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MICROSCOPIC AND X-RAY EXAMINATION OF ROCK FOR DURABILITY TESTING

December 1976
Final Report

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16. Abstract

Study of quarry rocks, core, weathered rock, and road base aggregates from 12 sources in western Oregon reveals that degree and type of alteration and textural distribution of glass are the chief causes of degradation in basaltic aggregate used in road construction. Smectitic clays are the alteration products most responsible for breakdown. Sampling for testing should include weathered rock.

Some standard tests for durability show a higher correlation than others with type and degree of alteration and with actual service records of basaltic rock. A standard petrographic microscopic test must precede other testing. A stain test using benzidine to reveal the presence and textural distribution of montmorillonite and nontronite clays shows promise as a supplement to standard AASHTO tests. In very doubtful cases, tests using activation by thermal neutron irradiation may be used to detect sodium distribution in rocks. Scanning electron microscopy is of value to detect micro-fracturing.

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PREFACE

The work of several Portland State University students contributed greatly to this study. Steve Van Atta, Chris Nastrom, and Billie Cox contributed by aiding in the tedious job of sample preparation. Graduate students Fran Olson and Andrew Ewing assisted in the X-ray diffractometry and neutron activation analysis.

Special thanks are due Tektronix, Incorporated, Beaverton, Oregon, for use of one of their SEM instruments during 1974 and 1975.

The author appreciates the cooperation of numerous other persons who by their efforts contributed in various ways to this research.

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MICROSCOPIC AND X-RAY STUDY OF BASALTIC ROCKS AND SUPPLEMENTAL DURABILITY TESTS

INTRODUCTION

The purpose of this microscopic and X-ray study of basaltic rocks is two-fold: the first is to determine the causes of accelerated degradation of basaltic rocks used in road construction; the second is to devise tests to amplify the existing AASHTO tests used to evaluate these rocks.

In western Oregon basaltic rocks are often the most readily available for road construction, while in the southwestern part of the state metavolcanic and metasedimentary rocks are also used. Andesitic volcanic rocks are commonly used in the Cascade Mountains of western Oregon. The basaltic rocks often have deleterious components and textures which make them borderline cases in durability testing. Reliable supplementary tests to reveal the presence and textural distribution of swelling clay alteration products, for example, will make it possible to accept a basaltic rock that might otherwise be rejected or to reject a rock which seems satisfactory on the basis of conventional durability tests.

It has been found through the study of basaltic rocks from 24 different sources scattered throughout six western Oregon counties that the presence, type and degree of alteration, and textural distribution of volcanic glass are the most critical factors controlling the rate of degradation. It was also found that in some basalts swelling clays may be present as alteration products of primary components other than glass. Such deleterious material if uniformly distributed in a basalt will continue to develop, bringing about rapid degradation.

Tests which proved most useful in detecting the presence of alteration products that cause rapid degradation in the rocks include the staining of smectite clay with benzidine and neutron activation followed by autoradiography. The latter test can be used to detect the degree of alteration on the basis of sodium ion distribution.

Previous Study

This report is the second and final report of a project which began in the summer of 1973 as an investigation of four quarries in the Nestucca River area of northwestern Oregon. The results of this first phase of the study have been published in Report Number FHWA-RD-74-20.

Plan of Study

After examination of basaltic rocks from 24 different localities during the summers of 1973, 1974 and 1975, ten sources were chosen for detailed study and development of tests. In the summer of 1974 additional samples were taken from quarries, drill cores, and road base courses. Two additional sources were sampled during 1975 to make a total of twelve. It was decided to concentrate on basaltic rocks, even though some greenstones and graywackes were also sampled. This decision was reached because the potential durability of basaltic rocks is commonly more difficult to assess. All of the quarries sampled in the 1973 study are included. Figure 1 shows the location of the rock sources, and Table 1 lists the source names, rock types, and service ranks. These sources were chosen for the study because most of them have known service records, there is an adequate record of AASHTO durability testing, and it is possible to sample road base aggregates manufactured from most of them.

The sampling plan for each source included taking samples from each of the following:

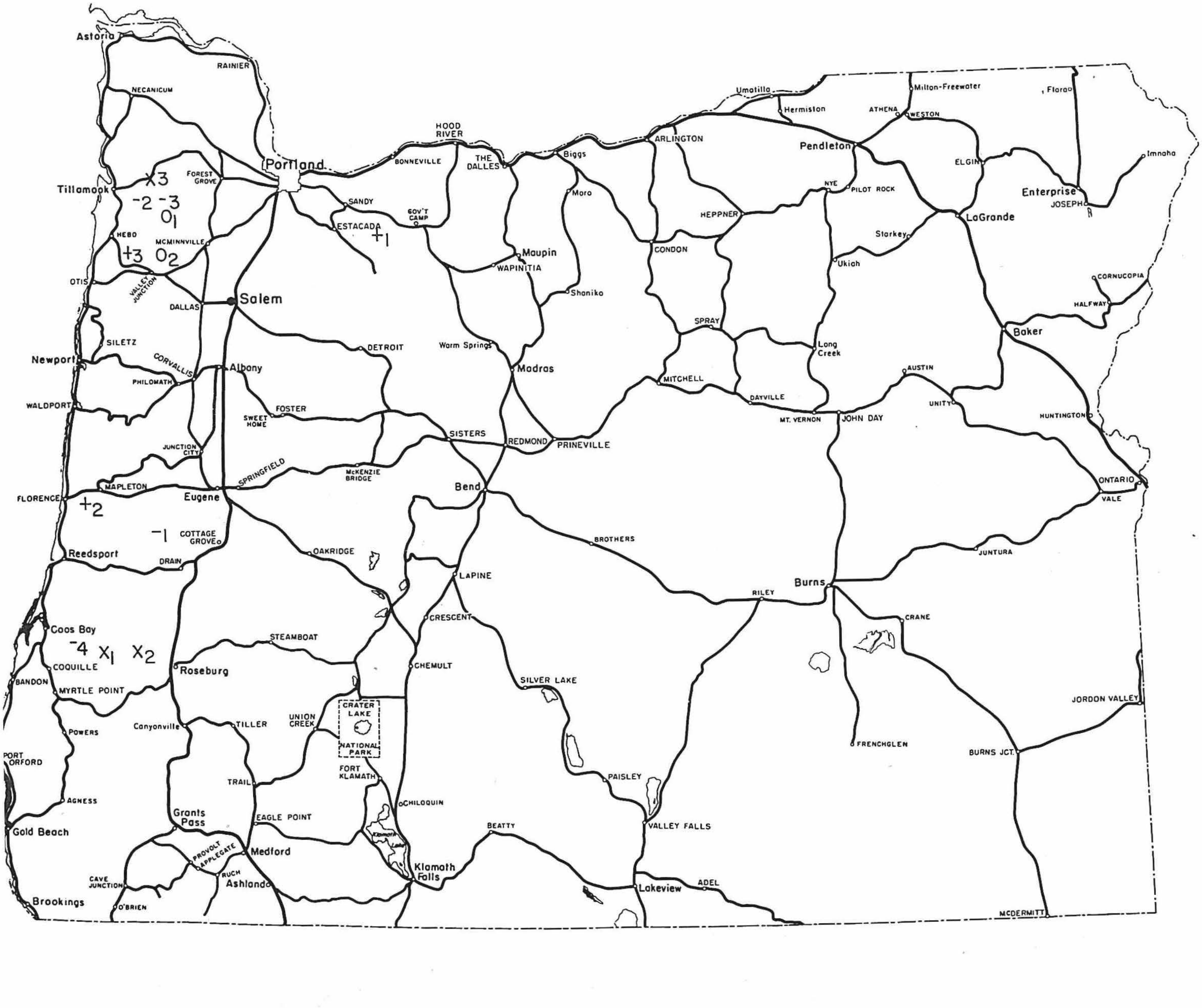

Figure 1. Location map showing the rock sources studied. For source names by symbol, see Table 1, page 4.

(1) "Fresh" quarry rock and/or drill core. (The term "fresh" is relative, since some weathering and/or hydrothermal alteration is inevitably present.)

(2) Weathered rock, C-soil horizon.

(3) Soil - B-horizon.

(4) Base course aggregate from roads known for certain to have been constructed with the source rock.

Methods of Study

All samples except soils were thin sectioned for determination of mineral composition and texture using the petrographic microscope. Selected samples from Ainsley (06-0021), King (06-0028), Blue Ridge (06-0090), Lookingglass (10-0291), Dovre Peak (29-0028) and Wanless (36-0032) quarries were also thin sectioned for exposure to thermal neutrons in the nuclear reactor at Reed College, Portland, Oregon. Additional thin sections were made for stain testing. In all, about 200 thin sections were prepared. The percentage composition of samples was determined by using a modification of the point-counting method of Chayes, 1956.

All samples chosen for study were prepared for X-ray diffraction analysis by pulverizing and separating them into 2.0 to 0.2 micron and less than 0.2 micron size fractions. The iron oxides were removed from all sized samples which clarified the results of X-ray diffraction. The procedure used in the 1973 (Van Atta and Ludowise, 1974) study whereby bromoform was used to separate low density alteration components prior to X-ray diffraction was abandoned since it was found in subsequent work that this produced no better X-ray results. X-ray diffraction was used to identify clay minerals and to study possible asphalt emulsion-clay reactions.

A few samples (Fish Creek, Hawley Creek, Wanless and Dovre Peak quarries) were examined using the electron microprobe to determine composition of alteration components and volcanic glass. The scanning electron microscope was also used to examine alteration texture.

RESULTS OF STUDY

Petrography

Field Occurrence and Rank of Basaltic Rocks

Occurrences of the rock types sampled are listed in Table 1 according to service rank, based on how roads constructed with them held up with use. Those with a positive rank (+) have given satisfactory service under normal usage with only the usual maintenance over a period of several years. Those with marginal rank (0) include the Wanless Quarry rock which has been used for roads constructed in 1971-72 in Yamhill County, Oregon. These roads have shown satisfactory service but under very light traffic. The Bald Mountain Quarry rock is also ranked as marginal since the Bald Mountain Access Road, constructed in 1966 and sealed in 1971, is now showing signs of base course degradation. Quarry rocks given a negative rank (-) have caused rapid failure in the base course of roads. These failures have sometimes developed in less than one year after completion of the project, as in the case of the Nestucca Access Road (Yamhill County, Oregon) and the Upper Siuslaw Road (Lane County, Oregon). Quarry rock ranked as unknown (x) either have not been in service long enough to judge their durability or have not as yet been used in road base construction.

TABLE 1 - SOURCES AND ROCK-TYPES SAMPLED,
INCLUDING RANKING OF IN-SERVICE PERFORMANCE

Source, Quarry No.	Location[1]	Rock Type	Rock Occurrence	Service Rank[2]
1. Fish Creek 35-03-0007	SW 34, T3S, R6E Clackamas Co., OR	Glassy Basalt	Lava Flow, Yakima Basalt, Columbia River Group	+
2. Roman Nose 35-10-0055	7, T19S, R8W Douglas Co., OR	Granophyric Gabbro	Intrusive into Tyee Formation (sandstone)	+
3. Bible Creek 35-29-0028	NESE, 7, T4S, R7W Tillamook Co., OR	Olivine Gabbro	Intrusive into Nestucca Formation (mudstone)	+
1. Bald Mtn. 35-36-0001	NESE 29, T3S, R6W Yamhill Co., OR	Glassy Basalt	Lava Flow, interbedded with Nestucca Formation mudstones	0
2. Wanless 35-36-0032	SW 34, T3S, R6W Yamhill Co., OR	Glassy, Vesicular Diabase	Lava Flow or shallow intrusive in Nestucca Formation mudstones	0
1. Hawley Cr. 35-20-0017	NWSW 5, T20S, R4W Lane Co., OR	Gabbro	Intrusive into Spencer Formation (sandstone)	-
2. Dovre Peak 35-29-0008	15, T3S, R7W Tillamook Co., OR	Glassy Gabbro	Intrusive into Nestucca Fm. mudstones	-
3. State 35-36-0001	NESW 16, T3S, R6W Yamhill Co., OR	Olivine Gabbro	Intrusive into Nestucca Formation mudstones	-
4. King 35-06-0028	SE 12, T29S, R12W Coos Co., OR	Amygdaloidal Basalt	Partly submarine flow and flow breccia, Roseburg Fm.	-
1. Ainsley 35-06-0021	21, T28S, R12W Coos Co., OR	Glassy Basalt, some pillow str.	Lava flow, partly submarine, Roseburg Formation	x
2. Lookingglass 35-10-0291	29, T27S, R6W Douglas Co., OR	Glassy Basalt, some pillow str.	Submarine lava flow, Roseburg Formation	x
3. Dovre Peak W 35-29-0047	NWNE 11, T3S, R11W	Diabase (glassy)	Intrusive, related to Dovre Peak Gabbro (35-29-0008)	x

[1] All locations from Willamette Meridian and Base Line

[2] Service Rank: + Satisfactory, 0 Marginal, - Unsatisfactory, x Unknown

The basaltic rocks included in this study may be classed into three groups, according to their origin:

(1) Submarine basaltic flows and breccias. Usually this type of occurrence includes a mixture of both lava flows and highly fragmented but well-cemented rock, although some submarine flows may show pillow structure (See Figure 2). Pillow structure can be a minor and non-uniform structural feature. Basaltic rocks in the King and Ainsley quarries in Coos County, and Lookingglass quarry in Douglas County, Oregon, belong to the Roseburg Formation, a partly submarine basalt lava complex of Eocene age. Most submarine basalts show a great deal of hydrothermal alteration due to the reaction of the lava with sea water. This reaction may take place both during extrusion of the lava and after extrusion. Palagonitic volcanic glass is almost universally found in rocks of this type and is often partially altered to smectitic clay. Therefore, submarine basalt subjected to conventional AASHTO tests to determine durability will usually fail.

(2) Lava flows (subaerial). These are tabular bodies of basaltic rock which may contain volcanic glass. They commonly exhibit some columnar jointing (See Figure 3). The degree of alteration is variable depending in part upon the nature of the surface over which the lava flowed. Where there was no appreciable water, there may be a relatively small amount of alteration. Where lava flowed over wet ground or into standing water, steam generated may have caused a considerable amount of alteration, first in the glass formed by sudden chilling, and second in the primary minerals. Therefore, subaerial lava flows may even in a single flow be quite variable in durability. The Fish Creek, Bald Mountain and Wanless quarry rocks are all parts of subaerial basaltic lava flows.

Figure 2. Pillow structure in submarine basalt. King Quarry (06-0028)

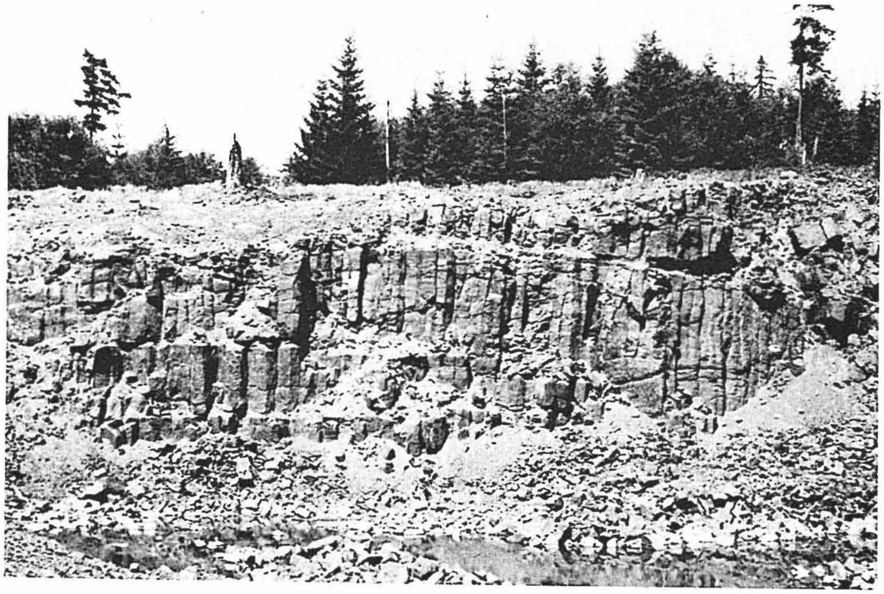

Figure 3. Subaerial basaltic lava flow showing columnar structure. Wanless Quarry (36-0032)

Figure 4. Intrusive gabbro with columnar structure.

Dovre Peak Quarry (29-0008)

Figure 5. Photomicrograph. Typical intersertal texture with volcanic glass (black and dark gray) between plagioclase feldspar and pyroxene crystals. Note large area of glass, upper center (black).

Fish Creek Quarry (03-0007)

(3) Intrusives. These are tabular or irregular bodies of rock which have been formed from intrusion of basaltic magma, either along and/or across bedding planes in sedimentary rock or along fractures and other zones of weakness in sedimentary or other types of rock. Because of the insulating capacity of the enclosing rock, heat is lost slowly. This brings about a coarser granular texture. If volatiles such as water are present in the parent magma or available from the surrounding rock, alteration of the intrusive rock may be considerable. Glass may or may not be a primary component. If glass is present, it usually shows some alteration due to reaction with volatiles. The primary minerals may also suffer alteration. The type and degree of alteration depends upon the chemical composition of the volatiles available, the temperatures and vapor pressures, and the rate of heat and volatile loss. Intrusive basaltic rock bodies are generally much more uniform in degree and nature of alteration, as well as alteration texture, compared to extrusive flow rock. Intrusive basaltic rocks are found in the Roman Nose, Bible Creek, Hawley Creek, State, Dovre Peak (See Figure 4), and Dovre Peak West quarries. For the most part they classify as gabbro, which may be considered a coarse-grained basalt.

With the exception of the submarine flows and breccias, there is no direct connection between the origin and occurrence of basaltic rocks and their serviceability for road construction. For example, both the Roman Nose gabbro and the Dovre Peak gabbro are intrusive rocks but the Dovre Peak rock is highly subject to degradation while Roman Nose is not. The difference is that Dovre Peak gabbro contains considerable amounts of altered volcanic glass, whereas the Roman Nose rock has no glass.

The degree to which the rock body has been subjected to hydrothermal alteration during emplacement is critical to its durability. Although rock may test satisfactorily for durability in the outer parts of the body, the inner rock will often yield much lower durability test results. This happens where volatiles are entrapped at sustained high temperatures in a very thick lava flow or in an intrusive body for a long enough period of time to cause alteration of the interior.

Rock Composition and Durability

Primary Components

In the initial phase of this project a detailed petrographic analysis was made of 19 aggregate source rocks, including a number of samples of weathered rock and road base aggregate from the four sources mentioned earlier in this report. These analyses are given in Report Number FHWA-RD- 74-20. It has been found, however, that the most critical factors in rock durability, those which must be determined in any realistic testing, are dependent upon alteration products and textures. Hence, only a summary of primary components and texture of the 12 rocks presently studied is included in this report. For definitions of primary components, see Appendix D.

The modal ranges of percentages of primary rock-forming minerals and glass in the fresh quarry rock or cores analyzed for this project are as follows:

Plagioclase Feldspar ($NaAlSi_3O_8 - CaAl_2Si_2O_8$)(An 70-90)[1] 25 - 50%
Pyroxene (one or more of the following)
    Augite $(Ca,Na,Mg,Fe^{+2},Mn,Fe^{+3},Al)_2 (Si,Al)_2O_6$
    Hypersthene $(Mg,Fe)_2Si_2O_6$ 15 - 35%
    Pigeonite $(Mg,Fe^{+2},Ca)(Mg,Fe^{+2})Si_2O_6$

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[1] Chemical formulas of minerals are taken from Deer, Howie and Zussman, 1962-63

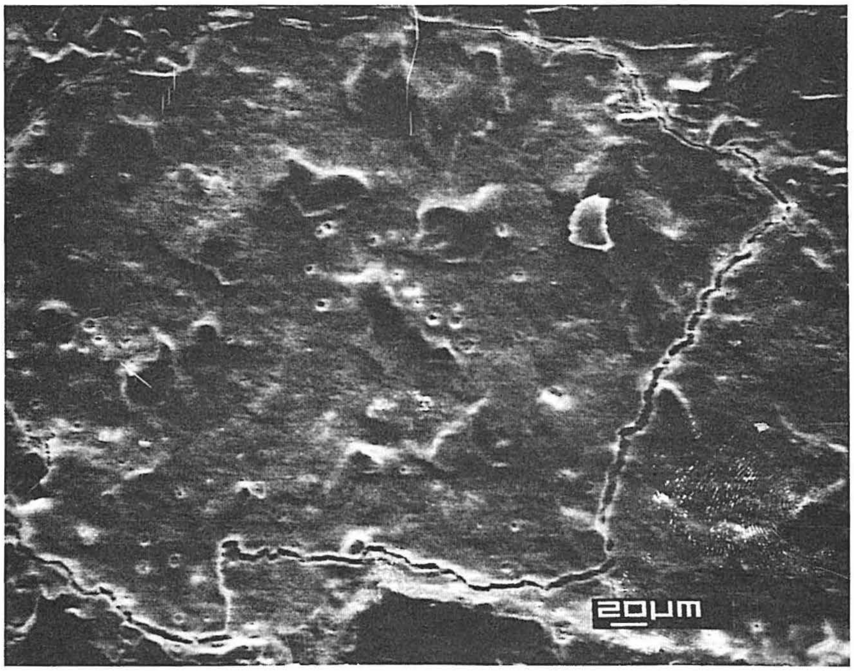

Figure 6. Scanning electron photomicrograph. Vesicle is filled with volcanic glass with microfracture surrounding glass filling. Dovre Peak Quarry (29-0008)

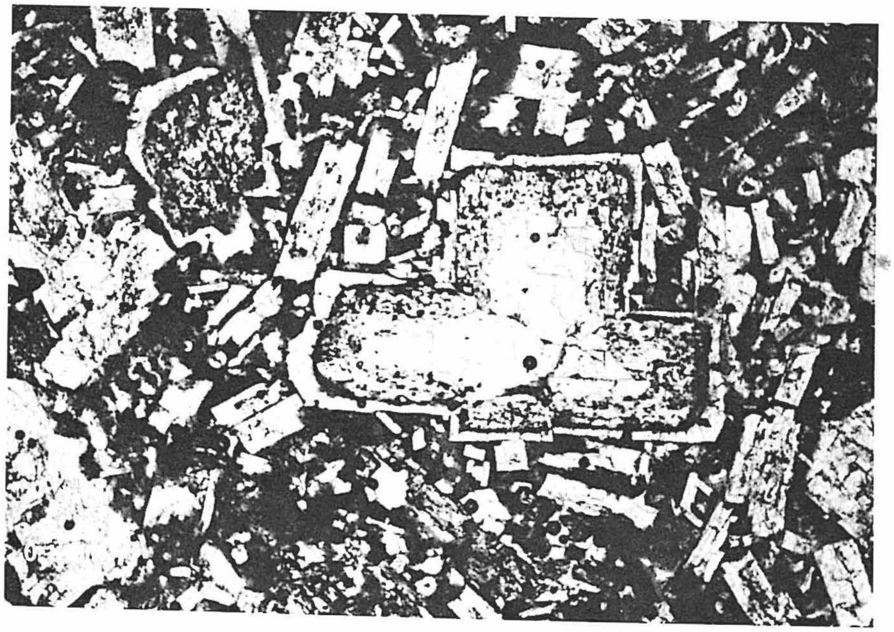

Figure 7. Corroded and overgrown feldspar crystals. Hawley Creek Quarry (20-0017)

Olivine $(Mg,Fe)SiO_4$	0 - 5%
Biotite $K_2(Mg,Fe)6\text{-}4(Fe,Al,Ti)_{0-2}(Si_{6-5}Al_{2-3}O_{20})O_{0-2}(OH,F)_{4-2}$	0 - 5%
Magnetite, $FeO\text{-}Fe_2O_3$ and Ilmenite, $FeTiO_4$	2 - 10%
Volcanic glass, including Palagonite	0 - 25%
Minor components, e.g., Apatite	Less than 1%

The textural distribution of these minerals are subophitic to intersertal. With subophitic texture the feldspar and pyroxene are intergrown without interstitial spaces filled with glass. With intersertal texture interstices between intergrown feldspar crystals are filled with glass. (See Figure 5.) Some of the rocks are porphyritic with phenocrysts of feldspar and pyroxene and, in a few rocks, olivine. Olivine is not an abundant constituent of any of the rocks studied. Those rocks with pigeonite pyroxene have probably had olivine converted to pigeonite in the course of primary crystallization.

Some basaltic rocks are amygdaloidal, having relatively large (5-10 times average primary crystal size) original gas vesicles filled with altered or unaltered glass, and/or a zeolite mineral, opal, chalcedony, or albite. These minerals are especially common in submarine basalts. Other critical structural characteristics include microfracturing in glass, especially in the vesicular glass (See Figure 6). Usually, glass is found in the interstices between feldspar and pyroxene crystals, and may be altered hydrothermally during the last steps of crystallization when the temperature drop is rapid enough to cause glass to form. These facts are fundamental to the explanation of low durability in many basaltic rocks.

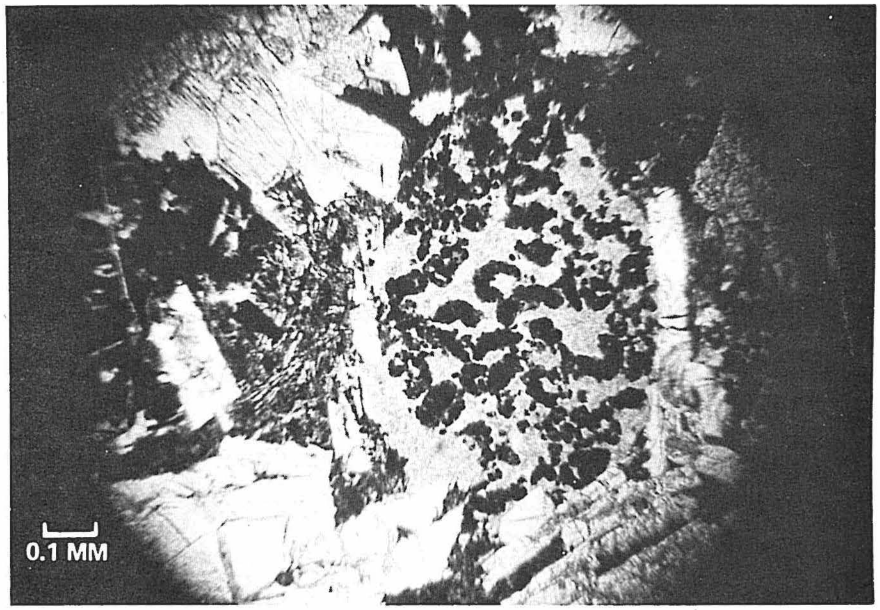

Figure 8. Vermicular smectite clay grown in glass can be seen right of center. Dovre Peak Quarry (29-0008)

Alteration of Primary Components

Hydrothermal or deuteric

Chemical reactions involving primary components of a basaltic rock may occur in two stages. If sufficient volatiles such as water are present during crystallization of a lava or a magma, and if the rate of change of temperature is not too rapid, hot fluids may react with crystals or, later, with glass to form a number of different alteration minerals. The formation swelling clays of the smectite group in glass (See Figures 7 and 8) is an example of hydrothermal or deuteric alteration. These minerals are formed at the expense of primary components. Hydrothermal or deuteric alteration takes place at temperatures and pressures greater than those associated with the second stage of alteration, which includes rock weathering, as explained below. It is also possible to alter hydrothermally by the nearby intrusion of another rock mass, by superposition of a lava flow, or by superheated fluids streaming through fracture systems in the original rock. Under suitable conditions of formation some rocks may develop very little or no hydrothermal or deuteric alteration. For definitions of alteration components, see Appendix D.

Weathering

The second stage of rock alteration takes place in the processes included in weathering, in which chemical interaction occurs between meteoric ground waters containing dissolved materials, including oxygen, and the minerals and glass making up the basaltic rock. All rocks at or near the earth's surface are subject to weathering, whether or not they have gone through a stage of deuteric and/or hydrothermal alteration. Essentially, degradation of rock aggregate in a road base is a case of accelerated weathering. The portion of the report dealing with testing will show that examination of weathered rock at the source site will yield a fairly accurate estimate of the minerals which may be generated in the course of degradation of road base aggregate.

TABLE 2 - A COMPARISON OF THE PERCENTAGE OF ALTERATION IN BASALTIC ROCKS WITH GOOD, MARGINAL AND UNSATISFACTORY SERVICE RECORDS

Rock Source	Service Rank	Fresh		Weathered C		Agg. Base Course		Notes
		Total Alt.	Smectite	Total Alt.	Smectite	Total Alt.	Smectite	
03-0007	$+_1$	25	8	21	?	20	2	All percentages
10-0055	$+_2$	45	3	71	8	62	4	from one sample,
29-0028	$+_3$	25^1	8^1	?	?	40	8	except -
								1 ave. 2 samples
36-0001	0_1	22^2	12^2	51	7	33	15	2 ave. 3 samples
36-0032	0_2	24	<1	64	9	18	2	3 ave. 4 samples
								4 ave. 5 samples
20-0017	$-_1$	37	13	34	32	47	47	5 ave. 6 samples
29-0008	$-_2$	34^5	13	57	11	45^4	25^3	
36-0007	$-_3$	21^1	14^1	?	?	36	24	
06-0028	$-_4$	49^1	27^1	74	36	62	36	
06-0021	x_1	27	15	87	43	-	-	
10-0291	x_2	46	3	60	23	-	-	
29-0047	x_3	44^1	26^1	-	-	-	-	

As mentioned earlier in this report, if glass is present in a basaltic rock it is apparently the first constituent to be altered. Hydrothermal or deuteric alteration will bring about the formation of the following minerals:

Hydrated iron oxides, goethite, lepidocrocite, FeOOH.

Silica, chalcedony SiO_2; opal, $SiO_2\ nH_2O$.

Zeolites, various Na, Ca, Al hydrated silicate minerals.

Chlorites, various Mg, Fe, Al hydroxy silicates.

Celadonite, K, Fe, Al hydroxy silicates.

Smectite. Clay minerals. Na, Ca, Al, Fe, Mg hydroxy silicates, with varying amounts of interlayer Na, Ca and H_2O.

Extensive alteration resulting in the formation of any or all of the above minerals may weaken a rock structure. The presence of even 10 or 15 percent smectite in glass may lead to rapid degradation when the rock is used for road base construction (See Table 2).

Smectite clay minerals are capable of incorporating layers of water molecules structurally in interlayer positions with consequent expansion of the mineral crystal lattice. Thus, hydration brings about mechanical disruption of the rock structure. Even on a minor scale this allows more water to enter through microfractures and promotes the further decomposition of glass and, finally, rock-forming minerals into more smectite and other alteration minerals.

Smectite minerals most commonly formed in basaltic glass or palagonite include the following:

Nontronite Fe, Ca Smectite

Montmorillonite Na, Al, Ca Smectite

and, possibly, Beidellite, Ca, Na, Al Smectite,

and Saponite, Mg Smectite.

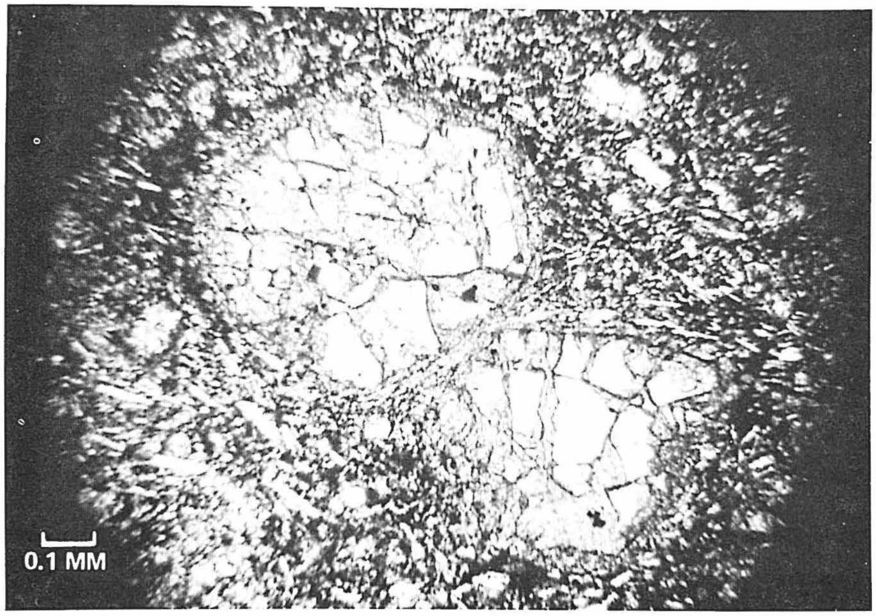

Figure 9. Photomicrograph. Olivine crystals with saponite (light gray) in fractures. Keene Creek Damsite, Josephine County, Oregon

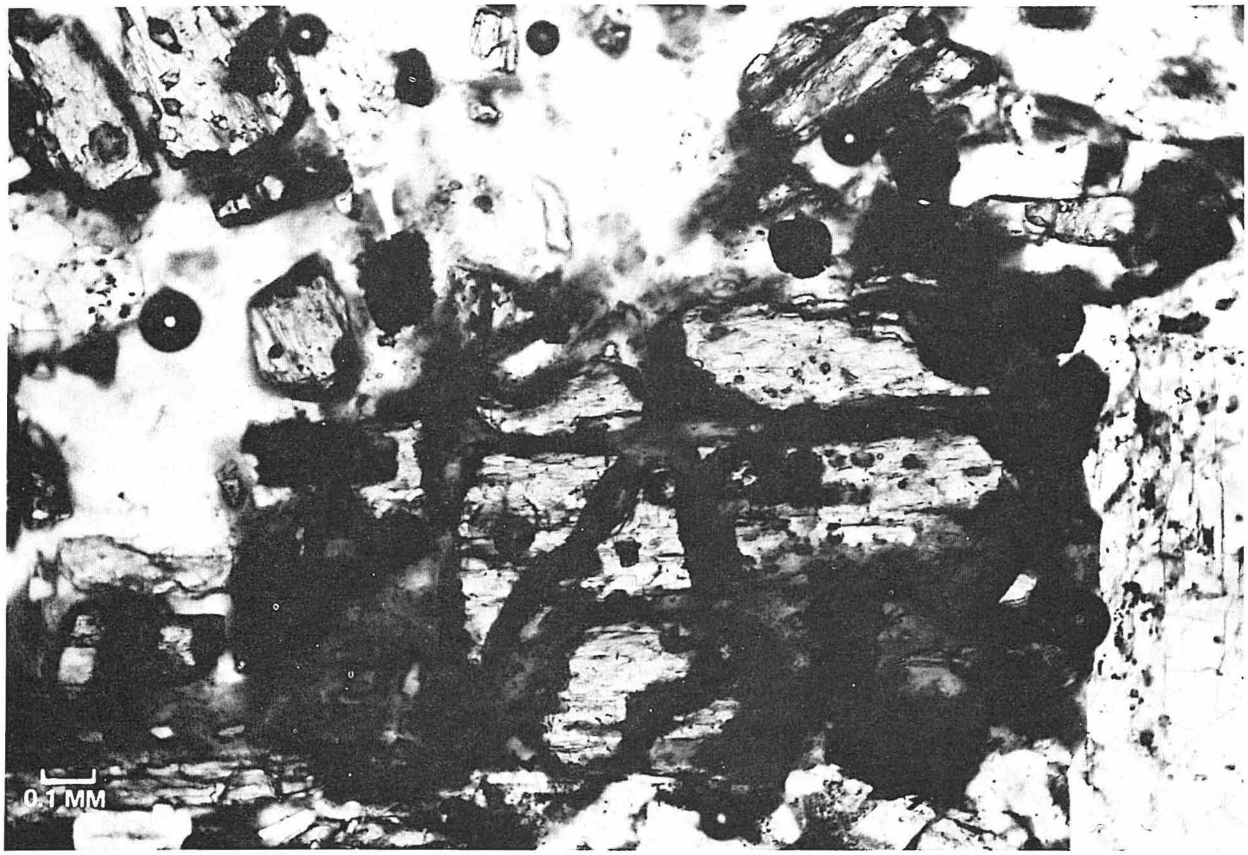

Figure 10. Photomicrograph. Smectite alteration with hydrated iron oxide (Black) filling fractures in pyroxene crystals (gray). Hawley Creek Quarry (20-0017)

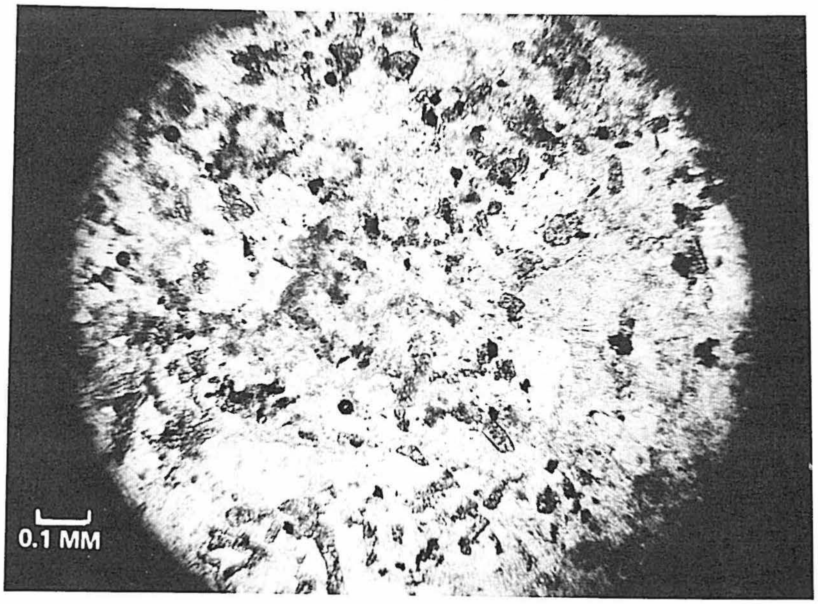

Figure 11. Photomicrograph. Vermiculite (dark gray) in gabbro. Roman Nose Quarry (10-0055)

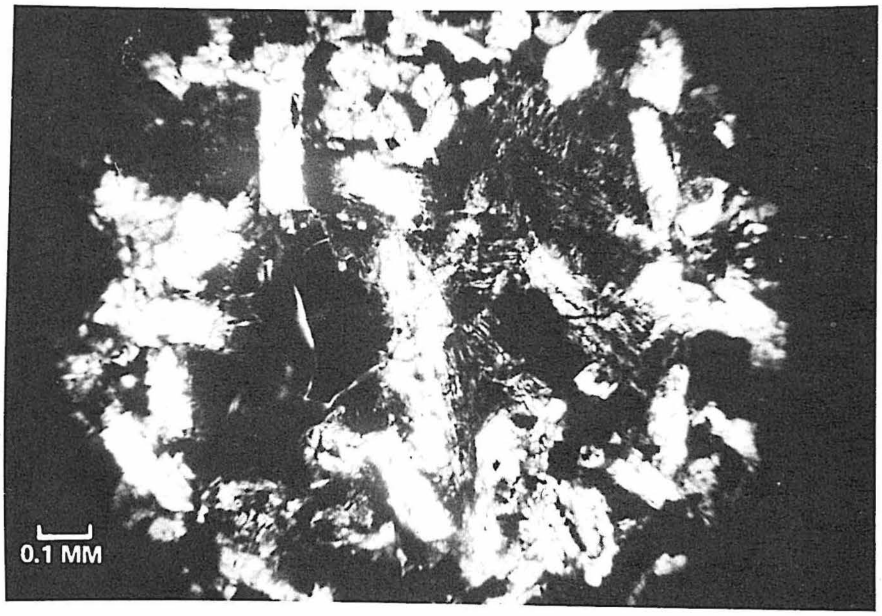

Figure 12. Photomicrograph. Smectite and hydrated iron oxide (dark gray) concentrated around magnetite-ilmenite crystals (black). Bald Mountain Quarry (36-0001)

Both nontronite and montmorillonite may be present as alterations of glass (See Table 8, Appendix B). Celadonite may also form from glass. Chlorite may be intimately intercrystallized with smectite. Texturally, smectite may be vermicular, lamellar, spherulitic, granular or in colloform bands.

Other minerals formed may include kaolinite and allophane, an amorphous clay.

Other primary components of basalt which are subject to hydrothermal or deuteric alteration include (in order of susceptibility) olivine, plagioclase feldspar, biotite, and pyroxene. Olivine is commonly altered to saponite, a magnesium smectite (See Figure 9), although it may also be altered to serpentine, iddingsite, chlorite, and chlorophaeite (for definitions of these minerals see Appendix D). Feldspar may be altered to smectite (commonly montmorillonite) or chlorite. Pyroxenes are commonly altered to chlorite hydrated iron oxides, and, sometimes, smectite (See Figure 10).

Biotite may be hydrothermally altered to vermiculite, which is also a swelling clay. Despite the ability of vermiculite to take water into structural interlayer positions causing expansion of the lattice spacing, some rocks containing this mineral do not degrade rapidly. For example, the Roman Nose gabbro (See Figure 11) which has a large amount of vermiculite (See Table 2 and Table 8) has a good service record. Apparently, the mineral is fully hydrated in this rock, and loss and re-gain of water does not take place readily, as in smectites. The amount of interlayer potassium ion present can effect this stabilization (Deer, Howie, and Zussman, Volume 3, p.251).

In addition to alteration minerals forming from glass, feldspar and pyroxene, they may also form in the following situations:

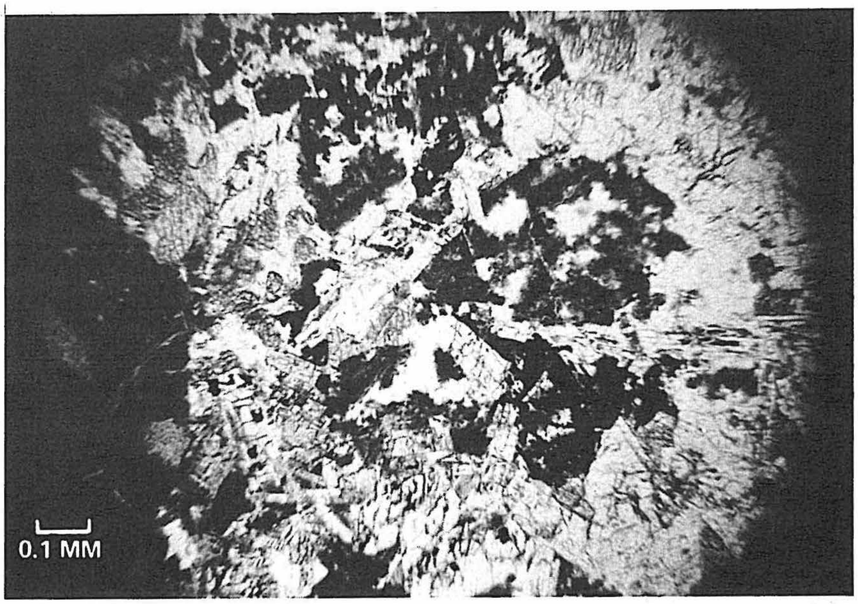

Figure 13. Photomicrograph. Interstitial smectite clay and hydrated iron oxide (dark gray) formed by alteration from glass.

Dovre Peak Quarry (29-0008)

Figure 14. Photomicrograph. Shows intra and parafractural alteration (smectite and hydrated iron oxide).

King Quarry (06-0028)

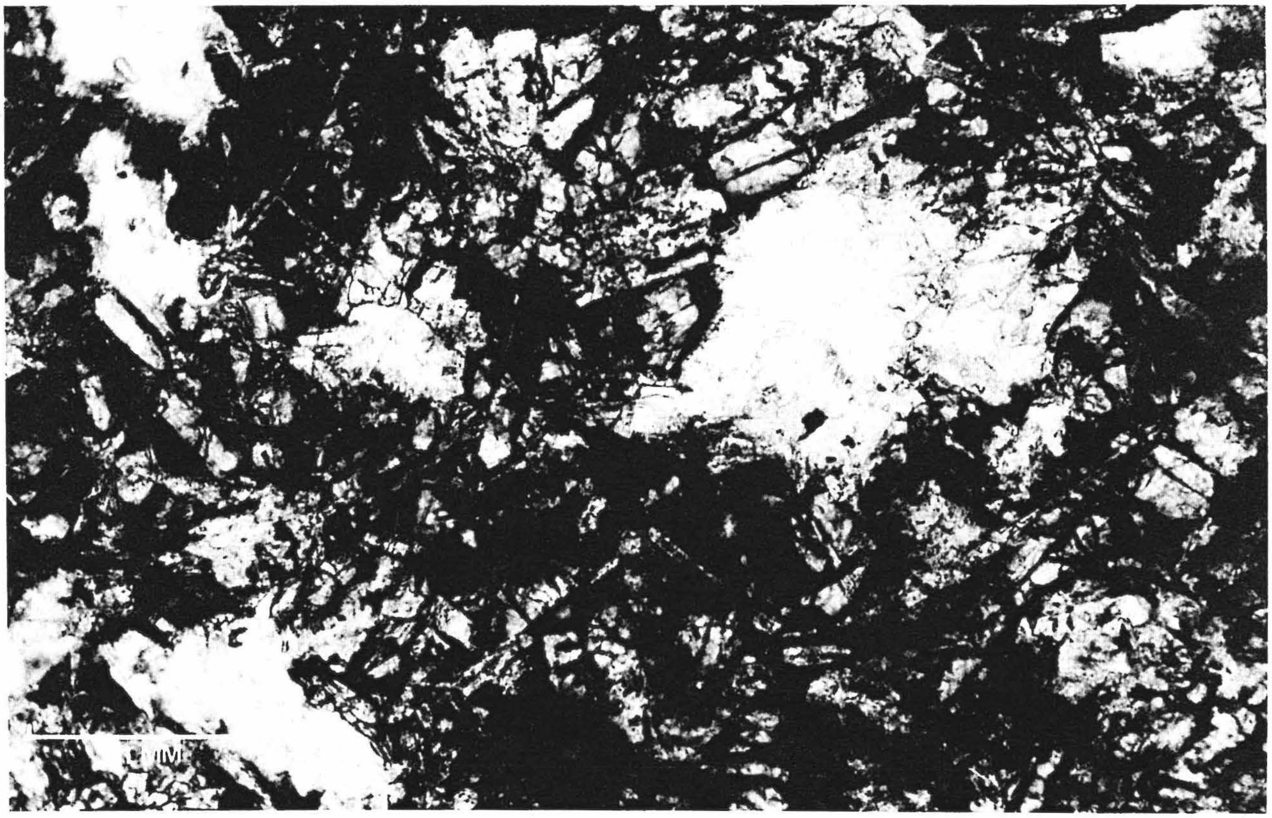

Figure 15. Photomicrograph. Alteration (gray) lining the vesicles (white). Blue Ridge source (06-0090)

TABLE 3 - TEXTURAL RELATIONSHIPS OF ALTERATION COMPONENTS
(Meant to categorize rather than rank; on a microscopic scale)

TEXTURAL TYPE		DESCRIPTION	ILLUSTRATION, THIS REPORT
A		Dispersed Throughout Rock Sample	
	1	Intragranular - within component grains, either in fractures, zoned, or dispersed	Figures 7,9,10
	2	Perigranular - contiguous on grain boundaries as a rind or layer	Figure 12
	3	Interstitial - within spaces between grains as alteration of original interstitial components	Figure 13
B		Localized in Particular Areas in Rock Sample	
	1	Intrafractural - filling fractures which cut through rock sample	Figure 14
	2	Parafractural - bordering fractures, alteration of components adjacent to fracture or through which fracture passes	Figure 14
	3	Amygdaloidal - vesicle filling, either wholly or in part	Figure 6
	4	Intraamygdaloidal - alteration of previous vesicle filling, e.g., glass, calcite, opal	Figure 8
	5	Vesicle lining - alteration of previous vesicle lining, e.g., smectite after glass	Figure 15

as precipitates around magnetite-ilmenite crystals (See Figure 12);

as fracture fillings, including microfractures (See Figure 14);

as progressive alteration of walls of fractures, affecting any mineral (See Figure 14).

The textural distribution of alteration products is probably as important as the mineralogy of alteration. West, Johnson and Smith (1970, p.7) observed that textural analysis is important in evaluation of rock durability and that such analyses are not common in testing.

The attempt in this study was to describe textural characteristics, rather than to quantify them. Table 3 lists the textural relationships of alteration products commonly found in the basaltic rocks included in the study. Work still needs to be done to correlate alteration mineralogy and textural combinations present in rocks which have given unsatisfactory service, but the evaluation of texture is included along with the alteration mineralogy of these rocks in Table 8 (Appendix B). It appears that most rocks with poor service records have a combination of generally dispersed interstitial or intragranular alteration and localized alteration in amygdules and fractures. An exception to this is the gabbro of Hawley Creek Quarry in which the intragranular and interstitial alteration is abundant and apparently includes quite a bit of saponite clay (See Figures 7 and 10).

Weathering Alteration

Weathering generally promotes the further development of alteration minerals already present in the rock. Exceptions to this were found in a few basaltic rocks where chlorite and kaolinite were present in C-horizon weathered rocks or in base course aggregate from roads. The presence of well crystallized smectite and other alteration in

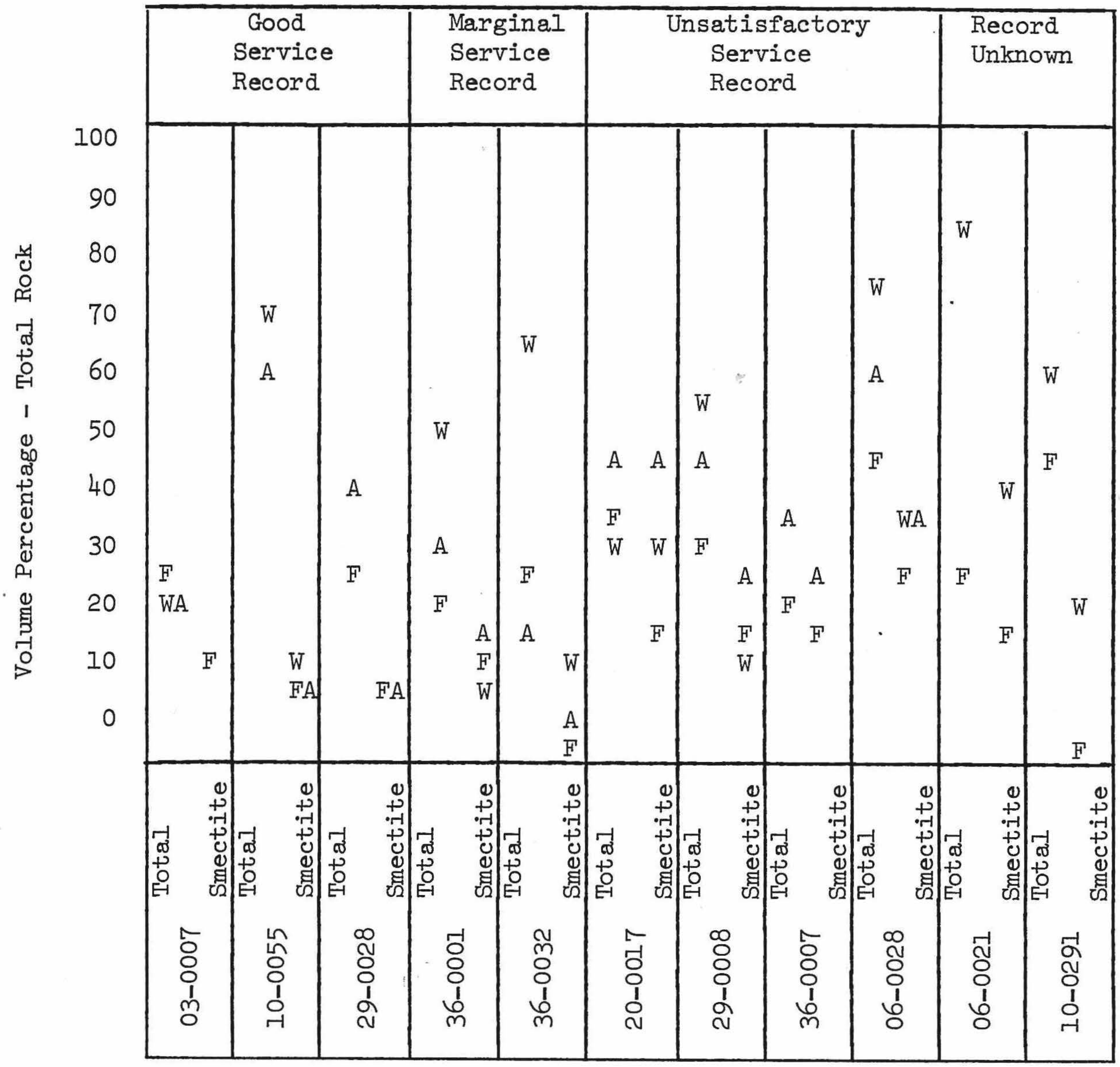

FIGURE 16 - COMPARISON OF ALTERATION OF UNWEATHERED, WEATHERED, AND BASE COURSE AGGREGATE ROCK WITH GOOD, MARGINAL, AND UNSATISFACTORY SERVICE RECORDS

F - Fresh, unweathered quarry rock
W - Weathered rock, C-Soil horizon
A - Road base aggregate

basaltic glass or palagonite always leads to rapid development of more smectite during weathering. As mentioned earlier in this report, examination of weathered C-horizon rock and/or X-ray diffraction of soils will readily show if smectitic clay is liable to form in the rock when it is placed in service in road construction.

Examination of Table 2 and Figure 16 reveals a regular pattern of development of alteration in basaltic rocks which have given unsatisfactory service, as compared to rocks with marginal or good rankings. Rocks with over 10 percent smectite almost all develop large amounts of smectite as well as large amounts of total alteration. Three cases of unsatisfactory rock road aggregate show a 50 to 100 percent increase in smectite (20-0017, 36-0007, 06-0028). The Dovre Peak aggregate is unusual in that it shows less total alteration than weathered rock from the C-soil horizon but over 100 percent increase in smectite. However; the alteration of the weathered rock in the C-soil horizon in each of the eleven quarries had more time to develop than the alteration minerals in the road base aggregate sampled.

Possible Emulsion - Clay Reactions

With respect to degradation, a comment on possible clay mineral-asphalt emulsion reactions needs to be made. In a single test clay-sized fractions of core samples from Blue Ridge (06-0090, 24 and 40 foot depths) and quarry rock from Steinman Creek were X-rayed (See Table 4). First, clay expansion with carbon tetrachloride solvent (CCl_4) was determined. Then a few cc of asphalt emulsion were dissolved in CCl_4 and the same specimen mount was treated with the solution. In two of the three specimens, 06-0090.24 and 06-0090.40, there was slight expansion which could be attributed to the asphalt emulsion. Since this possible reaction was not further tested, it is inconclusive at this point. However, it might prove fruitful to examine more thoroughly the possibility of clay-asphalt reactions.

TABLE 4 - RESULTS OF X-RAY DIFFRACTIONS,
EMULSIONS - CLAY REACTIONS

	06-0090.40	06-0090.24	06-0088
Untrd (Ca^{++} solv.)	14.289Å^{Ca}	13.381s,vbr	13.58Å,m,br
+ CCl_4		14.24Ås,vsh	14.66Ås,sh
+ Emulsion	14.717Å	14.47Åvs,vsh	14.47Ås,sh
Change	+0.428Å ?	+0.23Å	-0.19Å

vs - very strong
s - strong
m - moderate

vsh - very sharp
sh - sharp
vbr - very broad
br - broad

DURABILITY TESTS

Correlation of STANDARD AASHTO TESTS and Petrography of Samples

Standard Tests

Interpretation of the results of durability testing of some basaltic rocks using standard AASHTO durability measures involves a degree of uncertainty due to the nature of certain rock components, such as glass and smectite. These components are susceptible to chemical reactions and consequent development of a high percentage of structurally unsound alteration products, including swelling clays, which react with water, causing mechanical breakdown of the aggregate. Because of these factors, basalts have been recognized by other workers as requiring some special attention in routine testing. In a three-year study at Purdue University it was found that basalts, related fine-grained igneous rocks, and fine-grained metamorphic rocks fall into a group for which selected durability tests are more reliable (West, Johnson, and Smith, 1970, p.13). The L.A. Abrasion, Wet L.A. Abrasion, and Freeze Thaw Tests were found to be more accurate predictors of durability than other tests of base and subbase aggregates. In addition, they recommend that a complete petrographic analysis was a necessary testing procedure if the durability of basaltic rocks was to be accurately assessed.

Similarly, in a study project conducted by the Utah State Department of Highways Materials and Tests Division it was suggested that igneous rocks intended for use as riprap could be better evaluated by use of accelerated degradation tests rather than by other tests which are commonly used by that agency (Miles, 1970, p.32). In the Materials Section of the Federal Highway Administration, Vancouver, Washington, it has been known for some time that the fine durability test (AASHTO T-210) is a better predictor of basalt durability than some other tests. The results of this study when compared with standard AASHTO test results selected for evaluation of these rocks support this conclusion. Examination of Figure 17 and Table 5 reveals that all four quarry rocks which have received the lowest scores out of the 11 rocks tested in the fine durability test also rank as unsatisfactory in service records. These same four rocks have rather widely scattered test results, from good to poor, in other tests selected for evaluation.

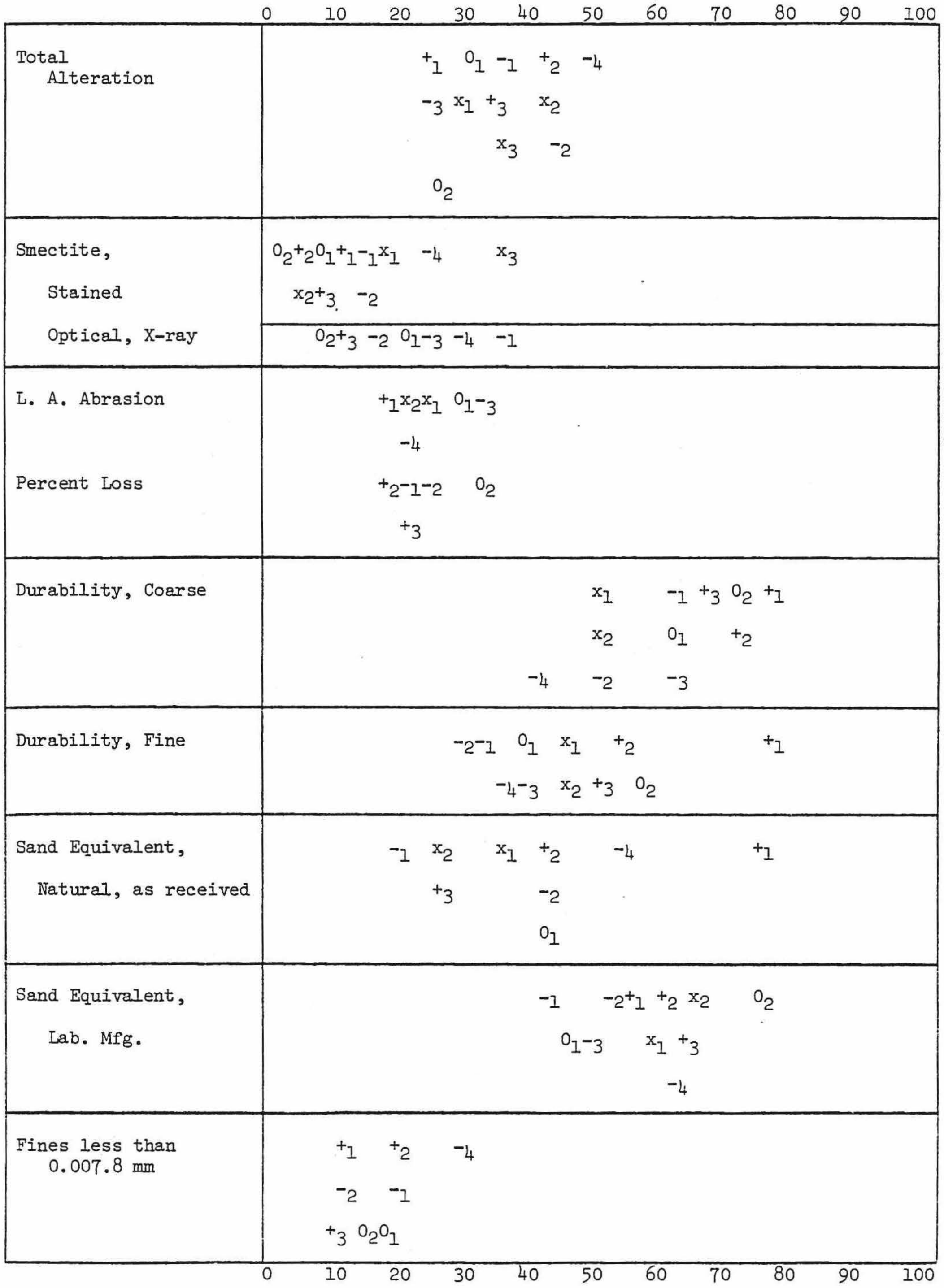

Figure 17. Alteration in Quarry Rocks and Lab Testing are Compared (For explanation of symbols, see Table 5)

TABLE 5
AVERAGES OF AASHTO TEST RESULTS

○ - Number of Samples Averaged; - Not Tested; ( ) Unacceptable for Forest Roads

Sample	L.A. Abras.	Durability Cs.	Durability Fine	Sand Equiv. Nat.	Sand Equiv. Mfg.	Sand Equiv. Rec'd Moist.
03-0007 $(+_1)$	17.85 ⑬	78.06 ⑮	78.5 ⑫	75.25 ⑧	56.6 ⑤	61.79 ㉔
06-0021 (x_1)	22.8 ⑲	58.6 ⑲	50.9 ⑱	36.33 ③	59.44 ⑬	51.5 ②
		Ethylene Glycol DMSO	0.16 4.2	⑥ ⑥		
10-0055 $(+_2)$	18.83 ⑥	72.66 ⑥	55.66 ⑥	43.8 ⑩	61.25 ④	58.14 ⑦
	(Vol. swell 0.04% - one sample)					
10-0291 (x_2)	22.25 ④	52.60 ⑤	48.60 ⑤	(29) ①	68.00 ⑤	DMSO ⑤ 9.8 Eth. Gly. ⑤ 3.8
20-0017 $(-_1)$	22.50 ④	62.50 ④	(32.75) ④	(19,25) (22) ②	(32,56) 44 ②	-
29-0008 $(-_2)$	25.33 ⑨	51.90 ⑩	(29.50) ②	41.2 ⑤	54.38 ⑧	-
36-0001 (0_1)	29.22 ⑨	63.56 ⑨	40.78 ⑨	42.25 ④	46.71 ⑦	-
36-0007 $(-_3)$	32.83 ⑥	63.00 ⑥	39.83 ⑥	-	50.33 ⑥	-
36-0032 (0_2)	33.50 ⑥	73.57 ⑦	59.00 ⑦	-	78.00 ⑦	-
	Ethylene Glycol Tests -		4 - no rocks cracked, 1-1, 1-5			
29-0028 $(+_3)$	(49 - 1) 22.75 ⑧	(23 - 1) 68.75 ⑧	(27 - 1) 53.13 ⑧	(28) ①	64.5 ⑧	51.0 ③
06-0028 $(-_4)$	22.0 ⑩	39.0 ㉛	(35) ㉛	56.0 ㉒	61.0 ⑥	56.0 ㉓
29-0047 (x_3)	20.8 ⑤	73.8 ⑤	41.6 ⑤		57.0 ④	
		Ethylene Glycol - DMSO	1.0 3.25	④ ④		

Accelerated Degradation Tests

Some materials testing laboratories have used organic chemicals which cause expansion in swelling clays, such as smectites, as a supplemental test to assess rock durability. The Utah Highways Materials and Tests Division terms these "accelerated degradation tests" (Miles, 1972, p.2). Ethylene glycol and dimethyl sulfoxide (DMSO)[1] are among the chemicals used by that agency. Ethylene glycol has long been known to cause rapid expansion (about 25 percent) in smectite clays. DMSO, which has a remarkable ability for penetration, also causes expansion (about 30 percent) in smectites. Problems arise in the use of results of these informal tests, however, because the results sometimes do not correlate well with service records of rocks in use, as noted by Miles in his study (1972, p.33).

In this present study DMSO caused varying degrees of expansion in smectites, depending upon the species, the interlayer cations such as sodium or calcium, and the degree of crystallinity and hydration. Another important factor was the presence of smectite in a mixed layer clay, such as montmorillonite-chlorite. An average of the increases in lattice spacing for each mineral listed in Table 6 shows that nontronite appears to expand less (3.2Å in five samples) than montmorillonite (3.8Å in 10 samples). Also, calcium saturated montmorillonite apparently expands less (3.81Å) than sodium saturated (4.07Å) when a standard montmorillonite sample is tested. Incidentally, DMSO tended to enhance and sharpen X-ray diffraction peaks in many samples. Also, in about half of the samples studied by X-ray diffraction, DMSO shifted the first order peak to at least 18Å (See Table 6). A side benefit of this study appears to be the possible usefulness of DMSO in X-ray diffraction analysis.

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[1] Crown Zellerbach Corporation, Chemical Products Division, Camas, Washington

TABLE 6 - X-RAY RESULTS OF TREATING STANDARD CLAYS AND ROCK ALTERATION PRODUCTS WITH DMSO

Sample No.	Type of Clay	001 Spacing		
		Before	After	Difference
Vantage Sandstone, (Nontronite matrix)	Nontronite, Na^+	15.76Å	18.39Å	2.63Å
A.P.I. #23	Montmorillonite, Na^+	14.71Å	18.78Å	4.07Å
	Montmorillonite, Ca^{++}	14.97Å	18.78Å	3.81Å
03-0007D	Montmorillonite	12.8Å	17.8Å	5.0Å
03-0007 Soil	Montmorillonite	14.01Å	17.72Å	3.71Å
06-0021C	Montmorillonite	14.24Å	18.09Å	3.85Å
06-0021D	Montmorillonite	14.24Å	17.72Å	3.48Å
06-0021F	Montmorillonite (?)	14.24Å	16.91Å	2.67Å
10-0291B	Nontronite	14.7Å	17.11Å	2.41Å
10-0291E	Montmorillonite	14.24Å	18.01Å	3.77Å
10-0291F	Montmorillonite	14.01Å	18.16Å	4.15Å
29-0008.13	Nontronite	14.01Å	16.91Å	2.90Å
29-0008F	Nontronite	14.01Å	17.17Å	3.16Å
36-0001C	Montmorillonite	13.46Å	16.41Å	2.95Å
36-0001E	Montmorillonite	14.10Å	17.65Å	3.55Å
36-0001.3	Montmorillonite	12.61Å	17.65Å	5.04Å
36-0007A	Nontronite (?)	14.47Å	18.16Å	8.69Å
36-0007.3	Nontronite (?)	14.24Å	18.09Å	3.85Å
36-0032A	Smectite	12.98Å	18.3Å	5.32Å

After DMSO was applied to the thin layer of clay prepared on ceramic tile for X-ray diffraction, many samples of clay expanded within an hour at room temperature, causing swelling that completely disrupted the sample and made it unsuitable for X-ray diffraction. Other samples which contained smectite reacted only slightly or not at all. These reactions are noted in Table 8, in Appendix B. There is some correlation between the thickness of the clay layer on the slide and the tendency to swell. This factor is well known in using ethylene glycol for X-ray diffraction. However, many samples which were as thick as others did not swell with DMSO. This fact could be useful in conjunction with informal tests with rock aggregate fragments immersed in DMSO in ethylene glycol. Pulverized rock samples may be sized to separate clay-sized material using settling in a glass cylinder, as in a sand equivalent test. A thin layer of this size fraction can then be placed on ceramic tile (22 x 44 mm), the excess liquid removed by suction, the layer air dried, and then tested by placing a few drops of DMSO on the mount at room temperature and by observing after one hour what effect the liquid has had on the clay. This might help in reaching a decision where tests of rock fragments in DMSO were inconclusive.

This testing procedure, of course, would need careful standardization before it could be employed in a testing laboratory on a regular basis. It appears, however, to have merit for further development and evaluation.

TESTS EMPLOYING STAINS

In basaltic rocks it appears that the development of smectite, chiefly from glass, is the principal cause of degradation when the rock is used in road base aggregates (See Table 2). Hence, supplementary testing methods to determine volume percentage of smectite are important. Staining techniques have been used to accentuate biological material since about 1838. In 1881, according to Grim (1968, p.407)

Behrens first tried staining minerals. Since that time, much literature has been written on the subject, concentrating for the most part on carbonate minerals and upon clays. Several governmental agency reports on tests using staining for identification of clay minerals are available, some of which are cited in the references for this report.

A prescribed testing procedure for staining clay samples for the purpose of detecting the presence of montmorillonite is given by Mielenz and King (1951).

Commonly, stain tests for clay mineral identification are used on clay-sized fractions, such as occur in soil samples. In this present study good success was achieved by staining uncovered thin sections of rock. The stain used is benzidine, a cyclic aromatic hydrocarbon compound. When a water solution of benzidine is applied to montmorillonite, a blue color appears. When nontronite is present, a blue-green or green coloration occurs. With saponite, Mg - smectite, apparently there is no color produced. Grim (1968, p.407) states that ions in the clay, such as iron, bring about oxidation of the benzidine. Page (1941, p.139) states that benzidine is "readily converted to a blue-colored semiquinone by the action of oxidizing agents."

Benzidine staining was tested in this present study on API (American Petroleum Institute) Standard clays, upon thin sections of rock with known smectite content, and upon rocks in which clay had not been identified. (The results of staining are summarized in Tables 7, 8, and 9.) Most of the smectite percentages reported in Table 2 and Figure 16 were determined from point counting of stained rock thin sections. This stain test appears to be fairly reliable, although only the clay exposed at or immediately subjacent to the rock surface will react with the stain. Thus, percentages determined will be low for the total volume of the rock sample. The success of the benzidine stain depends upon several factors: the degree of crystallinity; the interlayer adsorption capacity of the smectite crystal lattice (which

TABLE 7 - RESULTS OF STAIN TEST FOR SMECTITE

Rock Source Sample	Service Rank^1	Sample Type	Result of Stain^2	Smectite Present	Percentage of Rock
03-0007B	$+_1$	Fresh Quarry Rock	+		8%
03-0007Q		Road Base Agg.	+		2%
03-0054	x		+	Nontronite (Montmorillonite)	25%
06-0021C	x_1	Fresh Quarry Rock	+	Montmorillonite (Nontronite)	15%
06-0021D		Weathered Rock	+	Montmorillonite (Nontronite)	43%
06-0028A	$-_4$	Fresh Quarry Rock	+	Montmorillonite (Nontronite)	25%
06-0028C		Weathered Rock	+	Nontronite (Montmorillonite)	35%
06-0028D		Road Base Agg.	+	Nontronite (Montmorillonite)	36%
06-0060.95	x	Core	+	Nontronite	34%
06-0088	x	Fresh Quarry Rock	+	Nontronite	14%
06-0090.05	x	Core	+	Montmorillonite (Nontronite)	19%
06-0090.103		Core	+	Montmorillonite (Nontronite)	21%
10-0011B	x	Fresh Quarry Rock	√		7%
10-0055B	$+_2$	Fresh Quarry Rock	+	Montmorillonite	3%
10-0055G		Weathered Rock	+	Nontronite	8%
10-0055K		Road Base Agg.	+	Nontronite	4%
10-257	x	Fresh Quarry Rock	√	Nontronite ?	21%
10-0291B	x_2	Road Gravel	√	Montmorillonite Saponite ?	8%
10-0291D		Fresh Quarry Rock	√	Saponite ?	3%
10-0291E		Weathered Rock	+	Montmorillonite (Nontronite)	23%

[1] - See Table 1

[2] + Good, 75 - 100% complete
√ Fair, 25 - 75% complete
\- Poor to negative, 0 - 25% complete

TABLE 7 (Continued) - RESULTS OF STAIN TEST FOR SMECTITE

Rock Source Sample	Service Rank[1]	Sample Type	Result of Stain[2]	Smectite Present	Percentage of Rock
20-0009	x	Fresh Quarry Rock	-	Nontronite ?	9%
20-0017B	$-_1$	Fresh Quarry Rock	✓	Saponite ?	13%
20-0017E		Weathered Rock	-	Saponite ?	-
29-0008.7	$-_2$	Fresh Quarry Rock	✓	Montmorillonite (Nontronite)	5%
29-0008.5		Degraded Agg.	✓	Nontronite	19%
29-0008E		Road Gravel	✓	Montmorillonite	11%
29-0006B	x	Fresh Quarry Rock	-	Saponite ?	-
29-0028	$+_3$	Fresh Quarry Rock	✓	Nontronite	6%
29-0040	x	Fresh Quarry Rock	-	Nontronite ? Saponite ?	20%
29-0047	x_3	Core	+	Nontronite (Montmorillonite)	35%
36-0001A	0_1	Fresh Quarry Rock	✓	Montmorillonite	6%
36-0001C		Weathered Rock	✓	Montmorillonite	7%
36-0007.3	-	Road Base Agg.	+	Nontronite (Montmorillonite)	24%
36-0032A	0_2	Fresh Quarry Rock	✓	Montmorillonite ?	< 1%
36-0032W		Weathered Rock	+	Montmorillonite	9%
36-0032C		Road Gravel	✓	?	2%

depends in part on the cations already present in the interlayer positions); pH; orientation of adsorbed material (Theng, 1971, p.385-387). Theng also states that the intensity of blue coloration will be greater with Na^+ than with Ca^{++} smectite. He suggests that the reliability of the benzidine test can be improved by heating and washing the sample with a polyphosphate. Page (1941) considers the benzidine-blue test for montmorillonite unreliable because the color might be produced in soil samples by any factor which would cause oxidation of the benzidine, such as the presence of organic material. He found that ferric iron might cause the color change, but some samples studied by him which contained considerable Fe^{+++} produced no color change. Some workers have found that controlling the pH of the reaction produces more reliable results [Furukawa and Brindley, 1973, p.279, and Mielenz and King (1951)] and recommend that the benzidine and clay be brought together at a pH of 1.

These findings have been taken into consideration in this present study. Since rock thin sections are being tested, the presence of organic material, which might cause the oxidation of the benzidine to blue semiquinone, is very unlikely. Although Fe^{+++} in hydrated iron oxides is commonly present, there seems to be no correlation between its presence and the results of the stain test; that is, in the presence of hydrated iron oxide some alteration material is stained blue and, in other samples it is not. The benzidine stain test was tried with a water solution of benzidine at a pH of 1 and no improvement in staining was noted in rock thin sections which had previously shown poor results.

The reaction is most successful in the trioctahedral smectites, nontronite and montmorillonite. In the dioctahedral smectites, such as saponite, the benzidine stain apparently causes no color change. This proved to be the case in a sample of olivine basalt used as riprap in the Keene Creek Reservoir, twenty miles east of Ashland, in Jackson County, Oregon. This basalt suffered extensive degradation in a very short time after initial use. Examination of thin sections of this rock (See Figure 9) reveals the presence of saponite, which is substantiated by X-ray diffraction. In the case of olivine-bearing rocks, a negative stain test can be supplemented with X-ray diffractometry or with a DMSO test of the clay-sized fraction of pulverized rock, since smectite alteration products may be commonly present.

The benzidine stain test reveals not only the presence of montmorillonite and nontronite, but it also clearly shows the textural distribution of these deleterious minerals. The effectiveness of the stain is much better in weathered rock and in road base aggregate, which suggests that Na^+ smectite is present. A procedure is outlined below which after extensive testing has given reliable and consistent results.

Test Procedure

I. Preparation of rock sample

Prepare thin section of both fresh quarry rock or rock core sample, and weathered rock (C-soil horizon).

1. Grind this section to 30 microns thickness, at most. (Thin sections should be about 20 to 25 microns in thickness for best stain results.
2. Leave prepared rock thin sections uncovered.
3. Examine thin section, noting distribution and color of alteration, with temporary oil mounted cover slip (oil index of refraction, 1.54).

II. Preparation of staining solution

A. Weigh 0.4 gm benzidine (4.4' diaminobiphenol, $H_2NC_6H_5C_6H_5NH_2$) and make a saturated solution with 100 ml of distilled water.

Note: It is best to have some excess benzidine to insure saturation. The solubility of benzidine is quite low in water at 25°C.

Avoid contact with benzidine by skin, ingestion, or breathing dust (Robbins, 1967, p.1061).

B. Place solution with excess benzidine in a stoppered flask, preferably amber-colored. Keep from sunlight.

III. Staining procedure

A. Place uncovered thin sections face up in a shallow (1-2 cm deep) glass or plastic dish which can be covered. Culture (Petri) dishes work very well.

B. Pour enough saturated solution of benzidine into dish to cover rock thin sections. Include some grains of undissolved benzidine so that they are in contact with the rock thin section. This will insure saturation of the solution at all temperatures.

C. Cover dish containing rock thin sections and benzidine solution. With wax pencil, mark sample number, time and date on dish cover.

D. Leave thin sections in benzidine solution at least 24 hours. Optimum times for staining vary from 36 to 48 hours. If thin sections are cemented to microscope slides with epoxy resin, the epoxy cement should be mixed in exactly the right proportions. If it is not, the benzidine solution has a tendency to cause "puckering" of the mounted rock thin section, thereby spoiling it for further study.

E. After 36 hours, remove rock thin sections from the benzidine solution with forceps, and rinse by dipping in a beaker of distilled water (do <u>not</u> rinse in a stream of water). Shake off excess water and dry rock thin section in a gentle stream of air. DO NOT APPLY HEAT. Heating to any degree will destroy the stain. Place a drop or two of immersion oil (index of refraction 1.54) upon the rock thin section and cover with a No. 1 cover slip. This will insure that the stained thin section will not dry out -- it <u>must</u> <u>not</u> be allowed to dehydrate or the stain color will be destroyed. It has been found that stained rock thin sections will retain the stain color without change for up to six months if kept covered with oil and a cover slip. All attempts to make permanent mounts using epoxy or Permount result in loss of stain color in smectite clay.

F. Examine stained rock thin sections under moderate magnification (10 x objective) with a microscope. A petrographic (polarizing) microscope is best but an ordinary biological microscope can be used. If montmorillonite or nontronite is present with alteration minerals, they will be stained as follows: montmorillonite will be stained a light to moderate blue (5B 7/6 to 5B 5/6, Geological Society of American Rock Color Chart, 1970); nontronite will be stained light blue-green to dark yellowish green (5BG 6/6 to 10GY 4/4, GSA Rock Color Chart, 1970). It is necessary, of course, to have first examined the rock thin section before staining to judge whether or not a green coloration is due to staining or is simply the natural color of chlorite, nontronite, celadonite or other normally green alteration products. The green color of the stained nontronite is distinctly different in shade from the normal color of any of these minerals. The blue coloration of stained montmorillonite is totally unlike any natural coloration of alteration products in thin section.

If staining does not appear to be complete, remove cover slip, rinse slide free of oil by immersing in a beaker of ethyl alcohol and by agitating for 20 seconds. Remove slide, shake off excess alcohol and air dry. Repeat immersion in benzidine solution for an additional 12 to 24 hours. Re-examine slide for additional staining.

For a comparison of stained and unstained nontronite, see Figures 18 and 19.

IV. Analysis

A. Using either a line counting or point counting technique, determine the percentage of unaltered, primary minerals, alteration minerals which are not stained, and alteration minerals which are stained. A count of 300 to 500 points is sufficient for the level of accuracy involved.

B. Determine the percentage of alteration of total rock and percentage of smectite. The latter percentage determined by this technique will be an estimate and will tend to be less than the actual percentage, for reasons explained earlier in this section.

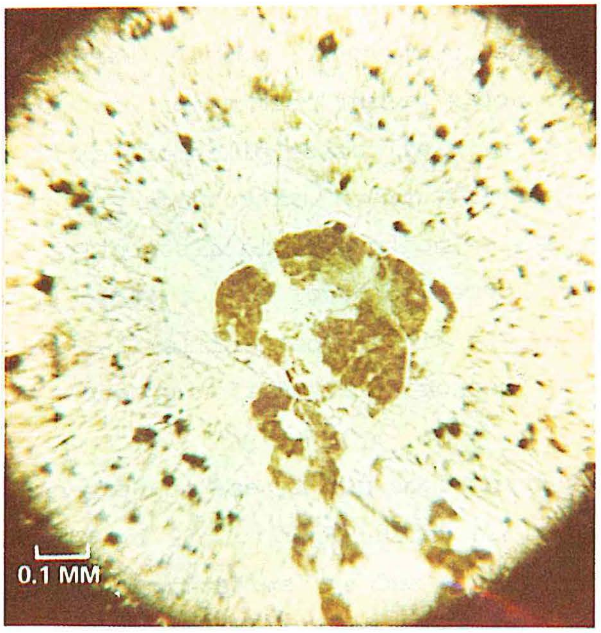

Figure 18. Photomicrograph. Unstained lamellar nontronite, Jackson County, Oregon. (Source 15-0135)

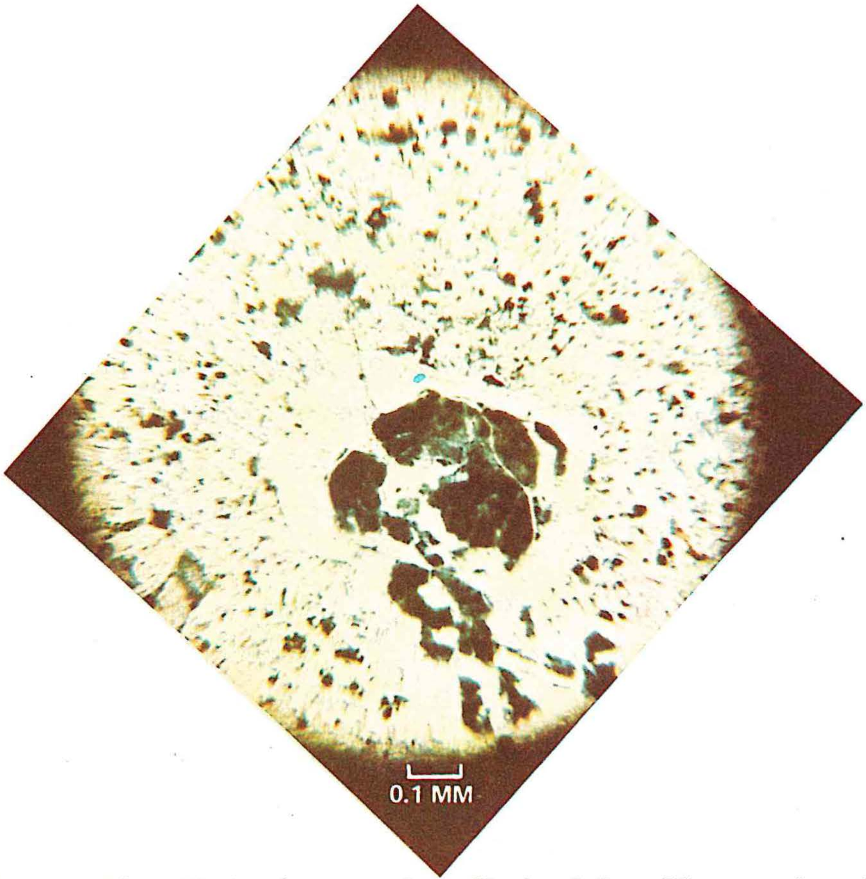

Figure 19. Photomicrograph. Stained lamellar nontronite.

If the amount of stained smectite exceeds 10 percent, according to the results of this study, the basaltic rock being tested is susceptible to accelerated weathering and consequent rapid degradation. Nelson B. Higgs in an independent study (Higgs, 1976) of basaltic rocks which are subject to rapid degradation, reached the conclusion that 11 percent montmorillonite is "sufficient to cause basalts to degrade."

TESTS EMPLOYING THERMAL NEUTRON ACTIVATION

The general distribution of sodium throughout a rock, as revealed by thermal neutron activation and subsequent autoradiography, is a possible indicator of good durability potential. Conversely, high concentration of sodium in fractures and highly altered areas of a rock may indicate low durability. In addition, the presence of high cation exchange capacity for sodium which shows up throughout the rock may indicate low durability. Concentration of ion exchange capacity for sodium only in localized areas within a rock sample may indicate satisfactory durability potential.

Tests using neutron activation and cation exchange of several of the quarry rocks studied in this project were conducted by Marvin H. Beeson of Portland State University. Description and results of these tests are included in Appendix A of this report.

CONCLUSIONS

The actual durability of rocks of basaltic composition which are structurally sound enough to pass standard AASHTO durability tests will depend mostly upon the presence or absence of glass, especially palagonitic glass, and upon the degree of alteration of this glass. Smectite clays are the main deleterious alteration products, and the amount and textural distribution of this material are the chief factors affecting durability. Alteration products, localized in areas such as fractures or vesicles, are less of a problem than generally distributed alteration, such as that which is intragranular or interstitial. Progressively rapid degradation, either in normal rock weathering and soil formation or in aggregate used in road construction, involves mostly the continued development of smectitic clays already present in the parent rock. Under some conditions alteration products may be formed which were not present in the parent rock, such as kaolinite and allophane. However, the effect of these minerals is insignificant when compared with smectite clays in the degradation process of basaltic rock used as road aggregate. In some basaltic rocks, components other than glass, for example olivine and pyroxene, are also altered to smectite. The petrographic examination of normally weathered rock from source areas will give an indication of the rock's potential for developing undesirable amounts of deleterious alteration products, especially smectite. Basaltic rock formed by subaerial lava flows will have less undesirable alteration components than submarine lava flows. Intrusive basaltic rocks may or may not have much deleterious alteration material. Determination of the type of occurrence of a basaltic rock body being examined as a possible aggregate source will aid in determining its potential durability.

Examination of the standard AASHTO tests applied to the rocks included in this study reveals that the durability of fines test correlates most closely with a poor service record because of degradation due to the development of large amounts of swelling clay. Accelerated degradation tests such as with ethylene glycol or DMSO probably depend for their success as durability predictors upon the crystal chemistry of smectite clays which may be present. If these tests are inconclusive, they should probably be supplemented with petrographic tests for the presence of smectite. DMSO applied to a thin layer of clay-sized (less than 0.002 mm) pulverized rock sample shows promise as a rapid indicator of the presence of smectites.

All basaltic rocks must be first examined in thin section to determine the textural distribution of alteration components and of glass. At this point, for a well-trained geologist familiar with the petrographic microscope, this procedure will suggest the type of testing which will prove most diagnostic.

Staining of uncovered rock thin sections with a saturated water solution of benzidine has proven to be a rapid method for detecting the presence of montmorillonite and nontronite. Besides the presence, the textural distribution of these clays can be easily seen under the petrographic microscope. Saponite is apparently not stained with this procedure. If a basaltic rock contains palagonite and/or olivine, and if staining does not reveal the presence of smectite, X-ray diffraction must be used to determine whether or not swelling clay is present.

The flow chart shown in Figure 20 is proposed for evaluation of durability testing of basaltic rocks. The right-hand side of the scheme allows for proceeding directly to stain tests if the rock is part of a submarine lava flow, flow pillow or breccia basalt, in which case the presence of montmorillonite and/or nontronite is almost assured. The same procedure would be the most economical of time and expense if thin section examination proved the presence of textural types A and B together (Table 3) or of altered glass and/or altered olivine. In the case of a negative stain test of rocks with altered glass and/or altered olivine, X-ray diffraction should be used to determine whether or not smectite clay (probably saponite) is present. In cases of further doubt, neutron activation of sodium and autoradiography would indicate the durability potential.

Rock with durability values of less than 55 for the coarse fraction and 40 for the fines should be subjected to the benzidine stain test. These values hold true for the basaltic rocks of the present study and may or may not prove to be universally applicable as "cut-off" values. It seems probable, however, that these would prove to be

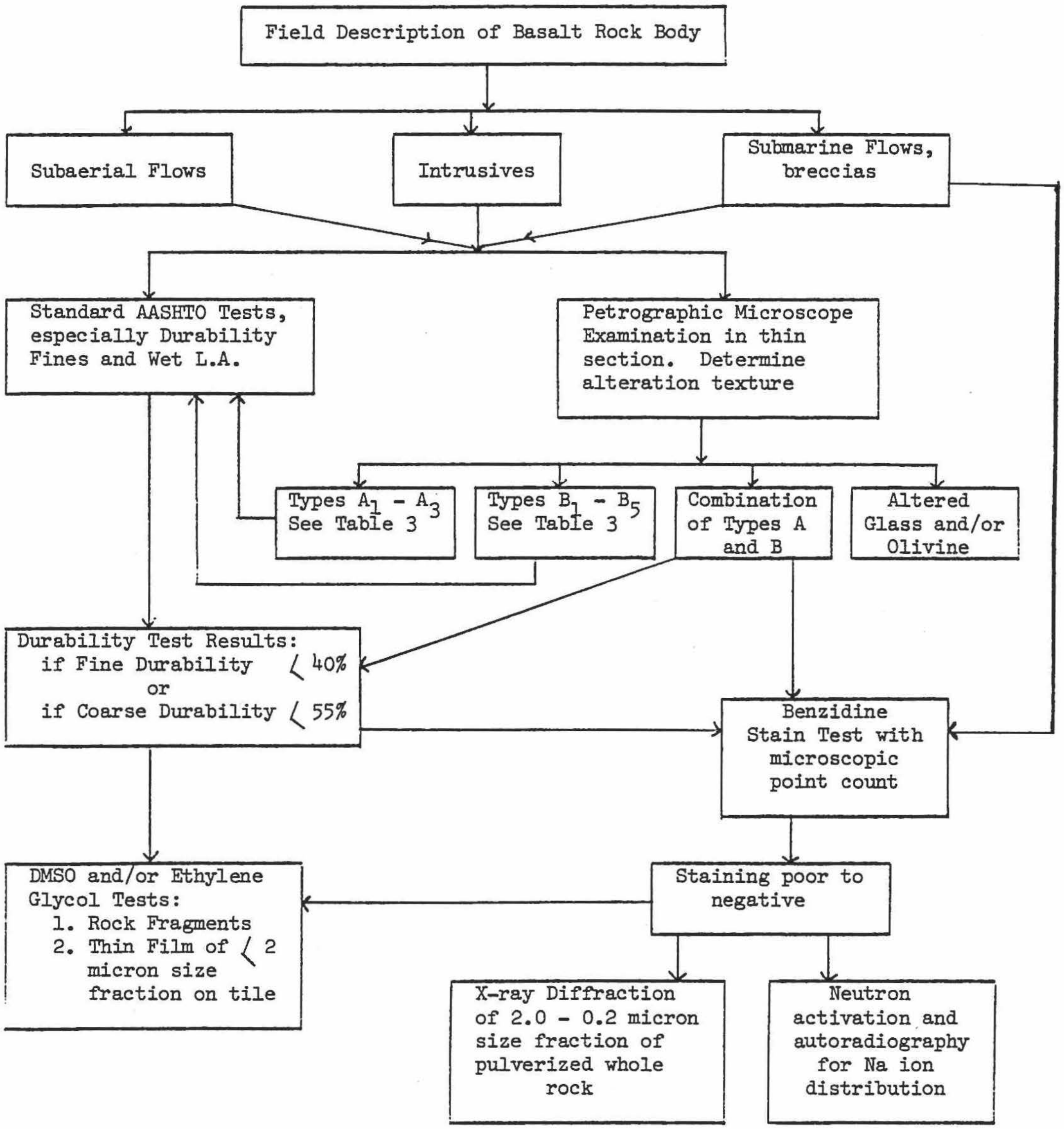

FIGURE 20 - SUGGESTED FLOW CHART FOR EXAMINATION AND TESTING OF BASALTIC ROCKS

reasonable values for most basalts, considering the diversity of types included in this project.

By combining knowledge of the presence and textural distribution of smectite clays in altered glass or other rock components with the results of standard AASHTO tests it will be possible to more surely assess the durability potential of basaltic rocks.

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APPENDIX A

GEOCHEMICAL STUDIES OF BASALT TO DETERMINE CHARACTERISTICS USEFUL IN EVALUATING DURABILITY

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INTRODUCTION

Twenty-six basaltic samples from ten quarries in western Oregon were studied by nuclear geochemical methods developed in my laboratory. The purpose of this study was to determine characteristics revealed by these methods which might be useful in evaluating rock durability. The study was essentially empirical in that characteristics found in samples from quarries which have produced durable aggregate are contrasted with those from quarries which have produced poor aggregate.* An attempt was made to relate these characteristics to the alteration texture and composition of the rocks and to suggest chemical reasons for durability differences. The genesis and post-solidification history of a basaltic rock is obviously very important in producing rocks of different durabilities, but too little is known about the histories of these samples to allow a coherent model to be developed.

The sources of samples of generally good aggregate were Fish Creek, Roman Nose, and Bald Mountain quarries; sources of poor aggregate were State, Dovre Peak, Blue Ridge, and King quarries; sources of marginal to poor aggregate were Ainsley, Wanless, and Lookingglass quarries.

EXPERIMENTAL PROCEDURES

Two thin sections, mounted on plastic, were made of each sample and then a number of operations were conducted in order to "map" the distributions of Mn, Na, Sm, Sc, Na cation exchange, Cs cation

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* Under the climatic conditions of western Oregon

exchange, and Br anion exchange. A flow diagram summarizing the major steps used in this study is given in Figure 21. Two kinds of experimental procedure were used, neutron activation autoradiography and neutron activated ion exchange autoradiography.

Neutron activation autoradiography for the distribution of Mn, Na and elements having longer-lived isotopes - The experimental procedure for determining the distributions of easily activated elements within a rock involves the following steps:

(1) Preparation of thin sections on plastic slides (no cover glass).

(2) Irradiation by thermal neutrons in a research reactor (Reed College, Portland, Oregon).

(3) Exposure of activated sections to X-ray film at successive times for nuclides having different half lives.

(4) Gamma ray counting to determine relative activity of radioactive nuclides.

(5) Preparation of enlargement prints from developed X-ray film for study.

Detailed specifications for irradiation and autoradiography are given in Table 1.

If only the distributions of Mn and Na are desired, a single short irradiation is sufficient. However, if elements having longer-lived isotopes (such as Sm, Sc) are desired, another longer irradiation is necessary. The specifications given in Table 10 were those used in this study. Although they gave satisfactory results, considerable latitude exists depending on the rock type and kind of film used.

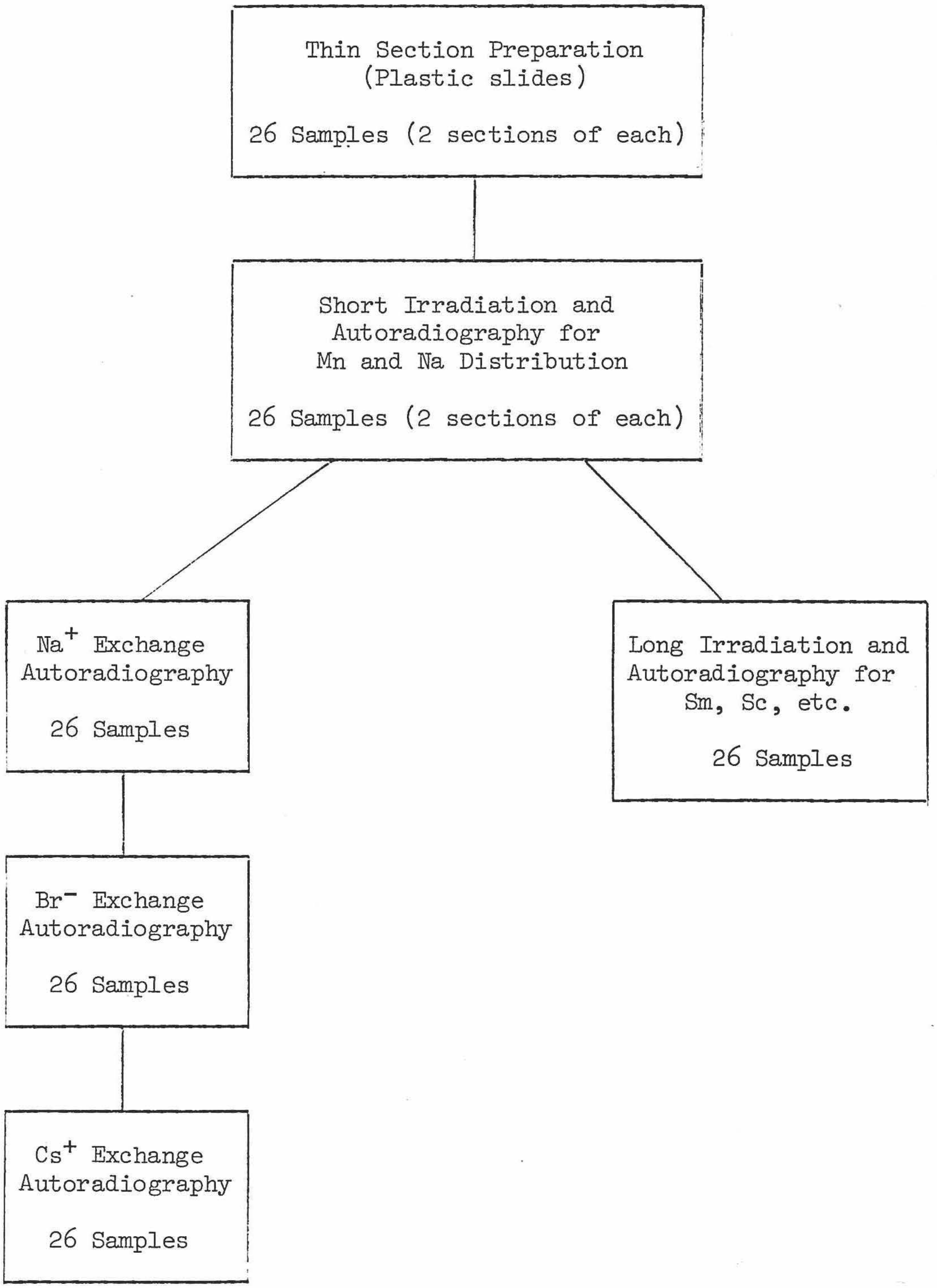

Figure 21 - FLOW DIAGRAM FOR EXPERIMENTAL PROCEDURE MAJOR STEPS

TABLE 10 - SCHEDULE FOR AUTORADIOGRAPHY

Short Irradiation - Flux $10^{11} n/_{cm^2 sec} \cong 5$ kw reactor power

duration 10 minutes

Autoradiographic exposure*

Element	Time since Irradiation	Time for Exposure	Industrial X-ray Film Type
Mn	1.5 hr.	2 hr.	AA
Na	20 hr.	13 hr.	AA

* Gamma ray spectrum taken between exposure for Mn and Na.

Long Irradiation - Flux $2x10^{12} n/_{cm^2 sec} \cong 250$ kw reactor power

duration 1 hour

Autoradiographic exposure*

Element(s)	Time since Irradiation	Time for Exposure	Film Type
Sm, Sc, Na	7d	21 hr.	AA
Sm, Sc	8d	3d (over-exposed)	AA
Sc	18d	27 hr.	AA

* Gamma ray spectrum taken before each exposure.

Neutron activated ion exchange autoradiography for Na^+, Cs^+ and Br^- exchange distributions - The experimental procedure for determining the distributions of ion exchange capacities involve the following steps:

(1) Preparation of thin sections on plastic slides (no cover glass). In practice, slides previously used in the autoradiographic study for Mn and Na distributions are used after the ^{24}Na activity is dead, which requires only a few days.

(2) Irradiation of reagents containing the ions of interest (but avoiding reagents having other elements with similar or longer half lives which activate easily) by thermal neutrons in a research reactor.

(3) Submergence of nonradioactive thin sections in radioactive solutions prepared from these reagents by solution in deionized water.

(4) Rinsing of thin sections with deionized water.

(5) Exposure of thin sections to X-ray film.

(6) Preparation of enlargement prints from developed X-ray film for study.

Detailed specifications for the preparation of activated ions and the subsequent ion exchange and autoradiography are given in Tables 11 and 12. The parameters used in the present study were determined by theoretical calculations and estimations. The results were generally satisfactory with the exception of the Br anion exchange experiment. The problem is unlikely to be remedied without significantly increasing the ^{82}Br activity since relatively few anion exchange sites are available in clay minerals relative to cation sites (Body, 1972).

TABLE 11 - PARAMETERS USED IN PREPARING RADIOACTIVE IONS

Ion	Reagent Used	Amount	Reactor Flux	Duration	Position in Reactor	Total Activity	Isotope Produced	Half-Life
Na^+	Na-Citrate	1g Na	$2\text{x}10^{12}\,\text{n}/\text{cm}^2\text{sec}$	1 min.	Rabbit	1.4 mci	^{24}Na	15 hr.
Cs^+	CsCl	1g Cs	$2\text{x}10^{12}\,\text{n}/\text{cm}^2\text{sec}$	1 hr.	Lazy Susan	.3 mci	^{134}Cs	2.1 yr.
Br^-	K Br	1g Br	$2\text{x}10^{12}\,\text{n}/\text{cm}^2\text{sec}$	4 min.	Lazy Susan	.8 mci	^{82}Br	36 hr.

TABLE 12 - PARAMETERS USED IN ION EXCHANGE AND AUTORADIOGRAPHY

Ion	Volume of Solution	Concentration of Solution	Time Irradiation to Exchange	Time for Exchange	Time Exchange to Exposure	Time for Exposure	X-ray Film Type
Na^+	200 ml	0.5% Na	0.5 hr. *	2 hr.	0.5 hr. *	3 hr.	AA
Cs^+	200 ml	0.5% Cs	3 wks. **	5 hr.	1d **	7 hr.(5d)	AA (R - single Coated)$^+$
Br^-	200 ml	0.5% Br	3d	2.5 hr.	2 hr. *	19 hr.	AA

* Short as possible.

** Due to very long half-life, this time period is quite unimportant.

\+ Due to very long half-life of ^{134}Cs, high resolution, slow film may be used.

Note: Radioactive materials should only be handled by a qualified person who is properly licensed. The use of radioactive solutions is especially dangerous and should be handled with caution in a laboratory designed for that purpose. Storage and disposal of all radioactive materials must be in accordance with State and Federal regulations.

RESULTS

For each sample studied, there resulted autoradiographs of two thin sections for Mn and Na distributions, autoradiographs of one thin section for Sm+Sc+Na, Sm+Sc, and Sc distributions; and autoradiographs of one thin section for Na cation exchange, Cs cation exchange, and Br anion exchange distributions. A sample from King quarry (06-0028 D) has been chosen to illustrate the different autoradiographs (except Br^- exchange) and to show the kind of information which can be gained from each (Figure 22). Except for this sample, the only autoradiographs which will be shown are those displaying a characteristic which is useful in evaluating rock durability.

Mn distributions - Mn tends to occur mostly in the oxide phases so that high Mn concentrations often indicate the presence of magnetite, ilmenite, hematite, or hydrated iron oxides. Since these patterns are usually very similar in good and poor durability rock, Mn distribution is probably not a very strong indicator of rock durability. Two patterns which have only been found in marginal or poor aggregate are: (1) patchy distribution of Mn, as in the Wanless samples (Figure 23) which is approximately the opposite of the Na distribution, and (2) Mn concentrated in fractures, as in the Lookingglass and Ainsley samples (Figure 24). Although the patchy distribution of Mn may be a meaningful indicator, this pattern is also picked up in the Na distribution and the Na and Cs cation exchange distributions. The Mn concentration in cracks (probably as oxides such as pyrolusite) may well be more common in poor than in good aggregate; however, Mn oxides are extremely common as coatings on rock fractures so that very little weight should be given to this criterion without further data.

Na distributions - The distribution of Na in a rock seems to be a very good indicator of rock durability. Samples of durable rocks tend to show a uniform distribution of Na throughout the rock in glass and in some primary minerals. Poorer durability rocks may show a similar pattern but tend to have some of the following characteristics not found in durable rocks (Figure 25): (a) Na concentration in fractures, (b) patchy pattern of Na distribution, (c) Na concentrated between primary minerals along grain boundaries to give a "spider web" effect. It is probable that these patterns all indicate a significant mobility of Na (and possibly some other components) in the post-solidification history of the rock and are a major danger signal with respect to rock durability. In the samples studied, no rock showing these patterns has proven to be a satisfactory aggregate.

Distribution of elements having longer-lived isotopes such as Sc - The distribution of elements indicated by longer-lived nuclides such as Sm and Sc are either little affected by rock alteration and therefore appear the same in samples of both durable and poorly durable rocks, or they display a patchy distribution that is shown even better by Na distribution or cation exchange autoradiographs. The King quarry samples (Figure 22) serve as an example. The patchy pattern is evident as long as the Na activity is still contributing, but the Sc seems to be quite uniformly distributed in the rock. The autoradiographs of the longer-lived elements are useful in this study for distinguishing between the more mobile (Mn and Na) and the less mobile (Sm, Sc) components of the rock but add little to the evaluation of rock durability.

Na and Cs cation exchange distributions - Zeolites, glass, and clay minerals, in this order, have much higher cation exchange capacities than the primary minerals in basalt (Truesdell, 1972). Therefore, these autoradiographs show the location of glass, some cavity fillings, and alteration minerals in the rock. The durable rocks tend to have generally low cation exchange overall, or have small isolated spots scattered throughout the sample. High cation exchange cavity fillings may occur in the most durable basalts. Cation exchange patterns of poor durability rocks are as follows (Figure 26): (a) generally high and pervasive cation exchange, (b) patchy pattern of cation exchange, (c) high cation exchange associated with fractures in the rock, (d) fractures having high cation exchange along them, and (e) Cs cation exchange pattern different from the Na cation exchange pattern (Figure 22). All of these characteristics seem to be related to the degree of post-crystallization alteration of the rock. The highest cation exchange occurs in areas of low Na concentration.

Br anion exchange - Very little Br^- exchange was observed in these samples except with the surrounding epoxy cement. The small amount of exchange that was recorded such as in the King quarry samples shows a weak pattern very similar to the Na cation exchange pattern. The experiment could be modified to yield better results, but it would probably not add much to the other data in evaluating rock durability.

In summary, the Mn, Na autoradiographs and the Na and Cs cation exchange autoradiographs display characteristics which are useful in evaluating the durability of basaltic rocks, while the Br anion exchange and longer-lived isotope (e.g. Sc) autoradiographs add little. The characteristics observed in the autoradiographs of the 26 samples from the ten quarries studied are recorded in Figure 27, in which characteristics are listed in groups according to the type of rock durability which they characterize. This type of chart could be profitably used to check samples of rock of uncertain durability. Note that two or three samples of each quarry are used in this evaluation.

Quarry

Durability	Characteristic	Fish Creek	Roman Nose	Bald Mountain	Wanless	Lookingglass	Ainsley	State	Dovre Peak	Blue Ridge	King
	No. of Samples	3	3	2	3	3	3	1	3	2	3
Poor	Na in fractures					?		?	x	x	?
	Patchy Patterns Mn				x						x
	Patchy Patterns Na				x	x			x	x	x
	Patchy Pattern of Na^+ & Cs^+ exchange				x	x			x	?	x
	Cs^+ different from Na^+							?	x		x
	"Spider Web" Na dist.							x	x	x	
Marginal	High cation exchange in fractures					x					
	High cation exchange next to fractures						x				
	Mn in fractures				?	x	x				
Good	Even distribution of Na in glass & primary minerals	x	x	?							
	Very low cation exchange except for cavity fillings	x	x	?							
	Durability as aggregate	G	G	G	M/B	M/B	M	B	B	B	B

Figure 27 - CHARACTERISTICS OBSERVED IN AUTORADIOGRAPHS WHICH ARE ASSOCIATED WITH BASALTIC ROCKS OF DIFFERENT DURABILITIES

One sample is usually not adequate to determine the presence of all characteristics. Only one sample of State quarry was studied which contains no obviously good characteristics but the lack of a fracture in this sample makes the evaluation uncertain.

DISCUSSION

The association of certain patterns of element distributions and cation exchange distributions, as observed in autoradiographs, with good or poor rock durability is strictly empirical. The cause and effect relationships cannot be thoroughly understood from the present data alone, but enough data is available to attempt a working model for better understanding and further testing. Before considering the complete history of the rocks which has produced a material that is either durable or not, consider the present nature of the rocks which can be deduced from the autoradiographs.

A characteristic which is common to all of the poor durability samples is a generally high cation exchange capacity which is either pervasive or occurs in distinct patches throughout the sample, excluding cavity fillings. High cation exchange areas, excluding cavity fillings which may be zeolite, are mostly alteration products (clays) or glass. Although natural glass has a substantial cation exchange capacity, this probably does not significantly alter the physical properties over relatively short periods of time; e.g., Fish Creek samples contain a lot of glass but the rock produces durable aggregate. This is partly because glass is an amorphous solid with a roughly 3-D network of Si-O bonds and partly because exchange must take place at the surface and slow diffusion must occur to change the interior of the glass. This leaves the clays as the culprits in allowing a fairly rapid change in physical properties of the rock through relatively minor chemical changes brought about by ion exchange and/or hydration and/or the addition of organic components (Deer, Howie and Zussman, 1962 - Sheet Silicates p.226). The clays most common in these basaltic rocks are the smectites (Van Atta and Ludowise, 1974), which are swelling clays with very high cation exchange capacities and, therefore, a large potential for change. The occurrence of these clays throughout the rock creates a situation for potential disintegration when the physical and chemical environment of this rock changes as in quarrying and road construction.

The distribution of Na, the most mobile major element occurring in these basalts, is simply an indicator of the amount of post-crystallization alteration which has taken place in the rock to produce a reorganization of high temperature primary minerals and unstable glass into lower temperature clay minerals. Apparently, if the Na has been mobilized to the point where it moves into fractures or is concentrated around grain boundaries enough alteration has occurred to affect the durability of the rock.

The difference in the distribution of Na and Cs cation exchange capacities in some poor durability samples is more difficult to explain. Most of the samples have Na and Cs exchange patterns which are virtually identical. Different exchange patterns indicate that there are at least two alteration minerals which have different compositions and structures which occur in the rock. It is possible that one of these products (chlorite?) is formed at higher temperature through hydrothermal alteration.

Clay minerals tend to indicate their most recent environment and when environmental conditions change they are subject to rather rapid changes (Body, 1972). Changes that take place may be cation exchange, subject to the law of mass action, and/or penetration of water or organic cations or liquids into the interlayer spaces producing swelling.* No cation exchange can take place without a medium of transfer

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* Crushing of rock probably opens fractures which permits more rapid penetration of water

(water) and cation exchange would depend on a change in chemical nature of the water. In terms of aggregate use this gives several alternatives: (1) do not use rock subject to rapid change; (2) keep the aggregate dry to prevent change; or (3) alter the chemical environment to prevent destructive change. Since the exact chemical process of degradation is not known, the first seems to be the best choice, however, it seems possible that change might be slowed or prevented by controlling the environment; e.g., addition of materials rich in certain ions.

A more fundamental and perhaps academic question concerns the processes that produce these different rocks. The possible origins of basaltic rock bodies, ignoring the origin of the magma itself, are as follows: (1) subaerial lava flow, (2) submarine lava flow, and (3) hypabyssal intrusion as a dike or sill. The mode of emplacement produces characteristics which may be important in post-solidification alteration which in turn affects rock durability. Some characteristics of each which might be important to alteration are:*

1. For subaerial lava flows
    - (a) Loss of volatiles,
    - (b) Moderate amount of glass is probable,
    - (c) Fine grained,
    - (d) Vesicular, and
    - (e) Little deuteric alteration.

2. For submarine lava flows
    - (a) Probably much glass, and more mafic,
    - (b) Pillow structures,
    - (c) Little loss of volatiles, and
    - (d) Some vesicles depending on depth.

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* Assuming all are of the same chemical composition initially

3. For hypabyssal intrusives
    (a) Coarser grained except at contacts,
    (b) Few vesicles, if any,
    (c) No loss of volatiles,
    (d) Probably little glass which is more silicic, and
    (e) Deuteric alteration probable.

These different types may then be subject to alteration by natural weathering processes or hydrothermal alteration (or both) in addition to initial deuteric changes.

Of the possible histories, subaerial lava flows which have only been subjected to surface weathering (such as Fish Creek) seem to be the best candidate for a durable aggregate because less post-solidification alteration should occur. A coarse-grained intrusive might be a second choice. Any rock which initially contained a large amount of mafic glass and volatiles (mostly water) is subject to rapid alteration. Any basaltic rock which has been hydrothermally altered should contain a significant amount of clay which will result in poor durability. The genesis of some of the rocks in this study is suggested above in the main text of this report.

CONCLUSIONS

The study of basaltic samples from quarries in western Oregon by neutron activation autoradiography and activated cation exchange autoradiography has revealed certain characteristics which are associated with rocks of good, marginal, or poor durability. The most useful characteristics are found in the autoradiographs for Mn, Na, Na cation exchange and Cs cation exchange. Autoradiography for elements having longer-lived isotopes such as Sm and Sc, and Br anion exchange produced little additional data and could well be omitted from these tests. The characteristics which are useful in evaluating rock durability are listed in Figure 27. Most of these characteristics relate to the mobility of Mn and Na which has resulted in a patchy distribution pattern or intrafractural concentration in rocks of poor durability, or to the pattern of cation exchange which is related largely to the kind and distribution of alteration minerals in the rock.

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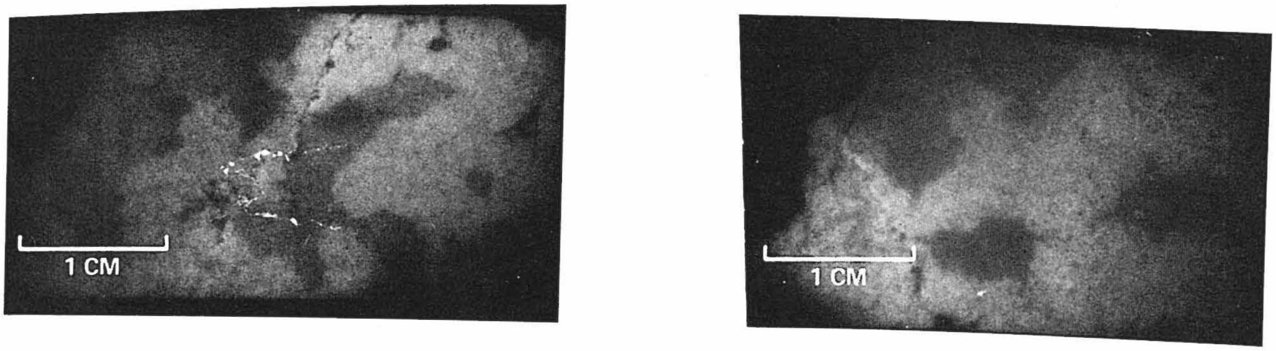
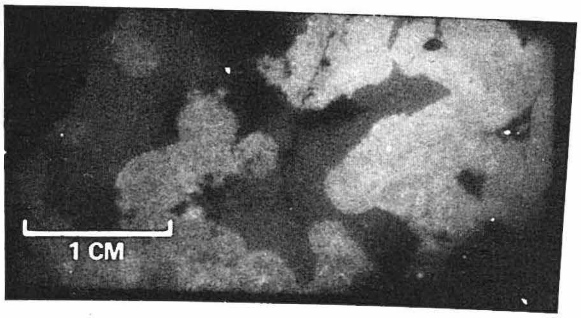
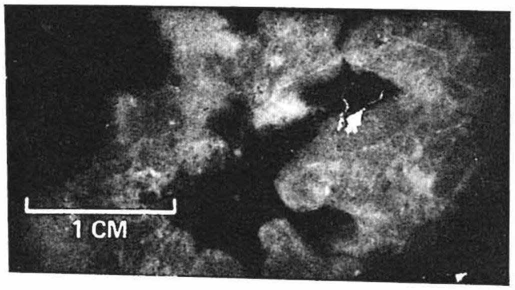


22a - Distribution of Activated Mn - Light areas

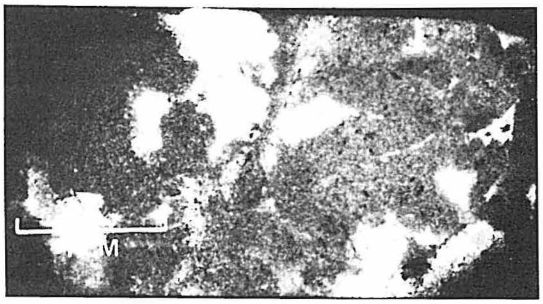


22b - Distribution of Activated Na - Light areas

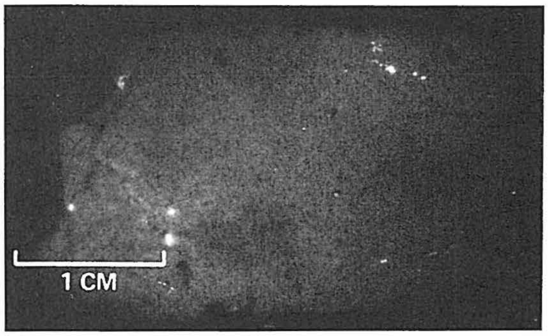


22c - Sodium cation exchange - Light areas

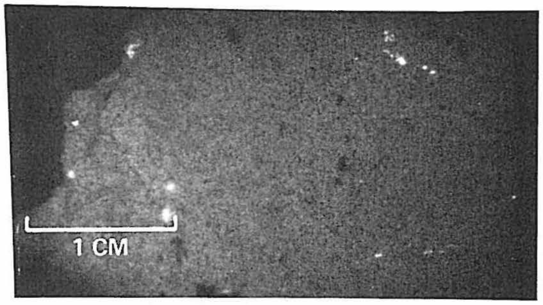
Figure 22 - AUTORADIOGRAPHS OF KING QUARRY SAMPLE 06-0028 D (ROAD BASE AGGREGATE, ELK CREEK ROAD, COOS COUNTY) SHOWING CATION DISTRIBUTION AND CATION EXCHANGE PATTERNS



22d - Cesium cation exchange - Light areas



22e - Activated Sm, Sc and Na - Light areas



22f - Activated Sc - Light areas

Figure 22 - Continued

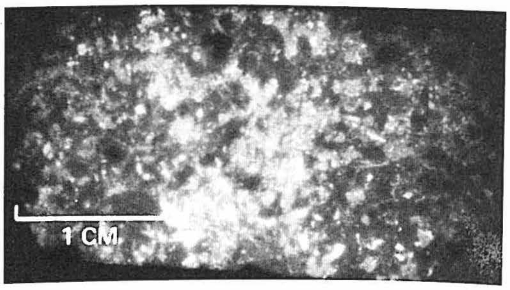


Figure 23 - Patchy Pattern of Activated Mn, Light areas - Wanless Quarry (36-0032 A)

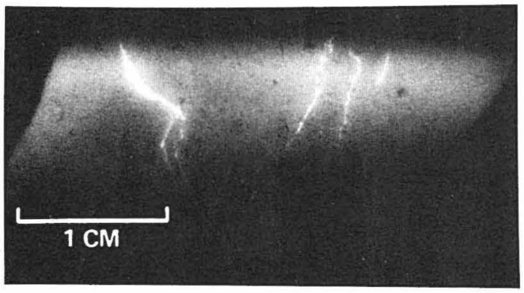


Figure 24a - Activated Mn in fractures, Light areas - Lookingglass Quarry (10-0291 E)

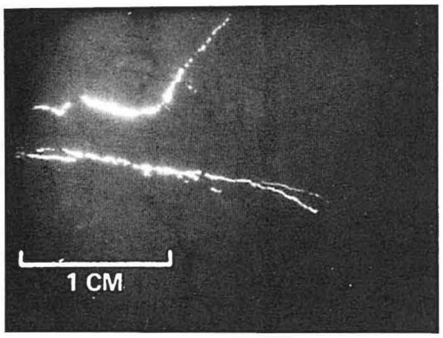


Figure 24b - Activated Mn in fractures, Light areas - Ainsley Quarry (06-0021 D)

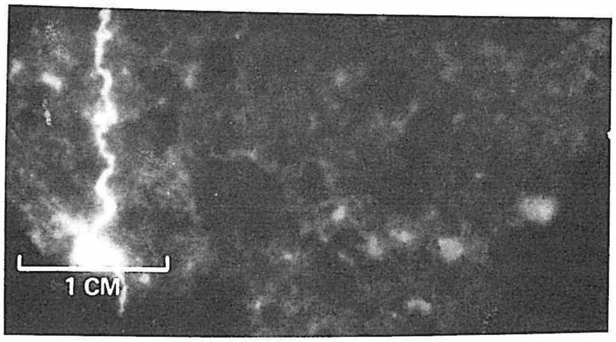


Figure 25a - Activated Na surrounding grains and in fractures, Light areas - Blue Ridge Quarry (06-0090.05)

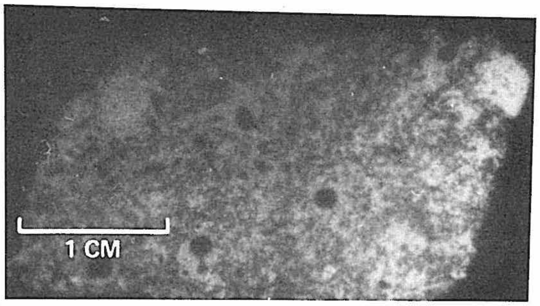


Figure 25b - Patchy distribution of activated Na, Light areas - Wanless Quarry (36-0032 W)

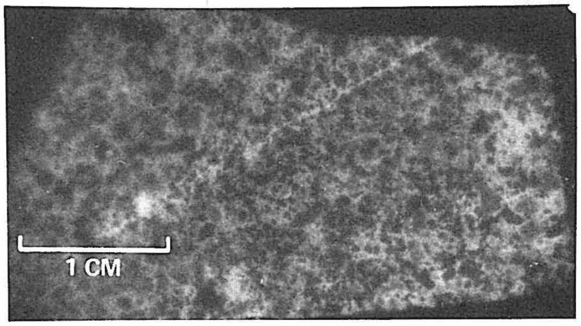
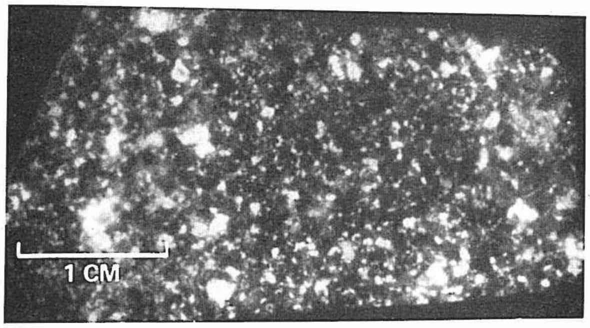
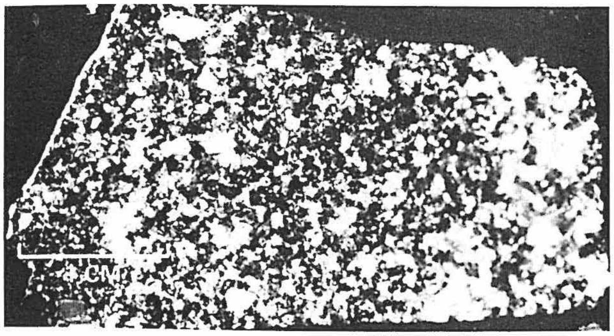


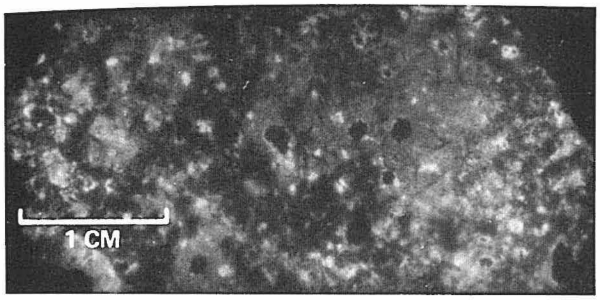
Figure 25c - "Spider Web" distribution of activated Na - Dovre Peak Quarry (29-0008.7)



26a - Sodium cation exchange - Dovre Peak Quarry (29-0008.7)
High total exchange

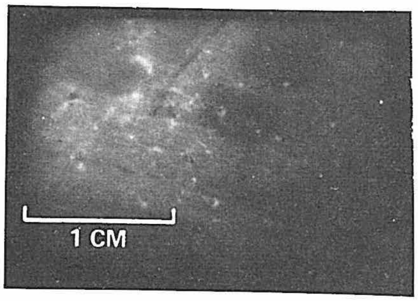


26b - Cesium cation exchange - Dovre Peak Quarry (29-0008.7)
High total exchange

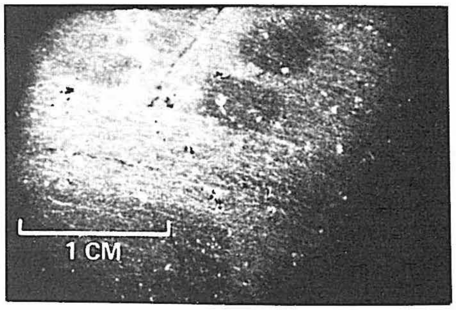


26c - Sodium cation exchange - Wanless Quarry (36-0032 C)
Patchy distribution

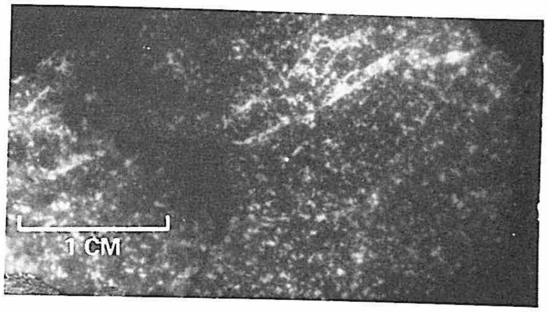
Figure 26 - DISTRIBUTION OF AREAS OF HIGH CATION EXCHANGE (light areas) IN FOUR QUARRIES WITH MARGINAL, UNSATISFACTORY OR UNKNOWN SERVICE RECORDS



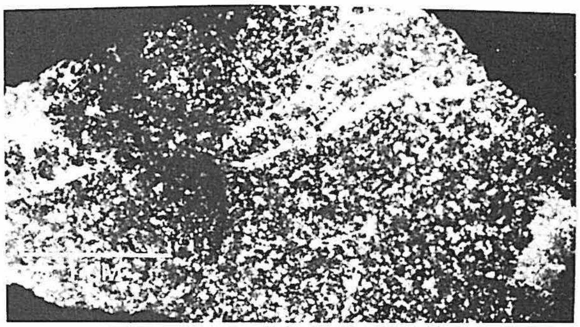
26d - Sodium cation exchange around fractures - Ainsley Quarry (06-0021 D)



26e - Cesium cation exchange around fractures - Ainsley Quarry (06-0021 D)



26f - Sodium cation exchange in fractures - Lookingglass Quarry (10-0291 D)



26g - Cesium cation exchange in fractures - Lookingglass Quarry (10-0291 D)

Figure 26 - Continued

APPENDIX B

TABLE 8 - ALTERATION MINERALOGY: Smectite

- No Test; + Present, Species not Determined; x Present, Percentage not Determined
1 - For meaning of numbers, see Table 3

Sample	Smectite X-ray	Smectite Stain	Smectite Optical	DMSO X-ray	DMSO Reaction	Textural Type[1]	Total Alteration
Fresh		6%		-			
03-0007B	Interstrat. ?	Mont. - 8%	?	1	-		25%
Soil	Interstrat.			17.8Å	+Swelling	A-3	
03-0007D	Ca - Mont.	-	-	19.2Å	Strongly	(B-4)	
				(/ 0.2_u)			
Base Agg. FC							
03-0007Q	-	Mont. - 2%	-	-	-		20%
C-Horiz.	Ca - Mont.			17.72Å			
03-0007 Soil	Interstrat.	-	-		Negative		21%
06-00021C "Fresh"	Montmor. 14.24Å Ca^{++}	15% Mont.	x	18.09Å	Negative	A-1,3	27%
06-0021D Weathered C-Horiz.	Montmor. 14.24Å Ca^{++}	43% Montmor. + Nontr.	x	17.72Å	Ca^{++} Sat. Negative Uutrtd, Swelled	A-1,2,3 B-1,2,4	87%
06-0021F Soil B-Horiz.	Interstrat.+ Montmor. 14.24Å	-	x	16.91Å	+Swelled	-	
06-0028 Fresh	-	28%	Montmor. 28%	-	-	A-1,3 B-1	47%
06-0028A Fresh	Montmor. 14.24Å	25%	-	17.51Å	+Strongly Swelling	A-1,2 B-1	50%
06-0028C Weathered Rock	Montmor. 13.18Å	35%	-	-	-	A-2 B-1,2	74%
06-0028D Road Base Aggregate	Montmor. 13.58Å	36%	-	-	-	A-3 B-1,2	62%
06-0028E Weathered Rock	13.58Å Montmor. Na^{+} ?	-	-	16.11Å	+Strongly Swelling	A-1,3 B-1,2	

TABLE 8 (Continued) - ALTERATION MINERALOGY: Smectite

- No Test; + Present, Species not Determined; x Present, Percentage not Determined
1 - For meaning of numbers, see Table 3

Sample	Smectite X-ray	Smectite Stain	Smectite Optical	DMSO X-ray	DMSO Reaction	Textural Type^1	Total Alteration
10-0055A "Fresh"	Too little Smectite Vermiculite		Vermic.	-	-	A-1,3	
10-0055B Fresh	Vermiculite	3% Montmor.	Vermic.	-	-	A-1,3 Ubiquitous	45%
10-0055G Weathered, C-Horiz.	Vermiculite	8% Nontr.	(Nontr. ?) Vermic.	-	-	A-1,3 Ubiquitous	71%
10-0055K Aggreg. Base Course	Vermiculite	4%	Vermic.	-	-	A-1,3 Ubiquitous	62%
10-0291 "Fresh"	Nontr. (+Interstr.) Mont.-Mica +Vermic. 14.38Å	-	Nontr. Alt. of Palagonite	-	-	A-1,3	
10-0291B Aggregate Gravel Rd.	Nontr. 14.7Å (12.5Å)	8% Montmor.	Nontr. Alt. of Palagonite	17.11Å	+Strongly	A-1,3 B-4	40%
10-0291D "Fresh"	-	3% Montmor. ?	Nontr. Alt. of Palagonite	-	-	A-1,3 B-4	46%
10-0291E Weathered C-Horiz.	Nontr. ? Montmor. 14.24Å	23% Montmor.	Nontronite -00-	18.01Å	+ Slight	A-1,3 B-1,5	60%
10-0291F Soil B-Horiz.	Montmor. 14.01Å			18.16Å	Negative	-	

TABLE 8 (Continued) - ALTERATION MINERALOGY: Smectite

- No Test; + Present, Species not Determined; x Present, Percentage not Determined
1 - For meaning of numbers, see Table 3
* - Good smectite peaks

Sample	Smectite X-ray	Smectite Stain	Smectite Optical	DMSO X-ray	DMSO Reaction	Textural Type[1]	Total Alteration
* 20-0017B "Fresh"	Saponite ? 14.72Å + Vermic. ?	13%	Montmor. Nontronite Alt.Hypers. 35% (+Hyd Fe-ox)	-	-	A-1,3	37%
* 20-0017E Weathered C-Horiz.	Saponite ? (13.18Å) (15.28Å)	No React.	+ 32% (Nontr.) ? ±Hyd Fe-ox	-	-	A-1,3	34%
* 20-0017F B-Soil Horiz.	12.8Å	-	-	-	-	-	
20-0017I Aggreg. Base Course	x (13.5Å)	No React.		-	-	A-1,3	47%
* 20-0017K Aggreg. Base Course	+ 12.54	No React.		-	-	A-1,3	
29-0008.5 Aggreg. Crusher Site	Nontr. 15.76	Nontr. 19%	Nontr. 27%	-	-	A-3 B-3,5	
29-0008A		Nontr. 13%	Nontr. 16%	-	-	A-1,2,3	44%
29-0008.7 Lower Unit, Fresh	+ Nontr. 15.017	Nontr. 5%	Nontr. 7%	-	-	B-5 A-1,3	46%
29-0008.13 Aggreg. Dovre Peak Cut-off Rd.	Nontr. + 14.01Å	-	-	+ 16.91Å	Negative		51%
29-0008E Weath. Rock C-Horiz.	-	11%	-	-	-	A-1,3 B-1,3	57%
29-0008F Soil B-Horiz.	Nontr. 14.01Å	-	-	17.17Å	Negative		

TABLE 8 (Continued) - ALTERATION MINERALOGY: Smectite

- No Test; + Present, Species not Determined; x Present, Percentage not Determined
1 - For meaning of numbers, see Table 3

Sample	Smectite X-ray	Smectite Stain	Smectite Optical	DMSO X-ray	DMSO Reaction	Textural Type[1]	Total Alteration
29-0028 "Fresh"	Nontr. 14.8Å	Nontr. 6%	Nontr. 10%	-	-	A-1,3	33%
29-0047 "Fresh"	Nontr. 14.7Å	Nontr. Montmor. 35%/16%	Nontr.	-	-	A-1,2,3	35%/16%
36-0001A "Fresh"	+ 14.91Å	Montmor. 6%	Nontr. 20%	-	-	A-1,2,3	32%
36-0001C Weathered, C-Horiz.	+ 13.46Å	Montmor. 7%	Montmor. -	16.41Å	Negative	A-1,2,3	51%
36-0001E Soil, B-Horiz.	+ 14.10Å	-	-	17.65Å	Negative	-	
36-0001.3 Degraded Agg. Rd. Base	+ 12.61Å	-	15	17.65Å	Slight	-	33%
36-0007A "Fresh"	Nontr. 14.47Å	-	Nontr. Montmor. M M 10%,12%	18.16Å	Slight	A-1,3	24%
36-0007.3 Agg., Chuck hole, Nest. Road	Nontr. 14.24Å	Nontr. (Montmor.) 24%	-	18.09Å	+Swelling Strongly	A-1,2,3 B-1	36%

TABLE 8 (Continued) - ALTERATION MINERALOGY: Smectite

- No Test; + Present, Species not Determined; x Present, Percentage not Determined
1 - For meaning of numbers, see Table 3

Sample	Smectite X-ray	Smectite Stain	Smectite Optical	DMSO X-ray	DMSO Reaction	Textural Type^1	Total Alteration
36-0032A "Fresh"	+ 12.98Å	Mont. ? < 1%	+ 6%	18.3Å	Negative	B-1,4,5	24%
36-0032C Aggreg., Gravel Rd.	+ 14.7Å	Mont. ? 2%	+ 8%	- -	- -	A-1 B-5	18%
36-0032W Weathered, C-Horiz.	+ 14.47Å	Mont. 9%	+ 8%	-	-	B-4,5	64%
36-0032S Soil B-Horiz.	+ 12.8Å	-	-	-	-	-	
36-0032.48 Fresh Core	12.8Å + 14.2Å	Mont. ?	+ 10%	- -	- -	- -	15%

APPENDIX C

TABLE 9 - RESULTS OF POINT COUNTING: ALTERATION

Slide	Unaltered		Altered Smectite		Alt. Non-Smectite		Glass and/or Palagonite	
	Count	%	Count	%	Count	%	Count	%
29-0047	316	51	213	35	87	14		
03-0007B	443	75	48	8	102	17		
03-0007Q	346	80	10	2	78	18		
03-0054	364	53	174	25	150	22		
06-0021C	274	68	61	15	47	12	23	6
06-0021D	83	13	286	43	290	44	0	0
06-0028A	290	50	145	25	146	25		
06-0028C	136	25	190	35	211	39		
06-0028D	234	38	224	36	164	26		
06-0060.95	145	40	123	34	91	25		
06-0088	399	54	101	14	177	24	60	8
06-0090.05	337	44	145	19	291	38		
06-0090.103	339	41	174	31	261	32	52	6
10-0055B	281	55	15	3	215	42		
10-0055G	274	57	36	8	170	35		
10-0055K	158	38	17	4	238	58		
10-0011B	497	63	56	7	242	31		Trace
10-0257	212	19	232	21	649	59		
10-0291B	569	60	79	8	300	32		
10-0291D	465	54	26	3	376	43		
10-0291E	275	40	141	23	231	37		
29-0008A	204	59	45	13	95	28		
29-0008E	502	43	131	11	546	46	1	Trace
29-0008.5	284	54	99	19	145	27		

TABLE 9 (Continued) - RESULTS OF POINT COUNTING: ALTERATION

Slide	Unaltered		Altered Smectite		Alt. Non-Smectite		Glass and/or Palagonite	
	Count	%	Count	%	Count	%	Count	%
29-0008.5	428	60	52	7	234	33		
29-0008.7	552	54	49	5	413	41		
29-0028	541	67	46	6	216	27		
29-0047	359	36	644	64				
29-0047	427	61	115	16	116	23		
36-0001A	499	63	50	6	204	26	36	5
36-0001C	340	47	51	7	319	44	7	1
36-0007.3	479	62	190	24	92	12	17	2
36-0032C	365	52	14	2	113	16	189	27
36-0032W	195	30	56	9	348	55	38	6
36-0043	381	60	52	8	199	32		

APPENDIX D

DEFINITIONS OF MINERALS

Analcite

A mineral with formula $Na(AlSi_2O_6) \cdot H_2O$. Analcite is considered to be closely related to feldspars in terms of structure, composition and modes of origin. It can, however, be included as a member of the zeolite group of minerals. (Deer, et al, Vol. 4, p.338.) The occurrence of analcite in the rocks of this study is not well understood, but it is apparently present interstitially.

Augite

A mineral of the pyroxene group, formula $(Ca, Na, Mg, Fe^{+2}, Mn, Fe^{+3}, Al)_2 [(Si, Al)_2O_6]$. (Deer, et al, Vol. 2, p.109.) Under the microscope, augite is pale brown and stands out more prominently than does plagioclase. Augite is a common pyroxene and is present in all of the rocks of this study as a primary mineral. It appears to be somewhat more resistant to alteration than the type of plagioclase feldspar found in these rocks. It can be altered in severely weathered specimens to hydrated iron oxides and clay, but in most of the rocks studied, augite is quite fresh, even in severely degraded base course aggregate.

Calcite

Calcium carbonate, $Ca CO_3$. A mineral formed in rocks studied in this report by deuteric alteration of minerals such as olivine, calcic plagioclase and, probably calcium-bearing glass. It tends to be found as vesicle fillings, but may also be included as one of the alteration minerals formed from interstitial glass.

Celadonite

A bright-green, blue-green or yellow-green alteration product found in some of these basaltic rocks; formula - $K_2 Al_2 Mg_2 Si_8 O_{20} (OH)_4$ or $K_2 Mg_2 Fe_2 + Si_8 O_{10} (OH)_4$. (Deer, *et al*, 1962, Vol. 3, p.217.) Celadonite is essentially equivalent to glauconite, which is formed in marine sedimentary environments. It is a member of the illite group of clay minerals; celadonite has no swelling properties. Commonly, aggregate celadonite may have a narrow border of saponite.

Chalcedony

The name "Chalcedony" is used in this report to distinguish a fibrous variety of quartz found as interstitial or vesicle fillings or linings. Deer, *et al*, (1963, Vol. 4, p.209) use the name "chalcedony" to designate all the compact minutely crystalline varieties of quartz, including agate, chert and flint. Other workers, such as Kerr, (1959, p.240), restrict the term chalcedony to the fibrous variety of quartz. Chert is a microgranular variety of quartz which is not found in any of the rocks of this study.

Chlorite

The chlorite group of minerals consists of several solid-solution series for which the formula $(Mg, Al, Fe)_{12} (Si, Al)_8 O_{20} (OH)_{16}$ is considered descriptive. (Deer, *et al*, 1962, Vol. 3, p.131.) Chlorites are very fine-grained and may be green, brown or sometimes yellow. Chlorite minerals are not especially abundant as deuteric alteration products in the basaltic rocks included in this study. Chlorite may also be formed in weathering. The so-called "swelling chlorites" are actually interstratified smectite and chlorite minerals (see smectite, below). The chlorite minerals found in rocks of this study are always associated with smectite.

Chlorophaeite

This name is used to designate a bright orange to deep green alteration product of olivine. (Deer, et al, 1962, Vol. 1, p.18; Williams, et al, 1954, p.44.) Chlorophaeite is generally reported to be isotropic but may show some birefringence when it consists of a mixture of chlorite, goethite and, possibly, calcite. (Deer, et al, 1962, op. cit.) Uncomonnon in the rocks of this study, chlorophaeite is present only in the olivine-bearing rocks where it is deep green.

Hydrated Iron Oxides

This general terminology has been employed in this report to include the following minerals. (Deer, et al, 1962, Vol. 5, p.118-127.)

Goethite - $FeO.OH$
Leprodocrocite - $FeO.OH$
Limonite - Amorphous $FeO, (OH, nH_2O$

All of this material has a deep yellow-brown to red-brown color. Hydrated iron oxides often occur intimately associated with other alteration products, such as smectites, where it causes a yellow or orange-brown coloration. Hydrated iron oxides often occur with and color chlorophaeite and iddingsite. Deer, et al, (Vol. 5, p.118) point out that limonite consists of cryptocrystalline goethite and lepidocrocite.

Ilmenite - Magnetite

In this report, ilmenite-magnetite refers to an intimate mixture of two oxides, $FeTiO_4$, ilmenite, and $FeO\ Fe_2O_3$, magnetite. In the rocks studied, these minerals are quite common in large (0.5 to 0.1 mm.) crystals which are often skeletal. Hydrated iron oxides are almost invariably associated with them, having been formed either deuterically (in fresher quarry rock) or secondarily (in weathered road aggregate). Ilmenite is very deep purplish-black in reflected light, whereas, magnetite is black.

Leucoxene

An alteration product formed from ilmenite. It is generally considered to be finely crystalline rutile, TiO_2. It is opaque and has a dull-white color in reflected light. Leucoxene is found in some of the badly degraded aggregate studied in this report.

Olivine

A general name for a solid solution series, formula $(Mg, Fe)_2 SiO_4$, ranging from $Mg_2 SiO_4$, forsterite, to $Fe_2 SiO_4$, fayalite. Olivine is not especially common in the basaltic rocks included in this study since it apparently was converted to pigeonite when the magmas crystallized. Olivine group minerals are especially liable to alteration, either deuterically or by weathering. The possible alteration products of olivine are quite numerous. Many of them have been given specific names, such as bowlingite or chlorophaeite, although recent studies show that these are not specific minerals but are, in reality, mixtures of several common minerals. (Deer, et al, 1962, Vol. 1, pp.18-20.) Most of the olivine present in some of the rocks of this study is completely altered to deuteric minerals.

Opal

Opal is an amorphous mineraloid of hydrated silica, formula $SiO_2.H_2O$, with the water content about 6 to 10 percent. Because opal is without crystalline structure, it often contains clay minerals such as nontronite, hydrated iron oxides, and other fine-grained alteration products. It is relatively difficult to identify under the microscope since it is isotropic zeolites, such as analcite. Most of what is identified in these rocks as opal is a turbid brownish or grayish interstitial material between framework crystals of pyroxene and plagioclase.

Palagonite

This name is used for brown to yellow or orange hydrated basaltic volcanic glass such as sideromelane or tachylite. (Gary, et al, 1972, p.509.) Palagonite is also reported to be green. (Kerr, 1959, p.424.) It occurs in basaltic rocks as rinds on pillows, amygdule linings, and as interstitial material within the rock fabric. (Gary, loc. cit., Williams, et al, 1954, p.39.) It is generally believed that palagonite is formed syngenetically by reactions of still-hot rock or volcanic ejectamenta with water. (Williams, et al, 1954, p.152.) Hay and Iijima (1968, p.368) have shown that palagonite is also formed by cold percolating ground water in normal weathering of volcanic glass.

These authors further point out (loc. cit., p.372) that palagonite may include crystalline constituents, namely goethite, nontronite and montmorillonite. Williams (loc, cit., p.153) reports fibropalagonite which is somewhat birefringent.

Palagonite occurs in the rocks of this study as vesicle and interstitial fillings. In both occurrences, palagonite may be somewhat altered. Much of the thoroughly altered interstitial material so common to all the rocks of this study may have originally been palagonite. It is a deep yellow brown and is isotropic, remaining black with crossed polarizing filters.

Pigeonite

A mineral of the pyroxene group, formula $(Mg, Fe^{+2}, Ca)(Mg, Fe^{+2})\ Si_2O_6$. Often present with augite, another pyroxene, as a primary mineral of rocks in this study. In most cases, it appears to have been formed at the expense of original olivine. Pigeonite is pale brown and stands out more prominently than does plagioclase feldspar.

Plagioclase

A mineral group which is a solid solution series, formula (Na, Ca) Al (Al, Si) Si_2O_8, with end members Na Al Si_3O_8 (Albite, Ab) and Ca Al_2 Si_2O_8 (anorthite, An). The mole-fraction of anorthite in a given crystal is designated as An_x where x is a percentage. The An content of rocks sampled in this study ranged from An_{47} to An_{69}. Plagioclase within this range of composition is called labrodorite (actually An_{50} - An_{70}). Labradorite is relatively susceptible to either deuteric alteration or weathering to clay (in cases of this study, montmorillonite and/or nontronite). However, labradorite is often quite fresh in these rocks. Chlorite may also form within plagioclase crystals by deuteric alteration. Labradorite, together with augite and/or pigeonite, forms the most abundant proportion of minerals in these rocks.

Smectite

This term is used to designate a group of clay minerals which includes montmorillonite, the aluminous member of the group. These minerals are extremely fine-grained, possess marked swelling properties, and high cation exchange capacities. According to current usage (Deer, et al, 1962, Vol. 3, p.226; Grim, 1968, p.77), the name smectite is now applied to what has been previously called the Montmorillonite Group of clay minerals. Actually, both terms are in current usage, although an effort is generally made to restrict the name montmorillonite to one member of the group.

The members of the smectite group which may occur as alteration products in the basalts of the present study include the following:

Montmorillonite - formula $(1/2\ \mathrm{Ca,\ Na})_{0.66}\ (\mathrm{Al}_{3.34}\ \mathrm{Mg}_{0.66})\ \mathrm{Si}_8\ (\mathrm{OH})_4\ \mathrm{nH_2O}$ vermiform, lamellar or scaly - yellow or brown color.

Nontronite - formula $(1/2\ \mathrm{Ca,\ Na})_{0.66}\ (\mathrm{Fe}^{+3})_4\ (\mathrm{Si}_{7.34}\ \mathrm{Al}_{0.66})\ \mathrm{O}_{20}.(\mathrm{OH})_4.\mathrm{nH_2O}$ green, brown-green, yellow green vermiform, spherulitic or radial aggregates. Pleochroic in green and yellow.

Saponite - formula $(1/2\ \mathrm{Ca,\ Na})_{0.66}\ \mathrm{Mg}_6\ (\mathrm{Si}_{7.34}\ \mathrm{Al}_{0.66})\ \mathrm{O}_{20}.(\mathrm{OH})_4.\mathrm{nH_2O}$ golden, amber, fibrous radial aggregates or scaly masses. Saponite is undoubtedly present in the alteration minerals of these rocks, but it could not be positively identified by X-ray diffraction.

A number of substances which may occur as alteration products of primary igneous rock-forming minerals of basalts are now known to consist of a smectite mineral or smectite plus other minerals. These alteration products are probably fundamentally deuteric in origin, being later further developed by weathering processes. (Deer, et al, Vol. 1, pp.18-20.) The following list defines these substances:

Bowlingite - According to Henin and Caillere, 1951, bowlingite is fibrous saponite. Deer, et al, (1962, Vol. 1, p.19) point out that X-ray studies by Wilshire show bowlingite to be composed of mixed-layer smectite-chlorite, together with serpentine and minor amounts of talc, quartz, mica and possibly sepiolite. Bowlingite is typically fibrous and green. It occurs in some of the olivine-bearing rocks of this study such as those from the State quarry.

Iddingsite - This alteration product of olivine may give the appearance of being a discreet mineral species because of optical homogeneity. However, X-ray studies by Wilshire, cited in Deer, et al, (1962, Vol. 1, p.19), show that iddingsite is composed predominantly of smectite and chlorite, together with goethite (red coloration); also with quartz and calcite and more rarely with mica and talc. Iddingsite is typically deep red-brown and may be lamellar or fibrous. It occurs with olivine and replacing olivine in a few of the rocks studied, such as those of the Bible Creek quarry.

The X-ray identification of smectites and other alteration products which include smectites is complicated by the variability of hydration (interlayer water), exchangeable cations, including the up-take of many different sorts of organic molecules, and the possibility of interstratification with other layer silicates such as chlorite. In general, the basal spacings of smectites lie between 12 and 15 angstroms.

The identification of individual smectites in this present study depended upon comparison of X-ray diffractograms and optical determination with the polarizing microscope. Nontronite is more easily identified as the most common and ubiquitous of the smectites present owing to its prominent green pleochroic color in rocks of this study. Yellow and brown smectites, seen under the microscope, are probably montmorillonite and/or saponite. However, since the X-ray diffraction peaks for the smectite minerals in these rocks are commonly quite broad, due to the complications cited above, it was not possible in this initial investigation to identify specific smectites in the same sample.

Zeolite

This name is given to a group of hydrated aluminum-calcium-sodium minerals, many of which are analogous to various feldspars. The general formula of the group is $(Na_2, K_2, Ca, Ba) [(Al\ Si)\ O_2]n \cdot XH_2O$. (Deer, et al, 1963, Vol. 4, p.351.) There are 22 mineral species included in the group. Many of the zeolites are fibrous. They are all colorless, and have a very low birefringence. Specific zeolites must be determined by X-ray diffraction, owing to the very fine grain size of the crystals. Many of the zeolites are common in hydrothermally altered basalts. In rocks of this study, fibrous zeolite was sometimes found filling fractures. Quantitatively, this fibrous zeolite appears to be unimportant since it was not evident in X-ray diffractograms.