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GEOLOGY OF PART OF THE NORTHERN CASCADES IN SOUTHERN BRITISH COLUMBIA

K. C. McTaggart and R. M. Thompson[1]

Department of Geology, University of British Columbia, Vancouver, B.C.

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The late Paleozoic(?) Hozameen Group consists of four divisions composed of various proportions of ribbon chert, basic lavas (now greenstones), limestone, and argillite, totalling at least 20 000 ft in thickness. In late Paleozoic or Triassic time, these rocks were metamorphosed to form the Custer Gneiss, a high-grade migmatitic complex of layered gneiss and schist. A second episode of high-grade regional metamorphism in Late Cretaceous time is associated with the emplacement of the Spuzzum Intrusions. This was followed by the Yale Intrusions (mainly foliated granodiorite), deposition of Eocene conglomerate and sandstone, and intrusion of Chilliwack batholithic rocks (mainly tonalite), which are partly of Miocene age. Several periods of deformation, some associated with the orogenies mentioned above, produced fold axes trending northwest, northeast, and northerly. The area contains three main fault zones. One separates the Custer Gneiss from its overlying cover of Hozameen rocks. A second, the Hozameen fault, separates the Hozameen beds from Mesozoic formations to the east and contains the 'serpentine belt'. The third, the Fraser River fault zone, is represented by the Hope and Yale faults.

INTRODUCTION

Location and Access

The area described lies 80 miles east of Vancouver, B.C. It is traversed by the Fraser Canyon highway, by the Hope–Princeton highway, and by a well-travelled secondary road extending from a point just west of Hope southeast to Ross Lake at the International Border (Fig. 1). Logging roads allow easy access to many places that a few years ago were accessible only with great difficulty.

The area is mountainous (Figs. 2, 3), elevations ranging between that of Hope, on the Fraser River at about 150 ft, and Silvertip Mountain at 8500 ft. Most valleys are choked with underbrush or logging debris and contain few outcrops. Ridges above 5500 ft offer the easiest travel and on many of these, rock exposures are plentiful.

Previous Work

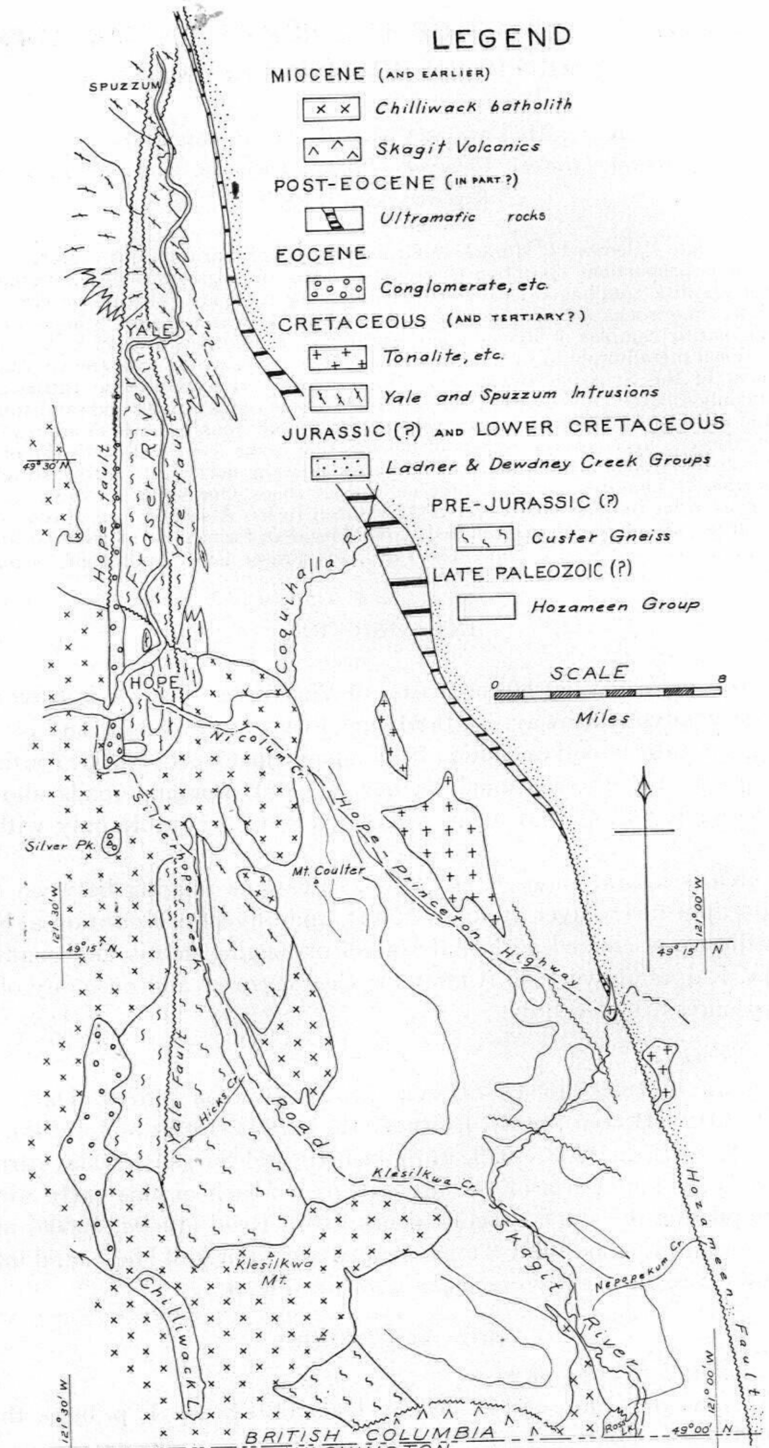
Bauerman in 1859 (1884), Selwyn (1872), Dawson (1879), Daly (1912), Camsell (1912), Bowen (1914), Cairnes (1921, 1923, 1924*a* and 1924*b*), W. E. Snow (field work in 1938, 1939, unpublished) and Sargent (1939) carried on mapping in various parts of the present area. Much of this early work has been compiled in the Hope Sheet (Cairnes 1944). Read (1960*a*, 1960*b*) mapped an area measuring about 6 by 8 miles immediately north of Hope, and information from his work has been incorporated into Fig. 4.

HOZAMEEN GROUP

Distribution and Stratigraphy

The Hozameen Group was named by Daly (1912, vol. 1, p. 500), the type

[1]Deceased, April 15, 1967.
[2]Revision received August 31, 1967.



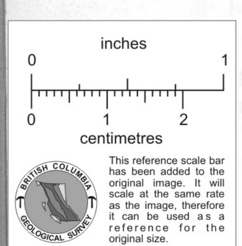


FIG. 1. Generalized geological map of the area around Hope, B.C.

PLATE I

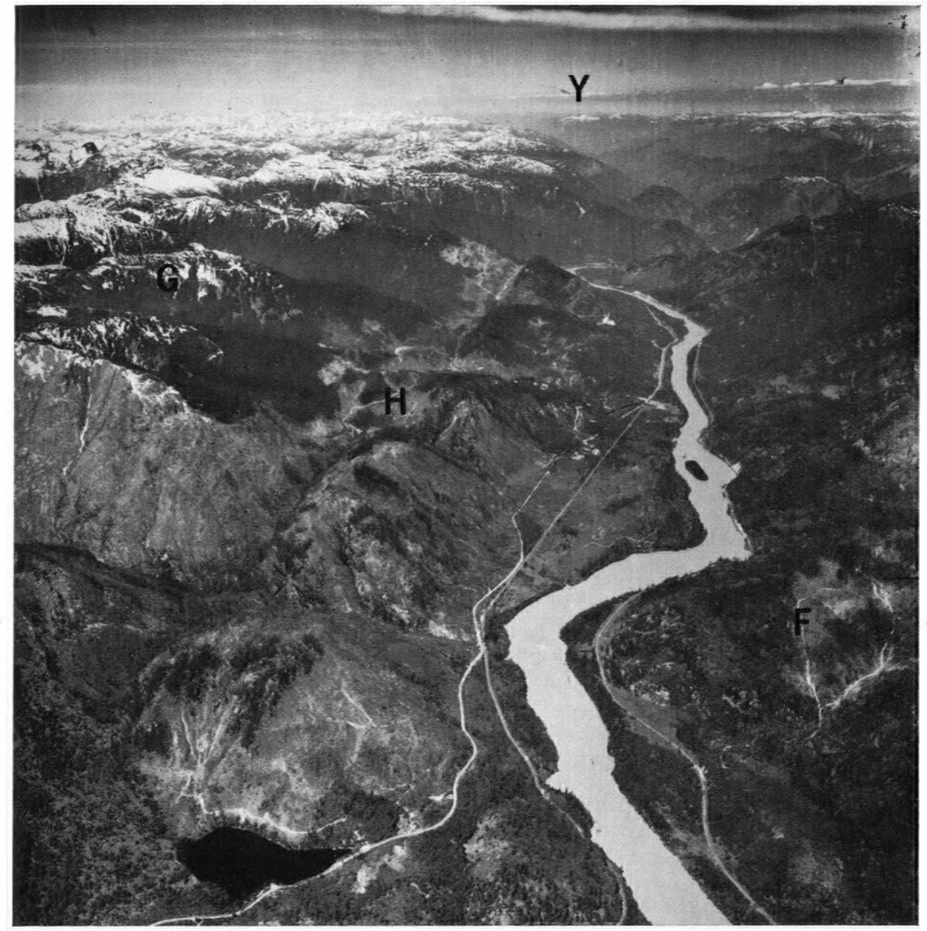


FIG. 2. Aerial view north from Hope, up Fraser River. Yale is on the river, in the middle distance, directly below **Y**. **H** is in one of a series of aligned saddles containing the Hope fault. The Yale fault runs from Yale south along the east side of Fraser River, through **F**. The Giant Nickel mine is just below **G**. The lake in the foreground is 2 miles north of the name "Hope" in Fig. 1. (B.C. Govt. airphoto X153R:2)

PLATE II

FIG. 3. Aerial view southeast from Hope. **HP** is Hope–Princeton highway (see Fig. 1). **S** is Silverhope Creek. **T** is Silver-tip Mtn. **S** is site of 1965 landslide. **M** is Marmot Mtn. **C** is Mt. Coulter. **H** is Hicks Creek. **Y** is Yola Creek. (B.C. Govt. airphoto X202R:2)

locality lying just south of the International Boundary, east of Skagit River (Fig. 5). Camsell (1911) and Cairnes (1921, 1923, 1924*b*) have described the rocks of the group as it occurs in various parts of the Hope Sheet (Cairnes 1944).

The Hozameen Group extends from south of the 49th parallel to the vicinity of Stout (Fig. 4), on the Fraser River. The authors recognize four stratigraphic divisions in this group.

The lowest division is exposed in a relatively small belt east of Marmot Mountain (northeast corner of Fig. 5). It is composed mainly of ribbon chert, but includes limestones locally about 1200 ft thick and several hundred feet of green altered volcanic rock, hereafter referred to as greenstone. Because the belt is faulted and folded, its thickness is uncertain, but it probably exceeds 5000 ft. An overlying division, almost entirely of greenstone but with limestone and chert lenses here and there, is about 2500 ft thick at Marmot Mountain, but appears to thicken towards the south to more than 4000 ft. The third division is almost entirely ribbon chert and argillite. Just west of Marmot Mountain it appears to be about 6000 ft thick and to thicken to about 10 000 ft to the south. The fourth (and highest) division, more than 7000 ft thick, consists of greenstone, chert, argillite, and limestone. Rocks of the Hozameen Group at and north of Hope (Fig. 4) are tentatively assigned to this highest division. Thicknesses cited above are perhaps greater than true thickness because of repetition by folding or faulting.

Lithology

Chert, mostly dark gray but locally almost white, is probably the most abundant of the sedimentary rocks. Most of it is of the 'ribbon' variety, in which $\frac{1}{2}$- to 3-in. layers that pinch and swell irregularly are separated by partings up to $\frac{1}{4}$-in. thick of slate or argillite. In a few places, sedimentary chert breccia and chert sandstone occur within predominantly chert successions. In others, chert is massive and so thick-bedded that bedding cannot be easily found. Thin-sections of chert show the usual microcrystalline aggregate, much of it dirty looking or with sericite flakes, with irregular seams of recrystallized quartz crossing in all directions. Rare spherical bodies of radiating quartz are probably radiolaria.

Limestone is abundant only in the lowest division; about 1200 ft of limestone are exposed on the northeast shoulder of Marmot Mountain and to the northwest on the Hope–Princeton highway. In other places, limestone occurs as isolated beds from 1 ft to 100 ft thick, commonly interbedded with greenstone rather than with chert. Many limestone beds are lenticular, but those on Mount Coulter and Mount Potter seem to be continuous for at least 6 miles. Most of the limestone is light-gray with a few pale buff-weathering dolomitic layers. Four-foot beds of reddish brown fine-grained dolomite are mainly confined to the upper divisions of the group. In thin-section, the average limestone is seen to be equigranular and fine-grained (about 0.1 mm), and most of it appears to have been sheared and recrystallized. One specimen contains poorly preserved oolites.

Dark gray or greenish-gray *argillite* occurs interbedded with ribbon chert and occasionally makes beds up to 50 ft thick. These are especially abundant in the two upper divisions. They do not outcrop as strongly as chert beds and may be more abundant than their scattered exposures suggest.

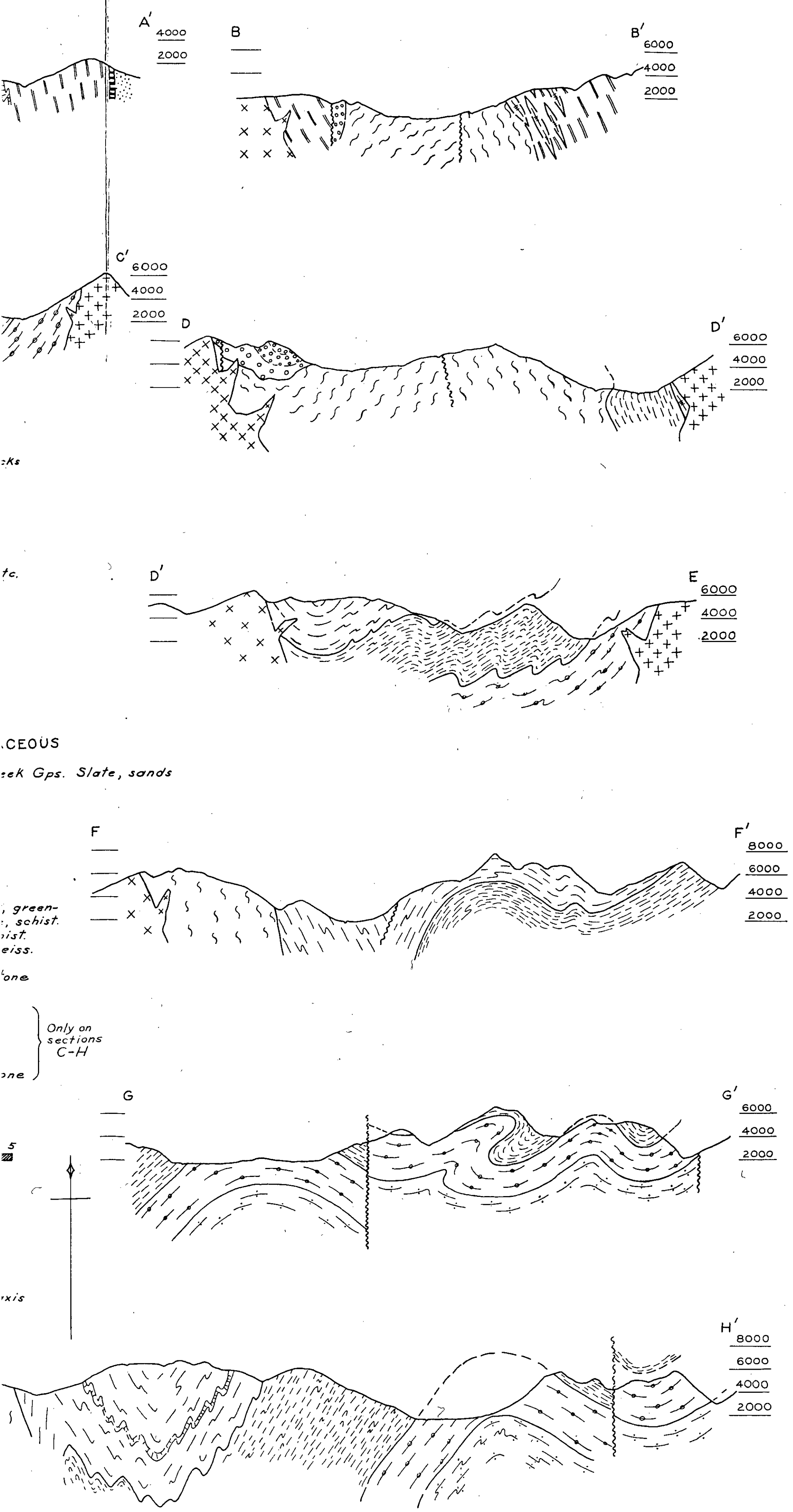
The term *greenstone* here refers to green, weakly metamorphosed volcanic rocks originally mainly basaltic but probably including some spilitic and andesitic varieties. The various greenstone successions of the Hozameen Group cannot be easily distinguished one from another petrographically. Pillow lavas are common in the second and fourth (i.e. highest) divisions. A spherulitic layer was recognized at intervals over a distance of 8 miles near Mount Potter.

All of the greenstones are more or less metamorphosed. Of some 50 specimens examined in thin-sections, none (except possibly some spilitic ones) retains its original mineral assemblage and, in many, shearing has destroyed both original mineral assemblage and volcanic texture. Most of the greenstones are green or greenish gray, massive, aphanitic, closely fractured, and commonly veined by calcite. Locally, phenocrysts of feldspar, zones of calcite amygdules, or vague spherulitic texture provide variety. A few medium-grained greenstones may be feeder dikes. Breccias, with fragments of vesicular and massive lava up to 3 in. across are rare, and fine-grained breccia or coarse tuff is locally not easily distinguished from similar cataclastic rock near faults. Pillows range from 6 in. to 6 ft in diameter, show amygdaloidal dark rims, and, locally, radial fractures.

In about two-thirds of the thin-sections of greenstone examined, intergranular, trachytic, sub-ophitic, porphyritic, or spherulitic textures can be made out. Feldspars are commonly so highly altered that they are recognizable only by their forms, textural relations, or by other indirect evidence. In five specimens for which determinations of composition could be made, they are albite and in three of these, clinopyroxene, apparently augite, is also recognizable. Almost all of the specimens contain pale green actinolitic amphibole, 'zoisite', green or brown chlorite, and calcite that replace pyrogenic minerals or fill microvesicles or fractures. Less common are prehnite, pyrite, and pyrrhotite. P. B. Read (personal communication) identified pumpellyite northeast of Hope. Stilpnomelane was found in greenstone near serpentine of the Hozameen fault east of Spuzzum (Osborne 1966). Some specimens are seen to be highly sheared, with closely spaced micro-faults separating semi-opaque zones and lenses, in some of which vague volcanic textures can be seen. Cairnes (1924*b*, p. 34) suggested, on the basis of a chemical analysis, that the greenstones are derived from somewhat acidic basalts or basic andesites. His analysis shows a high Na_2O-K_2O ratio, suggesting that the rocks may be spilitic, and it is probable that some of the albitic rocks described above are spilites.

Metamorphism

Over large areas, rocks of the Hozameen Group have approached equilibrium in the lowest part of the greenschist facies, or possibly the zeolitic facies. Near the Custer Gneiss, however, the grade is higher, and hornfels and skarn occur at contacts with granitic intrusions.



ɔe; cross-sections of the areas north and southeast of Hope.

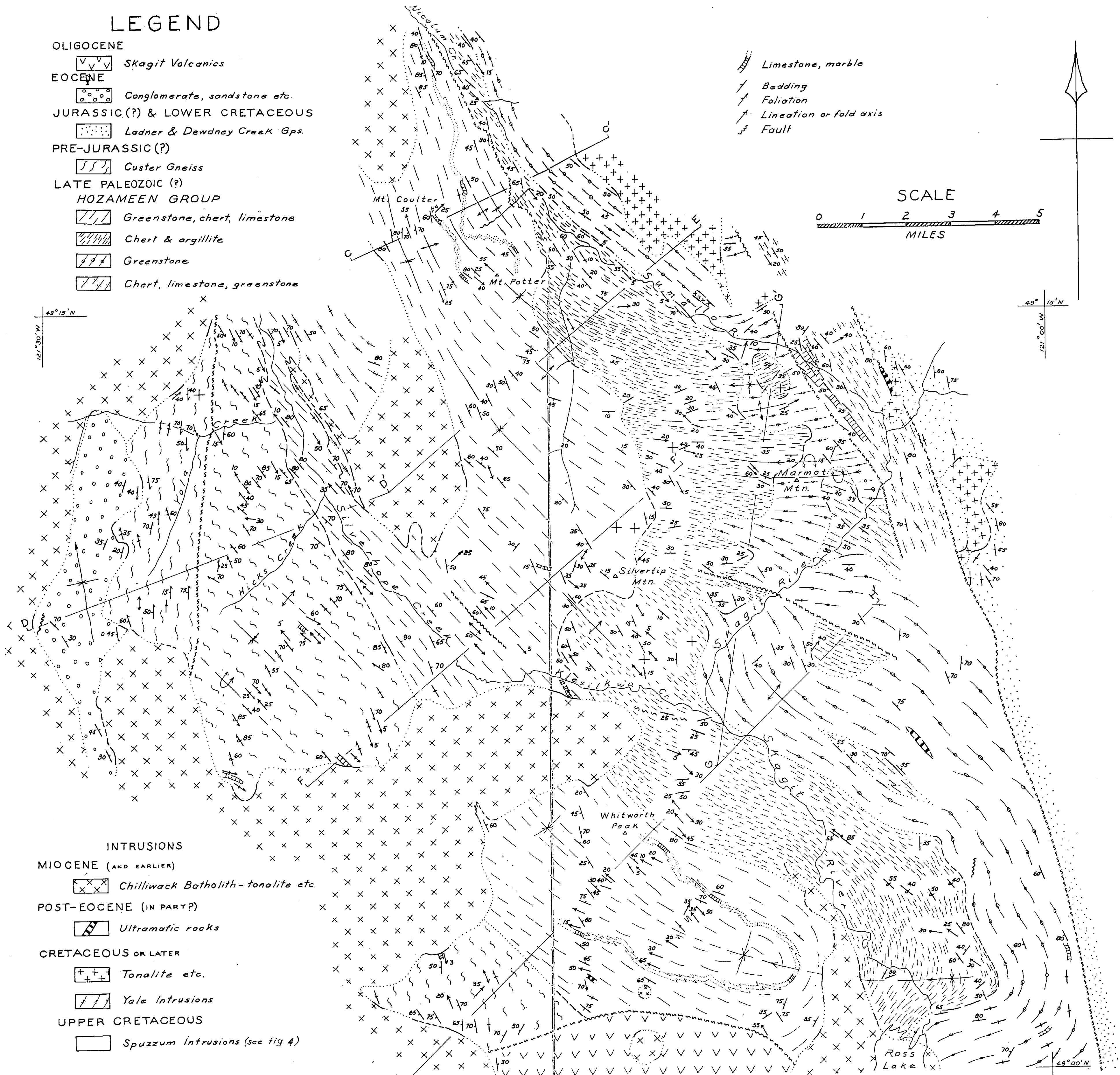


FIG. 5. Geological map of the area southeast of Hope.

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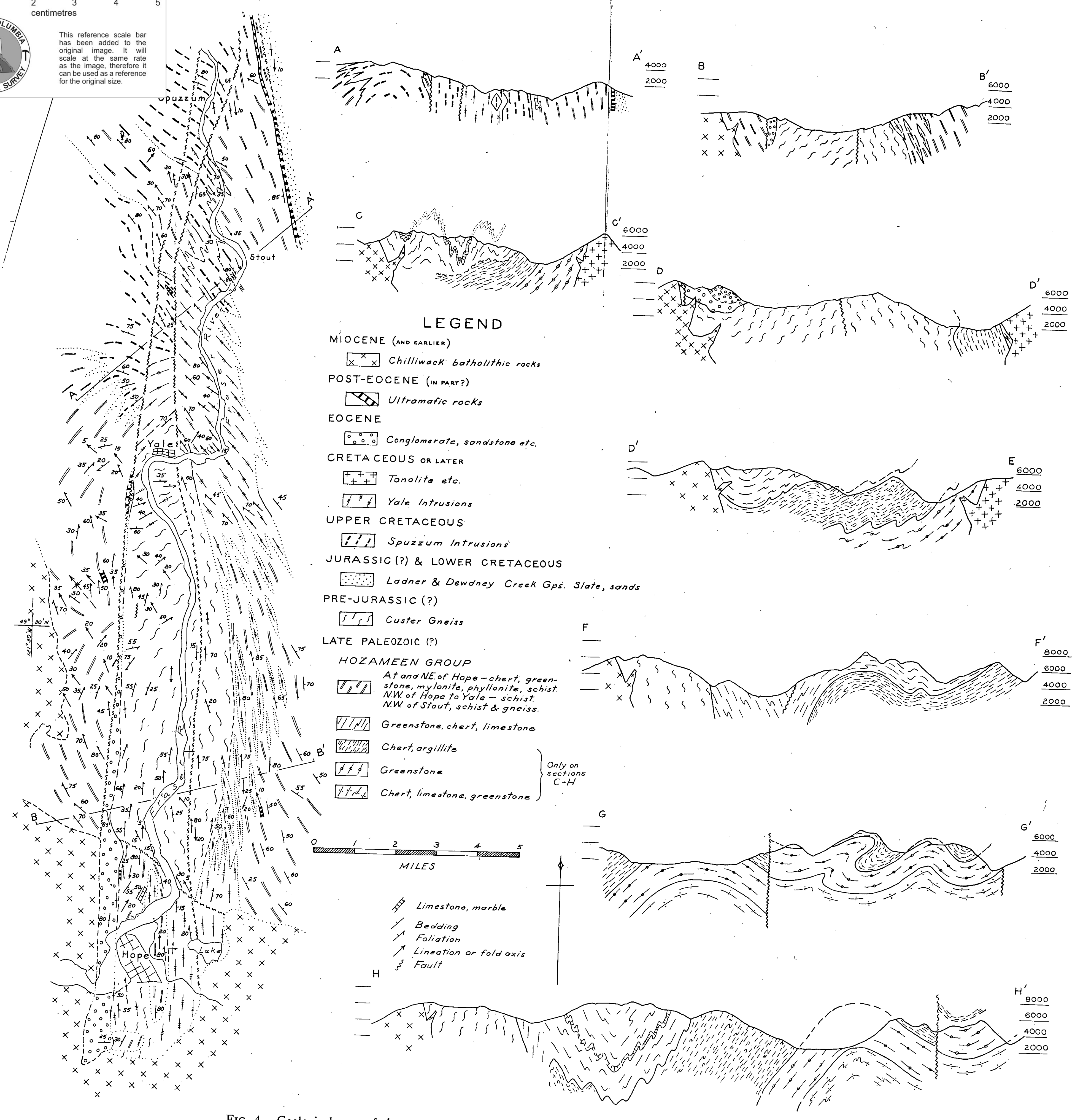

FIG. 4. Geological map of the area north of Hope; cross-sections of the areas north and southeast of Hope.

Along Silverhope Creek (Fig. 5), 100 to 200 ft from the contact with the Custer Gneiss, the rocks of the Hozameen Group show pronounced metamorphic effects. Cherts are changed to fine-grained quartzite in which dark layers outline elongate sheared-out lenticles and attenuated isoclinal folds. In thin-section, such rocks show strong preferred orientation of quartz, a few augen of oligoclase, and rare broken helicitic garnets. Undeformed biotite flakes are clearly later than the main shearing. Pelitic rocks are changed to biotite schist with $\frac{1}{4}$-in. pink garnets and have locally been reduced to fine-grained phyllonites. One section of phyllonite contains broken garnet and kyanite crystals strewn out in the foliation. Greenstones are converted to amphibolites—fine-grained foliates with a silky luster due to sub-parallel actinolite fibers. In thin-section, actinolite-rich layers are seen to alternate with layers of untwinned plagioclase (An_{30}) and original textures are completely destroyed. Still closer to the contact with the Custer Gneiss, the grain size of the Hozameen Group rocks increases, garnets up to $\frac{1}{2}$-in. in diameter appear, and intense contortion of microlayers indicates strong shearing along the foliation. Amphibole in these rocks is pleochroic in deeper colors than in those already described and is commonly sheared and reduced to augen. Plagioclase ranges from about An_{25} to An_{40}, shows both reverse and normal simple zones, and its rare twins have (001) or the rhombic section as composition planes. Minor quartz occurs in curved mosaics of fine-grained crystals showing strong undulatory extinction. Biotite is clearly later than much of the shearing. Chlorite, sericite, and actinolite are apparently related to post-metamorphic shearing and alteration. It seems clear that the grade of metamorphism increases towards the contact with the Custer Gneiss and there reaches that of the middle part of the almandine–amphibolite facies.

At contacts with granitic rocks, ribbon chert has been changed to laminated white sugary quartzite, with mica schist interbeds. Argillite has been converted to hornfels, with biotite, cordierite, and andalusite, and calcareous rocks to marbles containing garnet, vesuvianite, diopside, and magnetite, and, in one place, to the assemblage wollastonite–labradorite–hornblende. Greenstones are recrystallized to hornfels, with hornblende, plagioclase, and garnet and, in many, much biotite has been introduced.

In the area bordering the Hope–Princeton highway at and northwest of Skagit River (northeast corner of Fig. 5) greenstone consists of biotite, actinolite, and anthophyllite, and mosaics of plagioclase granules (An_{30} to An_{45}) pseudomorphous after original feldspar phenocrysts. This metamorphism may be due to minor granitic intrusions in this region or possibly to Upper Cretaceous regional metamorphism (discussed later in this paper).

Structure

Minor structures of the Hozameen Group include lineations, folds, and joints. Most lineations are regular corrugations on bedding surfaces, an inch or less from crest to crest, but some are vague and inconspicuous ridges and streaks, sporadic in their development. Ribbon cherts, structurally highly incompetent, everywhere show irregular open wavy folds or complex contortions and are

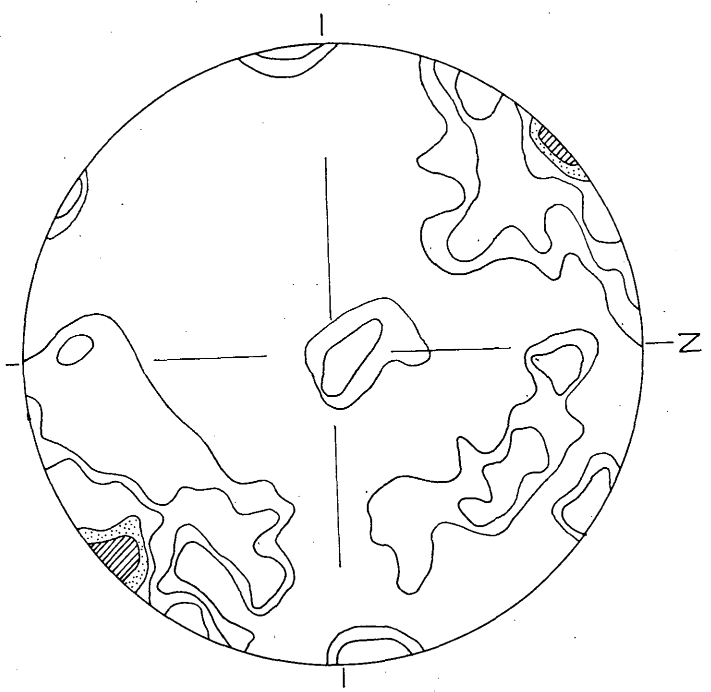

FIG. 6. Axes of small folds from the northeast quarter of Fig. 5, plotted on the lower hemisphere of an equal area net. Contours are: 11%, 8%, 4%, 2%, and 1% per 1% area.

locally broken,—disrupted 'ribbons' forming blocky chert breccia. Consequently, single isolated attitudes cannot be used with confidence in working out structures: of 20 attitudes, 10 are similar and probably representative of the general attitude. Ribbon cherts are especially contorted near contacts with thick massive greenstone units.

The axes of lineations and small folds are shown on Figs. 4 and 5. Overturned to recumbent folds, up to 20 ft in amplitude, many of them isoclinal, striking northwest and plunging gently, mainly northwest, are abundant on Silvertip Mountain and to the west (Fig. 5). Such folds give little information as to the sense of movement, because marker beds cannot be followed for any distance. Most lineations and small folds plunge gently northwest or southeast, but the axes of a few complex folds plunge northeast or southwest (Fig. 6). One northwesterly trending axis was seen to be folded about a northeast axis, but whether this relationship is a common one is not certain.

Greenstones of the Hozameen Group are closely jointed and traversed by small faults at close intervals, probably a consequence of their high competence, and large exposures generally reveal shear zones. Attitudes in greenstone, hard to find, were determined on interbeds of pyroclastic rocks, chert or limestone, or from layers of amygdules.

Upright anticlines and synclines range from broad open folds (section H-H′, Figs. 4, 5) to closely appressed large folds (section C-C′) that approach the isoclinal. Folds appear to tighten towards the northwest. A hypothetical fault is shown on Fig. 5 northeast of Mount Coulter (section C-C′) to account for the marked thinning there of the third division.

The structural relations of the Hozameen Group to the other units will be discussed as these units are considered and a general account of the structural development of the area is given in a later section.

Age

The age of the Hozameen Group is unknown. The only fossils found in it during the present work are some dubious brachiopods from marble at the south end of Sailor Bar tunnel in the Fraser Canyon. The group has been correlated by Cairnes (1924*b*, p. 42) with the Cache Creek Group on lithologic grounds, but it has similarities also to the Triassic Nicola Group.

Its relation to the Chilliwack Group to the southwest is unknown since it is separated from it by the Custer Gneiss and the Chilliwack batholith. The rocks of the Chilliwack Group, including much tuff, lithic sandstone, and fossiliferous limestone, are markedly unlike those of the Hozameen Group, but variations of sedimentary and metamorphic facies could account for many of the differences.

CUSTER GNEISS

Distribution and Lithology

The Custer granite-gneiss (referred to in this paper as the Custer Gneiss) was named by Daly (1912, vol. 1, p. 523). Misch (1952, 1966) referred to this rock unit as the "Skagit Gneiss". In the present area it underlies a belt that extends, with interruptions, from the International Border to Yale, in the Fraser Canyon.

In the area south of Hope, the gneiss is strikingly banded with layers that range in thickness from a fraction of an inch to several feet, and consists, over most of the area, of light and dark, parallel, medium-grained layers alternately rich in plagioclase or rich in biotite and (or) hornblende. Commonly, $\frac{1}{4}$-inch plagioclase augen are scattered sparingly through the rock. Most of the gneiss is migmatitic with bodies of pegmatite that range from layers of single plagioclase augen to irregular pinching and swelling layers averaging 6 in. in thickness, in which wisps of biotite outline large closely packed plagioclase augen. Layers of dark amphibolite, locally with $\frac{1}{2}$-inch red garnets, alternating with white feldspathic layers, are estimated to form 10% of the terrane. Irregular masses of almost massive plagioclase pegmatite and coarse- to medium-grained trondhjemite predominate in areas up to $\frac{1}{3}$ mile across. Foliated gray dikes and sills appear in many places to be venites formed by the softening and mobilization of certain of the gneisses. Vague agmatite of amphibolite fragments in biotite gneiss was seen in a few places. Unlayered but foliated and augened medium- to fine-grained leucogranodiorite dikes and sills are indistinguishable from members of the Yale Intrusions that are described elsewhere. Much less common than the gneisses described above are medium-grained hypersthene–plagioclase–biotite gneiss, rather fine-grained staurolite–kyanite–garnet schist, anthophyllite–talc schist, mylonite, quartzite, marble, and skarn.

TABLE I

Modes of rocks of the Custer Gneiss

Spec. No.	Qtz.	Plag.	Plag. comp.	Biot.	Hb.	Others
1	18	71	An_{38} An_{33}	2	9	
2	15	80	An_{24}	5	—	plag. has $\sim$ 2% Or in antiperthite
3	20	73	An_{29}	2	5	
4	15	85	An_{23}	—	—	plag. is antiperthitic
5	10	90	An_{25}	—	—	
6	—	40	An_{49} (outer zone) An_{42} (inner zone)	—	60	
7	10	85	An_{32}	3	2	
8	13	13	An_{26}	3	51	
9	—	30	An_{75}	—	63	5% garnet and 2% ilmenite (?)
10	8	85	An_{42}	1	1	5% hypersthene
11	20	62	An_{37}	10	—	6% garnet, 1% each of staurolite and kyanite
12	16	76	An_{36}	4	—	3% hypersthene, 1% K-feldspar

NOTES on specimens:
1. Yola Creek, ¼ mile from Silverhope Creek. Thinly ($\frac{3}{16}$ in.) layered gneiss, occasional ¼-in. plagioclase augen concentrated in layers. No. 2 is 2 ft away, stratigraphically.
2. Same locality as No. 1. Augen gneiss (sheared pegmatite). ¼ to ¾ in. plagioclase augen set in wavy biotitic matrix.
3. 1½ miles north of Klesilkwa Mountain (see Fig. 1). Thinly (⅛ in.) layered gneiss.
4. Same locality as No. 3. Trondhjemite, crystals to ½-in.
5. 4 miles northeast of north end of Chilliwack Lake (see Fig. 1). White pegmatite, crystals to ¾ in.
6. 1 mile northeast of locality 5. Layered, medium-grained amphibolite, dark part.
7. Same locality as No. 6. Light layer in amphibolite, ½ in. from No. 6.
8. 4 miles east of south end of Chilliwack Lake. Fine-grained amphibolite.
9. Same locality as No. 8. Coarse isotropic garnet amphibolite.
10. Same locality as Nos. 8 and 9. Dark, medium-grained weakly foliated rock, boudinage.
11. 1 mile north of Nos. 8 to 10. Rather fine-grained, weakly foliated schist.
12. 6 miles east of the south end of Chilliwack Lake. Medium-grained, dark, weakly foliated rock.

In the Fraser Valley between Hope and Yale (Fig. 4), exposures of Custer Gneiss are strikingly white, shattered, and crumbling. The whitened look is due to bleaching and alteration of the mafic minerals and to coatings of laumontite on closely spaced joints and faults.

Petrology

Although modes are of limited significance because most of the rocks are heterogeneous, the estimates on Table I give a general idea of the composition of various types.

Amphibolites include the following assemblages: diopside–plagioclase, diopside–hornblende–plagioclase and hornblende–garnet–biotite–plagioclase.

In several places, marble and skarn, and in two places, boudins of quartzite clearly derived from ribbon chert are interlayered with feldspathic gneiss. A specimen of meta-chert, from near amphibolite (No. 8, Table I), is 95% quartz with strong lattice orientation, scattered plagioclase (An_{32}), and minor biotite.

In thin-section, some *plagioclase* shows weak zoning, which is reversed in several specimens of amphibolite. (Composition was determined from sections normal to bisectrices or by the standard U-stage methods.) Little-twinned plagioclase in 5 pegmatites and trondhjemites from the southern part of the area has a composition determined as very close to An_{23}. In biotite–hornblende gneiss its composition ranges between An_{30} and An_{40} and in amphibolite from An_{26} to An_{75}. Specimens from layers only a fraction of an inch apart (6 and 7, Table I) show marked difference in plagioclase composition, but other adjacent ¼-inch laminae, alternately mafic-rich and mafic-poor, contain identical plagioclase. Porphyroblastic plagioclase augen in gneiss (1, Table I), amounting to about 2% of the rock, are An_{33}, whereas fine-grained plagioclase of the body of the same rock averages An_{38} in composition. Gneiss and adjacent pegmatite (1 and 2, Table I) show markedly different plagioclase compositions. Plagioclase from pegmatite is commonly, but not invariably, antiperthite, with scattered blebs of K-feldspar, bounded by (001) and (010) planes of the host, but irregularly bounded in the a-direction of the host. *K-feldspar* is uncommon except in antiperthite; where it does appear, as in some pegmatites, it has the appearance of being introduced, or recrystallized, after shearing that produced augen. *Quartz* occurs commonly as aggregates of elongate grains with undulatory extinction, which curve around plagioclase augen and show strong preferred orientation. *Biotite* is mainly fine grained and interstitial. In many specimens it is only slightly deformed or not deformed at all, and some has clearly crystallized after the deformation that produced augen of plagioclase. Color and pleochroism of *hornblende* range from strong to pale and pale types seem to be associated with alterations that have produced chlorite, sericite, epidote, prehnite, and laumontite. Slightly manganiferous almandine *garnets* are markedly poikiloblastic, with, in some, straight trains of inclusions lying at various angles to foliation.

Structure

Minor structures include lineations, mostly widely spaced, straight corrugations and small folds, the axes of which are shown on Figs. 4 and 5. Axial planes are generally parallel to the prevailing foliation and where foliation is near the horizontal minor folds are recumbent. In some places, however, foliation itself is disposed in open folds. Most small folds plunge gently and are parallel to similar folds in the Hozameen Group. Pegmatite boudins, 6 in. thick, are separated by about a foot, and masses of clear quartz lie between them. Elsewhere, meta-chert borders amphibolite boudins. Pervasive shearing, with the development of augen and accompanying micro-brecciation and mylonitization, has affected much of the Custer Gneiss and the immediately adjacent Hozameen rocks. Shearing was especially strong near Silverhope Creek (Cairnes 1924*a*, p. 54A) and northeast of Hope. The closely spaced fractures and faults along Fraser Valley north of Hope have already been described.

North of Hope, the Custer Gneiss and adjacent sedimentary, metamorphic, and igneous rocks outline a crude, northwesterly plunging antiform. This structure is the product of several episodes of folding and faulting. The Custer

Gneiss, both north and south of Hope, is divided (Fig. 1) into eastern and western blocks by the Yale fault (described in a later section). The eastern fault block, at Hicks Creek (Fig. 5), is considered to be made up of a series of folds, nearly upright and isoclinal, striking northwesterly and of very shallow plunge. These structures are suggested by the general distribution of attitudes and rock types, but in the absence of markers cannot be considered proved.

The western fault block, north of Hope, appears to consist of a broad arch, plunging northwest, that is superimposed on the small isoclinal, overturned to recumbent folds already mentioned. Northerly strikes near Fraser River are considered to be due largely to drag and crumpling near major north-trending faults.

The contact between Custer Gneiss and rocks of the highest division of the Hozameen Group has already been described (under the heading "Meta-morphism"). Chert, greenstone, limestone, and locally phyllonite of the Hozameen Group are succeeded over a distance of only a few hundred feet by garnet- and hornblende-bearing schists and by migmatitic gneiss. The rocks within the transitional zone, although highly sheared and deformed, contain no obvious and distinct fault surface. It appears that differential movement between the two rock units has been accommodated by pervasive shearing and recrystallization rather than by movement on discrete fault surfaces. The contact very gradually cuts across the layering of both Custer and Hozameen rocks along Silverhope Valley (Fig. 5), the contact trending northerly but the foliation and layering northwesterly. Over a distance of 6½ miles the contact encroaches about 1 mile across the strike of the rocks. This displacement cannot be due to isoclinal folding of the contact zone because fold axes and lineations plunge only gently and detailed mapping shows the contact to be steep.

Origin

The Custer Gneiss was probably formed by regional metamorphism and migmatization of Hozameen strata. The gneiss contact is believed to mark a migmatite front, the limit of injection, replacement, and recrystallization of earlier formed metamorphic rocks by trondhjemite and pegmatite. This conclusion is in general agreement with that reached by Misch (1952, 1966) and is opposed to that of Daly (1912, p. 526) and Cairnes (1924*a*, p. 54A), who considered that the Custer Gneiss was formed from a granodiorite batholith by a kind of metamorphic differentiation during intense shearing.

During early regional metamorphism, rocks of the Hozameen Group were more or less isochemically changed to phyllite, schist, marble, and quartzite, representatives of which are found now mainly at the margins of the gneiss but occasionally as relicts within the area of the gneiss (*see* Misch 1966, Pl. 7-1). The metamorphic front was nearly but not quite parallel to stratigraphic layers, producing the metamorphic contact along Silverhope Creek that cuts gradually across the bedding. The metamorphic environment corresponded over large areas to that of the almandine amphibolite facies and locally may have reached conditions of the hornblende granulite subfacies.

Migmatization followed and probably overlapped the period of isochemical

metamorphism with feldspathization, recrystallization, and the formation of pegmatite and medium-grained trondhjemite. The migmatite front reached only into the high-grade zones of the metamorphosed Hozameen rocks and closely paralleled the earlier metamorphic front. The apparent constancy of plagioclase composition in the pegmatite of the migmatites contrasts with the obvious variation in composition of plagioclase in associated gneiss (Table I). This suggests to the authors imperfect equilibrium between migmatizing agents and metamorphic rocks and that possibly these agents were watery magmas with limited powers of permeation and replacement rather than supercritical fluids or very dilute solutions (Orville 1963, p. 234) or clouds of ions. The pegmatite parts (modes 2, 4, and 5 of Table I) of the migmatites, composed of about 80% An_{23} that is weakly antiperthitic, and 20% quartz, are far from the compositions of first-formed melts in the system An-Ab-Or-SiO_2 (Winkler 1965), which, as An increases, become increasingly rich in Or. The effect of increasing P_{H_2O} is to shift first-formed liquids towards albite, countering the effect of increasing An, but even with no An, at 10 kilobars H_2O pressure (Luth *et al.* 1964) the first liquid is poorer in plagioclase than the rocks under consideration. It seems probable, therefore, that the migmatitic magmas are not initial liquids but were formed by prolonged melting of non-eutectic sodic plagioclase-rich and quartz-poor rocks (perhaps the spilitic(?) greenstones of the Hozameen Group) so that the melts produced, having left the boundary curves, contained considerable excess plagioclase when they were emplaced in the overlying metamorphic rocks.

As the gneisses deformed during metamorphism they at first recrystallized, but at a later stage cataclasis dominated, and with successive deformations the pervasive augen structure developed. Undeformed fine-grained biotite in the gneisses and marginal rocks was probably formed either after the main metamorphism and deformation but while the rocks were still hot or possibly during a later episode of metamorphism.

The migmatite front was an abrupt one, separating competent coarse gneiss that lacked surfaces of easy slip from incompetent schist, phyllite, and Hozameen beds. During and after metamorphism this contact was a zone where movement was concentrated as the incompetent Hozameen cover accommodated to and reacted with the migmatite below. This zone became one of injection, especially northeast of Hope (Fig. 4), where sills of the Yale Intrusions are concentrated.

The origin of hypersthene of several scattered occurrences within an area of at least 2 miles across (modes 10 and 12, Table I) is not clear. In other parts of the world, metamorphic hypersthene seems to be restricted either to high-grade contact metamorphism or to extremely high grades of regional metamorphism (granulite facies). Contact action seems unlikely in view of the distance, more than 1 mile, to the nearest known sizeable intrusion and the absence of contact rocks of other types. About 20 miles southeast of these occurrences, Misch (1966, p. 133) found hypersthene-bearing gneiss at the eastern margin of the Custer (Skagit) Gneiss. He considers it to be a tectonic lens of basement rock, apparently metamorphosed in pre-Devonian time, long before the Custer (Skagit) metamorphism. Foliated dioritic rocks possibly resembling certain of Misch's basement rocks are found near the hypersthene-bearing rocks of the present area and the whole assemblage might be construed as basement gneiss. These hypersthene-bearing rocks, however, show well-developed boudinage, are closely interlayered with the usual abundant pegmatites, contain hypersthene that seems to be in mineralogical and textural equilibrium, and appear to have been formed during the Custer metamorphism. It seems probable, therefore, that during the Custer (Skagit) regional metamorphism, conditions of the hornblende-granulite facies were locally attained.

The effect of Late Cretaceous metamorphism on the Custer Gneiss is not known. The quartz-feldspar-rich assemblage of the gneiss would probably not be sensitive to further regional metamorphism, but the late development of biotite mentioned earlier is perhaps such an effect. The shattered nature of the gneiss north of Hope is perhaps partly due to breaking of the competent gneiss during the formation and folding of incompetent pelitic schists to the west.

Correlation and Age

It seems reasonable to assume that the Custer Gneiss extends under large areas of Hozameen and other rocks forming a wide-spread basement complex. Its general resemblance to the Shuswap Complex to the east has been noticed by many.

The age of the development of the Custer Gneiss is unknown. It is younger than the Hozameen Group and older than Eocene beds, which rest unconformably on it. Conglomerates of the Dewdney Creek strata to the east do not seem to contain pebbles of the gneiss. Misch (1966, p. 113) concluded that the "Skagit metamorphism is likely to be latest Permian (to earliest Mesozoic?), or older", and (p. 103) "is pre-Jurassic and probably pre-Mesozoic".

LADNER AND DEWDNEY CREEK GROUPS

The Ladner and Dewdney Creek Groups, lying east of the Hozameen fault (Fig. 1), were not studied during the present work. They have been described by Cairnes (1924*b*) and Rice (1947) and are presently being examined by Coates (1967).

They consist of pelites, lithic arenites, and conglomerates totalling several thousands of feet in thickness and include both marine and terrestrial types. They are considered to be Late Jurassic(?) and Early Cretaceous in age.

SPUZZUM INTRUSIONS

Spuzzum tonalite and diorite underlie much of the mapped area north and south of the village of Spuzzum in the Fraser River canyon (Fig. 4). These rocks have previously been designated Custer granite-gneiss (Cairnes 1944), but the present authors consider them to be younger than and not related to the Custer Gneiss. The rocks have been described by Morris (1955), who studied a highway section a few miles north of the present area.

The common rock type is a striking coarse-grained biotite–hornblende tonalite, generally but not invariably gneissoid. It is made up of black hornblende and less brown mica, in crystals up to 10 mm in greatest dimension, showing generally a pronounced parallelism, set in a strongly contrasting white matrix of plagioclase and quartz. Hornblende and biotite make up about 25% of the rock. Quartz ranges from about 3 to 15%, and plagioclase makes up the balance except for accessory apatite, sphene, magnetite, and sporadic epidote. In 14 thin-sections, only traces of K-feldspar were seen except for rectangular antiperthitic patches in plagioclase. Plagioclase ranges in composition from An_{28} to An_{42} and in 7 specimens is close to An_{32}. It is weakly zoned or unzoned. Medium-grained diorite in which hornblende approaches 50% of the rock is fairly common and hornblendite is seen occasionally.

In northern exposures and especially just north of the mapped area, at the China Bar highway tunnel, pegmatites and aplites are spectacularly abundant. Pegmatites are of simple composition: quartz, plagioclase (An_{15}), biotite, and muscovite. Morris (1955) distinguished early pegmatites with irregular, gradational borders, probably metasomatic, and late pegmatites, zoned, showing dilation offset, probably magmatic or hydrothermal.

The tonalites, commonly gneissoid, change texturally from west to east. West of the Hope fault, the rocks show little cataclasis, and a strong foliation is probably due to magmatic flow or metamorphic recrystallization. Between the Hope and Yale faults, the foliation is partly due to cataclasis, whereas to the east of the Yale fault the rock, foliated in the same northwesterly direction, is, in most places, strongly sheared with interstitial quartz smeared out into wavy mosaics and showing a strong preferred orientation, feldspars partly reduced to augen, and mafic minerals bent or broken. The north-striking Hope and Yale faults apparently have acted as barriers to the propagation of northwest shearing, restricting it largely to the eastern belt. In a similar way, the metamorphic rocks at Stout, 3 miles to the south, include much mylonite, but to the northwest, high-grade schists and gneisses show relatively little sign of cataclasis.

Spuzzum tonalite shows a gradational and conformable contact with metamorphic rocks of the Hozameen Group in highway cuts southwest of Stout. Near the contact, structures resembling the plunging wrinkles of schist and gneiss are preserved in the tonalite. Venites, foliated parallel to their walls in some places but in others with foliation at an angle to their walls and parallel to the regional northwest foliation, cut across the gneissoid structure of the tonalite. Breccias are cemented by foliated venitic tonalite. Inclusions of schist, gneiss, and amphibolite, with foliation parallel to the foliation of the enclosing tonalite are common. These observations suggest that either the tonalite formed by the fusion of Hozameen rocks, which near Stout are rich in amphibolite and limestone, or that the Spuzzum tonalite was formed at least partly by the metasomatism of the country rocks.

High-grade metamorphism of a belt of Hozameen rocks extending northwestward from Stout and also of a 10-mile-long belt lying to the south, 2 miles or so west of Fraser River, is believed to have been contemporaneous with the development of the Spuzzum tonalite. This metamorphism is described in the following section.

Two miles southwest of Stout, tonalite is cut by foliated Yale granodiorite dikes. These become abundant southwards towards Yale and contain many inclusions, from fist- to barn-size, of dark tonalite. Foliation in the younger Yale Intrusions, mainly cataclastic, is generally parallel to that of the tonalite and gneiss to the north. Many of the inclusions of tonalite in foliated granodiorite are massive and it appears that they do not accept a foliation as readily as the more siliceous and less mafic granodiorite.

Potassium-argon age determinations of biotite and hornblende from a specimen of tonalite by W. H. White and his associates are: biotite—76 ± 3 m.y., hornblende—76 ± 4 m.y. (late Late Cretaceous), and this age is, in the absence of more compelling information, tentatively accepted for the Spuzzum tonalite and for its associated metamorphism.

The Spuzzum tonalite resembles in its petrography, structural relations, associated metamorphism, and age, the Black Peak quartz diorite of northern Washington (Adams 1964; Misch 1966).

METAMORPHIC ROCKS NORTHWEST OF HOPE AND NORTHWEST OF STOUT

A belt of metamorphic rocks lies west of the Hope fault and extends from the vicinity of Hope as far north as Yale (Fig. 4). To the north, a second belt extends northwest from Stout. The rocks of the first belt were included in the late Paleozoic Chilliwack Group by Cairnes (1944). The present writers have found no evidence for such a correlation and have tentatively included them in the Hozameen Group.

The first belt, the southern half of which was examined and described by Read (1960*a*) consists mainly of pelitic schists. The grade of metamorphism, in general, increases to the west. In some places, near the Hope fault, pelites are garnet–biotite schist but the greatest part of the belt consists of kyanite–staurolite–garnet–biotite schist typical of the staurolite zone of Barrovian regional metamorphism. In a re-entrant in the intrusive contact 6 miles northwest of Hope (Read 1960*a*, p. 36), pelitic schists contain sillimanite, staurolite is unstable, and conditions of the sillimanite zone appear to have been reached. Volcanic rocks are not common and are represented by amphibolites, some of them garnetiferous. Thin scapolite–diopside layers probably represent limy beds. Rare breccias, with laminated sedimentary fragments up to 8 in. across, seem little deformed though of high metamorphic grade. Aplite and granodiorite sills of unknown affinities, and dikes, with boudins and foliated, are recrystallized and commonly charged with euhedral pink garnets.

Pseudomorphs after andalusite, composed of staurolite, garnet, muscovite, and rarely kyanite, near the western edge of the belt, are considered by Read (1960*a*) to indicate superposition of regional metamorphism on an earlier contact metamorphism. He described chlorite and muscovite porphyroblasts and occasional fibrolite, which are developed in a zone about 1000 yards wide that parallels the intrusive contact to the west, an effect superimposed on the regional metamorphism.

The belt that extends northwest from Stout, surrounded and interrupted by Spuzzum tonalite, was probably, before erosion, continuous with the southern belt. At Fraser River, garnetiferous quartzite, biotite schist, amphibolite, mylonite, and marble are the main rock types, but to the northwest, west of the Hope fault, the metamorphic grade increases and the rocks include coarse garnet–biotite schist, granitoid gneiss, sillimanite–garnet schist, and coarse amphibolite.

In most places in the southern belt, foliation and bedding are parallel and are disposed in open northwesterly plunging folds. In others, however, one sees overturned and recumbent folds, and foliation is itself folded and metamorphic biotite strikingly crumpled. All fold axes seen, however, plunge northwesterly, and repeated folding has apparently been in a nearly constant direction.

In the northern belt, lineations and small folds plunge southeast at Fraser River, and schists disappear in this direction beneath relatively unmetamorphosed Hozameen beds. At the Hope fault, they plunge northwest.

Read (1960*a*, p. 69) concluded that the metamorphism is not directly related to the contact with the Chilliwack tonalite, pointing out that the sillimanite isograd does not follow the contact but is truncated by it, and that the main effects of the tonalite are a local coarsening of grain and the development of chlorite and muscovite with some fibrolite. The facts that the metamorphic grade at a point midway in the belt locally decreases toward the contact and that the Chilliwack batholith has, to the south, contact effects rather than regional ones support Read's conclusion. He (p. 73) suggested that the metamorphism was related to synkinematic intrusions lying to the west. The present writers concur, and, in view of the close relation of the Spuzzum tonalite and the presence of unusual garnet schists in both belts, believe that all of these regionally metamorphosed rocks and the Spuzzum Intrusions belong to the same episode of orogeny.

The history of these metamorphic rocks is perhaps as follows.

1. After the formation of the Custer Gneiss, those Hozameen rocks now lying immediately west of the Hope fault, southwest of Yale, formed the western part of a non-migmatitic cover overlying the gneiss, and were probably continuous with Hozameen rocks east of Fraser River and at Hope. These rocks were subjected to local contact metamorphism, or possibly to early low pressure conditions of the regional metamorphism that followed, with the development of andalusite.
2. Regional metamorphism, contemporaneous with and locally associated with the Spuzzum Intrusions produced in Late Cretaceous time (Table II) a metamorphic terrane ranging in grade up to the sillimanite zone, being especially high grade where downfolded into and surrounded by Spuzzum tonalite, northwest of Stout.
3. Faulting and shearing (mainly early Tertiary) were followed by emplacement of the Chilliwack tonalite to the west; the foliates were further deformed, and muscovite, chlorite, and fibrolite were developed in a zone parallel to the contact.

The occurrence of staurolite–kyanite–garnet schist in Custer Gneiss, south

TABLE II

Summary of geological history

Approx. time B.P. (m.y.)	Period or Epoch	Unit deposited or emplaced	Tectonic activity
			Late faulting, Fraser River zone.
18	Miocene	Skagit Volcanics Chilliwack batholith Hell's Gate Intrusions	Mild deformation (6)*
35			Folding (5) along northerly trending axes; renewed faulting on Fraser River zone; shearing of Spuzzum and Yale Intrusions
	Eocene	Eocene conglomerate, sandstone	Graben(?) along Fraser zone
70			Development of Fraser River fault zone
	Late Cretaceous		Hozameen fault blocked to NW by intrusions beyond map-area (see Fig. 5)
		Yale Intrusions	
76		Spuzzum Intrusions	Intrusion, metamorphism, and folding (4) on northwest axes
			Hozameen fault and associated deformation (3)
	'Mid-Cretaceous'		Folding (2) and thrusting on north-east axes
	Early Cretaceous	Pasayten Group	
		Dewdney Creek Gp.	
135	Jurassic(?)	Ladner Group	
	Pre-Jurassic	Custer Gneiss	Regional metamorphism and migmatization of Hozameen Group; folding (1) along northwest axes
	Late Paleozoic(?)	Hozameen Group	Subsiding eugeosyncline
	Pre-Devonian	Basement Complex†	High-grade regional metamorphism

*The numbers in parentheses refer to deformations listed under the heading "Folding".
†Not in present area.

of Hicks Creek (Fig. 5), suggests that perhaps the extensive tracts of similar schist north of Hope could be related to the Custer Gneiss in their development. The best evidence at hand, however, suggests that the Custer Gneiss is pre-Jurassic, whereas the Spuzzum tonalite and its associated metamorphic rocks are late Late Cretaceous in age. Furthermore, the facts that metamorphic grade in the schists northwest of Hope apparently increases away from the Custer Gneiss (Read 1960*a*) and that schists similar to these are found 30 miles to the north in the Ashcroft area where they are related (Hollister 1966) to quartz diorite of the Coast Intrusions where gneisses are not found, suggest that two

episodes of regional metamorphism occurred. It may be that late biotite in certain of the Custer gneisses and in nearby Hozameen rocks is due to this second metamorphism.

YALE INTRUSIONS

The Yale Intrusions, consisting mainly of sills but including composite masses each several square miles in area, occur sporadically in a southerly trending belt along Fraser and Silverhope valleys. Cairnes (1944) included them with Custer granite-gneiss, but since most of them are lithologically distinct, and clearly of younger age, the present writers have mapped them separately.

The Yale Intrusions show great variety, some of which is due to variation in original composition or texture, but much of which is due to various degrees of shearing and alteration.

For about 3 miles north of Yale, along Fraser River, the rocks are pale gray to white, sheared granodiorite and tonalite, commonly with feldspar augen that enclose abundant angular inclusions of relatively unfoliated Spuzzum tonalite and of Custer Gneiss. These intrusions are of many varieties, of which medium-grained, foliated biotite granodiorite is the most common. Other types are rather fine-grained, sheared and unsheared oligoclase porphyry, vaguely foliated aplitic granite, and gray sheared hornblende granodiorite and tonalite.

Several of these types occur as narrow dikes and sills within the metamorphosed Hozameen rocks near Stout (Fig. 4), but medium-grained granodiorite occurs also as foliated plutons hundreds of yards wide just to the south. South of Yale, west of the Yale fault, the intrusions are bleached and altered as well as sheared, and are pale gray, with vague chloritized mafic minerals marking the foliation. East of Fraser River, east of the Custer Gneiss between Hope and Yale, the Yale Intrusions form sills from a few feet to more than hundreds of feet thick, invariably highly sheared, and with strong foliation. In thin-section, they show a great variety of cataclastic textures (Read 1960*a*).

To the south, east of Silverhope Creek, a lenticular pluton about 8 miles long, heterogeneous and strongly foliated, includes many of the varieties described above. A coarse-grained granodiorite gneiss along its western margin consists of microcline phenocrysts, now $\frac{1}{2}$-inch-long rhomboid augen, set in a matrix of quartz and complexly zoned plagioclase. Sills and irregular masses of foliated pale gray to white granodiorite gneiss intrude the Custer Gneiss just west of Silverhope Creek.

In thin-section, all degrees of cataclasis are seen. Some rocks are mildly sheared and show only mortar structure, but others have reached a stage in which plagioclase porphyroclasts, fatly lenticular to strikingly spherical, are surrounded by a wavy mosaic of elongated quartz and feldspar. Some approach true mylonites. Such evidences of shearing, along with other textural and mineralogical features, are used as major criteria in assigning these rocks to this unit.

There is such a variety of rock types within the group that modes are of little value. The most common rock is a granodiorite, with 5 to 10% orthoclase, 20% quartz, 5% biotite, and much of the remainder zoned plagioclase ranging in composition from about An_{30} to An_{20}. In some places, K-feldspar approaches 50% of the rock.

Where dikes of the Yale Intrusions cut across older foliated rocks, the foliation in the dikes is commonly parallel to the foliation or layering of the adjacent rocks rather than to the dike walls. A parallel, though much less prominent foliation is found in the Hell's Gate Intrusion ($2\frac{1}{2}$ miles north of the area shown in Fig. 4), which belongs to the group of youngest intrusions (35 m.y., Baadsgaard *et al.* 1961) in the region. Thus, rocks of five geological units of widely ranging age—Hozameen Group, Custer Gneiss, Spuzzum tonalite, Yale Intrusions, and Hell's Gate Intrusions—show parallel foliation. It appears that the structures of the Custer Gneiss (and of the Hozameen Group from which it was derived) imparted a strong and enduring structural grain to this part of the crust. Subsequent foliation—produced in the tonalite partly as flow and partly as cataclastic structure, and in the Yale and Hell's Gate Intrusions mainly by cataclasis of crystallized rocks—was strongly controlled by this pre-existing structural grain.

The Yale Intrusions intrude the Hozameen Group, the Custer Gneiss, and the Spuzzum tonalite. They intrude rocks lying unconformably beneath Eocene sedimentary rocks and are intruded by young batholithic rocks south and east of Hope. They have been emplaced in abundance at and near the contact between the strata of the Hozameen Group and the Custer Gneiss, and have been there subjected to intense shearing. Some of the Yale Intrusions resemble the trondhjemites that form part of the Custer Gneiss; others are not easily distinguished in the Hell's Gate granodiorite (Morris 1955) a few miles to the north of the present area.

The Yale Intrusions are younger than the Spuzzum tonalite and older than Eocene sedimentary rocks, and are therefore latest Cretaceous or early Tertiary in age.

MINOR INTRUSIONS

Small plutons that lie across or near the Hozameen fault (northeast corner of Fig. 5) have been described by Cairnes (1923, p. 115A) as tonalite. They are younger than the Dewdney Creek rocks and younger than the Hozameen fault.

A pluton lying north of the Hope–Princeton highway (Fig. 5) (Cairnes 1923) is of granodiorite. It intrudes and sends many dikes into the lower divisions of the Hozameen Group.

EOCENE SEDIMENTARY ROCKS

Rocks originally assigned to the Lower Cretaceous Jackass Mountain Group (Cairnes 1944) on lithological grounds, and now considered to be Eocene in age, occur in patches isolated by younger intrusive rocks along a north-trending belt extending from Chilliwack Lake to Yale (Fig. 1).

The most abundant rocks are conglomerate, excellently exposed at Fraser River at the west abutment of the Hope Bridge and in road cuts to the north. The conglomerates contain well-rounded, commonly ellipsoidal boulders up to 3 ft across, but averaging between 1 and 4 in. across, set in an arkosic matrix.

Large surfaces of the boulders lie nearly parallel to scarce interbeds of arkose. Boulders in the beds just north of Hope include a high proportion of igneous rock types ranging from red granite to gray granodiorite; also included are boulders from the Yale Intrusions, and of Custer Gneiss, mica schist, chert, limestone, white quartz, and fresh sandstone that resembles that of the Dewdney Creek Group. Boulders in the lower beds, within a few feet of the basal unconformity, are notably rotten, and granitic boulders disintegrate to sand under a hammer blow. Such boulders may owe their condition to pre-Eocene weathering. In most places surfaces pass around boulders rather than through them.

Arkose beds account for less than 1/10th of the section near the base of the group but become, along with siltstone and shale, more common in higher beds seen north of Chilliwack Lake. Arkose beds locally contain poorly preserved leaves and sticks. Pebbles rather than boulders are more abundant at higher stratigraphic levels and, north of Chilliwack Lake, near the axis of a syncline, sandstone is abundant, occasional limy lenses are seen, and shale beds are common.

The basal unconformity is exposed in several places, the most accessible of which is on the south side of Fraser River, west of Hope, where it is vertical and strikes north. Boulders up to 6 in. are well rounded and of a variety of rock types, but many are clearly from the Yale Intrusions that, with Custer Gneiss and schist, forms the underlying floor. The unconformity is nearly vertical to the north (Read 1960*a*). Just south of Hope, the conglomerate rests on chert and volcanic breccia of the Hozameen Group, and appears to dip gently north. The basal rock there is in part, at least, a rather angular chert breccia, which is succeeded upward by a polymict conglomerate with scarce granitic pebbles.

The unconformity north of Chilliwack Lake, where the Custer Gneiss forms the floor, dips 20° to 40° W. The basal beds are composed of conglomerate with poorly rounded boulders of gneiss up to 1 ft in diameter. A few feet above the contact, chert and volcanic rocks of the Hozameen Group make up 50% of the roundstones.

The rocks dip nearly vertically north and west of Hope. North of Chilliwack Lake, the structure appears to be a syncline, plunging a little northerly.

The Eocene rocks during or after folding were cut by the steeply dipping Hope fault and later, the faulted assemblage was intruded by the Chilliwack tonalite, producing the present irregular distribution.

Locally the Eocene rocks have been strongly metamorphosed. North of Chilliwack Lake, the arkosic matrix of conglomerate at contacts with intrusions is thoroughly recrystallized, producing a granitic texture, and only the presence of scattered roundstones makes its origin obvious. Siltstone beds contain much metamorphic biotite and imperfect, large spongy cordierites. Highly contorted argillaceous interbeds with vague axial-plane cleavage contain small staurolite crystals and andalusite crystals, all strongly sericitized, and biotite and euhedral garnet are scattered throughout.

About 1 mile southwest of Hope, where the batholithic rocks have stoped only a little past the line of the Hope fault, conglomerates show the effects of both cataclastic and contact metamorphism. Black mylonite zones criss-cross the conglomerate at the contacts, most of them sweeping around and between well-rounded and little deformed boulders. The principal contact effect has been the development of biotite in megascopic scales and aggregates in mylonite and in the sandy matrix. Chert and volcanic grains are recrystallized and, locally, pelitic beds are changed to cordierite-biotite hornfels.

The Eocene rocks lie along the Hope fault of the Fraser River fault zone, and were perhaps deposited in a graben that has largely been obliterated by invading batholiths and by erosion. Eocene sedimentary rocks are also known some 60 miles north of the most northerly exposures of the present area, where they stand nearly vertically in the extension of this same fault zone (Duffell and McTaggart 1952, p. 61). Whether these now widely separated beds of Eocene rocks accumulated in a single elongate basin whose existence and form was controlled by the Hope and Yale faults, or whether they represent isolated Eocene basins of the type described at Princeton, Merritt, and Kamloops, is not known. To the south, Chuckanut (Paleocene?) beds and Hannegan (Oligocene) volcanic rocks (Miller and Misch 1963) lie near and along the extension of the Fraser River belt of faulting (Straight Creek fault) (Misch 1966, plate 7-1).

The Eocene age of these rocks has been established by G. E. Rouse (personal communication) on the basis of preliminary studies of pollen from beds just north of Hope.

ULTRAMAFIC ROCKS

Serpentinized ultramafic rocks, mainly peridotite, are abundant along the Hozameen fault (Fig. 1) between the Hope–Princeton highway and Fraser River north of Spuzzum, forming the "Serpentine Belt" of Cairnes (1930, p. 144). They also occur northwest of Hope and north and south of Yale, along and near the Hope fault (Fig. 4). Small bodies, apparently lenticular and measured in tens of feet are found in many places in the Hozameen Group. Some are near major faults. Daly (1912, p. 531) has described a harzburgite that intrudes Custer Gneiss near the International Boundary.

These ultramafic bodies resemble the "Alpine" type of Hess (1955, p. 391). They occur as elongate, perhaps lenticular bodies, show little sign of primary layering or zoning and are strongly sheared. They are highly serpentinized and locally rich in talc or associated with buff-colored quartz-carbonate rocks, and appear to have produced only negligible contact effects.

These "Alpine"-type ultramafic bodies contrast with the ultramafic rocks found at the Giant Nickel mine (Aho 1956, p. 444) and in the Tulameen area (Rice 1947, p. 33; Findlay 1963). The ultramafic body at the Giant Nickel mine, 6 miles northwesterly from Hope and just west of the mapped area (Fig. 2), is zoned, relatively unserpentinized and plug-like in outline. The second, in the Tulameen area, lying to the east of the mapped area, is a concentrically zoned complex that is considered to have crystallized from a peridotite magma.

Some of the ultramafic rocks along the Hope fault have been emplaced against Eocene rocks. It is possible, however, that these bodies are older than the rocks that enclose them and that they have moved into their present positions along faults. The Hope fault, reaching deep into the crust, has in some places intersected ultramafic masses perhaps occasionally of the type found at the Giant Nickel mine or even differentiated masses of the Stillwater type. Relatively small slices of these ultramafic masses may have been mechanically emplaced along these faults and in subsidiary fractures in the adjacent rocks as solid, relatively low-temperature intrusions as many workers have suggested (Duffell and McTaggart 1952, p. 76; Ragan 1963, p. 549). Support for this suggestion is found in the presence along the extension of the Hope fault (the Fraser River fault zone) at Lillooet, where hypersthene gabbro associated with serpentinized peridotite lies with its cumulate-type layering vertical in the fault zone (Brock 1956).

The 'Serpentine Belt', lying along the Hozameen fault, is emplaced between rocks of the Hozameen Group and those of Ladner and Dewdney Creek Group of Jurassic (?) and Early Cretaceous age. It leaves the fault, east of Spuzzum, lies entirely in rocks of the Hozameen Group, and apparently continues in that position for many miles to the northwest (Osborne 1966; Duffell and McTaggart 1952). In its thickest part, at Coquihalla River (Fig. 1), it is more than a mile wide and it extends for more than 30 miles.

SKAGIT VOLCANICS

The Skagit Volcanics (Fig. 5) were seen only in a few places and the authors can add little to earlier accounts by Daly (1912, p. 528) and Misch (1966, p. 138).

The formation consists of about 5000 feet of andesitic flows and pyroclastic rocks, which show, in general, only low dips. The contact with the Hozameen rocks to the north is marked in two places by rusty broken zones; in a third place, the volcanics occur at lower levels than Hozameen beds across a contact. These relations are compatible with a fault contact as suggested by Daly (1912), or possibly with a caldera wall. The volcanics are pierced by a small monzonite stock, which is correlated with the Chilliwack batholithic rocks. Misch (1966) reported that the volcanics south of the Canada–U.S.A. border also are intruded by the batholithic rocks.

CHILLIWACK BATHOLITH

Daly (1912, p. 534) examined and named the Chilliwack batholith at the International Boundary. Comparing it with the Snoqualmie batholith of Washington, he suggested a Miocene age, which was confirmed 50 years later. Misch (1966, p. 140) has shown the batholith south of the Canada–U.S.A. border to be composite, consisting of at least four main phases, ranging in composition from gabbro to leucogranite, and in age from Eocene to Miocene. Cairnes (1944) showed the batholith extending as far north as Hope, and the present authors tentatively include with it rocks northwest of Hope.

Areas underlain by the batholithic rocks were not systematically traversed during the present work and information was obtained mainly near contacts with other rocks and at points where access was easy. Consequently, although most of the batholithic rocks in the present area are close to tonalite in composition, showing strongest variation near margins and in outlying masses (and few internal contacts were seen), it is quite possible that detailed examination of the main batholithic mass to the west will show it to be a composite mass of successive intrusions.

Of 27 specimens examined in thin-section, 1 is hypersthene gabbro, 3 are of diorite, 10 are of tonalite, 9 are granodiorite, and 2 are granite according to Peterson's (1960) classification. Most common and typical is a medium-grained massive gray rock whose average mode, based on visual estimates of thin-section is: quartz 19%; K-feldspar 4%; plagioclase 65%; biotite 7%; hornblende 4%; and accessory minerals 1%. Quartz is typically unstrained. K-feldspar, commonly weakly perthitic, is untwinned. Quartz and K-feldspar are typically interstitial to the other main minerals and occasionally in acidic varieties show crude granophyric texture. Plagioclase commonly shows normal oscillatory zoning with considerable variation in pattern. Compositions of the inner zones as calcic as An_{60} are common and outer zones pass through An_{20}, but most compositions lie near An_{40}. In almost every thin-section, a few cores of zoned plagioclase piokilitically include minute crystals of hornblende, or augite, or hypersthene, and, not rarely, pyroxene rimmed by hornblende. Biotite, much of it closely associated with hornblende, probably is in reaction with it. Crystals of hornblende commonly contain irregular cores of augite, and rarely olivine, and the relation seems clearly one of reaction. Accessories include magnetite, zircon, and apatite, all mainly enclosed in biotite, as well as uncommon euhedral sphene and rare allanite.

In the easterly projecting parts of the batholith (Fig. 1), east of Chilliwack Lake, southeast of Hope and also in the outlying mass east of Hicks Creek, the rocks show considerable variety. Porphyritic, granophyric, and trachytoid types are common. In the eastern sections, quartz and K-feldspar increase in amount and plagioclase and mafic minerals decrease. Plagioclase is sodic and the rocks range through quartz monzonite to granite. In two places, several miles apart, plagioclase from border phases owes its blue color to abundant minute needles of rutile. Similar rutile-bearing plagioclase occurs in hypersthene gabbro that underlies a small area about 4 miles northeast of the south end of Chilliwack Lake.

The Chilliwack tonalite contrasts with the Yale and Spuzzum Intrusions in its general lack of either strong directive texture or signs of cataclasis. Joint surfaces are strikingly plane and continuous, and commonly present uninterrupted walls hundreds or even thousands of square feet in area. Inclusions are rare and most are a few inches across and round. At a few contacts, randomly oriented xenoliths of Custer Gneiss demonstrate movement and rotation within the tonalite.

The easterly projecting parts of the batholith cut directly across, and disturb very slightly, structures of the Custer Gneiss. The mile-long isolated inclusion of Eocene sediments that forms the cap of Silver Peak (Fig. 1) is apparently little displaced or rotated and is possibly a roof pendant. On the other hand, just north of Hope, most small folds in Hozameen phyllonites plunge north, away from the batholithic contact, suggesting that there the batholith lifted the roof of country rock. Clearly visible from Hope, the roof of the batholith 3 miles to the northeast appears to be gently dipping, and the overlying Hozameen contains many dikes. A tongue of granodiorite northwest of Ross Lake (Fig. 5) seems to have been injected along the contact between volcanic and sedimentary divisions.

In origin, the batholith appears to be magmatic. Sharp contacts, rotated xenoliths, thermal metamorphism, reaction relations between augite and hornblende, complexly zoned plagioclase, paragenetic sequence of minerals characteristic of magmatic crystallization, and, occasionally, granophyric and porphyritic texture, are together considered convincing evidence for such an origin. The mechanism of emplacement was probably magmatic stoping with local forcing aside of the country rock or lifting of the roof. Before emplacement, the Eocene beds with their marginal Hope fault extended south from Hope to the border (Fig. 1). This belt, largely of conglomerate and sandstone, seems to have been a barrier to extension of the intrusions to the east at Hope, but was breached southwest of Hope and also west of Chilliwack Lake. A pre-Eocene(?) northwesterly striking fault, now preserved only as a short segment $2\frac{1}{2}$ miles due north of Hope, may have facilitated stoping along its extension to northwest and southeast.

The batholith, with its Tertiary age and various structural and textural features, meets many of the criteria listed by Buddington (1959, p. 674) for emplacement in the epizone. One might speculate that the Skagit Volcanics are genetically related to the batholithic rocks in the way that many epizonal plutons have associated with them, and even intrude overlying slightly older volcanics derived perhaps from the same magmatic source.

The Chilliwack batholith intrudes Eocene rocks along the western border of the area. K-Ar dating by Baadsgaard *et al.* (1961) on specimens from points about 10 miles west of the present area gave an age of 18 m.y. and places that part of it in the Miocene. Misch (1966) stated that in northern Washington various phases were emplaced between Eocene and Miocene times.

The Hell's Gate granodiorite, lying only 3 miles north of the present map-area where it intrudes the Spuzzum tonalite, has been dated by Baadsgaard *et al.* at 35 m.y. and is probably related to the Chilliwack batholith.

STRUCTURAL GEOLOGY

Internal structures of the various groups have already been described and this section deals with structural features common to several of the groups and with the structural history of the area. Misch (1966, p. 104) and Danner (1966, p. 62) have described basement rocks, regionally metamorphosed in pre-Devonian time, that underlie large areas in northern Washington. The orogeny that produced these rocks has not been recognized in the area shown in Fig. 1.

Folding

There were several orogenic episodes, most of them involving folding and faulting, and some involving metamorphism and intrusion (Table II). Each new deformation obscured the evidence of earlier ones. Some deformations are marked by particular trends of fold axes and others possibly by distinctive fold geometries. The deformations listed below seem to be fairly well established in the present area, but in general it is impossible to assign a randomly chosen fold to any one of these deformations.

1. Northwest-trending folding and faulting during the development of the Custer Gneiss, affecting both Custer and Hozameen rocks (late Paleozoic or early Mesozoic?).
2. Northeasterly folding and thrusting (mid-Cretaceous?).
3. Deformation associated with the Hozameen fault (mid-Cretaceous?).
4. Folding and metamorphism of the Hozameen Group northwest of Hope and northwest of Stout, with accompanying emplacement of the Spuzzum Intrusions (late Late Cretaceous).
5. North-south folding and faulting along Fraser River (Eocene and earlier?).
6. Deformation (slight) accompanying emplacement of the Chilliwack batholithic rocks (Miocene and earlier?).

The earliest recognized orogeny (1) involved the formation of the Custer Gneiss at least partly from the rocks of the Hozameen Group. Most of the structural trends in the gneisses are northwest. North of Hope, and to the south, in the headwaters of Yola Creek, attitudes and fold axes are northerly but this trend may be due to re-alignment during deformation 5. Many folds in the Custer Gneiss and in the immediately adjacent Hozameen Group are isoclinal and, where dips are low, recumbent, and are probably related to shearing and movement along the contact between the two groups when migmatite and adjacent low-grade rocks reacted quite differently to tectonic forces. Direct evidence for the age of this first orogeny is lacking within the area. Monger (1966, p. 149) found, a few miles to the west, no evidence of orogeny between Early Pennsylvanian and Late Jurassic times. Misch (1966, p. 103) dated it as "pre-Jurassic".

Well-documented folding (Monger 1966) along northeasterly axes accompanied by overthrusting to the northwest, prominent to the west of the present area, west of the Chilliwack batholith, is considered to be mid-Cretaceous. Misch (1966, Fig. 7–17) suggested that these northeasterly trending orogenic axes, rather than affecting the present area, swing northward and northwestward beyond its western limits. There is, however, evidence that this northeasterly folding did affect the present area. A plot (Fig. 6) of 103 axes of small folds from the northeast quarter of Fig. 5 shows many striking northeasterly. Of 21 northeasterly striking folds, 3 were complete enough to be characterized as open upright folds, and 10 as recumbent and nearly isoclinal. Large folds

trending a little north of east on Marmot Mountain (Section G–G′, Fig. 4) are perhaps related. The junction of these last-mentioned folds with the dominant northwesterly trending folds, which lies 2 or 3 miles west and northwest of Marmot Mountain, appears on Fig. 5 (partly because of the map pattern used) to be effected along a series of smooth arcs. This appearance is misleading and it is probable that structures at the junction are more complex than can be worked out or illustrated on the scale of the present mapping.

Northeasterly trending folds (deformation 2) are deformed or cut off near the steeply dipping Hozameen fault (deformation 3), and beds have been made parallel with the fault (northeast corner of Fig. 5). Coates (1967), working to the east of the present area, has dated this fault as older than 84 m.y. (pre-middle Late Cretaceous?); the fault cuts Ladner and Dewdney Creek strata (Jurassic? and Lower Cretaceous) and thus appears to be near late Early Cretaceous in age.

Northwest folding (deformation 4), high-grade metamorphism of Hozameen rocks northwest of Hope and northwest of Stout, and emplacement of the Spuzzum Intrusions, apparently in late Late Cretaceous (76 m.y.) time, mark a notable orogeny. The trend of deformation is most clearly shown northwest of Stout where northwesterly trending high-grade metamorphic rocks form a trough or pendant in the Spuzzum tonalite. Strong northwest folding just east of the present area affecting Lower Cretaceous beds of the Dewdney Creek and Pasayten Groups, possibly contemporaneous with deformations 3 or 4 is clearly shown (Rice 1947, Map 888A) where conglomerate and volcanic formations follow this trend for many miles. Deformation 4 undoubtedly affected the already twice-folded Hozameen rocks and the Custer Gneiss, obscuring northeast folds (deformation 2) and compressing the earliest northwest folds (deformation 1).

Development of the Fraser River fault zone, probably at least as early as the Cretaceous Period, and the formation of northerly trending sedimentary basins, perhaps graben, in the Eocene Epoch, was followed by an episode of strong folding (deformation 5) and renewed faulting along north-trending lines. Eocene beds dip vertically for many miles. Intense shearing of Spuzzum and Yale intrusions, which trends northwesterly and northerly, is probably related to this deformation, the northwesterly trends being controlled by the pre-existing structural grain of the older rocks.

Minor and local deformation (6) that accompanied the emplacement of the Chilliwack batholithic rocks has already been described.

Faulting

Three major fault zones are: (1) the zone separating Custer Gneiss from the rocks of the Hozameen Group; (2) the Hozameen fault; and (3) the Hope and Yale faults together forming the southerly extension of the Fraser River fault zone.

The contact of the Custer Gneiss and the Hozameen Group is a wide zone of shearing and metamorphism. The rocks of the highest divisions of the Hozameen Group, moving against relatively unyielding Custer gneiss, were locally intensely sheared and reduced to phyllonite and mylonite (Cairnes 1923, p. 54A). This belt of disconnection along which the amount of movement is unknown is not shown as a fault on Figs. 1, 4, and 5. The shearing effects are particularly striking 4 miles northeast of Hope where Custer gneiss is succeeded to the east by mylonites and sheared sedimentary rocks that seem to be stacked as easterly dipping thrust plates, with hundreds of sheared sills of Yale granodiorite (Read 1960*a*, p. 88), above which, east of a boundary difficult to define closely, relatively unmetamorphosed rocks of the overlying Hozameen Group are found. The zone probably disappears as it runs into the Spuzzum Intrusions near Stout. A western part of this same zone, folded, broken, and preserved by down-faulting(?) just north of Hope, includes phyllonite that alternates with unsheared limestone and volcanic breccia. The zone was active during the formation of the Custer Gneiss and during later deformations. It is possibly the extension of the Ross Lake fault of Misch (1966, p. 134).

The Hozameen fault that bounds the Hozameen Group on the east was first mapped by Daly (1912) at the Canada–U.S.A. border and extended northwards by Cairnes (1924). Rice (1947, p. 52, Map 889A) examined the zone near the 49th parallel, named the zone, and described it as a westerly dipping thrust fault. To the north, the fault zone is occupied by the 'Serpentine Belt'. Sargent (1939, pt. F) mentioned the fault and described the serpentine masses from and near it. South of the Canada–U.S.A. border, Misch (1952, 1966) has mapped the zone for many miles, referring to it as the Ross Lake Fault Zone (which he distinguishes from the Ross Lake fault).

The zone brings together Hozameen Group and Jurassic(?) and Lower Cretaceous rocks of the Ladner and Dewdney Creek Groups. At the Hope–Princeton highway (northeast corner of Fig. 5) the fault zone apparently consists of parallel faults more than a mile apart. In this vicinity, the main fault is not deflected on crossing the Skagit valley and appears to be nearly vertical. Adjacent strata stand nearly vertical. To the south at Jack Mountain, 17 miles south of the border, Misch (1966) showed it to be nearly flat, and there, Hozameen rocks overlie Cretaceous rocks.

The deflection of the 'Serpentine Belt' in the latitude of Yale (Cairnes, 1944 and this paper, Fig. 1) contrasts with the relative straightness there of the Hope and Yale faults (Fraser River fault zone). The steepness of the Hozameen fault in the southern part of the area and its flatness in northern Washington suggest that it has been folded. These considerations suggest that the Hozameen fault is older than the Hope and Yale faults. The Hozameen fault is probably late Early Cretaceous in age.

The intersection of the Hozameen and Fraser River fault zones (Fig. 7) is at such a small angle that offset of one zone by the other is not easily demonstrated. The continuation of the Hozameen fault west of the Fraser River fault zone probably lies northwest of Keefers, to the north of the present area, and is marked by a prominent zone of ultramafic rocks, which is interrupted by granitic rocks west of Lytton (Fig. 7). It resumes in the headwaters of Texas

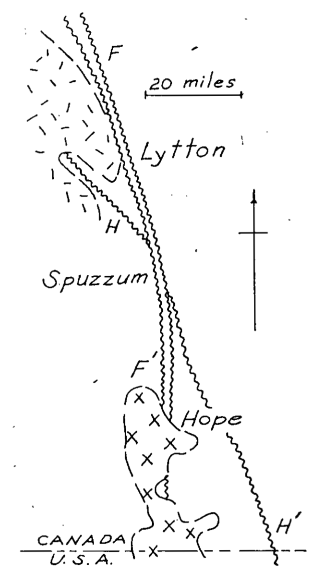

FIG. 7. Sketch map showing Fraser River fault zone (F–F') and Hozameen fault (H–H').

Creek (Duffell and McTaggart 1952) and perhaps is found again to the northwest as serpentinites in the Bridge River mining camp.

The Hope fault was first mapped by Read (1960*a*, *b*), who traced it from Hope towards Yale. He suggested that the fault originally extended south into the state of Washington, but that it had been intruded and obliterated by the Chilliwack batholithic rocks. He reported that the fault dips steeply and suggested, on the basis of mullion structure on adjacent subsidiary faults, that the last movement was dip-slip. The presence of Eocene rocks on the east and older rocks on the west suggests relative movement downward on the east. Abrupt increases in the areas underlain by deep-seated(?) Spuzzum Intrusions west of the fault zone support this suggestion.

The Yale fault extends, with interruptions, from the southern part of the area to north of Spuzzum where it appears to intersect the Hozameen fault at a low angle. One mile north of Yale, the fault is marked by a steeply dipping zone of mylonite many scores of feet thick. The rock involved in the fault there is foliated Spuzzum tonalite, which encloses masses of garnetiferous gneiss hundreds of feet across. The general foliation strikes west to northwest but at the fault zone it strikes nearly north. Mylonite ranges from a strongly sheared rock containing lenticles of gneiss and augen of feldspar in a black streaky groundmass to rocks so perfectly and delicately layered as to resemble laminated sedimentary rock. The troublesome distinction between layered mylonite and somewhat sheared bedded sedimentary rock was there resolved by the presence of garnets of the original gneiss, finely ground, strung out, and distributed through the most sedimentary-looking mylonite. The rocks are locally brecciated, and in some places mylonite is brecciated and intruded by extremely fine-grained clastic material with lamination crossing the general lamination of the mylonite. Small folds in the mylonite plunge southerly at moderate angles and the shapes of some folds suggest that the west side has moved relatively down.

The north-striking Hope and Yale faults belong to the Fraser River fault system (Duffell and McTaggart 1952; Trettin 1961, p. 95), which extends for more than 130 miles to the north. They resemble previously described faults of this zone in their attitudes, in the presence of serpentinized ultramafic rocks at intervals along them, and in the preservation along them of Eocene sedimentary rocks. The Yale fault is probably the continuation of the Straight Creek fault of northern Washington (Misch 1966, p. 108) and it is noteworthy that nearby structures swing from northwest (east side) to north (west side) as the fault is crossed, both south of the border and in the present area, e.g., at Yola and Hicks Creeks (Fig. 5).

It is possible that after the Hozameen fault (Fig. 7, H–H′) was sealed to the northwest (north of the present area) by batholithic intrusions, crustal stress was relieved by movement along the north-south lines of the Fraser River fault zone (Hope and Yale faults, F–F′). Movement along this zone probably controlled the deposition of the Eocene rocks that were later to be preserved by subsidence along these same faults. In late Tertiary times, after the Fraser River fault zone was, in turn, blocked to the south by the Chilliwack intrusions, stress was perhaps relieved partly by renewed faulting along the Fraser River zone and perhaps partly along the line (F–H′, Fig. 7).

Misch (1966, p. 108) dated the Straight Creek fault as early Eocene. Trettin (1961, p. 96) found Tertiary lavas astride one of the faults of the Fraser River zone to be undisturbed. Duffell and McTaggart (1952, p. 89) offered evidence that the Fraser River zone might have been active intermittently from Early Cretaceous to relatively recent times. Five miles north of Spuzzum, Spuzzum tonalite and Hell's Gate granodiorite (Morris 1955) dated by Baadsgaard *et al.* (1961) at 35 m.y. are in fault contact on the probable extension of the Hope fault. Such late Tertiary fault activity suggests that certain lineaments along the course of the Hope fault south of Hope might mark renewed movement on the fault after the emplacement of late phases of the Chilliwack batholith.

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