar veins.

   (*b*) Those resulting from leaching of the metamorphic rocks during stage 2(*c*). They include sericite and chalcedonic silica veins along with tele-frontal sulphides (Bradley, 1956).

ORIGINAL SEDIMENTS AND LAVAS

Owen Conglomerate

The members of this formation are of three types, viz., argillaceous, arenaceous and conglomeratic. With the exception of some argillites in the upper part of the formation the whole is almost everywhere silicified. The shaly partings are, in general, composed of chlorite and sericite with subordinate bands of angular silt-grade quartz and with haematite in varying proportions. In the partings of the Tubicolar Sandstone on the King River the iron mineral is probably magnetite, but in most other localities haematite has been introduced along with silica.

The quartz sandstones are seen in their unsilicified state only in the Tubicolar Sandstone where they consist exclusively of sharp particles of quartz schist, quartz crystals and chert. The matrix is chlorite or sericite, and in some places limonite of secondary origin. The most striking feature of these sandstones, and this also includes the sandstone dyke rocks at Lyell, is the apparent extreme angularity due largely to grain growth of fragments less than 0·2 mm. across (plate D, figs. 18 and 19). With increasing size, particles are progressively rounded. In the purple sandstones and grits the matrix is haematite and individual quartz schist particles are very heavily powdered with haematite along grain boundaries (plate D, fig. 3).

Conglomerate beds also consist of quartz schist, quartz and chert, with varying amounts of sericitic and chalcedonic matrix. White chert fragments (5 mm.) are common only in the grits of the Tubicolar Sandstone near the Comstock Mine, and there the angular particles comprise as much as 10 per cent of the whole. It is debatable whether the chert was formed before deposition or by silicification afterwards. It is also possible that many dark siliceous hornfels pebbles in the rest of the formation represent recrystallized chert, and were originally non-siliceous rock such as slate.

Lynch Conglomerate

The Lynch Conglomerate has been described (Pt. 1, p. 221) as the stratigraphic (and less altered) equivalent of the Dora Conglomerate. The formation consists of 3000 feet of tuffaceous greywackes grading up from coarse basaltic conglomerates at the base into silty and quartzose beds immediately below the Owen Conglomerate. The uppermost member is a subgreywacke grit with small quartzite and quartz fragment pebbles set in a sericitic and chloritic matrix. The varvoid silts are composed mainly of sericite with some chlorite, clay minerals and fine quartz. The major part of the formation, and the one which is the subject of most debate, varies from slate to tuffaceous breccia. The latter consists of particles of slate, basalt and trachy-basalt with broken crystals of augite and felspar with fine-grained sericite and chlorite.

Some alteration of augite to chlorite may have preceded deposition of the sediments, but in many rocks augite is fresh and was apparently buried shortly after derivation from its source rock. This

is consistent with rapid erosion and deposition in an active tectonic environment. In general the latter metamorphism of the rocks is directly related to grain size and content of basic rock fragments, so that the most altered rocks are the basaltic breccias and the least altered are the slates.

Basic Lavas

The spilitic lavas of the Cambrian geosyncline have already been described for the region, and in particular for the occurrences at King Island and Penguin, by Scott (1951 a and 1952). The reader is referred to these accounts for details of those rocks. Scott (1954) has also described the deuteric stages of alteration and some features of the regional metamorphism of these rocks. The Queenstown lavas, though lacking visible pillow structures, are mineralogically spilites, and similar to Scott's examples. Plate D, fig. 5 shows a typical member of the suite whose lavas commonly have isotropic or felsitic bases with phenocrysts and/or porphyroblasts of felspar, and sometimes bear large unaltered phenocrysts of augite. Even where augite is fresh, rocks are otherwise highly altered; vesicles are filled with calcite or quartz (not chlorite) and felspars are irresolvable masses of pinite or sericite. Study of numerous samples taken from the whole area of the range show that it is impossible in any given case to be certain of the composition of the original felspar. So widespread is the sericitising epidotising and introduction of secondary felspars that commonly there are not more than the faintest relics of original minerals.

Original felspar compositions in spilites may sometimes be deduced from the textures of the rocks, but deductive conclusions can usually be debated. Thus Scott (1951 a, p. 131) has deduced from the occurrence of graphic intergrowths of augite and albite in the lavas at King Island that the albite was primary. The ternary system diopside-albite-anorthite (Bowen, 1928, p. 46) shows that augite and albite may form eutectics in soda rich basalts, but it also shows that anorthite and augite may form eutectics in calcic rocks.

In basalts anorthite is very rare and it seems a reasonable assumption that the albite of the graphic intergrowth described by Scott was magmatic. Bowen's figure indicates that the eutectic proportions of albite to diopside are about 20/1 while the intergrowth in Scott's (1951 a, p. 4) rock has proportions fairly close to the 43/47 proportions of the anorthite diopside eutectic. The graphic intergrowths could thus signify that the original felspar was anorthite and that this felspar has been replaced by albite. The fact that the pyroxene in the intergrowths is diopsidic augite might, however, completely alter the picture and all than can be concluded is that idealized experimental information on crystallization is probably inadequate for dealing with the problem, and that Scott's evidence is inconclusive.

This is typical of the spilite problem. The rocks in question probably represent the best exposed and least altered of the Tasmanian spilites, so

rocks elsewhere can hardly be easier to interpret. Other empirical approaches, still using texture, are probably no more reliable than the last. The clearest case which can be made, and even this is weak, is that some rocks contain no recognizable albite, either secondary or original. Such rocks (plate D, fig. 5) may contain up to 10 per cent of highly altered felspar phenocrysts alongside unaltered augite, and it might be concluded that because albite is usually stable and appears quite fresh long after augite becomes unstable, the altered felspar was originally a calcic plagioclase.

Further empiric evidence, this time favouring an original high soda content in the lavas, is found in rock textures other than the graphic intergrowths discussed above. Some highly felspathic lavas on the Tullah Tram and on the Comstock Tram carry only small amounts of augite, perhaps 2-5 per cent, as ferromagnesian mineral, and on this score alone are probably trachy-basalts or augite-trachytes. Despite probable alterations of felspars to albite and oligoclase it seems unlikely that the rocks have ever been much different from what they are now.

Again, the general absence of ophitic or porphyritic-granular textures among the lavas indicate that they are not normal basalts. This is the more suggestive since basalts with relatively low proportions of augite might be expected to be ophitic rather than to have the simple porphyritic habits of the Cambrian lavas (Clark, 1952).

Among the original rocks of the region there are, apart from spilites, possible hornblende andesites. One from the tuffs on Lynch Creek contains hornblende which, though altered, appears to be an original mineral. In the vicinity some actinolite crystals occur, but these are acicular and clearly have grown on augite. While these cannot readily be confused with the idiocrysts of very decomposed hornblende occurring in the tuff the hornblende may still be secondary. This example along with a similar rock described by Scott (1954, p. 140) and a number of indisputed hornblende lavas recently discovered by Banks (personal communication) indicate a widespread but probably minor andesitic vulcanism in the region.

Fortunately, little depends on knowing the precise composition of the original lavas. Not only do deuteric and later metasomatic processes overlap and resemble each other, but from the ubiquity of the association it seems that the processes are related, and can be treated together. It is believed that most rocks originally belonged to a calc-basalt—trachy-basalt—trachyte-suite like those of present day oceanic environments, and they included sub-aerial as well as submarine representatives. It is believed also that the extrusion of the lavas was probably controlled by faulting movements related to those which later gave rise to the Dundas and West Coast Range geanticlines, and which controlled the upward passage of metasomatizing sodic solutions. It seems probable that these solutions were most active during the Tabberabberan orogeny, but they may also have had some effect during the Tyennan orogeny, and they may have been effective in causing contemporaneous spilitising of the lavas.

ALTERED ROCKS

The Anamorphic Sequence

Of all the rocks, the basic lavas are the most sensitive to the earliest changes of pressure and temperature. This is partly because of their mixed composition and partly because their felspars and pyroxenes are metastable. These contrast with hydrous minerals and quartz of the stable slates and quartzites. Attention will be directed first to the stages of alteration of lavas and tuffaceous greywackes.

Stage I. Calcic felspars are sericitised but there is little other change except that the silica and lime freed in this process find their way into vesicles of lavas and pervade the greywacke country rock. The latter is sometimes silicified along pervious breccia bands or veined with calcite and lavas are often completely silicified (Scott, 1954). Most of these effects, which could be the result of either deuteric or imposed metamorphism, require only low temperatures and the introduction of water and carbon dioxide.

Stage II. In the groundmass of the lavas, in the matrix of the tuffs, and not necessarily associated with original felspars, small clusters of red felspar are formed and red felspar veins cut the rock. Both felspars have a refractive indices np = 1·51, ng = 1·54 (Ab$_{95}$ An$_5$). In this and all the subsequent changes of plagioclase Eskola's spilite reaction is probably important. The reaction reads

$$CaAl_2Si_2O_8 + Na_2CO_3 + 4SiO_2 = 2NaAlSi_3O_8 + CaCO_3$$
1 ANORTHITE + 1 SOD. CARB. + 4 SILICA = 2 ALBITE + 1 CALCITE
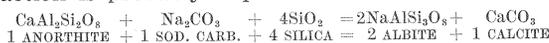
Eskola (see Barth, 1951, p. 286) has demonstrated that this reaction is reversible with pressure so one might conclude that the albitising, whether deuteric or imposed, occured at relatively low pressures. If solutions were juvenile this low pressure need not signify very shallow depth but merely that solutions had free egress to regions of low pressure. However hypothetical the source of these solutions might be, there is no question that silica, sodium and carbon dioxide were added, and it will be assumed for the present that there were solutions of this kind.

Stage III a. Solutions and reactions similar to the last, but with higher temperatures, caused the formation of many minerals of the lavas. Prehnite, which occasionally fills vesicles in the Rosebery Lavas and the King Island Lavas (Scott, 1951 a) may be formed along with albite, thus:

$$4CaAl_2Si_2O_8 + 2Na_2CO_3 + 6SiO_2 + 2(MgFe)SiO_3 + 3H_2O \gtrless 4NaAlSi_3O_8 + 2CaCO_3 + Ca_2Al_2Si_3O_{10}(OH)_2 + H_4(MgFe)_2Al_2SiO_9$$
4 ANORTHITE + 2 SOD. CARB. + 6 SILICA + 2 ENSTATITE + 3 WATER ⪌ 4 ALBITE + 2 CALCITE + 1 PREHNITE + 1 AMESITE
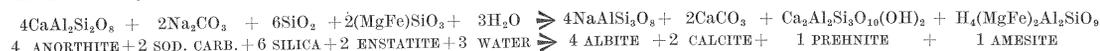
The amesite molecule may combine with serpentine coming from hydration of pyroxene to form chlorite and this would explain the occurrence of chlorite alongside prehnite in vesicles. It is characteristic of this stage that augite is broken down.

Stage III b. Probably at slightly higher temperatures or pressures there occurs a third reaction which introduces hydrogrossular.

$$4CaAl_2Si_2O_8 + 2Na_2CO_3 + 4H_2O + 2(MgFe)SiO_3 + 5SiO_2 \gtrless 4NaAlSi_3O_8 + CaCO_3 + CO_2 +$$
4 ANORTHITE + 2 SOD. CARB. + 4 WATER + 2 ENSTATITE + 5 SILICA ⪌ 4 ALBITE + CALCITE + CARBON DIOXIDE +
$$Ca_3Al_2Si_3O_8(OH)_4 + H_4(MgFe)_2Al_2SiO_9$$
HYDROGROSSULAR + AMESITE
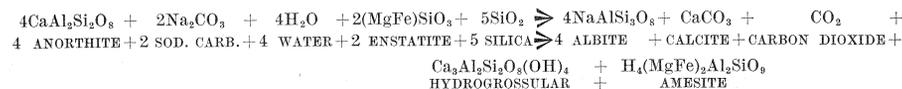
The close similarity between the last two reactions suggest that products of each should be found in close proximity. This is not only so among the Tasmanian spilites (Scott, *loc. cit.*) but is true among the pyroxenites and spilites of Dun Mountain in New Zealand where great veins of each mineral are found. The association of spilite and pyroxenite with hydrogrossular is probably general, although many workers have given descriptions of hydrogrossular without recognizing it as such. This is obviously the nature of the so-called " glass " which invades and lines vesicles in Teall's (1899, p. 86) example of Lower Palaeozoic spilites in the Southern Uplands, and in Stamp and Woolridge's (1923, p. 38) example. Ballsillie (1932, p. 109), at Ballantrae, also recognizes " vitreous matter " which " gathers into vesicles " and describes a similar material veining the neighbouring serpentine as having R I 1·728, and as being " like a variety of garnet ". See also Scott (1951 a). An important association of the hydrogrossular on Dun Mountain is that it forms the gangue mineral of chalcopyrite lodes (Bell *et al*, 1911, p. 60, and Grange, 1927, p. 160). Elsewhere in New Zealand it occurs in the association calcite, tremolite, chlorite and prehnite (Turner, 1935) which also occurs in Tasmania. It very clearly falls into a moderate temperature zone, perhaps about 200°C, and belongs to the greenschist facies. Hydrogrossularising is an important process associated with albitising.

Stage IV. Recrystallization of lavas proceeds rapidly with the final resorption of the original calcic felspars and the formation of new oligoclase-rich rocks. Important changes here are epidotising and formation of actinolite, but there is not yet the development of biotite or garnet which are commonly present in similar rocks (Turner and Verhoogen, 1951, p. 469). At this stage the rocks of Lynch Creek and East Queen River begin to grow minute stringers of quartz and epidote, and under the microscope small grains of quartz are recognizable as entities for the first time. Under the microscope epidote is scattered throughout the slides and grouped in clusters around that which was previously lime-rich felspar or vesicle fillings. Here such augite as had till now escaped chloritising becomes altered to fine needles or fibres of actinolite, and veins of tremolite cut the rocks. Occurrences of tremolite vary from veins some feet wide on Lynch Creek down to small isolated needles, and probably result from a re-organization of the material of the chlorite and calcite. From this point on there is a robbing of the rock of carbon dioxide, and a general dehydration, and calcite disappears. Although this has not been observed by the writer, reorganization of prehnite and hydrogrossular probably occurs with the first appearance of epidote, these two minerals being made over to epidote.

Stage V. In the succeeding stage of meta-morphism the rocks are substantially altered to felspar porphyries when the whole rock (e.g., Red Hills and on the Mackintosh River at Tullah) is made over to oligoclase Ab₉ An₃. Throughout all of the previous stages some chlorite has been present, but in diminishing amounts, and at the optimum of this stage it is usually about 4 per cent of the rock and the only ferromagnesian mineral. Epidote also disappears at this stage and its lime presumably goes into the new oligoclase felspar. Barth's (1951, p. 284) graph gives a temperature of under 300° for this reaction. These rocks are true syenites and it is small wonder that Twelvetrees gave them this name. As it is quite impossible to distinguish some of these from coarse trachytes under the microscope the only evidence of their origin must, perhaps, always be field observation of volcanic or sedimentary structure. It is at this stage that biotite first appears in faded wisps among the felspars. Always the minerals look as though they had been weathered and the felspars, no matter how new, are powdered and pitted with sericite or kaolin. The only index of newness now lies in the degree of idiomorphism of felspars or in the relict outlines which felspars occasionally leave behind them.

Stage VI. The blotchy syenites of the Murchison River provide the type of the next stage of alteration. Here the rock is coarse grained with crystals of red and pink felspar from 2-5 mms. across and with biotite and dark-green chlorite, obvious even in hand specimens. The felspar is now only in part oligoclase, and is 50 per cent or more of orthoclase. There is usually little twinning or zoning of the plagioclase and felspars are highly sericitized.

Stage VII. The final stage is represented by the granites of the Murchison River and Mount Darwin Plateau. Taking the latter occurrences first, the felspar is orthoclase, and quartz is very variable, from 10-40 per cent. Felspars are, on the whole, sericitized and are hypidiomorphic. The quarz is most interesting; it is interstitial and often occurs in tiny grains just as it might in veins or in a quartzite; groups are made up of individuals of differing sizes and it appears that the granite approaches normality with the growth of these crystals into larger compound units (plate B, fig. 6). The largest and most nearly normal of these crystals are conspicuously shadowy in their extinctions as though their constituent grains had been badly assembled.

The ferromagnesian minerals, biotite 1 per cent and chlorite 3 per cent, are also curious. The chlorite is so widely disseminated through the rock as to give it a greenish hue, but is inconspicuous in thin section. Some chlorite, which occurs in stringers, does not appear to be an alteration product of pre-existing minerals, but the biotite of the rock appears, because of its highly idiomorphic character, to be an alteration product of the chlorite. Biotite is very sparse indeed, so sparse that it appears in none of the writer's thin slices. It appears in the field, however, as hexagonal crystals some 3 mms. high and wide. Barth (1951,

p. 337) claims that such associations belong to the epidote amphibolite facies and choosing antigorite to represent chlorite he suggests the following reaction occurs at about 250°.

$$Mg_3Si_2O_5(OH)_4 + KAlSi_3O_8 \geqslant KMg_3AlSi_3O_{10}(OH)_2 + 2SiO_2 + H_2O$$

ANTIGORITE + ORTHOCLASE $\geqslant$ BIOTITE + 2QUARTZ + WATER

This provides a possible source for a small part of the granular quartz of the rock but the temperature suggested by Barth seems very low. Were these rocks schistose or hybrid gneissose types this low temperature would cause no surprise, but in interpreting the rocks in facies terms we now have to accept completely crystalline rocks as low temperature derivatives. The most common rock contains one-inch crystals of pink orthoclase set in a coarse groundmass of orthoclase, quartz and chlorite and though broadly stratified it is an undoubted granite.

That is a very broad picture of the granite which is very varied and which, in some bands, is fine grained or approaching graphic in texture, and which in some bands has both biotite and muscovite mica. Here again it may bear pegmatitic veins of chlorite with pyrite or irregular stringers (six inches wide) of magnetite, both clearly part of the rock and originating more or less *in situ.*

The Murchison River granite is similar to the Darwin granite except that chlorite is very minor, and biotite is more prominent. Interstitial quartz is present here in large crystals rather than granules, but shadowy extinction is general. This granite has one distinctive feature, viz., the presence, along the east bank of the gorge, of an aplitic phase paralleling the contact with the haematised conglomerate. The rock (plate D, fig. 6), is a typical aplite with interlocking grains of quartz and felspar in proportions of 40/60, and the felspar is orthoclase and orthoclase perthite in equal proportions.

Summary

The sequence of stages so far described is selective, but in the field there is an overlap of all stages and the sequence is thought to be representative. At first there were hydrating processes involving the formation of sericite and chlorite, and these were paralleled and followed by anamorphic reactions of building of felspars, biotite and tremolite. While the materials of different reactions were often used several times to build up new minerals, the alteration of basalts to potash granites necessarily involved the addition or subtraction of materials. In the first sericitising stage there was an influx of alumina and/or elimination of silica (*cf.* Turner and Verhoogen, 1951, p. 483). In the next three stages where albite was formed and augite and then chlorite eliminated there was an influx of soda and silica with an influx of lime, magnesia, and iron. In the Murchison syenite stage there was a progressive elimination of soda and water and an increase in potash. These are all absolute changes where individual pebbles, or beds of rock, can be said to have lost original minerals and gained others of quite different compositions.

The incoming of quartz in the potash granites probably represents a different and relative kind of change and may not mean that there has been an addition of silica to the syenites. The elimination of oligoclase and its replacement by quartz could readily mean that both soda and alumina have been removed and excess silica left behind. This kind of reaction would be different from the preceding examples also in that it must involve some change in volume.

Volume Changes in Metasomatism

The porphyroids, more than other rocks, demonstrate that it is equal volumes and not equal weights of minerals which replace each other. This principle, enlarged on by Turner and Verhoogen (1951, p. 483), may be critically important in determining reaction in rocks under great pressures or where other circumstances preclude migration of materials. In porphyroid metasomatism the principle may, however, be relatively unimportant in determining the course of reactions and may have a different kind of significance. For

example, if replacement of silicate rocks can be demonstrated to have occurred there must often have been migration of material to make up for the gain or loss of weight per unit volume. This is made clear by Lindgren (1924, p. 507) in relation to the iron silica and sulphur replacements at the contact zone at Bingham, and obviously the principle must apply to replaced silicate rocks also.

Nevertheless, there are reasons for supposing that there may have been some appreciable volume changes in porphyroid metasomatism. The aplite veins of the Murchison River granite are in two instances ptygmatically folded, a kind of folding which signifies to the writer that there has been a shrinkage of the rock enveloping the aplites. The shrinkage mechanism canot be unequivocally demonstrated by the examples on the Murchison River, but suitable cases can be taken from photographs of ptygmatic folds in a similar porphyroid granite of Finland (Sederholm, 1926, figs. 30-40). Useful examples showing two or more intersecting and ptygmatically folded dykes (fig. 20) are thought to be fully explicable in the following terms.
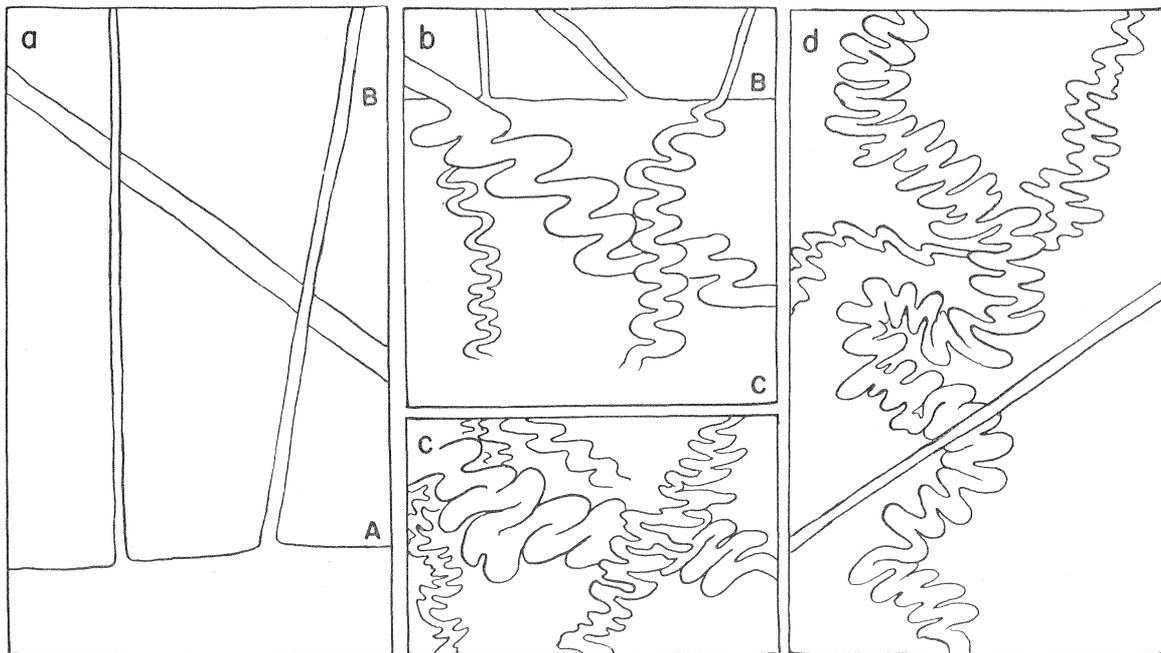

FIG. 20 a.—Three aplite dykes rise from the contact of a potassic granite into an oligoclase syenite. The potash front advances from a Level A to a higher level B and partial removal of silica and alumina decrease the volume of the altered rock in the proportion A-B to B-C fig. 20 b. The aplite *dyke* which has the same composition as the potash granite is unaltered and retains its volume, but it adjusts itself to its new vertical dimension by folding (20 b and c). The radius of folds in any dyke is related to the thickness of the dyke (20 c). When a dyke is tightly folded its effective thickness increases and it folds on a larger radius (fig. 20 d). (Based on Sederholm 1926, figs. 30-40.)

In the first instance (fig. 20 a), aplite veins run ahead of their respective front into the overlying zone. When the potash granite moves up and takes the place of the sodic syenite it appears that there is a reduction of the volume of the syenite. Dykes having the same composition as the granite are, however, unaffected by this change and, retaining their own volumes are folded in the manner shown (fig. 20 b and c).

For the Murchison granite this kind of reduction in volume coincides with the elimination of oligoclase and the incoming of quartz. This implies that soda and alumina have migrated in a wave beginning at this horizon.

The upper limit of the wave of aluminium metasomatism is well defined at several points in the range by the sericitizing and felspathising of quartzites. At the Lyell contact the replacement of

quartz by sericite clearly requires the addition of alumina and alkali, and if it is assumed that all of the quartz replaced has gone to sericite, there must have been an increase in volume by about 100 per cent. The intense local contortions of the sandstone dykes at Lyell suggest that there may have been some expansion and consequent re-adjustment of the schist along the contact. The schist must under these circumstances have tended to be squeezed into anticlinal crests or other zones of relief. This might explain the " mashing " which seems common at similar contacts elsewhere (Van Hise, 1897, p. 239) and the common difficulty in tracing beds across contacts. Apart from con-tortion there is no evidence of great increase in volume at contacts and it seems that silica must have been dissolved in large amounts to make way for the incoming sericite. The silica, apart from that required to make up sericite, has apparently passed upwards into the Owen Conglomerate. Fel-spathising of the quartzites, as at Darwin Spur, must also have involved the introduction of alumina and the removal of silica in the same way.

Retrograde Metamorphism

By the time late hydrothermal injection of the porphyroids commenced, the permeability which had directed earlier solutions along stratification planes had disappeared. Sericitising, chloritising and kaolinising were thus centred around broad crush zones like the Linda Disturbance, or late faults such as the N.E. tensional faults.

Late Sericitising and the Origin of Quartz Porphy-ries.

The term sericite, as generally applied to the micaceous alteration products of alkali felspars, appears to be conventional in that in many cases where sericite is used the mineral concerned is probably the soda mica, paragonite, and not the potash mineral. Yoder and Eugster (1955, p. 255) define sericite as " a field term used to describe any fine-grained white mica " and state, " The white micas include muscovite and paragonite ". " Sericite " will be used in this vague but customary sense in this account.

In view of the richness of the porphyroids in soda it must be expected that in some cases the hydration products of felspars will include para-gonite. Experiments by Morey and Chen (1955, p. 999) suggest, however, that in the breakdown of albite the potash impurities of the mineral tend to remain behind as muscovite, while sodium compounds pass into solution. Perhaps this ex-plains a small part of the relatively high concentra-tion of potash in the Lyell schists near Queens-town, and it suggests that in some places sericitis-ing may be merely a process of leaching of soda. At still other places it seems probable that sericitis-ing involves very little potash and the process is one of paragonitising.

The sericitising of the Owen Conglomerate at Lyell is, in fact, different from either of these processes, for it is clearly a process of introduction of potash. Analyses of the specimens of plate A by Mr. Ritchie (D.S.I.R., New Zealand) show the

following variations of alkalies across the contact zone of the Owen Conglomerate. Specimen 1 (plate A, fig. 3) is taken from the conglomerate at the stage of metamorphism where the quartz begins to lose its lustre and has an Na_2O content of 0·1%, and a potash content of 1·6%. Less than two inches away, where the rock is the sericite schist of plate A, fig. 6, the corresponding con-tents are Na_2O 0·4% and K_2O 4·2%. There has been an addition of potash to the quartzites to form muscovite.

The coarser quartz porphyries are non-schistose analogues of the quartz-sericite schists, and the common occurrence of orthoclase porphyroblasts in them indicates that potash was added to the rocks during their formation. Since the potash causing these alterations was introduced during the cooling phase of metamorphism it seems prob-able that there are two sericitising phenomena associated with porphyroid metasomatism. In the stage of advancing fronts sericitising probably involves leaching of soda, and in the second or late phase, sericitising involves an introduction of potash. The source of the potash in the second case is attributed by the writer to the leaching by late phase solutions of still deeper seated rocks, and it is supposed that sericitised potash granite occurs at a depth less than 5000 feet below the present quartz porphyries. Without this explana-tion the presence of a clearly defined high tempera-ture zone of introduction of potash (i.e., in the granites) is at variance with the introduction in the same area of potash in low temperature seri-cite (muscovite) schists. In the West Coast Range all felspathic rocks are sericitised in some degree; in general the felspar porphyries have suffered least, and progressing through rocks with increas-ing amounts of quartz to quartz porphyries altera-tion becomes more intense. In the quartz porphy-ries hydration has sometimes proceeded to the ex-treme where felspars have been wholly leached of alkalies and reduced to kaolin, as for example in the area within a forty chains radius of Queenstown.

During complete sericitising of alkali felspars some 20 per cent by weight of the original mineral is removed as silica in solution. Some of the silica so released from the porphyroids probably found its way through fault fissures and emerged at the surface in hot siliceous springs. Much silica was, however, precipitated in the aquifer of the Owen Conglomerate (Bradley, 1954, p. 231) and in veins. Where solutions can migrate so freely, hydration might easily go to completion and felspars be re-duced to kaolin; but this seems to have happened only on the Linda Disturbance at Queenstown. It seems instead that there was usually some struc-tural restriction on transport and that at times there was no appreciable movement of solutions. The rock and the immobile solutions constituted a closed system in which composition stayed constant and where it was possible for an equilibrium to be set up between quartz, felspar, sericite, water, potash and soda. In particular, silica accumulated until it reached saturation point and then crystal-lized in situ as quartz. Most workers would agree that this may be the mode of origin of quartz in sericite schists, but that is not all that is in-

tended here. The silica in the porphyroids very often crystallized at many centres within the sericitised felspar porphyries as idioblastic crystals, and so formed quartz felspar porphyries and quartz porphyries. This idea has been proposed in principle by several workers who have claimed that quartz phenocrysts may be porphyroblasts. Thus Scott (1954, p. 140 and plate 4, figs. 1 and 2), Stanton (1955, p. 606) and Goodspeed (1937) have all described the pimply protuberances around large quartz crystals as growth structures and have called the crystals porphyroblasts.

The main contribution of this work is to establish that this process of quartz porphyritising may be of regional extent, and further that it may be the result of retrograde metamorphism. This principle of sericitising and quartz enrichment applies equally to any felspathic rocks whether lava or greywacke, and whether or not they have been metamorphosed to felspar porphyries. The regional quartz porphyries in Tasmania include all these types, but since the felspar porphyries provide the most favourable raw material for such changes and naturally occur in the most favourable sites for late injection, most quartz porphyries are altered felspar porphyries. At second hand they are altered sediments and lavas and there is even some case for supposing that ultrabasic rocks near Dundas (Elliston, 1954, p. 173) may also be secondarily altered to quartz porphyry.

Even on the regional scale this general idea is not new for it was expressed long ago by Wadsworth (1887, p. 68) who stated " part of the corroded and fissured quartz penetrated by the groundmass in quartz porphyry . . . has been formed in the rock as an alteration product subsequent to the solidification of the rock, and is due to the migration and aggregation of the silica set free during the alteration of the rock ".

The proof of these assertions must usually rest in the final instance on the field demonstration that the porphyries have the structure of sediments (Bradley, 1954) rather than on microscopy, but there are numerous confirmatory lines of evidence, and some details of the crystallization of quartz are convincing.

Without listing the deficiencies of the magmatic theory on the following scores this thesis explains the presence of quartz phenocrysts in rocks ranging from sediments through granitoid rocks and augitic lavas in Tasmania to gabbros in Minnesota (Wadsworth, *loc. cit.*), and explains the presence of so-called quartz xenocrysts in the olivine basalts (Exeter Traps), along with quartz porphyry conglomerates on the margin of the Dartmoor Granite (Tidmarsh, 1932, p. 730).

This thesis of origin of quartz porphyries implies that similar regional porphyries in other parts of the world should also be associated with intense sericitising There are, it seems, very few quartz porphyries which are not highly sericitised; there are many in which the groundmass consists exclusively of sericite, and more than a few in which the groundmass is highly kaolinised.

In general, regional quartz porphyries are characteristic rocks, perhaps the most characteristic (next to pegmatites) of intensely pneumatolysed terrains. When they occur as veins as at Mount Bischoff, Tasmania, the quartz porphyries may have many of the characters of pegmatites and bear cassiterite and topaz.

Quartz Felspar Porphyry

The distinction made by previous Tasmanian workers between felspar porphyries, quartz felspar porphyries and quartz porphyries is a useful one in that it denotes the degree of alteration of the rocks. Under the microscope the first appearance of free silica in the rocks is in the form of an indeterminate granulation of the groundmass between the felspar crystals. The next stage shows some of these granules growing together in very irregular quartz porphyroblasts, 0·1 mm. across. At this stage there are few, if any, crystals showing resorption cavities or inclusions of any kind. In the next stage where quartzes are visible in hand specimens and are some 1·0 mm. across, the rock under the microscope is the ill-defined quartz porphyry or quartz felspar porphyry of convention; it has up to 5 per cent of quartz, but the felspars are still readily recognizable as felspars—this is the " quartz felspar porphyry " of this work.

Quartz Porphyry

Beyond this quartz felspar porphyry stage the groundmass of the rock becomes vague and hornfelsic looking; it is made up of many small irregular quartz grains, sericite flakes and specks of kaolin which may obscure the felspars completely. The final type of quartz porphyry, in which quartzes are some 5 mm. across and from 5-20 per cent of the rock, is what the writer would describe as the ideal quartz porphyry. This consists of quartz, often resorbed, set in a groundmass almost exclusively of sericite, but with perhaps a little chlorite. In hand specimen the rock is often a dark blood-red from specks of haematite scattered through it, but in thin section these are not obvious among the kaolin and sericite. This colouring tends to be distinctive of the more quartzose types, for the more felspathic frequently owe their colouring to chlorite and are often green. In the extreme type of quartz porphyry, flakes of sericite are commonly arranged in a rectangular pattern which suggests that they have been formed on cleavage planes of felspar, but this is probably not the case. This texture is the antithesis of the schistosity of the nearby and related sericite schists, and the cuboid ordering of the flakes seems to be the result of growth and adaptation in a strain-free environment. In the absence of strain, orthoclase grows in these rocks as pimply porphyroblasts (plate B, fig. 3), but the felspar usually remains less than 10 per cent of the rock and is prominent only in the Mount Bischoff porphyry. It seems from the degree of sericitisation of these felspars that newly formed orthoclase is very readily reconverted to sericite.

Shadowy Extinction

The quartzes of all the porphyries tend to have the shadowy extinction which is usually attributed to strain, and commonly have an irregular or pimply outline (plate C, fig. 5). Shadowy extinc-

tion in these rocks is, however, not the result of strain but of parallel or subparallel growth of quartz crystals. This can be seen in some specimens like plate C, fig. 1, which shows a large number of small quartz hexagons disposed side by side, but not quite parallel to each other. This kind of section can be duplicated very readily by cutting a section through the encrusting quartz crystals lining the inside of geodes, and the same structure is common in much fine-grained quartz from veins. It might be claimed that the section is, in fact, from a small vugh in the porphyries and that it has no other significance. In the porphyries there is, however, transition from the figured specimen through every gradation of disjunctive shadowiness to non-shadowy quartz. Disjunctive shadowiness is that where a large crystal is made up of a large number of discrete individuals, each of which has its own extinction and its own optic orientation (cf. Goodspeed, 1937). Orientations change abruptly from one crystal to the next, but the change is progressive across the larger compound grain and so extinction shadows move in one direction and in jerks. Even non-shadowy quartz has some submicroscopic disorientation, for it is common for the quartzes of the porphyries and of the potash granites to be biaxial and to have 2E as high as 10°. Although this is usually taken to mean that crystals have been strained the aggregate of plate C, fig. 1 would show a biaxial character if one used condenser and objective large enough to embrace all of the crystals at once. Conversely, the biaxial character of ordinary crystals to ordinary lenses could be due to the presence of submicroscopic crystals progressively disoriented from each other. If we follow this argument far enough down the scale of size we should arrive at disoriented unit cells which would represent a bent crystal and which would be a strained crystal of a kind. It happens, however, that crystals are not usually bent in earth movement but are usually sheared on varied planes and strain shadowiness is random. Such crystals which are common in the sheared quartz sericite schists show an irregular pattern of shadowiness and rarely give a clear biaxial figure. These shadows are of the type described by Hietanen (1938, figs. 4 and 13) from highly sheared quartzites. Neither they nor the Böhm lamellae described by Hietanen are quite the same as the disjunctive shadows of the porphyry quartzes.

Quartz Sericite Schists

Quartz sericite schists are strictly limited to narrow zones of intense faulting and at Lyell are most conveniently seen about half a mile from the Gap on the Queenstown road. The rock (plate A, fig. 6) is very similar to the quartz porphyries except that the sericite here is schistose and generally wraps around quartz crystals. In some cases sericite runs straight into the quartz grains as if the latter had formed after schisting and these same quartzes often have pimply margins. Quartz crystals, which commonly form less than 20 per cent of the rock, vary in shape and size; e.g., grains may be broken (plate D, fig. 4), equidimensional and round, bear resorption cavities, or may be irregular or elongate. Only the larger elongate crystals are aligned with the schistosity and they show no obvious optical orientation.

Shadowy extinction is general in these quartzes, but by contrast with the porphyry quartzes the movement of shadows is smooth in detail and is in random directions. From the distribution of fractures in the quartz of plate D, fig. 4 it may be concluded that breaking strains were unevenly distributed through that crystal. It seems probable, therefore, that in other crystals stressed to a point just short of breaking any residual strains would have distributions similar to that of the cracks. One should, therefore, expect extinction shadows at any one time to form a dark, irregular and rhomboidal grating which would expand or contract smoothly with the rotation of the microscope stage. This kind of strain shadow is common among the quartzes of the quartz sericite schists and will in a later paragraph be shown to have interesting implications.

Chloritization

Chloritization, like the previous processes, may be a late process as well as an early one of advancing fronts, and the late process is concentrated in shatter zones. Chloritized rocks resulting from this process are located around the intersection of shatter zones with lava breccias and conglomerates which escaped the earlier metamorphism, e.g., in the area within a twenty-chain radius of the Queenstown Smelters. Where Conglomerate Creek cuts the rocks twenty chains above the road bridge, the clays are just sufficiently strong to stand as outcrops in the stream bed, and here the sedimentary structure of a conglomerate shows up clearly, and relics of original individual felspars show up as paler green rectangles of sericitic clay in the darker green groundmass. Smears of the green material on a slide convey no more idea of its nature than does a smear of the clays of the kaolinised rocks. To convey this indeterminacy the term " earthy chlorite " is apt, but it is probable that the material is often more than 50 per cent kaolin and 25 per cent sericite. It is important to maintain the theoretical distinction between this material and the early or frontal chlorite sericite schists of the mine open cut, and fortunately there is a practical distinction also. The frontal chlorites are relatively tough and fissile and bear conspicuous disseminations of pyrite, whereas the late chlorite is massive clay without trace of sulphides. It might be tentatively supposed that the chlorite fraction of these rocks is the same as that of the late chalcopyrite veins which occur in the open cut. In the latter case sections can be made and the mineral determined as pennine.

METASOMATISM

General

Many accounts of metasomatism consider that exchange of material is restricted to a small bulk of mobile elements whose small ions are capable of passing through the interspaces of large ions such as those of oxygen and silicon. Read and Barth (1951, p. 313), who favour this view, see the proportion and position of oxygen ions as relatively unchanging during metamorphism, while

others like Poldevaart (1953, p. 501) assume where possible that the number of $(Si, Al)O_4$ tetrahedra in a silicate rock remains constant, and that changes are restricted to other constituents. Poldevaart recognizes, however, that in replacement ore bodies silica tetrahedra may be removed.

Just how ionic replacement is effected in metasomatism is understood no better than comparable ionic processes of crystallization and reaction in acid silicate melts, but one might agree with Lindgren (1933, p. 91) that " it is a process of practically simultaneous capillary solution and deposition ", and with Poldevaart (1953, p. 481) that " it takes place in the presence of a fluid phase-water ". Some system of particle-by-particle replacement seems to be the only possible mechanism which can explain pseudomorphic replacements of carbonate or silicate by sulphides. In these cases there are no complications of solid solution, or of exchanging small ions, &c., and it can only be concluded that there has been a wholesale change of material and a wholesale transport through what now seems to be solid rock. The scale of such phenomena is not always small, for many millions of tons of sulphides and silica must have been exchanged in the formation of ore bodies at Lyell.

Thus, while the principle that there should be the least possible migration of material accords with the economy of nature and is accepted here as a basic principle, it is clear that solid diffusion is not always the most effective transport mechanism. In the porphyroids transport in solution through fissures, between particles, and along crystal boundaries was probably more important than intra-lattice diffusion. The idea of a continuous system of fault fissures (arteries) of pore spaces (capillaries) and intergranular films (diffusional membranes) is as familiar as our own blood systems. In both systems transport may be effected by diffusion and bulk movement in large channels, and by diffusion alone in the smaller.

As distinct from the movement of cold water in surficial hydrological processes, transport in the porphyroids was by water at temperatures ranging up to 400°C, and it is considered that in this state water would in time penetrate the pores of most unmetamorphosed rocks. Other factors favouring transport of solutions in the porphyroids of the West Coast Range were the conglomeratic nature of the bulk of the sediments, the shallow depth at which metamorphism occurred, and the intense shearing of the less permeable strata.

To give some order of sizes involved in the transfusion system of the porphyroids it is suggested that, except for the slate rocks, solutions might reach through pore spaces to within six inches of every given point. Transport of ions in these solutions was primarily by diffusion but was at times by bulk movement also. Transport for distances less than six inches (usually less than two inches) is regarded as having occurred by diffusion through intergranular films.

R.S.—12.

Intergranular Films

The operation of films is best illustrated by reference to the growth of quartz porphyroblasts. In fig 21 a it is supposed that two quartz crystals A and B are suspended in water. This has some suitable flux dissolved in it and temperatures and confining pressure are such that water dissolves silica in appreciable amounts (Gillingham, 1948, p. 242). As crystal A is smaller than B it has a larger surface weight ratio, and because of this it may have a relatively larger number of unsatisfied bonds of its crystal lattice exposed at its surface, and may have a relatively higher free energy, than crystal B. The result of this is that the smaller crystal has, weight for weight, a lower heat of solution than the larger and will dissolve in the water more readily. If the water of our example becomes barely saturated with silica respective to the larger crystal, it must still be unsaturated for the smaller, which must dissolve away. Any resultant increase in the saturation of the solution must, however, cause the large crystal to grow and it will ultimately " absorb " the smaller (Turner and Verhoogen, 1951, p. 396).

If the width of the channel of fig. 21 a is decreased almost to vanishing point (fig. 21b) the same transfer process will operate more and more readily as the distance of travel of ions decreases until the stage of fig. 21 c is reached, where the lattices of the two crystals are nearly touching. The forms of adjacent surfaces are idealised in the figure for it is probable that crystal lattices will be strained and distorted at such margins. Despite this it is thought that the basic principle is probably valid and that there may be some irregular space between crystals which would accommodate ions of varying sizes. Sizes of spaces might vary widely depending on the kinds of crystal and lattice involved. Parallel flakes of mica or chlorite such as occur in a slate or schist would probably allow very little room and the same may apply to oriented grains in quartz schists. On the other hand, randomly oriented grains of framework crystals, of felspar and quartz, must often present spaces of at least the order of size of the unit cells to either side.

Growth of Quartz Porphyroblasts

We may thus visualize the existence between two quartzes of a film accommodating water as H and OH ions and perhaps as molecules. It is probable that at low temperatures the free charges to either side of the channel between A and B (fig. 21 c) create the same effect as if the solution were super-saturated, but with increasing temperature this condition must change and the water in the film become undersaturated with regard to the small crystal. Then unit cells would be disrupted in turn and $(SiO_4)^{4-}$ ions would be released into the solution. In general, the release would be from the small crystal and any freed $(SiO_4)^{4-}$ ion would simply move across from one crystal to the other, reorient itself and grow on the larger lattice. Succeeding ions would do the same in sequence and eventually the small crystal would be " absorbed " by the larger. In a rock consisting of small quartz crystals any larger one of these could thus build
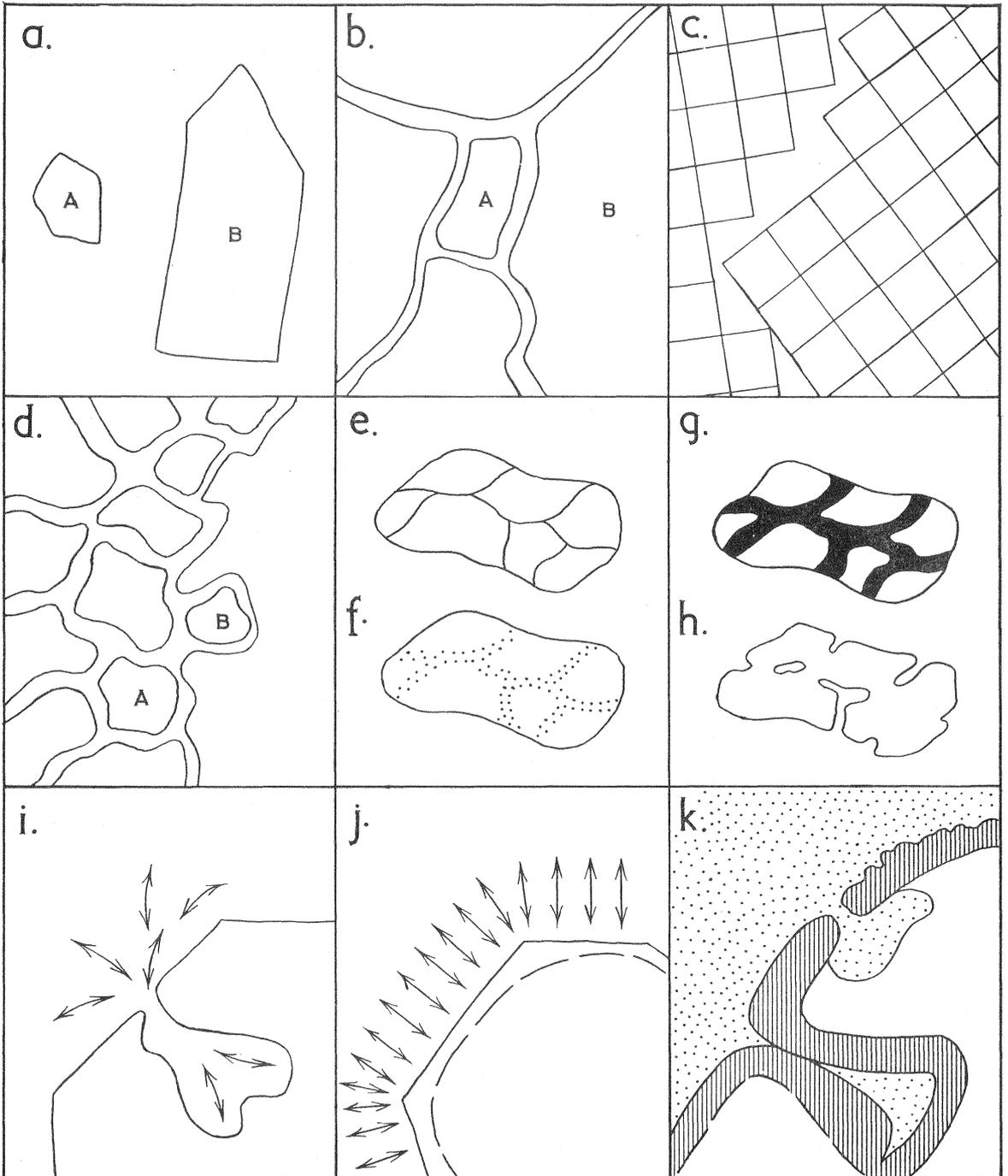
FIG. 21.—Resorption phenomena. 20 *a, b, c, d.* See text 20 *e:* shearing cracks in quartz. 20 *f:* shows a possible distribution of shearing strains in unbroken quartz crystal. 20 *g:* shows complete resorbtion of shear zones (*Cf.* plate D, fig. 4.) 20 *h:* shows partial resorbtion in a lightly strained crystal. 21 *i:* shows a picture of directions of diffusion of ions which is only true when a crystal has different solubility in different parts. 21 *h:* shows the pattern of diffusion of ions with a homogeneous crystal. 21 *k:* shows the effect of regrowth (shading) in closing resorbtion cavities. (*Cf.* plate C, fig. 6.)

itself into a porphyroblast. The operation of this process in quartz porphyries is well demonstrated by the pimply growths that can be seen on the margins of quartz crystals in thin sections. To make this obvious and unequivocal (in that there can be no possibility of magmatic origin) a porphyroblast that has grown in a quartzite has been chosen for illustration (plate C, fig. 5). Here the rock is an unstressed quartzite from Mount Bischoff, Tasmania; it forms the upward continuation of a quartz porphyry dyke. In more normal quartz porphyries quartz often grows in the same manner by the aggregation of very small quartz crystals such as occur in quartz felspar hornfels (Goodspeed, 1937).

Accompanying sericitization is a widespread saturation of surrounding rocks by colloidal silica; this sometimes silicifies the rocks with chalcedonic silica (Scott, 1954, p. 137), or at higher temperatures produces a hornfels with minute quartz granules. There seems to be a wide variation in the size of granules which might be formed in this way, so that when they are built up into larger crystals there is a corresponding variation of the "pimpliness" of the resultant porphyroblasts—for example, in thin section a fine-grained hornfels shows a relatively smooth outline and a quartzite shows a rough outline and so on.

Where obstacles, such as the minute felspar grains of hornfels and adinoles, lie in the path of growing quartzes they are not pushed to one side as happens in the growth of garnets. Nor does the quartz simply engulf the impurity and then in some unspecified way "clear itself", but the offending particle is chemically resolved and goes into solution. In fig. 21 d any particle of felspar such as A which is in equilibrium with the solution and its neighbours, will pass out of equilibrium if it is put into a position B where it is threatened with "capture".

In crystals a smooth outline represents a smaller relative surface and a lower free energy than does an irregular outline so that in adjustment towards lower temperature equilibria there is usually a tendency for crystals to fill in their depressions and round out their outlines. Despite the absorption of small crystals outside an optimum outline there is, it seems, a greater attraction on surfaces in the recesses of the crystal than on the protuberances for any spare ions which might be in solution. In the example fig. 21 d there must therefore be some tendency for solutions which lie in the recess around a potential inclusion of felspar to be poor in silica ions. If conditions are such that a felspar at A is in equilibrium with the quartz, the sericite and the solution, then the tendency at B must be for the mineral to be out of equilibrium. It will react with the solution to form sericite and silica in solution, and this silica will be deposited on the inside of the cavity. If a non-reactive compound lay in the path of the growing quartz it would be included in the grain, but since potential inclusions are usually silicates and are higher than quartz in Bowen's reaction series most potential

inclusions are resorbed. Quartz will, however, capture kaolin and water which may be considered lower in the reaction series, and chlorite which is near quartz.

Resorption of Quartz

The formation of resorption cavities in quartz crystals illustrates the principle of grain growth very clearly and demonstrates the extreme sensitivity of equilibria in intergranular films. When stress is applied to crystals, potential energy is imparted and the result is a warping or disordering of the ionic lattice. This energy, which is in excess of that normally possessed by the crystal allows a strained crystal to dissolve with greater ease than it would were it unstrained (Barth, 1951, p. 305).

Returning to the broken crystals of plate D, fig. 4 and to fig. 21 e-h we see again that quartz crystals may be unevenly strained throughout their lattices. A result of this is that strained crystals can never be in perfect equilibrium with enveloping solutions, and if the latter are saturated with respect to the unstrained parts of crystals they must be unsaturated with respect to the strained parts. If equilibria are critical and no other factor intervenes there must be some tendency towards solution of strained parts of crystals and the formation of resorption cavities. Ions released in this process must tend to migrate through the intergranular film and be precipitated on the unstrained parts of the same or adjacent crystals. (Fig. 21 k.)

Shapes of cavities are difficult to explain without this straining hypothesis. In any alternative thesis one must assume that solutions (magmatic or watery) must have had different solvent powers at different points around a crystal. This implies that ions migrate in the curious pattern of fig. 21 i and that they do not obey the known principles of diffusion. Most authorities would agree that the pattern of diffusion around crystals is that shown in fig. 21 j and that diffusion gradients around crystals are highest at corners and not in the middle of faces or in cavities. In general, crystals tend to be rounded off at corners.

Specimen quartz crystals dissolved in the laboratory do in fact become rounded, and so do felspars when resorbed in lavas.

Now, if it is accepted that resorption cavities indicate differential solution and that solutions themselves may not vary in solvent power the only alternative seems to be that the crystal being resorbed has variable solubility. Further, if the crystal has a uniform elemental composition any variation in solubility must be attributed to the arrangement of its particles, i.e., to a warping, straining or other disordering of its lattice.

This principle does not necessarily apply to minerals other than quartz, for in many crystals strain is taken up by gliding on cleavages, or by twinning; and many minerals (e.g., perthites) have variable compositions and solubilities in one crystal and this masks strain resorption effects.

The strain resorption effect can explain a number of puzzles in the literature and in the field. Misch (1949, p. 388) and much earlier Wadsworth

(*loc. cit.*) have proposed that resorption cavities are a result of crystal growth. Where growth occurs at the same time as resorption, the neck of a cavity tends to become constricted and finally to close up altogether (fig. 21 *k*). Only in this respect does Misch's explanation seem to be valid.

Up to this point a two-dimensional view has been taken of cavitation but it is a small step to imagine resorption as occurring in a plane normal to rock slices, and so to account for isolated islands of groundmass in the centre of crystals (plate C, fig. 6). It is easy now to see why it is that resorbed crystals should be so much more common in the dynamically stressed quartz sericite schists at Lyell than in the quartz porphyries. In general, it seems that schisting and porphyritising are complementary and that conditions favouring the one tend to eliminate the other. In eliminating shearing stress metasomatism has the same function as fluidity has in magmas, and it appears that the rocks of metasomatic environments will transmit shearing stress only for very short distances. Where stress is particularly intense, crystals are broken down into small units, but resorption immediately removes strain and regrowth of crystals follows. So rapid is this reaction that in the West Coast Range it is only around the latest faults that schisting occurs, and even along the Lyell Shear the porphyroids are characteristically non schistose.

Felspar Porphyroblasts

. The growth of felspar porphyroblasts is similar to the amoeboid growth of quartz crystals. Orthoclase and oligoclase porphyroblasts are respectively shown by plate B, figs. 3 and 5, and so far as growth is concerned the only difference between these and quartz crystals lies in the lack of resorption cavities and in the presence of zones and zoned inclusions.

Zoned Felspars

Zoned felspars in granites present one of the greatest difficulties to theses of origin of granites by dry diffusion. It seems improbable that a process of diffusion which allows the formation and preservation of unhomogeneous felspar crystals can at the same time permit the homogenising of wide granitic terrains made up of such crystals. In soda rich felspars it is common for zones to be only 0·1 mm. wide, and for successions of zones to vary in rhythmic or cyclic fashions (Barth, 1951, p. 150). These indicate sudden changes and reversals in composition of felspar and of the solutions or magmas which might have deposited them, and thus set problems for magmatists as well as dry diffusionists.

Interpreting crystal growth in terms of intergranular films provides a very feasible mechanism of origin of zones. One might visualise the growth of a felspar crystal on the wall of a pegmatite vein and imagine that composition, pressure and temperature of the solutions surrounding the crystal might vary because of opening or closing of the fissure. Then the growing crystal would be coated with layers of varied composition. As each layer was precipitated it would be out of circulation, and if there was no dry diffusion it would remain as a zone. Now, if the pegmatite vein is as in an earlier example, reduced to the size of an intergranular film, the zoning of crystals in solid rocks might be explained.

One might visualize a felspar as bathed in and growing in an intergranular film and that as the crystal grew the neighbouring crystals were resorbed to make room for the new felspar (fig. 22 *a-c*). The concentration of ions causing this growth and resorption might vary depending on steady migration of thermal zones or on sudden fluctuations of pressure in the continuous fluid system of pores.

It is because of such fluctuations that zoned inclusions in felspars become possible. As long as growth is slow and changes of composition of enveloping solutions are gradual there is time for the migration of ions, the filling of cavities and the resorption of potential inclusions. With sudden pressure changes it is possible for equilibria to change swiftly and for there to be sudden precipitation of a new kind of felspar whose constituent ions are evenly distributed through the solutions. With even distribution of ions it is possible and almost a consequence for growth of felspar crystals to be concentrated on the projecting pimples which thus grow together and capture inclusions.

Turning to the broader picture of intergranular films in rocks, it is possible to account for the metasomatic replacement of whole rock sequences. For simplicity it will be assumed for the moment that we have a quartz sandstone in which all pores and smaller intergranular spaces are pervaded by water at high temperatures. Clearly a recrystallization of the whole can be effected by exchange across intergranular films without a single ion moving more than its own width. This would satisfy the economy of movement of silica or oxygen as desired by Poldevaart, Read and Barth (*loc. cit.*). Now, if we have a uniform greywacke of the composition of granite, and if it be under conditions where it might crystallize as that rock, the maximum distance of migration of any element would be of the order of size of the constituent mineral grains. Since most of the rock is silicate there would be no need to require any of the larger ions to migrate more than their own width. These would stay roughly in constant positions while smaller ions migrated quite small distances through films, and readjusted themselves to the new equilibria. If the rocks were bedded and of variable composition, it is clear that there might be need for migration of ions from one bed to its neighbour, over distances of many feet. If large silica ions had to be moved there might be some difficulty, but were the formation permeable as in a conglomerate, or if the time factor were large, there would be no problem. On the other hand, if a bed like dynamically compacted Miners' Slate were involved, there would be no intergranular films between crystals and there would be no ready alteration of this rock.
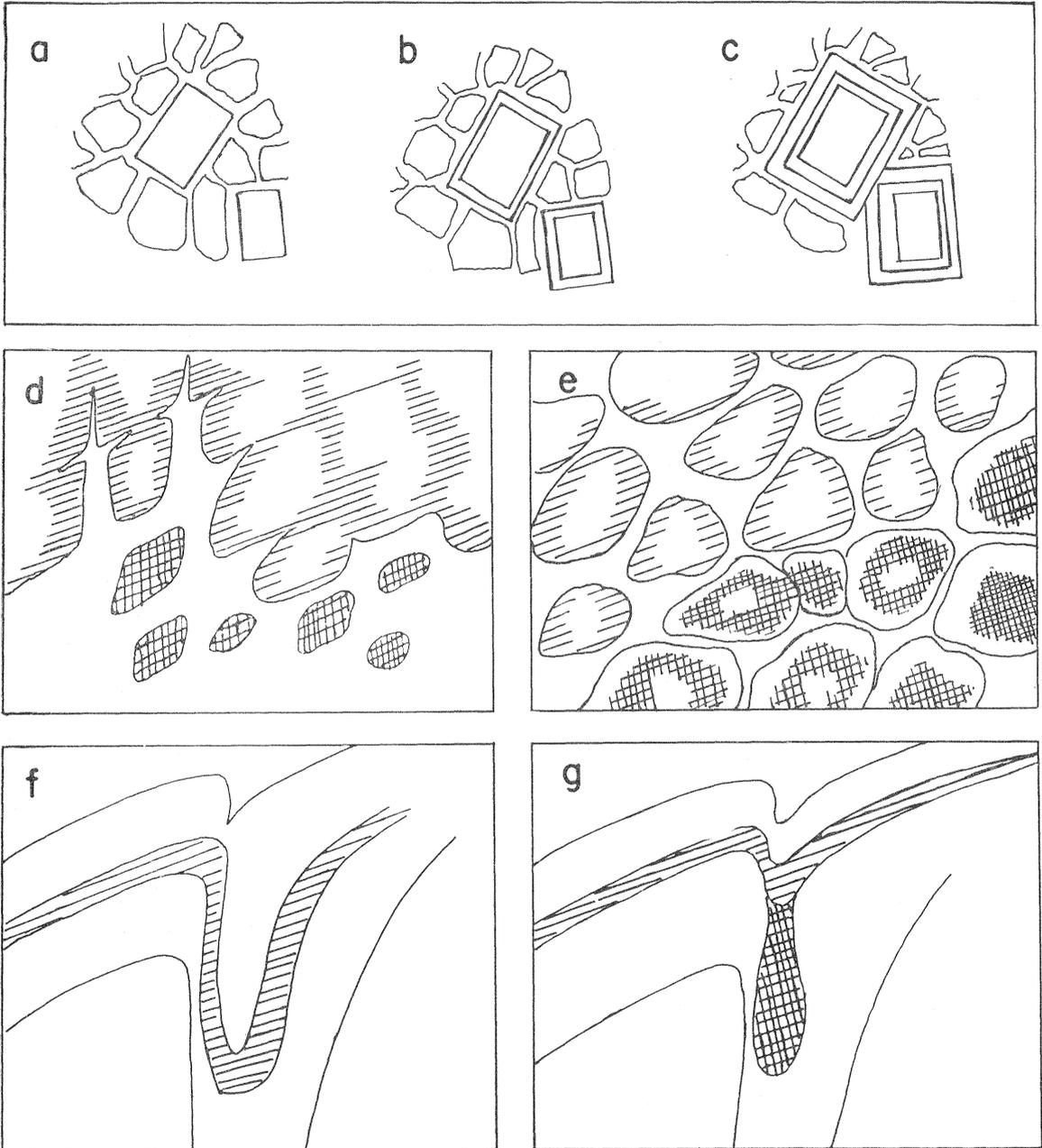
FIG. 22 *a*, *b*, *c*.—Stages in the growth of zoned felspars. 22 *d* and *e*: show how haematitic rocks and pebbles (shaded) may be captured into a zone of magnetite (cross hatched). 22 *f* and *g* show how a large part of a mineralized front may be captured.

The rules governing films and generally applying to film metasomatism of porphyroids can be set out thus:—

1. The thickness of films can be defined as the minimum thickness which, at the temperature prevailing, would allow he migration of the largest ions involved in silicate reactions. Films probably need be no larger than one order greater than the diameter of the largest ions. For practical purposes a rock being altered by means of such films can be regarded as solid throughout its metamorphism, and as only slightly less solid than granite at the surface today.

2. A slight solubility of silicates in water is all that is needed for exchange, because the distances of migration are so small. Obviously there must be some equilibrium between temperature, rates of migration, width of channel, such that the minimum width of channel would be maintained for each set of pressure-temperature conditions, i.e., at high pressures, low temperatures, and with low solubility the rates of diffusion and width of channels would be small. With increasing temperatures channels would widen until at melting they involved the whole rock.

3. Although water content of the rock might be low, say 2 per cent, all reactions might proceed in great dilutions of water, say 99 per cent.

4. The water and volatiles of the pore spaces need not in this static process ever be used up. Their effective role is comparable with that of catalysts.

5. Intergranular exchange will probably be at a maximum at the lowest depth compatible with high temperatures and retention of water.

6. The process will be at a minimum at great depths and in rocks with common orientations of crystal lattices (i.e., dynamic and deep seated metamorphism must generally be opposed to porphyroid).

7. For the common large ions of silicates the distance of migration is very close to the minimum which can be arranged with any other device, and need be little more than the diameter of the ion.

8. The equilibria existing across fluid interspaces are extremely sensitive to changes of temperature, pressure and concentration.

9. The process can happen only once to a given series of sediments. These rocks may, however, be subjected later to dry metamorphism.

10. The problem of the source of energy required to melt rocks in magmatic theory does not enter here, for very little rock is in solution at any one time, and because solutions are dilute and watery temperatures are at a minimum.

11. The mechanism does not depart from the already accepted principles of magmatism or metamorphism, and provides an important bridge between them.

Amplifying the last point, conventional magmatic schools accept and even proclaim the following ideas which are necessary or relevant to the hypothesis of intergranular diffusion and metasomatism. It is widely agreed that all the minerals of the alkali granites may form at relatively low temperatures from dilute water solutions (i.e., in pegmatites). It is agreed that diffusion in such solutions must be much swifter and more effective than is diffusion in acid melts and is much aided by volatiles. It is agreed that the parent material of granites may, and probably does, contain large amounts of water (Goranson, 1938).

Shand (1950), among others believes that a magma may to an appreciable extent consist of crystals; if this is so, and if the magma contains large amounts of water, the interstitial fluid must be very rich in water and must occupy narrow channels which in principle must be not unlike the intergranular films advocated here. There must be some point in any theoretical crystallization of granite magma where all magmatists are compelled to agree with Shand. Further, if and when crystallization from magmas has proceeded almost to the " last drop " and residual fluids finally react with early minerals to produce granite, the magmatist must logically find some stage where he is in complete agreement with this account. He cannot, therefore, object to the film mechanism on any point of principle.

Finally, the reaction series as proposed by Bowen (1928) and accepted by two generations of petrologists applies fully to the account given here for the origin of quartz porphyries. That series indicates that a succession of minerals may be precipitated in turn from a solution, and that at each stage the solution becomes enriched in the constituents of lower members. In the final instance orthoclase, then muscovite, and then quartz are precipitated from the " magma ". Alternatively, the series may be interpreted to mean that any one mineral may react with a " more acid " melt to form the next lower member in the series. Since it is improbable that quartz or muscovite can separate from dry quartz muscovite melt, those minerals must then be formed either by reaction of felspar with residual melt (clearly the only residual melt which can possibly exist with felspar at this stage is water) or must be precipitated from water solution (e.g., as in pegmatites). The first alternative is clearly the case of the quartz porphyries and the second directly implies that the interstitial quartz and muscovite of the potash granites has crystallized out of pegmatitic intergranular films. Although perhaps never expressed in these terms this is the magmatist's, not the granitiser's, view of formation of quartz and muscovite.

The Dora Conglomerate.

The Dora formation was described (Part I) as consisting largely of quartz porphyry conglomerate interbedded with occasional slaty beds, and as passing up near the top of pyritic chlorite beds and haematized conglomerate. At that horizon there is some passage through haematitic rocks from the porphyries below into the quartz conglomerate above.

It seems probable that the Dora formation was originally a felspathic greywacke conglomerate, perhaps quartzose towards the top, and that during the earlier stages of metamorphism it was permeated by felspathising solutions. Here were formed albite-oligoclase rocks of keratophyric types just reaching to a grade with biotite. The correlative formation at Lynch Creek has been described as bearing tremolite, but metamorphism there was gradational and rather mixed. At Lake Dora the entire formation is relatively uniform for metamorphic grade and occupies a marginal position between the biotite-chlorite sub-facies and the albite epidote-amphibolite facies of Turner and Verhoogen. The same formation on the other side of the range and below Mount Geikie contains the

hornblende-bearing rock described by Scott (1954, p. 140). The latter rock appears to belong to a slightly higher grade, viz., the albite-epidote-amphibolite facies.

The conglomerates in the immediate vicinity of the Red Hills copper prospects were not intensely pneumatolysed at a late stage and thus remain for our inspection, but elsewhere the Dora formation was widely injected by heated waters and converted to quartz felspar porphyry and quartz porphyry. The formation was pervaded by hot water, but it is evident that there was no great flow of water for there is little intense sericitising.

Because the system moved towards an equilibrium involving quartz and sericite it follows that quartz pebbles and slabs of slate in the formation would be unaffected by the quartz porphyritising. Had previous felspathising been intense everywhere there would have been no quartz pebbles, nor perhaps even slate fragments, left in the formation, but in some localities (the King Bridge) quartz pebbles were by chance unaltered by felspathising and, of necessity, unaltered by later quartz porphyritising. Late injection, which porphyritised the whole Dora formation and the Jukes Breccia, ignored quartz pebbles in those strata and in the Owen Conglomerate. Slaty fragments were not left entirely unaffected by this process, for their chlorite was destroyed, they were substantially leached of iron, and they were converted to yellowish sericite. Now they tend to be friable and have a weathered appearance.

At Lake Dora the matrix of the conglomerate often bears porphyroblasts of quartz and felspar and is like most of the pebbles, but it is almost always green and chloritic whereas the pebbles are often a dull brownish red.

Along sheared zones like the North Lyell Fault at the King Bridge, the matrix of pebbles consists almost wholly of sericite without porphyroblasts of quartz or felspar. This difference in matrices is to be expected between the rocks of stressed and non-stressed environments. In a conglomerate any shearing stresses must tend to be concentrated in the weak matrix of the rock, and pebbles must tend to be rotated. Any concentrated shearing tends, as we have seen, to favour the growth of sericite and to suppress the growth of quartz phenocrysts. The occurrence of sericite as the matrix of the drawn out porphyry conglomerate at the King Bridge, is thus quite consistent with the history given for rocks at Lake Dora.

Sporadically, as for example along Roaring Meg Creek, a third textural variation in the porphyries occurs. Here the porphyry consists of a slate breccia and it is only the matrix which has been porphyritised. It seems that parts of the greywacke sequence consisting of thin alternating bands of slate and tuffaceous sandstone reacted to shearing by breaking into a breccia of compacted slate and sandstone. As already shown, slates are not readily altered; in the first instance they are not readily permeable and in the second they are made of sericite and chlorite and would have little reason to react with solutions forming the sericite of the quartz porphyries. The result of metamorphism

of such a mixture is a breccia with a cement of porphyry or a porphyry filled with slate fragments. For similar reasons it is possible to have quartz pebbles or slaty pebbles with a quartz porphyry matrix. In the Magnet area of Tasmania a silicified limestone (probably the Smithton Dolomite) does form such a breccia.

Apart from Tasmania, a common mode of occurrence of quartz porphyries is as thick conglomerates or inclusion crammed breccias. Examples of the latter are exposed on the Buller River, New Zealand. (Morgan and Bartrum, 1915), and are interpreted by the writer as metamorphosed slate breccias in which the slaty fragments have been unaltered while the permeable matrix has been porphyritised. On the same river the younger Hawks Cray Breccia (Wellman, 1950) has to the present writer been similarly but less intensely porphyritised and mineralised with pyrite and uraniferous minerals.

Further afield the vast (15,000 ft. thick) Calumet and Hecla quartz porphyry conglomerates of the Michigan copper mining district are like the Dora Conglomerate in that they end abruptly against a mineralised fault. Almost every writer on these conglomerates has described them as having been permeated by metasomatising solutions, and has commented that they consist of felsite and quartz porphyry pebbles derived from some unknown source of batholith dimensions (Butler and Burbank, 1929, p. 53).

It is relevant to note here the common occurrence of breccia pipes and breccia dykes of quartz porphyry in copper bearing rocks. These have been observed in Arizona by Anderson et al (1955, p. 42) and described as explosion pipes, and the ? " relict pebbles " in some of them have been attributed to abrasion during transport by gas explosions in volcanic necks. This writer believes that they represent replacements, along pipes and fissures, of pre-existing breccias and conglomerates of lava and sediments.

The world literature on the porphyries, and particularly of those associated with copper and iron in Fennoscandia and Canada, is so full of references to thick quartz porphyry conglomerates, and has so few references to solid quartz porphyry bodies, that the writer believes that a very common and possibly *the most common mode of occurrence of the large quartz porphyry masses quoted in the literature is not as intrusions but as beds of conglomerate or breccia.*

Replacements at Sharp Contacts.

The simplest and, at this stage, most instructive example of replacement at a sharp contact is at Lyell where quartzitic Owen Conglomerate is replaced by haematite (plate A, figs. 2). The field phenomena have been described (Part I), and microscopic study simply confirms the findings based on hand specimens. The elementary fact is that there are no intermediate stages of change between quartz and haematite. The first figure shows the phenomenon described earlier from hand specimens, viz., that chert, quartzite and vein quartz are replaced in that order. In hand specimen the

first haematite to appear replaces the cherty matrix between pebbles, and under the microscope the first haematite replaces the matrix between the quartz grains in the quartzite. There is some suggestion in thin sections that small grains are replaced before large, and strained before unstrained grains, but this adds no new principle. Plate D, fig. 3 provides the most significant information, namely, that iron has migrated along grain boundaries. In a complementary manner it shows also that silicon or silica ions must have emigrated from the rocks. Presumably such emigration was also along grain boundaries, and at first sight it appears that as iron moved forward silica must have moved back along the same path. There is a limit to this, however, for the silicon has clearly not gone backward: there is only purer and purer haematite in that direction. The silica must in some way have passed through the completely silicified conglomerate. There is no doubt that the conglomerate was locally silicified at this stage, for the pebbles are often broken and replaced by haematite along cracks which run across matrix and neighbouring pebbles. $(SiO_4)^{4-}$ ions must, then, have passed through the quartzite fissures and along boundary films or, conceivably, by a process of exchange through crystal lattices. On the other hand, many of the quartz grains in the illustration (plate D, fig. 3) are now isolated by a surrounding layer of haematite. If grains like these were replaced by haematite to form solid haematite pebbles there must have been some migration of $(SiO_4)^{4-}$ ions through the surrounding wall of haematite. As the haematite is specular and is made of small grains, it seems that silica must have moved through the intergranular films surrounding the individual haematite grains. Furthermore, it is clear that if there was a continuing replacement of quartzite by haematite there must have been continuing reinforcement of iron ions moving up through the haematite.

It is concluded that iron and silicon or their oxide ions can each move through the films between quartz grains and between haematite grains. And now we can ask: do they move in watery films, in disordered marginal phases of crystals, or in a combination of both? Since chert grains are wholly replaced crystals of quartz are untouched, it seems that the films might have had the same constitution and composition as the chert (i.e., be disordered and contain water).

It seems most probable that the ferric ions may migrate through pores and films for some distance in front of the points where haematite crystals are first observed and that along with silica and hydroxyl ions in those places they form a disordered phase. It is presumably this thin dispersion of ferric ions which gives the rose colour to much of the conglomerate, and it is the first formation of crystalline haematite which causes the sudden change of pebbles from pink to black.

Replacement of Quartz by Sericite.

Although the haematite zone lies at the base of the zone of silicification it is not always equally thick or intense but may vary from fifty to zero

feet; if thin it may contain many unaltered pebbles of quartz. The chloritising and sericitising of the haematitic quartzites provides the sharpest and most dramatic contact of all.

The replacement of quartzite by sericite at this contact is real enough, although the phenomenon has not often been recorded and few workers would find it feasible. Replacement by sericite along grain boundaries is similar to that just described and presents the same problems of migration. Replacement is not simply by mica but involves some chlorite also, and it can be concluded that there has been a migration of aluminium in one form or other along intergranular films. In this process the quartzite is progressively replaced along grain boundaries so that quartz grains become smaller and finally disappear (plate A, figs. 3, 4 and 5). This disappearance takes place at different rates at various points along the outcrop, so that in some areas there are quartz sericite schists extending beyond the contact for 20 yards, and in others only for an inch.

Differential schisting of the sericitic rocks as compared with the quartzites is to be expected because of the very soft nature of the sericite, and this schisting, together with the unschisted quartzites and haematite " pebbles ", gives a very convincing but false appearance of unconformity.

Very similar replacements of quartzite by sericite have been described for the sub-Huronian unconformity below the Ajibik Quartzite in Michigan; Lamey (1934, p. 263) states, " Another unusual phase of contact metamorphism is the sericitisation of an impure quartzite ", and it was in such a context that Van Hise (loc. cit.) described the process of " mashing " of quartzite.

Adjacent to the quartz-schist contact at Lyell, is the sharply defined contact of chlorite against haematite. This contact can be readily traced for miles, for on one side there are exclusively green chloritic rocks (except for the two islands at Lyell), and on the other there are exclusively red and purple haematitic quartzite. Replacement here follows the previous patterns and calls for little comment. Confirmation of this type of sharp contact is provided by another example from Michigan described by Butler and Burbank (1929, p. 53): " In the iron rich boulders in the Calumet and Hecla Conglomerate the rock was chloritised at the front of the replacement wave and replaced by copper a little nearer the source, both processes evidently having been in progress at the same time and, in places, but a fraction of an inch apart " . . . " The front of the replacement wave in the amygdaloid is marked by the destruction of haematite ". It is remarkable to find that copper deposits from many parts of the world present the same kind of zoning and this confirms the writer in his interpretation of the zoning at Lyell.

Replacement of Quartzite by Felspar.

At Darwin Spur (Snake Spur, fig. 16 c) and across the main peak of Darwin summit, the Tubicolar Sandstone is felspathised and barely distinguishable. On the Spur, however, the formation is readily recognizable and there it is horn-

felsed and bears small pseudomorphs of kaolin and sericite after felspar (plate B, fig. 4). Exposures here indicate rather more clearly than at Lyell that the felspathising front at one time has been higher than the zones of pyritising and sericitising, At present the pyrite zone is 300 feet below the spur of Darwin, and the felspar zone should be below that again. At Lyell a very large part of the present sericite chlorite zone was completely felspathised at one stage, and it must be concluded that in both places there has been some fluctuation of zones. The pressure sensitive system of veins, fissures and films which apparently extended along the length of the range must have fluctuated violently when earth movement occurred, and zones may have retreated from a high optimum to the lower level seen at present.

Nature of "Pseudo-unconformities".

The sharpness of the contacts just discussed is not constant everywhere between the same pairs of rocks, for irregularity has been caused by the following factors:—

1. Chemical heterogeneity of the replaced rocks.
2. Textural heterogeneity of the replaced rocks.
3. Kind of material introduced.
4. Gross texture of the formations adjacent to the contact.
5. Level of isograds relative to the contact.
6. Concentration of reacting solutions.

The effects of these factors may be illustrated by descriptions of the following contacts.

Haematite Pebbles at Lyell.

Preferential replacement of chemically uniform quartzite pebbles has already been explained as largely due to textural differences. The same conclusion has already been arrived at by Goodspeed and Coombs (1937) who have shown how a sheared rock has been more readily replaced by diorite than unsheared rocks of the same composition. A significant point at Lyell is that individual pebbles of quartzite which have been completely replaced by haematite are sometimes quite isolated among wholly unaltered pebbles. This must be accepted as fact, and it seems that Goodspeed's conclusions may be applicable to many kinds of replacement. It is pertinent to the next section that, despite earlier views, there are probably no workers who would today regard the haematite pebbles at Lyell as derived laterite, and the contact as a true unconformity.

"Derived" Quartz Porphyry Pebbles.

At Lake Dora the basal beds of the Owen Conglomerate contain large quartz porphyry pebbles similar to the underlying quartz porphyries. These underlying porphyries have been described as keratophyres, and the overlying pebbles have been regarded by Carey and Banks (1954, p. 250) as evidence of unconformity. The writer has no objection in principle to unconformity at this stratigraphic level, and his arguments can readily be interpreted to mean that metamorphic contacts are likely to locate themselves at unconformities. Despite this, or even because of this, it is contended that the evidence of "derived" pebbles as indicating unconformity is here negative, for the pebbles can be explained adequately within a porphyritising hypothesis.

Quartz porphyritising of the Dora Conglomerate was accomplished under conditions involving precipitation of quartz, so that when quartz porphyritising solutions came in contact with the base of the Owen Conglomerate the quartz pebbles of that formation were not affected; but the same conditions in the same strata must have caused alteration of any felspathic pebbles to quartz porphyry just as readily as they did in the Dora formation. While the abundance of quartz pebbles close to the contact did not apparently affect the concentration of silica in solution, nor disturb equilibria, it seems probable that at higher levels in the formation concentrations of silica were strong and temperatures were probably lower. Under these conditions felspathic rocks were wholly replaced by chalcedonic or opaline silica.

In the same way as in the porphyry replacements there is some preferential replacement of certain rocks by haematite. It has been shown that haematite replacements of quartzite may be very delicately controlled by the energy state of quartz particles, and it appears that replacement of other rock types according to composition may be just as delicate. Although the haematite zone is well defined, and the position of the zone as a whole is independent of the composition of the original rocks, the top of the zone is irregular and the order of replacement of pebbles is often related to the original composition of the replaced pebbles. At Red Hills, for example, wherever a slab of haematitic slate or specular schist occurs among quartz pebbles in the sensitized border of the zone, the writer deduces that there has been a replacement of original slate or chloritic schist and that individual flakes of chlorite have been replaced by individual scales of specular haematite (see Part I, p. 231).

The contact at South Darwin is similar to that at Red Hills, for the Darwin granite had an origin little different from that of the felspar porphyries. The main differences lie in the extreme narrowness of zones at Darwin, and in the presence of magnetite at the contact. It appears that haematite pebbles were reduced to magnetite at relatively high temperatures, and that this process affected pure and impure haematite rocks. The result is that below the contact, pebbles of black magnetite or of greenish black chlorite-magnetite occur instead of the purple or russet haematitic pebbles that are typical above the contact. This relationship is common to contacts of many magnetite haematite deposits all over the world, and there is nothing remarkable about it. The phenomenon is, however, important to this thesis, for it must be explained why, in an environment of advancing fronts, this particular occurrence of haematite should have been left behind to be enveloped by high temperature zones, and to be altered to magnetite.

The answer to this problem is best given in terms of structure (fig. 22 *d.*). The diagram shows masses which may be of any size from two inches to a hundred yards or so across. During metamorphism, as temperatures rise and fronts advance, such blocks may be isolated from their neighbours and the advancing fronts pertaining to each block may also be isolated. With continuing metamorphism the frontal minerals of each enclosure become restricted to smaller and smaller spheres and finally form concentric or nodular inclusions. This applies to those cases where the original enclosure was either an angular fragment or a rounded pebble. Where the original particles were of haematite and were pebbles, as at South Darwin, there is only a slight diminution in size and the individual pebbles are substantially the same as they were before metamorphism. This is essentially Reynold's (1946) explanation of the zoning of basic xenoliths in granites; and the same explanation can be applied to the occurrence in certain nodular porphyries of zoned magnetite spheroids, e.g., in the Kiruna area (Geiger, 1910, pp. 704-6).

On the larger scale (figs. 22 *f* and 22 *g*), favourable structures, such as the sharp syncline at South Darwin or the overfold of Mount Sorrell, produce isolated or nearly isolated masses in which haematite and sulphides may be trapped, and in which zones might be compacted within a small compass. Under these circumstances rocks of the haematite zone may be converted into masses of magnetite such as occur at Mount Darwin, and thus in a general sense one might also account for a number of ore enclosures in granites. For example, the tourmaline nodules of the Heemskirk granite probably represent the result of continued restriction of a volatile front around shale inclusions in the granite, and the tin pipe at Heemskirk may represent a large scale structural trap. The localised abundance of volatiles in these trap structures is indicated by vughs (gas filled cavities) which are sometimes lined with cassiterite, muscovite, and tourmaline crystals (*c.f.* the drusy nodules of Geiger).

So far in this account, the reasons given for the location of sharp contacts at stratigraphic boundaries have been related to the temperatures and permeabilities of the rocks concerned, rather than to their original composition. This has served to emphasize that on porphyroid metasomatism the role of diffusion is more important than thin or local variations in composition in the unmetamorphosed strata. Thick sequences of monomineralic rock such as quartzite may, however, be important in controlling the trend of metamorphism.

In a general sense the trend of metamorphic processes is to produce a large scale re-distribution of elements and minerals in the crust, such that an increased chemical and mechanical stability is reached, and such that in the ideal instance an equilibrium is established between pressure and thermal gradients and rock types. For this reason, metamorphism only becomes possible when there is some pre-existing lack of equilibrium in the rocks. Conversely, if rocks in the crust should have already been arranged by some curious accident into zones similar to metamorphic zones there could be no metamorphism. Such a situation is unlikely to arise for the principal causes of disequilibrium are the processes of weathering, sedimentation, and sedimentary burial; nevertheless, sedimentary processes do produce some rocks which coincide in composition with those resulting from metamorphism, e.g., quartzites of the Owen Conglomerate. If, during metamorphism it further happens that such a bed of quartzite coincides in position with a metamorphic zone of silica precipitation, that bed must tend to prevent the migration and to stabilise the position of that zone. This is not an improbable situation for if there is an advance of zones such as has been described for the West Coast Range, the zone of silicification must tend to be halted at any thick quartzite bed such as the Owen Conglomerate. This does not mean that quartzite may not be altered (alteration has occurred at Lyell), nor does it mean that the zone of silicification should always reach up to the conglomerate (it does not do so in areas of gradational metamorphism); and it does not mean that thick quartzites like the Owen Conglomerate may not be completely replaced.

It does mean that the thick Owen Conglomerate presented a barrier to the advance of fronts, and that this was independent of the physical factors discussed earlier. The quartzite did not only tend to halt the zone of silicification but it also seems to have caused the telescoping of the succeeding zones. This telescoping and concentration might account in some part for the density of the pyrite zone below the quartzite contacts, and the diffuseness of pyrite in areas of gradational zoning may simply reflect the normal system of zoning. The common abbreviation of zones below quartzites at many granite contacts throughout the world may be explained in the same way. The abrupt arrestment of granitising processes at contacts with quartz haematite or quartz magnetite rocks is, perhaps, most forcibly described by Lamotte (1943, p. 116), who relates how fine-grained magnetitic quartzites have presented a barrier to transport and migmatising, and how in no single case has felspathising been affected across this barrier. Lamotte, as well as the writer, distinguishes the porphyroid type of metamorphism from others, and draws attention to the difference between the contacts of granites with siliceous and alumino-siliceous rocks.

NATURE OF SOLUTIONS.

The important role of sodic solutions in metasomatism has been stressed by many workers in independent studies of spilitising, granitising and sulphidising. Some, like Gilluly (1935), relate the two former processes to a common cause, the rising of sodic solutions along deep seated faults. Others, like Graton (1940, p. 251) have emphasized the importance of alkaline solutions in the transport of sulphides. So far as the state of water solutions is concerned the writer would agree with Graton that injection of rocks by steam is unlikely, and that injection below critical temperatures must be by superheated water. The behaviour of water at higher temperatures is, however, very difficult to gauge. Apart from surface tension effects mentioned earlier, it has been shown by Gillingham

(1948) that water above 400°C, and with free sodium ions, may dissolve appreciable amounts of silica.

Given temperatures of this order and sodium-bearing solutions, there seems to be no difficulty affecting the theses of intergranular films and of sodium metasomatism. The source of sodium as carbonate and silica as proposed by Eskola (*loc. cit.*) for the spilite reaction is, however, purely assumptive and this applies to most hypotheses concerning the origin of soda rich solutions.

There are two possible sources of those solutions, one by differentiation of sub-crustal basaltic magmas, the other by a regenerative or circulatory system whereby sodium is buried in the earth and then released. There is little doubt about the feasibility of the former process, for the oceanic volcanoes do give rise to sodic rock types and release huge amounts of carbon dioxide. The solutions released are, however, rarely saturated with silica and when involved in metasomatism appear to give rise to under-saturated rocks. This is well understood, and it is possible that such solutions could be formed at depth and rise along fault planes. It happens that metasomatism of granitising or spilitising type is rarely associated with undersaturated rocks (the nephelinitising at Haliburton is a notable exception) and some source of silica as well as soda is required to allow of granitising.

In a regenerative system these requirements can be met, and Eskola's reaction which has been shown to be reversible (Eskola, see Barth, 1951, p. 286) provides a possible explanation of such a system. According to Eskola the calcic plagioclases tend to be stable while the sodic varieties tend to be unstable at high pressures. Although experiment has so far demonstrated this reaction only for felspars between albite and andesine, the principle can be reasonably extrapolated throughout the full range of plagioclases. It becomes feasible in this view that normal sediments containing sodic plagioclase or elements in the proportion of that mineral may, on deep burial, react with lime rich minerals to give rise to anorthite molecules and ionic solutions of soda and silica. This scheme fits in with the regenerative system already proposed for the origin of the water involved in metamorphism and in the tranport of heat from depth.

It may be imagined that in the rocks at depth in the slowly subsiding Zeehan Syncline there was a vertical column of rocks in which the plagioclases at different levels were all being altered by pressure to more calcic types. At all levels, too, silica and soda were being released and collected in the efferent system of veins for upward migration. Such migration probably occurred with each phase of movement of the major geanticline, and it would be difficult to separate any one stage (such as the spilitising of the basalts) from any later phase of metasomatism. With this mechanism there is not, as with other devices, any problem of adequacy of the source in producing the requisite bulk of soda or silica for metasomatism, for subsidence and deep seated metamorphism might easily keep pace with granitising.

It follows from this argument that at some depth in the Zeehan Syncline calcic felspars, or masses of gabbro or of anorthosite must have been formed but there is no evidence that these occur. In other parts of the world where the crust has been deeply buried there is ample evidence of metasomatic formation of anorthosites, e.g., in Fennoscandia and Canada but for the purpose of this account it will simply be assumed that such anorthitising is possible and that it may occur in any deeply depressed region.

An important consequence of the aggregation, transport and dispersion of sodic solutions, is that this mechanism makes possible the collection and transport of sulphides and allows their ultimate deposition in disseminations or veins. Since normal argillaceous sediments may carry up to 192 grams of copper per ton (Rankama and Sahama, 1950, p. 700), and normal basalts up to 300 p.p.m. of copper (Goldschmidt, 1954, p. 179), and since " copper among sulphide forming minerals has one of the highest affinities for sulphur " (Rankama and Sahama, 1950, p. 696) it would be astonishing if copper were not collected from the geosynclinal tuffs and basalts of the Zeehan Syncline, and surprising if sulphides were not distributed along the Lyell Shear.

The connection between these deposits and those of the lopolithic areas of Michigan is now very clear; the connecting link is simply that in both areas part of the crust has been deeply depressed.

The processes of continual migration of soda and sulphides (and of potash) tend to be independent of zoning and to produce local concentrations, or zones of restricted extent close to faults like the Lyell Shear; but in general the principles of zoning already described still apply.

The final stage of ore genesis at Lyell was related to the late phase formation of the quartz porphyries. Late solutions are presumed to have leached low grade ores at depth and to have precipitated sulphides at higher levels as pipes and veins such as occur at North Lyell and Comstock. Silica carried along in the same solutions, but derived by leaching of silicates, was precipitated as replacements of the chlorite schists around these two bodies and deposited as vein fillings with chalcopyrite, bornite, and gold in the late and northeast tensional fault fissures. The details of a similar late-phase leaching and enrichment of pyritic ores have been set out more fully than this article allows by Lacey (1956). The writer's only comment here is that Lacey's account only touches on very late events which occurred after the formation of pipes like the Blow or the North Lyell bodies. Apart from this difference the principle of late leaching and enrichment is the same.

This account does not aim to discuss ore deposition further but merely to relate rock and ore genesis and this aim is now in part satisfied. Of the other aims listed in the introduction to this work most have been attempted and partly satisfied. Now, at least there is some relation between sulphides and quartz porphyries, and some connection between ores and basalt, and between metamorphism and structure. Further, there is now some direct relation between the ores of the West Coast Range and those of other regions.

Rock Types: POTASH GRANITE | SODA-POTASH SYENITE | SODA-POTASH PORPHYRY | SODA-SYENITE PORPHYRY | EPIDOTE-ALBITE-PORPHYRY | PYRITE-CHLORITE SCHIST | HAEMATITE | QUARTZITE

ANAMORPHIC PHASE

Conc'n in Solution: Si — Fe'' — Fe''' — S — Ca — Na — Al — K

Minerals: Orthoclase, Oligoclase, Pyrite, Haematite, Biotite, Sericite, Quartz, Epidote, Chert, Chlorite, Quartz, Albite, Magnetite

KATAMORPHIC PHASE

Concentration: Si — Al — K — S

Minerals: Kaolin, Sericite, Orthoclase, Quartz, Sulphide

Rock: Irregular quartz porphyries, chert veins, pyrite pipes, superimposed on rocks of first column.

FIG. 23.—A correlation of rock and mineral zones of the West Coast Range with diffusional zones or fronts.

A summary of the account is given in a diagrammatic form in fig. 23 which shows on the left-hand side the zones of rocks and minerals occurring at different depths and their interpretations in terms of relative concentrations of elements in solutions. There is no proportionality between curves for different elements and the curves only express general tendencies. Reading from left to right an upward slope in any one curve implies that the respective element was being taken into solution and a downward slope that the element was being precipitated. Thus the front of aluminium precipitation coincides with a front of sericitising and felspathising, and the zone of resorption of alumina coincides with the resorption of oligoclase.

On the right of the diagram the distribution of minerals and elements in the katamorphic phase is meant to be only suggestive. Thus sulphides, of copper and iron, are usually precipitated above the contact and not below. Kaolinization and sericitising may extend through all the rocks even into otherwise unaltered sediments (for example, at the Sandhill, Queenstown), but are most commonly associated with the felspar porphyries. Similarly orthoclase is not restricted to the zone shown but may extend in thin stringers high up in unaltered Devonian sediments (for example, on High Street, Zeehan). The felspar in all of these cases may be adularia.

In conclusion the writer would draw attention to the findings of Steiner (1953, p. 5) on the results of recent boring for steam in the geothermal district of Wairakei, New Zealand. This is a district of porphyritic ignimbrite rocks and of regional injection by steam along well marked fault lines.

Steiner demonstrates the existence of zones of sulphuric acid leaching (at a depth of 190 feet and temperature of 120°C), argillisation (450 feet, 160°C), zeolitising (600 feet, 160°C), and felspathising (900 feet 220°C). In the outermost zone occurs kaolinising and precipitation of opaline silica; in the next montmorillonitic clays and pyrite are precipitated; in the zeolite zone minor amounts of quartz and albite form; and in the felspathising zona adularia crystallises. The citing of these facts should not be taken to mean that the writer considers that quartz porphyry is now being formed immediately below the bore holes but Steiner's findings undoubtedly provide stimulating food for further thought.

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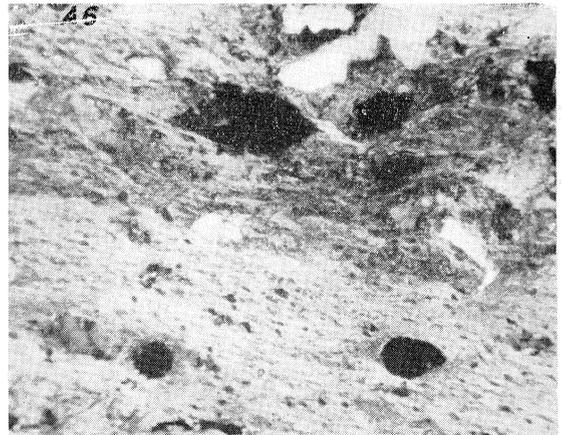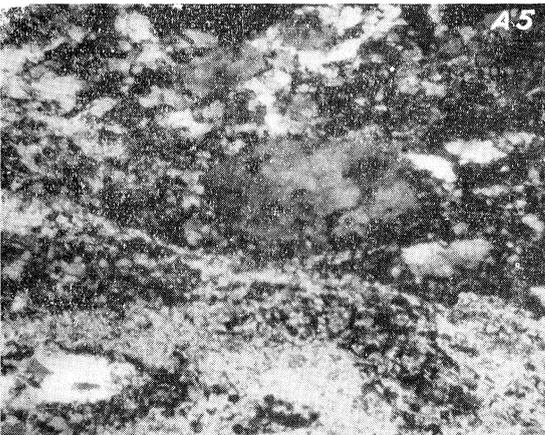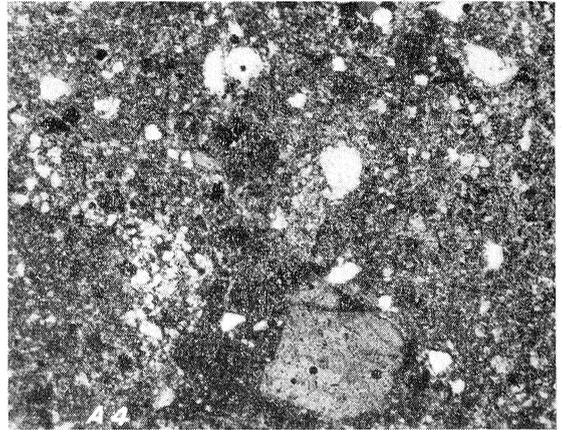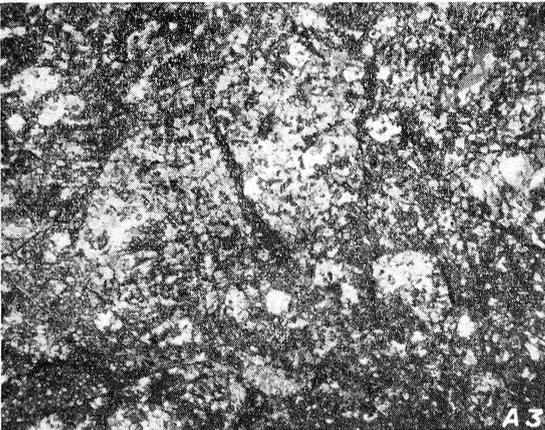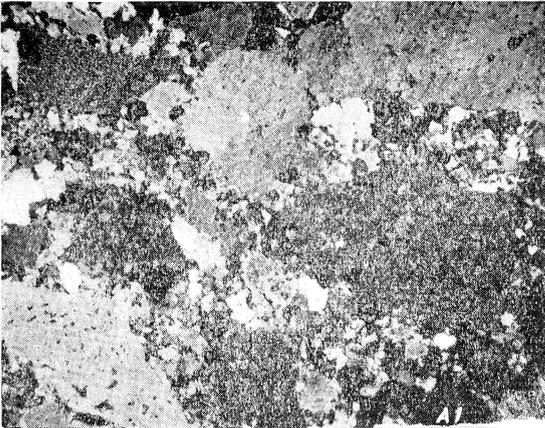
REPLACEMENT OF THE OWEN CONGLOMERATE

FIG. 1.—Tubicolar Sandstone, West Lyell. Note chert and quartzite pebbles, and matrix of chert and quartz grains; cross nicols: x 20.

FIG. 2.—Haematised Tubicolar Sandstone, Blow Open Cut. Note preferential replacement of cherty matrix, chert pebbles, and quartzite, in that order; ordinary light: x 20.

FIGS. 3, 4, 5 and 6.—Showing progressive alteration of quartzose Owen Conglomerate to sericite schist. Specimens came from within 2″ of the "contact" at Tharsis hogback. White and black lenses represent quartz. The rest is sericite; cross nicols: x 50.
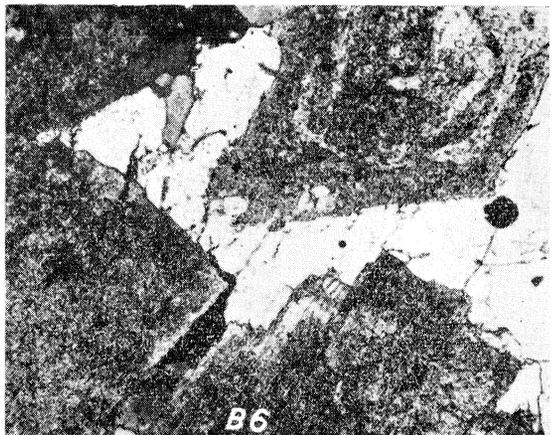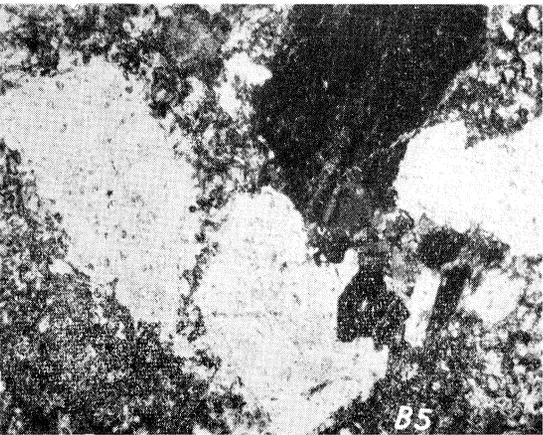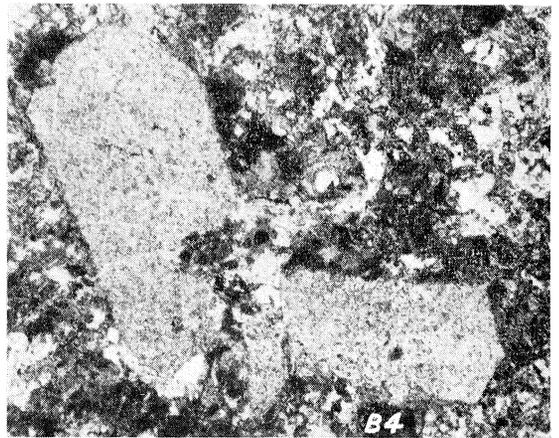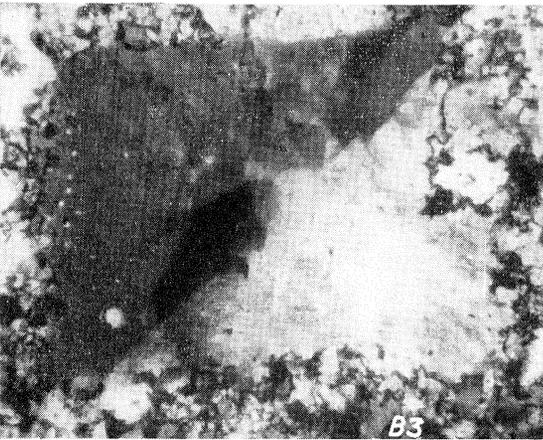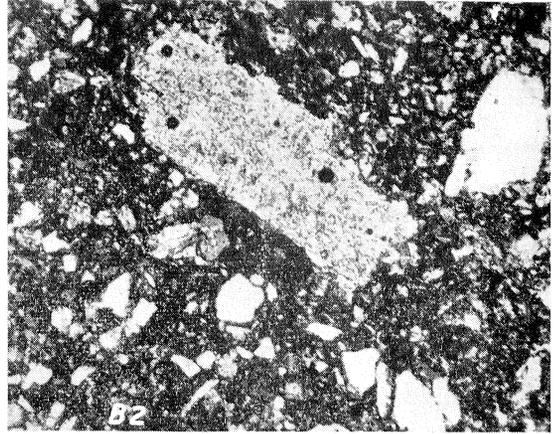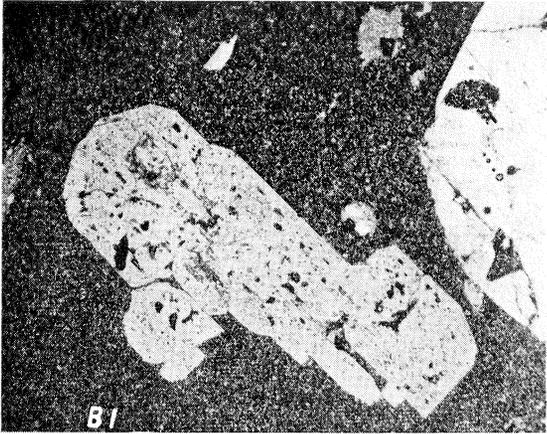
FELSPAR PORPHYROBLASTS

FIG. 1.—Quartz and orthoclase porphyroblasts in fine horn-elsic base, Lake Dora. Cross nicols: x 50.

FIG. 2.—Albite in subgreywacke at Lake Julia. Cross nicols: x 50.

FIG. 3.—Orthoclase from Murchison Syenite to show pimply margin. Cross nicols: x 50.

FIG. 4.—Sericitised felspar in Tubicolar Sandstone, Darwin Spur. Cross nicols: x 50.

FIG. 5.—Oligoclase with biotite in felspar porphyry near contact, Lake Dora. Note pimply margin of felspar. Cross nicols: x 50.

FIG. 6.—Orthoclase with ? oligoclase in Darwin Granite. Clear crystal is quartz. The intense sericitising is typical of all rocks. Cross nicols: x 50.
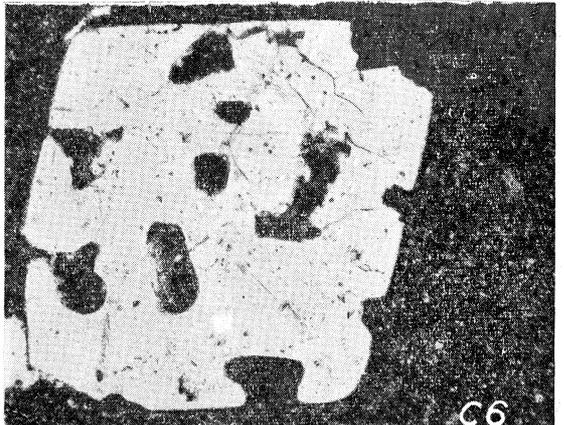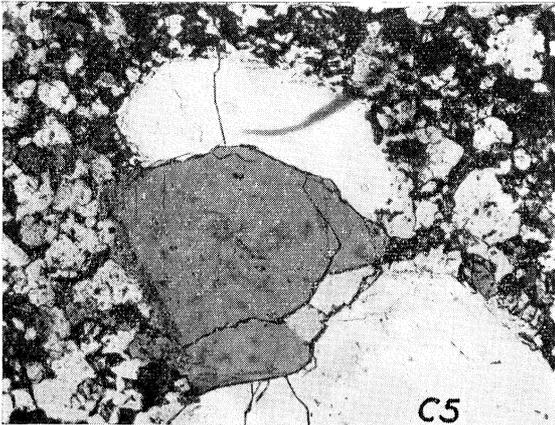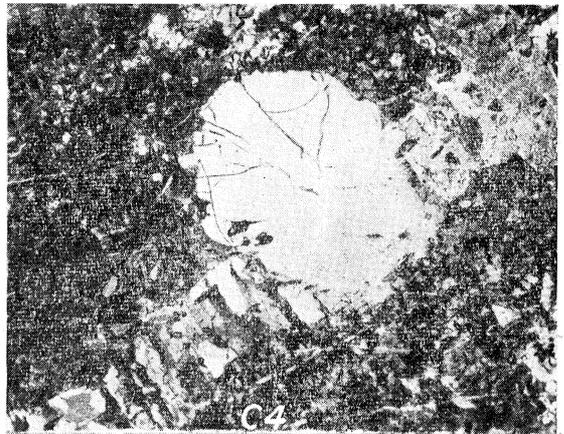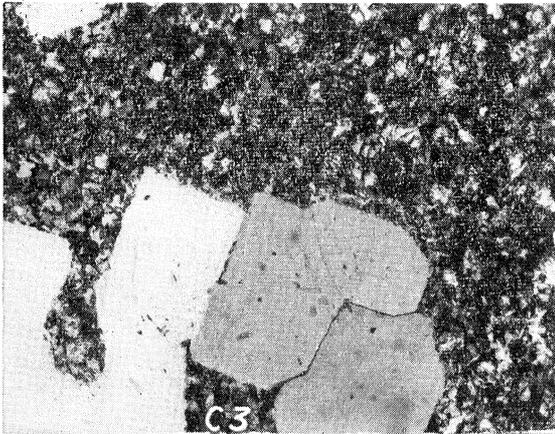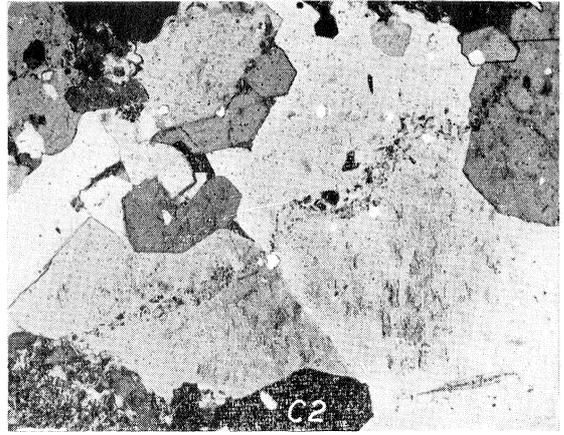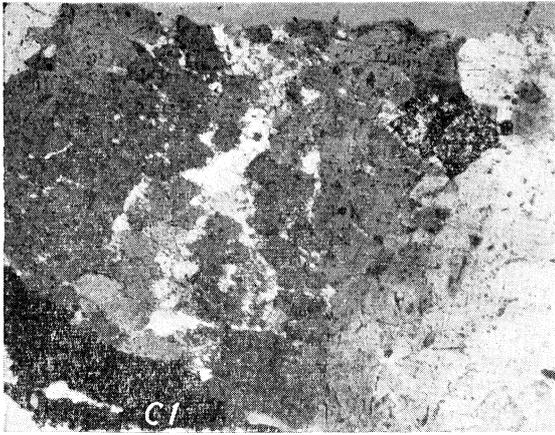
QUARTZ PORPHYROBLASTS

FIG. 1.—Quartz from foot wall of Murchison Mine to show disjunctive extinction. Cross nicols: x 50.

FIG. 2.—Quartz crystals from West Queen River porphyry. The train of inclusions across three crystals shows that crystals have grown in the solid. Cross nicols: x 50.

FIG. 3.—Typical quartz porphyry from Roaring Meg Creek on the Queenstown Porphyry body. Cross nicols: x 50.

FIG. 4.—Quartz porphyroblast replacing quartz vein replacing hornfels. Tullah Tram. Cross nicols: x 50.

FIG. 5.—Vein quartzite from Mount Bischoff. The porphyroblast has grown in the quartzite by absorbing small crystals. Note margins. Cross nicols: x 50.

FIG. 6.—Corroded quartz from Lyell Schist. Cross nicols: x 50.

NOTE.—When viewed by means of the universal stage the pimply structures on quartz crystals are seen to extend through the full thickness of the slide and are three-dimensional in form.
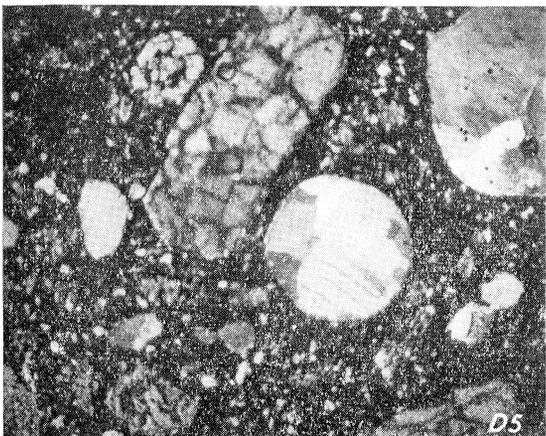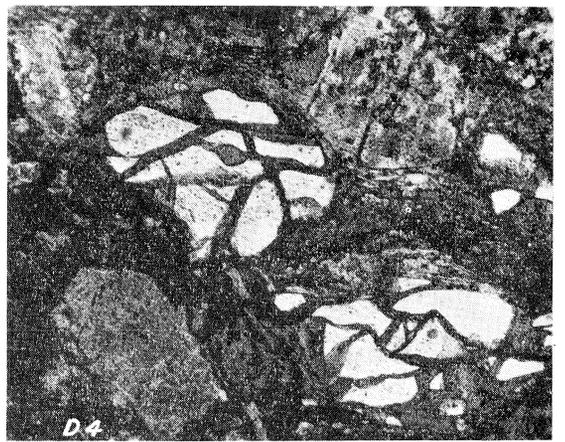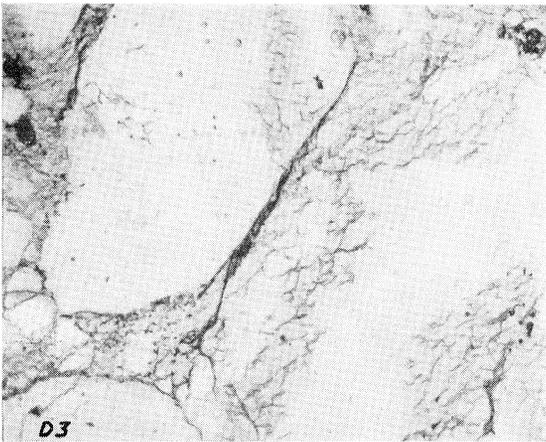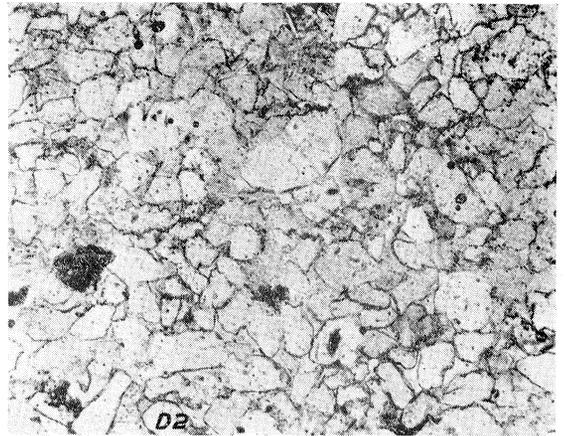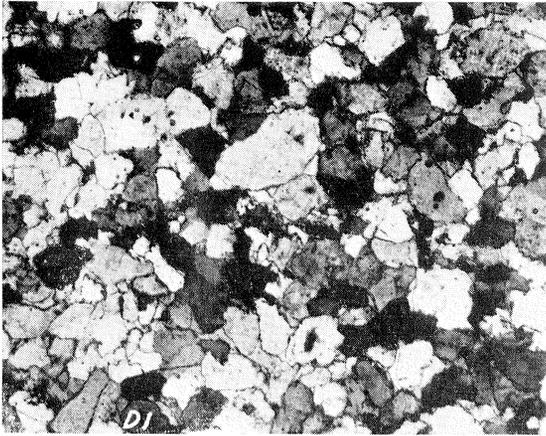
ROCK TEXTURES

FIG. 1.—Tubicolar Sandstone showing apparent angular grains. Cross nicols: x 50.

FIG. 2.—Same field as fig. 1. Original grains are outlined by haematite and were once subangular or round. Some grain growth has occurred and the haematite films have been included in the larger crystals. Ordinary light: x 50.

FIG. 3.—Quartzite pebbles, West Lyell contact. To show replacement of quartzite by haematite along grain boundaries. Ordinary light: x 100.

FIG. 4.—Quartz crystals. The crystals have not been broken and dislocated but have been replaced along fine cracks or strain zones. Note, no quartz particles touch other quartz particles; it is geometrically impossible to fit the particles to form a simple crystal shape; the even width of "fractures" suggests there has been removal of material. Ordinary light: x 50.

FIG. 5.—Typical vesicular basalt, Tullah Track, Rosebery. Large crystal is an augite phenocryst. Clear crystal on mid le t is a quartz porphyroblast. Three diffuse crystals along base are sericitised felspar. Vesicle fillings are quartz and calcite. Cross nicols: x 50.

FIG. 6.—Aplite from granite contact, Murchison River. Cross nicols: x 50.