Part V

THE NOWENDOC ULTRABASIC BELT

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Chapter 21

Introduction

The Great Serpentine Belt of N.S.W. is one of the classic occurrences of "Alpine"-type serpentinites (see Turner and Verhoogen 1960, p. 308), due mainly to the pioneering work of W. N. Benson (Benson 1913, 1915, 1918, 1926) and to more recent work by Osborne (1950) and Wilkinson (1953). The latter recognized the continuity of the N.S.W. occurrences with the numerous similar serpentinites throughout Queensland, and proposed that the whole belt be known as the Great Serpentine Belt of Eastern Australia (Wilkinson, 1953, p. 305), extending from Temple Bay, North Queensland to Mount George, N.S.W., approximately 1400 miles.

This part of the thesis deals with an investigation of a small part of the Great Serpentine Belt, herein named the Nowendoc Ultrabasic Belt. A brief description of the general geology of these intrusions is given in Part I .

Summary of Previous Work on the Great Serpentine Belt

The main conclusions of Benson (1913a, 1913b, 1915, 1918, 1926) concerning the Great Serpentine Belt are summarised below:

(1) The Belt possesses a linear character, it is rarely more than a mile in width and many of the serpentinite bodies occur within a zone of faulting (e.g. the Peel Fault system) separating highly deformed from less deformed rock. Other serpentinite intrusions belonging to the Belt are found well away from the major fault zones.

(2) The serpentinites have been derived almost exclusively from harzburgite, with only a minor amount of lherzolite. Pyroxenite is rare, but a small amount of enstatolite is reported.

(3) Gabbros are relatively common within the sheet-like masses of ultramafic rock, the larger masses described as forming broad gneissic intercalcations lying more or less concordantly within the belt. Smaller masses of gabbro are said to cut irregularly through the serpentinite. The gabbros are saussuritised to varying degrees, and olivine gabbros appear to be rare.

Osborne (1950) and Proud and Osborne (1952) described the ultramafic intrusions at Wood's Reef, near Barraba. They reported ultramafic rock that had undergone little serpentinisation, and brucite and tremolite were noted as products of serpentinisation. Evidence of multiple emplacement of ultramafic phases was considered to be provided by "intrusion breccias", which suggested a harzburgitic phase followed by a dunite. Associated gabbros and dolerites were thought to have been emplaced after the dunitic phase.

Wilkinson (1953) divided the serpentinized ultramafics of N.S.W. and Queensland into three groups.

(1) Massive Serpentinites

(2) Schistose Serpentinites

(3) Composite rocks and serpentine breccias.

The relationship observed between these rock types was explained by two phases of ultramafic activity. The initial intrusion gave rise to normal (i.e. massive) serpentinized peridotite, which was later brecciated and invaded by the second phase of schistose serpentinite. It is suggested that these two phases may have been emplaced in the Middle Devonian and Lower Carboniferous respectively.

This interpretation has subsequently been revised.

Wilkinson (1969), p. 304 suggests the above relationship is the result of a primary magmatic initial phase, with the later phases tectonic in character, with the latter derived from rocks emplaced during the initial phase.

Since 1961, several research students from the University of New England have investigated small areas belonging to the Belt. Bofinger (1961) (Bingara), Lusk (1961) (Gulf Creek), Goodwin (1962) (Port Macquarie), Bultitude (1965) (Dungowan), Morrow (1967) (Baryulgil), and Matthias (1967) (Hastings Valley and Port Macquarie) described and mapped the serpentinised ultramafics belonging to the areas named. The great similarity of their geologic and petrologic description emphasizes the remarkable uniformity of the ultramafics of the Belt. It is clear that serpentinization is almost complete throughout, however occurrences of original olivine and pyroxene are reported by Bultitude (1965) at Dungowan, Morrow (1967) at Baryulgil, and at Port Macquarie by Goodwin (1962) and Matthias (1967).

Matthias (1967) and Goodwin (1962) described megascopic layering in a rock at Port Macquarie, interpreted by them (and also by Wilkinson (1935) p. 311) to be of "relict primary magmatic origin". This consists of a layer of enstatolite several inches thick enclosed in serpentinised peridotite. Chromitite layering is not reported.

The dominant rock types of all intrusions are schistose serpentinites and "composite" rocks, in which inclusions of massive serpentinite occur in a schistose matrix. The above students unanimously agree with Wilkinson (1953) that such rocks are the result of two periods of emplacement of ultramafic material (see Wilkinson, 1953 p. 312).

Chapter 22

GEOLOGY AND PETROGRAPHY OF THE NOWENDOC SERPENTINITE

Introduction

Petrologic work on the Nowendoc Ultrabasic Belt is concentrated on the Nowendoc Serpentinite, as it contains a substantial amount of partially serpentinised peridotite, and the transition from peridotite to serpentinite can be closely studied.

Field Relationships

Several phases are present within this intrusion. An irregularly shaped area of the southern part of the intrusion is occupied by partially serpentinised peridotite, (Plate 17A). Surrounding this is progressively more serpentinised peridotite which has been broken into blocks separated by varying proportions of schistose serpentinite. The remainder of the intrusion is occupied by "composite rock" (Wilkinson, 1953, p. 309) consisting of inclusions of massive serpentinite in a schistose matrix (Plate 17B).

The prominent, blocky outcrop of the partially serpentinised peridotite weathers to a rusty red-brown colour, with lighter coloured enstatite grains etched out in relief on weathered surfaces, (Plate 17C). Weathering processes have also revealed a strong megascopic foliation, (Plate 17C and 18A). This contrasts with the massive serpentinite, which occurs as angular to rounded inclusions of black to dark grey-green rock in a matrix of pale green translucent schistose serpentine, and weathers to a dull black surface in which a megascopic foliation is lacking. The transition between the unserpentinized peridotite and massive serpentinite is gradational, but at least one locality contains several angular inclusions (3') of unserpentinized peridotite mixed up with smaller rounded inclusions of massive serpentinite, both in a matrix of schistose serpentine.

In several parts of the main peridotite outcrop, a weakly developed mineralogic layering is also observed, (Plate 18B), consisting of bands up to several inches across, relatively rich in enstatite. This layering is parallel to the strong cataclastic foliation of the peridotite.

Either this layering represents an original igneous layering, subsequently transposed into the strongly developed cataclastic foliation, or alternatively it may have developed during the emplacement of the peridotite, that is, it is essentially metamorphic, similar in style to a gneissic lamination.

The angularity of the massive serpentinite inclusions tends to be related to their size. The larger inclusions of massive serpentinite (2' - 4') are angular to sub-angular, (e.g. Plate 18C), while the smaller inclusions are more rounded. In addition these inclusions have an outermost layer which is black and enriched in granular magnetite, while the interior consists of typical deep green massive serpentinite.

The blocky outcrop of the partially serpentinised peridotite is cut by numerous joints occupied by thin sheets of schistose serpentine, some of which resembles cross-fibre chrysotile. Similar structures on a microscopic scale are observed in thin sections of the peridotites.

Petrography

The aims of this short study are

(1) to examine the original peridotite and its serpentinisation and

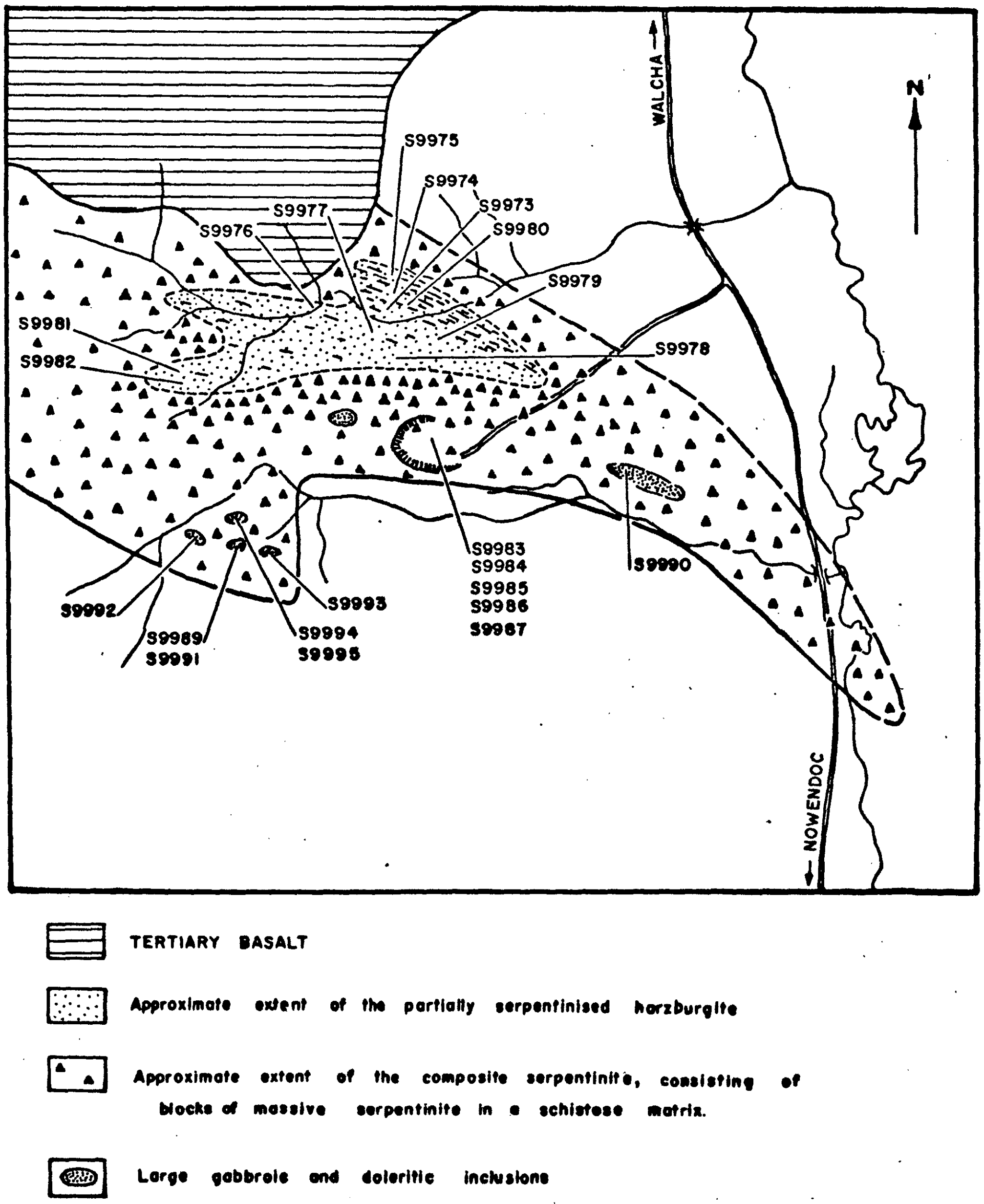
(2) to determine the relationship between the massive and schistose phases of serpentinite.

The locations of sectioned specimens, showing their relationship to the peridotite are given on Fig. 23.

The intrusion has been divided initially into three rock types.

FIG. 23.

GEOLOGIC MAP SHOWING THE RELATIONSHIP BETWEEN THE MAJOR CONSTITUENTS OF THE NOWENDOC SERPENTINITE, INCLUDING LOCALITIES OF SECTIONED SAMPLES.



(1) Partially serpentinized peridotites, comprising those portions of the intrusion that retain some relic olivine and orthopyroxene.

(2) Completely serpentinized peridotite, in which all trace of original olivine and pyroxene has disappeared. These may be further subdivided into:

(a) Massive serpentinite inclusions, in which the original peridotite fabric is preserved, although completely replaced by serpentine minerals.

(b) Schistose serpentinite, in which there is no trace of the original peridotite fabric.

(3) Feldspathic variants, i.e. inclusions of altered gabbroic and doleritic rocks.

Partially Serpentinised Peridotites

No thin sections are absolutely free of the effects of serpentinisation, the least serpentinised material collected is estimated to contain approximately 15% of serpentine materials. Modally the peridotites are harzburgites (see Johannsen, 1938, Vol. 4, p. 438). There appears to be relatively little modal variation in the specimens studied, visual estimates indicating the following:

Olivine	75 - 85%
Orthopyroxene	15 - 25%
Clinopyroxene	< 1%
Spinel	1 - 2%

The harzburgites may be divided into two textural groups:

(a) Mylonitised harzburgite

(b) Relatively massive harzburgite.

(a) Mylonitised Harzburgite

The mineralogy before serpentinisation consisted of granular olivine, euhedral orthopyroxene, and an accessory amount of anhedral, embayed, coffee-brown spinel. The texture is cataclastic, but approaches hypidiomorphic granular.

Olivine grains occur in two size populations, (see Plate 19A). The coarse fraction (1 - 2mm) has undulatory extinction and may be highly fractured, with serpentine minerals commencing to grow along the fractures within this coarse undulant olivine. No deformation lamellae are observed. Fine grained (0.1mm) granulated olivine forms elongate or lensoidal aggregates, which may swirl around deformed orthopyroxene grains. A thin film of serpentine minerals separates the individual grains of finely granulated olivine. A preferred orientation of these aggregates is thought to be responsible for the megascopic foliation observed in outcrop. Orthopyroxene grains are euhedral, rectangular in outline, with a prominent cleavage. Grain size may be up to 4mm, but is usually 2 - 3mm. The cleavage is often bent, and grains usually display undulatory extinction patterns. Exsolution lamellae of clinopyroxene are common. Serpentinisation has commenced along the orthopyroxene cleavages, but is not as advanced as that affecting the accompanying olivine. Traces of clinopyroxene are present in most thin sections as small (0.3mm) euhedral grains adjacent to larger orthopyroxene, and rarely also as inclusions within orthopyroxene euhedra.

Embayed, fractured, anhedral coffee-brown spinel (picotite) up to 2mm is a constant accessory. This is mantled by a thin film of finely divided opaque material, probably a mixture of chromite and magnetite.

Colourless serpentine minerals form a matrix-like framework, isolating individual grains of olivine and pyroxene by a thin wall of serpentine minerals. Aggregates of finely divided brucite occur with this "matrix" serpentine. The original olivine grain boundaries are marked by trails of extremely fine opaque granules, probably magnetite, produced as a by-product of the serpentinisation of the original fayalite-poor olivine.

Crossing all the thin sections are lensoidal veinlets up to 1mm wide containing the assemblage serpentine, brucite and magnetite (see Plate 19B). Similar veinlets containing only fibrous serpentine may also be present. The brucite-magnetite rich veinlets are most abundant in S9975, in which the majority are parallel to the cataclastic foliation of the peridotite.

(b) Massive Harzburgite

A hypidiomorphic granular texture, without any granulation of the olivine, distinguishes these rocks from those that have been mylonitised (see Plate 19C). Serpentinisation has produced a pale green pleochroic serpentine mineral, as well as the normal colourless variety.

Small, subrounded olivine grains are isolated by a thin wall of serpentine minerals, however these small olivine grains are sub-individuals in optic continuity with surrounding olivine suggesting the original olivine grainsize to be 2 - 3mm, equivalent to that of accompanying orthopyroxene. Slight undulatory extinction has been preserved in the coarse olivine grains, showing that the original massive harzburgites are not completely free of the effects of cataclasis.

Orthopyroxene grains have deformed cleavages and undulatory extinction, in agreement with the above. Clinopyroxene exsolution lamellae is again common and a trace of clinopyroxene is present, as smaller grains adjacent to larger orthopyroxenes.

Spinel remains a common accessory, and in the more serpentinised specimens, the spinel anhedra appear to be more heavily mantled by finely divided opaque material consisting of magnetite and chromite.

The serpentine mineral replacing the bulk of the rock consists of a mixture of the normal colourless variety and a pale green to pale yellow pleochroic variety. In areas of the thin section where the pale green serpentine minerals envelope small olivine grains, the trails of opaque granules are observed. From this it is deduced that the pale-green serpentine mineral is probably an iron-serpentine enriched variety and that the serpentine minerals observed within the individual thin sections vary in composition, especially with respect to Fe and Mg contents.

A colourless serpentine mineral occurs in cross-cutting veinlets, often associated with a little brucite and magnetite, similar to veinlets observed in the mylonitised harzburgite. In many of these veinlets, only the remnants of the original brucite-rich core remain, as it appears that the brucite has been replaced by colourless cross-fibre serpentine mineral.

Relationship Between the Mylonitised and Massive Harzburgites

The two groups are very similar in degree of serpentinisation and mineralogic and modal composition. The basis for dividing the harzburgites is the differing amount of cataclasis prior to serpentinisation. There appears to be a complete gradation between these two groups, with the more massive harzburgites occupying the interior of the peridotite, and the mylonitized varieties adjacent and parallel to the north-east contact. In addition the weaker foliation of the more massive harzburgites parallels that of the mylonitized peridotite.

The development of these two varieties of harzburgite is seen as an expression of the different amount of penetrative movement that separate parts of the same body have undergone. This must have taken place when the peridotite was a relatively solid body, prior to serpentinisation, and below the temperature at which annealing recrystallization was effective.

Completely Serpentinised Peridotite (Massive Serpentinite)

The original olivine and pyroxene has disappeared, however the outline of the original fabric is still preserved. Colourless, intricate mesh serpentine, which may develop "hour glass" structure (Deer, Howie and Zussman V. 3, (1962) p. 183) has replaced olivine. Colourless "bastite" serpentine pseudomorphs after orthopyroxene preserve the cataclastic deformation of the original pyroxene cleavage. Narrow veins of colourless cross-fibre chrysotile occur, usually associated with aggregates of fine granular opaque oxide.

Spinel is again an accessory, less abundant, but still retaining its coffee-brown colour. Chromite was also identified. Fine grained, scattered anhedral magnetite granules are common. No brucite was detected.

The zoning of massive serpentinite inclusions mentioned earlier was investigated by cutting thin sections across several of the inclusion contacts. The zoning was found to be due to a considerable enrichment of granular opaque material (mostly magnetite) within the rim. The contact of the inclusion with the schistose phase is extremely sharp, with the colourless schistose serpentine almost devoid of opaque mineral phases.

Relationship Between the Massive Serpentinites and the Incompletely Reconstituted Harzburgites

The evidence suggests that the transformation from the unserpentinized harzburgite to the massive serpentinite was a continuous process of replacement of olivine and pyroxene by serpentine minerals, and that it took place without any increase in volume of the massive serpentinite. The gradual replacement of original olivine and orthopyroxene by serpentine minerals has preserved the fine detail of the parent peridotite fabric, where the original olivine grains are now represented by the polygonal structure known as mesh serpentine, and the orthopyroxene has been replaced by bastite pseudomorphs of serpentine mineral,

The outcrop consisting of inclusions of both massive serpentinite and unserpentinised harzburgite in a schistose serpentine matrix indicates that the "brecciation" or disaggregation of the original peridotite commenced before serpentinisation had been completed.

Schistose Serpentinite

The inclusions of massive serpentinite are embedded in a green to grey translucent schistose serpentine matrix. The amount of schistose serpentine is extremely variable throughout the intrusion, and shows a great variety of minor structures. It typically has a crude foliation which swirls around inclusions of massive serpentinite, (Plate 20A). Mesoscopic folds of this crude foliation are developed, but are irregular in distribution and outline, and the fold axes appear to be almost randomly oriented. Near the contacts of the serpentinite intrusions, the proportion of massive serpentinite decreases and the schistosity is better developed and more planar.

Original peridotite fabrics such as those preserved in massive serpentinite are never observed. Textures of the schistose serpentine are extremely variable, ranging from extremely schistose to a virtually "massive" variety of schistose serpentine. The coffee-brown spinel, which survived the initial serpentinisation is not found in the schistose phase.

The relative proportion of schistose to massive serpentinite is not easy to estimate, but appears to be lowest adjacent to the partially serpentinised harzburgite, where it exists in the outcrop as a kind of net-veining structure separating angular blocks of massive serpentinite or partially serpentinised harzburgite. The proportion of schistose serpentine increases as the inclusions become more rounded, and appears to be higher in the completely serpentinised Coolpacurripa Serpentinite than in the Nowendoc Serpentinite.

GABBROS AND DOLERITES

Introduction

Benson (1913) commented on the frequent occurrence of small gabbroic and doleritic bodies within the Great Serpentine Belt. The Nowendoc Serpentinite likewise possesses inclusions of gabbro or dolerite, many now altered to rodingite.

The least altered, obviously feldspathic examples are found adjacent to the partially serpentinised peridotite within the Nowendoc Serpentinite. Two varieties were found, a medium grained, dark greenish, but obviously feldspathic gabbroic type, and a finer grained variety, rich in feldspar, light brown to grey in colour. Five separated outcrops of the latter were mapped, and it is believed that they once formed a single body that has been disrupted by subsequent movement of the serpentinite.

The other intrusions of the belt also contain numerous inclusions of altered gabbroic or doleritic rock, many possessing mineral assemblages typical of rodingites.

The Least Altered Gabbro (S/9990)

The original mineralogy consisting of calcic plagioclase, brown hornblende, clinopyroxene and opaque oxide, has been partially replaced by an assemblage of lower temperature secondary minerals, consisting of actinolite, chlorite, albite, prehnite, zoisite, sphene.

Petrography

Randomly oriented plagioclase laths (2mm) are now heavily clouded with secondary alteration products. Composite grains possessing a spongy clinopyroxene core are mantled by a rim of brown hornblende, and euhedral brown hornblende individuals (2mm) also occur as separate grains.

Brown hornblende euhedra are fringed by fibrous outgrowths of colourless to pale green actinolite amphibole, or alternatively, marginally replaced by pools of pale green anomalously blue birefringent chlorite. Skeletal grains of finely divided sphene may possess cores of unaltered opaque oxide. Prehnite and zoisite are scattered throughout, prehnite as small anhedral grains, zoisite as prismatic aggregate.

Albitised Hornblende Dolerite

Five separated outcrops of this rock were mapped (see Fig. 23). It is slightly finer grained than the gabbro described above, and possesses a pale brown to grey colour in hand specimen.

Petrography

The rock possesses a panidiomorphic granular texture with intergranular clear albite separating euhedral prisms of brown hornblende, (Plate 20B). A visual estimate suggests the original rock consisted of approximately 50% calcic plagioclase and 50% brown hornbelnde.

Once again there is considerable evidence of secondary alteration. The original calcic plagioclase has been replaced by clear albite, with the secondary calcic minerals epidote, zoisite and grossular replacing the anorthite of the original calcic plagioclase. Brown hornblende is rimmed by fibrous outgrowths of pale green to colourless actinolitic amphibole, and may also show marginal alteration to chlorite. The original accessory amount of opaque oxide has been replaced by finely divided sphene aggregates. No quartz was observed. Secondary epidote granules may be retained as inclusions in coarse albite patches. Zoisite is present as scattered, randomly oriented prismatic aggregate. Veinlets also contain an isotrppic mineral with very high relief, thought to be grossular garnet. The secondary clear albite patches show a slight undulatory extinction, and adjacent grains of albite may have sutured boundaries, suggesting the rock has undergone some cataclasis.

Rodingite

This term, originally proposed by Bell, Clarke and Marshall (1911), has been redefined by Coleman (1966), and refers to altered gabbros that consist predominantly of hydrated calcium aluminium silicates and relict pyroxenes, restricted to serpentinites. Coleman (1966) analysed numerous rodingites from the New Zealand serpentinites and demonstrated that the formation of such rocks requires the addition of calcium to and removal of silica from original rocks of gabbroic or doleritic composition.

Most of the rodingites collected are dark to pale green in colour, very compact, and fine grained. All were characterised by combinations of various Ca-Al silicates and chlorite.

From the limited number of specimens collected, it appeared that two varieties of rodingite could be recognized:

(1) varieties with relic clinopyroxenes

(2) grossular-chlorite rock, without relic clinopyroxene, (Plate 20C).

Relict clinopyroxene-bearing variety.

The coarse gabbroid texture is usually fairly obvious, and the euhedral clinopyroxenes are only marginally replaced by uralitic amphibole or chlorite. Outlines of original plagioclase laths are preserved, but are now replaced by chlorite, zoisite and small amounts of grossular. Aggregates of finely divided sphene are scattered throughout the rock.

Grossular Chlorite Rock, lacking relict clinopyroxene

The outlines of the original fabric are still discernible, but the original plagioclase laths are replaced by pale-green chlorite. The remainder of the rock is composed of anhedral grossular, tremolitic amphibole and a small quantity of anhedral aggregate of a dirty-brown semi-opaque material, (Plate 20C).

It is suggested that these two varieties have arisen by alteration of two distinct parents. The grossular-chlorite rock is thought to have arisen by further alteration of the albitised hornblende dolerite. This is supported by the great similarity of the fabric preserved in the grossular-chlorite rock, and that of the albitised hornblende dolerite. A specimen of the grossular-chlorite rock was also collected from an inclusion within the Nowendoc Serpentinite, adjacent to the outcrops of albitised hornblende dolerites, and may have originally been part of the same body.

The original igneous clinopyroxene is apparently resistant to alteration, and the inclusions of rodingite containing relict clinopyroxene are thought to represent clinopyroxene-bearing gabbros, unaltered equivalents of which are not exposed.

Albitite

A small body of leucocratic rock was discovered within the Cooplacurripa Serpentinite, where its outcrop is crossed by the Cooplacurripa River. Unfortunately the exposure was too poor to establish the field relations but the body appeared to possess a sheet-like form, broadly concordant to the foliated serpentinite.

The rock is composed of anhedral to subhedral interlocking albite (β = 1.531) grains, 0.8-1mm., with granoblastic texture similar to that of a metamorphic rock. There is no evidence of any cataclasis. An estimated mode contains 90% albite and approximately 10% of chlorite, zoisite and a little sphene.

Chapter 23

MINERALOGY

Olivine

The β refractive index of ten olivines was measured, and their composition estimated from the determinative chart of Troger (1959) p. 37.

The variation in composition is limited, (see Table 17). There is no obvious change in the olivine composition with increasing amount of serpentinisation of the peridotite as described by Smith and MacGregor (1960) for the Mount Albert intrusion, Quebec.

Olivine compositions determined from similar alpine-type peridotites are listed for comparison. It is obvious that olivines from the Nowendoc Serpentinite possess a restricted range in composition, very similar to that of olivines from alpine-type serpentinites in other parts of the world.

Orthopyroxene

The β refractive index of eight enstatites was measured and their composition estimated using the determinative chart of Troger (1959) p. 59. The uni-

Table 17

Olivine Compositions from the Nowendoc Serpentinite.

Spec. No.	n_β*	Composition (% Fo molecule) Troger, (1959)
S/9980	1.671	90.5
S/9981	1.671	90.5
S/9982	1.671	90.5
S/9973	1.667	92.0
S/9974	1.667	92.0
S/9975	1.669	91.0
S/9976	1.669	91.0
S/9977	1.670	90.5
S/9978	1.670	90.5
S/9979	1.671	90.5

* Maximum error in the refractive index determination is believed to be ± .002, with a resultant error of approximately ± 0.5% Fosterite molecule.

Olivines from Similar Alpine-type Peridotites Elsewhere.

Location	Composition (% Fo)	Reference
Burro Mountain, Calif	90.8 - 91.6	Page (1967)
The Lizard, Cornwall	89.4 - 91	Green (1964)
Dun Mtn. and Red Hills, N.Z.	89.4 - 93.8	Challis (1965)
Hyachine, Japan	88 - 93	Onuki (1963)
Twin Sisters Dunite, U. S. A.	90	Ragan (1963)
Tinaquillo, Venezuela	90	Mackenzie (1960)
Glen Urquhart, Scotland	96	Francis (1956)
Totalp Serp., Switzerland	95	Peters (1968)

Table 18

Orthopyroxenes from the Nowendoc Serpentinite

Spec. No.	n_β ($\pm$.002)	Composition (% Enstatite Molecule) Troger, (1959)
S/9973	1.669	92
S/9975	1.669	92
S/9976	1.669	92
S/9977	1.668	93
S/9978	1.668	93
S/9979	1.668	93
S/9981	1.668	93
S/9980	1.669	92

Orthopyroxenes from Elsewhere in the Great Serpentine Belt of N.S.W.

Reference	Location	Composition (% En)
Wilkinson (in Joplin, (1964))	Gulf Creek, N.S.W.	94
Bultitude (1965)	Dungowan, N.S.W.	92, 94
Morrow (1967)	Baryulgil, Eastern Part of the Great Serpentine Belt, N.S.W.	92

formity of the refractive indices indicate no significant variation in enstatite composition throughout the peridotite, (see Table 18).

Spinel

The following two parameters were measured for a spinel from S/9973, one of the least serpentinised peridotites.

$$n = 1.910 \ (\pm .005)$$

$$a = 8.205 \ \text{Å} \ (\pm .002)$$

Refractive indices of spinels from several other sections were also measured.

Spec. No.	n (± .005)	Remarks
S/9983	1.910	Massive serpentinite
S/9976	1.915	Partially serpentinised peridotite
S/9979	1.910	Partially serpentinised peridotite

The refractive index, unit cell and colour of the spinel from S/9973 conform to those of a picotite, approximately Hercynite 53, Spinel 15, Chromite 25, Magnesiochromite 7 (mol. %) (see Deer, Howie and Zussman, V. 5, 1962, p. 61). The uniform refractive indices suggest little variation in composition. The variation of spinel composition with increasing serpentinisation reported by Smith and MacGregor (1963) was not detected at Nowendoc, although the data is limited.

Opaque mantles surrounding picotite suggest instability during serpentinisation, with alteration of the picotite to magnetite and chromite, (the identity ofthese phases was confirmed by X-ray powder photograph). This reaction is more advanced in the massive serpentinite than in the partially serpentinised peridotites, and this is interpreted to be the result of slow replacement of picotite by magnetite and chromite during progressive serpentinisation.

Serpentine Minerals

Whittaker and Zussman (1956) recognized the following serpentine mineral species:

Ortho	)	
Clino	)	Chrysotile
Para	)	
Lizardite		
Antigorite		

and their X-ray method for the identification of the serpentine varieties is adopted here. The samples were crushed and the serpentine mineral fraction separated from the olivine-pyroxene-spinel-magnetite fraction using heavy liquids. The serpentine fraction was scanned on the X-ray diffractometer using Cu radiation from approximately $2\theta = 5^{o}$ to $2\theta = 63^{o}$, and using the data of Whittaker and Zussman (1956), the varieties of serpentine mineral present were identified, and their relative proportion estimated. All the samples examined contained only lizardite and clino- and ortho- chrysotile, with no trace of antigorite. Reproductions of the diffractometer traces of the X-rayed samples are compared in Fig. 24.

Fig. 24

Explanation

1. Schistose serpentinite from quarry, (see Fig. 23), predominantly clino-chrysotile, with no brucite.

2. Translucent green rind encasing a massive serpentinite inclusion from quarry, consisting of a mixture of ortho- and clino-chrysotile, with no brucite.

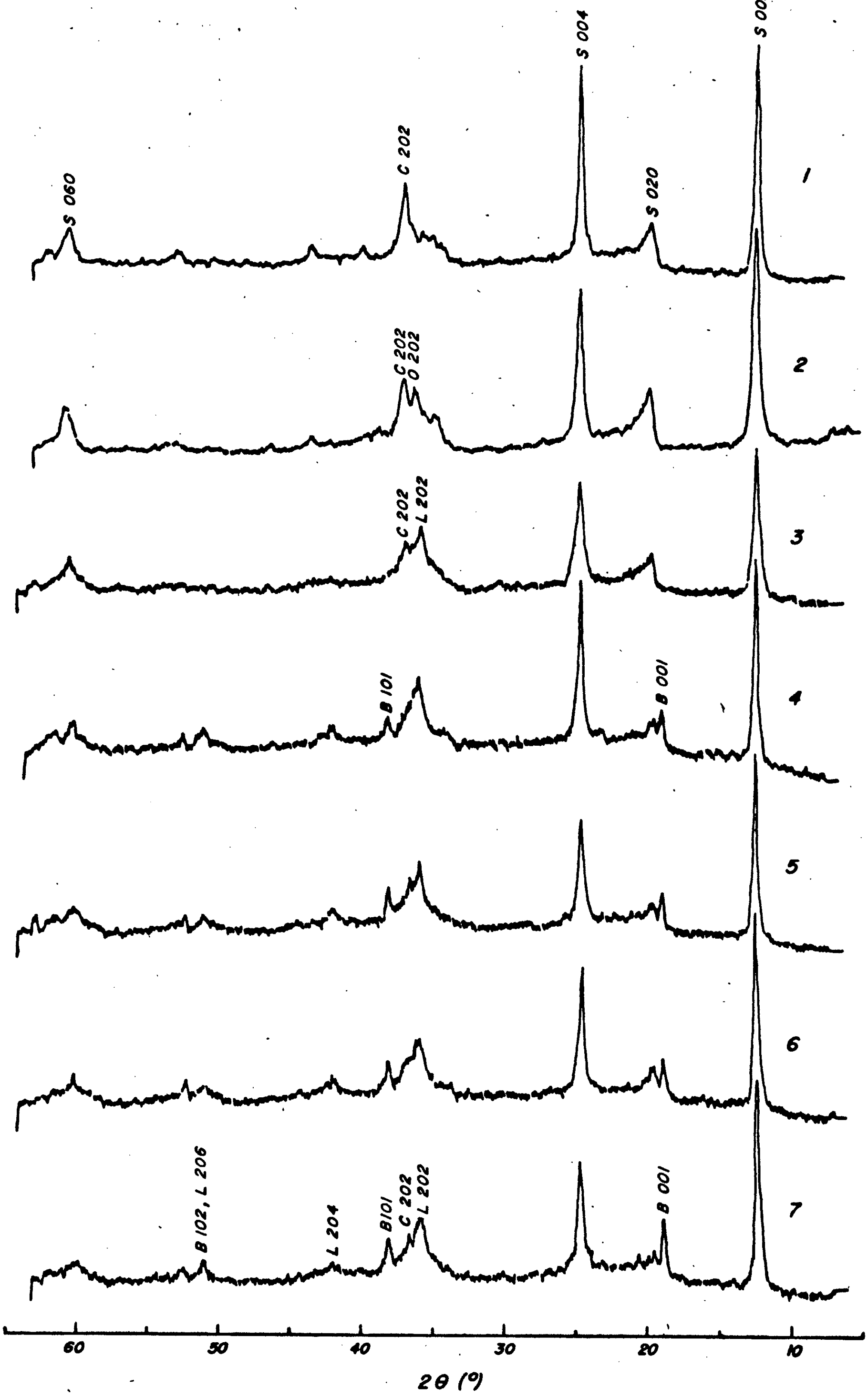
3. Massive serpentinite inclusion from quarry, predominantly lizardite with subordinate clino-chrysotile and no brucite.

4 - 7.

Serpentine mineral fractions from the partially serpentinised peridotites, with a decrease in the degree of serpentinisation from samples 4 to 7. All are predominantly lizardite with subordinate clino-chrysotile. Brucite is present in all samples, but the brucite (001) intensity decreases with increasing serpentinisation.

FIG. 24.

Diffractometer traces of the Serpentine Minerals.



Distribution of the Serpentine Mineral Varieties

The diffractometer traces of the serpentine minerals separated from the partially serpentinised ultramafics are very similar and are all found to be predominantly lizardite, with subordinate chrysotile. Optical methods for distinguishing the serpentine mineral species are unsatisfactory, however the numerous small veinlets in the partially serpentinised harzburgites, containing a fibrous, asbestiform serpentine mineral, are thought to be predominantly chrysotile. The serpentine mineral replacing the bulk of the rocks is thought therefore to be lizardite. The diffractometer traces of these serpentine mineral fractions also show relatively strong brucite peaks.

The massive serpentinite is predominantly lizardite, with perhaps a slightly higher proportion of accompanying chrysotile. No brucite peaks are observed.

Two specimens of the schistose serpentinite phase were X-rayed. A sample from the translucent green rind which typically encases rounded inclusions of massive serpentinite is found to be a mixture of ortho- and clino-chrysotile. A second sample from the schistose serpentinite is found to be comparatively pure clino-chrysotile.

The distribution of serpentine minerals agrees with that reported by Coleman (1966) p. 17, for the New Zealand serpentinites. Coleman also found that the massive serpentinite was predominantly lizardite with minor ortho- and clino-chrysotile, whereas the "foliated" serpentinites (equivalent to the schistose serpentinites) were mixtures of ortho- and clino-chrysotile, with only very minor lizardite or antigorite.

Pale Green, Pleochroic Serpentine

A variety of serpentine mineral, pleochroic from pale yellow-green to pale green, occurring in the partially serpentinised massive harzburgites, and was deduced to be a slightly iron enriched variety, co-existing with normal colourless serpentine materials. Lizardite is the predominant variety of serpentine mineral in the partially serpentinised rocks, and it is believed that the majority of the chrysotile component exists in lensoidal veinlets. It is therefore probable that the pale-green, pleochroic serpentine mineral is an iron-enriched variety of lizardite.

Using an electron microprobe, Page (1967) found that lizardite constituted the most iron rich serpentine mineral in the Burro Mountain Serpentinite, California, with up to 10% of the iron-serpentine molecule. Page (1967) also recognized three main textural varieties of serpentine at Burro Mountain:

(1) colourless to pale green lizardite pseudomorphs after enstatite (bastite);

(2) dark green, irregular, platy serpentine combined with areas of cross and slip-fibre serpentine replacing olivine (mesh texture);

(3) late cross-cutting colourless, cross-fibre chrysotile (veins). These textural varieties are also recognizable in the Nowendoc Serpentinite, although type (2) is represented by a mixture of green serpentine mineral and a colourless serpentine accompanied by magnetite dust.

A similar phenomenon is described by Shteynberg and Malakhov (1964), who observed that serpentinisation of a dunite in the Urals is unaccompanied by separation of dust-like magnetite, and the serpentine mineral produced, said to be chrysotile, was green under transmitted light. They suggested that the separation of magnetite granules resulted from metamorphism (i.e. recrystallization) of already formed serpentinite, not during the early "autometamorphic" serpentinisation.

Brucite

Brucite is found only in the partially serpentinised ultramafics, as fine-grained aggregates and in lensoidal veinlets along with magnetite and chrysotile. It is absent from the completely serpentinised peridotite (or massive serpentinite), and from the schistose serpentinite.

Small quantities of brucite were concentrated by treating the earlier separated "serpentine" mineral fraction to further heavy liquid separation. Samples were sufficiently concentrated to allow measurement of the brucite d(001) spacing, using silicon as an internal standard.

Brucite d(001) Spacings from the Partially Serpentinised Peridotites

Specimen No.	d(001) Å (third decimal place not significant)
S 9973	4.756
S 9974	4.755
S 9975	4.754
S 9976	4.755
S 9978	4.757

The d(001) of pure $Mg(OH)_2$ is 4.77 Å and the d(001) of $Fe(OH)_2$ is 4.597 Å. If, as assumed by Page (1967), linear variation in the values d(001) between $Mg(OH)_2$ and $Fe(OH)_2$ exists, then the above d(001) spacings suggest that the brucite contains 10 mol per cent $Fe(OH)_2$, with no perceptible variation in composition throughout. The above brucites are separated from samples ranging from the least serpentinised (S 9973), to one approximately 60 - 70 per cent replaced by serpentine (S 9975), in which brucite is also relatively common. The brucites from the harzburgites containing the pale green serpentine minerals (S 9976), (S 9978) show no variation in composition.

Page (1967) carried out a similar study at Burro Mountain, California, and found a very wide range in brucite composition, from 0 to 50 per cent $Fe(OH)_2$, with the majority of the brucites having between 18 and 32 mol per cent $Fe(OH)_2$.

Mineralogy of the Gabbros and Dolerites.

Plagioclase

Albitic plagioclase is preserved only in the least altered gabbro and the albitised hornblende dolerites. It is low temperature albite with $2V_\gamma > 70^o$. The β refractive index of albites from three samples of the albitised hornblende dolerite are given below.

Albites from the Albitised Hornblende Dolerites

Specimen No.	$n\beta (\pm .002)$	mol % An Chayes (1952)
S/9992	1.533	1
S/9993	1.535	4
S/9995	1.533	1

Clinopyroxene

Co**l**ourless spongy clinopyroxene is rimmed by brown hornblende in a gabbro inclusion from the Nowendoc Serpentinite, and in many rodingites, coarse euhedral colourless clinopyroxene is the only original mineral surviving, A clinopyroxene from a rodingite S/9998 possessed β = 1.684.

Brown Hornblende

Primary euhedral brown hornblende is an abundant mineral of the albitised hornblende dolerites. Some of its optical properties are:

α = 1.655	-	Very pale brown
β	-	Pale brown
γ = 1.679	-	Pale brown

Outgrowths of actinolitic amphibole, apparently in optic continuity with the host brown hornblende, are ubiquitous.

Chapter 24

PETROGENESIS OF THE NOWENDOC SERPENTINITE

Introduction

The petrogenesis of the Nowendoc Serpentinite can be considered in two stages:

(1) crystallization of the olivine, enstatite and spinel of the harzburgite, along with the gabbroic and doleritic phases.

(2) serpentinisation of the peridotite and alteration of the gabbros and dolerites.

The Original Peridotite

The observation of Benson (1926) that the original peridotites of the Great Serpentine Belt are dominantly harzburgites is confirmed for these intrusions.

Without knowledge of the overall chemistry of the peridotite, and the precise chemistry of the mineral phases, no worthwhile conclusion as to the original pressure-temperature conditions of crystallization can be reached. The abundant exsolved lamellae of clinopyroxene in the enstatite mineral phase are, however, interpreted to mean that crystallization took place initially at elevated temperatures. There is no evidence available to determine whether this initial period of crystallization involved crystal-liquid equilibrium, or alternatively whether it involved the attainment of equilibrium by solid-state reactions under deep crystal conditions.

Following this period of initial crystallization the peridotite underwent cooling, during which the enstatite exsolved lamellae of clinopyroxene. Also following this initial period, cataclastic textural features were developed, with the production of a strong cataclastic foliation towards the margins of the peridotite body. It is clear that the time relationship between these events is important.

Although the evidence is scanty, some textural features suggest that cataclasis in part coincided and in part preceded exsolution of clinopyroxene. There is no justification for assuming that exsolution wholly preceded cataclasis.

The textural evidence on which this is based is mainly the relationship between kink bands and exsolved lamellae. Some clinopyroxene lamellae terminate against kink bands, while others cross without interruption. In addition, where the enstatite is bent rather than kinked, it is not uncommon to find thickening of the exsolved lamellae in the region of maximum curvature of the enstatite cleavage. These features, while not definite, are enough to suggest that exsolution of clinopyroxene from the enstatite and cataclasis throughout the peridotite are related in time.

In terms of the possible mechanisms of emplacement, this relationship clearly favours emplacement of the peridotite as an essentially solid body. Emplacement by this mechanism is seen as following an initial period of crystallization under higher P - T conditions. Alternative emplacement mechanisms, for example as an ultramafic magma, cannot easily explain the development of the cataclastic foliation and its intensity distribution throughout the peridotite except by ascribing it to later cataclasis. The relationship between the foliation of the peridotite and the serpentinite at Nowendoc indicates that cataclasis wholly preceded serpentinisation.

The peridotite within the Nowendoc Serpentinite is believed to have been derived by the mobilization at elevated T and P of essentially solid peridotite. Modern techniques of experimental deformation at elevated temperatures have shown that emplacement as a solid is not incompatible with the physical properties of peridotite under typical deep crustal conditions, (Ragan, 1967, p. 167). The hot-solid peridotite probably behaved in some respects similarly to a magma during emplacement, i.e. it flowed upwards along a steeply inclined plane of structural weakness in the crust, in this case the Nowendoc Fault zone.

Although outcropping poorly, the present contact rocks of the Nowendoc Serpentinite are of uniformly low metamorphic grade. There is no evidence of a thermal aureole of the kind described by Mackenzie (1960), Green, (1964) or Challis (1965), however the structural environment and degree of serpentinisation at the margins of the intrusion suggest that the peridotite is probably displaced from its original contact rocks.

Without chemical data it is rather pointless to discuss the genesis of the gabbro and dolerite inclusions. These bodies appear to be quite separate from the peridotite, with no inclusions of rock types intermediate between gabbro and peridotite. The rimming of clinopyroxene by pale brown hornblende in one of these inclusions suggests that the albitised hornblende dolerites originally evolved from a gabbroic parent also present as inclusions.

Serpentinisation

The second stage of the evolution of the Nowendoc Serpentinite commenced with the alteration of the original olivine, pyroxene and spinel, which are replaced by a combination of serpentine minerals, brucite, magnetite and chromite. Serpentinisation is deduced to have commenced only after the emplacement of the peridotite by solid or semi-solid flow had ceased; if it was concurrent, the preservation of the original textures within the massive serpentinite would not be expected. Low temperature hydrothermal metamorphism affecting the accompanying gabbros and dolerites is thought to have been concurrent with the serpentinisation of the peridotite.

Reactions of Serpentinisation

The recent work of Page (1967), (1968) suggests the following reactions take place during serpentinisation:

(1) Olivine + Enstatite

$$(Mg,Fe)_2SiO_4 + (Mg,Fe)_2Si_2O_6 + H_2O + O_2$$

Chrysotile + Lizardite + Magnetite

$$\rightleftharpoons (Mg,Fe^{2+})_6Si_4O_{10}(OH)_8 + (Mg,Fe^{2+},Fe^{3+})_6Si_4O_{10}(OH)_8 + Fe_3O_4$$

(2) Olivine

$$(Mg,Fe)_2SiO_4 + H_2O + O_2 \rightleftharpoons$$

Brucite + Chrysotile + Lizardite + Magnetite

$$(Mg,Fe)(OH)_2 + (Mg,Fe^{2+})_6Si_4O_{10}(OH)_8 + (Mg,Fe^{2+},Fe^{3+})_6Si_4O_{10}(OH)_8 + Fe_3O_4$$

According to Page serpentinisation at Burro Mountain commenced with reaction (1), and then somewhat later reaction (2) operated, and brucite was generated. As expressed above, these reactions incorporate the chemical differences between the serpentine mineral varieties determined by Page (1967), (1968) to be that lizardite is more iron rich than chrysotile, and contains some of this iron in the trivalent state.

The above reactions are believed to represent fairly accurately the transformation that took place within the Nowendoc Serpentinite. They involve the simple addition of only water and oxygen to the rock, without removal of any constituents, thereby implying a substantial volume increase during serpentinisation. Within the Nowendoc Serpentinite, it appears, however, that serpentinisation commenced with reaction (2), with brucite appearing as a mineral phase at the onset of serpentinisation, when the olivines are marginally altered to serpentine and fine grained brucite. Brucite has also nucleated along with magnetite in lensoidal veinlets within the serpentinising peridotite. Reaction (1) also operated but replacement of enstatite is not as advanced as that of the accompanying olivine, so operation of reaction (1) probably followed or was less effective than reaction (2).

Brucite in Alpine Serpentinites

In an important paper by Hostetler et al (1966), it was demonstrated that brucite is a common mineral phase of many Alpine serpentinites, and that it apparently accompanies the serpentine minerals at the onset of serpentinisation. According to Hostetler et al (1966), brucite arises from the reaction:

Olivine (Fa_{10})

$$(Mg,Fe^{2+})_2SiO_4 + H_2O + O_2 \rightleftharpoons$$

Clinochrysotile Brucite

$$(Mg,Fe^{2+})_6Si_4O_{10}(OH)_8 + (Mg,Fe^{2+})(OH)_2$$

Magnetite

$$+ Fe_3O_4$$

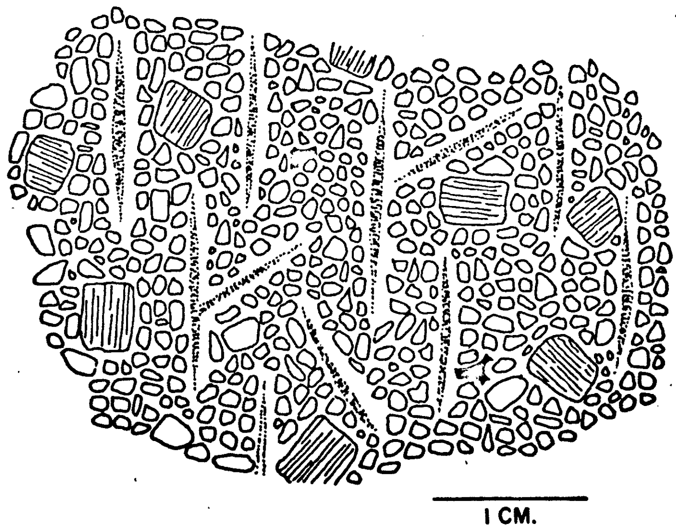
Hostetler et al (1966) believe that unless it can be shown that magnesia and silica have been removed from the mass, volume increases of 35 - 40 per cent must occur during serpentinisation. The presence of brucite is believed to demonstrate that no such loss occurred. This expansion is thought to have been accommodated by tectonism during the ascent of these bodies along major faults.

It has been determined that brucite in the Nowendoc Serpentinite is confined to partially serpentinised peridotite, where it occurs both as finely divided material associated with the serpentine replacing the bulk of the rock, and as narrow (1mm) lensoidal veinlets cutting through the peridotite, e.g. Plate 19B and Fig.

25. These veinlets are typically surrounded on a micro-scale by an aureole of completely serpentinised peridotite. Identical veinlets containing only a cross-fibre variety of serpentine mineral (chrysotile) are equally common. In terms of the serpentinisation process, these veinlets are believed to arise from segregation of brucite, magnetite and chrysotile during serpentinisation of the immediately surrounding peridotite. The volume occupied by these veinlets is herein interpreted as increments in an overall volume increase of the peridotite during serpentinisation. The original texture of the peridotite is thereby preserved duting the early stages of serpentinisation when only a relatively small percentage of the peridotite has been replaced by serpentine minerals.

This interpretation of the brucite + magnetite and chrysotile veinlets means that Mg and Fe and a fluid of chrysotile composition migrated over short distances and nucleated within these veinlets. The site of these veinlets was probably dictated by slight original anisotropies within the peridotite, such as a direction of incipient fracture, a direction of preferred orientation, or the cataclastic foliation. In a specimen des-

FIG. 25.



Partially serpentinised harzburgite, showing the distribution and form of the lensoidal serpentine and brucite-magnetite veinlets.

cribed earlier, brucite-magnetite veinlets are semi-penetrative parallel to the cataclastic foliation of the partially serpentinised peridotite.

In slightly more serpnetinised peridotites, the early formed veinlets of brucite are replaced by colourless cross-fibre serpentine (chrysotile). The remnants of the early formed brucite may be clearly observed, surrounded and replaced by asbestiform serpentine. No brucite was found in the massive or schistose serpentinite. Experiments carried out by Carlson _et al_ (1953) showed that replacement of brucite by serpentine is possible at temperatures as low as 200°C by the action of vapour-borne silica. This silica may have been dissolved in the serpentinising fluid from the adjoining crustal rocks, but could also be the silica that migrated from the gabbros and dolerites during rodingitization, and been introduced into the peridotite as serpentinisation proceeded.

Constant Volume or Volume Increase?

Turner and Verhoogen (1960) p. 318 stated:

"microscopic fabric and field relations of undeformed serpentinites show clearly, however, that serpentinisation is commonly accompanied by little or no increase in volume".

To explain equal-volume serpentinisation, Turner and Verhoogen (1960) p. 319 suggested the following reaction:

$5Mg_2SiO_4$	+ $4H_2O$ $\rightleftharpoons$	$Mg_6Si_4O_{10}(OH)_8$	+ $4MgO$	+ SiO_2
Olivine	Introduced	Serpentine	Removed	
(700gm,219cc)	(72gm)	(552gm, 220cc)	160gm	60gm

They admit that the major difficulty of this hypothesis is the vast quantities of water that would be needed to remove magnesia and silica to maintain a constant volume. Carlson _et al_ (1953) determined that the solubility of magnesia in pure water decreased markedly with increasing temperature, from 2.1×10^{-4} mole per litre at $30^{\circ}C$ to 1×10^{-5} mole per litre at $250^{\circ}C$. Turner and Verhoogen (1960) also admit that magnesium metasomatism of adjoining rocks would be expected, but that such a phenomenon is rarely observed, although a number of instances of regional silicification in serpentinite belts have been recorded.

In general agreement with Turner and Verhoogen (1960), Thayer (1966) believes that the fact that serpentinites vary widely in composition suggests that they could not form by simple addition of water to ultramafic rock. Textural evidence of lack of volume increase is also cited and the necessary removal of MgO and SiO_2 is done by appealing to the solvent power of connate water containing dissolved salts. In a discussion of Thayer (1966), Page (1967) demonstrated a regular and absolute loss of calcium relative to magnesium and iron during the serpentinising process. Thayer (1967), in a reply, admitted that a volume increase may occur in some situations, but added that proof of volume increase would be very difficult in typical "Alpine" peridotites.

A hypothesis of constant volume serpentinisation cannot however explain:

(1) the overall lack of magnesium metasomatism around serpentinites,

(2) an adequate water source to remove MgO and SiO_2 necessary to maintain constant volume,

(3) the widespread occurrence of brucite in "Alpine" serpentinites.

It therefore appears that serpentinisation of typical "Alpine" peridotite should be accompanied by a substantial volume increase (30 - 40% according to Hostetler et al (1966), and greater if dissolved silica is introduced with serpentinising water.).

Undoubtedly the most compelling evidence of a lack of volume increase during serpentinisation is preservation of the original textures of the parent peridotite in massive serpentinites. The outlines of the original olivine and enstatite are immaculately preserved, and it seems inconceivable that an increase in volume could take place without having some visible effect on the texture of the massive serpentinite. It is believed, however, that the importance of many other textural features have not been realised, and that when these are considered, together with the structural features and physical properties of the intrusion, there exists plausible means of accommodating a substantial volume increase. This aspect is discussed at length below.

Composite Serpentinite and Serpentine Breccias

These terms, introduced by Wilkinson (1953), refer to the development of rock consisting of inclusions of massive serpentinite of variable size and angularity in a matrix of schistose serpentinite. Such a relationship has been reported by Wilkinson (1953) p. 310 to be typical of the serpentinite intrusions throughout the 1400 mile long serpentine belt of Eastern Australia. The literature available suggests that these composite rocks or breccias are also a characteristic constituent of typical serpentinised "Alpine" ultramafic intrusions elsewhere in the world.

The Franciscan serpentinites of California, containing one of the classic belts of "Alpine" ultramafic intrusions, are described by Bailey et al (1964) p. 79 as follows:

> "the typical serpentinite mass consists of two different components - blocks and matrix. The blocks, which may range in size up to 10 or more feet, but are generally smaller, consist of virtually completely serpentinised peridotite in which the original texture is well preserved. .... The shapes of the large blocks tend to be rectangular with rounded corners, whereas the smaller ones are generally much rounder. Between the blocks is a highly sheared, nearly schistose serpentinite sometimes referred to as slickentite. The proportion of "matrix" to blocks is quite variable, there being generally less matrix where the blocks are largest, and a gradation to a marginal zone that is largely slickentite, with only small, scattered rounded boulders".

Similar structural relationships are reported by Page (1967) from the Burro Mountain Serpentinite, California, and also in a serpentinite of the Tiburon Peninsula, California, (Page (1968) p. B25). The border phases of the largely unserpentinised Trinity Ultramafic Pluton and the Twin Sisters Dunite, described by Lipman (1964) and Ragan (1963) respectively, consist of serpentinised peridotite, in places highly sheared but commonly containing blocks of massive serpentinite, and with an inward gradation to fresh peridotite. The similarity of the structure of these border phases with the composite rocks of the completely serpentinised peridotites of the Franciscan described above suggests they are analogous.

Several intrusions belonging to the 1600 mile long Appalachian Serpentine Belt of the Eastern United States are described by Chidester (1962). He records their internal structure as follows:

p. 71 "It consists of relatively unsheared polyhedral masses from an inch or less to several feet across, bounded by shells of highly sheared serpentinite from a fraction of an inch to several inches in thickness, and traversed sparsely by irregular, weak and discontinuous small shear zones".

In this same Appalachian Belt, Jahns (1967) p. 145 divides the serpentinite intrusions of the Roxbury district, Vermont, into:

(1) A marginal zone of intensely sheared serpentinite.

(2) An intermediate zone of shear polyhedrons in a matrix of highly sheared serpentinite,

p. 146

"The size and angularity of polyhedrons increase irregularly but progressively inward from the marginal zone of sheared serpentinite, accompanied by increases in the ratio of polyhedron to matrix material".

(3) A core of irregular broken and sheared massive serpentinite.

From these descriptions, the similarity of the internal structure of the Franciscan (Mesozoic) and Appalachian (Lower Palaezoic) Serpentinites is obvious, and both are very similar to that of the Nowendoc Serpentinite. The Franciscan and Appalachian Serpentinites belong to two of the best known and perhaps best described continental serpentine belts, and the widespread development in these belts of composite serpentinites or serpentine breccias suggests that the development of such internal structure is an important phase of the evolution of typical "Alpine" serpentinites.

Further occurrences of such internal structure have been provided by Coleman (1966), with examples from the New Zealand Serpentinites, and from the Caribbean, where similar rocks described by Mattson (1964) were recovered from the AMSOC drill hole on Puerto-Rico.

Within the Great Serpentine Belt of N.S.W., Benson (1913) p. 583 described composite serpentinite at Nundle as "large or small nodules of massive serpentinite...... imbedded in the sheared mass". The means of conversion of massive to schistose serpentinite is described as "mechanical alteration" suggesting that Benson believed that progressive deformation of massive serpentinite gave rise to the schistose phase. Wilkinson (1953) reported the widespread occurrence of composite serpentinite throughout the belt, and deduced that the relationship demonstrated that "the inclusions were solid at a time when the matrix was fluid or extremely plastic", (p. 311).

Along with Proud and Osborne (1952), Wilkinson then suggested that the inclusions and matrix represent the injection of successive phases of ultramafic material.

There are few other explanations available for this apparently widespread structural feature of "Alpine" serpentinites. In agreement with Benson (1913), Jahns (1967) implies but does not state explicitly that the inclusion-matrix relationship is due to progressive deformation of massive serpentinite. The other explanation, discussed below, is that offered by Raleigh and Paterson (1965) following their study of experimental deformation of serpentinite.

<u>Experimental Deformation of Serpentinite</u>

Raleigh and Paterson (1965) studied the physical behaviour of typical serpentinite at elevated pressures and temperatures. They concluded:

(1) Typical serpentinite possesses similar strength to most other crustal rocks at temperatures below a limit somewhere in the range 300 - 600°C, the position of this limit being apparently fixed by the first appearance of appreciable water pressure in equilibrium with the serpentinite.

(2) Tectonic intrusion is plausible if the serpentinite is at a temperature at which an appreciable water pressure is in equilibrium with its mineral assemblage. Sliding on fracture surfaces will then be possible at low shear stresses because of the weakening effect of the pore pressure of water.

(3) Approximately 20% strain rendered the mesh texture unrecognizable in massive serpentinite, plastic flow cannot therefore have been the mechanism of emplacement in which mesh textures are preserved.

(4) General plastic deformation will not occur, because the mode of failure is brittle fracture, which will be confined to a pattern of localized fracture zones depending on the nature of external constraints. Original mesh texture is therefore preserved.

Scarfe and Wyllie (1967), in a similar study, agree that the weakening of serpentinite is caused by liberation of water during dehydration, and suggest that the presence of brucite is probably responsible for the lower temperature weakening of the Fidalgo Island Serpentinite compared with the brucite-free Tumut Pond Serpentinite. Thus they conclude "the presence or absence of brucite in serpentinite may provide an important control on various tectonic processes discussed by Raleigh and Paterson (1965)" (Scarfe and Wyllie, 1967 p. 946).

The serpentine breccias described by Wilkinson (1953) are explained by Raleigh and Paterson (1965) as having originated from faulting of a mass of serpentinite with the schistose phase and angular fragments having their parallels within the fault zones of the weak and brittle experimental specimens. Brecciation, it is suggested, might well have occurred during intrusion under conditions in which the serpentinite is weakened and embrittled as a result of partial dehydration.

The Origin of Composite Serpentinite and Serpentine Breccias

The "inclusion-matrix" internal structure appears to be a characteristic feature of typical "Alpine" serpentinites, and the following explanations of this phenomenon have been offered:

(1) Progressive deformation of massive serpentinite, (Benson 1913, Jahns 1967, Wilkinson, 1969).

(2) Successive emplacement of serpentinite phases, (Proud and Osborne 1952, Wilkinson 1953).

(3) Fracturing during partial dehydration and embrittlement of massive serpentinite, (Raleigh and Paterson, 1965).

Close examination of the relationship between the blocks and matrix rules out (1). The contacts of the inclusions are extremely sharp, and at the contact the "schistose" serpentinite is often not at all schistose microscopically, e.g. Plates 21A and B, and Plates 22A and B. The massive serpentinite inclusions also develop rims enriched in magnetite, a feature that would not be expected if marginal deformation of the inclusions gave rise to the schistose serpentinite.

Much of the above also applies to (2), as Wilkinson (1953) p. 312 believes that the brecciation of massive serpentinite by later serpentine gave rise to angular inclusions of massive serpentinite which subsequently became rounded by mutual abrasion. The block-matrix relationship is not unequivocal evidence of multiple intrusion, and it is not believed that this is capable of being a general explanation of this widespread internal structural feature of "Alpine" serpentinites.

Wilkinson, (1969) p. 304 has, however, slightly revised his earlier view. The serpentine breccias are now interpreted by Wilkinson as the result of multiple emplacement, the first phase of which is primarily magmatic, with later phases derived from the initial phase in response to later tectonic stress after emplacement in deep seated thrusts.

The third hypothesis above is also difficult to accept. Raleigh and Paterson (1965) provide little detail of the fine structure of their experimentally deformed specimens, but the criticisms of (1) above are probably equally applicable to (3). It is also difficult to apply this experimental work to natural serpentinite intrusions, as the experimental procedure consisted of deforming and partially dehydrating serpentinite using an external heat source. This arrangement bears little resemblance to what takes place during evolution of natural serpentinite, however the importance of this study lies in the determination of the P - T conditions at which serpentinite yielded by plastic and brittle deformation and is capable of tectonic emplacement.

It thus appears that no published work to date has satisfactorily explained the common inclusion-matrix structure of typical "Alpine" serpentinites. It is, however, possible to arrive at a widely applicable explanation of the development of this structure by accepting the following conditions:

(1) Serpentinisation takes place by simple addition of water (and perhaps oxygen) to peridotite and is accompanied by a substantial volume increase, (Hostetler et al, 1966).

(2) An appreciable water pressure may develop in equilibrium with serpentine minerals, when tectonic intrusion becomes plausible, (Raleigh and Paterson, 1965).

(3) Migration or diffusion of a fluid of essentially serpentine composition is possible over short distances throughout the serpentinising intrusion.

The major steps to produce the block-matrix relationship are outlined below:

(1) Cooling and thermal contraction of the peridotite, resulting in the formation of joints along which water may migrate into the intrusion.

(2) Migration of water from the surrounding crustal rocks and the commencement of serpentinisation reactions. In the thin sections of the least serpentinised material this is observed to take place by the marginal replacement of olivine and enstatite by serpentine, brucite and magnetite. To preserve the texture of the peridotite, the small excess of

material of serpentine, brucite and magnetite composition undergoes small-scale local migration to nucleate as small (1mm) lensoidal veinlets, (e.g. Fig. 25), a characteristic textural feature of the peridotite and the massive serpentinite. Thus the material of serpentine composition left over after equal volume replacement of the surrounding peridotite migrates into the joint planes where it crystallizes to become the progenitor of the "schistose" serpentine matrix.

As serpentinisation of the peridotite continues, the proportion of schistose serpentinite increases as material of serpentine composition migrates from the peridotite, preserving its texture, into the joints and veinlets. Selective enlargement of the small veinlets leads to disaggregation of the peridotite body as serpentinisation proceeds. The end product of the above process consists of angular blocks of serpentinised peridotite separated by a network of sheets of structureless serpentinous material, the volume of which equals the overall volume increase of the peridotite body during serpentinisation.

(3) As the serpentinisation reaction is independent of pressure (Bowen and Tuttle (1949), Kitahara et al (1966)), the increase in volume outlined above will result in a great increase in pressure within and around the serpentinising peridotite. This increase in pressure is concurrent with serpentinisation, and will therefore be in equilibrium with the water pressure, conditions at which tetonic intrusion becomes plausible according to experiments of Raleigh and Paterson (1965). The release of this accumulated pressure is believed to take place by migration of the serpentinising material upwards along the steeply inclined fault plane.

As pointed out by Wilkinson (1953), the relationship observed between the inclusions and matrix suggests that the inclusions were solid at a time when the matrix was relatively mobile or plastic. A possible reason for this difference in physical properties is the fact that the inclusions are predominantly of lizardite, while the matrix consists almost entirely of chrysotile. Although no experimental data is available, this relationship can be explained if under the high water pressures chrysotile serpentine is mobile and capable of plastic flow while the adjacent lizardite serpentine of the inclusions is slightly stronger, yielding only by brittle deformation.

To explain the relationship observed at the surface, tectonic intrusion as the result of pressure increase must be capable of transporting blocks of massive serpentinite as inclusions within the schistose serpentinite phase generated during the volume increase.

Alternatively, according to Fyfe (1967) serpentinisation is an exothermic reaction, thereby providing a source of internal heat. Serpentinisation commences with replacement of olivine by brucite and serpentine, but as the process continues the heat of reaction could lead to the partial dehydration of the brucite that crystallized earlier, with the resultant embrittlement and weakening of the peridotite, (Raleigh and Paterson (1965), Scarfe and Wyllie (1967).

If this is concurrent with the migration of serpentinised material upwards within the fault zone, this weakening and embrittlement would be an extremely effective method of disaggregating the partially serpentinised material that still contains early formed brucite. The matrix of schistose serpentinite, containing no brucite would then deform at high water pressure by plastic or ductile flow, while the brucite bearing peridotite is weak and embrittled (see Fig. 10, p. 3978 of Raleigh Paterson, 1965).

The steps outlined above results in a body consisting of 30 - 40% by volume of schistose serpentine representing the volume increase, separating angular blocks of massive serpentinite. Much of the Nowendoc Serpentinite may be plausibly interpreted in this way, but generally the proportion of schistose serpentinite appears to be too high for this simple relationship to be valid.

The final stage involves the rounding and reduction in the volume occupied by the originally angular inclusions of massive serpentinite, and a further increase in the proportion of schistose serpentinite. During the rounding and reduction in size, the rims of the inclusions became enriched in fine grained granular magnetite. Marginal shearing of the inclusions is not capable of explaining this reduction in size because:

(a) the margins of the inclusions are extremely sharp, and thin sections cut across the contacts of the inclusions show no sign of any deformation at the boundaries of the inclusions, Plates 21 and 22.

(b) magnetite enriched rims are unlikely to develop within the inclusions during marginal shearing.

(c) the inclusions contain mainly lizardite with subordinate chrysotile, whereas the schistose serpentinite consists of chrysotile serpentine mineral.

It is probable that a component of the massive serpentinite inclusion becomes unstable and undergoes a reaction at the rim of the inclusion to deposit magnetite, and at the same time material of chrysotile composition migrates to the inclusion boundary where it is expelled as chrysotilic serpentine. The difference between lizardite and chrysotile serpentine varieties was found by Page (1967), (1968) to be the greater amount of iron in lizardite, part of which is trivalent. The deposition of magnetite and the migration of material into the schistose serpentinite probably took place by lizardite becoming unstable at the interface between the inclusions and the schistose serpentinite. The reaction is essentially as follows:

$$(Mg,Fe^{3+},Fe^{2+})_6Si_4O_{10}(OH)_8 + O_2 \rightleftharpoons$$

Lizardite

$$(Mg,Fe^{2+})_6Si_4O_{10}(OH)_8 + Fe_3O_4$$

Chrysotile Magnetite

Page (1967) deduced that, at Burro Mountain, California, serpentinisation proceeds in a changing PO_2-T enviroment, and noted that:

> "the first phases to form during alteration are magnesium rich. Later in the serpentinisation sequence, the phases become more iron rich. At a later time, or possibly at a lower temperature, recrystallization and new alteration tends to form magnetite and magnesium rich brucites and serpentine (especially cross-fibre chrysotile)." p. 337.

These observations are compatible with those from Nowendoc Serpentinite, where Page's "recrystallization and new alteration" took place at the interface between the massive and schistose serpentinite.

How this exchange actually occurs at the inclusion contacts is obscure, but it must involve the crystallization of magnetite within the inclusion, and the expulsion of material of chrysotile composition. Eventually the rim of the inclusion, as expected, becomes choked with magnetite preventing further migration. It was observed, however, both in thin section and outcrop, that these massive serpentinite inclusions were very prone to fracturing, (see above) continually exposing fresh surfaces for the process to continue, and continually reducing the inclusion size.

Summary and Conclusions

It has been shown above that the hypothesis that volume expansion accompanies serpentinisation provides a ready explanation for the development of the serpentine breccias characteristic of "Alpine" serpentinites.

The initial stages of serpentinisation are believed to involve the peripheral replacement of olivine grains and the migration and deposition of serpentine, brucite and magnetite in narrow lensoidal veinlets which are a common textural feature of the partially serpentinised harzburgite. The original texture of the peridotite is thereby preserved, and the volume occupied by these veinlets is believed to represent a slight volume increase, with nucleation of serpentine, brucite and magnetite from a fluid of serpentine composition taking place within veinlets after equal volume replacement of the immediately surrounding peridotite.

Selective enlargement of favourably situated and oriented veinlets, and the migration of serpentine into joints and fractures within the peridotite during further progressive serpentinisation has had the effect of rafting apart blocks of the peridotite as further fluid of serpentine composition was contributed to the enlarging veins.

The textures of the peridotite are thus preserved within the massive serpentinite, and the intrusion assumes the appearance of being made up of blocks of serpentinised peridotite in a matrix of schistose serpentinite.

Once serpentinisation is under way, effects attributable to the pressure developed during volume increase appear. This pressure should initially be concentrated at the leading edge of the steeply inclined sheet of peridotite until in excess of the confining pressure, when it is believed the serpentinised material would be emplaced further upwards within the Nowendoc Fault zone.

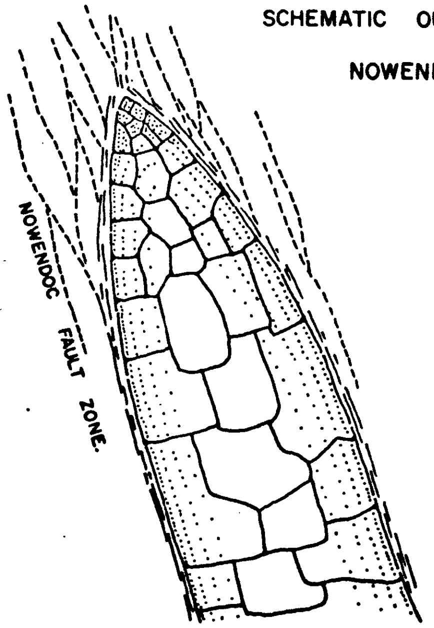
Rare outcrops were found where inclusions of both massive serpentinite and partially serpentinised material were mixed, both in a matrix of schistose serpentinite. This suggests that the mechanical disaggregation of the peridotite took place while the serpentinising process was active, and the mixing took place during migration of the serpentinising intrusion along the steeply inclined fault plane.

Finally, the originally angular massive serpentinite inclusions become rounded and undergo a reduction in size, and develop rims enriched in magnetite. This is believed to result from the transformation of the lizardite serpentine of the massive serpentinite inclusions to a chrysotilic variety of the schistose matrix with the deposition of magnetite within the rim of the inclusion.

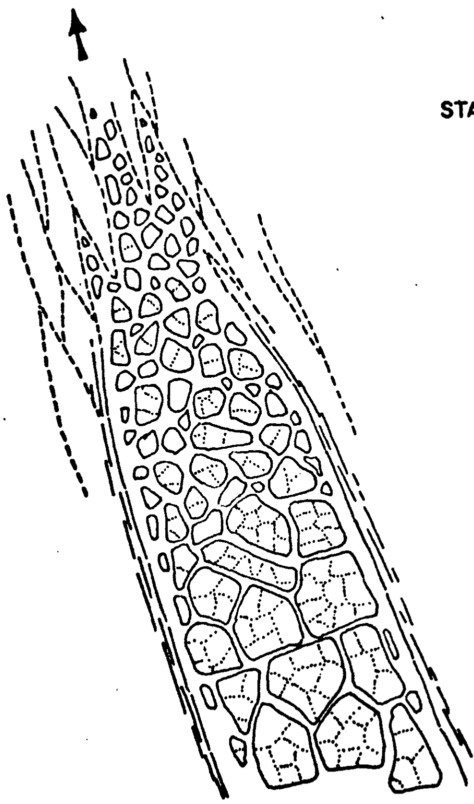
Fig. 26 illustrates schematically the evolution of the Nowendoc Serpentinite as deduced from this study of its petrology and internal structure. Some aspects of the hypothesis outlined here are still somewhat conjectural. The source of water for serpentinisation is tacitly assumed to have been the crustal rocks into which the relatively anhydrous peridotite was emplaced. Only very small quantities of water in the wall rocks are necessary to initiate serpentinisation. In addition, lengthy discussion of the P - T conditions of serpentinisation

FIG. 26.

SCHEMATIC OUTLINE OF THE EVOLUTION OF THE NOWENDOC SERPENTINITE.



STAGE I. Emplacement of hot peridotite by solid flow, followed by cooling, thermal contraction and jointing of the peridotite sheet, thereby providing routes for the migration of water from surrounding crustal rocks into the peridotite.



STAGE 2. With water present, serpentinisation commences. The peridotite is split up into blocks by migration of serpentine into the joints during volume increase and concurrent migration of serpentinised material upwards within the fault zone under conditions of high P_{H_2O}.

and the stability of serpentine and brucite has been avoided as it is not really relevant.

Age of Emplacement

The emplacement of the various serpentinites of the Great Serpentine Belt has been given ages ranging from Devonian, (Bryan and Jones, 1945), Carboniferous (Benson, 1913a; Carey and Browne, 1938), to Permian, (Voisey, 1939).

One of the great attractions of the hypothesis of serpentinite emplacement outlined above is that the quite complicated internal structure is explained by a single cycle of serpentinisation, and the necessity to invoke multiple intrusion to explain this structure is avoided. This does not mean that multiple emplacement has not affected some serpentinite intrusions, however the Nowendoc Serpentinite is interpreted to result from only one cycle of serpentinisation, with no evidence of re-intrusion.

The emplacement of the Nowendoc Serpentinite post-dates the youngest folding in the Oxley Metamorphics, and this folding can be indirectly correlated with the emplacement of the Tia Granodiorite, for which an approximate 250 m.y. age is inferred. The Nowendoc Serpentinite is also in contact with relatively undeformed unmetamorphosed Permian sediments. This suggests that serpentinisation and emplacement is of Permian age or younger. The relationship of serpentinisation to the age of emplacement of the original peridotite is less clear. The simplest interpretation is that it is an early phase of the same tectonic event.