TERTIARY LOW-ANGLE FAULTING AND RELATED GOLD AND COPPER MINERALIZATION ON MOUNT WASHINGTON, VANCOUVER ISLAND

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INTRODUCTION

The structural style of Vancouver Island, as perceived by the author in the course of reconnaissance mapping for the Geological Survey of Canada, 1963 to 1981, was one of rather rigid tilted blocks, separated by numerous high-angle faults. That concept has now been shown to be incomplete and in need of revision.

Firstly, deep seismic soundings carried out in 1984 under the LITHOPROBE program, have been interpreted as demonstrating a series of northeast-dipping low-angle thrust faults, imbricating the island's crust (Sutherland Brown and Yorath, 1985). In addition, post-retirement work by the writer, initially undertaken to revise geological mapping of the Alberni map area (Muller and Carson, 1969), has yielded field evidence of low-angle fault zones. Some of these faults occur within Triassic (Karmutsen) volcanic rocks, others are at the base of the Upper Cretaceous Nanaimo Group and had previously been considered as minor dislocations parallel to the unconformity. Lastly, but most importantly, renewed mineral exploration on Mount Washington by Better Resources Ltd. has confirmed the existence of a major set of interfingering near-horizontal faults at about the 1450-metre elevation.

These new findings, combined with data obtained on preliminary review-excursions into the Beaufort Range and Nanaimo Lakes area, strongly suggest low-angle faults are a widespread and important feature of the island's structure.

Low-angle, normal or detachment faults have been recognized in the last decade in several parts of western North America, especially the Basin and Range structural province. There they have been identified as conduits for hydrothermal mineralizing fluids and as the present site of precious and base metal ore deposits (Wilkins and Heidrick, 1982; Spencer and Welty, 1986). Recognition of such faults is therefore of prime importance to mineral exploration.

The present study was undertaken to establish more clearly the existence of detachment faults on Vancouver Island. Mount Washington, with its now well-explored low-angle fault, presented an obvious starting point. The fault is described in detail in a paper by R. Dahl (in preparation) and this paper deals mainly with rocks and structures below the fault.

The report is of a preliminary nature and lacks the refinements and confirmation provided by petrological, geochemical or geophysical data. Nor has any but the most minimal use been made of the extensive footage of diamond drilling completed over many years by several mining companies. Nevertheless, where appropriate, data of earlier workers have been used in preparing the map (Figures 1-10-1A and B) and report It is hoped that geologists concerned with the geology and structure of Mount Washington in particular, and of Vancouver Island in general, will seriously consider the proposed interpretations. This may require *the proverbial "Leap of Faith" but may lead to new* approaches toward understanding the complex geology and contribute to exploration of the mineral deposits of Mount Washington as well as other parts of Vancouver Island.

LOCATION AND ACCESS

The map area shown on Figures 1-10-1A and B is about 15 kilometres by road northwest of Courtenay. Its northeastern part lies within Tree Farm Licence No. 2 of Crown Forest Ltd. (formerly Crown Zellerbach Co. Ltd.) and its southwestern part in Strathcona Provincial Park. The dividing line of these two domains runs from Ramparts Creek to the top of Mount Washington and thence almost due west to Buttle Lake.

Road access is by several adequately maintained unpaved mainline logging roads from Courtenay or Campbell River and by Crown Forest Branch 62. The latter road has become the main road to Mount Washington Ski Village and the adjacent part of Strathcona Park.

HISTORY OF EXPLORATION AND MINING

The following historical data are summarized from earlier accounts by Carson (1960), McGuigan (1975) and company assessment or annual reports. Placer gold was panned during the Thirties from the Oyster River, draining a small part of Mount Washington. Gold-quartz veins were discovered and staked on the Central and West Arms in 1940 by the brothers McKay and exploratory work was done on these in 1941 by K.J. Springer. In 1944-1945 The Consolidated Mining and Smelting Company of Canada, Limited (Cominco) performed further work involving trenching and driving of a short adit into what is now called the Domineer zone. In 1951 Noranda Exploration Company, Limited diamond drilled 13 holes in the general area of the present pit but considered the results discouraging.

British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork, 1988, Paper 1989-1.

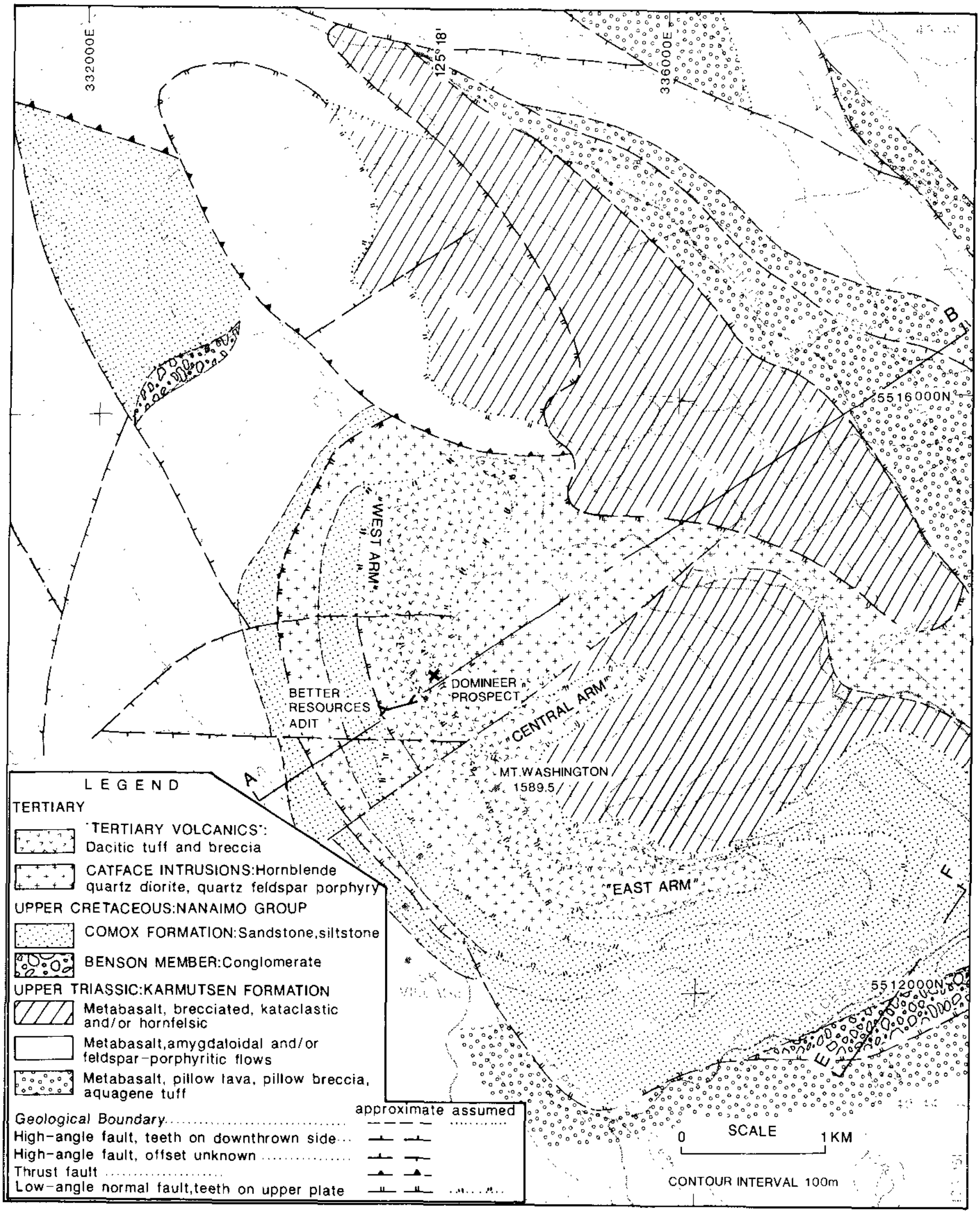

Figure 1-10-1A. *Geological map of Mount Washington, west side.*

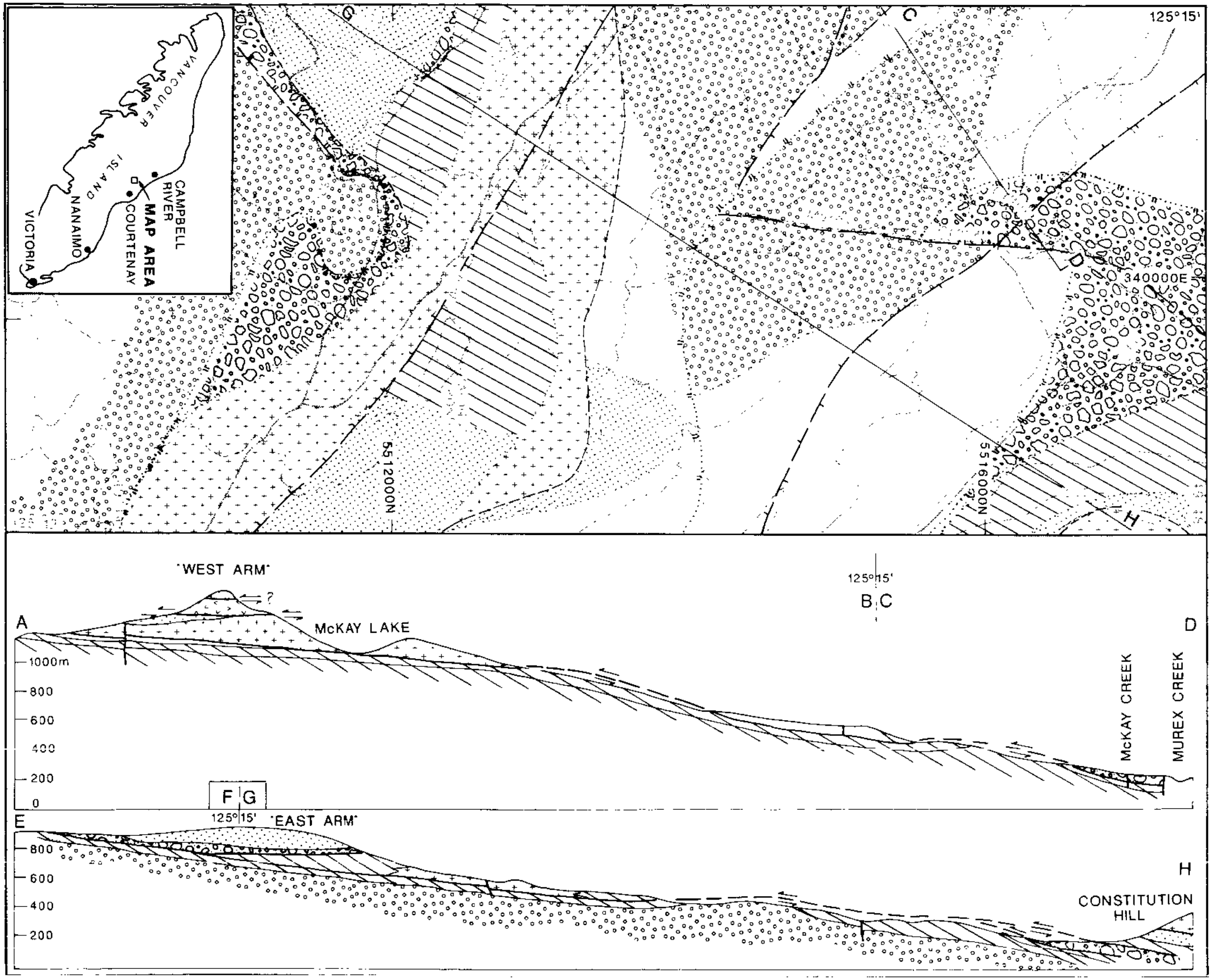

Figure 1-10-1B. Geological map of Mount Washington, east side and structural sections.

In 1956 the newly formed Mount Washington Copper Company Ltd. built the access road to the West Arm and trenched showings discovered on Murex Creek. Noranda then formed a joint venture with that company to explore the deposits in 1957. A road was built to the Murex showings and a program including further trenching, drilling, geological mapping, and geophysical and geochemical surveys was completed. Low-grade copper mineralization was discovered and this resulted in more drilling, trenching and stripping in 1958, in the area of the present pit. A near-surface flat-lying mineralized zone, containing several veins and outcropping in several places, was outlined over an area of about 75 by 180 metres. Subsequently, the companies could not reach an agreement on mining royalties with Canadian Pacific Railway Ltd., holders of the Esquimalt and Nanaimo Railway land grant, and no further work was done.

Cominco again became interested in the property in 1963-1964, did geological mapping and completed 22 drill holes totalling 3840 metres. Subsequently the Mount Washington Copper Company made the necessary financial arrangements and developed a small open-cut mine on the orebody outlined by Noranda. A small mill was built about 4 kilometres east of the pit and 335 600 tonnes of ore averaging 1.16 per cent copper, 0.34 gram gold and 17.1 grams silver per tonne were treated in 1965 and 1966.

Since the shutdown of the mine, 2117 metres of diamond drilling has been completed by Marietta Resources Company Ltd. and 240 metres by Mount Washington Copper Comany Ltd. in 1971. Imperial Oil Limited optioned the property from 1972 to 1974 and completed 27 drill holes totalling 2182 metres.

More recently the property, after laying dormant for some years, was acquired by W. Botel and H. Veerman. Subsequently it was sold to Better Resources Ltd. which has conducted an intensive exploration program from 1983 to the present. During those years a total of 67.6 line-kilometres of geochemical sampling and 248 diamond-drill holes aggregating 14 215 metres were completed. In addition 4000 metres of access road and 278 metres of underground exploratory incline were constructed.

GENERAL GEOLOGY

PREVIOUS WORK

The first and still most comprehensive study of the geology of Mount Washington is a Master's thesis by Carson, followed by a Doctoral thesis and two papers dealing in part with the same topic (Carson, 1960, 1969, 1973). Carson established the general geological setting for a "basement" of several thousand metres of Triassic Vancouver Group volcanics, overlain unconformably by Upper Cretaceous Nanaimo Group shale and sandstone. He considered quartz diorite, exposed in the area surrounding McKay Lake, to be an Early Tertiary intrusive stock. The stock, after breaking through Karmutsen volcanic rocks, would have spread laterally as dykes, sills and small laccoliths into the Cretaceous sediments now exposed at higher elevations.

He also distinguished several types of breccia, presumably related to the intrusion. He described the "Murray breccia", exposed at the top of the West Arm, as "an oval, pipe-shaped diatreme, about 2500 by 800 feet in surface dimensions" and "shown by diamond drilling to extend at least 700 feet". A similar breccia was reported on Murex Creek. The breccias were described as consisting of "angular and rounded fragments of dacite porphyry, Nanaimo Group sedimentary rocks, Karmutsen Formation volcanic rocks, and broken and unbroken crystals of plagioclase, quartz and hornblende in a comminuted matrix of similar but much finer material".

Another breccia was named "Washington breccia", an inferred collapse breccia, occurring "in narrow, steeply dipping zones at the fringes of the stock". It is characterized by abundant angular fragments, few rounded fragments, and a magnetite-rich matrix. Carson speculated that the breccias were formed "after the intrusion of much porphyry, possibly by explosions and gas-streaming caused by a build-up of gaseous pressure from the still-active stock".

McGuigan (1975) made another detailed study of the Mount Washington breccias. In addition to the Murray and Washington breccias, he distinguished and named separate Murex, McKay, Quarry and Oyster breccias and subdivided the Murray breccia on the basis of clast and matrix content. Somewhat differing from Carson, he attributed the formation of these rocks to "multiple stages of breccia formation by a combination of collapse and fluidization mechanisms". Both Carson and McGuigan emphasized, however, that the breccia zones follow the Karmutsen-Comox unconformity.

LITHOLOGIC MAP UNITS

Seven lithologic units, distinguished on the map presented in Figures 1-10-1A and B are, in chronological succession: (1 to 3) Upper Triassic Karmutsen Formation, (4 to 5) Upper Cretaceous Nanaimo Group, (6) Early Tertiary Catface intrusions and (7) Tertiary volcanics. The first six units have been described in detail in many publications (for example Muller and Carson, 1969; Muller *et al.*, 1981) and their characteristics will only be summarized in this report. Unit 7 is newly described and will be dealt with more fully in a report by R. Dahl in preparation.

In the following brief discussion the formations are allocated to the lower, middle and upper structural plates, to be outlined and discussed in the section on structure. The names "West Arm", "Central Arm" and "East Arm", introduced by Carson (1960) for the three main ridges of Mount Washington, are retained in this report.

(1) KARMUTSEN FORMATION: PILLOW LAVA AND PILLOW BRECCIA

The Upper Triassic Karmutsen Formation is a thick sequence of metabasaltic (tholeiitic) rocks that underlies a large part of Vancouver Island and forms all of the lower plate and part of the middle plate on Mount Washington. Pillow lavas and pillow breccias of this unit underlie part of the northeastern and southern lower slopes of the mountain. Nowhere, apart from a few roadcuts in pillow breccia near the ski village, do they produce the spectacular outcrops common elsewhere on Vancouver Island. In many exposures the pillows and original pillow fragments have been deformed and brecciated and can only be identified by a few remaining characteristic shapes and lighter coloured pillow rims. Nests of quartz and epidote, so common as space-filling between pillows elsewhere, are also lacking. In many instances field identification of pillow breccia and aquagene tuff is still possible on the evidence of small devitrified, silica-rimmed lava pellets, visible with a hand-lens, in the matrix on a fresh surface. Low-grade metamorphism of the basaltic rocks to prehnite-pumpellyite grade is generally believed to have occurred in pre-Tertiary time and some retrograde change to yet lower chlorite grade may have attended Tertiary faulting.

(2) KARMUTSEN FORMATION: LAVA FLOWS

Metabasaltic lava flows form the upper part of the Karmutsen Formation wherever the volcanic stratigraphy can be established. The flows outcrop on the northeastern and northwestern slopes of Mount Washington and form parts of the lower and middle plates. They are typically distinguished by amygdules of quartz and/or a dark green mineral, probably pumpellyite, and less commonly by plagioclase phenocrysts less than 2 millimetres long. Subdiabasic texture may be detected with a hand-lens. Flow-tops and clear separation of flows were rarely observed in this area. However, in several exposures there is a crude separation into irregular layers by horizontal fracturing and slip within the structural plate.

(3) KARMUTSEN FORMATION: BRECCIATED AND/OR HORNFELSIC METABASALT

The rocks of a large part of the Karmutsen Formation have been transformed to an extent where attribution to either Unit 1 or 2 is impossible. The changes are due to two different, not necessarily related events. First, emplacement of Catface intrusions into the Karmutsen in early Tertiary time produced a contact aureole of microdiorite and hornfelsic metabasalt. In one instance, exposures of dioritized volcanic rocks with a few veins and dykes of fine-grained quartz diorite alternate with limited outcrops of the intrusive rock.

More importantly, the rocks have been intensely fractured into breccia and cataclasite. Viewed with a hand-lens the massive, generally well-indurated rocks are seen to be composed of subangular fragments and porphyroclastic feldspars in a matrix of dark green chloritic material, commonly pervaded by stringers and lenticles of a black serpentinous substance. These rocks are quite distinct from aquagene tuffs due to the absence of green, white-rimmed globules of devitrified glass. Detailed petrographic work will be required to properly identify and describe the cataclasites.

(4) NANAIMO GROUP: BENSON CONGLOMERATE

The Upper Cretaceous Nanaimo Group unconformably overlies all older formations on Vancouver Island and the basal conglomerate is known as the Benson member of the Comox Formation. In the mapped area the conglomerate is mainly exposed to the southeast, where it forms the base of the middle plate. Its contact with the Karmutsen Formation is, in the structural framework proposed here, considered to be a detachment fault that has locally followed the unconformity.

Clasts in the conglomerate are predominantly metavolcanic, presumably Karmutsen rocks. They are generally well rounded and vary in size from pebbles up to about 5 centimetres in diameter, to boulders up to 30 centimetres across. Unlike conglomerates in the main Nanaimo and Comox sedimentary basins, these rocks are well indurated and fracture across the clasts rather than showing rounded clasts on rock faces. Not uncommonly, quartz occurs in veins and forms envelopes around individual clasts. In the matrix, sandy to gritty greywacke has been converted to a dark green pseudo-metavolcanic substance. Near the fault zone the rocks are commonly hematitic and/or limonitic.

Boulder conglomerate at the base of Cretaceous sandstone in the northwest corner of the map area may be autochthonous and is deeply weathered, highly fractured and loosely consolidated.

(5) NANAIMO GROUP: COMOX SANDSTONE AND SILTSTONE

Metasandstone and metasiltstone, several hundred metres thick, make up most of the middle plate on the East Arm. Toward the northwest the thickness decreases to less than 100 metres but there sandstone is also part of the lower plate. The sandstones are mainly medium grained, well-cemented to quartzitic arkose or, in the lower part of the unit, greywacke. Bedding is poorly developed and many apparent bedding planes are in fact shear planes. Crossbedding, characteristic of these sandstones elsewhere, may have been obliterated by internal dislocation. On the other hand, anastomosing nondepositional shear-laminations are common. Deep limonitic and hematitic staining is also a general characteristic rarely encountered in the Nanaimo Lowlands sedimentary basins.

Metasiltstones overlie sandstones on the East Arm and are also exposed on the Central and West arms of Mount Washington. Well-preserved fern leaves in carbonaceous siltstone in a small pit at the end of logging spur 62F (5512840N, 337440E) are also used to delimit the base of the upper plate (Table 1-10-1). They also indicate that some of these rocks, although slightly metamorphosed, are part of the Comox Formation. A sequence of grey, silicic, quartzofeldspathic metasiltstones, forming the crest of East and Central Arm and the steep walls of the upper Murex Creek valley was included in the Comox Formation by Carson (1960) and McGuigan (1975). These rocks, in several places interlayered with quartz feldspar porphyry, are tentatively included with Tertiary tuff of Unit 7, on the basis of lithological resemblance.

(6) CATFACE INTRUSIONS: QUARTZ DIORITE AND QUARTZ-FELDSPAR PORPHYRY

The name "Catface intrusions" was introduced for all high-level plutons, sills and dykes of Vancouver Island (Muller *et al.*, 1981) and is applicable to the Mount Washington intrusive rocks of Tertiary age. The crystalline rocks form the base of the middle plate, above the 1200-metre level in the West Arm area, and extend northeast to the middle reaches of the Murex Creek drainage. Similar rocks also form the bulk of Constitution Hill, northeast of the area of Figure 1-10-1B. The outcrop area around McKay Lake, more than 1 kilometre in width, has been considered a central stock that forced its way upward through Karmutsen volcanics and laterally into the Cretaceous strata (Carson, 1960, 1973). Good exposures of the intrusive contact with Karmutsen volcanics are seen on the mine road, 300 metres northwest of the crossing of McKay Creek (5515250N, 335050E); on the easterly branch of Murex Creek, just above the crossing of logging spur 101-I (5514450N, 339830E); and in the creek draining the old tailings pond, downstream from the crossing of Branch 101 (5514200N, 340350E). In the latter location the creek appears to follow the contact zone for about 500 metres, and exposures of dioritized volcanic rocks with a few veins and dykes of fine-grained quartz diorite alternate with limited exposures of the intrusive rock. On the other hand none but faulted subhorizontal contacts between the intrusion and Cretaceous strata were seen in this study.

The crystalline rocks have been studied and described in detail by Carson *(ibid.)*. Away from the contact zones the rocks are fine to medium-grained equigranular hornblende diorite. Adjacent to intrusive contacts, and in dykes, sills and apophyses, the rocks are quartz-feldspar-hornblende porphyry with conspicuous hornblende needles varying in length from about 2 to 10 millimetres.

(7) TERTIARY VOLCANIC ROCKS

Volcanic rocks of probable Tertiary age have not been reported previously on Mount Washington. They were recently identified, with some degree of certainty, by R. Dahl in the course of detailed fieldwork on the upper western slopes. Thus far they appear to have been variously identified as *intrusive* rock, as *Murray (diatreme) breccia* and as *Cretaceous clastic sediments*. Several roadcuts on the higher part of the West Arm provide convincing evidence of pyroclastic origin. Layered white-weathering dacite tuff, varying from fine-grained ash to coarse-grained crystal tuff and breccia, is exposed in several cuts.

In anticipation of conclusive identification by more fieldwork and detailed petrographic study, the rocks are here assumed to be tuff and volcanic breccia, genetically related to Catface intrusions. The areal distribution of these Tertiary volcanic rocks is uncertain. Some rocks, shown on earlier geological maps as Cretaceous metasiltstone, are probably fine-grained tuff while others, previously identified as quartz-feldspar porphyry, may be crystal tuff. Rounded quartz grains and broken feldspar crystals, noted by Carson (1960), could be an indication of pyroclastic origin. Of all the breccias described by Carson (1960) and McGuigan (1975) the Murray breccia which, as Carson noted, is crudely layered, is most likely a part of the extrusive sequence. The rocks of the upper plate, except for its lower part on the East Arm, have provisionally been mapped as Unit 7 Tertiary volcanics in this study. Possibly Unit 7 includes some sediments of Unit 5 and intrusive rocks of Unit 6. Conversely, areas mapped as Units 5 and 6 may include rocks of Unit 7.

BRECCIAS

The rocks of Mount Washington include many different types of fragmental rocks that have been subdivided, named and described by Carson and later McGuigan. Carson introduced Murray and Washington breccia and McGuigan added the names Murex, McKay, Glacier, Quarry and Oyster brec-

Table 1-10-1
EXPOSURE AND LOCATIONS OF LOW-ANGLE FAULTS

(1) General Location and Type of Outcrop	(2) Northing, Easting	(3) Hanging, Footwall Lithology	(4) Attitude	(5) Breccia?
1. Oyster River [Eagle Canyon] (S)	5524800N 332850E	B.Cgl. K.Pbr.	350/30N	R
2. Br.181, SW side of Helldiver Lake (R)	5523500N 337425E	N.E. K.F.	Flat	R
3. MB. Oyster Main-line, 0.1 km N of Br. 8	5521200N 325900E	B.Cgl. K.Pl. + P.Bay	Undulating	N
4. Gully above MB Br. 8, 1.3 km S of Oyster Main-line (S)	5520125N 325050E	B.Cgl. K.Cl.	040E	N
5. *Rossiter Main*, creek crossing (R,S)	5519350N 330475E	K.F. K.F.	*Antiformal*	R
6. Br. 160, 0.15 km S of Br. 160A (R,Q)	5518925N 330075E	K.F. K.F.	Flat to dip 10 E	R
7. Sharp left bend of Murex Creek (S)	5518100N 339975E	B.Cgl. B.Cgl.	90/25S	R
8. Br. 161, 0.8 km N of Piggot Ck. bridge (R)	5517700N 328975E	K.Pl. K.F.	Flat	N
9. Creek near end of Br. 105F (S)	5517475N 337325E	K.F. K.Br.	350/30N	R
10. Piggott Ck., 0.8 km S of bridge [Elnora] (S)	5516325N 329925E	K.F. K.F.	240/10NW	R
11. Main-line, 0.4 km NNW of NW end of Wolf Lake [Lupus] (Q)	5516275N 341750E	N.E. K.F.	Antiformal	R
12. Junction of Br. 126 and Br. 130C2 (Q)	5515900N 334000E	Q.D. C.A.	Flat	N
13. Mine road, sharp turn N of old mine (Q)	5515700N 334600E	N.E. Q.D.Cl.	Undulating	N
14. Creek 0.8 km S of N tip of Wolf Lake [Ref. Hurst, 1927]	5515150N 341725E	C.S.? K.Br.?	Dip 30 E	S
15. Better Resources adit	5513900N 333900E	T.V. C.A.	Slight dip	S
16. Murex Creek prospect	5514450N 337675E	K.Cl. K.Br.	55/40SE	S
17. 0.75 km NNW of summit [Domineer] (A)	5514200N 334375E	T.V. T.V.	Antiformal	S
18. N flank of Central Arm, prospect	5514100N 335150E	T.V.? Q.D.	0/30E	S
19. Near end of Br. 62F (fault unexposed; Q,R)	5513000N 337700E	C.A. C.Cl.	Flat?	N
20. Ski area service road and quarry (Q,R)	5512550N 335075E	Q.D. N.E.	20/20SE, 90/25S	R
21. Ramparts Ck., above ski access road [Photon (R,S)	5511200N 335350E	C.S. K.Pbr.	Steep NE?	R
22. Br. 53, near forks with Br. 53E	5509425N 342425E	N.E. K.Cl.	320/40NE	R
23. Browns River, 3.5 km W of logging bridge	5506200N 346575E	C.S. K. or Q.D.	Flat	N

Column (1): Main roads and numbered branches (Br.) are of Crown Forests Ltd. Roads marked "MB" are of MacMillan Bloedel Ltd.
Prospect or claim names shown in [brackets]; Ref.; *see* references
(A) = Adit; (Q) = Quarry; (R) = Roadcut and/or roadbed; (S) = streambed and/or cut.
Column (2): Northings and eastings measured from field map locations.
Column (3): B.Cgl. = Benson Conglomerate; C. = Comox; C.Cl. = mylonitic siltstone; C.A. = argillite; C.S. = sandstone/siltstone; K. = Karmusten; K.Br. = brecciated; K.Cl. = cataclasite; K.F. = flows; K.Pbr. = pillow breccia; K.Pl. = pillow lava; N.E. = not exposed; Q.D. = quartz diorite; T.V. = Tertiary volcanics.
Column (4): Azimuth of strike/degrees and direction of dip of fault zone if measurable.
Column (5): Distinctive fault rocks: N = no mineralization seen; R = Rosewall breccia; S = sulphide mineralization.

cia. Most of these varieties are typical of a specific outcrop area and further distinctions seem to be made on the basis of composition, size and shape of the clasts and matrix, and contact relationships with adjacent rocks. Both Carson and McGuigan appear to favour the genesis of all these varieties by intrusive emplacement in semi-fluid state or as a result of collapse in a subvolcanic environment.

This study has not focused specifically on the various breccias of Mount Washington but a few general observations must be made. Two distinct and different modes of brecciation should now be considered in addition to subvolcanic quasi-intrusive emplacement. First, the Murray and perhaps the Washington breccia, exposed at higher elevations, are more likely extrusive pyroclastic deposits rather than diatreme fillings. Second, the other named varieties of fragmented rocks are probably, in large part, neither intrusive nor volcanic but tectonic breccias formed as a result of detachment faulting. The newly named Rosewall breccia, referred to in a subsequent section and not previously distinguished in this area, is everywhere associated with a low-angle fault.

STRUCTURAL GEOLOGY

CHARACTERISTICS OF LOW-ANGLE NORMAL FAULTS

Before introducing the concept of detachment faulting to the structure of Mount Washington (and possibly a large part of Vancouver Island), a brief review of this structural style is in order.

In the southwestern United States the structural character of the Basin and Range geological province was traditionally viewed to be fashioned exclusively by high-angle normal faulting. However, mapping and structural analysis since about 1970 has shown that this region is pervaded by low-angle normal-slip faults. These faults, also termed detachment faults, are generally Oligocene-Miocene in age (Davis, 1984). In contrast to thrust faults, they superpose younger on older rocks and are the result of structural extension rather then compression.

A great number of studies of these structures are now available, dealing mainly with mountain ranges on both sides of the Colorado River in California and Arizona. Detachment faults in the Whipple Mountains of California and Rawhide, Buckskin, and Harcuvar mountains of Arizona have been a prime object of investigation (for example, Davis *et al.*, 1980, 1986; Gross and Hillemeyer, 1982; Wilkins and Heidrick, 1982). There, the autochthonous lower plate is structurally overlain by an allochthonous upper plate, resting on a flat, commonly undulating detachment surface. It is now well established that northeastward movement of the allochthonous plate in the order of tens of kilometres has occurred. The upper plate is fragmented into many separate fault blocks by normal faults terminating at, or converging with, the detachment fault. Commonly there is a second detachment fault, a few hundred metres above the main fault, dividing the allochthonous rocks into a middle and upper plate.

In the Colorado River region the lower plate is mainly composed of Precambrian and younger crystalline rocks; the upper plate consists of a heterogeneous assemblage of Mesozoic and Tertiary crystalline, metasedimentary and metavolcanic rocks that may include late Tertiary volcanic and sedimentary deposits.

A readily mappable, resistant unit typically marks the sole of the fault. Its detachment surface has been described as a "dense, compact, flinty, comminuted microbreccia that weathers dark reddish brown to patina". Below the fault "the flinty microbrecciated surface grades downward to various combinations of shatter, crush, and crackle breccia; a relationship consistently found by [several other authors]" (Wilkins and Heidrick, 1982). The breccia is commonly bleached and chloritized and may extend to over 300 metres below the detachment surface ("chlorite breccia zone"). Brecciation of upper-plate rocks is much less pervasive and commonly limited to the first few metres above the fault plane (Phillips, 1982).

A special class of mineral deposits, genetically and spatially related to detachment faults, is now well established. The deposits occur in fault-associated breccia zones (Drobeck *et al.*, 1986) and may be preferentially located on synformal and antiformal "megagrooves" of the detachment surface. A sequence of early copper and iron sulphides, followed by massive specular hematite, in turn followed by fracture-filling chrysocolla and malachite has been cited (Spencer and Welty, 1986). Mineralization by hydrothermal fluids may have occurred during faulting as a result of unusually high geothermal gradients, but does not appear to be directly related to magmatic activity. Metals produced are predominantly copper with additional lead and zinc as well as gold and silver. Manganese is concentrated at higher levels of the fault zone and locally occurs in vein and stratabound deposits.

SOME KEY EXPOSURES OF LOW-ANGLE FAULTS

The author became aware of the possible existence of low-angle faults in the summer of 1986, on Rosewall Creek in the Beaufort Range between Cameron and Comox lakes. In 1987 more representative exposures were identified adjacent to the present study area and three typical outcrops are described in the following section. In addition Table 1-10-1 shows locations of 23 representative exposures of these faults.

INTRA-KARMUTSEN FAULT

On Rosewall Creek, 50 kilometres southeast of Mount Washington and a short distance upstream from the bridge of the B.C. Forestry road (5477950N, 356580E), a conspicuous red breccia is exposed. It is seen both in the bed of the creek and further upstream in the wall of a small canyon headed by a waterfall. The breccia is generally composed of angular, highly altered, strongly hematitic to limonitic rock fragments in a matrix of massive or vuggy quartz and calcite. In some places it includes irregularly laminated layers of microbreccia. Identifiable pillow lava is exposed above and below the fault zone which encloses at least one layer of cataclastic metabasaltic rock and is inclined about 20 degrees to the northeast. The breccia is also exposed in several places on old logging roads adjacent to Rosewall Creek and its tributary Roaring Creek, where pillow lava forms the hangingwall in several instances. The brecciated rocks are clearly not part of the normal Karmutsen sequence and can only be explained as evidence of a low-angle fault. For conveniece they are informally named Rosewall breccia. The fault zone and breccia can be traced intermittently across Mount Schofield toward Horne Lake.

CRETACEOUS COMOX STRATA ON TRIASSIC KARMUTSEN ROCKS

Low-angle faults within the Karmutsen Formation could be interpreted as thrust faults but an important outcrop on Browns River (Table 1-10-1, No. 23) exposes an unequivocal low-angle normal fault. The fault was noted during earlier mapping but ignored as a minor disturbance following the unconformity. The hangingwall, downstream and east of the fault zone, is composed of gently northeast-dipping sandstone, grading downward into siltstone and coaly shale with some plant fragments. The lowest undisturbed Comox beds are rubbly siltstone and flaky shaly coal, composed mainly of flattened plant stems, dipping 10 degrees northeast. The upper part of the fault zone is composed of sedimentary material that grades downward into a mélange of metavolcanic material. The clasts are light green, entirely altered (chlorite-albite?), more or less ellipsoidal fragments, up to about 50 centimetres long. They are locally distinctly imbricated at a strike of 310 degrees. Flatly undulating glide surfaces are also well exposed in the stream bed and the fault zone is cut by vertical faults striking 060 degrees. Further upstream and lower down in the fault zone there are cataclastic fragments of quartz diorite (also exposed on the hill south of the river) and some pink-coloured Rosewall-type breccia. Karmutsen metavolcanic rocks, structurally underlying the fault zone, are exposed in the canyon further upstream.

CRETACEOUS BENSON CONGLOMERATE ON KARMUTSEN METAVOLCANICS

A third example of a low-angle fault is on the Eagle Gorge claim in the canyon of Oyster River (Table 1-10-1, No. 1). There Rosewall breccia, up to 2 metres thick and overlying Karmutsen pillow lava and aquagene breccia, is exposed east of a rock island in the middle of the canyon. The fault zone is in part irregular unstructured breccia but the middle part is a well-layered mylonitic rock striking 350 degrees and dipping 30 degrees east-northeast. Benson boulder conglomerate, dipping 20 degrees northeast, overlies the fault zone a short distance downstream.

The lithology of this fault zone was described in detail by Northcote (1984) and is quoted verbatim. "The zone appears to be bleached and has a porcellain-like appearance. It has been crackled and filled with quartz and chalcocite with lesser pyrite. These veins are irregular in attitude and range from hairline to 1 or 2 centimetres of massive chalcocite. [Thin sections show] a breccia of altered, partly devitrified, porphyritic, microlitic volcanic glass. The breccia matrix has been veined and impregnated by quartz with lesser sericite. A polished thin section under reflected light shows sieve-like aggregates of chalcocite grains forming irregular elongate masses several millimetres in length in quartz gangue. The chalcocite contains myrmekitic intergrowths of bornite and chalcopyrite. Aggregates of covellite grains form small masses generally isolated in quartz gange." An assay of a random chip sample of mineralized material yielded: copper, 7.78 per cent; silver, 19.54 grams per tonne; gold, 0.14 gram per tonne. The volcanic glass observed by Northcote may indicate pseudotachylite was formed in the fault zone.

SUBDIVISION IN STRUCTURAL PLATES

The Mount Washington area is structurally divided into three major units: a lower plate of autochthonous "basement" and middle and upper plates inferred to have been emplaced by lateral dislocation. The writer believes this novel structural model to be supported by convincing evidence. However, the preliminary interpretation clearly needs substantial review, elaboration and clarification in field and office. For the purpose of this discussion the three structural plates are subdivided into Areas A to H (Figure 1-10-2).

LOWER PLATE

The lower plate is predominantly composed of Karmutsen pillow lava, pillow breccia and lava flows. Near the contact with the sole fault of the middle plate the rocks are generally highly deformed and fractured, and display cataclastic textures.

Area A is at the northwest edge of the Forbidden Plateau and includes all the area southwest of the basal fault trace that encircles Mount Washington. In the northwest, Karmutsen flows are overlain by a veneer of Benson conglomerate and Comox sandstone and siltstone. In the south, pillow lavas and pillow breccias as well as lava flows are exposed.

Area E is a structural window, traversed by McKay Creek and its tributaries, and bordered by middle-plate Karmutsen metabasalt of Area F to the northeast and by quartz diorite and Karmutsen rocks of Areas B and D to the southwest. In Area E the rocks assigned to Unit 3 are largely brecciated and cataclastic, presumably as a result of proximity to the now-eroded middle-plate sole fault. Area G is bracketed between middle-plate Cretaceous strata to the northeast and middle-

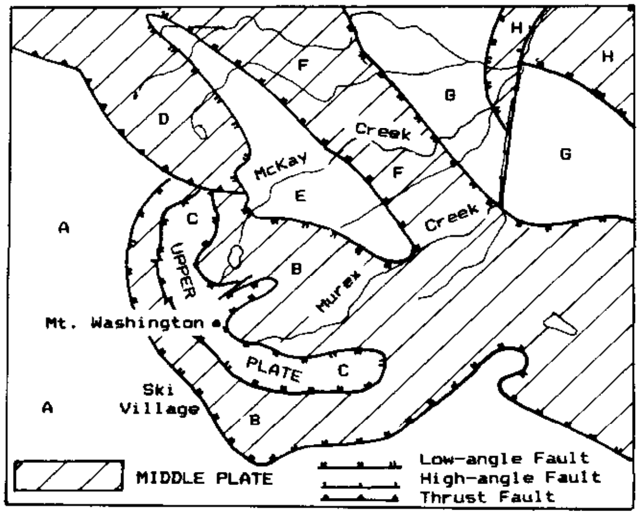

Figure 1-10-2. Structural sketch map of Mount Washington.

plate Triassic and younger rocks to the southwest. This area is also underlain by rocks of Units 1 and 2.

Lower plate rocks are offset by several northwest-striking high-angle faults and a few faults striking almost due north. One fault, conspicuous in the topography, is occupied by Murex Creek above its confluence with McKay Creek. It offsets the middle-plate sole fault and overlying conglomerate of Area H, but terminates against the trace of the sole fault in Area F.

MIDDLE-PLATE SOLE FAULT

The basal fault of the middle plate is presumed to be a major detachment fault, and is pivotal to the structural model presented here. Unlike Arizona, where such faults may be well marked and conspicuous in the landscape, the Vancouver Island terrain tends to conceal the faults by overburden and vegetation. Only a limited number of stream and road-cuts expose the faults and in many outcrops the footwall or the hangingwall is not seen. Table 1-10-1 lists examples of available outcrops of the basal faults of both middle and upper plates.

Exposures of Rosewall breccia, discussed in a foregoing section, were found to be useful markers of low-angle faults while gossans and limonitic stain zones may be related to both low and high-angle faults. Dark brown flinty cataclasite, with or without porphyroclastic feldspars, is also a common marker of the fault zones. These rocks form ledges, waterfalls and canyons providing good exposures. A zone of brecciated and chloritized rocks, extending up to 300 metres below the sole fault, has been described in the Basin and Range Province. Similarly rocks underlying the fault zone in the Mount Washington area are extensively fractured and form wide zones of brecciation that are mainly mapped as Unit 3. Thick zones of breccia have also been encountered in many diamond-drill holes, but have generally been interpreted as non-structural breccia.

Rocks a few metres above the fault zone tend to be largely intact with original textures or fossils well preserved. Open subhorizontal fractures in hangingwall layered rocks, including sandstone, lava flows and also some pillow lavas, give many vertical cuts an appearance of loosely stacked slabs.

The middle-plate sole fault appears to be an excellent aquifer and large parts of its trace are well marked by elongate lakes or marshy areas. In several instances streams follow the fault zone, but unlike streams on steep faults, that continuously cut down into the fault zone, watercourses on low-angle faults may oscillate across the zone between the lower and upper plates. For instance, at Location 9 (Table 1-10-1) the edge of the middle plate of Karmutsen amygdaloidal lavas forms a steep cliff, well washed by the stream. A 20-centimetre band of Rosewall breccia marks the fault at the base. Above it one encounters alternating areas of smooth, well-polished unbroken flows and areas of rough, hummocky, dark rusty weathering breccia; northeast-dipping shear zones, almost parallel to the slope, can be seen in the sidewall. Clearly, the slope of the cliff and the stream are nearly coincident with the fault. Similarly, on Murex Creek at the south end of the McKay Creek structural window (Table 1-10-1, No. 12) the creek meanders across the fault zone for a considerable distance.

MIDDLE PLATE

The middle plate underlies the largest part of the study area (Areas B, D, F and H). Area B covers the middle elevations of Mount Washington, between 1000 and 1300 metres. In the northeast, at Murex Creek, it merges with Area F. Catface quartz diorite is the nucleus of the plate and forms the base in the West Arm–McKay Lake area. According to Carson (1960) the McKay Lake quartz diorite is a central stock that produced, as offshoots, the sills and breccia pipes underlying the highest parts of the mountain. This interpretation has, until the present time, been accepted by later workers including the writer. However, the structural model presented here demands that the intrusive body is rootless and severed from its original base. Examples of this type of detached structural relationship are common in the Basin and Range Province.

The intrusive rocks are overlain by hornfelsic, dioritized and brecciated basaltic rocks (Unit 3) in the upper Murex Creek area. The contact is intrusive and in many places dykes and apophyses of light-coloured quartz diorite can be seen invading dark metavolcanic rock in the contact zone. Presumably the metavolcanic rocks represent the roof and sidewalls of the intrusive body, carried along as it became dislocated. Upper Cretaceous sediments, composed of a thin sequence of metaconglomerate (Unit 4), succeeded by metasandstone (Unit 5), rest on either quartz diorite or metavolcanic rocks, and in the south part of Area B form the sole of the plate.

Area D of the middle plate is composed of metabasalt flows of Unit 2 and breccia and cataclasite of Unit 3. In this area the rocks are entirely different in composition from those of Area B and the two zones may well have moved independently. Rocks in Area D have been thrust southwestward over those of Area B. They are also in thrust contact with the lower plate consisting of Triassic flows overlain by Cretaceous conglomerate and sandstone of Area A. Within Area D "The Oyster Breccia zone is a 1200-foot [360 metre] diameter collapse breccia with Comox breccia fragments collapsed at least 700 feet [200 metre] into the surrounding Karmutsen volcanics" (Better Resources Ltd., Annual Report, 1988). Although sufficient data are not available, the structural model presented in this report may allow a different interpretation of the Oyster breccia. Comox rocks, intersected in diamond-drill holes below Karmutsen volcanics of the middle plate, may be part of a brecciated Comox sandstone of the lower plate, coextensive with sandstone exposed directly to the west in Area A.

Area F is a belt of flat-lying to gently dipping Karmutsen metabasalts, partly pillow lava and pillow breccia (Unit 1) and partly amygdaloidal and/or porphyritic flows (Unit 2). The northwest-striking belt is regarded as a thin skin of middle-plate rocks, sitting on rocks of the same formation in the lower plate. To the south the volcanics are in intrusive contact with quartz diorite and overlain by Comox sediments.

Area H is a small area in the northeast corner of the map but extends far into the lowlands underlain by Cretaceous strata. It also includes the quartz diorite of Constitution Hill. The basal part of the zone is boulder conglomerate and metaconglomerate, well exposed on McKay and Murex creeks near their confluence. Steep faults intersect and offset the trace of the sole fault and form the contact between conglomerate and metabasalt of the lower plate in several stream exposures. The sole fault is not exposed but is projected to intersect McKay Creek about 400 metres southwest of the Rossiter Main bridge (5516950N, 339225E). There sheared, cataclastic, barely recognizable pillow lava is separated by a covered interval from a hematitic to limonitic, irregularly deformed conglomerate. The low-angle fault between Benson conglomerate and Karmutsen metavolcanics is well exposed beyond the area of Figure 1-10-1, on and near Oyster River (Table 1-10-1, Nos. 1 and 3).

Subsidiary low-angle faults within the Benson conglomerate are well exposed in a canyon 600 metres downstream from the junction of McKay and Murex creeks (Table 1-10-1, No. 7). A major fault, exposed in a sharp bend of the canyon, displays a zone of Rosewall breccia 30 centimetres thick, composed mainly of irregularly banded hematitic quartz, dipping 25 degrees to the south. A second fault plane is exposed in the next bend of the creek and forms a broad arch, undercut by the stream. The cobble layers in these cuts occur in fault-bounded lenses, separated by strongly imbricated hematitic silt layers with a rhomboid fracture pattern. Considerable low-angle dislocation within the formation is plainly apparent in these exposures.

Quartz diorite of Constitution Hill, overlying a narrow belt of Karmutsen metabasalt and Comox sandstone, is inferred to be in thrust-fault contact with the conglomerate. The thrust fault and the sole fault presumably converge southeastward towards Wolf Lake, just east of the study area, where two mineral prospects (Table 1-10-1, Nos. 11 and 14) are related to low-angle faults.

Thus the middle plate, as tentatively outlined in the preceding paragraphs, is composed of several dissimilar fragments. It can be argued that the core of the plate is a dislocated mass of Tertiary intrusive rock, to which underlying Triassic volcanics as well as overlying Cretaceous sediments are more or less firmly attached by intrusive contacts.

Further investigation should determine if similar structures exist in other parts of Vancouver Island. Preliminary field data suggest that similar low-angle faulting may be present in the Beaufort Range and may continue into the area of Tertiary sills north of Nanaimo Lakes.

UPPER PLATE BASAL FAULT

Better Resources Ltd. drove an exploratory incline into the west flank of the West Arm at about 1325 metres elevation in 1987. It follows the basal fault of the upper plate for almost its full length of 278 metres, providing proof of the existence and detailed information on the nature of a low-angle fault system in the Mount Washington area, and by extension, on Vancouver Island. A detailed analysis of the geology in the tunnel and its vicinity is provided in the report of R. Dahl in preparation. The fault zone consists of several interfingering fault planes that, according to the Better Resources 1988 Annual Report, generally have a slight westerly dip. The fault is clearly the locus of mineralization and has been intersected as an altered, locally mineralized shear zone in numerous drill holes. Beyond the exploration area the present study has tentatively identified the fault in several places at elevations above 1100 metres on the three spurs of the mountain (Table 1-10-1, Nos. 13, 15, 17, 18, 19 and 20). As projected, the fault plane has an overall northeasterly dip of 5 to 8 degrees, but may arch to a gentle westerly dip towards the west slope of the mountain. On the West Arm the shear zone that hosted the orebody at the old Mount Washington mine forms part of the fault. Further north several cuts and pits adjacent to the mine road (Table 1-10-1, No. 13) expose dark brown flinty cataclasite indicative of the fault zone. Prospect pits (Table 1-10-1, No. 18) provide a location for the fault on the Central Arm. Further southeast, on the East Arm, the trace of the fault is projected near the end of Branch 62-F (Table 1-10-1, No. 19). There roadcuts expose mylonitized siltstone forming the presumed top of the middle plate and which are separated by a short covered interval from coaly argillite, with well-preserved fossil leaves, exposed in a small pit and interpreted as the basal part of the upper plate. Lastly, at the eastern edge of the Mount Washington ski area, Rosewall breccia is exposed along the service road and at the base of quartz feldspar porphyry in a small quarry.

The Domineer prospect (Table 1-10-1, No. 17) is considered by the Better Resources geologists to be associated with the same fault zone exposed in their exploratory tunnel. Figure 1-10-1 shows a subsidiary fault, tentatively projected about 100 metres above the basal fault of the upper plate, to include the Domineer together with other indications of a low-angle fault at that level on the Central and East Arm.

UPPER PLATE

The upper plate is composed of rocks that up to the present time have been identified as Comox sediments, quartz diorite, quartz diorite porphyry, Murray breccia and Washington breccia (Carson, 1960, 1973; McGuigan, 1975). The present investigation has not dealt with these rocks in detail but the writer acknowledges that most or all of them are probably extrusive pyroclastic volcanic rocks. Thus all upper plate rocks of the West Arm have tentatively been categorized as Tertiary volcanics (Unit 7). On the East Arm the plate is inferred to consist of a basal section of Comox sediments overlain by Tertiary volcanics, and in the ski area to the southwest the volcanics overlie intrusive rock. These contacts are arbitrary and subject to reinterpretation.

CONCLUSION

Two major low-angle faults separate Mount Washington into lower, middle and upper plates. The lower plate is composed of Upper Triassic (Karmutsen) metavolcanics; the middle plate is made up of diverse segments with Karmutsen volcanics, Cretaceous (Nanaimo) sediments and Tertiary (Catface) quartz diorite; and the upper plate is inferred to include Tertiary volcanics together with some Cretaceous sediments and Tertiary quartz diorite. The plane of the lower sole fault appears to slope northeastward, intersecting the northeast slope of the mountain at several levels. Thus alternating areas of lower and middle-plate rocks are exposed at the surface. Although no data are available it seems possible that the sole fault extends eastward, at or below the base of Cretaceous sediments, in the Nanaimo Lowlands of eastern Vancouver Island.

The fault zones are clearly good conduits for epithermal fluids and are locally well mineralized. It seems, however, that of all mineral claims staked on fault-related mineralized breccias, those adjacent to Tertiary intrusions and/or the associated volcanic rocks have shown the most promise.

Despite a considerable amount of fieldwork by the author in the small area of Figure 1-10-1 and previous work by many others, more detailed fieldwork is yet required to consolidate and improve the structural model presented here. Extension of these investigations into the eastern ranges and Nanaimo Lowlands of Vancouver Island is also needed to probe the extent of detachment faulting. Such fieldwork will need support by petrographic, and perhaps geophysical and dating studies. It is hoped other research and exploration geologists and their organizations will be encouraged to carry forward the study of these structures. They yield a fertile field for both research and mineral exploration.

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