

## REGIONAL ZEOLITE ALTERATION OF THE SUSTUT GROUP, NORTH-CENTRAL BRITISH COLUMBIA

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### ABSTRACT

Throughout the Sustut Basin in north-central British Columbia, rocks of the continental Sustut Group are extensively zeolitized. Sandstone, mudstone, conglomerate and tuff comprise a sequence up to 2300 m thick. The Sustut Group was deposited in a fluvial environment characterized by alluvial fans, meandering and braided streams, and temporary overbank lakes and swamps. Heulandite, albite, analcime, quartz, and clay minerals typify altered tuffs and tuffaceous sediments, and laumontite, albite, calcite, quartz, and clay minerals form in non-tuffaceous sandstones. Textures of these minerals indicate solution and replacement of the vitric portion of the tuffs and open-space filling in the surrounding permeable sandstones. Albite and analcime-quartz assemblages, and heulandite and laumontite-quartz assemblages are interbedded. Composition and amount of volcanic detritus determine the type of alteration. Heulandite and analcime-quartz are restricted to tuffs, laumontite-quartz to non-tuffaceous sandstones, and albite occurs preferentially within the tuffaceous part of the sequence. Tuffs were altered within a few million years after deposition under inferred conditions of temperature and pressure not exceeding 65°C and 0.4 kb. Hydrolysis of vitric fragments within tuffs locally increased alkalinity and therefore solubility of silica. Variation in silica activity apparently is the primary control on the spatial distribution of alteration minerals within the Sustut Group. High silica activity in tuffs and adjacent tuffaceous sediments favoured heulandite and albite. Low silica activity away from tuffs favoured formation of laumontite and possibly prehnite.

### INTRODUCTION

Zeolites occur in rocks deposited in a wide variety of sedimentary and volcanic environments ranging from open marine, through fresh water, saline lacustrine, to hydrothermal alteration zones and hot springs. Zeolites are stable within a range of temperatures and pressures ranging from near-surface conditions to esti-

mated depths of 13 km and temperatures up to 300°C. Zeolites are most common in Mesozoic and Cenozoic volcanogenic rocks and less common in other calcite-free clastic sedimentary rocks (Hay 1966). In this respect, Mesozoic and Cenozoic volcanic and associated sedimentary successions of the Canadian Cordillera should be ideal hosts for the development of zeolites. Previous studies of zeolite-bearing rocks from the Insular Belt of British Columbia were reported by Carlisle (1971), Stewart & Page (1971), and Surdam (1973). In the clastic foreland deposits of the Rocky Mountains, occurrences of zeolites were described by Mellon (1967), Carrigy (1971), and Ghent & Miller (1973). Monger & Hutchison (1971), in their compilation of metamorphism in the Canadian Cordillera, suggested that rocks of zeolite and sub-greenschist facies should be particularly widespread in the volcanic and volcanoclastic rocks of the Intermontane Belt (Fig. 1). In this paper we describe zeolite alteration of clastic rocks that were deposited in a basin of the Intermontane Belt. The Sustut Basin in north-central British Columbia contains up to 2300 m of sandstone, mudstone, conglomerate, and tuff of Late Cretaceous to Eocene age (Lord 1948; Eisbacher 1971). This basin affords a unique opportunity to investigate conditions of regional zeolite alteration over an area of about 9000 square km. The tectonic setting and sedimentology are known and allow analysis of alteration of the sediments in relation to stratigraphic and structural variables of the basin. Alteration of the sediments has resulted in widespread development of heulandite, laumontite, albite, calcite, kaolinite, illite, montmorillonite, and sporadic analcime, clinzoisite, sphene, and prehnite. Preliminary study of the alteration minerals indicated that rock type and solution chemistry were probably significant controls on the distribution of alteration minerals (Read & Eisbacher 1973). In our discussion we shall use the term 'alteration', fully aware that other investigators might refer to the same mineral assemblages as 'diagenetic', 'authigenic', or 'metamorphic'.

This study is based on 10 months of field work from 1969 to 1972 by Eisbacher, and

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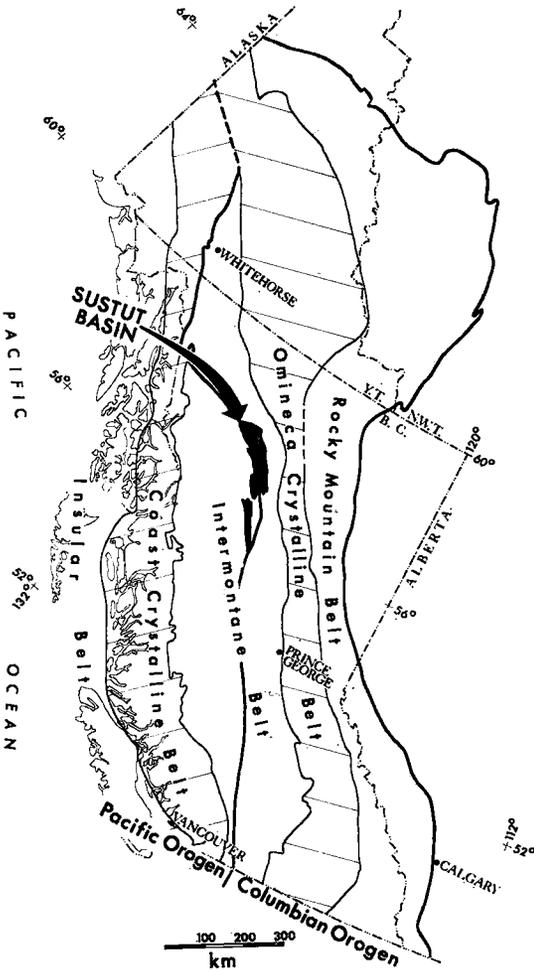


FIG. 1. Tectonic framework of the Canadian Cordillera showing the distribution of tectonic belts and the location of the Sustut Basin.

examination of 250 samples of tuff, tuffaceous and non-tuffaceous sandstones in thin section and by means of x-ray diffraction by Read.

**SEDIMENTATION AND DEFORMATION OF SUSTUT GROUP**

The non-marine Sustut Group was deposited in a late-orogenic basin along the west side of the Omineca Crystalline Belt over volcanic, granitic, and sedimentary terrane of the Intermontane Belt (Fig. 1). The Group is the youngest successor basin assemblage of the north-central Canadian Cordillera and ranges in age from Late Cretaceous to Early Tertiary (Eisbacher, in press). Sustut Group is divided into two formations, each of which has two distinct members (Fig. 2).

The lower unit, the Tango Creek Formation, rests with profound angular unconformity on a pediment of Upper Triassic volcanics and younger granitic intrusions on the east side of the Sustut Basin. Westward, this formation lies with angular unconformity on the Upper Jurassic sedimentary Bowser Assemblage (Fig. 3). Tango Creek Formation was deposited in an environment of meandering and braided rivers and extensive overbank swamps (Eisbacher 1971, and in press). Paleocurrent determinations indicate that rivers flowed southwestward during deposition of the Niven Member, and the maximum clast sizes in conglomerates suggest that the headwaters of the streams entered the basin on three or four major alluvial fans (Fig. 4). The petrology of the Niven Member in the lower part of the Tango Creek Formation suggests that, in addition to volcanic and granitic units, quartzose sedimentary rocks of the Cordilleran miogeocline were exposed near the source of the rivers (Fig. 5). During deposition of the Tatlatui Member the rivers seem to have been partly diverted to a northward flow, and gradients were generally decreased (Fig. 4). The composition of sandstones of the Tatlatui Member reflects derivation from Upper Jurassic Bowser Assemblage.

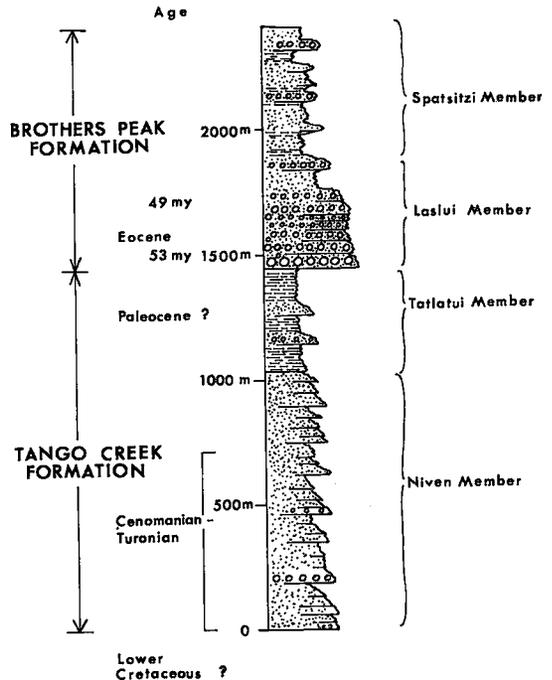


FIG. 2. Generalized composite section of the Sustut Group with approximate ages of formations and members.

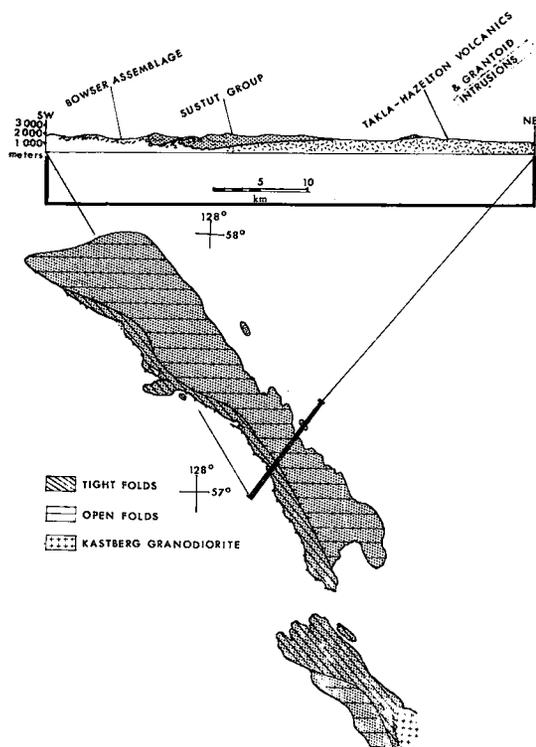


FIG. 3. Sketch map of the Sustut Basin and a northeast structural cross-section illustrating areas of intense folding and areas characterized by broadly open folds.

The upper unit, the Brothers Peak Formation, is characterized by the abrupt appearance of coarse conglomerates, which rest with erosional contact on Tango Creek mudstones and sandstones (Fig. 2). These conglomerates were derived mainly from the west and represent deposits of alluvial fans that prograded south-eastward over low-lying swampy terrane (Fig. 6). The change in drainage between deposition of Tango Creek Formation and Brothers Peak Formation is related to the continued growth of folds to the west in the Bowser Assemblage. This syn-depositional deformation involved most of the southwestern segment of the Sustut Basin (Fig. 3), and Tango Creek sediments were presumably reworked into Brothers Peak Formation (Eisbacher, in press). The distinctive feature of Brothers Peak Formation is the interlayering of conglomerate with numerous ash-fall tuffs. Macroscopically, these tuffs are composite sheets which show much evidence of reworking by flowing water (Figs. 7, 8). The fine grain size of pyroclastic fragments (less than 1 mm) clearly points to a distant eruptive source. Radiometric data indicate that the tuffs

are Eocene. Probably they were erupted in the Sloko volcanic province and then carried by high-level west winds into the Sustut Basin and beyond (Fig. 9). Their preservation within the coarse clastic rocks of Brothers Peak Formation indicates that the alluvial fans prograded into standing or slowly moving bodies of fresh water which impeded the erosional force of sporadic debris flows. Modal compositions of Brothers Peak sandstones reflect reworking of Tango Creek and Bowser sandstones and admixing of feldspar and vitric fragments from tuffs (Fig. 5).

#### ALTERATION MINERALOGY\*

##### Heulandite

Based on Si/Al ratio, heulandite (with Si/Al of 3), and clinoptilolite (with Si/Al of about 5) are end-members of a continuous solid solution series (Boles 1972, p. 1472). Based on optical, x-ray and thermal characteristics, heulandite-clinoptilolite minerals from Brothers Peak Formation seem to be heulandite, rich in Ca and Si, as defined by Boles (1972). Based on sign of elongation, they have Si/Al equal to or smaller than 3.52 (see Appendix). Heulandite is confined to tuffs and tuffaceous mudstones.

##### Analcime

Analcime compositions were estimated using the x-ray determinative curve of Coombs & Whetten (1967). Analcime in tuffs of the Brothers Peak has a composition close to  $(\text{Na}, \text{K}, 2\text{Ca})_{14}\text{Al}_{14}\text{Si}_{34}\text{O}_{96} \cdot n\text{H}_2\text{O}$  (see Appendix). This composition is in the range of "sedimentary" analcime of Coombs & Whetten (1967) and corresponds to either their group A (analcime formed from siliceous volcanic glass by reaction with saline water) or to their group B (analcime formed in a burial metamorphic environment).

##### Laumontite

Laumontite ( $\text{CaAl}_2\text{Si}_4\text{O}_{12} \cdot 4\text{H}_2\text{O}$ ) was determined optically and verified by x-ray.

##### Albite

Laths of albite "cement" show polysynthetic twinning and simple twins on albite, Carlsbad albite, and Carlsbad twin laws. Determination of the composition by four-axis universal stage using determinative curves of Slemmons (1962)

\*See also Appendix.

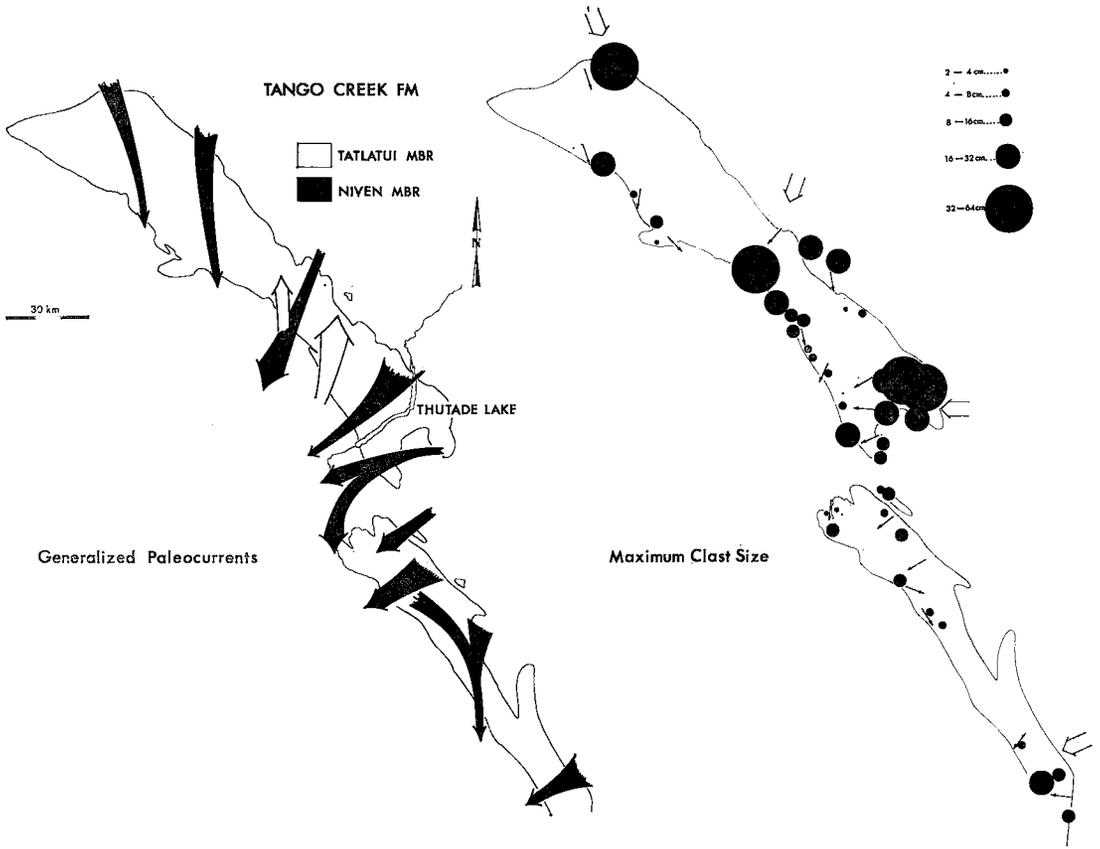


FIG. 4. Maximum size of clasts in conglomerate, mean paleocurrent vectors from crossbedding measurements, and apices of the principal fluvial systems (diagram on the right); generalized paleocurrents for the two members of the Tango Creek Formation (diagram on the left).

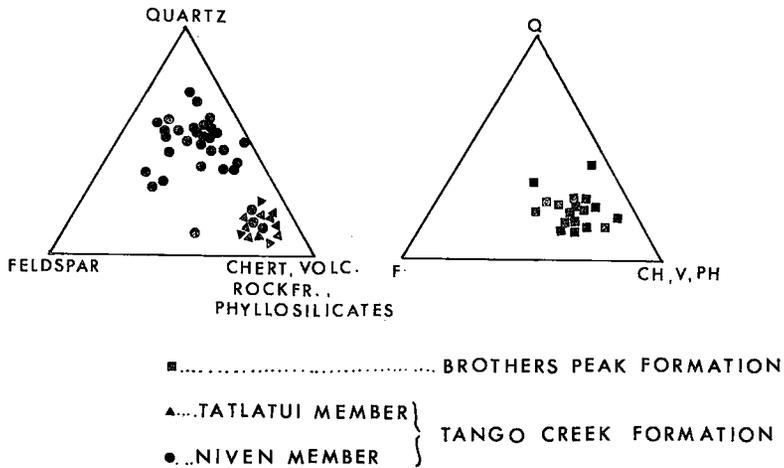


FIG. 5. Modal composition of Sustut sandstones.

yielded compositions of  $An_0$  to  $An_5$  (Fig. 13). This albite is of an intermediate structural state which contrasts with the albite of framework grains that has a low structural state. Although Peterson (1962) and Baskin (1956) reported some diagenetic albite of low structural state based on x-ray investigations, diagenetic albite is commonly of intermediate structural state based on optical investigations (Fichtbauer 1956; Milton *et al.* 1960). Based on scant data, albite of zeolite-bearing rocks formed under burial metamorphic conditions has a low structural state (Dickinson 1962).

**Prehnite**

Prehnite was found in one locality (see Fig. 14) as fracture fillings and was identified optically.

**Clay minerals**

Clay minerals occur alone or with calcite and form a common matrix in Sustut sandstones. They also occur with zeolites and albite as the alteration product of glass fragments. X-ray

diffractograms (see Appendix) indicate that a major part of the altered volcanic glass is kaolinite, montmorillonite, and minor celadonite. Near the base of the Sustut Group, kaolinite is well-crystallized and ordered.

**PETROGRAPHY OF ALTERED SANDSTONES**

Because proximity to tuffs apparently controls the type of alteration in the Sustut Group, the different alteration assemblages are described with respect to rock types. This approach differs from the frequently applied divisions based on mineral assemblages related to depth of burial of zeolite-bearing rocks, but seems to be justified in this terrane where occurrences of analcime, albite, heulandite, and laumontite overlap within the stratigraphic sequence (Fig. 16). As emphasized above, tuffaceous mudstone, and tuffaceous sandstone are restricted to the Brothers Peak Formation (the upper unit of the Sustut Group), whereas non-tuffaceous sandstones are throughout the Sustut Group.

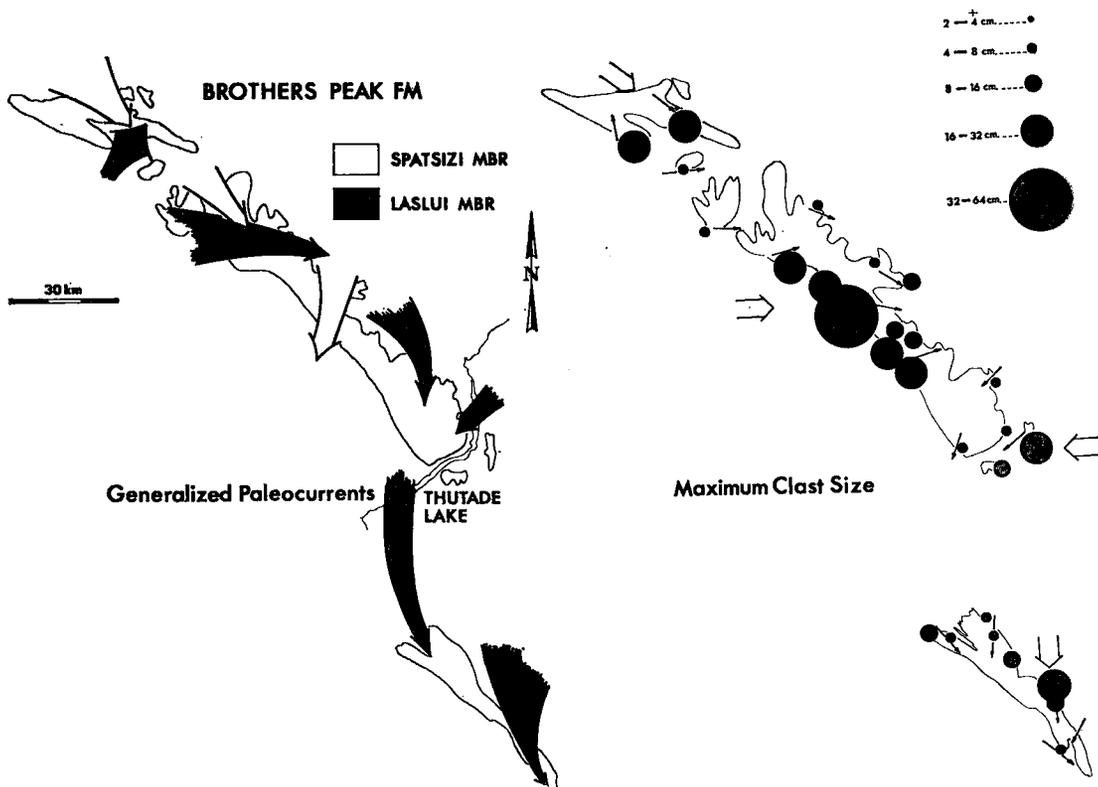


FIG. 6. Maximum size of clasts in conglomerate, mean paleocurrent vectors from crossbedding measurements, and apices of the principal fluvial systems (diagram on the right); generalized paleocurrents for the two members of the Brothers Peak Formation (diagram on the left).

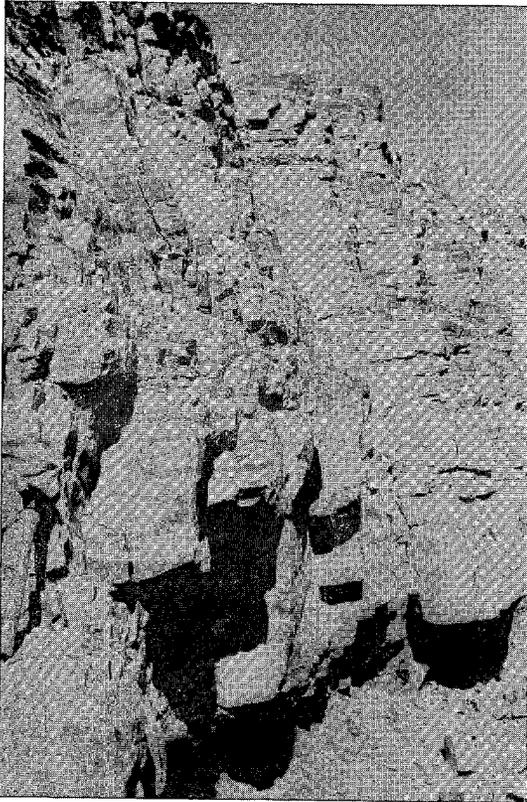


FIG. 7. Part of a composite ash-fall tuff unit in Brothers Peak Formation. The interval shown in this photograph corresponds to the "Graded, light green tuffs" of Figure 8. Scale is indicated by the pick in the left foreground.

### Tuff and tuffaceous mudstone

Within the Brothers Peak Formation, framework grains of originally vitric tuffs consist predominantly of glass, 10 to 40% crystals of plagioclase ( $An_{25}$  to  $An_{45}$ ), some quartz, minor sanidine, and rare biotite. Shards and pumice fragments up to 0.7 mm long occur locally and are not welded. With an increase in the proportion of crystals to about 75%, vitric tuff grades into crystal tuff. With a decrease in crystal and shard content, tuffs grade into tuffaceous mudstones.

Glass fragments in the tuff and tuffaceous mudstone are completely altered, and outcrop characteristics of these rocks are controlled by the predominant alteration mineral. Tuffs rich in heulandite are hard, almost porcellaneous in appearance, ranging from light buff on the weathered surface to shades of olive-grey to olive-green on the fresh surface. Tuffs rich in albite are porcellaneous and break with a conchoidal fracture. Fresh surfaces are cream to light grey but, in contrast to heulandite-rich tuffs, weather cream-coloured. Albite-analcime tuffs are porcellaneous, but consist of white spherules of analcime 2 to 10 mm in diameter, set in a light grey groundmass rich in albite. Analcime spherules locally coalesce to form white layers parallel with bedding (Fig. 10). Completely altered specimens of tuff show delicately preserved bedding, cross-bedding, graded bedding, channeling and soft-sediment slumping. Locally, fractures up to a few mm wide are filled with heulandite and/or calcite.



FIG. 8. Example of a composite ash-fall tuff between two sandstone units illustrating sedimentary structures and a typical distribution of alteration minerals (Ab=albite, H=heulandite, Ac=analcime). Current directions derived from crossbedding within tuffs are generally identical to those measured in adjacent sandstones.

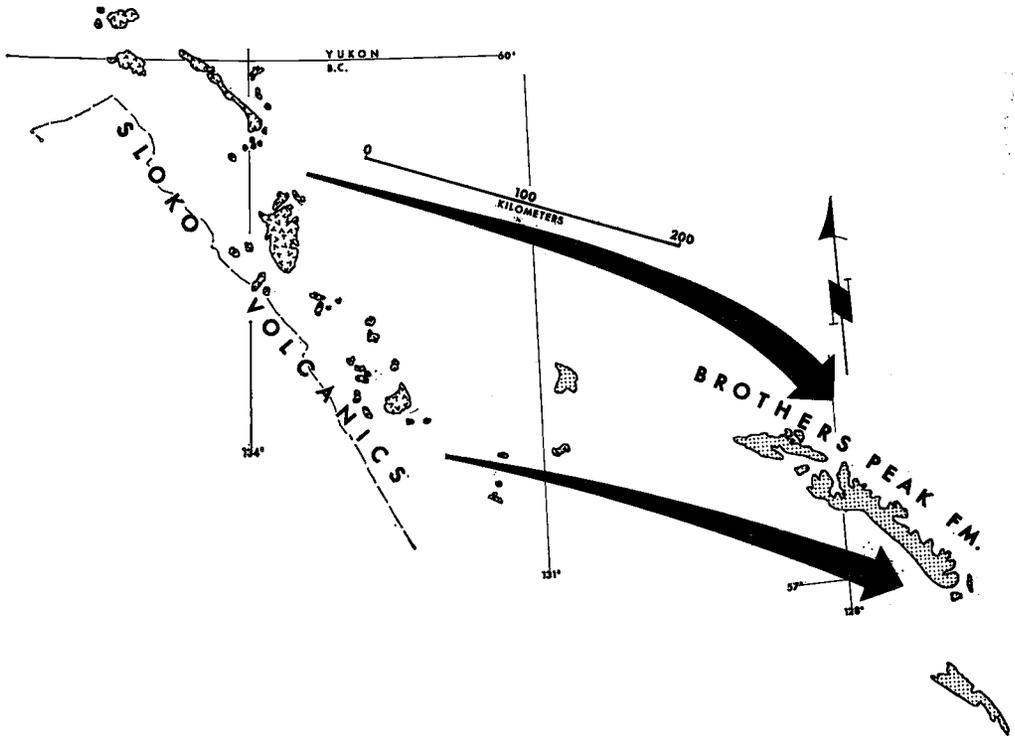


FIG. 9. Inferred source area and wind transport direction of ash-fall tuffs within the Brothers Peak Formation.

Of the tuffaceous sediments of the Brothers Peak Formation, about 60% are altered to heulandite, 25% to albite, and 15% to analcime. In heulandite-bearing tuffs, former glass shards (0.1 to 0.5 mm long) are outlined by a thin coating of montmorillonite or celadonite less than 0.03 mm thick. Inside the montmorillonite coating, blades of heulandite (up to 0.15 mm long) are oriented perpendicular to the coating and form pseudomorphs of glass shards (Fig. 11a). Original vesicles in the shards are rimmed with montmorillonite or celadonite and are filled with radiating blades of heulandite. Less commonly, heulandite forms a clear rim and montmorillonite makes up the inner portion of replaced shards. Fine layers of pseudomorphic montmorillonite and heulandite also replace originally layered pumice fragments. Textures of albite-bearing tuffs are similar to those rich in heulandite. Parallel laths of albite, up to 0.05 mm long, replace shards embedded within a very fine-grained matrix of montmorillonite and albite. Within the analcime spherules of analcime-albite tuffs, analcime replaces vitric shards and, with montmorillonite, forms a finer-grained matrix (Fig. 11d). Because analcime in these rocks is granoblastic, no textures point

directly to open-space filling. However, textures of albite only 0.5 mm away from analcime do indicate open-space filling. Analcime may also have filled cavities within dissolved glass shards. The undisturbed preservation of shards and pumice fragments and the ubiquitous textures indicating filling of open spaces and local cavities suggest that the tuffs and tuffaceous mud-

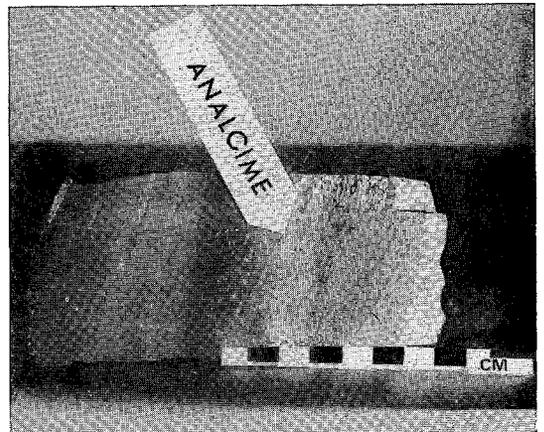


FIG. 10. Specimen of laminated grey-green tuff. The light patches are analcime.

stones remained coherent and undisturbed during solution and replacement of the glass fragments. Replacement of vitric material is complete and few cavities remain.

Of the non-vitric framework grains only biotite shows some alteration. Contorted biotite flakes (up to 0.4 mm long) locally show ragged margins and low birefringence. These flakes are pleochroic in shades of brown and are partly altered to celadonite. Biotite makes up less than

5% of tuffs, and less than one-tenth is altered. Framework plagioclase shows a wide compositional range within individual specimens and among different tuff layers (Fig. 13). In tuffs, plagioclase has retained its intermediate to high structural state, and is unaltered (Fig. 12). The compositional range of plagioclases is the same in all tuffs regardless of whether the alteration assemblages are soda-rich or calcium-rich (Fig. 17).

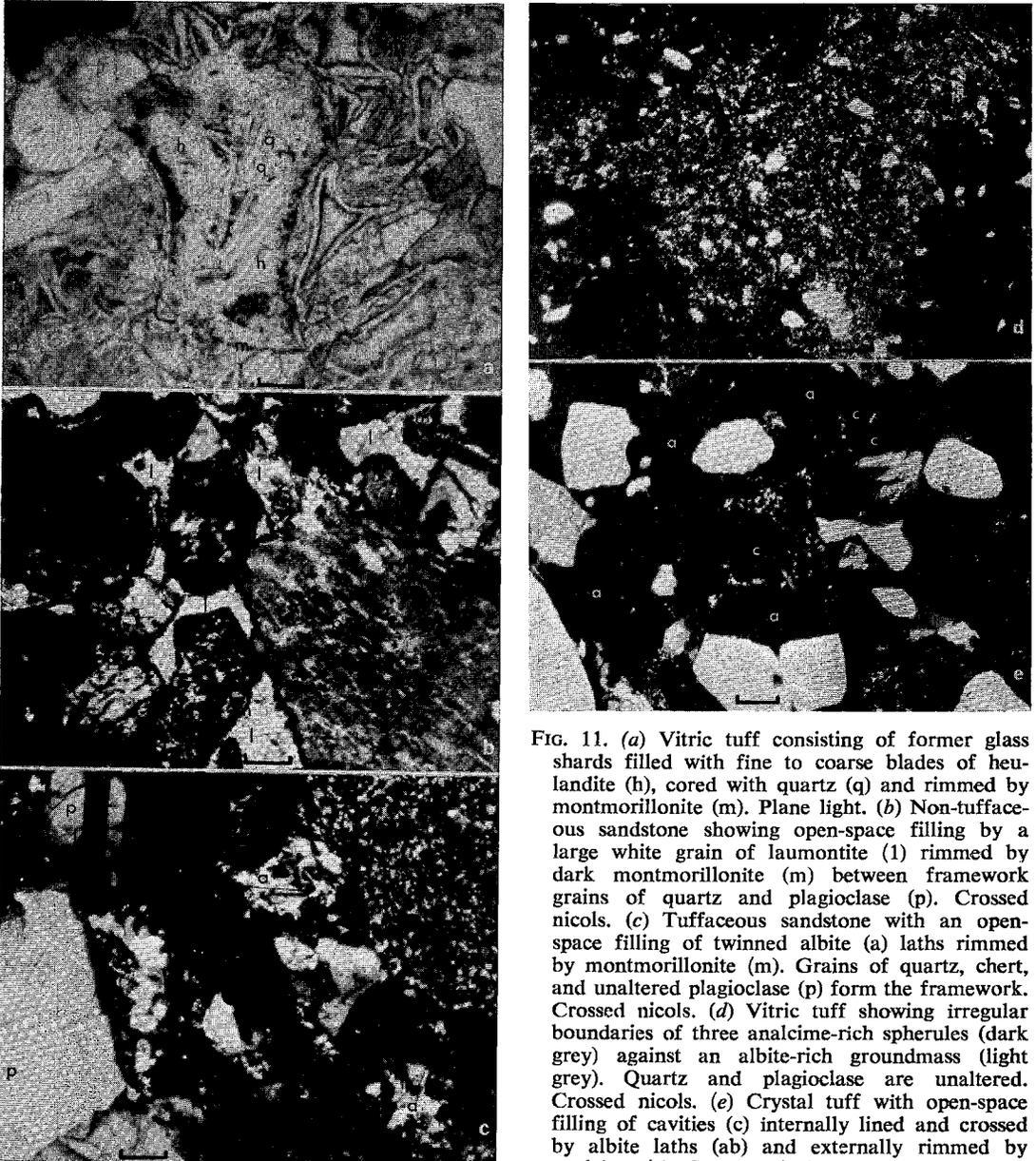


FIG. 11. (a) Vitric tuff consisting of former glass shards filled with fine to coarse blades of heulandite (h), cored with quartz (q) and rimmed by montmorillonite (m). Plane light. (b) Non-tuffaceous sandstone showing open-space filling by a large white grain of laumontite (l) rimmed by dark montmorillonite (m) between framework grains of quartz and plagioclase (p). Crossed nicols. (c) Tuffaceous sandstone with an open-space filling of twinned albite (a) laths rimmed by montmorillonite (m). Grains of quartz, chert, and unaltered plagioclase (p) form the framework. Crossed nicols. (d) Vitric tuff showing irregular boundaries of three analcime-rich spherules (dark grey) against an albite-rich groundmass (light grey). Quartz and plagioclase are unaltered. Crossed nicols. (e) Crystal tuff with open-space filling of cavities (c) internally lined and crossed by albite laths (ab) and externally rimmed by analcime (a). Crossed nicols.

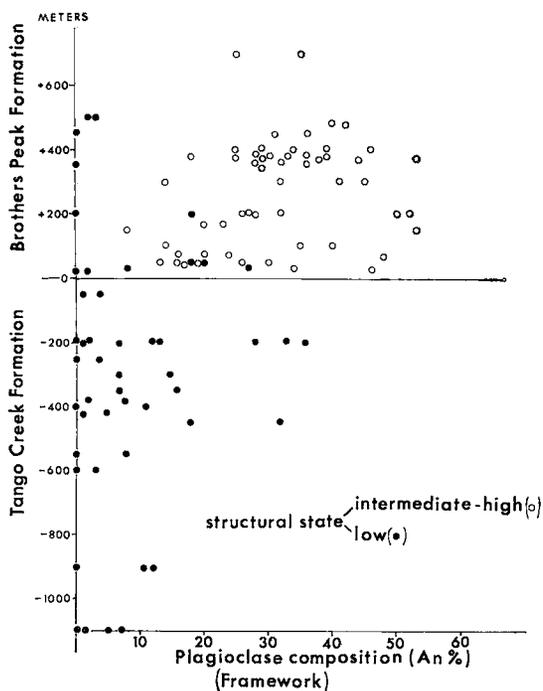


FIG. 12. Relationship among composition, structural state, and stratigraphic position of framework plagioclase grains in Sustut Group.

### Tuffaceous sandstones

The framework grains in these rocks consist predominantly of complexly twinned plagioclase that has an intermediate to high structural state and ranges in composition from  $An_{25}$  to  $An_{45}$ . Non-tuffaceous minerals of the framework are chlorite, hornblende, epidote, sphene, quartz, chalcedony, and microcline. Plagioclase, biotite, sanidine, and some quartz were added to the alluvial sands by reworking of ash-fall tuffs. The cream to light grey of the tuffaceous sandstones results from the colour of the feldspathic framework. Admixed carbonaceous debris causes darker shades of colour.

In tuffaceous sandstones, a quartz-albite cement fills the intergranular pore space; however, framework grains are thinly coated (up to 0.02 mm) with montmorillonite, even at points of mutual contact. Within much of the pore space, a rim up to 0.04 mm thick, composed of quartz and locally celadonite, surrounds coarser quartz and blades of albite up to 0.15 mm long (Fig. 11c). Sporadically, small blades of heulandite take the place of the fine-grained quartz rim. Some pore spaces are filled by coarse quartz, and others by randomly

oriented blades of coarse albite that extend from wall to wall across the pore space. Idiomorphic calcite, sphene, and clinzoisite occur locally with albite and quartz as pore filling. The successive inward coating of the cementing minerals indicates that they filled open pore spaces. Finely layered pumice fragments clearly retained their external form during replacement by albite-montmorillonite. In the pore filling, however, textures indicative of shards or vesicular and layered pumice are absent. In this respect fillings of primary voids in tuffaceous sandstones are texturally similar to those of non-tuffaceous sandstones described below.

### Non-tuffaceous sandstones

Non-tuffaceous sandstones of the Sustut Group are sub-quartzose with framework grains of quartz, chert, low structural state plagioclase ( $An_0$  to  $An_{25}$ ), microcline, biotite, muscovite, chlorite, epidote, and minor hornblende. They are cemented by laumontite or quartz-albite, illite, kaolinite, montmorillonite, calcite, or quartz. Sandstones cemented by laumontite break around grains whereas those cemented by quartz-albite break across framework grains. Laumontite fills pore space, forming large single grains commonly poikiloblastic and up to 3 mm in diameter. Locally, zones of celadonite up to 0.03 mm thick form layers within pore

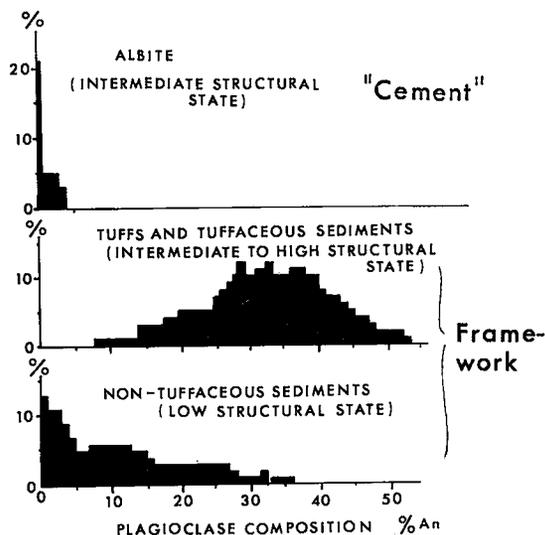


FIG. 13. Composition of framework plagioclase grains in tuffaceous and non-tuffaceous Sustut rocks as compared with the composition of interstitial albite.

spaces filled by laumontite (Fig. 11b). Sporadically, calcite accompanies laumontite. In a few localities blades of albite surround a core of laumontite and suggest that laumontite was deposited after albite. Sphene and clinzoisite occur as very fine-grained zones or coarser single grains interstitial to the framework. Textures of quartz-albite cement are identical with those in tuffaceous sandstones.

#### REGIONAL DISTRIBUTION OF ALTERATION MINERALS

Alteration mineralogy of the Sustut Group is related to and apparently controlled by rock type and proximity to tuff layers. Within the Brothers Peak Formation, heulandite and analcime occur only in tuffs, and most of the albite formed within 20 m of tuff. Sandstones of the

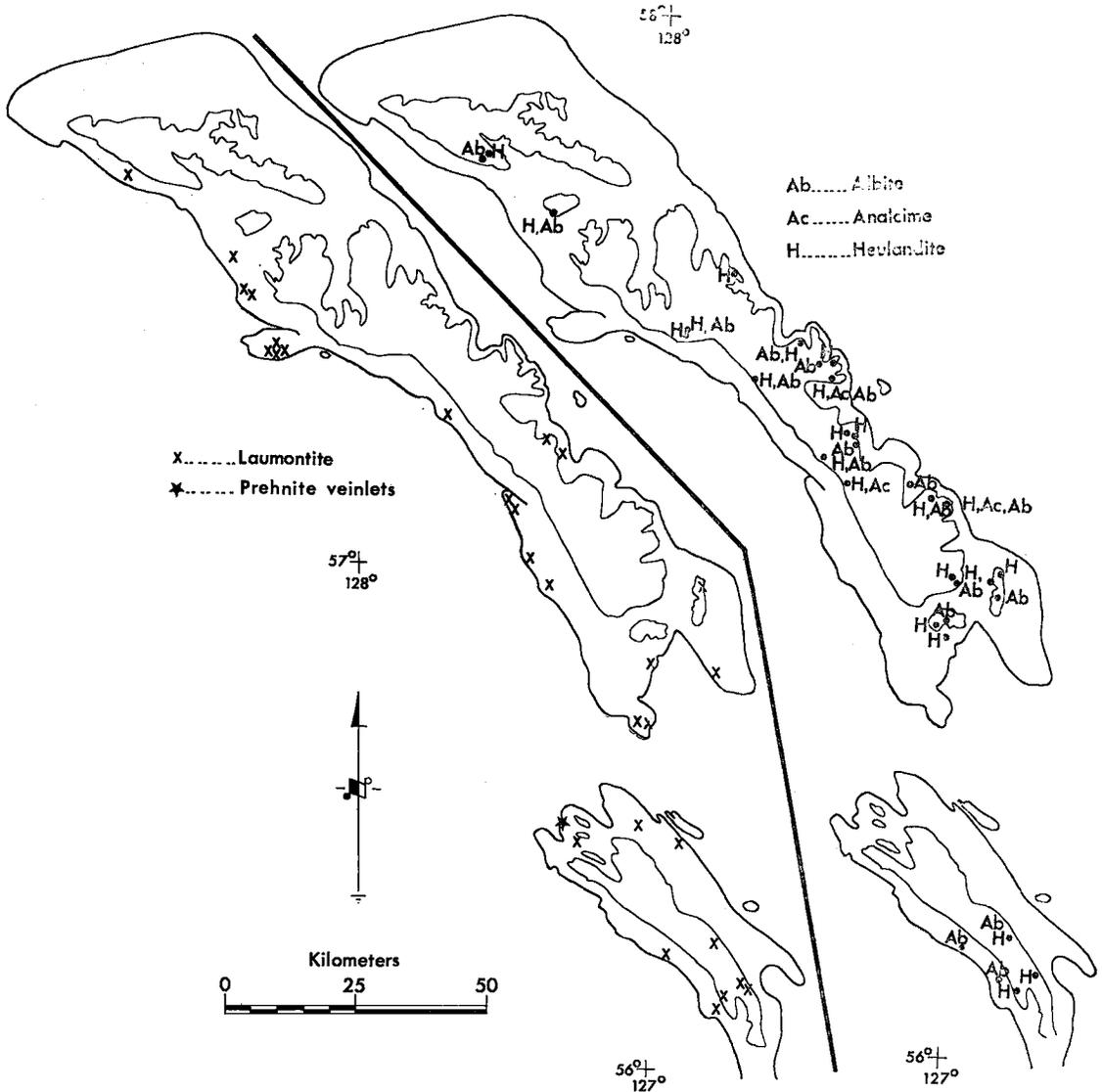


FIG. 14. (left): Regional distribution of laumontite and occurrence of prehnite veinlets in Tango Creek Formation (between thick line and thin line) and Brothers Peak Formation (within the area surrounded by thin line).

FIG. 15. (right): Regional distribution of albite, analcime, and heulandite in Tango Creek Formation (between thick line and thin line) and Brothers Peak Formation (within the area surrounded by thin line).

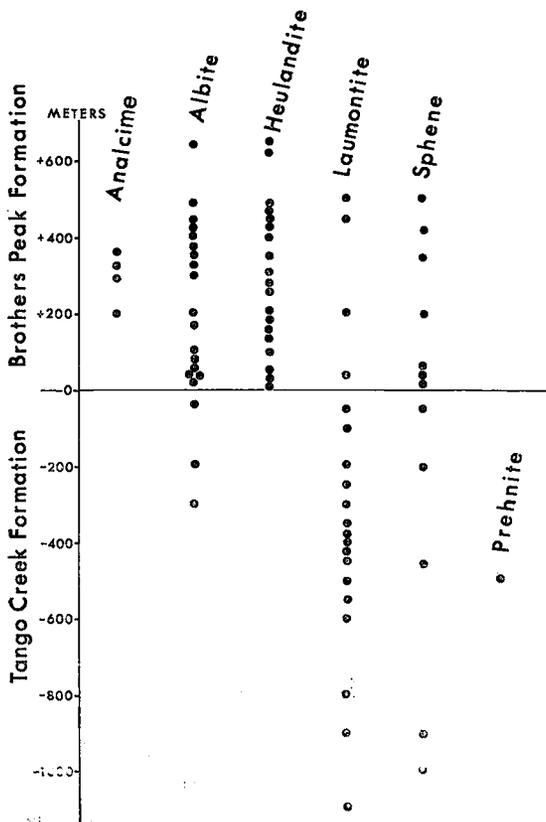


FIG. 16. The vertical distribution of analcime, albite, heulandite, laumontite, sphene, and prehnite shown in relation to the base of the Brothers Peak Formation.

Sustut Group have either albite-quartz or laumontite cement, but laumontite is restricted to non-tuffaceous sandstones. This spatial relationship between mineral assemblage and rock type is documented on both outcrop and regional scales (Figs. 8, 19). Shards are altered to heulandite-bearing assemblages throughout the Sustut Basin in spite of thickness changes within the Brothers Peak Formation from about 300 m along the east side of the basin to a maximum of at least 1000 m along the western edge of the basin. In addition, northeasterly-directed thrust faulting along the southwestern margin of the Sustut Basin may have resulted in a tectonic load on parts of the Brothers Peak Formation (Fig. 3). Laumontite- and quartz-bearing sandstones are interbedded with heulandite-bearing tuffs throughout the formation. Within Brothers Peak Formation, rock type, not depth of burial, controls the type of zeolite alteration. Alteration assemblages bearing zeolite-albite seem to be

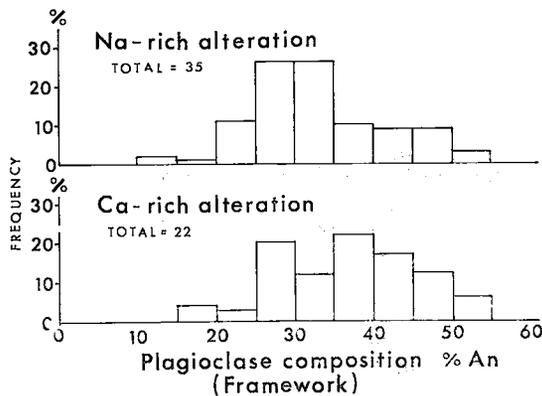


FIG. 17. Composition of framework plagioclases in sediment affected by sodium- and calcium-rich alteration. The similarity of the histograms suggests that framework plagioclase has not been changed to supply Ca for the Ca-rich alteration.

widespread throughout the Sustut Group. Alteration seems to have been restricted to permeable rocks, thus permitting the circulation of interstitial fluids.

The permeability resulted from primary porosity created during deposition of matrix-poor sandstones, from secondary porosity created by solution of vitric fragments in tuff layers and tuffaceous sandstones, and from fracturing, of sandstones, related to regional or local deformation of Sustut strata. The distribution of alteration minerals within the Sustut Basin is shown in Figures 14 and 15.

SOURCE OF THE SODIUM AND CALCIUM

The alteration mineralogy of Sustut sandstones can be characterized as calcium-rich where laumontite, heulandite, calcite, and montmorillonite are developed, or sodium-rich where analcime and albite are developed. Calcium-rich alteration extends throughout the Sustut Group, whereas sodium-rich alteration developed over a restricted vertical range close to tuffs of the Brothers Peak Formation (Figs. 16, 19).

Dissolution of the vitric part of the tuffs and organic materials such as calcareous freshwater shells provided the material necessary for the alteration minerals described above. Sodium for analcime and albite, and calcium for heulandite probably were derived from dissolved vitric framework grains of the Brothers Peak Formation. The most likely source for laumontite and disseminated to concretionary calcite in non-tuffaceous sandstones and mudstones of the Sustut Group is probably organic. Calcite cement is only rarely associated with calcium-

bearing zeolites (Fig. 18). This relationship, common in other zeolite-bearing areas (Zen 1961), results from a high ratio of the chemical potential of  $H_2O$  to  $CO_2$  ( $\mu_{H_2O}/\mu_{CO_2}$ ).

Within Brothers Peak Formation and probably within Tango Creek Formation, framework plagioclase has retained its original composition and structural state (Fig. 12). The compositional range of framework plagioclases in tuffs is the same for specimens affected by calcium-rich or sodium-rich alteration (Fig. 17). This indicates that framework plagioclases did not alter or contribute calcium for the development of calcium-bearing zeolites. In the Sustut Group, absence of zeolite-forming reactions involving albitization of a more calcic plagioclase contrasts with their importance in burial metamorphic terranes such as the Triassic of New Zealand (Coombs 1954), the Cretaceous of Puerto Rico (Otlora 1964), and the Triassic of Vancouver Island (Surdam 1973).

#### TIME OF ALTERATION

Whole-rock K-Ar age determinations were made for two samples of tuffs from the Brothers Peak Formation. One from the lowest tuff

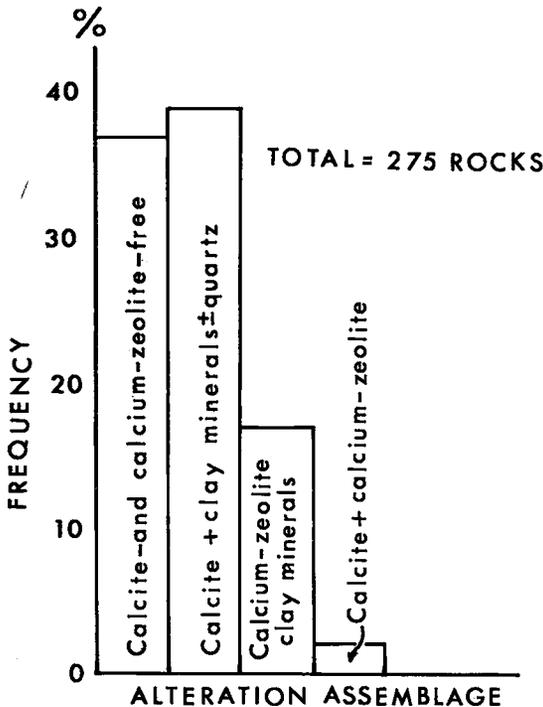


FIG. 18. Relative abundance of alteration mineral assemblages in Sustut Group.

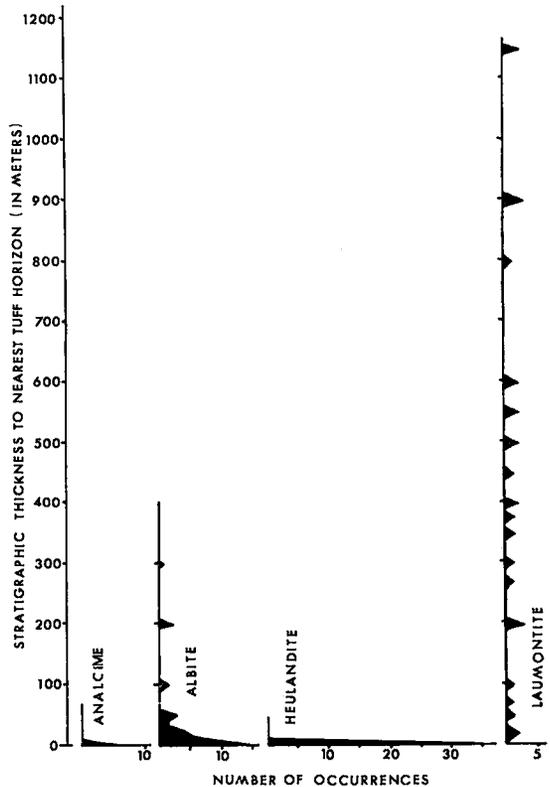


FIG. 19. Distribution of analcime, albite, heulandite, and laumontite relative to nearest tuff horizons in Sustut Group.

horizon yielded a date of  $53 \pm 6$  m.y., another from a tuff about 400 m above the base of the Brothers Peak Formation yielded a date of  $49 \pm 5$  m.y. (Eisbacher 1971). Both samples show alteration of the tuff into a heulandite-montmorillonite assemblage. Because no substantial amount of sanidine or biotite is present in these specimens, the K-Ar dates probably reflect the time of alteration. Three K-Ar age determinations on biotite from the presumed volcanic source areas of the Brothers Peak tuffs (see Fig. 9), gave ages between 57 and 49 m.y. (Lambert 1972; Souther & Wanless, pers. comm. 1974). Thus, alteration of Sustut tuffs probably occurred within a few million years after eruption and deposition.

#### ENVIRONMENT OF ALTERATION

As outlined above, the Sustut Group was deposited in a fluvial environment with regional gradients that changed direction during

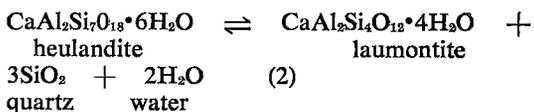
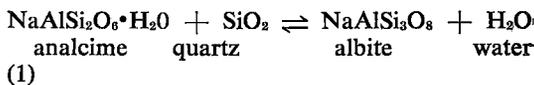
deposition of the sediments. During periods of low gradients, local swamps and small lakes developed within the overbank area of meandering streams and at the distal end of alluvial fans. These areas of low-gradient deposition were particularly favourable for the preservation of tuffs (Eisbacher, in press). Fossil flora from continental deposits of Late Cretaceous to Early Tertiary age in north-central British Columbia indicate a warm and humid mesothermal climate (Rouse 1967, Rouse *et al.* 1970). No evidence of hot, arid lacustrine environments has been found within the Sustut Basin. Redbeds are limited to a few mudstone units within the lower Tango Creek Formation (Eisbacher, in press). The distribution of alteration minerals is regional, not sporadic, and is apparently unrelated to the few, volumetrically insignificant sills and plutons of granodiorite in the south-eastern part of the basin (Kastberg Granodiorite). Because alteration was probably completed in Eocene time, younger basaltic dykes reported by Lord (1948) cannot be related to zeolite alteration. Within the Sustut Basin, a regionally high geothermal gradient, caused by the emplacement of a large volume of intrusive rock, is improbable.

If the tuffs were altered after deposition of the entire Brothers Peak Formation, the maximum stratigraphic thickness overlying the basal tuffs would not have exceeded about 1000 m (Eisbacher, in press). The maximum fluid pressure might have ranged from 0.40 kb lithostatic pressure to less than 0.15 kb hydrostatic pressure. Pressures during alteration of the Tango Creek Formation depend upon timing of the alteration. If alteration occurred after deposition of the overlying Brothers Peak Formation, then maximum burial could have been 2800 m, corresponding to a pressure of 0.75 kb lithostatic pressure to less than 0.30 kb hydrostatic pressure. Most of the laumontite-bearing Tango Creek Formation has been deformed along the southwest side of the Sustut Basin. Thus, fluid pressure during alteration locally may have exceeded 0.75 kb lithostatic or 0.30 kb hydrostatic at the base of the Sustut Group. If alteration occurred before deposition of the Brothers Peak Formation these pressures would be reduced to about one-third. Assuming an average surface temperature of 15-20°C and a normal geothermal gradient of about 35°C/km, maximum temperatures during alteration could not have exceeded 65°C at the base of the Brothers Peak Formation and about 120°C at the base of the Tango Creek Formation. At present, regional heat-flow in north-central British Columbia seems to be normal (J. G. Souther, pers.

comm. 1973), but extrapolation to Eocene time is not possible.

## DISCUSSION

Alteration minerals of the pairs albite-analcime and heulandite-laumontite may be related by reactions such as the following if quartz and water are present.



Many workers, including Coombs (1954), Otálora (1964), and Surdam (1973), consider reaction (1) important in the appearance of albite under conditions of increasing pressure and temperature. Factors such as the composition of analcime, disorder of albite, activity of water, and the form in which silica is present can affect markedly the temperature of this reaction at low pressures (Campbell & Fyfe 1965; Thompson 1971; Liou 1971). In experiments, the reaction of analcime in the presence of quartz and pure water to produce albite of intermediate to high structural state proceeds at approximately 190°C, with  $P_{\text{H}_2\text{O}}$  equal to or less than 0.45 kb. However, Campbell & Fyfe (1965) calculated that albite can be stabilized at 25°C in the presence of highly metastable forms of silica or solutions supersaturated with silica.

Textural relations and distribution of analcime, quartz, and albite in Sustut sandstones show that reaction (1) did not take place. Brothers Peak tuffs containing these minerals show that analcime and albite generally fill pore space, with no indication that albite filled space formerly occupied by analcime (Fig. 11e). In spherulitic analcime-albite tuffs, quartz crystals within analcime spherules and in the albite groundmass appear unaltered (Fig. 11d). These textures indicate that quartz and analcime did not react to form albite. Ragged analcime grains cut by albite laths such as those reported by Iijima & Hay (1968) are not found in Sustut tuffs.

The breakdown of heulandite to form laumontite and quartz has been suggested in several terranes, such as the Triassic rocks of New Zealand (Coombs 1954) and the Middle Jurassic tuffs of Oregon (Dickinson 1962). These

field data and scant experimental data (Thompson 1971) indicate that reactions (1) and (2) occur at about the same pressure and temperature conditions. However, chemical activity of water and the form of silica probably affect the temperature and pressure conditions of both reactions. In rocks of the Sustut Group, heulandite and laumontite mainly fill open spaces in tuff and non-tuffaceous sandstones, respectively, and no textures show laumontite replacing heulandite. Interbedding of albite, analcime, heulandite, and laumontite indicates that conditions other than temperature and pressure controlled the formation of these minerals.

Recently, Iijima & Utada (1971) have shown that in three deep drillings in Upper Cenozoic marine deposits along the Sea of Japan, Caclinoptilolite, analcime, and laumontite occur in volcanogenic rocks at depths of 2400 to 3500 m and at temperatures of 60 to 120°C. They also suggest that albite formed at temperatures above 120°C and at depths exceeding 4000 by reaction of analcime with quartz in the presence of interstitial water of chlorinity less than 6 g/l. They rule out any local hydrothermal alteration. The temperature for albite formation as given by Iijima & Utada is at least twice the value inferred for the crystallization of albite in the Sustut Group.

#### CONCLUSIONS

Sodium and some of the calcium in alteration minerals of the Sustut Group were derived by hydrolysis of vitric fragments within tuffs and tuffaceous sediments of the Brothers Peak Formation. Calcium also was derived from organic framework constituents such as shell fragments from within the sedimentary succession. During hydrolysis, silica and many cations, including Na and Ca, were released into solution, and their respective chemical activities determined the type of alteration minerals (analcime, albite, heulandite, laumontite, or prehnite) in primary or secondary pore space and fractures. Assuming that alumina remained fixed during this process, albite and heulandite were stabilized under conditions of high silica activity within the altered tuffs. Laumontite and possibly prehnite were stabilized in an environment of lower silica activity in areas away from the altered tuffs.

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APPENDIX

Analcime

Composition of analcime was estimated from the determinative curve of Coombs & Whetten (1967).  $\Delta 2\theta$ (analcime<sub>639</sub> - Si<sub>331</sub>) was measured on powder mounts by using Ni-filtered  $\text{CuK}\alpha_1$  radiation with  $1^\circ - 0.2\text{mm} - 1^\circ$  slits, a scan speed of  $\frac{1}{2}^\circ/2\text{a}/\text{min.}$ , and a chart speed of 120 cm/hour. Iijima & Hay's comparison (1968, p. 186) of Si/Al ratios as determined by Coombs & Whetten's determinative curve with those obtained from microprobe analysis shows that Si/Al ratios from the determinative curve differ up to -0.10 from those obtained from microprobe work.

Specimen	No. of measurements	$\Delta 2\theta$ (Analc <sub>639</sub> -Si <sub>331</sub> )	Composition based on O=96
70-55-2aE	14	1.964	(Na,K,2Ca) <sub>13.8</sub> Al <sub>13.8</sub> Si <sub>34.2</sub>
71-33-7	10	1.935	(Na,K,2Ca) <sub>14.1</sub> Al <sub>14.1</sub> Si <sub>33.9</sub>

Heulandite

Heulandite was identified by using a combination of optical, thermal, and x-ray characteristics. Thermal characteristics were investigated by preparing three powder mounts on glass slides of each specimen. Each mount was irradiated using Ni-filtered  $\text{CuK}\alpha$  radiation with a scan speed of  $1^\circ/2\text{a}/\text{min.}$  and slits and chart speed as above. Of the three mounts of each specimen, one was heated for 2 hours at  $230^\circ\text{C}$ , a second for 2 hours at  $280^\circ\text{C}$ , and a third for 15 hours at  $450^\circ\text{C}$ . After heating, each specimen was placed in a desiccator and cooled for 1 hour at  $20^\circ\text{C}$  before x-raying. From optical, x-ray, and thermal characteristics, the heulandites belong to Boles' Group 1 and 2 and are calcium-rich heulandites tending to silica-rich. Based on sign of elongation, they have Si/Al < 3.52. Specimens listed below have negative elongation.

Specimen	Thermal Characteristics			Heulandite type
	2 hrs @ $230^\circ\text{C}$	2 hours @ $280^\circ\text{C}$	15 hours @ $450^\circ\text{C}$	
69-28-6	A <sup>†</sup>	I <sup>†</sup>	Total destruction	heulandite-Ca
69-39-4a	A	I major, A minor	Total destruction	heulandite-Ca
69-39-4c	A	total destruct.	A much reduced	heulandite-Ca
69-42-09	A	I	A much reduced	heulandite-Ca

<sup>†</sup>A is initial phase with  $d_{020} = 9.97-9.05\text{\AA}$ , I is contracted phase with  $d_{020} = 8.73-8.87\text{\AA}$ .

Clay minerals

The identification of clay minerals was based on the scheme of Warshaw & Roy (1961) and the characteristics of clay minerals from Carroll (1970). Montmorillonite is light green with refractive indices in the range 1.535 to 1.570. It has a 14.0 Å basal spacing which expands on glycolation to 17 to 18 Å. Celadonite is brownish green with refractive indices in the range 1.625 to 1.645. It has a basal spacing of about 10.0 Å in untreated and glycolated material. Kaolinite is very pale green with refractive indices in the range 1.55 to 1.57. It has a basal spacing at about 7.0 Å in untreated and glycolated material. After heating kaolinite for 2 hours at  $575^\circ\text{C}$ , this basal reflection disappears.

All specimens were ground, then mixed with water and allowed to settle for 10 minutes before removing some of the supernatant fluid and letting the slurry evaporate on glass slides for x-ray diffraction, glycolation, and thermal studies. Identifications were based on changes after glycolation and on thermal changes after heating for 2 hours at  $575^\circ\text{C}$ .

Sample	Formation & rock type	Stratigraphic position above or below base of Brothers Peak Formation	Clay minerals
71-30-3A	Brothers Peak vitric tuff	350 meters above base	montmorillonite-type mineral
70-37-5E	Brothers Peak vitric tuff	170 meters above base	kaolinite
70-37-2E	Brothers Peak non-tuffaceous sandstone	150 meters above base	kaolinite
72-15-1	Brothers Peak vitric tuff	30 meters above base	kaolinite, 7Å chlorite and celadonite
72-15-3	Brothers Peak vitric tuff	30 meters above base	kaolinite, 7Å chlorite and celadonite
70-52-1bE	Brothers Peak vitric tuff	20 meters above base	kaolinite, montmorillonite-type mineral
71-20-11	Tango Creek non-tuffaceous sandstone	500 meters below base	kaolinite and mainly relict muscovite
71-20-12	Tango Creek non-tuffaceous ss	550 meters below base	kaolinite, mainly relict muscovite
70-33-4aE	Tango Creek non-tuffaceous ss	900 meters below base	mixed layer montmorillonite-type mineral, kaolinite