"TUYAS," FLAT-TOPPED VOLCANOES IN NORTHERN BRITISH COLUMBIA.[1]

W. H. MATHEWS.[2]

ABSTRACT. Several flat-topped, steep-sided volcanoes, here named '*tuyas*,' situated in northern British Columbia, consist of nearly horizontal beds of basaltic lava resting on outward-dipping beds of fragmental volcanic rocks. It is concluded that (1) these 'tuyas' were formed by volcanic eruptions into several 'intraglacial' lakes thawed through the Pleistocene Cordilleran ice-sheet by the volcanic heat; (2) the levels of these lakes were maintained by rocky spillways along the course of drainage of their meltwaters toward the ice-front; and (3) the lavas capping the mountains were extruded from the volcanoes after they had been built above the lake levels, and the outward-dipping beds were formed by the aqueous chilling of the lava when it reached the water's edge.

INTRODUCTION.

SEVEN extinct volcanoes conspicuous for their flat summits or flanking benches were observed during the mapping of the Tuya-Teslin area of northern British Columbia by Dr. K. DeP. Watson and the writer. Field evidence precluded the possibility of these flat-summits or benches having developed either by block faulting or by dissection of a formerly much more extensive surface underlain by horizontally bedded volcanic rocks. Instead, each mountain appears to mark a local center of eruption and to have been only slightly modified by erosion. No explanation was offered when these and the other volcanoes of the area were described (Watson and Mathews, 1944). Subsequent review of information on subaqueous and subglacial volcanism has, however, suggested a possible origin for these flat-topped volcanoes by eruption into lakes thawed through the ice-sheet. Lack of specimens and the inaccessibility of the Tuya-Teslin area have, unfortunately, made it impossible to do further work in testing this hypothesis.

Acknowledgements for helpful discussion and criticism during the preparation of this manuscript are due to Drs. K. DeP. Watson, Howel Williams, and H. S. Bostock and to Prof. Hans Ahlmann.

DISTRIBUTION OF THE VOLCANOES.

The seven known volcanoes having flat tops or benches are found in an area about 50 miles in length from northeast to

[1] Printed by permission of the chief mining engineer, B. C. Dept. of Mines.

[2] Assoc. Mining Engineer, B. C. Dept. of Mines, Victoria, B. C.

southwest, and about 20 miles in width (Text Fig. 1). Three of them, Ash Mountain and two unnamed volcanic piles a few miles east and southeast (Text Fig. 1, Nos. 1 and 2), lie within the mountainous part of this area; the other four, Kawdy Mountain, an unnamed mountain 5 miles to the southeast (Text Fig. 1, No. 3), Tuya Butte, and Isspah Butte, lie on or at the edge of an extensive uplifted peneplain known as Kawdy Plateau.

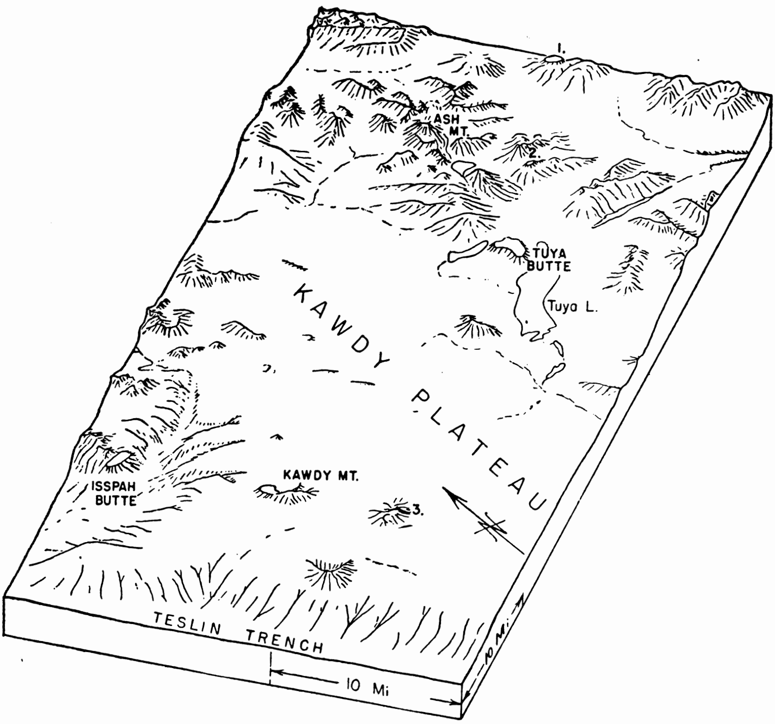

Fig. 1. Block diagram of the Tuya Lake area. Vertical scale exaggerated by two times.

Other volcanoes of similar size and comparable degrees of dissection, but lacking flat tops are known within the same area, and at intervals for at least 50 miles to the south and southeast (Kerr 1925; Hanson and McNaughton 1936). These rise from a few hundred to about 2000 feet above their bases. Some have conical outlines only slightly modified by erosion; others are irregular in shape. The northern end of Kawdy Plateau, moreover, is underlain by extensive sheets of flat-lying basic flows and minor fragmental material, similar in lithology to the rocks of the flat-topped volcanoes. All these volcanic rocks have been grouped in the published maps and descriptions in the 'Tuya formation,' a stratigraphic unit not to be confused with the name '*tuya*' here proposed for the flat-topped volcanoes themselves.

FORM AND INTERNAL STRUCTURE.

The typical flat-topped volcano, or 'tuya,' is roughly circular to elliptical in outline, rising from a few hundred to almost 1500 feet above its base to a summit plateau one half to almost two miles in length. There is no accordance in the elevation of the summit plateaus between the different tuyas nor are there any benches or plateaus at corresponding levels on nearby conical volcanoes.

Fig. 2. Diagrammatic structural cross-section of Isspah Butte and area to the northeast, showing flat-lying lavas (wide horizontal lines), the underlying breccias (dash-dot lines inclined parallel to the stratification) resting on an erosion surface developed on folded Permian sediments (steeply inclined line pattern). Pre-volcanic surface indicated by dashed line. Two buried valleys and three recent valleys have been cut below the level of the peneplain surface. The breccias in the middle and northeastern part of the section strike parallel to the line of the section and dip at angles of from 10 to 25 degrees.

Each tuya is capped by one or more flat-lying flows of columnar basalt, from a few tens to almost 100 feet in thickness. These flows dip at angles averaging only 2° or 3° from a broad mound or ridge which may lie near one edge rather than at the center of the tuya. Although the upper part of a tuya may be compared with the products of fissure or shield eruptions, it is by no means a broad, symmetrical cone. No pipe or dike that might serve as a feeder to the flows has been recognized around the margins of the tuyas except perhaps near the northeastern end of Isspah Butte, where a plug-like structure of doubtful origin is exposed on the south face.

The summit flows are underlain by beds of coarse and fine, yellowish to gray and black, poorly consolidated fragmental material of basaltic composition, which dip outward about 30° from one or more points within the tuya. The contact between the lavas and these underlying rocks is well exposed in profile on cirque walls and on the cliffs that commonly girdle the upper slopes of the tuya. This contact consists of one or more steps with very broad, nearly horizontal 'treads' and short sloping 'risers' parallel to the stratification (Text Figs. 2 and 3). The summit lavas rest conformably on the 'treads'. At the northeastern end of Isspah Butte and on the west face of Tuya Butte the flows rest conformably on 'risers,' but elsewhere they appear to lap discordantly across them. In a few places where a lava cap is absent on a summit plateau, as on the northeastern end of Isspah Butte (Text Fig. 2), the fragmental rocks are truncated by a flat surface that coincides with the top of the adjacent lavas (Pl. 1, Fig. 1). Elsewhere, as on Kawdy Mountain (Text Fig. 3), a cone of fragmental debris has been built several hundred feet above the level of the lava cap.

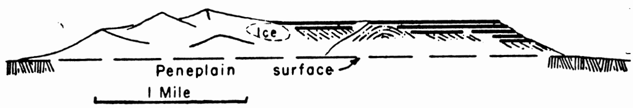

Fig. 3. Natural section of the north face of Kawdy Mountain. (from photos and field sketches) Conventions as in Fig. 2.

Deposits of volcanic debris, dipping at angles of 20° to less than 10°, extend for as much as one and one half miles from the base of the steeper slopes of the tuyas. In some places, at least, these deposits consist of mud-flows or stream-borne material probably derived by erosion from the higher slopes. Elsewhere the tuyas may be surrounded only by talus and small fans that rest on the erosion surface cut in much older rocks.

Some departures from the typical form and structure of the tuya may now be noted. The conspicuous bench on the southwestern slope of Ash Mountain is underlain, in part at least, by pillow basalt rather than by fragmental debris. This bench, moreover, may have been partly buried by the irregular cone of 'ash' or granulated basalt making up the higher part of the mountain. A few isolated pillows amid the 'ash' at the summit of the mountain recall descriptions of the products of subglacial basaltic eruptions of the Palagonite formation of Iceland (Peacock 1926B, Nielsen and Noe-Nygaard 1936, and Noe-Nygaard 1940). The bench of Kawdy Mountain is underlain not by a single conical pile of fragmental material but by at least two coalescing piles, one overlapping the other (Text Fig. 3). The flat-topped volcano five miles to the southeast has not been examined at close hand, but judging from the lack of cliffs even on the wall of a cirque cut in its northwestern face, it is composed entirely of fragmental material. Its upper surface is broadly dome-shaped (Pl. 1, Fig. 2).

EXTERNAL RELATIONS.

All the volcanic rocks included in the stratigraphic unit known as the Tuya formation rest unconformably on folded beds of Permian and Lower Mesozoic age or on deroofed batholithic rocks of post-Lower Mesozoic age. After the intrusion of these batholithic rocks the area was subjected to a long period of erosion during which an almost featureless peneplain, now the Kawdy Plateau, was developed. This peneplain was subsequently uplifted relative to the Teslin Trench at the western edge of the area (Text Fig. 1) along what is apparently a fault scarp or sharp monoclinal fold. Headward erosion by streams has cut youthful valleys extending northeastward as much as 15 miles from this scarp. At Isspah Butte and two miles to the northeast (Text Fig. 2) the volcanic rocks of the Tuya formation extend down into two of these valleys and, hence postdate the uplift of the Kawdy Plateau. Kawdy Mountain, the mountain five miles to the southeast, and Tuya Butte rest on the surface of Kawdy Plateau well beyond the limits of this recent stream-cutting. These three mountains have, therefore, been subjected to only local stream erosion which has carried debris from the higher slopes and deposited it on the adjacent peneplain surface.

Ash Mountain and other volcanoes (Text Fig. 1, Nos. 1 and 2) in the mountainous northeastern part of the area rest on an erosion surface whose irregularity approximates that of the present topography.

Any fault scarps more than a few feet in height on Kawdy Plateau, and more than a few tens of feet in height in the mountains would be readily recognizable, but none has been found. It can be stated with assurance, therefore, that the tuyas are not bounded by faults.

GLACIATION.

Cirques cut by local glaciers, of which only one, that of Kawdy Mountain, now remains, or scattered erratics deposited by the continental ice-sheet, are found on all the tuyas examined in detail. None of the tuyas, however, is deeply eroded by ice. Nowhere has the core of a tuya been exposed by erosion, except perhaps on Isspah Butte where stream cutting is currently active. Neither are there any large accumulations of volcanic debris in the glacial drift on the lee side of a tuya to testify to the removal of any major part by continental glaciation. The stream-carved topography in the older rocks at the western edge of Kawdy Plateau, moreover, is not appreciably ice-worn. Some mountain valleys have been rounded, deepened, and perhaps widened by ice action, and numerous cirques have been cut in the higher peaks, but few ridges have been rounded by overriding continental ice. Nevertheless erratics left by continental ice are found up to elevations of 6500 feet on the slopes of Ash Mountain, and the presence of lava pillows on its summit at an elevation of about 6850 feet, the highest point of the area, suggests that the whole region was at one stage buried by the Cordilleran ice-sheet. At its climax this sheet extended westward to the Pacific coast, more than 150 miles away, and eastward for at least 200 miles.

AGE OF THE TUYA FORMATION.

The precise age limits of the unfossiliferous Tuya formation is not known. None of the rocks of this formation in the Tuya-Teslin area are known to be post-glacial, although similar lavas in the Stikine canyon, 50 miles to the south, may be of this age. The absence of deep dissection of the volcanoes, as well as the similarity of the surface on which they rest to the present topography, indicates a Pleistocene age, although a late Tertiary age may not be precluded for some of the rocks.

DISCUSSION.

Any explanation of the origin of these flat-topped volcanoes must account for the following observations:

1. Since the tuyas have undergone relatively little erosion, it must be recognized that the summit flows, although sufficiently fluid to move across slopes of only 2° to 3°, never extended far

beyond their present limits, nor are they known to have poured down the slope of a tuya to its base, nor were they restricted from spreading laterally by any natural barrier now existing in their vicinity.

2. Although the upper part of a typical tuya is composed of flows without interbedded fragmental material, the lower part is composed of steeply-dipping fragmental material without interbedded flows.

3. The 'treads' between the summit flows and the underlying fragmental beds cut discordantly across the stratification on the latter, whereas the 'risers' are concordant with this stratification.

A clue to the origin of the tuyas is suggested by Nielsen's description of the recent volcanic eruption under the Vatna ice-cap in southeastern Iceland (Nielsen 1936), and by Fuller's study of aqueous chilling of lava on the Columbia Plateau (Fuller 1931).

Nielsen, who visited the scene of the 1934 eruption at Grimsvotn on Vatnajokull a few weeks after the outburst, pictures the sequence of events as follows:

1. A subglacial eruption during which volcanic heat melts the lower layers of the ice to form a subglacial lake which enlarges upward and laterally as the eruption continues.

2. When the thawing of the ice has reached a point not far below the surface of the glacier, in the case of the 1934 eruption about 50 meters, the meltwater finds an avenue of escape toward the periphery of the ice cap. No doubt the warmed water rapidly enlarges this avenue of escape through the ice and the greater part, if not all, of the subglacial lake is drained and the icy roof of the chamber collapses. This sudden drainage is one of the causes of the catastrophic floods, known to Icelanders as 'Jökulhlaup,' like that in 1934 when about 10 cubic kilometers of water poured from the ice tongue within a few days.

3. Once the icy roof above the scene of volcanism is broken and thawed, the activity may continue as a subaerial eruption with "ejection of steam, ash, bombs, fragments of the substratum, and possibly small quantities of lava."

4. Once activity ceases the glacier encroaches on the scene of the eruption and, after many years of quiescence, may largely fill the hollow created by the thawing of the ice.

Nielsen (1936) and Noe-Nygaard (1940) also present evidence to indicate that some subglacial eruptions may have much less spectacular manifestations than that of the Grimsvotn eruption, and be accompanied by less violent but more prolonged thawing and flooding of the glacial streams.

If a major eruption took place in the Tuya-Teslin area through the Cordilleran ice-sheet at any one of its more advanced stages we might expect somewhat different results than prevailed in Iceland in 1934. Ice-dammed lakes are notoriously variable in level wherever they drain across or through smaller bodies of ice, as was the case in Iceland. If, instead, such a lake drains by an overland outlet its level either remains constant or sinks slowly as the outlet channel is eroded. In the Tuya-Teslin area there is abundant evidence that the levels of many ice-dammed 'proglacial' lakes were so maintained and for time enough for the development of strandlines, stream deltas, and outlet channels carved in glacial drift and bedrock (Watson and Mathews, 1944). None of these proglacial lakes, however, appears to have been situated at a center of volcanic activity. Instead we must picture the eruptions taking place in a lake, thawed over the vent and surrounded on all sides by ice, but extending from the glacial floor to the surface. Such a lake may be referred to as an '*intraglacial*' lake.[3] The level of such a lake, like that of a proglacial lake, could not fall below that of any rocky spillway on the downstream course of its drainage. If, too, the waters heated by volcanic activity maintained wide drainage passages through the ice between the intraglacial lake and such a spillway, the lake-level could not rise to an appreciable height above this spillway. Even if the ice-sheet were growing, the level of the lake could be maintained at a constant height as long as sufficient heat were supplied from volcanic sources; but if the ice-sheet were shrinking, from time to time new and lower outlet channels might be created and the intraglacial lake, like the proglacial lake, would fall in stages. In either case, once volcanic activity ceased, the outlet channels might become sealed and the ice might encroach into the lake, to heal in time the scar formed on its surface and perhaps to bury the products of the eruption.

Products of the volcanic activity that had been erupted below lake-level would show the effects of aqueous chilling.

[3] Accounts of lakes in Antarctica surrounded on all sides by ice have been obtained from the Byrd Antarctic Expedition of 1946-47, but it remains doubtful whether they have been developed by thawing of the ice-sheet by volcanic heat.

Lava suffering rapid chilling in this way may give rise to pillows (Anderson 1910), 'foamy brown glass' (Kôto 1916), or breccia (Sampson 1926, Fuller 1931). Pillow lavas, referred to as 'globular basalts', and breccias have been described by Peacock (1926A, 1926B), Nielsen and Noe-Nygaard (1936), and Noe-Nygaard (1940) as the products of subglacial eruptions of Pleistocene and Recent age, although these authors consider that many of the pillows have been formed by the intrusion of magma into water-soaked breccias rather than by extrusion of lava into subglacial bodies of water. Pillows, whether formed in open water, in subglacial lakes, or in water-soaked breccias, have thick shells of clear basic glass (sideromelane) (Peacock and Fuller 1928), characterized by an absence of black opaque minerals that had no opportunity to crystallize in the rapidly chilled lava crusts. The brecciated material consists, not of arcuate shards as in typical subaerial tuffs, but of spherical pellets and shell-like fragments, developed by perlitic and conchoidal fracturing, together with larger masses of basalt commonly in ropy or ellipsoidal forms. The finer fragments are made up largely of sideromelane, its hydration product palagonite, and the less rapidly chilled opaque glass known as tachylite.

A flat-lying flow resting on a persistent horizon of cross-bedded breccia on the Columbia Plateau is pictured by Fuller (1931, 1934) as having originated in the following manner:

"A fluid lava on encountering a local body of water would tend to granulate like molten slag and would thus form a fine breccia which would accumulate to a depth approximately equal to that of the water. The fine breccia would settle until its surface attained an angle of repose which, owing to the roughness of the fragments, would be relatively steep. If the molten cascade continued to pour out into the water, the accumulation of granulated glass would gradually advance like the foreset bedding of a delta. The inclined bedding would be preserved by the thin sheets and the ropy or ellipsoidal masses, which failed to granulate. Except for the possible effects of rising steam, the flow would gradually advance on top of these foreset beds as if on dry land."

The tuyas of the Tuya-Teslin area may thus be conceived as originating partly by subaqueous and partly by subaerial eruption of basic lava through intra-glacial lakes. The first products of the eruption, which would resemble the subglacial breccias and pillow lavas of Iceland, would accumulate in a

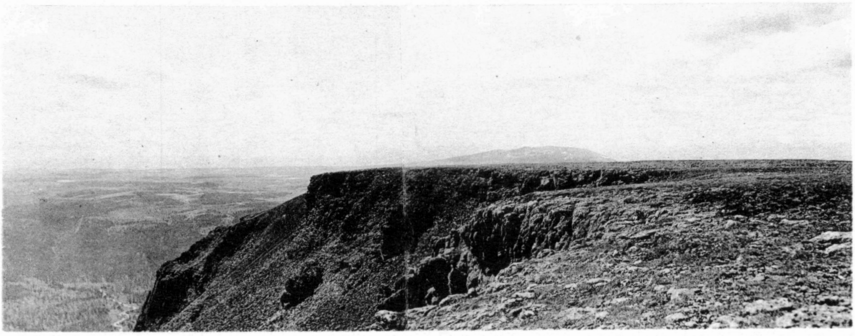

FIG. 1

FIG. 2

PLATE 1.

Fig. 1. South face of Isspah Butte, as seen from the east. Rounded cliffs in the immediate foreground are composed of breccia; angular cliffs beyond, of summit lavas; Kawdy Plateau in the middle distance on the left. (from a photo).

Fig. 2. Truncated cone five miles southeast of Kawdy Mountain as seen from the summit of Kawdy Mountain. (from a photo).

cone or low mound at the scene of activity. The truncated cone five miles southeast of Kawdy Mountain may be of one such center in which the products failed to accumulate to the surface of the lake. Whether the broad dome-shaped summit is an original form or the result of subaqueous wave erosion is problematical. The higher part of Ash Mountain may also be typical of the subglacial or subaqueous stage of eruption. Provided a cone were built above the surface of the water, however, flat-lying flows could have been extruded from the summit and these, on reaching the shores of the lake, would have granulated to form deltas of breccia which would then have been overridden by the advancing flows. If the lake surface sank during the eruption, the lava could have flowed down the front of the breccia delta as far as the new water-level where the process of granulation, delta-building, and slow spread of lava would have been repeated. Lava of somewhat different physical characteristics might give rise to accumulations of pillow lava, such as occur under the bench on the southwestern slope of Ash Mountain, instead of breccia.

The unusual form of the flat-topped volcanoes may thus reflect the unusual circumstances of their formation: the eruption of basic lava under a large ice sheet in which lakes could form and persist with a relatively constant lake level during the course of volcanic activity. The cones and lava sheets of the Tuya formation elsewhere in northern British Columbia must have been built under other circumstances, many perhaps during interglacial periods, or when the ice was so deep that all the eruptions were subglacial or subaqueous. Flat-topped volcanoes are not to be expected in many parts of the world, especially since most Pleistocene and Recent volcanism has taken place at or beyond the limits of extensive ice-sheets. One flat-topped volcano has, however, been reported[4] from the southern Coast Mountains of British Columbia, and four similar flat-topped volcanoes, Burfell, Bláfjall, Sellandafjall, and Herdubreid, occur in northeastern Iceland. Although the origin of these Icelandic 'table mountains' has been attributed by some to block faulting and by others to glacial erosion of extensive sheets of lava and breccia (Van Doorninck 1935), they nevertheless share many of the characteristics of the tuyas of northern British Columbia and may well have been

[4] L. R. Harrison, Vancouver, B. C., personal communication.

formed in the same way. Perhaps confirmation of the hypothesis outlined above may be found in one of these more accessible volcanoes.

References.

Anderson, T.: 1910. *The volcano of Matavanu, in Savaii*, Quart. Jour. Geol. Soc. London, **66**, 621-639.

Fuller, R. E.: 1931. *Aqueous chilling of basaltic lava on the Columbia River Plateau*, Amer. Jour. Sci., 5th ser., **21**, no. 124, 281-300.

————. 1934. *Structural features in the Columbia River lavas of central Washington* (a criticism and reply to a paper by M. G. Hoffman), Jour. Geol., **42**, no. 3, 311-328.

Hanson, G., and McNaughton, D. A.: 1936, *Eagle-McDame area, Cassiar district, British Columbia*, Geol. Surv., Canada, Mem. 194.

Kerr, F. A.: 1926. *Dease Lake area, Cassiar district. B. C.*, Geol. Surv., Canada, Summ. Rept. for 1925, part A, 75-119.

Kôto, B.: 1916. *The great eruption of Sakura-jima in 1914*, Jour. Coll. Sci., Tokyo. Imp. Univ., **38**, art. 3, 1-237.

Nielsen, N.: 1936. *A volcano under an ice-cap, Vatnajokull, Iceland, 1934-36*, Geog. Jour., London, **40**, 6-23.

————, and Noe-Nygaard, A.: 1936. *Om den islandske Palagonitformation's Oprindelse* (with German summary), Geog. Tidssk, K. Dansk. Geog. Selsk., **39**, no. 2, 89-122.

Noe-Nygaard, A.: 1940. *Sub glacial volcanic activity in ancient and recent times—studies in the palagonite system of Iceland, No. 1*, Folia Geographica Danica, **1**, no. 2, K. Dansk. Geog. Selsk.

Peacock, M. A.: 1926A. *The Palagonite formation of Iceland*, Geol. Mag., **63**, 385-399.

————: 1926B. *The geology of Vijey, southwest Iceland: a record of igneous activity in glacial times*, Trans. Roy. Soc. Edinburgh, **54**, 441-465.

————, and Fuller, R. E.: 1928. *Chlorophaeite, sideromelane and palagonite from the Columbia River Plateau*, *Am. Min.*, **13**, 360-382.

Sampson, E.: 1926. Quoted by Pardee, J. T.. and Bryan, K., in *Geology of the Latah formation in relation to the lavas of the Columbia Plateau near Spokane, Washington*, U. S. Geol. Surv., Prof. Paper 140A.

Watson, K. DeP., and Mathews, W. H.: 1944. *The Tuya-Teslin area, northern British Columbia*, B. C. Dept. of Mines, Bull. 19.

Van Doorninck, N. H.: 1935. *Die Enstehung der Schildvulkane und der Vulkanischen Tafelberge Islands*, K. Akad. van Wetens., Amsterdam, *Proc. Sect. of Sci.*, **38**, 77-87.

Department of Mines,
Victoria, B. C.