GEOLOGY AND MANGANESE DEPOSITS OF THE
NORTH SHORE OF COWICHAN LAKE
VANCOUVER ISLAND B.C.

by

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ABSTRACT

SUMMARY

The north side of Cowichan Lake, Vancouver Island B.C. is underlain by volcanic rocks, sediments, and intrusives of Mesozoic age. The oldest rocks, Jurassic or Triassic flows known as the Sicker andesites, are conformably overlain by about 3000 feet of cherty tuffs, coarser pyroclastics, and small lenses of limestone known as the Sicker sediments. Cherty tuffs form the lower members of the Sicker sediments, felspathic tuffs the central members, and coarser pyroclastics the upper members. About 2000 or 3000 feet of basaltic and andesitic flows conformably overly the Sicker sediments.

The Sicker andesites and sediments and younger flows are intruded by large dyke-like bodies of granodiorite or quartz monzonite, known as the Saanich granodiorite and correlated with the Coast Range intrusives.

Upper Cretaceous shales sandstones and conglomerate unconformably overlie the volcanics and intrusives.

The Sicker series and overlying flows are tightly folded into overturned and asymmetrical north-westerly trending synclines and anticlines. The Cretaceous rocks are gently folded and dip north along a narrow belt on the north side of a down-faulted block.

Manganese deposits occur in the lower cherty beds of the Sicker sediments as lens shaped bodies parallel to the bedding of the sediments. They are commonly in chert free from felsparic material, and are always associated with jasper or jaspery sediments. The main manganese minerals are rhodonite, spessartite, an unidentified yellow manganese silicate, and small amounts of rhodochrosite. Residual manganese oxides coat the surfaces of the deposits.

Several features of the deposits, such as the fact that rhodonite commonly cross cuts and replaces the chert suggest that the deposits are of replacement origin. Other features such as their bedded appearance and the fact that they occur at about the same horizon in the Sicker sediments indicate a sedimentary origin. Theoretical considerations support the view that the deposits are sedimentary and suggest that the replacement features were formed by metamorphism.
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Previous Work</td>
<td>1</td>
</tr>
<tr>
<td>Geography and physiography</td>
<td>3</td>
</tr>
<tr>
<td>Chapter I General Geology</td>
<td>5</td>
</tr>
<tr>
<td>Summary of geology</td>
<td>5</td>
</tr>
<tr>
<td>Detailed Descriptions</td>
<td>7</td>
</tr>
<tr>
<td>Sicker Andesites</td>
<td>7</td>
</tr>
<tr>
<td>Sediments within the Sicker andesites</td>
<td>9</td>
</tr>
<tr>
<td>Sicker sediments</td>
<td>10</td>
</tr>
<tr>
<td>Flows Younger than the Sicker sediments</td>
<td>16</td>
</tr>
<tr>
<td>Saanich granodiorite</td>
<td>17</td>
</tr>
<tr>
<td>Minor intrusives</td>
<td>18</td>
</tr>
<tr>
<td>Cretaceous rocks</td>
<td>19</td>
</tr>
<tr>
<td>Structure</td>
<td>20</td>
</tr>
<tr>
<td>Chapter II The manganese deposits</td>
<td>24</td>
</tr>
<tr>
<td>General Geology</td>
<td>24</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>27</td>
</tr>
<tr>
<td>Description of deposits</td>
<td>31</td>
</tr>
<tr>
<td>Size and grade of the deposits</td>
<td>36</td>
</tr>
<tr>
<td>Features indicating the origin of the deposits</td>
<td>38</td>
</tr>
<tr>
<td>Chapter III Origin of manganese deposits</td>
<td>41</td>
</tr>
<tr>
<td>Marine sedimentary deposits</td>
<td>42</td>
</tr>
<tr>
<td>Sources of manganese</td>
<td>42</td>
</tr>
<tr>
<td>Transportation of manganese</td>
<td>43</td>
</tr>
<tr>
<td>Deposition of manganese in sea water</td>
<td>45</td>
</tr>
<tr>
<td>Manganese of volcanic origin</td>
<td>46</td>
</tr>
<tr>
<td>Summary</td>
<td>48</td>
</tr>
</tbody>
</table>
ILLUSTRATIONS

Fig. 1 Index map showing the position of the Cowichan Lake map-area. 58

Fig. 2 Sketch map showing the structure of part of the Cottonwood Creek manganese deposit. 59

Fig. 3 Sketch map showing the structure of the Shaw Creek manganese deposit. 59

Fig. 4 Steeply dipping cherty tuffs. 60

Fig. 5 Tightly folded cherty tuffs. 60

Fig. 6 Tightly folded cherty tuffs. 61

Fig. 7 Fragmental flow top in the Sicker andesites 61

Fig. 8 Poorly developed columnar jointing in the flows above the Sicker sediments. 62

Fig. 9 Photomicrograph of typical cherty tuff. 62

Fig. 10 Photomicrograph showing siliceous oolites in cherty tuff. 63

Fig. 11 Photomicrograph showing siliceous oolites in manganiferous chert. 63

Fig. 12 Photomicrograph showing rhodonite cross-cutting and replacing cherty beds. 64

Fig. 13 Polished surface of a specimen from the Hill 60 manganese deposit. 64

Fig. 14 Polished surface of bedded manganiferous chert. 65

Fig. 15 Polished surface showing faulted beds of yellow manganese silicate in jasper. 65

Fig. 16 X-ray powder photograph of quartz. 66

Fig. 17 X-ray powder photograph of quartz and the yellow manganese silicate. 66

Fig. 18 X-ray powder photograph of spessartite. 66

1 Structural sections north of Cowichan Lake (in pocket)

2 Geological map of the north side of Cowichan Lake (in pocket)
ACKNOWLEDGMENTS

The writer would like to thank Dr. H. Sargent of the B.C. Department of Mines for his assistance during the field season and for his help in making thin sections and maps available for laboratory work.

Thanks are also due to various members of the Department of Geology at the University of British Columbia, especially to Dr. H.C. Gunning for his suggestions, and to Dr. R.M. Thompson for his work on the yellow manganese silicate.
During the summer of 1948 the writer was employed by the British Columbia Department of Mines to carry on geological mapping and to examine a number of mineral deposits north of Cowichan Lake, Vancouver Island B.C. Geology was mapped on a scale of one inch equal to half a mile and an area (referred to in this thesis as the map-area) along the north shore of Cowichan Lake about 20 miles long and five miles wide was covered. Mineral deposits in the area include several occurrences of manganese, and the origin of these deposits has been made the main subject of this thesis. Although the thesis describes the general geology of the area, emphasis has been placed on the phases of the general geology that throw some light on the origin of the manganese deposits.

Previous Work

A preliminary report based on reconnaissance surveying of southern Vancouver Island was published by
the Geological Survey of Canada in 1912 (Clapp, 1912). The report covered Vancouver Island east of Alberni Canal, but was of a preliminary type and included no detail along the north shore of Cowichan Lake. A bibliography and description of early exploration and geological work on southern Vancouver Island appears in this report. Later detailed work by C.H. Clapp and H.C. Cooke resulted in the publishing of several memoirs and maps (Clapp, 1913, 1914 and Clapp and Cooke, 1917) of the geology of southern Vancouver Island. The western margin of Clapp's Duncan sheet lies about three miles east of the east end of Cowichan Lake and it was possible for the writer to make the Cowichan Lake map a direct extension of the Duncan sheet.

Detailed descriptions of several mineral deposits of the Cowichan Lake area, including descriptions of the manganese deposits appear in the annual Reports of the British Columbia Department of Mines (1918, 1919, and 1920).

During the summer and fall of 1939 geological work was done along the north shore of Cowichan Lake by a party in training under the Dominion-Provincial Mining Training Project. This work consisted mainly of exploration of the known manganese deposits and prospecting for new deposits but some geological mapping was also undertaken. Plans and an unpublished report on the manganese deposits were drawn up by Dr. H. Sargent of the
B.C. Department of Mines, and these have been used extensively by the writer.

**Geography and Physiography**

Cowichan Lake, lying in a deep northwesterly trending valley near the center of southern Vancouver Island, averages 1 1/2 miles wide, is 15 miles long and 550 feet above sea level. The Village of Lake Cowichan lies at the east end of the lake, and the logging town of Youbou is on its north shore about seven miles west of Lake Cowichan. A public highway, the extension of the Duncan-Lake Cowichan highway, runs as far west as Youbou and a branch line of the Canadian National Railway runs along the north shore of the lake as far as its west end. Private logging roads extend up most of the valleys trending north from the lake, and the hillsides above them have been logged to elevations of about 2500 feet. Hillsides generally are steep, and outcrops fairly abundant except in depressions or valley bottoms, where glacial drift may reach a depth of 20 or 30 feet. In the larger valleys, however, creeks have cut through the glacial drift and exposed the underlying bedrock.

The Cowichan Lake map-area lies west of the peneplaned surface described by Clapp, (Clapp, 1912), and few of the features of the old peneplane are noticeable in it. The north shore of the lake is marked by steep hillsides rising 2000 or 3000 feet above the lake that at least in part form a fault line scarp resulting from post-Cretaceous
faulting. Northerly-trending ridges, separated by deep relatively straight valleys extend four or five miles north from the lake and join a northwesterly-trending line of hills that marks the divide between the Cowichan Lake and the Chemainus and Nanaimo River drainages.

Glacial erratics and straie indicate that the continental ice sheet covered even the highest hills (elevation 5000 feet above sea level) in the map-area. Valley glaciers have left cirques and cirque lakes. Terraces of glacial till line the sides of the larger valleys, and spurs projecting into the valleys are cut by water-worn channels that have been formed by streams flowing from retreating valley glaciers.
CHAPTER I  GENERAL GEOLOGY

Summary of Geology

The map-area is underlain by flows, breccias, sediments and intrusives of Mesozoic age. The oldest rocks are volcanics and tuffaceous sediments of the Vancouver group thought to have been laid down in late Triassic or early Jurassic time. The lower members of the Vancouver group consist of great thicknesses of conformable andesitic flows containing small lenses of sediments. These are conformably overlain by a well defined band of cherty tuffs and coarser pyroclastics about 2000 or 3000 feet thick known as the Sicker sediments. The Sicker sediments in turn are conformably overlain by at least 2000 feet of flows similar in composition to the Sicker andesites.

The Vancouver group is intruded by long, dyke-like bodies of granodiorite and quartz monzonite correlated with the Saanich granodiorite, and by minor intrusions mainly of gabbroic and dioritic composition.

Both the Vancouver group and the intrusives are overlain unconformably by Upper Cretaceous conglomerate, sandstone, and shale.

The Vancouver group has been highly folded into northwesterly trending synclines and anticlines that in general dip southwest. The Cretaceous sediments are gently folded, and are exposed in the map-area only in a
down-faulted easterly trending belt just north of Cowichan Lake.

**TABLE OF FORMATIONS**

<table>
<thead>
<tr>
<th>AGE</th>
<th>NAME</th>
<th>LITHOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Cretaceous</td>
<td>Haslam Formation</td>
<td>Marine black concretionary shales</td>
</tr>
<tr>
<td></td>
<td>Benson Formation</td>
<td>conglomorate and sandstone</td>
</tr>
<tr>
<td>Upper Jurassic?</td>
<td>Minor Intrusives</td>
<td>gabbro and diorite dykes sills and irregular bodies</td>
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<tr>
<td></td>
<td>Saanich Granodiorite</td>
<td>granodiorite, quartz monzonite and alaskite</td>
</tr>
<tr>
<td>Lower Jurassic and/or Upper Triassic</td>
<td>2000 to 3000 feet of basaltic and andesitic flows</td>
<td>cherty tuff, fine grained felspathic tuff, coarser pyroclastics and minor limestone. 2000 to 3000 feet thick</td>
</tr>
<tr>
<td></td>
<td>Sicker sediments</td>
<td>Andesitic flows with small lenses of tuffaceous sediments</td>
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<td></td>
<td>Sicker andesites</td>
<td></td>
</tr>
</tbody>
</table>
Detailed Descriptions

The Vancouver group of volcanic rocks underlies about 75 percent of the map-area, volcanics being absent only where erosion has exposed later intrusives and where small areas have been covered by Cretaceous sediments. Clapp has divided the Vancouver group into the Vancouver Volcanics, the Sutton limestone, and the Sicker series (Clapp, 1912). The Sicker series has been further divided into the Sicker Andesites and the Sicker sediments (Clapp and Cooke, 1917). Only the Sicker sediments were positively identified in the map-area, but flows and sediments underlying the Sicker sediments and constituting the oldest rocks exposed in the area, are probably part of the Sicker andesites.

The Sicker sediments form the youngest member of the Vancouver group described by Cooke (Clapp & Cooke 1917), but at least 2000 feet of flows conformably overlie the Sicker sediments in the Cowichan Lake map-area. While similar lithological sequences have been described at other points on Vancouver Island it is not possible to correlate the upper flows at Cowichan Lake with any that have been previously named.

Sicker Andesites

The Sicker andesites exposed in the Cowichan Lake map-area are mainly flows, but with them are small discontinuous bands of tuffaceous sediments. Three phases of flow rocks, all essentially of the same composition, can
be recognized. Fragmental amygdaloidal phases occur at the
tops of thick flows, massive porphyritic phases occur in
the central parts, and narrow, often obscure, amygdaloidal
phases occur at the bottoms. The massive phases are
typically dark green, porphyritic andesite, but occasionally
they are light green or brown. Green hornblende phenocrysts
up to three millimeters in length and frequently smaller
plagioclase phenocrysts are set in an aphanitic groundmass
composed of a felted mass of hornblende and smaller
amounts of plagioclase, in typical rocks. In places augite
phenocrysts are present and some of the hornblende has formed
by alteration of augite.

Fragmental phases contain mainly rounded
amygdaloidal fragments, from one to four inches in diameter,
surrounded by porphyritic andesite (Fig. 7) similar to that
of the massive phase. In thin section the fragments appear
to be of essentially the same composition as the surrounding
andesite but contain a larger proportion of phenocrysts some
of which appear bent or broken. Fragmental phases appear to
represent parts of the flow near the original surface, and
within a foot or so of the surface highly amygdaloidal
fragments make up most of the rock and occasionally
irregular cavities are present between them. Amygdaloidal
bottom phases in the Sicker andesites are aphanitic and
lack structures other than amygdules.

The relative thicknesses of the three phases
varies from flow to flow and probably within the same flow.
The massive phase constitutes the largest part of the rocks, and because of the large amounts of the massive phase, and because of the widespread alteration of the flows, individual flows can be recognized only on good exposures. Some thin flows appear to be made up entirely of the fragmental phase. In Widow Creek, for example, directly below the Sicker sediments a fragmental flow top 100 feet thick is overlain by a lens of jaspery sediments and this in turn is overlain by a flow made up entirely of the fragmental phase. Such fragmental flow tops characteristically mark the base of the overlying Sicker sediments.

The Sicker andesites, though rarely schistose, have been widely altered. They contain abundant epidote and chlorite, and probably much of the hornblende is an alteration product. Sericite, fine grained albite and quartz can be seen in some thin sections. The fragments in the fragmental phases have been more severely altered than the rock enclosing them, and the concentration in them of epidote and quartz has given rise to epidote nodules characteristic of the Sicker andesites.

**Sediments within the Sicker Andesites**

Lenses of fine grained, cherty, and coarser probably tuffaceous sediments occur within the Sicker andesites. The lenses are generally small, averaging 100 feet thick and several hundred feet long, but on the hills east and west of McKay Creek cherty tuffs with few intercalated flows aggregate 1000 feet in thickness. The smaller
lenses are commonly thin bedded, black, rusty weathering and resemble argillites. Other lenses vary in grain size and composition both along the strike and from bed to bed. In Shaw Creek, between the north and west forks for example, thin-bedded, light-colored, highly cherty tuffs grade into fine-grained green poorly bedded sediments along the strike, within a distance of less than a quarter of a mile. The cherty rocks are overlain by flows but grade downward into fine grained green sediments within a thickness of less than 200 feet of beds. No thin sections of these fine-grained sediments have been studied but in hand specimen they closely resemble coarser types of the Sicker sediments found to be made up of sub-angular fragments of rock similar in composition to the surrounding andesite. In places, especially where they have been highly altered, these sediments closely resemble flow rocks and on the accompanying map undifferentiated areas marked as Sicker andesites may locally contain sediments.

**Sicker Sediments**

A thick series of cherty tuffs, coarser sediments, and minor limestones known as the Sicker sediments conformably overlies the Sicker andesites. A well defined, though probably not continuous, flow top marks the top of the Sicker andesites and at all places where the contact was seen the lowest beds of the Sicker sediments lie parallel to the surface of the flow.

In general, the lower beds of the Sicker sediments
are cherty tuffs, the central beds are fine grained tuffs, while the upper beds are coarser pyroclastics. The character of the beds, however, varies along the strike so that there is no well defined sequence. The lowest beds of the Sicker sediments exposed a few hundred feet west of Widow Creek, for example, consist of about 15 feet of thin-bedded, black rusty weathering slate-like tuffs. East of Widow Creek thin bedded green and white cherty tuffs lie directly on the flow rocks, while south of Sherk Lake a three foot bed of jasper lies between the flow top and the overlying cherty tuffs. Fine-grained green to buff unbedded sediments as much as 50 feet thick form the base of the Sicker sediments in Shaw Creek. Thus, there is considerable variation in the lithology of the lowest beds, and nowhere in the series can beds be correlated on lithological similarities. Nevertheless, in general, cherty tuffs form the lower beds, felspathic tuffs the central beds, and coarser pyroclastics the upper beds of the series.

The lower 200 or 300 feet of beds are mainly light colored, well bedded cherty tuffs made up of green, red, light grey or black beds alternating with lighter commonly white beds one-half to two inches thick. Some beds grade from one to another by a gradual decrease in grain size or in the amount of coloring matter, but many show sharp breaks between the beds and primary features such as local unconformities are noticeable. In thin section all colors of beds appear to be of about the same
composition. They are made up of angular fragments of quartz and feldspar, in the finer types 0.01 mm across and in the coarser averaging 0.3 mm. (Fig.9). Where identifiable the feldspar is always andesine, and andesine probably makes up 80 percent of the grains, although many of the smaller grains are too small to be identified as either quartz or feldspar. Green beds contain epidote, green opaque material, or fine needles possibly of amphibole. Red varieties, both jaspery sediments and jasper, contain hematite and darker varieties contain biotite and opaque material.

All the cherty beds contain cryptocrystalline quartz both as irregular lenses and as spherical nodules. In the more felspathic varieties the quartz seems to be most abundant in certain beds, while in the more cherty beds quartz is distributed throughout. The nodules, which are made up of a mosaic of very fine quartz, are strikingly spherical and uniform in size, averaging 0.3 mm in diameter. (Fig.10). A poor radial structure can be seen near the edges of a few and semi-opaque material occurs near the centers of others, but in general they lack internal structure. Commonly thin beds of opaque material bulge around the nodules and never is there any indication of bedding passing through them, although some are lens shaped and grade outward into thin beds of cryptocrystalline quartz. Later quartz-feldspar veinlets that cut the rocks also cut the nodules. Thus, they appear to be syngenetic, and resemble small concretions or oolites; nothing in them
Indicates they are organic remains.

The presence of the oolites suggests that silica, as a chemical sediment, was being deposited at the same time as the tuffaceous material. Pure cherts made up almost entirely of recrystallized silica are present in the Sicker sediments and are especially abundant near the manganese deposits. It is probable that all gradations exist between pure felspathic tuffs and pure cherts.

Above the cherty members the rocks are more poorly bedded, coarser grained, and darker colored. Thin sections show them to be made up of angular crystals of feldspar, with some quartz, 0.1 to 0.2 mm across, surrounded by fine grained biotite and some opaque material. These dark poorly bedded rocks are in general very uniform and make up as much as 1000 feet of beds, but in places green cherty tuffs and coarser pyroclastics are interbedded with them.

Coarse pyroclastics are present in small amounts throughout the Sicker sediments but are most abundant in the upper part of the series. They are all of essentially the same composition, but vary from green, well-bedded millimeter rocks made up of angular grains less than one mm across to unbedded rocks made up of fragments up to an inch or two across. The finer grained varieties resemble greywacke and contain angular fragments of porphyritic volcanic rock similar in composition to the Sicker andesite. Some of
the coarser grained varieties contain angular fragments of oolitic cherty tuff, single quartz and feldspar crystals, and a few contain rounded fragments of limestone. The grains are surrounded by opaque dusty-looking material, by epidote and other secondary minerals, and very rarely by calcite. In specimens containing limestone fragments, calcite is rarely present in the cementing material. No positive evidence could be found either in the field or in thin section as to the origin of these rocks. However, because they are associated in many places with cherty tuffs, and because they contain angular grains that lack chemical cementing material, even where the grains themselves are limey, it is probable that they are of pyroclastic origin.

Two small lenses of limestone and calcareous tuff were found within the Sicker sediments. The first, a lens about 300 feet thick and half a mile long, lies on the southeast slope of Mount Franklin between elevations of 3200 and 3600 feet. This lens, which appears to be less than 300 feet from the base of the Sicker sediments, is made up of beds that range from almost pure crystalline limestone to calcareous tuff in which limey material is almost absent. Some of the more coarsely crystalline beds appear to be crinoidal, but only occasionally can crinoid stems be recognized. In places the limestone contains angular isolated fragments of andesite up to 8 of an inch across. These limestone-andesite breccias appear to have formed as beds of limey ooze or groves of crinoids into which
volcanic material fell before consolidation.

A second small bed of limestone was found on the southwest slope of Mount Londarl extending north into the east fork of Cottonwood Creek. It is made up of a series of small lenses the largest of which is about 100 feet thick and less than 1000 feet long. They are made up of finely crystalline impure white limestone and grade both along and across the strike into beds of tuff. The lenses are within 100 feet of the top of the Sicker sediments, and hence not in the same horizon as the first limestone lens.

The thickness of the Sicker sediments varies from place to place, and because of the close folding and the fact that both top and bottom of the series are not exposed in any one section, it is difficult to make an accurate estimate of the thickness. The thickest section is exposed in the Shaw Creek syncline but in places the thickness of this section has been increased by folding. The top of the Sicker sediments is not exposed in the part of Shaw Creek that has been mapped, but several thin flows intercalated with the uppermost beds suggest that the section is almost complete. An average of 3000 feet of beds is exposed, the easterly limb being thicker than the westerly limb. A thickness of 3000 feet is adequate to explain the exposures and structural relations elsewhere in the map-area and is consistent with estimates made by Cooke. (Clapp and Cooke, 1917).
Flows Younger than the Sicker Sediments

Porphyritic andesites and basalts that conformably overlie the Sicker sediments outcrop on the hills along the northeast edge of the map-area. East of Mount Landalt and west of Mount Service the flows are andesitic and closely resemble the Sicker andesites. Fragmental and amygdaloidal varieties are common but no other primary structures were found. On Mount Landalt and Mount Service the flows are uniform porphyritic basalts, consisting of white-weathering phenocrysts of labradorite up to three millimeters across, set in an aphanitic groundmass of hornblende, augite, and plagioclase. Steep cliffs on the slopes of El Capitan and Mount Landalt make it possible to distinguish poorly developed columnar jointing in the basalts (Fig. 8). Amydules and rarely fragments can be distinguished near flow contacts.

Cooke found the Sicker sediments to be the youngest members of the Vancouver group exposed in the Duncan area, (Clapp and Cooke, 1917) but since the flows above the Sicker sediments in the Cowichan Lake area appear to be conformable with the Sicker sediments there seems to be no reason to exclude them from the Vancouver group. It is probable that more complete sections of the upper part of the Vancouver group will be found north of Chemainus River and northeast of Shew Creek and when these sections have been studied it may be possible to subdivide the Vancouver group more completely.
Saanich granodiorite

The Vancouver group is intruded by large dyke-like bodies of quartz monzonite the most continuous of which is over 15 miles long in the map-area and averages about half a mile wide. Clapp shows it to extend some eight miles east of the map-area. A second body of quartz-monzonite outcrops less than two miles north of the first and the two almost merge west of the head of McKay Creek. By their age and lithology they are correlated with the Coast Range intrusives and are thought to be upward-extending apophyses of a larger intrusive body.

The quartz monzonite is essentially a medium grained, light colored rock made up of about equal amounts of quartz, andesine, and orthoclase. Biotite and hornblende make up about 10 percent of the rock and small amounts of apatite, zircon, magnetite, and pyrite are commonly present. Dark, medium-grained, rounded inclusions are common in the quartz monzonite and the proportion of dark minerals increases toward the contacts.

The quartz monzonite bodies form the westward extension of the Saanich granodiorite mapped on the Duncan sheet but only one of several thin sections studied from the Cowichan Lake area was of granodiorite. Clapp points out that the composition of the granodiorite varies, much of it being near quartz diorite. It is probable, therefore, that some if not much of the Saanich granodiorite of the Cowichan Lake area is more basic than quartz monzonite.
A more acid phase lacking dark minerals is exposed west of McKay Creek. On the high hills west of McKay Creek the intruded volcanic rocks have not been completely eroded away so that the top or end of an apophysis of quartz monzonite is exposed. About 200 feet below the end of the apophysis, quartz monzonite containing biotite and hornblende grades upward into medium to coarse grained alaskite. Alaskite is rich in quartz and contains less than 10 percent andesine and large amounts of microperthite and micropegmatite. Alaskite tapers upward into dyke-like bodies rich in quartz and commonly containing sulfides.

Minor Intrusives

Several types of igneous rocks intrude the Vancouver group and some intrude the quartz monzonite. The largest of these are irregular bodies of gabbro and diorite. Hornblende, plagioclase, and augite are the main constituents, andesine occurring in varieties containing most hornblende, and leucodiorite in those containing augite. Much of the augite is altered to hornblende, and biotite, chlorite, epidote, and sericite have developed in the more highly altered types.

In Steese Creek canyon, where the contact of the diorite with the quartz monzonite is well exposed, the diorite intrudes the quartz monzonite in dyke-like offshoots from the main diorite body, and the quartz monzonite appears
altered by the intrusion. Hence, the diorite is younger than the quartz monzonite, and may correspond to diorite porphyrite dykes described by Clapp (Clapp and Cooke, 1917, p.198).

Dykes and sills, some felsitic in composition and others more basic intrude the volcanic rocks, but very few intrude both the volcanics and the quartz monzonite. Many of the basic types closely resemble the Sicker andesites and are often difficult to distinguish from them.

Cretaceous Rocks

Upper Cretaceous shales, sandstones, and conglomerates outcrop along a narrow belt on the hills just north of Cowichan Lake extending from Cottonwood Creek to Maybe Creek. A basal conglomerate made up of rounded pebbles averaging 2 inches in diameter rests with marked unconformity on both the volcanics and the quartz monzonite. Pebbles in the conglomerate are of local origin being mainly of volcanics. Only in places close to outcrops of quartz monzonite do quartz monzonite pebbles occur in the conglomerate. Massive greyish-brown sandstone is present as distinct beds throughout the conglomerate and the conglomerate grades upward into pure sandstone.

Black shales of the Haslam formation conformably overlie the conglomerate and near the base of the shale formation beds of conglomerate occur within the shales. The shales are unbedded and highly fractured, breaking on the surface into ellipsoidal clusters of rod-like splinters.
The shales contain hard siliceous concretions some of which are over a foot in diameter and ellipsoidal in shape.

Poorly preserved fossils are present in the shales and concretions, and by means of them it has been possible to correlate the shales exposed in the map-area with the Haslam formation found elsewhere in southern Vancouver Island. (Clapp and Cooke 1917). The conglomerates and sandstones therefore, probably belong to the Benson formation.

**Structure**

The Vancouver group has been closely folded but only in the Sicker sediments has the structure been worked out in detail. Since the Sicker andesites and the flows above the Sicker sediments appear to be conformable with the Sicker sediments, and since bands of sediments and individual flows in the andesites conform fairly closely with the general structure indicated by the Sicker sediments, it seems probable that the Vancouver group is folded into synclines and anticlines broadly similar to those of the Sicker sediments.

The Sicker sediments in the main part of the map-area have been closely folded into northwesterly trending overturned and asymmetrical synclines. Along the northeast edge of the map-area the southwest limb and possibly the crest of an anticline are exposed.
The axial plane of the most easterly syncline strikes about north 70° west and dips southwest at about 50°. The rocks of this syncline outcrop continuously from the east edge of the map-area to Sherk Lake and toward the west the structure trends more nearly northwest. West of Cottonwood Creek the axial plane of a poorly defined syncline strikes north of northwest and dips steeply southwest, and in Shaw Creek the axial plane strikes north 15° west and dips steeply west. Thus, the axes of folding trend more nearly north toward the west and more nearly east toward the east. The most easterly syncline and the syncline west of Cottonwood Creek are overturned, most of the rocks dipping southwest, but the Shaw Creek syncline is asymmetrical and not as tightly folded as those farther east.

The structure of the anticline along the northeast edge of the map-area is not well exposed, and its relation to the synclines is complicated by post-Cretaceous faulting. In general however, the rocks of the anticline are flat-lying and appear to form the gently dipping southwest limb of an overturned anticline corresponding to the syncline on the southwest.

In many places, especially in the synclines the sediments are highly contorted by minor folds (Fig. 5) parallel to the regional trend, and by others across the regional trend. In the Shaw Creek syncline, especially in the lower cherty beds, pronounced minor folds with axes
trending about north 70° east are superimposed on minor folds, resembling drag folds, that trend north 20° west. The cross folds generally produce only gentle plunges in the regional structures, commonly to the northwest or sharp warps in the drag folds.

Locally, however, regional structures plunge at angles up to 20° for distances of half a mile owing to the effect of cross-folding. Cross folding along axes at about 45° to the regional trend and minor faulting have produced the complicated outcrop pattern of the Sicker sediments between widow Creek and Sherk Lake.

The structure of the Sicker sediments has been complicated by post-Cretaceous faulting. Two continuous, almost vertical faults trend northwesterly through most of the length of the map-area. The southerly fault, near the shore of Cowichan Lake, forms the north contact of the small area of Cretaceous sediments between Youbou and Meade Creeks. The thickness of the Cretaceous rocks indicates that the rocks on the southwest side of the fault have moved down more than 1000 feet in relation to the rocks northeast of the fault. The horizontal displacement has probably been small, but the position of the lower contact of the Sicker sediments in Meade Creek south of the fault suggests that rocks southwest of the fault moved west in relation to those northeast of the fault. Near the northeast side of the map-area a major fault has displaced the rocks in the opposite direction. Rocks northeast of this fault have
moved down, probably between 2000 and 3000 feet in relation to those southwest of the fault. The horizontal displacement appears to have been small.

The Cretaceous rocks strike east and dip north at angles of about 10° in the west and of 40° in the east. The northern contact of the sediments is marked by a fault, while the southern contact marks the unconformity between the sediments and the underlying crystalline rocks. The lower contact of the sediments south of Meade Creek is parallel to the slope of the hill so that irregularities in the surface on which the conglomerate was laid down have produced a complicated outcrop pattern.
CHAPTER II  THE MANGANESE DEPOSITS

The discovery in 1918 of manganese ore at Hill 60 led to intensive prospecting for manganese along the north shore of Cowichan Lake and the discovery of a number of small deposits. The largest of these was in Shaw Creek, but three other deposits were staked and since the original stakings several small occurrences have been found. Ore reported to total 1117 tons was shipped in 1919 and 1920 from the Hill 60 deposit and a little work in the form of trenching and testing was done in 1918 and 1919 on the Shaw Creek deposit. Very little work was done on the other deposits and since 1920 no work other than that of the Mining Training Project has been done on any of the deposits.

The Hill 60 manganese deposit is east of the eastern edge of the Cowichan Lake map-area. The main showings are between 2500 and 2700 feet above sea level, four miles due east of the Village of Lake Cowichan. The location of the other five deposits is shown on the accompanying map. In the summer of 1948 all the deposits were less than a mile from a private logging road or public highway, but although favorably located none of the deposits is of economic value.

General Geology

The manganese deposits occur in the cherty
Sicker sediments that, owing to their resistance to weathering and erosion form relatively numerous moss-free outcrops. Near the manganese deposits, the overburden and outcrops contain conspicuous black oxides that obscure the form and size of the primary mineralization. At the Hill 60 deposit a large open pit and shaft extend ten or fifteen feet beneath the oxidized layer, but only shallow prospecting trenches have been made at the other deposits and several of them are poorly exposed.

The deposits are all in the lower cherty members of the Sicker sediments, the Shaw Creek, Wardroper Creek, Sherk Lake and Cottonwood Creek deposits being within 200 feet of the base of the series. The other two large deposits are possibly within the lower 200 feet of the series; the position of the Meade Creek deposit is obscured by faulting, and by the fact that the base of the series is not exposed, and that of the Hill 60 deposit is obscured by large bodies of intrusive rock. Several less important occurrences of manganiferous beds that have been found are all in the same lower members of the Sicker sediments.

The deposits have the form of lens-shaped bodies with long axes parallel to the bedding of the sediments. In the more tightly folded beds the relation of the manganese-bearing lenses to the bedding is often obscure but in the slightly folded beds the lenses containing manganese
minerals are obviously related to the bedding. The lenses vary from an eighth of an inch to several feet in thickness and from a few inches to 30 or 40 feet in length. Larger lenses are all short in relation to their thickness and appear to be made up of closely spaced smaller lenses. Small lenses are either bedded or massive, rhodonite tending to be massive, the other silicates tending to be bedded. In the tightly folded deposits individual manganese-bearing beds appear to follow the folding and are thinned and displaced in the same way as the surrounding beds. Within the manganese beds, however, rhodonite forms irregular masses and occasionally well defined veinlets cross-cutting the enclosing rock.

The deposits are always associated with massive jasper or jaspery sediments. Massive jasper occurs in beds six inches to two or three feet thick that near the manganese deposits are commonly cut by well defined quartz veinlets. Jaspersediments are pink to brick red and generally well bedded; they owe their color to finely divided hematite. Beds of massive jasper and substantial thickness of jaspery sediments that contain no manganese are common throughout the lower members of the Sicker sediments.

Thin sections of rocks associated with manganese deposits show them to be mainly quartz. The quartz occurs as a mosaic of grains less than 0.1 mm across. Thus these grains are larger than those of the quartz in siliceous lenses of the normal cherty tuffs. Outlines of siliceous
oolites can be seen in some thin sections of manganese bearing rocks. (Fig. 11) and those too are more coarsely crystalline than those in the normal cherty tuffs. The bedding is often obscure in thin sections, but may be marked by bands of opaque material or by fine-grained manganese silicates. (Fig. 12). Rocks of the manganese deposits thus differ from the normal cherty tuffs in two respects. First, they consist mainly of quartz and smaller amounts of manganese minerals and contain no recognizable tuffaceous material. Second they are coarser grained and resemble recrystallized cherts.

Mineralogy

The following manganese minerals were found in the Cowichan Lake deposits:

Rhodonite, \( \text{Mn} \ (\text{Ca}, \text{Fe}) \ \text{Si}_3 \text{O}_6 \)

Garnet, probably spessartite, \( \text{Mn}_3 \ \text{Al}_2 \ \text{Si}_3 \ \text{O}_12 \)

Unidentified yellow manganese silicate

Neoctocite, manganiferous opal

Rhodochrosite, \( \text{Mn} \ \text{CO}_3 \)

Undifferentiated oxides

Rhodonite is the most abundant manganese silicate occurring mainly as irregular masses in chert or in chert containing other manganese minerals. Light pink rhodonite is the commonest type but red-brown, well-crystallized rhodonite was found in the Hill 60 deposit. No difference in
optic properties between the pink and red-brown rhodonite could be detected. As seen in thin section, much of the brown variety is euhedral and occurs within large crystals of quartz in what might be referred to as a poikilitic arrangement. The red-brown rhodonite in quartz appears to have been recrystallized by the intrusion of an andesitic dyke to which it is spatially related.

The rhodonite is massive and fine grained; only in the largest crystals can cleavage be distinguished. Rhodonite occurs as masses with vague outlines and as short lenses parallel to the bedding of the rocks. (Fig. 14). The lenses in themselves are massive even though bedding may be well developed in the surrounding chert and manganese silicates. A few small, well-defined quartz veinlets also contain rhodonite. Hence, in all respects the rhodonite appears to replace chert and other manganese silicates.

Garnet was found in several thin sections of the manganese-bearing rocks but is too fine grained to be recognised in hand specimens. Euhedral grains of garnet about 0.1 mm across occur in bands lying parallel to the bedding of the sediments. Garnet is generally closely associated with the yellow manganese silicate, and brown bands that commonly alternate with pink or yellow bands in the well-bedded deposits contain abundant garnet. Because of the close association of garnet with the manganese-bearing rocks, and because of the fact that the surrounding
rocks have not been subjected to a high grade of metamorphism the garnet is probably spessartite. Garnet is too fine grainod, however, for its chemical composition or many of its physical properties to be determined.

A yellow manganese silicate is abundant in the Hill 60 deposit and was found in small amounts at the Meade Creek and Wardroper Creek deposits. In hand specimens the mineral appears to be closely associated with quartz of the cherty rocks in the form of very fine fibrous often closely spaced sheets lying parallel to the bedding of the sediments (Fig. 13). Thin sections of even the most massive material contain as much as 50 percent quartz. The manganese mineral occurs with the quartz in equidimensional grains of high relief and less than 0.01 mm across. By comparing the index of the crushed mineral with oils of known refractive index, the index of the manganese mineral was found to be less than 1.765 but greater than 1.750. It was not possible to separate the manganese mineral from quartz by means of "heavy" liquids, but spectrographic and x-ray analyses were made of material composed only of quartz and the yellow manganese mineral. In addition to silica and manganese, considerable amounts of iron and magnesia were found to be present. This composition, together with the refractive index suggest that the mineral is a manganese pyroxene such as sobralite, but x-ray data to confirm this are not available. The x-ray powder photograph of quartz
and the yellow mineral is shown in Fig. 17, and that of pure quartz is shown in Fig. 16. Assuming that none of the lines of quartz are exactly the same as those of the yellow mineral, the extra lines of Fig. 17 represent the x-ray pattern of the yellow mineral. The pattern is relatively simple and was thought to possibly correspond to that of spessartite. (Fig. 18) but several distances can be noticed. Thus, the yellow mineral remains unidentified.

Rhodochrosite is present in small amounts in most of the deposits and occurs as disseminated grains and veinlets cutting the manganese silicates. It may be pink, white, or brown and is generally fine grained. The highest concentration of rhodochrosite found occurs in a small lens in the Cot-onwood Creek deposit. A thin sections of the brown carbonate from this lens shows it to replace rhodonite, which forms half the specimen. In other places where the age of the rhodochrosite in relation to rhodonite could be determined, rhodochrosite is always later than the rhodonite.

Small amounts of neoctocite occurring in well defined veinlets in rhodonite and rhodochrosite, were identified in two thin sections. The veinlets appear to be related to the surface, and the neoctocite is probably a product of weathering.

Black, generally hydrous manganese oxides coat the surface of the deposits and form branching veinlets along fractures in the silicates for several feet below the surface.
The oxides have been produced by weathering of the manganese silicates, but residual concentrations of oxides are small. The oxides were not identified.

**Description of Deposits**

The manganese deposits vary from simple lenses or manganese-bearing beds to complexly folded and metamorphosed deposits in which the relation of the manganese lenses to the bedding is obscure. The Wardroper Creek and Meade Creek deposits occur in relatively undeformed beds but the Shaw Creek and Cottonwood Creek deposits are in highly folded beds, and the Hill 60 deposit has been complicated by intrusion. The more complex deposits will be described in detail, but the simpler deposits need only be described in general.

Small lenses, or beds of manganese-bearing material an inch or two thick and two or three feet long occur southwest of the main Hill 60 deposit in sediments otherwise free from manganese. Similar beds an eighth of an inch thick and a foot or two long occur in the jaspery sediments east of the north fork of Shaw Creek. The Meade Creek and Wardroper Creek deposits appear to be made up of similar larger and more closely spaced lenses separated by beds relatively free of manganese minerals. At the Meade Creek deposit the small lenses are relatively closely spaced and form discontinuous bodies two to three feet thick and extending along the strike of the beds for 200 to 300 feet.
The Wardroper Creek deposit is similar but the manganese bearing lenses are much narrower. Internally rhodonite lenses are commonly massive but other manganese silicates are always well bedded (Fig. 14). On a small scale, beds containing garnet and the yellow manganese mineral grade along the strike into lenses of massive rhodonite.

The main Hill 60 deposit from which ore has been shipped occurs in jaspery sediments that strike on the average north 65° to 70° west and dip southwest generally at angles greater than 55°. Although steeply dipping, the rocks are not contorted by minor folas. The main concentration of manganese minerals occurs as a lens-shaped body some 80 to 100 feet long and 30 or 40 feet thick with its long axis parallel to the bedding of the sediments. Jaspery sediments containing small manganese-bearing lenses extend east and west along the strike of the sediments for over 400 feet from the main deposit.

Ore was probably shipped from a large open pit some 80 feet long 30 feet wide, and 15 or 20 feet deep. An adit crosscuts beneath the pit and a shaft extends below the main floor of the pit. The adit is caved and the best exposures of the manganese-bearing material are in the walls of the pit and smaller open cuts beside it.

Two types of primary manganese-bearing material occur in the main deposit. Brown to red-brown massive rhodonite rock occurs on the hanging-wall side of the large pit and along its west end. In thin section some of this
dark rhodonite appears as euhedral grains in quartz, but more commonly rhodonite is anhedral, occurring in irregular masses intimately associated with quartz. Some specimens contain rounded brown fragments about three eighths of an inch in diameter surrounded by dark red rhodonite. In thin section, the fragments appear to be mainly very fine-grained carbonate, possibly rhodochrosite with small amounts of quartz. These fragmental types resemble the coarser pyroclastics of the upper part of the Sicker sediments and may be of the same origin, although pyroclastics as coarse grained as these have not been found elsewhere in the lower cherty members of the Sicker sediments.

Most of the broken rock in the bottom of the pit is made up of pink rhodonite and a yellow manganese silicate. Pink massive crystalline rhodonite, commonly associated with the yellow silicate outcrops along the north side of the big pit. The yellow silicate nearly everywhere occurs as microscopic grains in quartz. The grains form interleaved lamelae, probably representing the original bedding. (Fig. 13) Rhodonite, on the other hand, occurs as crystals up to several millimeters long and forms irregular masses and occasionally well defined veinlets cutting the yellow mineral. In the east end of the pit massive pink rhodonite contains irregular masses of carbonate, veinlets of quartz, and lenses of chalcopyrite. The quartz veinlets and sulfides do not form a well defined zone, although they seem to be confined to the east end of the pit. They do not extend across the
strike beyond the normal limits of the manganese lens into the cherty sediments. However, the rocks immediately to the east of the pit are covered by overburden so that the east end of the manganese-bearing lens is not exposed. Toward the west the outcrops show a gradual decrease in manganese content until a little over a hundred feet west of the pit the rocks are greyish-white very cherty sediments containing no manganese minerals.

The Cottonwood Creek deposit, less than half a mile west of the head of Widow Creek, occurs in tightly folded jaspy and cherty sediments probably within 200 feet of the base of the Sicker sediments. The deposit, exposed in several prospecting trenches, covers an area not more than 100 feet from north to south and 50 feet from east to west. It is made up of several small, tightly folded lenses containing manganese minerals widely separated by jaspy sediments relatively free of manganese. A diagrammatic sketch of the structure, deduced from a knowledge of the shape of surrounding minor folds and from correlating the attitudes of beds exposed in the trenches and outcrops near the deposit, is shown in Fig. 2.

In addition to secondary oxides, rhodonite and rhodochrosite are the only abundant manganese minerals in the Cottonwood Creek deposit. Within the manganese-bearing beds, some of the rhodonite and quartz still shows the outlines of bedding, but more commonly rhodonite occurs
as poorly defined masses throughout the quartz. In thin section the manganese-bearing rock appears as a mosaic of fine quartz grains containing masses of rhodonite that follow no well defined veinlets or zones of replacement. Brown carbonate-bearing material in which bedding can be distinguished occurs in one lens. Massive jasper present near the manganese lenses is cut by irregular, but well defined, quartz veins and in places contains pyrite.

The Shaw Creek deposit is half a mile west of the north fork of Shaw Creek and 2½ miles up the north fork from its junction with the east fork. The deposit is similar to the Cottonwood Creek deposit in that it lies within highly folded jaspery sediments near the base of the Sicker sediments. A northwesterly trending belt of scattered outcrops and trenches containing manganese minerals covers an area about 300 feet long and 100 feet wide. Minor folds trending north 20° west and plunging northwest at angles up to 30° tend to obscure the relation of the manganese bodies to the sediments (Fig. 3).

Small lenses containing manganese minerals lie parallel to, and seem to form beds within the sediments. Larger bodies are made up of black siliceous material cut by irregular masses of pink rhodonite. Two such bodies exposed over widths of two to four feet and over lengths of 20 to 30 feet show no internal structure. Bedding cannot be distinguished in hand specimens and thin sections of the black material are opaque. The irregular masses of
rhodonite become more numerous beneath the surface and it appears that bodies of black siliceous material are mainly rhodonite and quartz that have weathered to dense siliceous material containing black oxides of manganese.

The Sherk Lake deposit differs in several respects from the others. It occurs within a bed of jasper two or three feet thick that lies at the base of the Sicker sediments directly on the surface of the upper flow of the Sicker andesites. The jasper is cut by well defined, irregular quartz, veinlets about 4 of an inch thick. The manganese minerals occur as irregular masses in the jasper the largest of which is about 1 1/2 inches wide and six or eight inches long. The bed of jasper extends over 1000 feet along the contact but only in places does it contain manganese minerals. Rhodonite, rhodochrosite and quartz are the main constituents of the manganese-bearing masses. In thin section the rhodonite appears to replace jasper and rhodochrosite replaces rhodonite.

Size and Grade of the Deposits

Ore shipped from the Hill 60 deposit averaged over 50 percent manganese and less than 20 percent silica. The low silica content indicates that the ore was probably obtained from the oxidized surface of the deposit. Analyses reported in the Minister of Mines Report (1918, 1919, and 1920) range from about 16 to 55 percent manganese and from 6 to over 60 percent silica. About the same range
in manganese and silica content is reported from the Shaw Creek deposit. Many of the samples highest in manganese are lowest in silica and it is probable that they were taken from residual oxides on the surface. In general the depth of residual oxide rarely exceeds two or three feet, although oxides are present in joints in the bed rock to greater depths. Picked samples of silicates from below the layer of oxides taken by Dr. Sargent in an attempt to determine the probable tenor of the primary mineralization ranged from about 14 to 30 percent manganese and were probably high in silica.

At the Hill 60 deposit the lens of highest grade material is about 30 feet wide and somewhat over 60 feet long on the surface. Open-pit work and crosscutting have shown that the depth extent of the main lens is comparable to its length on surface. The Shaw Creek deposit is of about the same dimensions as the Hill 60 deposit but is more highly folded. The other deposits are all of much smaller size. Thus, while some of the more highly mineralized material is of commercial grade, none of the deposits so far discovered is large enough to be of economic value.

Attempts to find residual deposits in the valleys and depressions below known primary silicate deposits have been unsuccessful. Glacial erosion has probably destroyed any residual concentrations that may have accumulated in pre-Glacial times.
Features Indicating the Origin of the Deposits

Many features of the manganese deposits indicate that they are of sedimentary origin and were formed at the same time as the enclosing sediments. Other features indicate that they were formed later than the sediments by replacement of certain beds by manganese-bearing solutions. The most significant features of the deposits suggesting their origin are the following:

1) The deposits are confined to the lower cherty beds of the Sicker sediments and although small bodies of similar cherty sediments occur elsewhere in the series, none of them contain manganese. The fact that no manganese deposits have been found in the upper members of the series suggests that the manganese had been incorporated in the lower beds before the upper ones were laid down, or that for some unknown reason, the lower beds were the only ones suitable for mineralization.

2) The general shape of the larger bodies could have resulted from either replacement of the sediments or from sedimentary deposition of the manganese. In many places the manganese is confined to beds that show primary structures, minor faults and, small folds identical with those of the surrounding sediments. (Fig.15). In other places, especially where beds containing small lenses of manganese minerals occur in slightly folded rocks, the conformable relation of the manganese-bearing beds to the
surrounding sediments is very marked. Such features suggest that the manganese deposits formed by sedimentary processes.

(3) The rocks of the manganese deposits are recrystallized chert containing little beside quartz and manganese minerals. The fact that they grade along strike into normal cherty tuffs suggests that they have formed by silicification of cherty tuffs. On the other hand, the manganiferous cherts may have formed as lenses of silica into which no tuffaceous material was deposited. The abundance of siliceous oolites and the absence of any evidence, either textural or mineralogical, of angular feldspar grains might suggest a sedimentary origin for the silica.

(4) The cross-cutting and replacing features of the rhodonite within the manganese lenses strongly suggest a replacement origin for the deposits. Massive rhodonite either in lenses or irregular masses replaces surrounding chert and manganese-bearing beds in nearly all the deposits and in places, small well-defined quartz-carbonate-rhodonite veinlets are present. Rarely, as at the hill 60 deposit sulfides also are present.

On the other hand, replacing and cross-cutting relations are seen only within the manganese-bearing lenses. With the possible exception of the Sherk Lake deposit, no manganese-bearing veinlets or replacements have been found either along edges of larger lenses or by themselves in
bods free from manganese. Small veinlets similar to those in the manganese deposits occur in the tuffs away from the deposits. In rocks rich in plagioclase the veinlets contain quartz and plagioclase and in cherty rocks they are mainly quartz. The material in these veinlets seems to have been derived from the surrounding rocks, and it seems possible that the rhodonite-quartz veinlets in the manganese lenses formed in a similar way. Similarly, the irregular masses of rhodonite may have formed by reconstitution of the manganiferous cherts.
CHAPTER III  ORIGIN OF MANGANESE DEPOSITS

Field and laboratory studies indicate two possible methods of formation of the Cowichan Lake manganese deposits. They may have formed either as replacements of cherty tuff by hydrothermal manganese-bearing solutions or as manganese oxides or carbonates that were laid down with the cherty tuff and were later converted to manganese silicates. In an attempt to determine the characteristic features and relative importance of these processes, and the transformations involved in the formation of manganese deposits by them, a study was made of the published writings on the genesis of manganese deposits. Manganese deposits may be syngenetic or epigenetic. Syngenetic deposits include those of sedimentary either marine or terrestrial origin, while epigenetic deposits include hydrothermal replacements and residual deposits formed by weathering and concentration of manganese from any of the other types. All deposits may be metamorphosed so that their ultimate origin is obscure. The Cowichan Lake deposits show no similarities in primary mineralization to residual or strictly hydrothermal deposits but closely resemble metamorphosed marine sedimentary deposits. The following chapter briefly summarizes the method of formation of manganese deposits in oceans, describes some features of metamorphosed deposits, and shows how the Cowichan Lake occurrences may have formed by metamorphism of sedimentary deposits.
Marine Sedimentary Deposits

Sources of Manganese

Manganese deposits of sedimentary origin are formed either by concentration of the small amounts of manganese originally present in igneous and sedimentary rocks or by the deposition of manganese from volcanic sources.

Most igneous and sedimentary rocks contain small amounts of manganese; in igneous rocks it commonly occurs as silicates and in sediments as carbonates and oxides. Hanson (Hanson 1932) has tabulated the manganese content of igneous rocks given by Daly (Daly, 1914) and Clarke (Clarke, 1920). Clarke's analyses vary from 0.02 percent MnO in granites and rhyolites to 0.15 percent MnO in basic igneous rocks. Analyses given by Daly vary from 0.14 percent in acid types to 0.25 percent MnO in basic types, there being a regular increase in the manganese content with a decrease in the acidity of the rock. This may be due to the fact that minerals abundant in basic rocks, such as pyroxene and olivine tend to contain more manganese, either as impurities or as essential constituents than do minerals abundant in acid rocks such as alkali feldspar and quartz. Thus igneous rocks, which form about 95 percent of the lithosphere, contain small but significant amounts of manganese.

The manganese content of sedimentary rocks varies, but in general shales and sandstones contain less manganese.
than limestones and dolomites. Six analyses of sandstone and chert given by Wells (Wells 1937) in which manganese is reported average 0.03 percent MnO and two analyses of shale average 0.01 percent. In over twenty samples of normal limestone in which manganese is reported, some contain no manganese and others as much as 6 percent MnO. Manganese may be present in clastic sediments as carbonates or oxides in the cementing material, as grains of oxides in very fine clastic sediments, or as grains of carbonates or silicates in coarser sediments.

**Transportation of Manganese**

In the normal processes of rock weathering and erosion, the manganese in igneous and sedimentary rocks is released. According to Clarke manganese is taken into solution as the carbonate or sulfate. Dale notes (Dale 1915) that manganese in river water results from the solution of manganiferous silicates, the manganese being converted first to the carbonate or oxide and later carried in solution as the bicarbonate.

Experimental work by Savage (Savage, 1936) showed that "manganese in primary distribution in rocks is taken into solution chiefly by the action of percolating carbonated waters", but carbonic acid, formed by decaying organic matter is also effective. The experiments also showed that manganese is carried in solution chiefly as the bicarbonate. In alkali or neutral solutions the manganese bicarbonate
splits up and unstable manganous hydroxide forms. Oxidation and precipitation of MnO₂ may be prevented by the presence of organic matter in the manganese-bearing waters. Under these conditions manganese might be transported as a mixture of the bicarbonate and of oxides.

Manganese is present in most rivers and spring waters in small amounts. Analyses of fifteen samples of Mississippi river water taken by Weib (Hanson, 1932) show the manganese content to range from 0.044 to 0.128 parts per million. From these analyses Hanson has shown that some 40,000 tons of manganese are discharged into the Gulf of Mexico every year by the Mississippi River. Municipal water supplies are commonly contaminated by manganese and much work on the precipitation of manganese has been done by chemists interested in purifying domestic water supplies (see Twenhofel, 1926, and Zapffe 1931). Spring waters in general contain more manganese than river waters. Twenhofel states that "the content (of spring waters) ranges from a trace to 117 parts per million; commonly it ranges from 0.5 to 5 parts per million." (Twenhofel, 1926). According to Clarke (Clarke, 1924) carbonate and sulfate waters are relatively high in manganese while chloride solutions are generally low. Dittmar (Clarke 1924) states that manganese can readily be detected in sea water but gives no analyses, and hence the change in the manganese content of river waters as they pass into the sea cannot be estimated.
Deposition of Manganese in Sea Water

Savage has carried out experiments on the precipitation of manganese and concludes that "a bicarbonate solution of manganese must become neutral or slightly alkaline before precipitation can take place," and manganese may be precipitated first as hydrated manganous oxide (Mn O.0H) that may later be oxidized to Mn O2. The following equations may represent the reactions:

(Savage 1936)

\[
\begin{align*}
2 \text{Mn} \left(\text{HCO}_3\right)_2 + 4\text{H}_2\text{O} & \rightarrow 2 \text{Mn} \left(\text{OH}\right)_2 + 4\text{H}_2\text{O} + 4\text{CO}_2 \\
2 \text{Mn} \left(\text{OH}\right)_2 & \rightarrow 4\text{H}_2\text{O} + 0 = 2 \text{Mn} \text{O}0\text{H} + 5\text{H}_2\text{O} \\
2 \text{Mn} \text{O}0\text{H} & \rightarrow 5\text{H}_2\text{O} + 0 = 2 \text{Mn} \text{O}_2 + 6\text{H}_2\text{O}
\end{align*}
\]

Thread bacteria and the catalytic action of MnO2 are important in increasing the rate at which Mn O2 is precipitated (Zapffe, 1931).

Manganese in deep sea sediments is well known but the processes by which the manganese is precipitated are not well understood. It is possible that Mn O2, either from shells and bodies of marine animals that have sunk to the sea bottom or from rocks along the sea floor, may act as a catalyst in aiding the precipitation of manganese oxides suspended or dissolved in the deep sea waters.

The manganese may occur as coloring matter in the sea sediments, as coatings on the sea floor, or as manganese nodules (Twenhofel, 1926). Finely divided coloring matter
in deep sea sediments is found to be made up of manganese oxides and hydroxides. Samples of sediments from the north Atlantic Ocean contain from a trace to over four percent manganese. (Carrens 1939). Red muds contain most, but blue muds and globogerina ooze also contain manganese. Coatings of manganese oxides on shells and stones on the sea bottom are reported from the Clyde Sea (Twenhofel 1926) and manganese oxides coating the rocky sea bottom are reported along the shores of the East Indian Archipelago (Carren. 1939). Manganese nodules are common in many of the world's largest manganese deposits and are found to be forming in the present seas.

Manganese appears to be precipitated mainly as the oxide in marine deposits, but manganese carbonate may be precipitated from bicarbonate solutions in the presence of limestone. The following equation represents the reaction (Savage 1936) $\text{Mn} (\text{HCO}_3)_2 + \text{Ca CO}_3 = \text{Ca} (\text{HCO}_3)_2 + \text{Mn CO}_3$

Twenhofel points out that manganese carbonate is not precipitated except by replacement of pre-existing rock, generally a carbonate (Twenhofel 1926)

**Manganese of Volcanic Origin**

Volcanic springs have been suggested as the source of several manganese deposits such as those of Cuba and Haiti, California (Taliaferro and Hudson 1943) and of the Olympic Peninsula (Fardee 1927). Analyses of hot-spring waters, which might reveal the importance of a volcanic source of manganese, rarely report the manganese content.
Sixteen analyses of hot-spring waters from the St. Helena Range in California vary from zero to 2.2 percent MnO and are high in silica and sulfates (Allen and Day, 1924). Allen and Day note, in addition that "manganese in small quantities is no doubt present in many (hot) spring waters where it has not been looked for." Analyses of hot spring waters of Yellowstone National Park reported by Gooch and Whitfield (Gooch and Whitfield 1888) are low in manganese. All 38 samples were tested for manganese, four contained only traces the remainder contained no manganese. Analyses of volcanic gases and hot-spring waters from Lassen National Park (Allen and Day 1925) do not report the manganese content but soluble salts, essentially sulfates, that are products of fumerolic activity, contain from 0.01 to 0.07 percent metallic manganese. Shipley reports that manganese, in places in considerable quantities, is present in many encrustations around fumeroles in the Katmai region in Alaska. One encrustation contained 17.3 percent MnO (Shipley 1920).

Thus, although the data are few, it seems probable that small amounts of manganese are present in many volcanic springs and that large quantities of these waters might constitute a source of significant amounts of manganese.

Twenhofel points out the close association between volcanic activity and manganese deposits. Manganese nodules
are most abundant on the shores of volcanic islands and there appears to be a genetic relationship between volcanic material and manganese in marine deposits.

It seems probable that conditions of deposition of manganese of volcanic origin would be similar to those controlling the deposition of manganese derived from river waters. Volcanic activity may be important not only in providing a source of manganese, but also in bringing about conditions favorable for the precipitation of manganese. Volcanic activity may increase the temperature of the sea water, leading to a growth of bacteria and an increased rate of chemical reaction, or may provide agitation leading to a loss of carbon dioxide or to oxidation. Such conditions would favor the precipitation of manganese oxides. The presence of limestone, possibly precipitated by volcanic activity, may aid in the formation of manganese carbonate.

Summary

Thus, manganese originally present in igneous and sedimentary rocks may be released and transported by rivers as manganese bicarbonate or as oxides, and on reaching the sea be deposited as oxides or as the carbonate. Similarly, manganese entering the sea from volcanic sources may be deposited as oxides or as the carbonate. Theoretically shallow basins near shore would be well suited to the deposition of manganese. Grains of oxides formed by oxidation in rivers, by change of alkalinity on reaching the sea, or by oxidation in shallow sea waters, would be
deposited along with fine sediments near shore, while manganese in solution might react with limey beds to form manganese carbonate. Shallow, warm, agitated waters of seas in volcanic regions would be particularly favorable for the deposition of manganese either oxides or the carbonate. Manganese either as suspended oxides or dissolved bicarbonates that become carried farther out to sea might be precipitated as oxide encrustations, nodules, or fine coloring matter in deep sea oozes.

**Metamorphosed Manganese Deposits**

Manganese deposits of strictly hydrothermal origin that show features similar to those of Cowichan Lake seem to be rare or non-existent. Several deposits that are thought to have formed by the metamorphism of sedimentary deposits, however, show features that closely resemble those of the Cowichan Lake deposits.

Deposits of the Olympic Peninsula, Washington are similar in some respects to those of Cowichan Lake. (Pardee 1921, 1927, Park 1942, and Green 1945). They occur in a series of Eocene rocks made up of interbedded basaltic flows, pyroclastics, clastic sediments, and some limestone. The manganese deposits are lens shaped or tabular and lie parallel to the bedding of the surrounding sediments. They are usually in red siliceous limestone and are always associated with basaltic flows. The main minerals are bementite (hydrorous manganese silicate) and
hausmannite (\(\text{Mn}_3 \text{O}_4\)). Rhodonite and rhodochrosite are rare but jasper is abundant. The deposits are thought to have formed as sedimentary manganese carbonate deposited with limestone and later converted to silicates and oxides by hydrothermal solutions and in part by volcanic activity. Hausmannite probably formed under special oxidizing conditions while silicates formed by reactions with silica-rich solutions.

The manganese deposits of California are strikingly similar to those of Cowichan Lake. (Talioferro and Beidson, 1943). They occur in Jurassic chert and quartzite as pods and lenses lying parallel to the bedding of the sediments. Orebodies in the Coast Ranges contain mainly rhodochrosite cut by quartz veinlets, but in some bementite, hausmannite, and neoctocite are abundant. In deposits of the Sierra Nevada the principal primary manganese mineral is rhodonite, but spessartite is usually present and in places is abundant. Rhodochrosite and bementite are minor.

All the California deposits in Jurassic chert are thought to have formed as sedimentary manganese carbonate that accumulated in marine basins. Deposits of the Coast Ranges are only slightly metamorphosed and contain mainly original manganese minerals. Rhodonite-spessartite deposits of the Sierra Nevada occur only in metamorphic rocks and hence are thought to be metamorphosed sedimentary carbonate deposits of the same ultimate origin as those of the Coast
ranges. The source of the manganese in both the Washington and California deposits is thought to have been related to volcanic activity.

The reactions involved in the formation of rhodonite and spessartite may be similar to those involved in the formation of other pyroxenes and garnets by metamorphic processes. Under heat and pressure the siliceous carbonate may break down to form rhodonite.

\[
\text{Mn CO}_3 \cdot \text{SiO}_2 = \text{Mn SiO}_3 \cdot \text{CO}_2
\]

Impurities other than silica may give rise to other silicates. Spessartite readily forms by thermal or regional metamorphism of sediments containing either large or small amounts of manganese carbonate or oxides. Manganese-bearing garnet is found in the chlorite and biotite zones of regional metamorphism and differs in this respect from other garnets that are found only in zones of higher grade metamorphism.

Origin of the Cowichan Lake Deposits

Conditions of Formation of the Sicker Sediments

Clapp has outlined the conditions of formation of the Vancouver group (Clapp and Cooke, 1917) and many of his theories have been substantiated by the work in the Cowichan Lake district. The long period of volcanic activity during the Triassic and Jurassic began with outpourings of great quantities of lava. The fact that the volcanics are closely related to the Sutton limestone, which formed at least in part by the accumulation of marine
organisms, suggests that the flows may have been submarine. No direct evidence, however, for the submarine origin of the Sicker andesites was found in the Cowichan Lake area. The occurrence of angular and unstratified tuffs in the Duncan area led Clapp to believe that volcanic vents above sea level formed volcanic islands on the shores of which limy beds accumulated.

In the Cowichan Lake area there is abundant evidence that the Sicker sediments are water lain and probably of marine origin. The shorty tuffs are well bedded; individual beds contain sorted grains and show gradations in grain size; bedding planes are marked by local unconformities possibly poorly preserved ripple marks; and some limy tuffs are cross-bedded. The presence of siliceous oolites in the tuffs indicates that they are water lain and probably marine, and that chemical precipitation was taking place at the same time as pyroclastic grains were being deposited. Further evidence of the marine origin is provided by the close association of limestone lenses and the tuffs. Limestone lenses range from limy tuffs containing only a small proportion of limy material to relatively pure limestone.

The Sicker sediments may thus have formed in relatively shallow seas around volcanic islands or near some larger center of volcanic activity. Volcanic activity may have added manganese to the seas, and favorable conditions of precipitation may have resulted in the deposition of
manganese along with other chemical sediments.

Conclusions

Field and laboratory evidence substantiated by theoretical considerations suggests that the Cowichan Lake manganese occurrences formed as sedimentary deposits. Manganese, possibly derived from volcanic springs, may have been deposited as oxides, or under special conditions as the carbonate. Manganese seems to have accumulated in regions where silica was being deposited most rapidly, such as regions close to volcanic springs supplying abundant silica and manganese or regions in which conditions of chemical deposition were most favorable. Subsequent burial, folding, and metamorphism, possibly aided by hydrothermal solutions converted the oxides or carbonates to silicates and produced the replacement and cross cutting relations seen in many of the deposits. Uplift and erosion exposed the manganese silicates to the atmosphere, and weathering has formed the coating of black oxides, the stringers of neoctocite, and possibly some of the carbonate that replaces the silicates.
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ILLUSTRATIONS
Fig. 1 Index map showing the position of the Cowichan Lake map area. (cross hatched area)
Fig. 2 Sketch map showing the structure of part of the Cottonwood creek manganese deposit.

Fig. 3 Sketch map showing the structure of the Shaw creek manganese deposit.
Fig. 4  Steeply-dipping cherty tuffs 
(east of Widow Creek.)

Fig. 5  Tightly-folded cherty tuffs 
(west of Widow Creek.)
Fig. 6  Tightly-folded cherty tuffs (west of Widow Creek.)

Fig. 7  Fragmental flow top near the top of the Sicker andesites (east side of Widow Creek)
Fig. 8 Poorly developed columnar jointing in the flows above the Sicker sediments (west slope of Mt. Landalt)

Fig. 9 Photomicrograph of typical cherty tuff showing lens of angular grains of andesine in fine cherty material (x15 crossed nicols)
Fig. 10  Photomicrograph showing siliceous oolites in cherty tuff (x13, crossed nicols)

Fig. 11  Photomicrograph showing siliceous oolites in manganiferous chert (x13)
Fig. 12 Photomicrograph showing rhodonite cross-cutting and replacing cherty beds. Rhodonite (and manganese oxides) black, bedding almost horizontal (x15 plane light)

Fig. 13 Polished surface of a specimen from the Hill 60 deposit showing banded yellow manganese silicate and irregular masses of rhodonite. (1) yellow silicate and quartz, (2) rhodonite and quartz, (3) quartz veinlet.
Fig. 14 Polished surface of bedded manganiferous chert from Meade Creek deposit. (1) lens of rhodonite, (2) garnetiferous bed, (3) lens containing siliceous oolites, (4) manganese oxides related to surface fractures.

Fig. 15 Faulted beds of yellow manganese silicate in jasper from near the Hill 60 deposit. (1) fault (2) yellow silicate coated with oxides (3) jasper.
Fig 16. X-ray powder-photograph of quartz

Fig 17. X-ray powder-photograph of quartz and yellow manganese silicate

Fig 18. X-ray powder-photograph of spessartite.
STRUCTURAL SECTIONS
NORTH OF COWICHAN LAKE
BC
HORIZONTAL SCALE 1" = 2640 FT
VERTICAL SCALE 1" = 2500'