REPLACEMENT BRECCIAS OF THE LOWER KEECHELUS.

G. E. GOODSPEED AND HOWARD A. COOMBS.[1]

The lower Keechelus is an important formation of the Cascade Range of Washington and in many localities consists of great thicknesses of breccias. A detailed study of new exposures of these breccias at the "type locality" along the eastern shore of Lake Keechelus has led the writers to question the validity of the original explanation of pyroclastic origin. They offer instead the interpretation of *recrystallization replacement* to be applied to certain of these breccias. By this mechanism it is believed that a sandy shale has been gradually changed into an igneous-appearing rock as a process of additive hydrothermal metamorphism.

The central Cascades of Washington are composed of a series of Tertiary sediments and volcanics invaded by granodioritic batholiths. The invaded rocks have been folded into a series of anticlines and synclines trending in a northwest-southeast direction. Later deformation in a north-south direction has had a controlling effect on the topography of the present Cascade Range. Unconformably capping the range are the Pleistocene volcanoes of Mt. St. Helens, Mt. Adams, and Mt. Rainier.

GENERAL DESCRIPTIONS.

Lake Keechelus is approximately 70 miles southeast of Seattle on the Sunset highway which connects the Puget Sound region with eastern Washington. This road crosses the main divide of the Cascade Range through Snoqualmie Pass and the lake is but four miles southeast of the pass. (See sketch map.)

The first allusion to the rocks now known as the Keechelus andesitic series was made by Smith and Mendenhall when they stated, "Two types of rock occur within the area here discussed (Snoqualmie quadrangle). Of these, one is andesite and the other rhyolitic and both have beds of pyroclastics associated with the lavas."[2]

Six years later Smith and Calkins named this material the Keechelus andesitic series while engaged in geologically mapping the Snoqualmie quadrangle. They described it as follows: "It consists mainly of andesitic material with some basalt and rhyolite and a small amount of sedimentary rock. The vol-

[1] Presented at the June meeting of the Cordilleran Section of the Geol. Soc. of America held in conjunction with the Pacific Coast meeting of the A. A. A. S. Seattle, June, 1936.

[2] Smith, G. O., and Mendenhall, W. C.: Tertiary Granite in the Northern Cascades. Bull. Geol. Soc. Am., Vol. XI, April 7, pp. 223-230, 1900.

canic rocks comprise lavas, agglomerates, and tuffs, the fragmental rocks probably predominating on the whole, although the proportion varies in different localities." [3]

In 1915 W. S. Smith encountered Keechelus andesite while working in the Skykomish basin, which lies approximately 30 miles due north of the Snoqualmie area.[4] He mentions the

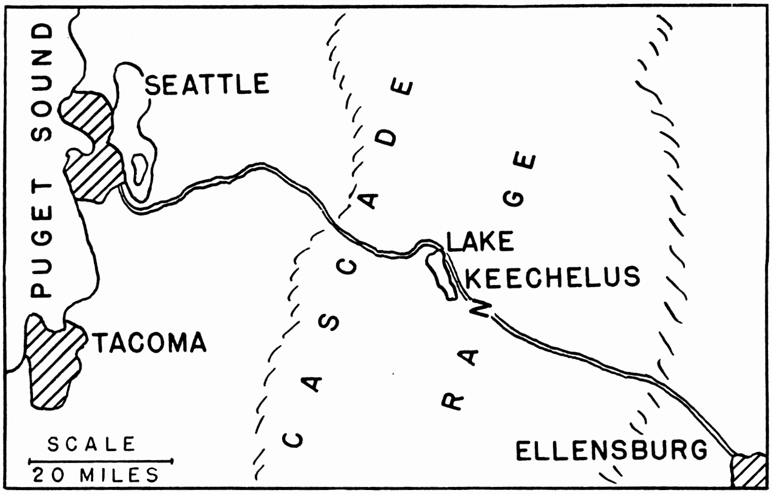

Fig. 1. Sketch map showing location of Lake Keechelus.

volcanics as being "a series of tuffs with intercalated andesite flows, felsitic sheets, and andesite dikes. The Keechelus terrane is composed chiefly of an indurated tuff in which are fragments of basaltic rocks showing flow structure mixed with quartzitic fragments."

Extensive masses of this same formation have also been found to the west, southwest, and south of the Snoqualmie quadrangle by Fuller,[5] Coombs,[6, 7] and Warren[8] respectively.

[3] Smith, G. O., and Calkins, F. C.: Snoqualmie Folio. No. 139, Geol. Atlas of the United States, 1906.

[4] Smith, W. S.: Petrology and Economic Geology of the Skykomish Basin, Washington. School of Mines Quart., Columbia Univ., Vol. 36, 1915.

[5] Fuller, R. E.: The Geology of the Northeastern part of the Cedar Lake Quadrangle. M.S. Thesis. 1925.

[6] Coombs, H. A.: Extension of the Keechelus andesitic series. (Abstract.) Proc. of the Geol. Soc. of Am. for 1934, p. 336, published 1935.

[7] Coombs, H. A.: The Geology of Mt. Rainier National Park. Univ. of Wash. Pub. in Geol., Vol. 3, No. 2, pp. 131-212, July, 1936.

[8] Warren, W.: Tertiaries of the Washington Cascades. Pan American Geologist, Vol. LXV, May, 1936.

The areal extent of this formation when completely known will undoubtedly total more than a thousand square miles. Although it shows striking variations in thickness, the average could be placed very conservatively at a thousand feet. Smith and Calkins sought to divide this formation into an upper and lower portion. However, they encountered difficulty in attempting to represent these divisions on a map, and finally abandoned the idea. They state: "In short, the criteria, while sufficient to establish the presence of two distinct groups of these volcanics, fail, except locally, to serve as a basis for the determination of the boundaries between them." Although it is often impossible in the field to distinguish upper from lower Keechelus, nevertheless, there are certain criteria that have a general application in discriminating between the two portions.

Structurally, the lower part has suffered intense folding (at least in those regions where the structure can be determined), whereas the upper portion is either horizontal or but moderately warped.

Lithologically, the lower portion has an altered appearance due to the abundance of kaolinitic material and such minerals as antigorite and clinochlore, which impart to the rock a very drab green or gray color. Contrasted to these are the lavas of the upper part, which may appear so fresh that they are difficult to distinguish from the flows of the Pleistocene volcanoes. The lower unit of the Keechelus contains many holocrystalline types such as diorite porphyries and quartz diorites. These are never found associated with the flows of the upper portion. The rocks of the lower unit are also extremely massive. Andesitic breccias can be seen in a 2000-foot vertical section with no appreciable change from top to bottom, as at Mt. Wow in Mt. Rainier National Park. On the other hand, the flows in the upper portion present color differences and a diversity in jointing that makes the individual members easily separable.

Topographically, the attitude of the younger lavas is expressed in some of the flat-topped park areas, whereas the lower portion is deeply dissected and, because of its massive character, exerts little influence on the drainage pattern.

AGE RELATIONSHIPS.

The age relationships of this formation are apparently well established. In the northern half of the Snoqualmie quadrangle the lower part of the Keechelus was found to overlie, unconformably, the Swauk, Teanaway, and Guye formations—all of Tertiary age. The youngest of these is the Guye, its age being determined as Miocene on paleobotanical evidence. In the southern half of the Snoqualmie quadrangle the Keechelus is overlain by Ellensburg beds of very late Miocene age. Hence the age of the Keechelus may be confined to the Miocene. However, this point is open to very serious doubt. (See G. O. Smith,[9] Warren,[10] and Coombs.[11])

During very late, or post-Miocene time, the Keechelus was invaded by the Snoqualmie granodiorite and many of the usual attendant metamorphic effects are common.

PETROGRAPHY OF THE BRECCIAS.

Some of the best exposures of the lower Keechelus breccias are in the new road cuts of the Sunset Highway along the eastern shore of Lake Keechelus. The predominant type is a tough, greenish gray rock, with a varying amount of angular fragments and with an aphanitic groundmass liberally sprinkled with white feldspar crystals (1-2 mm.) in length. Most of the fragments are of a reddish brown hue contrasting with the greenish gray of the groundmass, although there are many fragments of the same general tint as the groundmass. A field determination as that of an indurated pyroclastic is well warranted. However, the massiveness and the thicknesses up to 3,000 feet are unusual for pyroclastics.

A casual interpretation would be that fragments of fine-grained volcanics and abundant crystals of quartz and feldspar are enclosed in a matrix of glass or devitrified glassy material exhibiting flow structure. The presence of small spherulites in the groundmass could be cited as a further substantiation of this interpretation. However, in the study of many thin sections certain features are noticeable which are not entirely appropriate to such an interpretation. The fragments themselves are definitely of sedimentary origin and consist chiefly of small angular to rounded quartz grains in a dark brown, fine-grained matrix. In some of these fragments there is a remarkable gradation from the original sedimentary texture to a crystalloblastic one. Porphyroblasts of small size in the nature of microlites give a marked resemblance to phenocrysts. A few

[9] Op. cit., p. 8.
[10] Op. cit., p. 246.
[11] Op. cit., p. 166.

of the fragments show this transition within a single fragment, the clastic portion grading gradually into the recrystallized portion.

Many fragments exhibit a gradation into the groundmass. Ragged borders are common, and in some instances the relic material from fragments is strewn through the groundmass in a manner that simulates flow structure or shards. In other instances there is a gradual merging of fragment and groundmass.

The development of plagioclase porphyroblasts is noticeable both in the fragments and in the groundmass, and they can be seen in various arrested stages of growth. Some appear to have been formed by the coalescing of many small crystals which are in alignment so as to produce the necessary optical continuity in the larger crystal. Irregular borders, especially in the earlier stages, the inclusion of fine sedimentary material giving rise to sieve structures, and a turbidity due to included kaolinic material are some of the characteristic features of the porphyroblasts. Most of the plagioclase crystals are so turbid or so complexly twinned as to make optical measurements difficult, but some can be definitely determined as oligoclase with about 25 per cent An. The average length of the plagioclase crystals is about 1 mm. Some sections are traversed by irregular veinlets of feldspar which are probably orthoclase. This feldspar is also seen surrounding some of the plagioclase and also occurs as smaller crystals in the groundmass.

Although nearly all of the larger quartz crystals in this fragmental rock could readily be explained as resorbed phenocrysts, some of them appear to have been formed by the cementing together of several individuals, and they exhibit features similar to those usually seen in a quartzite. A few of the quartz crystals show a tendency toward idiomorphism, but most of them have corroded outlines. Some are penetrated in a very peculiar way by spherulitic aggregates of crystallites. Thin extensions of quartz from the larger crystals into the groundmass appear in some cases to be the result of corrosion and in others to the further growth of the quartz. The chief criterion used in these interpretations was the position of small protuberances of the quartz in relation to a crystal face. In those believed to be due to corrosion the crystal face or the maximum development toward a crystal face is irregularly corroded, while in those believed to be caused by further growth, the extension is beyond and added to the original crystal.

Spherulitic growths are one of the most puzzling features of this breccia. They commonly range from 0.1 mm. to 0.2 mm. in diameter, and occur not only in the groundmass but also in partially disintegrated fragments. They may be arranged around a small quartz crystal or even intimately intergrown with quartz. Some of the spherulites are associated with chloritic material and some have a nucleus of chlorite. The fibers of the spherulites have a refringence and birefringence slightly lower than quartz. Some have parallel extinction, others have an extinction angle of nearly 30°. Some of the spherulites probably consist of more than one mineral, but perhaps most of them are chalcedonic quartz.

Chloritic material occurs in rounded patches and in irregular segregations which are usually associated with ferruginous material. Although most of the chloritic material is in irregular patches, some suggests a pseudomorphic relationship to an earlier formed mafic mineral. One section shows an aggregate of epidote which is probably a pseudomorph. The ferruginous material appears on casual inspection to be related to flow structure, but careful study of many sections shows that the frayed irregular shapes assumed by this material are shapes inherited from original fragments or shapes formed incident to the replacement of the fragment by the groundmass.

Even though many features of this fragmental rock are not in accord with those of a true flow breccia, it is doubtful that any other interpretation would have been seriously advocated if it had not been for a few chance occurrences that are most provocative in suggesting an unusual mode of origin for these fragmental rocks. One of these occurrences is situated at a midway point along the eastern shore of Lake Keechelus at a rock cut on the Sunset Highway a few hundred yards south of the Lake Keechelus Inn.

At this location the outcrop is a very peculiar mixture of a very fine-grained dark brown rock and the greenish gray fragmental rock described in the preceding paragraphs. A variety of breccia forms are found in this mixture; some appear as irregular lacy-like fragments of the dark brown in the grayish green, some as long tabular masses of the dark rock almost dike-like in appearance, and others as a very coarse breccia with angular fragments. From a casual examination of the outcrop it might even be interpreted that a basic igneous material had injected the lighter colored rock. The shape of patches of the light rock in the dark might be considered as fragments, but on the other hand there is no visible evidence of chilled borders or any effect of baking on the light greenish gray rock. This question is answered by petrographic studies of many thin sections which show the true nature of the dark rock and also furnish evidence for a new interpretation of the mode of origin of the breccia. Under the microscope the dark brown rock is seen to be definitely of clastic origin, consisting of grains of quartz and feldspar (0.5 to 0.1 mm. in size) a few rounded rock fragments and numerous bright red specks of iron oxide and a few small irregular aggregates of chlorite in a finer grained clastic matrix. This very fine matrix is composed chiefly of minute fragments of quartz and feldspar with an indeterminable cementing material which may be a mixture of kaolinitic and ferruginous material. Some sections show streaks of finer material about 0.5 mm. thick. These are doubtless due to bedding although some of them have no particular alignment. There are occasional ramifying veinlets of secondary silica which traverse both the coarse and fine clastic material. Some sections of this indurated sandy shale contain feldspar porphyroblasts. These authigenic constituents are usually readily distinguished from the allogenic constituents by the following criteria. The porphyroblasts commonly show gradational relationships with surrounding material as contrasted with the even boundaries of the detrital grains, and they commonly have hair line extensions into the surrounding material, whereas the allogenic grains are usually minutely fractured and show an infiltration of the cementing materials into these fractures. The feldspar porphyroblasts may be euhedral and usually exhibit an even distribution of turbidity in contrast to the clearness of the allogenic grains even of very small size. The turbidity of the authigenic feldspar is probably due in part to the inclusion of material and in part to the development of kaolinitic material incident to the formation of the feldspar. It is usually possible to distinguish this type of material from that which is imposed upon an already existing crystal. Secondary alteration commonly follows previously existing structural features such as cleavage cracks, whereas the kaolinitic material formed contemporaneously with the growing porphyroblast shows no such structural control.

Those thin sections of the coarse breccia showing a mixture of the dark indurated sandy shale and the finer grained greenish gray breccia present evidence for which a new interpretation seems necessary. In these sections the clastic portions usually exhibit numerous feldspar porphyroblasts. The "groundmass" of the fine-grained gray breccia has a cloudy nebulous appearance as compared to the clastic material and frequently occurs in veinlets and patches of irregular outline. On close inspection it is seen that this nebulous groundness has apparently gradually encroached upon the clastic material and

Fig. 2. Outcrop showing lacy-like remnants of dark brown, indurated sandy shale in an igneous-appearing matrix.

is filled with relics of the detrital material. Some of these relics are angular fragments a millimeter or more in size, others are of individual grains and finer detrital material. The larger fragments show various stages of absorption by the groundmass and commonly exhibit frayed borders or gradational contacts. Within the groundmass perhaps the most striking feature is the development of porphyroblasts. Although feldspar porphyroblasts occur sporadically in the dark brown clastic material, they form a dominant part of the grayish green groundmass. Gradational borders, the inclusion of material, and other features make it more appropriate to interpret the crystals as porphyroblasts instead of phenocrysts. In many sections, narrow irregular veinlets of the "groundmass" are so filled with these crystals that it would be very difficult to conceive of them as phenocrysts. The termini of some of the veinlets of the groundmass grade into porphyroblasts and it is not uncommon to see a feldspar porphyroblast gradational on one side into the clastic material and on the other side into the groundmass.

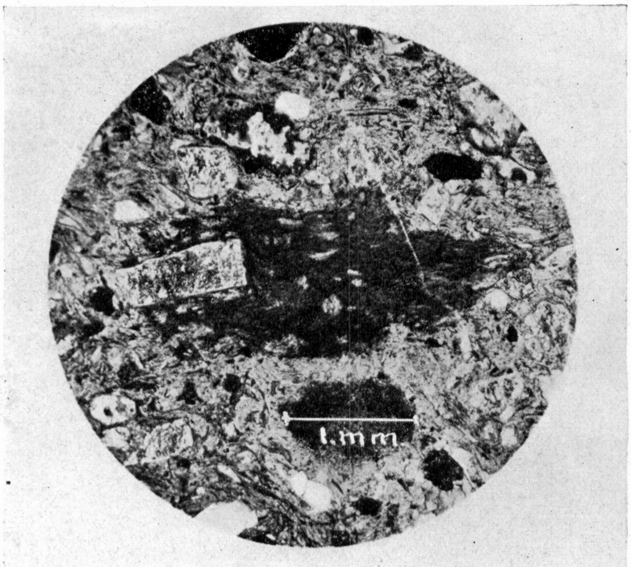

Fig. 3. Photomicrograph of the igneous-appearing matrix showing "fragments" of the indurated sandy shale. The largest of these fragments is partially recrystallized and contains many small porphyroblasts. Note the extension of a large plagioclase porphyroblast extending from the fragment into the matrix.

Many of the quartz crystals show evidence of corrosion, irregular outlines and embayments being common. Some of the embayments show radiating acicular crystallites which grade into the quartz crystal in a way that suggests vermicular replacement. These crystallites are apparently identical with the spherulitic aggregates common to the groundmass. Some of the porphyroblasts are compound crystals and have apparently been formed by the coalescing of several smaller individuals.

When viewed in reflected light the groundmass has not only an opaque appearance due probably to the kaolinitic material but has also a distinct greenish tinge on account of the chloritic material. Some carbonate is also in evidence in the groundmass. The clastic material, on the other hand, is usually filled with small bright specks of iron oxide, and under reflected light does not exhibit the opaqueness or the greenish color that is characteristic of the groundmass.

Chemical analyses of the dark brown clastic rock (K1) and the grayish green groundmass (K2) were made from as uncontaminated material as possible. It must be borne in mind that the matrix or groundmass always contains a varying number of small fragments of the clastic rock. The analyses are as follow:[12]

	K1 Sedimentary "Fragments"	K2 Matrix
SiO_2	60.55	71.00
Al_2O_3	16.80	14.25
Fe_2O_3	2.42	.83
FeO	5.53	2.74
MgO	1.95	.80
CaO	3.55	1.80
Na_2O	4.92	4.25
K_2O	.58	2.15
H_2O+105° C.	2.30	1.20
H_2O—105° C.	.55	.45
TiO_2	.68	.30
P_2O_5	.14	.09
MnO	Trace	Trace
	99.97	99.86

It is of interest to note that the indurated sandy shales have a substantial iron content, a considerable amount of CaO and over eight times as much soda as potash. On comparing this analysis with that of the greenish gray matrix, a decided increase in SiO_2 and K_2O, and a marked decrease in Fe_2O_3, FeO, MgO and CaO is noticeable. There is but a slight decrease in Na_2O. This chemical analysis is very similar to the analyses of many rocks that have been considered typical dacites. If only this grayish green rock had been studied, and if its association with the clastic rock had not been observed, the interpretation as dacitic lava would have been appropriate in spite of certain peculiar petrographic features.

CONCLUSIONS.

The two most obvious interpretations of the mode of origin of these breccias of the Lower Keechelus would probably be

[12] Analyses by W. H. Herdsman, of Glasgow, through the courtesy of Dr. Richard E. Fuller.

that of a pyroclastic accumulation or of a dacitic flow breccia. Petrographic studies indicate clearly that the assumption of pyroclastic accumulation is inadequate. The clastic nature of many of the fragments and their evident resorption into the groundmass are characteristics that are not common in true pyroclastic deposits. It is true that certain features in the groundmass might casually be interpreted as shards, but careful examination indicates that they are not the result of accumulation of small irregular particles of volcanic glass but that they are related to the disintegration and replacement of fragments by the groundmass.

There are several minor objections to explaining the rock as a dacitic flow breccia. Chief among these are the lack of demarcation of flows and the development of porphyroblasts instead of true phenocrysts, but many of these distinctions are not easily made. However, the relationship of this supposed lava to the dark brown indurated sandy shale presents convincing evidence against this explanation. The irregular form of many patches of the grayish green rock surrounded or nearly surrounded by the dark brown rock of sedimentary origin imposes serious difficulties on any interpretation involving the penetration or injection of magma or lava, since it is very difficult to conceive of a mechanism to form such cavities which allow the penetration or injection of magma or lava. On the other hand much of the evidence, such as gradational contacts and the development of porphyroblasts, suggests that the clastic rock has been metamorphosed by penetrating emanations and that a progressive recrystallization replacement has taken place in which the sandy shale has been gradually changed into a rock that could be called a dacitic flow breccia.

There are many exposures in the Cascades of Washington where the Snoqualmie granodiorite has invaded the Lower Keechelus, and in this immediate vicinity (along the eastern shore of Lake Keechelus) the granodiorite can be expected at a depth of but a few hundred feet.[13] It is, therefore, logical to assume that the emanations came from the granodioritic mass.

The efficacy of hydrothermal emanations has been definitely established by Fenner in his bore-hole investigations in Yellow-

[13] Goodspeed, G. E., and Coombs, H. A.: Quartz-Diopside-Garnet Veinlets. Amer. Miner., Vol. 17, No. 12, p. 554, 1932.

stone Park,[14] and by Bastin in his study of the "aplites" of Gowganda and Elk Lake, Ontario.[15] It is not exceeding reasonable expectations to postulate that thermal emanations penetrating sandy shale along bedding planes and numerous joint cracks might cause a recrystallization replacement that would ultimately produce a rock very similar to one formed by the crystallization of a lava. Perhaps some true glass was formed by hot gases, and that later, the glass was devitrified and replaced by the succeeding hydrothermal solutions. Some of the banding in the groundmass and perhaps the spherulitic aggregates might have originally formed in a true glass. In the neighboring counties of Chelan and Okanogan there are several occurrences of glassy rocks having petrologic relations which suggest that thermal emanations and hydrothermal solutions have played an important rôle in their mode of origin.

It is obvious from the chemical analyses that considerable amounts of silica and some potash have been added while iron, lime, magnesia, and some alumina have been removed. It might be expected that as *recrystallization replacement* advances the resulting rock would no longer be permeable to the activating emanations; therefore, a progressive spreading of replacement through permeable clastic material would continue while remnants apparently in the form of fragments that were protected from further action might remain unchanged. The chief result of this mechanism would be the production of large masses of igneous-appearing rocks formed in place by processes of additive metamorphism.

[14] Fenner, C. N.: Bore-Hole Investigations in Yellowstone Park. Journal Geology, Vol. XLIV, No. 2. 1936.
[15] Bastin, E. S.: Economic Geology, Vol. 30, No. 7, pp. 715-734, 1935.

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