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Title: STRATIGRAPHY, PETROLOGY, AND MINERALOGY OF THE COLESTIN FORMATION IN SOUTHWEST OREGON AND NORTHERN CALIFORNIA

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Harold E. Enlows

The Colestin Formation in the vicinity of the type area, southwest Oregon and northern California, is informally divided into three members and consists of a minimum of 3030 feet of andesitic to basaltic volcaniclastics and lavas. Southeast of the type area the Colestin Formation thins rapidly and in California forms a narrow, linear, discontinuous outcrop belt which pinches out in the vicinity of Black Mountain.

In the type area the lower member consists of 2124 feet of volcanic lithic sandstones, conglomerates, epiclastic breccias, ash-flow tuffs, and intermediate to basic lavas. The middle member contains mudstones, feldspathic and lithic sandstones, and intermediate to

basic lavas and pyroclastic breccias. The upper member consists of 534 feet of siltstones, volcanic lithic sandstones, epiclastic breccias, conglomerates, and a single ash-flow unit. In California the Colestin Formation sediments are poorly sorted volcanic lithic sandstones, epiclastic breccias and conglomerates.

The late Eocene time of southwest Oregon was characterized by a subtropical to tropical climate. The depositional record during this time indicates that volcanism was occurring within and around the present site of Colestin Springs. Evidence suggests that the Colestin Formation within the thesis area is a nonmarine, fluvial sequence of mostly volcaniclastic rocks deposited on a gently sloping flood plain which was occasionally devastated by lavas and ash-flows from nearby volcanism, but more often by slurry floods and lahars. Much of the volcanic material in the slurry floods was probably pyroclastic debris which fell in the highlands surrounding the Colestin Formation and was swept down after heavy rains. At other times the sediments of the Colestin Formation indicate streams and lakes existed in the Colestin basin. As volcanism increased the Colestin sediments were finally covered by a thick sequence of lavas, flow breccias and tuffs of the Roxy Formation.

The Colestin Formation sediments have been moderately to highly altered since deposition in the late Eocene. The authigenic minerals of the Colestin Formation have formed in the the depositional or post-depositional environment and include corrensite, chlorite, montmorillonite, mica, vermiculite, a kaolinite group mineral, heulandite, clinoptilolite, laumontite, opal, quartz, calcite, pyrite, and albite.

Paragenetic sequences have been determined for the authigenic minerals. In general it appears that in the type area chlorite was one of the first authigenic minerals to form followed by crystallization of heulandite and corrensite. In the Colestin sediments in California chlorite followed by crystallization of corrensite and calcite are typical. Quartz when observed has formed later than heulandite and corrensite. Evidence for the time of formation of montmorillonite cannot be found but it is thought that much of the montmorillonite is detrital except for that found in the lavas and ash-flows.

Most of the authigenic mineral assemblages were formed under alkaline, reducing conditions. These conditions were influenced by the rock types in which the authigenic minerals occurred. Corrensite is restricted to sediments and montmorillonite is the primary alteration of the lavas. Since bulk chemical composition was probably similar for the sediments, lavas, and ash-flows, the differences in authigenic mineral assemblages is probably due to permeability and mineralogy.

Channel lag and fill deposits of the Colestin Formation are coarse-grained sandstones and conglomerates containing relatively small amounts of matrix. The frequent occurrence of montmorillonite in the lag and fill deposits is the result of alteration of lithic fragments. Quartz occurs in these deposits probably because they were highly permeable and allowed fresh, silica-bearing groundwater to keep alkalinity low and favorable for the precipitation of quartz.

The flood plain deposits in which detrital clays were deposited contain montmorillonite partially altered to chlorite and corrensite. Channel bar(?) deposits contain less montmorillonite because of the presence of fewer lithics than in the other types of Colestin sandstones.

Zeolites, corrensite, chlorite and undifferentiated kaolinite group/chlorite minerals predominate in the graded and non-graded slurry flood deposits. The highly labile nature of the pyroclastic debris and mafic minerals in these deposits led to the eventual formation of alkaline groundwater, and the crystallization of corrensite, chlorite and zeolites.

The lacustrine sediments are believed to have undergone the least diagenesis due to their relative impermeability. Montmorillonite content is high in the lake sediments and is probably detrital. In one instance a reworked tuff bearing fossil diatom tests contains kaolinite and quartz as major authigenic minerals. These minerals were probably formed in the depositional environment by leaching of the more labile cations.

The base of the Colestin Formation within the thesis area was buried by at least 7000 feet of volcaniclastic rocks and lavas. Temperatures probably ranged from no less than 30°C to more than 125°C. Most of the Colestin Formation belongs to the low grade zeolite facies of Coombs (1959).

Stratigraphy, Petrology, and Mineralogy of the Colestin Formation in Southwest Oregon and Northern California

by

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TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

LIST OF TABLES (Cont.)

LIST OF TABLES (Cont.)

STRATIGRAPHY, PETROLOGY, AND MINERALOGY OF THE COLESTIN FORMATION IN SOUTHWEST OREGON AND NORTHERN CALIFORNIA

INTRODUCTION

Location and Accessibility

Exposures of the Colestin Formation studied in this thesis extend from the South Fork of the Umpqua River near Tiller, Oregon (Figure 1) to Black Mountain south of the Klamath River in California.

Detailed studies of the Colestin Formation were limited to the area extending from the type locality at Colestin Springs to the Klamath River.

The thesis area may be reached by Interstate Highway 5 which cuts through the Colestin Formation from the summit of Siskiyou Pass southward to the California border. Two generations of partially abandoned U.S. Highway 99 provide excellent access from Siskiyou Pass to the California border, and Oregon State Highway 66 cuts through the Western Cascades in an easterly direction just north of the thesis area. Many unpaved roads in Cottonwood Creek Valley provide excellent access to more remote exposures of the Colestin Formation. In California access is limited to U.S. Highway 99 and a partly paved road paralleling the Klamath River from Hornbrook, to the Oregon border, and to private roads which in many instances are closed to public use.

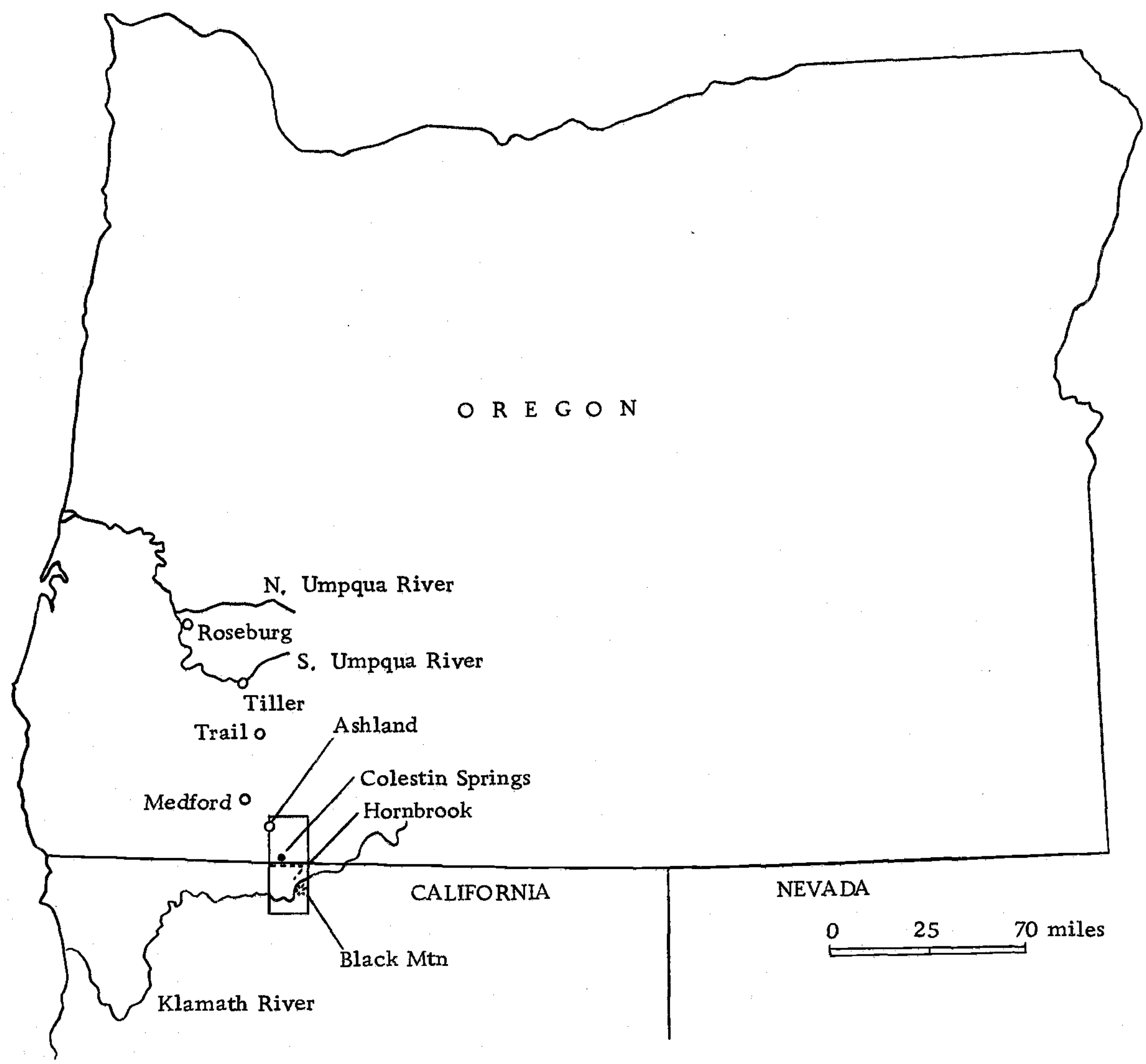

Figure 1. Index map showing the locality of the thesis area. That part of the Colestin Formation which was studied in detail lies within the Ashland, Ore.-Calif., and Hornbrook, Calif. 15 minute quadrangles which are indicated on the map.

Purpose

When this thesis was first formally proposed by the author a number of reasons were presented why this study should be undertaken. Most of these reasons grew out of the fact that except for Wells' (1956) map and description of the Colestin Formation little detailed information was available concerning the formation. Thus the purpose of this study was simply to learn everything possible about this formation using the thesis proposal as a general guide. As it turned out some of the original reasons for investigating this formation were not fulfilled, while others were. But more importantly as work progressed many more interesting facts and problems were uncovered and investigated.

It would be inappropriate at this time, after the thesis work is done, to list the original purposes of the investigation, especially those objectives which as work progressed were found incompatible with the direction the thesis had taken. Obviously it was impossible to foresee many of the problems before work had begun. Therefore some of the purposes set forth below were formulated as the thesis work progressed. The main objectives of this investigation were to:

1. Re-map in more detail than Wells' 1956 map, the type locality of the Colestin Formation.
2. Describe megascopically the rocks of the Colestin Formation in the vicinity of the type locality.

3. Perform a detailed petrographic study of the Colestin Formation sediments.
4. Determine the depositional environment of the Colestin Formation sediments.
5. Determine the source of the sediments.
6. Determine the post-depositional history of the Colestin Formation sediments.
    a. Study in detail the authigenic minerals of the Colestin Formation sediments.
    b. Determine depth of burial of the Colestin Formation and investigate the authigenic mineral zonations.
    c. Compare authigenic mineral assemblages of different rock types with one another, i.e., authigenic mineral assemblages of coarse versus fine sediments, authigenic mineral assemblages of igneous versus sedimentary rock, and authigenic mineral assemblages of sediments deposited in different depositional environments.

Field and Laboratory Procedures

This report is based on field work conducted for three months during the summer of 1969 and several weeks during the summer of 1970. Stratigraphic sections were measured either by Jacob's staff or tape and compass methods. Geological data was plotted on low altitude aerial photographs in the field and later transferred to a base map made of enlarged portions of the 15 minute Ashland, Oregon-California, and Hornbrook, California, quadrangles (U.S. G.S. topographic map series).

Approximately 150 thin sections were studied in detail and modal analyses made by point counting. The number of points counted per thin section ranged from 147 to 1389, the lower counts were caused by the coarseness of some samples. In order to attain more accurate analyses on clasts in the coarse clastics a method proposed by Nesbitt (1964) incorporating both thin section and rock slab point counts was used. An example of this calculation is found in Appendix III in addition to a description of how the rock slabs were prepared and point counts made.

Refractive index determinations were made on various grains to assist in determining the chemical composition, identify the mineral species or to characterize the grain. In all cases the refractive index was determined using a sodium monochromatic light source. Index oils were immediately checked after each determination using an Abbe refractometer and sodium light. In addition to determining the refractive index of grains, the refractive indices of fused beads of feldspar glass were determined. The table relating anorthite content to refractive index by Schairer and others (1956) was used.

X-ray analysis was used in conjunction with optical, heat and chemical methods for the determination of zeolites, phyllosilicates, quartz, and carbonate.

A procedure suggested by Harward (oral communication) and used by the Soils Department at Oregon State University was utilized for the identification of the clay minerals. The x-ray identification of kaolinite group minerals in the presence of chlorite presented special problems which were not completely solved. Both heat treatment and in some cases acid dissolution were performed in an attempt to distinguish the chlorite from kaolinite group minerals.

The distinction between heulandite and clinoptilolite was made by heating the zeolite for 14 hours at 450 degrees C (Mumpton, 1960).

Appendices I and II contain a more detailed discussion of the x-ray procedures relative to the identification of zeolites and phyllosilicates.

Partial chemical analysis of the intrusive rocks and lavas was performed by x-ray emission spectroscopy. Soda content was not determined.

PREVIOUS WORK

One of the first geologists to mention the volcaniclastic rocks lying at the base of the Tertiary sequence of Cascade lavas and sediments was Diller (1907) in his account of the coal fields in the vicinity of Ashland and Medford, Oregon. Winchell (1914) briefly mentions the volcaniclastic sediments overlying the Umpqua Formation in Bear Creek Valley and gives chemical analyses of the Colestin Spring water.

The early Tertiary volcaniclastic sediments near Medford and Ashland were first mapped in detail by Wells (1939) in 1930 but were not given the formal name, Colestin Formation by Wells until 1956 when he revised the geologic map of the Medford quadrangle. Subsequently the Colestin Formation has been recognized as far south as the Klamath River (Williams, 1949, p. 25) and as far north as Calapooya Creek (Peck and others, 1964).

Kays (1970) has recently mapped and described the Colestin Formation in the vicinity of Tiller. Elliott (unpublished Ph. D. thesis, 1970, Oregon State University) recently completed a study of the Cretaceous rocks in the Cottonwood Creek Valley, and McKnight (unpublished Ph. D. thesis, 1970, Oregon State University) investigated the Tertiary and Cretaceous rocks in Bear Creek Valley near Medford, Oregon.

Other geologists who have contributed regional studies of the early Tertiary rocks cropping out along the western edge of the Southern Cascade Range include Williams (1942), Wilkinson (1941), Hutchinson (1941), Weaver (1948), Callaghan and others (1938), Bailey (1966), Strand (1963), and Wells and Peck (1961).

ROCK NOMENCLATURE AND IDENTIFICATION

Pyroclastic Rocks

A slightly modified version of Fisher's (1961) classification of volcaniclastic rocks is used in the discussion of pyroclastic rocks (Table 1).

Autoclastic rocks of Fisher's classification were not recognized in the thesis area and are not included in Table 1 below.

Table 1. Classification of volcaniclastic rocks. Modified from Fisher, 1961.

Dominant grain size mm	Pyroclastic* primary or reworked	Epiclastic*+	Equivalent*+ nongenetic terms
	Pyroclastic Breccia	Epiclastic volcanic breccia	Volcanic breccia
64		Epiclastic volcanic conglomerate	Volcanic conglomerate
	Lapillistone		
3	Coarse tuff	Epiclastic volcanic sandstone	Volcanic sandstone
1/16			
1/256	Fine tuff	Epiclastic volcanic siltstone	Volcanic siltstone
		Epiclastic volcanic claystone	volcanic claystone

* May be mixed with nonvolcanic clastic material.

\+ Add adjective "tuffaceous" to rocks containing pyroclastic material less than 3 mm in size.

The upper size limit for ash in a lithified tuff is generally considered 4 mm. Fisher (1961) proposes changing this limit to 2 mm to agree with Wentworth's sediment size scale. Throughout this thesis 3 mm was found convenient and is used for the boundary between "conglomerate" and "sandstone" or "lapillistone" and "tuff" for sedimentary and pyroclastic particles, respectively.

In this paper pyroclastic is defined as fragments produced by volcanic explosion and extruded as discrete particles from vents. "Primary," when used with one of the above pyroclastic terms (Table 1), indicates pyroclastic material that has not been moved from its place of deposition before its lithification (Fisher, 1961). "Reworked" used in association with one of the above pyroclastic terms indicates that ash-fall material has been moved from its original place of deposition and redeposited before lithification.

Epiclastic Rocks

Epiclastic Rocks refer to mechanically deposited sediments of any size consisting of weathered products of older rocks.

If a volcaniclastic sediment contains shards or relict shard texture and volcanic lithic fragments, it is called a reworked tuff or lapillistone provided the rock contains greater than 50 percent shards or relict shard texture, and if less, it is called a tuffaceous epiclastic volcanic sandstone, conglomerate or breccia.

For petrographic descriptions of sandstones and conglomerates the classification of Crook (1960) is used. This classification is one of the best suited for the types of sedimentary rocks found in the thesis area. Gilbert's well known sandstone classification cannot be used because of the impossibility of distinguishing detrital matrix from inhomogeneous diagenetic minerals precipitated from solutions. Figure 2 represents Crook's (1960) classification of sandstones.

Vallier (1967, unpublished Ph. D. thesis, Oregon State University) lists several criteria for distinguishing between pyroclastic and epiclastic rocks. Many of his criteria could not be applied to the volcaniclastic rocks of this study. For example, Vallier states that volcaniclastic rocks are considered pyroclastic if there are abundant pumice fragments, glass shards or their relicts. He gives as evidence of an epiclastic origin the lack of distorted and elongated crystals and fragments. Both of these criteria are useless in this work because many Colestin sediments possess pyroclastic textures because of the pyroclastic nature of the source rock, and epiclastic rocks possess distorted and elongated fragments due to burial pressure.

Criteria found useful for recognizing an epiclastic origin are:

1. The many different lithic types representing clasts in the rock.
2. The presence of primary sedimentary structures such as graded bedding and cross-bedding.
3. The presence of rounded rock and mineral clasts.

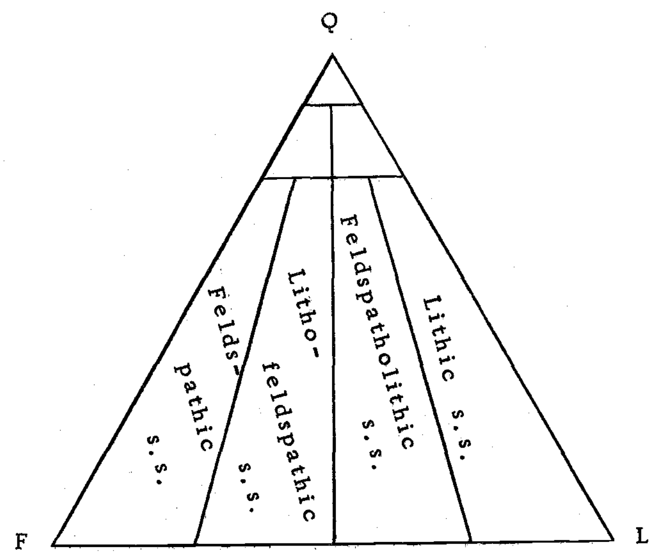

Figure 2. Generalized QFL diagram for sandstones. Modified after Crook, 1960.

The rock names of subquartose sandstones are based on a feldspar to lithic ratio where:

A. Feldspathic sandstone = F/L ratio of ∞ to 3
B. Lithofeldspathic sandstone = F/L ratio of 3 to 1
C. Feldspatholithic sandstone = F/L ratio of 1 to 1/3
D. Lithic sandstone = F/L ratio of 1/3 to 0

Criteria for recognizing a pyroclastic origin include:

1. The presence of a homogeneous vitroclastic or relict vitroclastic groundmass with or without abundant feldspar phenocrysts and with few lithic fragments.
2. A uniform homogeneous bed through a considerable thickness of strata reflecting no sorting of material by hydraulic processes.
3. The presence of welded shards as in an ash-flow tuff.

STRATIGRAPHY

Introduction

Wells (1956) gave the name Colestin Formation to a sequence of volcaniclastic rocks which were particularly well exposed near Colestin Springs in the extreme southeastern part of the Medford quadrangle. According to Wells, approximately 2000 feet of volcanic fragmented material including agglomerate, conglomerate pyroclastics, shale, sandstone and lava flows are excellently exposed in natural cliffs and road cuts along former and present U.S. Highway 99.

Since Wells' study additional outcrops have been exposed by the building of Interstate Highway 5 which parallels U.S. Highway 99 within the thesis area.

The Colestin Formation from the type locality (Colestin Springs) to where it pinches out near Hornbrook, California has been studied in detail and four partial stratigraphic sections have been measured. A composite stratigraphic section totaling 3030 feet was measured at Wells' type locality near Colestin Springs and is designated the type section of the Colestin Formation. A partial stratigraphic section was measured near the Oregon border and two additional sections measured near Shelton Creek and the Klamath River in California.

The Colestin Formation within the thesis area rests upon Cretaceous marine and lacustrine sandstones and mudstones with erosional and angular discordance. The upper contact of the Colestin Formation is gradational with the overlying Roxy Formation. Wells (1956) defined the upper contact as the uppermost layer of waterlaid pyroclastics that is followed by at least 100 feet of flows with or without interlayered non-waterlaid pyroclastics. Wells' definition is probably as good as can be devised for mapping the contact on a regional basis, primarily because of the impossibility of tracing any one horizon for more than several miles and the lack of a distinct sharp boundary.

During the field mapping a light colored resistant ash-flow tuff was discovered near the top of the Colestin Formation in that part of the thesis area lying in Oregon. This tuff crops out parallel to the upper contact of the Colestin Formation from the type area to the California border, a distance of five miles. It can be used to indicate proximity to the upper contact at localities where the overlying lavas have been eroded away or where several thin lavas with covered intervals are present.

Type Section, Colestin Formation

Introduction

The type section of the Colestin Formation is a composite section (section B, plate I) measured and/or defined at three principal localities (Figure 3). A partial stratigraphic section 294 feet thick was measured along the Interstate Highway 5 road cut at the summit of Siskiyou Pass located in the SE 1/4, sec. 29, T. 40 S., R. 2 E. (Ashland 15 minute quadrangle). Two prominent ledge-forming units were traced from Siskiyou Summit approximately 0.8 miles to the NW 1/4, sec. 29, T. 40 S., R. 2 E. where 363 feet of section were measured along the natural cliff found there. The section measured along the natural cliffs is essentially a repeat of the 294 feet at Siskiyou Summit but gives some indication of the lateral variability of the Colestin Formation (see plate I).

Exposures which lie within the middle of the Colestin Formation crop out in the valley occupied by Colestin Springs. A representative sampling of these rocks is described but is not included within the stratigraphic column due to uncertainty in stratigraphic positions and thicknesses. A partial stratigraphic section 1929 feet thick lying below the rocks found in the Colestin Valley was measured in a single traverse beginning along Mill Creek in the NW 1/4, sec. 11, T. 41 S., R 1 E. and ending in the SW 1/4, sec. 36, T. 40 S., R. 1 E. at the top of a ridge capped by olivine basalt. The bottom 195 feet of the type section were measured in the SE 1/4, sec. 3, T. 41 S., R. 1 E.

The Colestin Formation at the type locality is informally divided into three members based on gross lithologic and textural characteristics. The upper 706 feet of the Colestin Formation are referred to as the "upper member." The "middle member" consists of the next lower 336 feet of measured section and also includes many of the sediments in Cottonwood Valley near Colestin Springs not included in a measured section. The lower 2124 feet of section are referred to as the "lower member."

From careful photogeologic interpretation and extensive field studies it appears that an unknown amount of Colestin Formation has been faulted out in Cottonwood Valley near Colestin Springs. Thus the 3030 feet of measured section are a minimum thickness for the Colestin Formation at the type locality.

Lower Member

Introduction. The lower member of the Colestin Formation consists of 2124 feet of volcaniclastics and interbedded lavas. The upper one-half of the lower member is poorly exposed and its lithologic description generalized. The lower one-half is well exposed along Mill Creek in secs. 2 and 11, T. 41 S., R. 1 E., where it was measured.

Siltstones. Siltstones are rare in the lower member and where present tend to be gradational into coarser material. Volcanic siltstone is present in the lower member just above the Cretaceous contact, and appears to be gradational into the underlying mudstone, but consistently greater dips (20 to 30 degrees in the Cretaceous and 15 degrees or less in the Colestin) indicate the contact is an angular unconformity with the Cretaceous mudstones.

Sandstone. The sandstones of the lower member are massive or thickly bedded, unsorted and coarse to very coarse grained. Pebbles are usually subangular. Large pumice fragments and relict shards are common and indicate at least a partial pyroclastic source.

Rounded quartzite pebbles and sand-size quartz grains are found only in the upper one-half of the lower member, becoming abundant above unit 16 (section B, plate I). The quartzite pebbles generally appear as float but rare outcrops indicate this portion of the lower member is composed mostly of poorly sorted pebbly sandstone and conglomerate predominantly of volcanic origin, and containing some quartzite and granitic detrital clasts.

Conglomerate and Breccia. The well exposed lower one-half of the lower member contains few conglomerates or breccias. A pebble count taken from a subangular epiclastic breccia approximately 60 feet above the Cretaceous contact reveals 100 percent volcanic lithics. Laterally the epiclastic breccia pinches out and at about the same stratigraphic level a volcanic conglomerate consisting of well rounded clasts ranging from pebble to boulder size appears in its place.

Ash-flow Tuffs. Three distinct ash-flow tuffs are present in the lowest 661 feet of the lower member. The lowest ash-flow tuff (unit 3, section B, plate I) is yellowish gray to olive gray, and forms a resistant ledge where measured. Plagioclase phenocrysts and eutaxitic texture characterize this bed.

The middle ash-flow tuff of the lower member (unit 11) is 12 feet thick and dark gray. In hand sample it has the appearance of a fine-grained basalt. Phenocrysts are very small and hard to distinguish from the groundmass. A slight tendency towards platiness and inclusions of black carbonized wood fragments also characterize this ash-flow.

The highest ash-flow tuff (unit 13, section B, plate I) caps the major ridge making up most of the northern one-half of secs. 11 and 12, T. 41 S., R. 1 E. The upper 60 feet of this ash-flow are characteristically a grayish green and forms massive cliffs. Light grays prevail in the bottom 64 feet whereas from 64 feet to 125 feet red vertical banding perpendicular to eutaxitic structure and extreme platiness are characteristic. The total thickness of this ash-flow tuff is 185 feet.

Lava Flows. Stratigraphically, unit 7 is the lowest lava flow cropping out in the type area. It is 25 feet thick, dark gray and has plagioclase phenocrysts embedded in a dense aphanitic groundmass.

Unit 16, a series of thin basic to intermediate lavas with thin and irregular interbedded flow breccias terminate the sequence of well exposed lower member rocks. Overlying unit 16 is poorly exposed volcaniclastic rock thought to be approximately 1000 feet thick. Quartzite pebbles are commonly found as float in this covered zone (unit 17, section B, plate I).

The highest unit in the lower member is a thick sequence of poorly exposed olivine basalt. It is most easily observed cropping out and forming the cap rock of a slightly tilted fault block in SW 1/4, sec. 36, T. 40 S., R. 1 E.

Middle Member

Introduction. Poor exposures and complex faulting within Colestin Valley make stratigraphic relations uncertain. As a result of this, only 367 feet of the middle member have been measured. Many outcrops of middle member sediments occur in secs. 29, 30 and 31, T. 40 S., R. 2 E. and have been studied but not measured because of poor stratigraphic control. The locations and descriptions of representative samples not within the measured portion of the middle member are listed in Table 2.

Sandstones and Conglomerates. Locally the middle member of the Colestin Formation is composed of better sorted and finer-grained sediments than the lower member. Middle member volcanic lithic clasts are noticeably less abundant than in the lower member. Many lithic poor sediments of the middle member resemble Cretaceous rocks cropping out to the southwest along Cottonwood Creek, but petrographic and stratigraphic studies indicate they belong to the Colestin Formation.

Table 2. Location and description of representative outcrops for the middle member of the Colestin Formation, not included within the measured section.

Location and Sample No.	
F-1: Railroad cut 1400 feet west of tunnel entrance in the NW 1/4, sec. 29, T. 40 S., R. 2 E.	White, very fine-grained reworked tuff with leaf fossils. Overlain by medium-grained biotite bearing sandstone. Dike and sill present. The reworked tuff is at about the same stratigraphic level as sample 178 taken from the type section.
Sample 178 (dike): Stream bottom in the SW 1/4, sec. 30, T. 40 S., R. 2 E.	Tuffaceous(?) volcaniclastic sandstone and siltstone, and cobble conglomerate. A basic dike is also present.
Sample 33: Railroad cut and stream bottom in the SW 1/4, sec. 31, T. 40 S., R. 2 E.	Fine-grained, well sorted, mica bearing calcareous sandstone overlain by coarse poorly sorted volcanic lithic sandstone and underlain by alternating lenses(?) of highly weathered brown pebbly sandstone and conglomerate, and hackly shale.
Sample 161: Fifty feet west of railroad crossing in the NW 1/4, sec. 31, T. 40 S., R. 2 E.	Friable, hackly, brown claystone overlying channel (?) deposit of clean pebbly sandstone. Pebbles are well rounded and all nearly of equal size. Channel is cut into coarse-grained biotite bearing sandstone which appears to contain angular boulders of the same lithology as the biotite sandstone.

In at least one instance a clean, very fine-grained calcareous sandstone closely resembling many of the Cretaceous sediments is found interbedded between poorly sorted pebbly sandstones characteristic of the Colestin Formation. The measured portion of the middle member consists of 367 feet of strata located in the center, SW 1/4 NW 1/4, sec. 29, T. 40 S., R. 2 E. This section is composed of a subrounded volcanic cobble conglomerate near the lower contact and is overlain and underlain by moderately sorted medium-grained sandstone. The sandstone beds are massive and apparently tabular or lens-shaped.. Contacts are sharp and slightly undulatory. In addition to the sandstone and conglomerate a reworked tuff is present near the top of the middle member. The covered zone overlying unit 25 (section B, plate I) is believed to be composed mostly of this reworked tuff. Within the reworked tuff thin cross-bedded strata alternate with carbonaceous laminae and beds of claystone. Apparently this sequence was deposited in a lacustrine environment occasionally possessing weak currents.

Flows and Pyroclastic Breccia. Thin, basic to intermediate lava flows crop out at the top of the middle member (unit 28, sec. B, plate I). They are poorly exposed and difficult to trace laterally. The lavas appear to be highly porphyritic to non-porphyritic dense basaltic andesites in hand samples. Phenocrysts are commonly plagioclase but minor amounts of mafic minerals occur.

True pyroclastic breccia is rarely found within the Colestin Formation in the area studied, but a single occurrence of a coarse breccia containing three to four varieties of volcanic rock clasts is found in the SW1/4NW1/4, sec. 29, T. 40 S., R. 2 E. Laterally it appears to grade into finer pyroclastic material and its presence may indicate a nearby vent.

Upper Member

Introduction. The upper member of the Colestin Formation consists of 534 feet of volcaniclastic rocks. The upper one-half of this member is well exposed on an Interstate Highway 5 roadcut at the summit of Siskiyou Pass. The units exposed here average ten feet in thickness and dip gently to the north.

Siltstones and Claystones. The description of the siltstones of the upper member is taken entirely from the outcrop at the summit of Siskiyou Pass where they are best exposed. The siltstones vary from grays to brown and are more friable than the coarser-grained rocks. Siltstone beds range in thickness from 1 to 15 feet and the average of 11 beds is 6 feet. They compose about 15 percent of the exposed portion of the upper member.

Contacts between beds are generally sharp and planar or slightly undulatory, but at least one upper contact is erosional with five feet of relief. In most instances the siltstones appear to have been moderately to highly tuffaceous. One bed contains what appears to be a highly altered vitrophyre(?) about four inches thick. Many of the claystones when placed in water disaggregate readily and expand indicating the glass shards have probably been altered to montmorillonite. A few beds of siltstone and claystone grade downward into coarser, friable material with tuffaceous matrix and abundant rounded pebbles. Others contain thin coal seams (two inches thick), carbonized wood fragments and moderately sorted sandstone lenses.

Sandstones. In distinct contrast to the siltstones, most of the sandstones are firmly cemented rocks. The average thickness of 25 beds measured at Siskiyou Summit and along the natural cliffs northwest of there is 21 feet. Sandstone and pebbly sandstone compose 60 percent of the exposed portion of the upper member and are by far the most common rock type. Most are massive unsorted deposits while others possess well defined graded beds. Texturally they are characterized by poor sorting, coarse to very coarse-grained sands and the presence of varying amounts of pebbles. The roundness of the sand-size material is almost always subangular whereas pebbles and larger sizes may vary from angular to well rounded. Subangular pebbles are by far the most abundant except in channel deposits where rounded pebbles and cobbles are common. Fine-grained volcanic lithic fragments dominate all grain sizes from fine sands upward. Many of the labile clasts, including pumice, have been partially flattened and squeezed between more resistant particles and against one another as a result of deep burial, in some instances giving the rock a eutaxitic-like texture.

Thin coal seams, petrified logs and stumps in growth position and carbonized wood are locally abundant in many of the sandstones of the upper member of the Colestin Formation. Zeolites and occasionally calcite cement is abundant in some units.

Conglomerates and Breccias. Conglomerate beds are generally thinner than the average sandstone and make up 15 percent of the exposed portion of the upper member. Channel conglomerates are common in the upper member and usually contain abundant subrounded to well rounded pebbles and cobbles. Epiclastic breccias make up about eight percent of the exposed portion of the upper member and usually grade into subangular pebbly sandstones.

Clasts coarser than sand size are represented by a wide variety of fine-grained volcanic lithics. A few beds in the upper member contain quartzite pebbles and cobbles and rarely intrusive igneous clasts are found.

Ash-flow Tuff. In the upper member at the type area a prominent ash-flow tuff is easily recognized and has been used as a marker bed. It can be identified in the field by its light color, a tendency to form ledges from 2 to 30 feet thick, clear vitreous plagioclase and quartz phenocrysts and the presence of black carbonized wood. The ash-flow tuff first crops out in the NW 1/4, sec. 29, T. 40 S., R. 2 E.

south of the major northeast trending fault separating the Mount Ashland batholith from the Colestin Formation. It is exposed almost continuously from the fault to where it is last observed in sec. 18, T. 48 N., R. 6 W. just south of the Oregon border.

Field Investigations in Oregon Southeast of Type Area

Southeast of the type area within the region indicated in Figure 3 the sediments of the Colestin Formation change sufficiently from those described at the type section to warrant additional description.

It is apparent from the outcrop pattern of the Colestin Formation (Figure 4 and plate 2) that it thins rapidly southeast from the type area. Sediments characteristic of the upper member thin to the southeast and are absent near the California border. Rocks similar to those of the middle member make up most of the outcrops southeast of the type area. The lower member appears to be much thinner than at the type area with either the lateral extension of unit 13 or possibly unit 3 (ash-flow tuffs) resting directly upon Cretaceous mudstones.

A partial stratigraphic section measured near the California border in the NW 1/4, sec. 15, T. 41 S., R. 1 E. (section C, plate I) consists of approximately 100 feet of medium- to coarse-grained sandstone overlying the ash-flow tuff marker bed. In general lithology and texture it closely resembles the sandstone of the middle member at the type section.

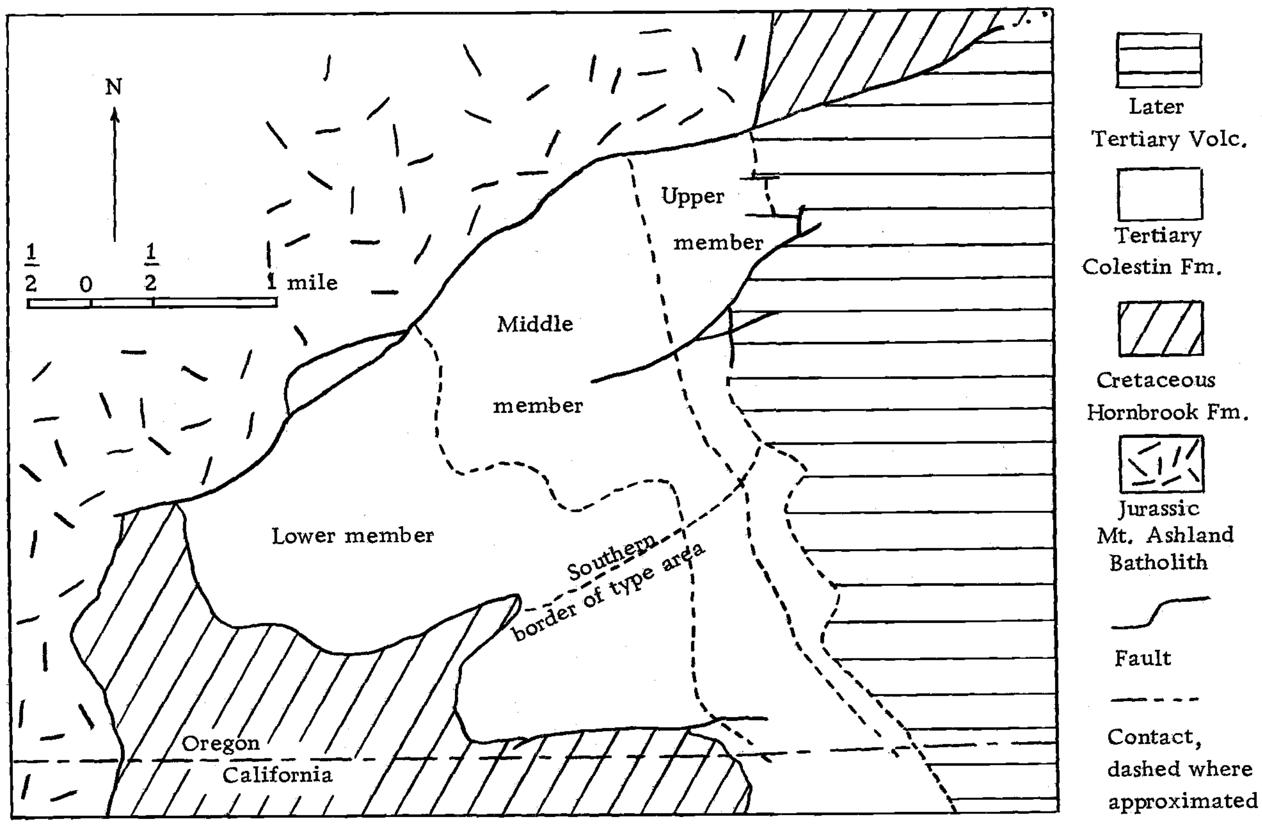

Figure 3. Geologic sketch map of the Colestin Springs area showing approximate outcrop position of the upper, middle, and lower members of the Colestin Formation.

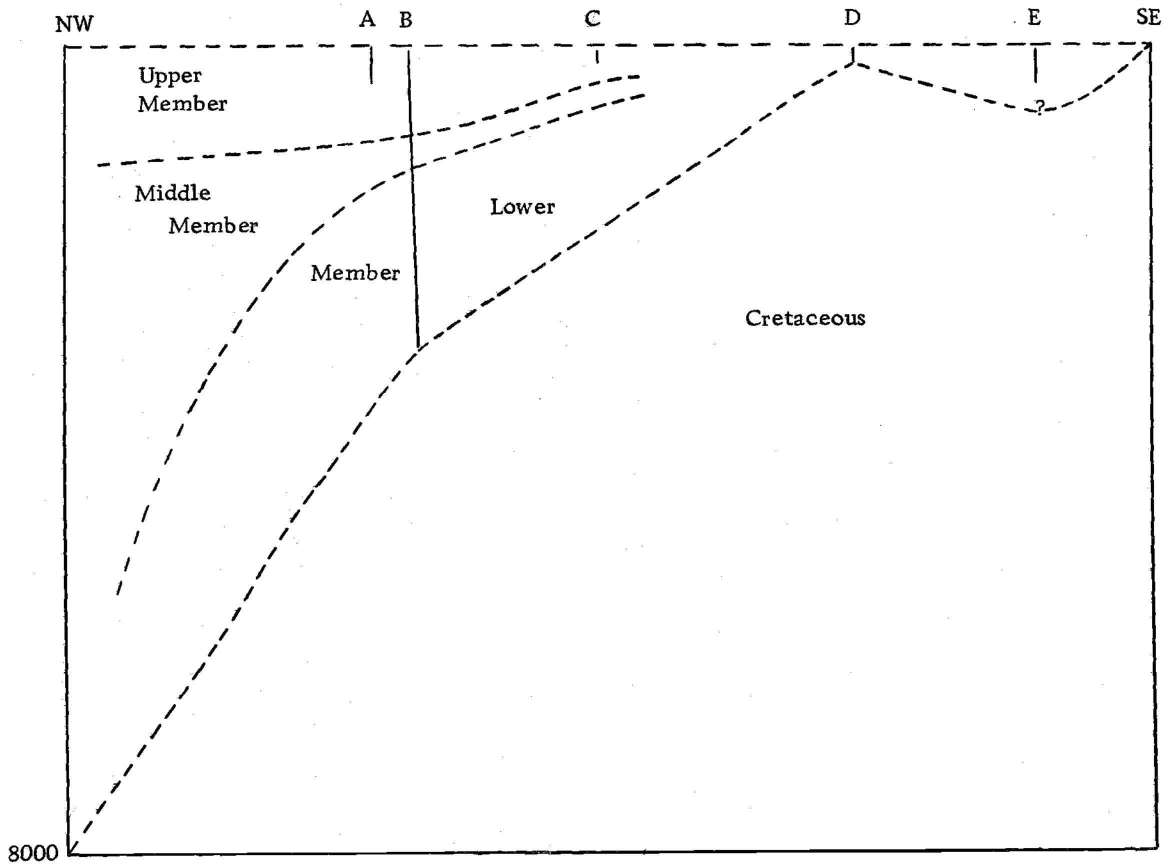

Figure 4. Hypothetical cross-section through the Colestin Formation in the vicinity of Colestin Springs. Capital letters refer to stratagraphic sections (plate 1). The thickening to approximately 8000 feet toward the northwest is based upon information taken from McKnight (1971).

Outcrops which are representative of the sediments in this area are well exposed in the roadcuts of former U.S. Highway 99 in secs. 4 and 9, T. 41 S., R. 2 E. Here a partial composite stratigraphic section has been constructed from estimated thicknesses of the units (Figure 5).

In the SW 1/4 SE 1/4, sec. 8, T. 41 S., R. 2 E. a small outcrop of mostly fine to medium-grained laminated and cross-laminated sandstone overlying a dark claystone is exposed in an otherwise covered area. The sandstone contains well preserved plant fossils consisting of leaves, twigs, and carbonized wood. The underlying claystone appears to be of lacustrine origin. The ridge paralleling old U.S. Highway 99 from the California border south for one-half mile is capped by ash-flow tuff which is probably correlative to ash-flow units in the lower member at the type area. The tuff overlies with angular unconformity Cretaceous mudstones.

Shelton Creek Measured Section

Introduction

The stratigraphic section measured at Shelton Creek (section D, plate I) in the center, sec. 8, T. 47 N., R. 6 W., of the Hornbrook, California, quadrangle consists of 122 feet of epiclastic volcanic sediments and igneous rock. The contact with underlying Cretaceous sediments is well exposed and is an erosional and angular unconformity.

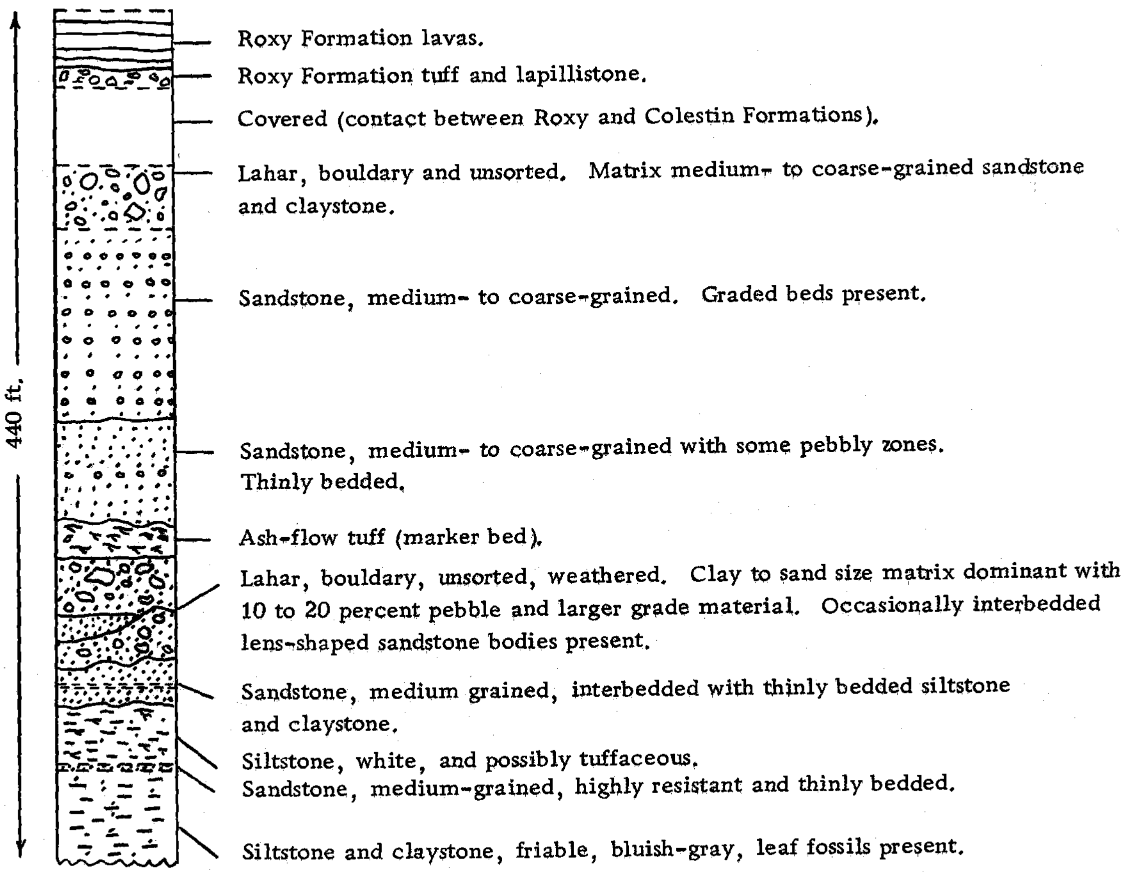

Figure 5. Composite section representing outcrops along U. S. Highway 99 in sec. 4, T. 41 S., R. 2 E. Thicknesses estimated.

The upper contact is covered but immediately overlying the Colestin Formation is a succession of thin andesitic lavas of the Roxy Formation. Several hundred feet to the north of this section the Roxy lavas are resting upon the Cretaceous sediments indicating the Colestin sediments in this area were probably deposited in small basins and valleys cut in Cretaceous mudstones and sandstones.

Claystones and Siltstones

Three siltstone beds ranging from 6 to 12 inches thick crop out at Shelton Creek. Their upper contacts are sharp and possibly slightly erosional. Lower contacts are sharp and planar to slightly undulatory. The siltstone units are variable in thickness and tend to pinch-out laterally. They appear to be tuffaceous and the lowest siltstone may be a reworked tuff. The lowest siltstone also contains leaf fossils and thin lenses of black carbonaceous claystone. Cretaceous mudstones and shales are found several feet below the erosional unconformity with the Colestin Formation. They contain a large amount of organic material and numerous leaf fossils. The mudstones are friable and attempts to extract some of the better leaf specimens were unsuccessful.

Sandstones, Conglomerates and Breccias.

Poorly sorted pebbly volcanic sandstone, conglomerates and breccia make up 72 percent of the Shelton Creek measured section. The average thickness of seven units of pebbly sandstone is 13 feet. Lower and upper contacts of these beds are generally sharp and slightly undulatory to highly erosional as along the Cretaceous contact. Pebble grade material may range from less than one percent of the rock to over 20 percent. Occasionally pebbly sandstone grades into pebble conglomerate. The pebbles range from angular to subrounded, the majority being subangular. Volcanic lithics make up the largest portion of pebble material. Some of the sediments contain coarse pyroclastic lithics such as pumice and tuff clasts, but they are highly altered and difficult to identify. A few subrounded quartzite pebbles are present.

The sand grade material of the pebbly sandstone is poorly sorted ranging from fine- to very coarse-grained. The sand-size grains are subangular with one notable exception, the sandstone and conglomerate overlying the Cretaceous sediments contain subangular to subrounded grains in about equal proportions. Most of the pebbly sandstones are thinly to very thickly bedded, contain no apparent graded bedding, are poorly sorted and may contain silicified wood, carbonized wood, and black carbonaceous material. Two separate horizons contain large silicified tree stumps in growth position (units 6 and 8).

Several lens shaped bodies of moderately sorted, volcanic sandstone were found in the Shelton Creek measured section (section D, units 6 and 7, plate I). The grains are subangular and medium to very coarse-grained. Large carbonized leaf impressions are found along some of the bedding planes. Near the top of a sandstone lens in unit 6 asymmetric ripple marks are found.

The basal conglomerate and sandstone overlying the Cretaceous rocks here contain subrounded volcanic pebbles and sand-size material. The lens-like nature of the basal unit indicates this material was deposited in a channel.

Igneous Rock

The only igneous rock observed in the stratigraphic section measured near Shelton Creek occurs just above the basal conglomerate and sandstone. The mafic igneous rock is highly weathered, friable and poorly exposed. The coarse grain size of the groundmass suggests this phaneritic rock is a sill or dike rather than a flow.

Klamath River Measured Section

Introduction

The Klamath River stratigraphic section was measured in the NW 1/4, sec. 26, R. 49 S., R. 6 W. (section E, plate I). The bottom of the section measured begins along the paved road adjacent to the north side of the Klamath River. As much as 300 feet of Colestin Formation may be present below the measured portion but is covered. The exposed portion of the Klamath River section consists of 362 feet of conglomerate and sandstone. No pyroclastic or other primary igneous rocks were discovered.

Siltstones and Claystones

One unit of friable claystone 20 feet thick is present in the lower part of the section. It generally forms a covered slope but is exposed here due to the construction of a new access road. A single resistant volcanic siltstone five feet thick crops out near the middle of the section. It contains a few pumice fragments and lithics up to 3 mm in diameter in a silt-size matrix.

Sandstone, Conglomerate and Breccia

Sandstones, conglomerates and epiclastic breccias are exposed in a series of well exposed cliffs where this section was measured. The tabular sandstone bodies tend to be poorly sorted and contain mostly subangular clasts. Several of the units display excellent graded bedding, especially unit 7. Sandstone lenses are present in some of the conglomerates and are composed of thin to thickly bedded, medium to coarse-grained material.

Volcanic pebble to boulder conglomerates containing subangular to rounded volcanic clasts in a coarse to medium-grained sand matrix make up about one-third of the exposed units. Near the base of the section an eight foot thick highly indurated cobble conglomerate (unit 4) is present. Overlying this unit with a sharp undulatory contact is a highly weathered friable cobble conglomerate which may be a regolith. A similar sequence of fresh consolidated conglomerate underlying a highly weathered friable conglomerate occurs slightly higher in the section.

PETROGRAPHY

Introduction

The petrographic study of the Colestin Formation is divided into two sections. The first section deals with those properties which are useful in the interpretation of provenance, depositional history and the classification of the rock. The second section deals primarily with the diagenetic minerals and the post-depositional environment in which they formed.

In describing the textures of the volcanic lithic fragments found in the volcaniclastic rocks and matrix material, a modification of the textural terms proposed by Dickinson (1970) are used (Table 3).

Type Section: Lower Member

Sandstones and Conglomerates. The detrital components of the sandstones and conglomerates of the lower member (Table 4) are almost entirely composed of volcanic lithics. Rock fragments constitute from 11 to 72 percent of the rock and many lithics tend to be distorted and squeezed between more resistant clasts making it difficult at times to distinguish distorted lithics (paramatrix) from true matrix. The original texture of lithic fragments include felsitic, lathwork and microlitic types. Most of the lithics are altered to various phyllosilicates making textural distinction inaccurate.

Table 3. Textural terms of Volcaniclastic Rocks. Modified from Dickinson (1970).

Volcanic lithic fragments

A. Felsitic-grains are an anhedral microcrystalline mosaic either granular or seriate. Mostly quartz and feldspars. Includes tuffs and lavas.

B. Microlitic-grains contain subhedral to euhedral feldspar plates and prisms in pilotaxitic, felted, trachytic or hyalopilitic patterns of microlites. Mostly intermediate type lavas.

C. Lathwork-grains contain plagioclase laths in intergranular and intersertal textures. Mostly basaltic rock types.

D. Vitric to vitrophyric or alteration products.

Interstitial material

A. Orthomatrix-primary detrital or recrystallized detrital matrix material.

B. Epimatrix-inhomogeneous interstitial material grown in originally open interstitices during diagenesis.

C. Pseudomatrix-discontinuous interstitial paste formed by the deformation of weak detrital grains.

Table 4. Modal analyses of epiclastic rocks from the lower member (section B, plate I).

Sample	106	108	110	111	112	115	117	91	103
Lithics $\geq$ 3 mm*	-	11	35	32	29	-	42	31	33
Total Lithics **	19	54	58	72	67	17	65	56	57
Pumice	-	-	-	-	(1)***	(6)	(2)	(7)	(6)
Plagioclase	4	3	5	3	9	3	5	10	12
Clinopyroxene	T	T	1	-	T	-	T	T	1
Opaque	1	1	1	-	-	T	1	T	1
Other	-	T	2	-	-	-	T	T	-
Clay Pseudomorph	-	-	-	-	-	-	-	T	-
Matrix	75	42	33	24	23	79	28	34	29
Cement quartz	-	-	-						

* Includes pumice.

** Pumice not included.

*** Amount included within parentheses is included in total lithics.

Plagioclase is the dominant detrital mineral ranging from about 3 to 11 percent of the rock. It varies from clear and fresh to highly altered grains. The dominant alteration mineral of the plagioclase is albite which commonly attacks the grain along fractures or zone boundaries and has a "dirty" appearance in contrast to the rather clear detrital portion of the grain. Other detrital constituents include magnetite, clinopyroxene, pumice and rare quartzite grains. Cements include heulandite, microcrystalline quartz, calcite, corrensite, and more rarely laumontite, opal and phyllosilicates. The lower member sediments contain only trace amounts of cement compared to the 18 percent maximum in the upper member sediments. The matrix minerals appear to have recrystallized and to be marked with mixed phyllosilicates of authigenic origin.

Ash-flow Tuffs. At least three separate ash-flow tuffs occur in the lower member of the Colestin Formation. From the bottom up they are designated as units 3, 11, and 13. Unit 13 (section B, plate 1) is the thickest and may be composed of more than one ash-flow. Units 11 and 3 are separated by coarse sediments and are much thinner than 13. Units 13, 11 and 3 average 14, 13 and 8 percent plagioclase phenocrysts respectively.

Unit 13 contains a devitrified zone that includes the middle 135 feet of the ash-flow. Devitrification products include feldspar and quartz. Within this zone alteration of the andesine produces a black, opaque material under transmitted light which appears white and cotton-like under reflected light. X-ray diffraction analysis of altered, hand-picked plagioclase did not reveal the nature of the alteration product. However, it is thought to be a poorly crystallized kaolinite group mineral.

In the non-devitrified zone of unit 13 shards have been replaced by clinoptilolite and phyllosilicates including a mica, corrensite, and montmorillonite. The phyllosilicates were identified by x-ray diffraction (see pages 98, 103, 111). Andesine phenocrysts range from fresh to highly altered and average about 0. 8 mm in length. Albitization is the most common form of alteration outside the devitrified zone.

Unit 13 contains fresh andesine phenocrysts which average about 1 mm in length, embedded in a heulandite and clay mineral matrix. The groundmass clearly shows shard texture and seems to be poorly welded.

Unit 3 contains fresh andesine phenocrysts averaging 1 mm in length. Many contain inclusions of a long, needle-like greenish mineral which was not identified. The groundmass is composed entirely of vermiculite, identified by x-ray diffraction (see page 110), heulandite, and minor amounts of microcrystalline quartz. Heulandite fills the interior of the shards while vermiculite is usually restricted to the spaces between shards. Quartz phenocrysts are found but are rare and the grains are corroded and embayed. Pumice is fairly abundant and has been replaced by clay minerals and heulandite. Modal analyses of the ash-flow tuffs are presented in Table 5.

Lavas. The igneous rock terminology used on the following pages is based primarily on the anorthite content of the rock in question. If over 50 percent by volume of the total feldspar in the rock is An_{50} or less the lava is considered an andesite. If greater than An_{50} the rock is considered a basalt. The statistical method of Michael Levy was used to determine the anorthite content of both groundmass plagioclase and plagioclase phenocrysts unless noted otherwise.

Unit 7 is stratigraphically the lowest lava flow cropping out in the Colestin Formation at the type section. The flow is a porphyritic basalt containing phenocrysts of labradorite (An_{61}), clinopyroxene, hornblende (forming at the expense of clinopyroxene), and trace amounts of hypersthene set in a groundmass of indistinct labradorite (An_{59}) laths, iron ore and bright yellow, highly birefringent montmorillonite identified by x-ray diffraction (see page 104), forming an intersertal texture.

Plagioclase makes up most of the phenocrysts and averages about 1.3 mm in length. The average anorthite content of four plagioclase phenocrysts is An61 (fusion method). The chief alteration product in this lava is a bright golden yellow mineral identified by x-ray diffraction as montmorillonite. It is found replacing hypersthene and labradorite phenocrysts and the groundmass indiscriminately.

Table 5. Modal analyses of Pyroclastic Rocks from the lower member of the Colestin Formation (section B, plate I).

Sample	113	114	86	93	94	95	96	98	99	100	101
Total Lithics	16	20	14	13	T	5	12	13	9	11	17
Pumice	(6)	(12)	(2)	(7)	(T)	(3)	(11)	(2)	(2)	(5)	(5)
Plagioclase	4	11	3	13	10	18	14	13	13	13	16
Quartz	-	T	-	-	-	-	-	-	-	-	-
Opaque	1	1	3	1	1	1	T	2	1	1	1
Clinopyroxene	-	-	T	T	-	T	T	T	T	-	-
Other	T	T	-	T	-	T	T	T	T	-	-
Clay Pseudomorph	-	-	-	-	2	1	1	-	T	T	1
Matrix	79	66	79	68	87	74	72	71	76	74	65
Cement											
Zeolite	T	-						T			
Quartz	-	-	T	4							

Unit 16 (section B, plate I) is a group of several lava flows. A thin section from one of the lower flows reveals a microporphyritic basalt with intergranular to intersertal and hyaloophitic texture. Labradorite phenocrysts (An62) average about 1/2 mm in length and are set in a groundmass of labradorite (An_{57}), clinopyroxene microlites, iron ore and montmorillonite. Labradorite and clinopyroxene phenocrysts are partially replaced by montmorillonite.

Unit 18 is a single flow of porphyritic olivine basalt. The groundmass is pilotaxitic and ranges from intergranular to intersertal. Phenocrysts include olivine, bytownite (An85), iron ore and clinopyroxene. Iddingsite and possibly montmorillonite (saponite?) rim most of the olivine, and montmorillonite replaces much of the clinopyroxene both in the phenocrysts and groundmass. Groundmass plagioclase is labradorite (An64).

Modal and partial chemical analyses of three lavas from the lower member are presented in Table 6.

Pebble Counts. A pebble count of unit 2, a subangular pebble conglomerate contains 100 percent volcanic lithic fragments, and 13 slab point counts of lithics greater than 3 mm contained only volcanic lithic detritus. Quartzite pebbles are seen in poorly exposed outcrops just above unit 16 (section B, plate I) and are abundant in float throughout the rest of the lower member above this unit.

Table 6. Modal and partial chemical analysis of selected lavas from the Colestin Formation. "T" indicates trace amounts.

Sample Number	80	104	121
Phenocrysts			
Plagioclase	29	10[1]	1
Clinopyroxene	4	1[2]	T
Orthopyroxene	T	-	-
Olivine	-	-	11
Hornblende	2	-	-
Opaque	1	-	2
Groundmass			
Devitrified glass	21	-	-
Plagioclase	17	51[3]	54
Clinopyroxene	20	24[4]	25
Opaque	2	3	4
Clay minerals	4	11	3
Partial Chemical Analysis[5]			
SiO_2	58.0	55.0	51.5
Al_2O_3	17.0	17.3	17.2
FeO	8.4	9.6	9.0
CaO	6.8	7.8	9.7
MgO	3.2	4.4	6.6
K_2O	1.10	0.92	0.93
TiO_2	0.98	1.00	1.08

[1]Two percent of this is clay alteration of plagioclase.

[2]One percent of this is clay alteration of clinopyroxene.

[3]Four percent of this is clay alteration of plagioclase.

[4]Five percent of this is clay alteration of clinopyroxene.

[5]Partial chemical analysis was performed by Dr. E. M. Taylor and Dr. M. A. Elliott of Oregon State University using x-ray fluorescent techniques. For comparison of these fluorescent values with wet chemical analyses, the latter should be recalculated on a water and carbonate (CO_2) free basis. Sodium values were not obtained.

Type Section: Middle Member

Sandstone and Mudstone. The most common sediments in the middle member are friable mudstones and pebbly sandstones, the latter usually containing a small amount of quartzite pebbles and a high content of volcanic lithics. Poorly exposed outcrops of mudstones and sandstones are commonly encountered in the type area, but the rock is friable, highly weathered and not suitable for sampling.

Outcrops of a better sorted, finer-grained sandstone characterized by higher feldspar and lower volcanic lithic content than those of the lower and upper member make up a significant number of the middle member exposures. The measured portion of the middle member is made up of four sandstone beds containing moderately sorted grains whose average diameter ranges from 0.1 mm to 1.0 mm. They contain a high proportion of feldspar and minor amounts of volcanic and quartzite lithics (Sample 76, Table 7). Detrital biotite, white mica and monocrystalline quartz grains may also be present in an inhomogeneous paste-like matrix. Microcrystalline quartz, chlorite and corrensite are found as cements and recrystallized matrix.

A reworked tuff overlies the coarser sandstone in the measured portion of the middle member (section B, plate I, unit 24) and may comprise much of the covered zone overlying unit 25.

Table 7. Modal analyses of two sandstones from the middle member of the Colestin Formation.

	Sample 161*	Sample 176+
Total Lithics	17	18
Volcanic lithics	(10)	(18)
Quartzite lithics	(5)	
"Granitic" lithics	(2)	
Feldspar (undifferentiated)	34	
Volcanic Plagioclase		44
Opaques	5	T
Clay Pseudomorphs		1
Mica	7	
Quartz	9	
Unknown	6	
Matrix	21	32
Cements		
Phyllosilicate		4
Zeolite		T
Calcite	1	

* See Table 2 for location of this sample.
+ Sample location is indicated on section B, plate I.

Thin section and x-ray diffraction of whole rock samples of the reworked tuff indicate the presence of a kaolinite group mineral (see page 109) chlorite, quartz, and mica, detrital plagioclase grains, and highly altered lithics (rare) in a completely recrystallized matrix. Chlorite pseudomorphs after glass shards are plainly visible indicating the pyroclastic nature of the original rock. Kaolinite group minerals and quartz are not easily distinguished from one another but it appears that much of the original glass has been replaced by microcrystalline quartz, and a kaolinite group mineral which are intimately intergrown in the groundmass. Mica occurs as authigenic(?) scaly masses which are probably recrystallized detrital material. Fragments of opaline shell material present in this reworked tuff resemble diatom tests.

Samples 161 (Table 7) and 33 (see Table 2 for outcrop description and location) represent rock types which are locally abundant within the middle member of the Colestin Formation. Unfortunately in most instances their exact stratigraphic position within the middle member is unknown. Mineralogically they resemble in varying degrees Cretaceous sandstone of the Hornbrook Formation.

Sample 161 is a friable, medium-grained, moderately sorted sandstone locally containing well rounded pebbles of chert(?) and Quartzite. The matrix is an inhomogeneous phyllosilicate paste. A modal analysis of a portion of this rock containing no pebble-size material is given in Table 7.

Sample 33 is a very fine-grained, well-sorted sandstone with subangular grains and abundant calcite cement which is slightly clouded by montmorillonite. Biotite, white mica, zircon, quartz, zoned volcanic plagioclase, quartzite and chert? lithics have all been identified in this rock. The lithics are estimated to make up less than two percent of the sandstone with plagioclase representing the dominant detrital grain.

Lava Flows. The igneous rock terminology used on the following pages is based primarily on the anorthite content of the rock in question. If over 50 percent by volume of the total feldspar in the rock is An_{50} or less the lava is considered an andesite. If greater than An_{50} the rock is considered a basalt. The statistical method of Michel Levy was used to determine the anorthite content of both groundmass plagioclase and plagioclase phenocrysts unless noted otherwise.

Unit 28, section B, plate I represents typical lavas from the middle member. Table 8 presents modal and partial chemical analyses of two samples from unit 28. Sample 307 from unit 28 is a porphyritic basalt with a felted groundmass of labradorite (An_{52}) microlites, magnetite and dark, nearly opaque clay minerals replacing what was probably pyroxene. Phenocrysts are commonly 1/2 to 1 mm long lath-shaped labradorite and bytownite, and tabular pyroxene crystals. Plagioclase is fresh and may contain crystals and glass inclusions sometimes aligned along zone boundaries. Plagioclase zoning is progressive normal or oscillatory in character. Pyroxene includes augite and hypersthene. Rarely the hypersthene possesses reaction rims of augite.

Sample 309 from unit 28 is a porphyritic andesite with a fresh, very fine grained, pilotaxitic groundmass. Phenocrysts, which average about 1.0 mm in length, are mainly labradorite (An_{59}), and clay (saponite?) or carbonate pseudomorphs. Iron ore replaces hornblende whereas clinopyroxene is fresh. The groundmass plagioclase is andesine (An_{40}).

Table 8. Modal and partial chemical analysis of unit 28 (section B, plate I). "T" indicates trace amounts.

	Sample 307	Sample 309
Phenocrysts		
Plagioclase	22*	16**
Clinopyroxene	4	
Orthopyroxene	5	
Opaque		2
Clay Pseudomorphs	2	2
Calcite Pseudomorphs		T
Groundmass	67	80
Partial Chemical Analysis***		
SiO_2	55.3	60.5
Al_2O_3	16.2	18.9
FeO	8.5	6.1
CaO	9.5	5.5
MgO	4.3	2.2
K_2O	1.15	1.40
TiO_2	0.79	0.78

* An_{64}, An_{72}, and An_{71} for three grains using Carlsbad-albite method.

** An_{59}, for one grain using Carlsbad-albite method.

*** Source of data given in Table 7.

Type Section: Upper Member

Ash-flow Tuff. The marker bed ash-flow tuff is the only conspicuous rock of this type found in the upper member. It contains a few highly altered angular volcanic clasts with microlitic texture. The main alteration product in these clasts appears to be iron oxide. Pumice fragments make up two percent of the rock and are partially flattened giving the ash-flow an eutaxitic texture. The color of the pumice is similar to that of the groundmass; hence it is not conspicuous. Subhedral to euhedral plagioclase phenocrysts average about 1 mm in length and almost always possess oscillatory or normal zoning. Twinning is generally of the Carlsbad, albite, or pericline type, but is not always present in all crystals. Five plagioclase glass beads have an average refractive index indicating 33 percent anorthite content. Quartz phenocrysts are much rarer than the plagioclase and are highly embayed. The extreme resorption of the quartz and its association with plagioclase suggest the quartz was not in equilibrium with the parent magma of the ash-flow and may be the result of crystal settling in a differentiation magma chamber.

The matrix is composed of clinoptilolite and montmorillonite identified by x-ray (see page 104) which have replaced glass shards and other pyroclastic debris leaving a clearly visible relict shard texture. Carbonized wood fragments are abundant throughout the ash-flow tuff and are apparently the result of volcanism occurring in forested areas.

The modal analysis of the ash-flow tuff appears in Table 9.

Table 9. Modal analysis of marker bed ash-flow tuff, upper member, Colestin Formation. "T" indicates trace amounts.

	%
Pumice	2
Lithic	3
Plagioclase	14
Quartz	3
Opaque	2
Carbonized wood	1
Hornblende	T
Zircon	T
Biotite	T
Matrix	75 (mostly clinoptilolite and clay minerals)

Conglomerate, Breccia and Sandstone. The epiclastic rocks of the upper member of the Colestin Formation contain from 53 to 89 percent lithic fragments (Table 10) by far the most abundant detrital constituent in the upper member of this formation. The lithics range from sand to boulder size. The majority are of volcanic origin with quartzite or intrusive and sedimentary lithics comprising the rest. Lithics range from angular to rounded, but most are subangular except in some channel deposits. Sorting is very poor. The volcanic clasts possess a wide variety of textures and no attempt is made to describe them in detail. It is sufficient to say that three types of

Table 10. Modal analyses of Epiclastic Rocks from the upper member of the Colestin Formation. "T" indicates trace amounts.

Sample	270	260	259	247	252	224	228	230	239	241
Volcanic Lithics ≥ 3 mm*	38	67	28	40	0	30	T	60	31	4
Quartzite Lithics ≥ 3 mm	0	0	T		T	T				
Total Lithics	76	89	88	89	66	56	66[1]	71[2]	67	53
Plagioclase	3	T	3	2	12	28	7	8	5	17
Clinopyroxene	1	T	T		T		T	T	T	T
Opaque	1			T	T	2	1	1	1	1
Other		T							1[3]	1[4]
Matrix	1	6	7	T	12		17	20	21	19
Cement:										
Calcite	0									
Clay minerals	0	2				7			5	8
Zeolite	18	2	2	9	10	T	8			
Quartz	T					7				
Chlorite									T	

* Includes pumice

1 Trace of granitic lithics

2 Forty percent of lithics in this sample are pumice fragments.

3 Trace of hornblende and one percent of clay pseudomorphs.

4 Clay mineral pseudomorphs.

volcanic textures are present: felsitic, representing devitrified tuffs and silicic flows; microlitic, representing intermediate lavas, and lathwork representing basic flows. Microlitic textures are generally the most common with varying amounts of the other two. Pumice and shard texture is abundant in some units and its presence probably indicates a significant contribution of reworked pyroclastic debris.

Detrital mineral grains commonly include clinopyroxene, plagioclase and magnetite but plagioclase is the only detrital mineral that ever becomes abundant (unit 44, plate I). Detrital quartz is very rare and usually found in those units containing quartzite lithics.

Detrital matrix is considered material less than about 0.04 mm diameter. Difficulty is encountered, however, in distinguishing between detrital and diagenetically produced minerals in the less than 0.04 mm range. In point counting, orthomatrix and epimatrix are combined and counted together as matrix. Cements include clinoptilolite, heulandite, microcrystalline quartz, and phyllosilicate minerals. The cement generally makes up from 0 to 18 percent of the rock.

Pebble Counts. Analysis of particles greater than 3 mm in diameter was accomplished by point counting polished rock slabs or chips from pebbles. Out of 12 rock slabs from the upper member of the Colestin Formation 11 contained 100 percent volcanic lithics (recalculated so that total pebbles greater than 3 mm in diameter equaled 100 percent). The twelfth sample (sample 301, Table 11) taken from a channel deposit contains 75 percent volcanic pebbles, 22 percent quartzite pebbles, and 3 percent "granitic" pebbles (see section A, unit 2, plate I, for location).

Table 11. Combined rock slab and thin section model analysis of Sample 301 from the upper member of the Colestin Formation. "T" indicates trace amounts.

Volc. Lithics $\geq$ 3 mm	24
Gtzite Lithics $\geq$ 3 mm	7
"Granitic" Lithics $\geq$ 3 mm	1
Total volc. lithics	40
Total sedi. lithics	10
Total "granitic" lithics	1
Total qtzite lithics	19
Total unidentified lithics	1
Total lithics	71
Plagioclase	5
K- feldspar	1
Volcanic quartz	1
Augite	T
Opaque	1
Mica	T
Zircon	T
Quartz (non-volcanic)	2
Cement	
Zeolite	11
Clay minerals	8

A pebble count taken from unit 31 (section B, plate I) at Siskiyou Summit on Interstate Highway 5 contains 100 percent volcanic lithics. A second pebble count taken stratigraphically just below the ash-flow marker bed (unit 52, section B, plate I) indicates 78 percent volcanic lithics, 17 percent quartzite, a trace of gneiss, fine-grained metamorphic? and shale, and 3 percent "granitic" lithics.

Petrography of Rocks in Oregon Southeast of the Type Section

Ash-flow Tuffs. A modal analysis of the marker bed ash-flow tuff (Table 12, sample 126) collected in the NW 1/4, sec. 15, T. 41 S., R. 1 E. near the California border contrasts slightly with the modal analysis of this same unit taken at the Siskiyou Summit on Interstate Highway 5 (Table 9). Near the California border the marker bed contains more pumice and less plagioclase. The groundmass at both localities is composed of zeolite and clay minerals. Highly embayed quartz phenocrysts are present at both localities but are less abundant near the California border.

Table 12. Modal analyses of two ash-flow tuffs from the Colestin Formation in Oregon southeast of the type section. "T" indicates trace amounts.

	Sample 18	Sample 126 (Marker Bed)
Lithics	2	9
Pumice	3	9
Plagioclase	15	3
Clay Pseudomorph	1	
Biotite		T
Quartz		T
Zeolite Pseudomorph		1
Opaques	T	T
Matrix	79	78

A second ash-flow whose modal analysis is given in Table 12 (sample 18) directly overlies Cretaceous mudstone near the California border. This ash-flow tuff megascopically resembles units 13 and 3 measured at the type section. Similarities in modal analyses and stratigraphic position suggest unit 13 or 3 at the type area is correlative to this ash-flow near the California border.

Sandstones. Two thin sections were made of sandstones cropping out near the California border. The one for which a modal analysis is given (Table 13) is located just above the marker bed ash-flow tuff.

Table 13. Modal analysis of an epiclastic rock from the Colestin Formation in Oregon southeast of the type section. See Plate I, stratigraphic section C for the location of sample 120.

	Sample 130
Volcanic lithics	18
Pumice	2
Plagioclase	19
Opaques	1
Hornblende	1
Clay Pseudomorphs	1
Quartz	1
Groundmass*	58

* Mostly shards replaced by zeolites.

The unit from which sample 130 was collected is a striking example of a fluvial sandstone containing shards derived from the underlying ash-flow by reworking of the upper unconsolidated portion. This rock is a moderately sorted, coarse grained sandstone. Volcanic lithic fragments and plagioclase make up the framework and shards replaced by zeolites and clay minerals make up the groundmass.

A second sample taken in the SW 1/4 SE 1/4, sec. 8, T. 41 S., R. 2 E. is petrographically similar to middle member sandstones at the type section. Detrital plagioclase and subordinate volcanic lithics are found in a recrystallized past-like matrix of clay minerals and minor clay mineral cement.

Petrography of Rocks from the Shelton Creek and Klamath River Sections

Epiclastic Rocks. A total of 12 thin sections of specimens collected from rocks at the Shelton Creek and Klamath River measured sections were studied. Modal analyses of two of these rocks are given in Table 14.

Table 14. Modal analyses of two epiclastic rocks from the Klamath River measured section.

	Sample 205	Sample 210
Volcanic Lithics $\geq$ 3 mm	17	13
Total Lithics	78	67
Plagioclase	4	11
Calcite Pseudomorphs		1
Clay Pseudomorphs		2
Opaques		T
Matrix	2	
Cement		
Calcite	15	8
Corrensite	1	11

In general the rocks of Shelton Creek and the Klamath River section resemble the rocks of the upper member at the summit of Siskiyou Pass. Lithic fragments are still the dominant detrital particle but possibly more felsitic and definitely more porphyritic volcanic lithics are found in the Klamath River and Shelton Creek sections.

Plagioclase is the second most abundant detrital material but is never observed in greater quantities than the volcanic lithics. Quartzite grains are occasionally seen but were rare in the specimens studied. Undoubtedly they are locally abundant.

Calcite replaces plagioclase grains and is the dominant cementing material along with microcrystalline quartz. Corrensite and montmorillonite identified by x-ray diffraction (see pages 98 and 103), and chlorite are also found as cement and as orthomatrix and epimatrix. Zeolite cement is not found as such, but authigenic zeolite is observed as small needle-like crystals projecting from cavity walls and embedded in calcite cement.

Two pebble counts, the first from unit 14 and the second from unit 15 in the Klamath River section indicate these rocks contain 100 percent fine-grained porphyritic and non-porphyritic lithic fragments. Figure 6 is a triangular diagram on which 26 analyses of epiclastic rocks from the Colestin Formation have been plotted. Twenty of the 26 fall in the lithic arenite category, and only one in the feldspathic arenite region of the diagram. The remainder fall somewhere in between these two categories.

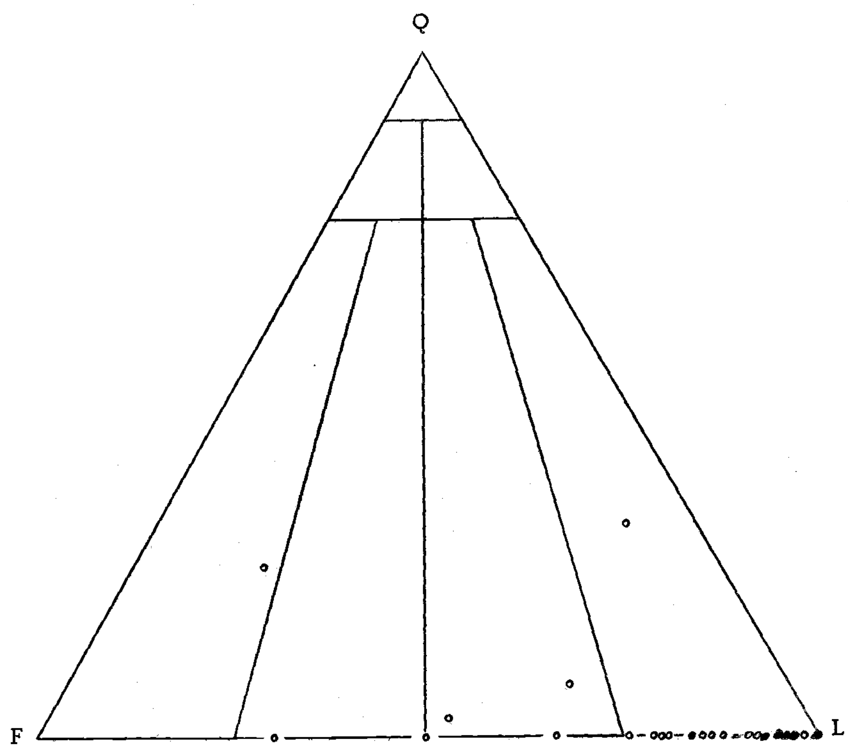

Figure 6. QFL diagram modified from Crook (1960) showing epiclastic rock types found in the Colestin Formation. Q + F + L = 100% (see Figure 2 for rock names).

○ indicates modal analysis of single rock specimen

● indicates modal analysis of two or more rock specimens.

DEPOSITIONAL ENVIRONMENT OF THE COLESTIN FORMATION

Introduction

The discussion of depositional environments of ancient fluvial deposits necessarily includes a study of the paleotopography and paleoclimate in addition to the more specific environmental aspects. Toward this end investigators such as Cheney (1956, 1940), Weaver (1937), Williams (1942, 1948, 1949), Peck and others (1964), Snavely and others (1963) and many more have contributed greatly to the paleogeography and climatic conditions existing during early Tertiary time in Oregon.

Broader Aspects of the Depositional Environment

The Eocene epoch spans a period of time from about 37 to 54 million years ago. The Colestin Formation was deposited during the later part of this epoch probably somewhere between 37 and 43 million years ago (Peck and others, 1964). The paleoclimate of the late Eocene in Oregon is deduced primarily on the basis of fossil floras and to some extent on marine invertebrate fossils (Chaney, 1940, p. 472). These fossils indicate the late Eocene in Oregon was subtropical to tropical in character with little or no frost and abundant rainfall (Chaney, 1940; Peck and others, 1964).

Climatic conditions which now prevail in most of the lowlands of Central America (for example Panama and Nicaragua) are probably very similar to those of the late Eocene in southwestern Oregon (Kendall, 1962). In the tropical moist climate of Panama and Nicaragua average monthly temperatures are consistently in the 70's and 80's, and rainfall may average around 100 inches per year. If these conditions prevailed in the late Eocene of Oregon, vegetation similar to the tropical rain forests of Central America probably existed. This is borne out by subtropical and tropical fossil vegetation found in such strata as the late Eocene Clarno Formation of eastern Oregon, in fossil assemblages collected by Peck and others (1964) from the Colestin Formation in the thesis area, and by fossil leaf specimens collected by this writer at a previously unknown fossil locality in the thesis area (Table 15).

Table 15. Fossil leaves from the Colestin Formation. Identified by Jim Thompson, graduate student in the Department of Botany, Oregon State University. Fossil locality: SW 1/4 SE 1/4, sec. 8, T. 41 S., R. 2 E.

Metasequoia occidentalis
Cordia oregana
Platanus
Anona preseticulata
Ficus (*goshenensis*?)
Magnolia sp. ?
Ocotea ovoidea

Fossil floras are not only good paleoclimate indicators, but also good topographic indicators (Chaney, 1956, p. 7). Similarities in floral assemblages from western and eastern Oregon almost conclusively prove that no large mountainous barrier existed at the present site of the Cascade Range in the late Eocene. During this time broad subtropical to tropical lowlands extended eastward across Oregon and Washington allowing warm moist ocean breezes to sweep far inland and essentially homogenize climatic conditions throughout Oregon. In the highlands surrounding these lowlands the subtropical vegetation was mixed with trees of temperate climatic habit such as the redwood, alder, tan oak and elm (Williams, 1942). The depositional record of the late Eocene indicates vast quantities of volcanic material were being deposited in Oregon during the late Eocene so that the lowlands must have been dotted here and there with active volcanoes (Williams, 1942). The Klamath Mountains, a nonvolcanic highland, lay immediately to the south and west and was slowly rising during late Eocene time.

Specific Aspects of the Depositional Environment

In recent years the study of fluvial sediments has been approached in two manners, complementary to the other. Investigators such as Visher (1965), Allen (1964, 1965), Stanley (1968) and Belt (1968) have based environmental interpretations on models constructed from observational data collected from present day fluvial environments. Other investigators such as Dott (1963), Fahnestock and Hauschild (1962), Wolman and Leopold (1957), and many others have used theoretical and experimental data such as flume experiments to help in the reconstruction of ancient fluvial environments.

Fluvial Origin of the Colestin Formation Sediments

The Colestin Formation from the type locality to the Klamath River is of non-marine origin. Wells (1956) suggested that the clastics were deposited by overloaded streams that were rapidly stripping volcanic material from the surrounding area. Plant fossils have been collected from the Colestin Formation by Peck and others (1964), and the observation by this writer of many fossil leaves, transported logs, carbonized wood, coal seams and several tree stumps in situ as well as the textural and structural characteristics of the rocks themselves confirm a non-marine origin and suggest a fluvial environment for much of the Colestin Formation.

Primary Sedimentary Features

Primary sedimentary structures are rare but those found include asymmetric ripple marks (rare), cross-bedding (rare), graded bedding (common), scour and fill features (common), planar bedding (common) and laminations (rare). The three dimensional aspects of the units usually cannot be ascertained, but occasionally tabular bodies, or possibly thin wedges and lenses, were recognized. Graded beds tend to be laterally continuous for at least the length of the out-crop and in one case could be traced along a continuously exposed cliff face for about 0.75 miles and was presumably wedge or tabular shaped. Massive pebbly sandstones, conglomerates and breccias as well as the finer clastic sediments were observed both as tabular and lens shaped bodies.

Comparison with Fluvial Models

The fluvial sediments of the Colestin Formation are generally high in volcanic fragments and pyroclastic debris and were deposited in an active volcanic region whereas most of the published work on fluvial models has been derived from sediments notably lacking in volcaniclastic material. Very little has been done in developing models for various climatic conditions or in developing fluvial models of active volcanic regions. Those deficiencies should not be overlooked when attempting to "fit" the clastic sediments of the Colestin Formation to various fluvial models described in the literature.

Some of the factors which must be considered in comparing the published fluvial models with sediments from the Colestin Formation are:

1. Most of the experimental and observational data used to formulate models has been with rivers or flood waters moving and carrying "normal" loads whereas rivers and floods in active volcanic regions may be highly charged at times with volcaniclastic debris, perhaps approaching very viscous liquid flow conditions (Dott, 1963, p. 109, 113 and Williams, 1952, p. 19).

2. Availability of large volumes of loose detritus on a periodic basis combined with tropical or subtropical storms capable of depositing 15 inches of rain in a short period of time.

3. Sudden damming of rivers by lava flows and lahars, forming lakes whose waters may later be released suddenly by erosion of the barrier.

Fluvial models developed or summarized by Stanley (1968), Visher (1965), and Allen (1964, 1965) are used in the environmental interpretation of the "normal" sediments in the Colestin Formation.

Channel Fill and Lag Deposits

Channel fill deposits form by vertical aggradation of a rapidly abandoned channel such as a cut-off meander loop or through gradual filling of a channel which is subsequently abandoned (Allen, 1964). In shape they appear as thick narrow curved prisms containing sediments from the finest to coarsest grades.

Channel lag deposits according to Allen (1964) represent the coarsest material available to a river and form elongate lenses of pebble or pebbly sand or coarser material and have erosional contacts. Numerous examples of channel fill and channel lag deposits are found in the Colestin Formation. Two of the most accessible and best exposed examples of channel fill deposits are found in the type section on Interstate Highway 5 at Siskiyou Summit. The first is a channel conglomerate (unit 55, section B, plate I) cut into a volcanic pebbly sandstone (unit 54) both of which grade upward into siltstone containing a sandstone lens. A second example is a channel partially filled with conglomerate cut into unit 50, a volcanic pebbly sandstone, and overlain by the marker bed ash-flow tuff. The rapid abandonment of the channel was probably caused by the filling of the stream bed by the ash-flow tuff.

Channel fill deposits are recognized in the Colestin Formation by their cross-sectional channel shape and lower erosional contact. In most, but not all, cases the sediments which fill the channel are characterized by coarse-grained sandstone and conglomerate with many subrounded pebbles and cobbles arranged in crude beds.

Channel lag deposits cannot always be distinguished from wide channel fill deposits in two dimensional exposures. Unit 2, section A (plate I) is one of the best examples of a channel lag deposit within the Colestin Formation. This unit is a cobble to pebble conglomerate composed of rounded to well rounded cobbles and pebbles and containing coarse sandstone lenses. It averages five feet in thickness and can be traced 0.75 miles before it disappears beneath cover. It is not present about 0.8 miles along this same cliff where outcrops are again present. The lower contact is erosional.

Slurry Flood and Mudflow Deposits

Introduction. Volcaniclastic sediments common to volcanic regions or at least typical of volcanic regions have been described by several investigators. Reference to reports by Mullineaux and Crandell (1962), Fiske and others (1963), Grater (1948), Williams (1952), Parsons (1964) and Dorf (1960) have been used in this thesis for the interpretation of certain units.

Lahars as defined by Mullineaux and Crandell (1962), include all of the broad textural range of debris flows and mudflows of volcanic origin. Fiske (1963) in addition defines a slurry flood as intermediate between mudflow and heavily loaded streams and consist of floods of turbulent water carrying mud and sand, pebbles and boulders, chunks of ice and uprooted trees which race down the valleys in devastating surges. All gradations probably exist between lahars and slurry floods just as gradations exist between slurries and "normal" floodwaters.

Slurry Deposits. A large part of the exposed fluvial sediments of the Colestin Formation are poorly sorted, massive to poorly stratified subangular, pebbly, lithic sandstones and breccias. They have intact frameworks and contain very small to moderate amounts of clay and silt-size material. Transported logs, tree stumps in growth position, carbonized wood fragments, pumice and lenses of moderately sorted sandstone are found in varying amounts in most of the units of the upper and lower member at the type section and in the Shelton Creek and Klamath River measured section. They are generally overlain by thin units of volcanic siltstone and claystone with planar non-erosional contacts whereas the lower boundary ranges from planar to highly erosional.

The single most telling piece of evidence for violent rapid deposition of these sediments is the presence within the sediments of upright tree stumps up to four feet in diameter. They apparently represent late Eocene forests which were buried by thick deposits of coarse debris swept down from relatively distant highlands by violent storms.

The great majority of flood deposit models described in the literature do not fit the characteristics of those of the Colestin Formation. Typical overbank sediments as summarized by Allen (1964) are fine-grained, ranging from medium sand to clay. Internal small scale cross-stratification, small asymmetric ripples, plant debris and coarse beds overlying suncracked silts are also found in overbank deposits. The most important differences in the flood deposits in the models and those interpreted as flood deposits in the Colestin Formation are the grain size of the sediments and the lack of current-formed structures such as ripple marks, cross-stratification and mud cracks.

The more important similarities include erosional bottoms, the vertical sequence of coarser sediments at the bottom overlain by silts representing possible retreat of flood waters or at least of less turbulent conditions, and the presence of exotic material such as logs and plant debris.

Fiske and others (1963) have described slurry deposits which may be similar to those of the Colestin Formation. Grater (1948) describes such a flood which occurred in the Kautz Creek valley on the slopes of Mount Rainier on October 2, 1947. This slurry flood left a deposit varying from stratified to unstratified and in places shows crude upward grading of boulders.

The flood deposits of the Colestin Formation differ in that most contain subangular pebbles or cobbles and only rarely a boulder or cobble which is very much larger than the average cobble for that unit. This contrasts sharply with the Kautz Creek valley flood in which boulders up to 13 feet in diameter were carried along by the turbulent water. This difference may simply be due to the lack of larger boulders in the source area for the Colestin Formation floods, or to less viscous flood waters and lower gradients. A combination of these is most likely since the slopes of Mount Rainier contain large amounts of coarse bouldery glacial debris and less finer pyroclastic material than is found in the Colestin sediments (Fiske, 1963, p. 84). Also, the Colestin Formation in the thesis area was not deposited directly on the slopes of a volcano but on a flood plain some distance from the volcanoes. Thus by the time the slurry floods reached the Colestin basin dilution by streams, and low gradients inhibited the transport of large boulder size material.

The massive unsorted deposits of the Colestin Formation are interpreted as originating after the occurrence of violent storms in active volcanic regions producing large amounts of pyroclastic material. This newly deposited debris was gathered into turbulent slurry flows (tending toward the less viscous kind) which swept down the steep valleys and out onto forested floodplains of low gradient. Here they travelled for great distances depositing huge volumes of coarse unsorted volcanic debris.

Lahars. Fiske (1963) reports both subaerial and subaqueous mudflows (lahars) in the late Eocene Ohanapecosh Formation and Williams (1952) describes them from Nicaragua. Curtis (1903) describes them from West Indian volcanic eruptions and Van Bemmelen (1949) describes them from Indonesia up to 40 kilometers long having originated from heavy rain fall on slopes covered with loose material or by earthquakes.

A few mudflow deposits are found in the Colestin Formation but their scarcity probably indicates most did not reach the basin in which the Colestin sediments were deposited. The best exposures of lahars in the thesis area are present along U.S. Highway 99 in secs. 4 and 9,

T. 41 S., R. 2 E. (see Figure 5 for their stratigraphic position). These lahars are poorly sorted, massive deposits of debris ranging from clay to boulders three feet in diameter. The lower lahar in Figure 5 contains densely welded ash-flow tuff boulders as well as a heterogeneous assemblage of intermediate to basic, fine-grained volcanic clasts. Most of the fragments are subangular. The matrix is composed of clay to medium to coarse sand and comprises greater than 50 percent of the rock. Occasionally lenses of better sorted fluvial deposits are found within the lahar. In at least one instance the lower contact of a lahar is observed overlying lacustrine or possibly fine-grained fluvial sediments composed of claystone and well sorted sand.

Graded Deposits

Some of the most characteristic sediments of the Colestin Formation are graded deposits of coarse sandstone, pebbly sandstone and epiclastic breccias. These sediments are generally slightly better sorted and finer grained than the non-graded slurry deposits and may be interbedded with them. Individual graded beds may vary from less than an inch thick to over six feet, but the most common thickness appears to be about six inches. Rarely tuffaceous claystones less than one inch thick separate graded units, but more commonly graded units are separated from each other by fairly sharp, planar boundaries.

Generally the top of each graded bed consists of sand or sandy silt. Carbonized wood fragments are found in some of the thicker graded sequences, and some contain pumiceous material.

The graded units within the Colestin Formation are definitely water laid. Fiske and others (1963, p. 10) described volcanic breccias and sandstone which appear to be similar to the graded subangular sandstone and epiclastic breccias of the Colestin Formation. Fiske noted the presence of rare cross-bedding, ripple marks and slump structures. No structures other than grading were discovered in the Colestin Formation in these particular sediments. On the other hand clay size material is only rarely found interbedded with the graded unit although it was common in the sediments described by Fiske (1963). Many of the graded units are pebbly sandstone and very coarse sandstone indicating a fairly high energy level must have been involved in delivering these sediments to the Colestin basin.

The relative rarity of silt and clay-size material at the top of each graded bed and the lack of erosional contacts between graded units suggests conditions were rarely favorable for the deposition of fine sediments.

The graded sediments of the Colestin Formation are believed to be related to the slurry flood deposits. The main difference between the two is thought to be in the depositional environment in which they came to rest. The unsorted slurry deposits were probably deposited on flat, low gradient floodplains by the distal portion of slurry floods or mudflows. The graded deposits may have resulted from slurry deposits becoming ponded perhaps in shallow basins or lakes. This resulted in slackening of energy and the deposition of the coarser debris. Before clay size material could settle out or possibly because suspended clay and water was rapidly drained away, renewed surges of coarse flood material was introduced forming successive coarse grained graded deposits without interlayers of clays and silts.

If these sediments had formed by subaqueous mudflows, an origin attributed by Fiske to many of the Ohanapecosh sediments, siltstones and finer material at the top of each graded unit and in general interbedded claystone and siltstones characteristic of lacustrine or marine conditions would be expected. However, the graded beds of the Colestin Formation are in many cases overlain and underlain by fluvial sediments suggesting quiet water probably existed only during the deposition of the graded unit. As an example, the lowest sedimentary unit represented in stratigraphic section A plate I is a slurry flood deposit overlain by a thin channel lag deposit. This is in turn overlain by another slurry deposit with channel boulder conglomerate near the upper contact. Overlying this is nearly 60 feet of well developed graded beds, each bed ranging from less than an inch to about one foot thick. The finest grade material in this 60 foot interval is fine sand. No other sedimentary structures were observed and no interbedded claystone or siltstones seen. The graded bed sequence is in turn overlain by another channel deposit.

Mullineaux and Crandell (1962) state that, "farther from the volcano vertical grading is probably the single most useful indication of origin (of a lahar); where this feature is present in deposits of coarse nonvesicular material far from the source, we believe it is a criterion of mass transport of the material in a flow mobilized by water."

Channel Bar(?) Deposits

Medium-grained to coarse-grained, moderately sorted, thin to thickly bedded sandstones are occasionally encountered in the Colestin Formation. In some cases they are clearly deposited in fluvial environments and possess cross bedding or asymmetric ripple marks and are lens shaped. More commonly, however, these units are thin to thickly bedded massive sandstones. They generally possess fewer lithics and more feldspar than the less well sorted units and are undoubtedly formed by reworking of the latter.

Lacustrine Deposits

The Colestin Formation contains numerous thin clay and siltstone lenses many times associated with thin coal seams. The coal seams are never very extensive and probably the result of local accumulations of transported organic debris in abandoned channels or other areas of slackwater associated with fluvial sediments.

Major accumulations of clay and siltstone in the middle member, at the type area and moderate amounts in the area southeast of the type section in Oregon suggest that lacustrine environments prevailed at times in the Colestin basin. In rare instances the lacustrine sediments are well laminated, contain leaf fossils, diatom tests and large amounts of altered pyroclastic material. Usually, however, the claystones and siltstones are poorly laminated, almost massive accumulations of clays and silts. The moderate to thick sequences indicate the lakes in which these sediments were deposited may have been fairly large.

SOURCE OF THE SEDIMENTS

Dickinson (1970) has recently introduced terms applicable to the study of subquartzose sandstones. An explanation of these terms is given in Table 16.

A number of the sediments from the Colestin Formation have been plotted on a QFL diagram (Figure 6). From this diagram it is obvious that lithic arenites are the most common rock types found in the Colestin Formation. In many instances relict shard texture is visible in the Colestin sediments suggesting that pyroclastic blankets were important sources for the Colestin Formation. The P/F ratio is essentially unity for the Colestin Formation indicating the provenance supplied only plagioclase feldspars. In sample 301 the P/F ratio is .83, the V/L ratio is 0.8 and the C/Q ratio is 0.9. In all other cases the V/L and C/Q ratio approach unity. The C/Q ratio simply implies that most of the quartz is derived from supracrustal rather than subcrustal sources, in this case from supracrustal quartzite provenances. The high V/L ratio suggests a volcanic provenance dominates over other types.

Andesitic provenances yield detritus with microlitic textures, high P/F ratios and almost no quartz (Dickinson, 1970). The Colestin sediments, with a few exceptions, fit these characteristics almost exactly. In addition determinations of the anorthite content of

Table 16. Primary detrital grain parameters (modified from Dickinson, 1970).

Q, F, L, where Q+F+L = 100 percent.

1. Q is the sum of:

   a. Monocrystalline quartz grains.
   b. Polycrystalline quartz or chalcedony fragments.

2. F is the sum of:

   a. Monocrystalline feldspar grains.

3. L is aphanite rock fragments less:

   a. quartose and chalcedonic types.

Secondary Detrital Grain Parameters

C/Q, P/F, V/L where each is less than or equal to 1.0

1. C/Q = ratio of: Polycrystalline-cryptocrystalline quartz-chalcedony-opal lithic fragments (C) to total quartzose-chalcedonic-opaline grains (Q). This parameter is intended to reveal the supracrustal nature of the source (i.e., a ratio of the quartzose lithics to total quartzose grains. A high ratio indicates supracrustal sources were important).

2. P/F = ratio of plagioclase (P) to total feldspar (F). This ratio indicates relative importance of plagioclase bearing rocks in the source area.

3. V/L = ratio of volcanic rock fragments (V) with igneous aphanite textures to total unstable aphanite rock fragments (L) which can include shale, schists, and other rock types.

plagioclase grains (Table 14), support the conclusion that the Colestin Formation was derived mainly from andesitic pyroclastic and flow rocks.

Certain units within the Colestin Formation contain a relatively high proportion of quartzite lithics and it appears that periodically rivers leading to the Colestin basin passed through quartzite provenances.

TRANSPORT

Pebble and boulder size material in the Colestin Formation ranges from angular to well rounded. The more angular material is generally found in slurry and mudflow deposits whereas channel lag and fill deposits contain the entire range from angular to well rounded clasts.

The angularity of pebble and boulder size material in slurry flood and mudflow deposits is not necessarily an indication of transport distance since a cushioning effect occurs between fragments (Mullineaux and Crandell, 1962). Angular and subangular fragments could easily occur in a mudflow or slurry flow 20 miles from its source whereas under normal fluvial conditions these same clasts would be rounded to well rounded (Potter and Pettijohn, 1963).

Channel fill and lag deposits generally contain angular to well rounded clasts. When quartzite pebbles are present in channel deposits, they are always rounded indicating a source at least 10 to 20 miles distant (Potter and Pettijohn, 1963). Rounded as well as subangular volcanic lithics in the same sedimentation unit indicate multiple volcanic sources. This conclusion is supported by the wide variety of lithics which are found in the same beds.

PALEOCURRENT INDICATORS

Paleocurrent indicators in the Colestin Formation are rare and even if they were abundant would be of limited use because of the straight, narrow outcrop belt of this formation (Potter and Pettijohn, 1963). The paleogeography, however, has been studied on a regional scale, and apparently volcanic source areas lay to the east. northeast and southeast, and were positive areas where active volcanoes existed (Snavely and others, 1963).

Quartzite exposures are known to exist west and southwest of the Colestin basin. These localities offer possible sources for the quartzite pebbles but it is also possible, if not probable, that quartzite exposures existed to the east and north during the late Eocene. Thus the specific source of the quartzite pebbles cannot be determined.

MINERAL ALTERATIONS

Introduction

The volcaniclastic rocks of the Colestin Formation have been moderately to highly altered since their deposition during the late Eocene. The diagenetic minerals thus formed have been studied in detail and include many varieties of phyllosilicates, zeolites, albite, quartz, opal, carbonate and pyrite.

Alteration of Glass Shards

Relict glass shard texture is found in both ash-flow tuffs and epiclastic sediments of the Colestin Formation. Heulandite, clinoptilolite, montmorillonite, chlorite and kaolinite group minerals have been identified replacing shards, but the zeolites are by far the most common replacement mineral.

Hay (1962) found that much of the clinoptilolite in the John Day Formation crystallized in cavities from which the glass shards had already been dissolved. In other cases Hay found that clinoptilolite crystallized almost as soon as the glass had dissolved with only a thin aqueous interface between the glass and clinoptilolite. The evidence Hay uses for complete dissolution of the glass before crystallization of the zeolite is not found by this author in the Colestin zeolite pseudomorphs. This may suggest that as the glass dissolved, zeolites immediately crystallized in their place in the Colestin Formation. The interstitices between zeolite pseudomorphs after glass shards in the Colestin Formation is generally filled with a phyllosilicate. Mica, vermiculite, montmorillonite and corrensite have all been identified in close association with the zeolite pseudomorphs.

The following are detailed descriptions of five of the more important occurrences of zeolite replacement of glass shards.

I. Location of sample: Measured section B, unit 13, sample 100, plate I.

The sample is an ash-flow tuff. Mica, montmorillonite, and clinoptilolite were identified by x-ray techniques. The zeolite replaces the coarser shards, generally growing inward perpendicular to the shard wall. A grass-green moderately high birefrigent clay pervades the rest of the groundmass which under crossed nicols appears to be devitrified. The individual clay mineral particles are usually about four microns in diameter but are much coarser where they fill central cores of zeolite pseudomorphs after glass shards. This green clay mineral was identified as montmorillonite by x-ray diffraction. A second phyllosilicate is observed as clay pseudomorphs after an unknown lath-shaped mineral (plagioclase?). This clay mineral is bright golden yellow and pleochroic. Hand picked samples which were x-rayed indicate mica.

II. Location of sample described: Section B, Unit 13, Sample no. 95, plate I.

Mica was identified by x-ray. A small broad peak indicating a spacing of 12 A in the Mg-saturated sample and 13.4 A in the Mg-ethylene glycol sample was identified. Upon K-saturation the peak collapses to 10 A. This diffraction pattern is thought to represent an irregularly interstratified montmorillonite-mica or possibly vermiculite-mica mixed layer clay. The groundmass of a portion of the ash-flow tuff exhibits very faint shard texture. This texture is preserved by small (4 to 5 micron) yellowish-green moderately high birefrigent clay particles. The clay mineral is distributed throughout a hazy devitrified groundmass, sometimes clustered so thickly as to be almost opaque. The closely packed areas are generally centered around clay pseudomorphs after pyroxene and possibly plagioclase and may merge with the clay forming the pseudomorph. The clay mineral within the pyroxene pseudomorphs is coarse, golden yellow and pleochroic and arranged in radial to scaly masses. Although identification of the golden yellow mineral was not attempted in this sample by hand-picking, x-ray diffraction of whole rock samples indicate a mica similar to that in sample number 100.

III. Location of sample described: Section B, unit 13, sample no. 93, plate I.

Montmorillonite, zeolite and minor chlorite were identified in this portion of unit 13 by x-ray diffraction. Shard texture is clearly visible and no devitrification is observable. The coarser shards are completely replaced by clinoptilolite, although discrete very fine-grained green clay particles are randomly distributed in many of the zeolite pseudomorphs. In the spaces between the shards montmorillonite is predominant and appears to be intimately associated with small anhedral grains of clinoptilolite. Some coarse clay is present as greenish-yellow, moderately high birefrigent pseudomorphs after lithics and possibly individual minerals.

IV. Location of sample described: Section B, unit 11, sample no. 86, plate I.

Heulandite, montmorillonite and corrensite were identified by x-ray techniques. This ash-flow tuff has a non-devitrified groundmass possessing a clearly discernable vitroclastic texture. Shards are outlined by a very fine-grained green, moderately high birefrigent clay mineral similar to that in sample 93 but here it is greener and does not have a yellowish tinge except along weathered partings in the rock where it is golden yellow to brown, and possesses moderately high birefrigence. The green clay is found as random particles included in the coarser heulandite pseudomorphs and in the intersititices between the shards. The montmorillonite and mixed-layer clay could not be distinguished in thin section although it is believed that the montmorillonite may be the green clay which has been altered along partings to the golden-yellow mixed-layer clay.

V. Location of sample described: Section B, unit 3, sample no. 113, plate I.

Quartz, heulandite?, and vermiculite were identified by x-ray techniques. The groundmass of this ash-flow tuff is replaced by zeolites and phyllosilicates and exhibits relict shard texture. Quartz is found lining cavities and in felsite lithic fragments. Heulandite is found filling cavities and replacing glass shards. Vermiculite varies from yellowish-green to reddish brown, has moderately high birefringence, is very fine-grained and occupies the interstices between coarser shards as well as being included with the zeolite pseudomorphs as randomly distributed grains.

Alteration of Detrital Plagioclase

Detrital platgioclase ranges from completely fresh to clay mineral pseudomorphs and albitized grains, but by far the greatest number fall somewhere in between these extremes. The most common minerals replacing plagioclase are albite, zeolites, phyllosilicates, carbonate and an unidentified substance which appears as small black opaque, irregularly shaped grains and fibers under transmitted light but white with a cotton-like texture under reflected light. Hand-picked plagioclase grains whose surfaces were completely altered to this material were x-rayed but the substance could not be identified (see page 39).

In the lower member the plagioclase of the volcaniclastic rocks are commonly replaced by a colorless, optically positive mineral possessing a minimum refractive index of not lower than 1.530. This refractive index is outside the limits of the common zeolites and the replacement is undoubtedly albite whose minimum refractive index is near 1.528 ± 0.002. The detrital plagioclase in the lower member is commonly 50 to 85 percent albitized. The replacement by albite usually occurs along the edges of the grain, leaving small irregular patches of unaltered plagioclase in its wake, as it moves through the mineral, giving the grain under crossed nicols a patchwork appearance. The contact between the unaltered plagioclase and the authigenic albite is jagged and has a cox-comb like appearance. The albitized portion of the grain is always filled with small inclusions similar in appearance to the unidentified alteration described earlier. Greenish to colorless phyllosilicates are included also, and in some cases zeolites can be observed replacing glass blebs within the same plagioclase grains that are being albitized. In the upper and middle members of the Colestin the feldspar is usually fresh to moderately altered along fractures within the grain. This alteration product usually appears to have lower relief, a strong pinkish color and is probably a zeolite rather than albite although no attempt was made to confirm the zeolite replacement.

The only complete pseudomorphs of zeolites after plagioclase occur in the lower portion of unit 9, section B of plate I where broad tabular subhedral heulandite grains occasionally replace lath-shaped grains presumably once plagioclase. Plagioclase may be replaced by small flecks of white mica, chlorite, a kaolinite group mineral, and calcite or complete pseudomorphs after calcite and montmorillonite minerals may be formed.

Alteration of Mafics

Orthopyroxene is found in several of the lavas within the Colestin Formation but is never found in the volcaniclastic rocks. If ever present, it has been completely destroyed. Clinopyroxene, probably augite, varies from fresh to complete clay mineral or clay mineral-calcite pseudomorphs. The most common alteration product is a highly birefringent saponite-like mineral. Hornblende is commonly altered within the igneous rocks of the Colestin Formation. It is found rarely in some of the ash-flow tuffs but never in the epiclastic rocks. The alteration product is usually a highly birefringent yellow montmorillonite.

Biotite and white mica are either fresh or altered to chlorite. The chloritized mica is found solely in the well sorted sediments of the middle member and may represent second cycle detrital products which have been eroded from the Cretaceous marine sandstone underlying the Colestin Formation.

Alteration of the Lithics

Within the detrital lithics, which are generally fine-grained intermediate volcanic types, the groundmass feldspar and phenocrysts if present are set in a secondary phyllosilicate paste. Apparently, of the minerals commonly found in andesitic volcanic rocks of the Colestin Formation, feldspars and opaques are the last to be altered.

Occasionally detrital lithics occur fresh or only slightly altered to phyllosilicates in the sedimentary rocks of the Colestin Formation. Usually the fresh clasts possess larger mineral grains and hence are more resistant to chemical attack than finer-grained lithic clasts, or the fresh clasts contain a greater abundance of feldspar which is more resistant to chemical attack than the mafics. Other unaltered lithic clasts in the Colestin Formation containing microcrystalline quartz are more silicic in character and would be expected to be less altered than mafic lithic clasts.

Alteration has progressed to such a degree that not a single occurrence of a mafic mineral such as amphibole or pyroxene, can be found in the groundmass of the lithic clasts in the lower and middle member and only rarely in the upper member, all have been replaced by phyllosilicates. The decomposition of mafic minerals and pyroclastic glass originally occurring in the Colestin Formation have undoubtedly influenced the chemical environment of the Colestin Formation during diagenesis.

MINERALOGY OF AUTHIGENIC MINERALS

Clinoptilolite-Heulandite

Hey and Bannister (1934) concluded that clinoptilolite was essentially the high-silica end member of the heulandite structural group. Mumpton (1960) and Mason and Sand (1960) both conclude that heulandite and clinoptilolite are distinct mineral species but with similar structure and x-ray patterns. Mason and Sand conclude that the basic difference in the two species is the relative abundances of K and Na, and Ca, with clinoptilolite being K and Na rich and heulandite Ca rich. Mumpton agrees with this but presents evidence that the most important difference in the two minerals is the silica content. He defines heulandite as having a silica to alumina ratio of 5.5 to 6.5 and clinoptilolite a ratio of 8.5 to 10.0, and attributes the greater thermal stability of clinoptilolite to the increased silica content. Mumpton also found that heulandite undergoes a structural change to "heulandite-B" at about 230 C and becomes amorphous at 350 C, whereas clinoptilolite is stable to temperatures of approximately 750 C. He suggests using an x-ray pattern of the material heated overnight at 450 C to distinguish between the two minerals.

Mason and Sand (1960) note that from the available data no heulandite has a beta refractive index lower than 1.488 and no clinoptilolite a beta index higher than 1.485 and that this difference can be used to distinguish clinoptilolite from heulandite. Shepard (1961) found natural zeolites that behave thermally as though both clinoptilolite and heulandite or a heulandite-like mineral are present. In more recent work Hay (1963) reports an intermediate zeolite exhibiting the refractive index of clinoptilolite and the thermal properties of both heulandite and clinoptilolite.

Heulandite is abundant in the upper and lower members of the Colestin Formation at the type locality but is absent or very rare in the middle member and in the Shelton Creek and Klamath River measured sections. Heulandite from the thesis area ranges from large tabular, subhedral grains one-half millimeter long to indistinct mosaics of tiny anhedral grains replacing the groundmass of ash-flow tuffs. The coarser grains are generally found as cement or replacing large glass shards. The better developed crystals of heulandite exhibit perfect (010) cleavage and are usually developed with tabular plates parallel to these cleavage planes. Birefringence is low ranging from 0.004 to 0.006 in the three samples in which all three principal indices were determined (Table 17). Both optically positive and negative crystals were found, although positive crystals predominate.

Most of the heulandite from the Colestin Formation when heated to 450^{o}C for 14 hours either transforms to heulandite-B or becomes amorphous, but several exceptions to this occur. In a number of samples x-rayed, heulandite heated to 450^{o}C for 14 hours converted to an

Table 17. Some physical properties of clinoptilolite and heulandite.

Name and Locality	Optical Constants	Phase(s) and relative intensities of (020) peaks after heating
Clinoptilolite: John Day Formation (Hay, 1962, p. 126).	Ny: 1.479 to 1.485 ±0.002	9.0 A
Clinoptilolite: John Day Formation (Hay, 1962, p. 126).	Ny: 1.485 ±0.002	9.0 A (weak) 8.7 A (very weak) 8.3 A (very weak)
Clinoptilolite: Colestin Formation, section B, unit 53, plate I, sample 246.	Not determined	9.1 A (modified
Clinoptilolite: Colestin Formation, section B, unit 13, plate I, sample 92.	Not determined	9.2 A (modified
Clinoptilolite and Heulandite: Colestin Formation, section B, unit 38, plate I, sample 236.	Ny: 1.483 + 0.002 Ny: 1.490 + 0.002	9.0 A (unmodified)
Clinoptilolite and Heulandite: Colestin Formation, section B, unit 46, plate I, sample 254.	Not determined	9.1 A (modified) 8.4 A (weak)
Clinoptilolite and Heulandite: Colestin Formation, section B, unit 46, plate I, sample 255.	Ny: 1.479 to 1.496 + 0.002	9.0 A (modified) 8.4 A (weak)
Heulandite: John Day Formation (Hay, 1962, p. 126).	Ny: 1.489 + 0.002	8.3 A
Heulandite: John Day Formation (Hay, 1962, p. 126).	Ny: 1.495 + 0.002	8.3 A
Heulandite: Cape Blomidon, Nova Scotia (Hay, 1962, p. 126).	Ny: 1.501	No pattern
Heulandite: Paterson, N. J. (Hay, 1962, p. 126).		8.3 A (very weak)
Heulandite: Colestin Formation, section B, unit 58, plate I, sample 260.	Zoned crystal: Ny: (core): 1.487 + 0.002 Ny: (rim): 1.492 + 0.002 Non -zoned crystal: Ny: 1.488 + 0.002	8.3 A
Heulandite: Colestin Formation, section B, unit 9, plate 1, sample 82.	Ny: 1.490 to 1.495 + 0.002	8.14 A
Heulandite: Colestin Formation, section B, unit 5, plate 1, sample 115.		8.6 A (very weak)

unidentified phase which produced a small x-ray peak ranging from 8.14 A to 8.18 A and in one sample an unknown phase occurred with a peak at 8.6 A. Milligan and Weiser (1937) indicate that heulandite exists in at least three modifications in the temperature range 0 to 400 C and show dissimilar x-ray patterns of heulandite in the different phases whereas Mumpton (1960) found one phase change in heulandite at about 250 C. This suggests the phase changes of heulandite are not consistent. Also, if it is true that the greater thermal stability of clinoptilolite relative to heulandite is due to additional "structural silica" in the clinoptilolite lattice as Mumpton (1960) believes, it may be that variations in the amount of silica in different heulandites accounts for the occurrence of different phases found in heulandites from the Colestin Formation as well as the different phases found in the investigations of Mumpton, and Milligan and Weiser.

Hay (1962) found heulandite crystals in the John Day Formation in which the rims had lower refractive indices than the cores. Heulandite from the Colestin Formation is commonly zoned but refractive indices of the rims are consistently higher than that of the cores. Apparently during formation of the John Day heulandite the activity of silica increased with time whereas in the environment in which some of the heulandite of the Colestin Formation formed the silica activity decreased.

Heulandite in the Colestin Formation was identified by x-ray and thermal studies following the suggested procedures of Mumpton (1960) (see page 90, this thesis). Small grains of the heulandite identified by x-ray and heat treatment were mounted on a spindle stage and the principal indices of refraction determined by oil immersion. The refractive indices of heulandite are given below for samples taken from units 58 and 9, sec. B, plate I.

Table 18. Refractive indices of heulandite from units 58 and 9.

Unit 58*: Sample 260			
1.	Alpha (rim) = 1.492 ± 0.002	2.	Alpha = 1.488 + 0.002
	Alpha (core) = 1.486 + 0.002		Beta = 1.488 + 0.002
	Beta (core) = 1.487 + 0.002		Gamma = 1.492 + 0.002
Unit 9: Sample 82			
1.	Beta = 1.495 + 0.002	3.	Alpha = 1.490 + 0.002
2.	Beta = 1.494 + 0.002		Beta = 1.490 + 0.002
			Gamma = 1.490 + 0.004
4.	Alpha = 1.491 + 0.002		
	Beta = 1.495 + 0.002		
	Gamma = 1.497 + 0.002		

* Note that the heulandite from unit 58 possesses refractive indices very close to the lowest possible for heulandite according to Mason and Sand (1960).

Clinoptilolite was identified in four units of the Colestin Formation using thermal and x-ray techniques suggested by Mumpton (1960) (see page 90, this thesis). Two occurrences are very fine-grained replacements of glass shards in ash-flow tuffs but in two other cases clinoptilolite and heulandite occur as cavity fillings in epiclastic sandstones (Table 17). The crystals vary from fine anhedral mosaics in the ash-flows to tabular crystals 0.25 mm long in the sandstone. Birefringence is very low ranging from Nz - Nx = 0.003 to 0.006 in two samples.

The refractive indices of four zeolite grains from unit 46 were determined (Table 19). Three of the grains possess refractive indices within or at the upper limit of refractive indices possible for clinoptilolite. The fourth crystal is zoned and possesses a beta refractive index which ranged from 1.492 $\pm$ 0.002 at the core to 1.496 $\pm$ 0.002 at the rim both of which are in the heulandite range. The x-ray diffraction pattern of the zeolite(s) from unit 46 indicates a strong 9 A reflection which is not destroyed but modified after heating and a weak 8.4 Å phase.

Table 19. Refractive indices of four zeolite grains taken from unit 46, sample 255 and two zeolite grains taken from unit 38, sample 236.

Sample 255					
1.	Alpha =	1.484 + 0.002	2.	Alpha =	?
	Beta =	1.486 + 0.002		Beta (rim) =	1.496 + 0.002
	Gamma =	1.490 + 0.002		Beta (core) =	1.492 + 0.002
				Gamma (core) =	1.496 + 0.002
3.	Alpha =	?			
	Beta =	1.479 + 0.002	4.	Alpha =	?
	Gamma =	1.483 + 0.002		Beta =	1.481 + 0.002
				Gamma =	?
Sample 236					
1.	Nx =	1.482 + 0.002	2.	Ny =	1.490 + 0.002
	Ny =	1.483 + 0.002			
	Nz =	1.485 + 0.002			

The beta refractive indices of two zeolite grains from unit 38 were determined and found to be 1.483 ± 0.002 and 1.490 ± 0.002 (Table 19). The latter measurement is much too high for the beta refractive index of clinoptilolite (Mason and Sand, 1960; Deer and others, 1963), but falls well within the heulandite range. The heated x-ray diffraction pattern of this material shows no B-heulandite peak, but this may be due to comparatively small amounts of heulandite in the sample relative to clinoptilolite. In any case there appears to be minerals possessing the refractive indices of heulandite as well as clinoptilolite and the thermal properties of at least clinoptilolite in unit 38.

In both units 46 and 38 refractive index determinations suggest both clinoptilolite and heulandite are present. The x-ray diffraction pattern in both units although not precisely characteristic of either heulandite or clinoptilolite seems to support the optical data and suggests both heulandite and clinoptilolite are present.

Hay (1962) describes a zeolite from the John Day Formation with a beta refractive index between heulandite and clinoptilolite which produces a weakened 9 A peak in addition to a B-heulandite reflection. He interprets this data as evidence for a zeolite intermediate between clinoptilolite and heulandite but this writer feels the data could also represent discrete clinoptilolite and heulandite in the same sample. The number of beta refractive index determinations made by Hay on his sample are unknown but must have been small due to the fine-grained nature of most zeolites in claystones (Hay, 1962, p. 226). If more determinations had been made beta refractive indices both within the heulandite and clinoptilolite range may have been found as is the case of unit 46 and 38 in the Colestin.

A third explanation should be considered. Mumpton (1960) reports that when potassium and sodium of "normal" clinoptilolites is exchanged for calcium to give calcium-rich clinoptilolite, the 9 A (020) reflection is weakened after heating to 450 C for 15 to 20 hours. Mumpton also states that calcium clinoptilolites although unreported in nature might eventually be found in sediments similar to those of the Colestin Formation. Thus calcium clinoptilolite could account for the modification of the 9 A peak in the Colestin Formation samples.

In conclusion it is believed the data derived from zeolites in units 46 and 38 are suggestive of the co-existence of both heulandite and clinoptilolite in the rock of these two units. This is based primarily on the presence of refractive indices characteristic of both heulandite and clinoptilolite and the presence of beta heulandite as well as clinoptilolite reflections after heat treatment.

Phyllosilicates

Introduction

The clay minerals of 75 samples taken from the measured sections (plate I) and 11 samples taken from key outcrops of the Hornbrook and Colestin Formations were studied in detail.

The clay minerals were identified by x-ray diffraction techniques following the procedures discussed in Appendix I. Since whole rock samples were generally used to obtain the less than 2 micron fraction for clay analysis certain problems arose in distinguishing detrital clay, in situ alterations of lithics and matrix material, and diagenetic clay cements from one another. Where the origin of the phyllosilicate is in doubt it is so stated and if the mineral identity is uncertain, the mineral name is followed by a question mark.

Corrensite

Lippman (as reported by MacEwan, and others, 1961) first gave the name corrensite to a regular interstratification of chlorite and "swelling chlorite" but in a later study refers to corrensite as a regular interstratification of chlorite and vermiculite. MacEwan, Amil and Brown (in Brown, 1961, p. 426) point out that the minerals described by Lippman preserve both the 28 A and 14 A reflections after heating to 550 C for one-half hour. Since vermiculite should collapse to 9 A or 10 A when heated to 300°C (Walker, 1956) a regular interstratification of chlorite and vermiculite would give a first order spacing of about 24 A when heated above 300°C. Thus vermiculite cannot be one of the components in Lippman's original corrensite but apparently is a true regularly interstratified chlorite-vermiculite as reported in his second description of a corrensite (Lippman, 1956). Since his original description, the term corrensite has generally been accepted for a regular interstratification of chlorite and vermiculite and will be used as such in this thesis (Peterson, 1961, 1962; Bradley and Weaver, 1956; and Grim and others, 1960).

A regularly interstratified chlorite-vermiculite clay was identified in 38 of the 86 clay samples studied. This clay mineral is characterized by a large basal spacing of about 29 A followed by higher orders of reflections which are nearly exact sub-multiples of the primary spacing (Table 20). Corrensite does not expand appreciably on solvation with glycerine or ethylene glycol. Air dried, K-saturated corrensite x-rayed at 54 percent relative humidity indicate an apparent disordering of the regular interstratification and the collapse of the structure to 13.4 A. K-saturated corrensite heated to 500 degrees C and x-rayed at 6% relative humidity indicate a collapse of the structure to 12.6 A. The x-ray pattern produced by a K-saturated sample strongly suggests a collapsed 10 A vermiculite regularly interstratified with 14 A chlorite. The K-saturated sample heated to 550°C supports the chlorite-vermiculite interpretation since the 14 A chlorite peak is not destroyed when heated to 550°C and vermiculite collapses to 10 A giving a 14 + 10 A or 24 A basal spacing a with strong 12 A second order reflection.

Several descriptions of regularly interstratified clay minerals similar to corrensite are described in the literature and appear to support the chlorite-vermiculite interpretation for this mineral. Table 20 provides a partial summary of the x-ray data for corrensite reported in the literature and for the Colestin Formation.

The optical properties of corrensite have not been described in the literature except in a very general manner (Harvey and Beck, 1960). This is probably due to the very fine nature of previously described corrensite. The corrensite studied in this thesis is in many instances coarse-grained and provides an excellent opportunity to obtain reliable optical data.

Coarse, chemically precipitated corrensite ranges from dark green to yellowish green in some rocks and is a pale greenish-yellow to bright golden yellow in others. Strong to weak pleochroism is generally present. Maximum absorption is parallel to cleavage traces when they are aligned parallel to the polarizer of the microscope. Maximum absorption colors range from dark green to bright yellow and at a position of least absorption may exhibit pale yellow or pale yellowish-green hues. Well developed unidirectional cleavage is

Table 20. X-ray diffraction data for corrensite from the Colestin Formation and for those reported in the literature.

	Mg-saturated, R.H. 54%	Glycolated, Mg-saturated, R.H. 54%	K-saturated, R.H. 54%, air dry at 20 C.	K-saturated, R.H. 6% and Dried at: 105 C	300 C	500 C
(001)	29.0	30.4	?	?	?	24.5 (weak)
(002)	14.3	15.3	13.6	13.4	13.4	12.1
(003)	9.6		8.3	8.1	8.2	
(004)	7.2	7.7	7.2	7.1	7.2	
Brazer Limestone corrensite (Bradley and Weaver, 1956)						
	Untreated	Glycolated				550 C
(001)	29	31				23
(002)	14.6	15.5				12.0
(003)	9.7	10.2				8.0
(004)	7.2	7.7				6.0
Corrensite from Triassic sediments (Lippman, 1956)						
	Mg-saturated air dried	Glycolated, Na-saturated				
(001)	29	31.5				
(002)	14.5	15.6				
(003)	10	10.0				
(004)	7.2	7.75				
Corrensite from the Salado Formation (Grim, Droste, Bradley, 1960)						
	Untreated					
(001)	30.0					
(002)	14.48					
Corrensite from Mississippian carbonate rocks (Peterson, 1961)						
	Untreated	Glycolated				550 C
(001)	29.4	31.2				
(002)	14.7	15.6				12.1
(003)	10.0	10.0				10.0
(004)	7.4	7.8				8.0

observed and when crushed the mineral breaks into very thin, scaly aggregates much like chlorite.

The coarse varieties generally grow in sheaf-like aggregates nearly perpendicular to cavity walls, but in at least one sample lath shaped fibrous crystals occur. It also commonly occurs as irregular linings around cavities as clouded, scaly, paste-like masses of highly birefringent clay. In thin section observation of corrensite the maximum birefringence was estimated to range from high first order to middle second order interference colors but a fairly reliable refractive index determination on a specimen from unit two indicates a high (N_z-N_x = 0.054) birefringence. A second less reliable determination revealed a birefringence of N_z-N_x = 0.026. If the more reliable figure is taken as the correct birefringence then the difference between the observed and calculated birefringence is partially resolved in the following manner. The measured thickness of the grain on which the refractive indices were determined was found to be 0.01 mm. Using Kerr's (1959) interference color chart a mineral with 0.01 mm thickness and birefringence of about 0.05 produces a high first order interference color. Thus unusually thin grains and a partial masking by the mineral's color may produce the lower interference colors usually observed.

In one determination the optic sign of corrensite was found to be negative, the cleavage traces parallel to the faster ray and the principal indices to be:

Alpha = 1.575 ± 0.002
Beta = 1.625 ± 0.002
Gamma = 1.629 ± 0.004

Coarse grained corrensite was hand-picked from two units. The first hand-picked sample was extracted from the interstitices of a pebbly sandstone (unit 35) where it occurs as a bright yellow to greenish-yellow phyllosilicate cement. This mineral closely resembles yellow nontronite but x-ray diffraction patterns conclusively prove it to be corrensite. A second sample occurring as a pore filling and associated with heulandite cement is green to yellowish green and moderately pleochroic. Under crossed nicols the coarser grains closely resemble mica and in general the grain cannot be distinguished from celadonite*, but again x-ray diffraction patterns prove beyond doubt that this mineral is corrensite. The possibility of mis-identification of corrensite for montmorillonite is quite apparent.

Montmorillonite

The term montmorillonite is used here for the group of minerals which, when Mg-saturated and solvated with ethylene glycol, expand from approximately 15.3 A to 16.9 A.

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*In one instance the central portion of a corrensite aggregate displays faint bluish pleochroism similar to that of celadonite. X-ray patterns of the clay extracted from the whole rock sample show a small 10 A peak suggesting minor amounts of celadonite may be present in at least this one sample.

Montmorillonite is recognized from x-ray patterns but extreme difficulty is encountered in pin-pointing in thin section the specific phyllosilicate which produces the smectite reflection. Where it can be identified, the finer varieties usually range from pale brown to green and have low to moderate birefringence. Grain morphology is usually indistinct but occasionally scale-like masses occur. It probably makes up much of the alteration product of the lithic clasts as well as forming epimatrix in the volcaniclastic rocks. It is also found as the major clay mineral produced by alteration in units 53 and 11, which are thin ash-flow tuffs, and in the top of unit 13 a thick ash-flow tuff where montmorillonite gives the tuff a characteristic deep green color.

Of four lavas in which alteration to clay minerals was identified all contained montmorillonite as the sole authigenic clay identifiable by the x-ray diffraction methods used by the author. In one sill studied montmorillonite was associated with minor amounts of corrensite although the latter is generally absent from the igneous rocks. Montmorillonite occurs in the groundmass and as clay pseudomorphs in the four lavas and one sill whose clay minerals were studied. Partial to complete pseudomorphs are present and from crystal outlines and the identification of unaltered portions of the original material, plagioclase and pyroxene were identified as the parent material. The montmorillonite ranges from bright golden yellow to reddish or greenish yellow and forms highly birefringent scaly to rarely fibrous aggregates within the pseudomorphs. Pleochroism is variable and appears to be limited to small fibrous areas which are generally coarser grained than normal and exhibit slightly higher birefringence. These areas exhibit the optical properties of corrensite and may represent small areas of the montmorillonite altering to this mineral. By far the largest portion of the pseudomorphs, and in some cases the groundmass, is montmorillonite. This was established by hand-picking clay pseudomorphs from one sample for x-ray identification.

Kaolinite Group/Chlorite Undifferentiated

The distinction between kaolinite group minerals and chlorite in clay mineral samples is not always a simple matter. In this study no attempt was made to remove free iron oxide or other impurities which tend to increase secondary fluorescence thus background interference was significant and x-ray diffraction patterns of the (060) reflection for chlorite and kaolinite group minerals impossible to interpret. Several unsuccessful attempts were made to resolve the (004) chlorite and (002) kaolinite reflections for purposes of identification.

Dissolution of chlorite with HCl and heat treatments were attempted but results from acid treatments indicate that chlorite is not always dissolved and confusion with kaolinite still exists (Table 21). Heat treatment was successful in that it enhanced the 14 A peaks of

Table 21. Results of acid and heat treatments on four clays possessing strong 7 A reflections.

Sample No. and clay mineralogy	Mg-saturated R.H. 54%		K-saturated and x-rayed at 6% relative humidity		
			Treatment: 1M HCl for 3-1/2 hrs at 20 C	Treatment: 1M HCl for 3 hrs at 105 to 110 C	Treatment: heated at 500 C for 2-1/2 hrs
Sample 102, section A, plate I Corrensite and a 7 A reflection	7 A (S)[1, 2] Correnaite (S)	7 A (M) Corrensite (M)	7 A (M to W) Corrensite (?)	7 A (absent) Corrensite (?)	7 A (W to absent) 14 A chlorite (M) Corrensite (S)
Sample 241, section A, plate I Montmorillonite, Corrensite and a 7 A reflection	7 A (S) Montmorillonite (S) Corrensite (S)	7 A (W, B[3]) Mont. (S) Corrensite (S)	7 A (W and B) Mont. (S) Corrensite (M)	7 A (W to absent) Mont. (W) Corrensite (absent)	7 A (absent) 14 A chlorite (W) Mont. (M) Corrensite (M)
Sample 247, section A, plate I Corrensite and a 7 A reflection	7 A (S) Corrensite (S)	7 A (S) Corrensite (?)	7 A (M) Corrensite (?)	7 A (absent) Corrensite (absent)	Broad peak from 12.3 A to 14 A (S) (chlorite and corrensite)
Sample 232, section A, plate I Montmorillonite, and a 7 A reflection	7 A (S) Montmorillonite (S)	7 A (M) Mont. (S)	7 A (M to W) Mont. (?)	7 A (absent) Mont. (S to M)	7 A (absent) 14 A chlorite (M)

[1] S = Strong reflection - peak height essentially same as in Mg-saturated sample.
M = Moderate reflection - peak height significantly modified (as compared to the same reflection in the Mg-saturated sample)
W = Weak reflection - barely discernable from background but clearly present.
Absent = reflection not discernable.

[2] The 7 A reflection is either the (002) chlorite or (001) kaolinite reflection, or possibly both.

[3] B = Broad peak

chlorite although the absence of a 14 A peak does not necessarily mean chlorite is absent. As a result, in most of the 86 samples studied, x-ray distinction of kaolinite group minerals and chlorite was not performed and the 7 A reflection identified only as a "kaolinite group mineral/chlorite" peak.

Chlorite

Chlorite was assumed to be present in cases where a 14 A peak was discernable after heating the clay mineral sample to 550 C for 2-1/2 to 3 hours. No conclusions can be made concerning the presence of chlorite in a sample which produces a strong 7 A reflection prior to heating, and a modified 7 A peak and no 14 A peak after heating, because sometimes the 14 A peak is weak compared to the second order peak at 7 A (Brindley, 1961, p. 85). In the case of the Colestin samples the 14 A peak may simply be hidden by background interference. However, from optical studies it is apparent that chlorite is much more common than kaolinite group minerals in the Colestin sediments with possibly two or three exceptions.

A strong 7 A reflection can represent a fourth order corrensite reflection, a (002) chlorite reflection, a (001) kaolinite reflection or some combination of two or all three. Corrensite can be distinguished from chlorite and kaolinite in the Mg-ethylene glycol saturated samples where, for the former, a shift of the 7 A reflection to slightly higher d-spacings occurs (Table 20).

Results of acid dissolution performed on four samples each containing a strong 7 A reflection prior to acid treatment are given in Table 21. In all four samples the 14 A peak which appears after thermal treatment suggests the presence of chlorite. Acid treatment at room temperature does not destroy the 7 A peak thus suggesting either kaolinite is present or the acid too weak to destroy chlorite. A second acid treatment at elevated temperature tends to support the conclusion that kaolinite is not present in any of the four samples. On the other hand the acid treatment may have been too severe (Brindley and Yowell, 1951) on the second attempt as indicated in sample 247 and 232 where montmorillonite was partially destroyed.

The 14 A reflection when present after heating to 550 degrees C is definite proof chlorite is present in the four samples. The presence of a 7 A reflection indicates that kaolinite could be present but in the presence of chlorite it could not be confirmed.

Chlorite can be identified optically as epimatrix and as phyllosilicate cement in many of the samples studied.

In conclusion, chlorite is definitely present and is probably responsible for most of the 7 A peak. The presence of kaolinite group minerals cannot be proved for these four samples with the data at hand.

Kaolinite Group Mineral

A kaolinite group mineral, identified on the basis of optical and x-ray data, makes up a large portion of the rock samples derived from unit 24 (plate I) at the type section. In thin section small amounts of mica, chlorite and plagioclase can easily be identified as discrete particles set in a fine-grained, low birefringent material composed of interlocking anhedral grains. X-ray diffraction confirms the mica, chlorite and plagioclase but also indicates quartz and a kaolinite group mineral by the presence of a strong 26.6 A quartz reflection and a very strong 7 A reflection which appears to be much too strong for a second order chlorite reflection in a specimen containing as little chlorite as is indicated in thin section of this rock. On heating to 550 C for 2-1/2 hours the 7 A peak is almost completely destroyed, although a well-formed 14 A peak remains almost constant in intensity both before and after heating. This suggests a kaolinite group mineral has been destroyed by heating whereas chlorite has remained unaffected. This is the only occurrence in the thesis area in which a kaolinite group mineral appears to be present in larger quantities than chlorite. This unique occurrence of a kaolinite group mineral will be discussed in more detail under diagenesis.

Vermiculite

Vermiculite is used here for a mineral with a strong 14 A reflection which does not expand upon ethylene glycol or glycerine solvation, but collapses to 10 A when saturated with potassium and x-rayed at both six percent and 54 percent relative humidity. A vermiculite possessing the above characteristics was found in units 4 and 3, section B (plate I) near the base of the type section. Unit 3 is an ash-flow tuff and the vermiculite occurs in much the same manner as montmorillonite does in other ash-flow units of the Colestin Formation; simply as very fine-grained material within the interstitices of zeolitized shards and intimately intergrown with a zeolite. In unit 4, a coarse epiclastic sandstone, both vermiculite and corrensite are present. Apparently the corrensite and vermiculite are intimately intergrown and are very fine-grained.

Optically the only phyllosilicate recognizeable in both units 4 and 3 is a material which varies from a greenish-brown to a more common reddish brown vermiform, highly birefrigent mineral. In unit 4 this material sometimes lines cavities which later were filled with microcrystalline quartz cement, but may also be included in the quartz cement giving it a clouded or dirty appearance.

Mica

Mica was identified in at least ten samples studied by x-ray diffraction techniques. Two samples are known to contain coarse detrital biotite and muscovite and five samples are clay stones and siltstones in which the origin of the mica is not known. In three of the samples (100 and 95, unit 13, and sample 53, unit 10) the mica is authigenic. At the top of unit 13 an ash-flow tuff, clay mineral pseudomorphs after plagioclase? and pyroxene? are present. Optical properties of this mica are almost identical to those of the montmorillonite clay pseudomorphs found in several igneous rocks and described under the montmorillonite section of the thesis. However, in unit 13 x-ray analysis of hand-picked clay mineral pseudomorphs showed that the highly birefringent, slightly pleochroic, golden yellow phyllosilicate is a mica.

In the middle and lower portion of unit 13 the devitrified groundmass is filled by a fine-grained authigenic mica in addition to the mica pseudomorphs, whereas near the top of the unit the mica pseudomorphs are associated with a green montmorillonite in the groundmass. In unit 10 a coarse epiclastic volcanic rock, the mica is associated with corrensite and chlorite(?) and could not be distinguished optically.

Regularly Interstratified Montmorillonite-Mica

One occurrence of a regularly interstratified montmorillonite-mica clay was discovered in the SW 1/4 SE 1/4, sec. 8, T. 41 S., R. 2 E. This clay is found in an indurated claystone underlying cross-bedded and fossiliferous sandstone. The claystone is undoubtedly of lacustrine origin. Results of x-ray studies of this material are shown in Table 22.

Table 22. X-ray data for regularly interstratified montmorillonite-mica.

Mg-Sat. d. R.H. 54%		Mg-Ethylene Glycol R.H. 54%	K-Sat. d., R.H. 6% Dried at 105C.
(001)	25.4 A	27.8 A	10.1 A
(002)	12.5 A	13.6 A	

Authigenic Quartz

Authigenic quartz cement is generally present as a mosaic of fine to coarse anhedral grains, but is occasionally found as fibrous chalcedony in some of the ash-flows. A few occurrences of opal filling small cavities is found in unit 2 near the base of the type section. Quartz is also a major devitrification product in unit 13.

Authigenic Albite

In the porous central portion of unit 2, about 72 feet above the Cretaceous contact authigenic albite is found as small tabular crystals approximately 0.05 to 0.015 mm. They project inward toward the center of open cavities giving the rock a vuggy appearance under the binocular microscope. The bases of the crystals are attached and intimately intergrown with corrensite epimatrix and cement and rarely with massive laumontite cement. The crystals have very low birefringence. The beta refractive index determined on two grains was 1.533 $\pm$ 0.002 in both cases. These indices agree almost perfectly with the 1.532 $\pm$ 0.003 beta refractive index reported by Baskin (1956) for nearly pure ($An_{0.5}$) authigenic albites. Most of the authigenic albite crystals are simple albite growth twins (i.e., not polysynthetically twinned). In one instance Roc Tourne' twinning, which is twinning after a combination of the albite and Carlsbad twin laws, was observed. This type of twin has only been observed in authigenic albite according to Baskin (1956).

Authigenic albite also occurs as a replacement of detrital plagioclase and has been discussed in an earlier section of the thesis.

Laumontite

Laumontite is found in unit 2 near the base of the lower member at the type section. It is found in association with phyllosilicates (mostly corrensite) and authigenic albite. The laumontite is rare but when observed forms as a massive cement filling cavities lined with albite crystals and clay minerals. It possesses two directions of well developed cleavage at nearly right angles, is optically negative, and has a higher birefringence ($N_Z - N_X = 0.01$) than heulandite. The maximum and minimum refractive indices of this mineral are alpha = 1.509 ± 0.002 and gamma = 1.519 ± 0.002 which are within the range of laumontite (Deer and others, 1963).

Carbonate

All of the occurrences of authigenic carbonate minerals within the Colestin rocks are believed to be calcite. X-ray diffraction patterns of numerous samples containing a carbonate invariably turned out to be calcite. The term calcite is used in this thesis when x-ray diffraction studies confirm this species. Carbonate is used when the mineral is probably calcite but has not been confirmed by x-ray studies.

Carbonate minerals in the Colestin Formation are found as cement and occasionally as partial pseudomorphs or small patches replacing plagioclase and pyroxene, and as amygdules in lavas and dikes. The sediments investigated in the Klamath River and Shelton Creek areas contain most of the calcite cement found in the thesis area. The calcite appears to a large extent, to have formed in preference to heulandite and clinoptilolite. The middle member at the type section locally contains abundant calcite cement as the dominant authigenic mineral.

Authigenic Pyrite

Authigenic pyrite is found near the bottom of the measured section along the Klamath River. It occurs as very small anhedral to perfect cube-shaped crystals disseminated throughout light green volcanic sediments.

DIAGENESIS

Introduction

The formation of authigenic minerals within a sedimentary rock is directly related to a number of factors. These factors are composition of host rock, environmental pH, cation concentration, environmental Eh, and pressure and temperature (Packham and Crook, 1960).

As a result of the relatively low temperature and pressure under which most diagenetic changes occur, very slow reaction rates are to be expected and thus metastable phases tend to be common. This is abundantly clear in respect to the mineral assemblages found in the Colestin Formation. Indeed, if metastable assemblages did not exist, paragenetic sequences of authigenic minerals could not be determined, simply because early formed minerals would be completely replaced or modified by later ones. In one respect metastable assemblages are important in that they reveal, at least in part, the "history" of the local environment. On the other hand, it would be convenient if equilibrium or near equilibrium assemblages occurred as in metamorphism so that the mineral facies concept and thermodynamic considerations could be more readily applied to authigenic minerals.

The authigenic mineral assemblages of the Colestin Formation are believed to have been formed in the depositional or post-depositional environment. A considerable body of evidence points to this conclusion:

1. Altered, flattened or elongate lithics with delicate, frayed edges could not have been preserved during transport.
2. In many of the finer sediments phyllosilicate alteration transgresses grain boundaries.
3. Uniformity of alteration of lithics in a given unit imply depositional or post-depositional alteration.
4. Rarity of oxidized lithic fragments suggest reducing conditions.
5. All of the major authigenic minerals identified attacking detrital particles are also found as cement suggesting post-depositional alteration.
6. Corrensite has not been found under surficial weathering conditions as far as this author knows by any investigator.
7. Many of the sand grains are subangular indicating very short transport and little time for alteration.
8. Many of the sediments were rapidly buried by violent flood deposits allowing little time for alteration in the depositional environment.
9. Frequent and intense rain rapidly stripped pyroclastic debris from highlands allowing little time for in situ weathering.

Paragenesis

A paragenetic sequence in the Colestin Formation is clearly observed in many samples indicating probable physio-chemical variations in the post-depositional environment. In addition, certain assemblages appear to have formed contemporaneously or nearly so and are consistently associated with one another. In cases such as these investigations such as Zen (1959) and Peterson (1961, 1962) believe chemical equilibrium may be approached.

The determination of the paragenesis of authigenic minerals is based on numerous criteria. A mineral is assumed younger than a second mineral if the first is enclosed by the second. Two authigenic minerals are considered to be contemporaneous or nearly so when both are observed to occur as the younger (surrounding mineral) as well as the older (included mineral) in the same rock, and are consistently associated with one another. Minerals deposited in open spaces are assumed younger than minerals that bound the voids at the time of filling. Islands of host mineral left in optical continuity in a sea of guest mineral and pseudomorphism were used on numerous occasions to determine the paragenetic sequence. In all cases the final conclusion as to the relative age of a mineral was based on many observations.

Table 23 lists the authigenic minerals found in the Colestin Formation in the thesis area. Major minerals are those which occur

Table 23. Authigenic minerals of the Colestin Formation.

Type Section (section B, plate I) - Lower Member				
Major:	Corrensite	Minor:	Quartz	Montmorillonite+
	Zeolites		Albite	Opal
	Chlorite		Calcite	Laumontite
			Vermiculite	White Mica
Middle Member - Lithic Arenites				
Major:	Corrensite	Minor:	Montmorillonite+	
	Chlorite		Quartz	
			10 A mica	
Middle Member - Reworked Tuff				
Major:	Quartz	Minor:	Chlorite	
	Kaolin		10 A mica	
Middle Member - Litho-feldspathic				
Major:	Montmorillonite+	Minor:	Chlorite	
	Calcite			
Upper Member				
Major:	Heulandite	Minor:	Quartz	
	Corrensite		Calcite	
	Chlorite		Clinoptilolite	
	Montmorillonite+			
Klamath River and Shelton Creek Stratigraphic Sections				
Major:	Corrensite	Minor:	Montmorillonite+	
	Chlorite		Zeolites	
	Calcite		Quartz	
			Pyrite	
Ash-Flow Tuffs				
Major:	Montmorillonite	Minor:	Vermiculite	
	Zeolites (Clinoptilolite and heulandite)		Quartz	
			Albite	
			Chlorite	
			10 A Mica	
Lavas, Sills and Dikes				
Major:	Montmorillonite	Minor:	Kaolinite group/ chlorite undifferentiated	
			Calcite	
			corrensite	
			Laumontite?	
			Iddingsite	
			Quartz	

+ May not always be authigenic.

most frequently in the Colestin Formation.

The three most abundant authigenic minerals found in the volcaniclastic sediments (Table 23) of the lower member include corrensite, heulandite and chlorite. Heulandite and corrensite appear to have formed at about the same time. In one specimen where calcite cement is abundant, the calcite formed later than the corrensite-heulandite assemblage. Quartz also formed later than this assemblage, but its relationship to the calcite is uncertain. Chlorite appears to have formed early and is altering to or at least gradational into corrensite.

Heulandite and vermiculite occur together in unit 5, a tuffaceous sandy siltstone. Most of the heulandite in this unit appears to be replacing shards whereas the vermiculite is probably disseminated throughout a paste-like matrix. Directly beneath unit 5, a pebbly sandstone is present which contains vermiculite associated with corrensite and quartz. The quartz appears to have crystallized later than the clay minerals.

Within the porous zone of unit 2 corrensite, quartz, opal, laumontite and albite are present as authigenic minerals. The albite occurs both as tiny euhedral crystals projecting inward from cavity walls and as massive replacements of detrital plagioclase grains. The paragenetic sequence appears to be corrensite and albite followed by quartz and laumontite.

Three distinct sediment types are found in the middle member of the Colestin Formation. Lithic arenites similar to those found in the upper member are present but may be better sorted and lack pebble grade material characteristic of the upper member. These sediments typically contain corrensite and chlorite. Heulandite is conspicuously absent, but this may be due to the limited number of samples investigated. The paragenetic sequence is chlorite, corrensite, and quartz.

A thick unit of lacustrine, reworked tuff contains a unique assemblage of authigenic minerals not found in other rocks examined during the course of this study. This assemblage include kaolinite group mineral, chlorite, mica and quartz. Petrographic evidence indicates all four are authigenic except possibly the mica, but the paragenesis could not be determined.

Litho-feldspathic arenites (two samples) were found to contain montmorillonite with minor amounts of chlorite in one sample and calcite, montmorillonite and minor amounts of chlorite and detrital mica in the second.

In the lower part of the upper member including units 30 through 38 the most common authigenic minerals are montmorillonite and quartz. Minor minerals include corrensite, chlorite, calcite and zeolites. The quartz crystallized prior to the formation of the clinoptilolite and montmorillonite. Quartz also crystallized before corrensite and chlorite in samples containing these minerals. Calcite occurs as complete pseudomorphs after plagioclase. Heulandite occurs in a siltstone and the paragenetic sequence was not determined.

In the upper part of the upper member including units 39 through 59 the most common authigenic minerals are heulandite, montmorillonite+, corrensite and chlorite. Minor minerals include quartz and clinoptilolite.

From petrographic observations it appears that chlorite was one of the first authigenic minerals to form, followed by crystallization of heulandite and corrensite. Quartz when observed has formed later than heulandite and corrensite. In one originally porous channel sandstone (unit 44, section B, plate I) quartz has largely replaced the heulandite cement. Corrensite appears to have crystallized directly from solution, by recrystallization of detrital matrix material, as an alteration product of chlorite and as a replacement of mafic minerals within clastic lithic fragments. Petrographic evidence suggests that corrensite, in at least some units, began crystallizing before heulandite and continued until sometime after crystallization of heulandite ceased.

Montmorillonite generally occurs as an alteration of lithic fragments or volcanic glass. Its time of formation relative to the other authigenic minerals is uncertain, except in ash-flows where it appears

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+ May not always be authigenic.

to have formed prior to and possibly during the formation of heulandite.

In one occurrence (unit 46) calcite cement is observed and petrographic relations indicate it probably formed before the heulandite-corrensite mineral assemblage. The heulandite-corrensite pair did not replace the calcite when it formed but precipitated in pores of the original rock whereas the earlier formed calcite generally replaced the groundmass of the original rock. This relationship suggests calcite may be stable under the same conditions necessary for the precipitation of heulandite and corrensite.

In units 38 through 30 measured at Siskiyou summit the paragenesis as well as the authigenic mineral assemblages differ slightly from that found above unit 38.

Heulandite is never abundant in the Klamath River or Shelton Creek measured sections. It typically occurs as long acicular crystals which appear to have started crystallization slightly before crystallization of calcite and then ceased forming as calcite began to crystallize and enclose the tiny heulandite crystals. Quartz is found in porous zones and is usually clouded with scaly masses of green low birefringent chlorite. In unit 7, section E near the bottom calcite with included heulandite crystals have been extensively replaced by quartz whereas near the middle of unit 7 microcrystalline quartz with included chlorite has been replaced by calcite which is clouded with corrensite?. Apparently in the middle portion of unit 7 an early quartz-chlorite assemblage was followed by formation of heulandite crystals then replaced by a corrensite-calcite assemblage. Small crystals of pyrite are found in the lower part of unit 7 but their place in the paragenetic sequence could not be determined.

The lower member of the Colestin Formation contains, in at least the exposed portion, a large volume of ash-flow tuff. The authigenic minerals found in these rocks are listed in Table 23. The phyllosilicate minerals and zeolites appear to have formed at about the same time. In one ash-flow montmorillonite fills the groundmass and mica forms pseudomorphs. Quartz apparently is the last formed mineral in the ash-flows except where it is found as a devitrification product. Albite occurs as replacement of more basic plagioclase phenocrysts.

Mineral Assemblages of Igneous Rocks

Within the middle member, in unit 28, several lava flows crop out. The dominant alteration product of these lavas is a bright golden yellow, scaly montmorillonite forming pseudomorphs after plagioclase and pyroxene. It also occurs in the groundmass. Calcite and quartz are present with the montmorillonite forming composite pseudomorphs of calcite, montmorillonite and quartz. The quartz generally forms amygdules and fine interstitial fillings. The paragenesis is usually impossible to determine, but in at least one instance the sequence as determined by successive mineral growths in a vesicle of sample 307 is montmorillonite, calcite and quartz.

Summary of Mineral Assemblages

The four lavas (and probably the majority of igneous rocks found within the Colestin Formation) contain montmorillonite as the major authigenic phyllosilicate (Table 23). Zeolites, corrensite and chlorite appear to be rare or completely absent. The ash-flow tuffs commonly contain montmorillonite and clinoptilolite or heulandite as the major authigenic constituents but in the devitrified zone of one, mica is abundant and in another vermiculite seems to occupy the position normally held by montmorillonite. Corrensite is rare or absent in these rocks.

The authigenic mineral assemblages of the sedimentary rocks are not as easily summarized. Montmorillonite is relatively common in all Colestin sediments but whether or not it is authigenic in most of these sediments is not clear. Corrensite is abundant in most of the lithic arenites but seems to be rare or absent in lithic poor sediments. Chlorite and calcite are more abundant in the Klamath River and Shelton Creek section whereas heulandite and corrensite are more abundant in the type section. Authigenic quartz is unpredictable in its occurrence. It is probably most abundant in the more porous rocks, and has formed either as the last or first recognizable authigenic mineral in the Colestin Formation.

In conclusion, from the information at hand, three general changes in the post-depositional environment can be recognized. The earliest post-depositional environment recognizable was conducive to the formation of chlorite and possibly in some cases to quartz. At a later time corrensite and heulandite (in the type section) and calcite and corrensite (in the Klamath River section) formed. At some time after the formation of the corrensite-heulandite assemblages the post-depositional environment was generally favorable for the precipitation of quartz.

The authigenic mineral assemblages were influenced by the rock type in which they formed. For example corrensite is essentially restricted to sediments and montmorillonite is the primary alteration mineral of the lavas. Since the actual bulk chemical composition of the lavas, ash-flows and sediments are probably similar, the difference in authigenic mineral assemblages is probably due to other factors, such as permeability and mineralogy. For example andesitic glass shards such as occur in the many tuffs and sediments liberate a greater number of mobile cations such as K, Na, Ca, and Mg than do the minerals of the lavas, where these same cations are essentially locked up. Groundwater solutions rich in the necessary cations were free to move through the more permeable sediments and tuffs whereas the necessary concentrations of certain cations such as Ca and Si may have been restricted from the less permeable lavas, which still had their Ca locked up in plagioclase. In still other cases the depositional environment may have influenced the authigenic mineral assemblages. The lacustrine deposits, represented by unit 24, rich in tuffaceous bottom sediments and supporting a large diatom population must have existed for some time without the addition of coarse sediments. The silica content of the lake was high, and apparently leaching of the tuffaceous sediments occurred, thus forming a kaolinite group mineral, quartz, and minor chlorite and mica. After burial and compaction the low permeability of these rocks protected them from the saline, high pH groundwaters characteristic of the Colestin Formation. Lastly, in porous sediments low in lithic and glass fragments but high in feldspar and quartz, such as is typical of certain sediments of the middle member, authigenic minerals are commonly calcite, or montmorillonite. In these cases the sediments appear to have been derived in part from Cretaceous sediments and the high carbonate content may reflect the erosion of calcite cemented Cretaceous sediments and the reprecipitation of calcite in Colestin Sediments.

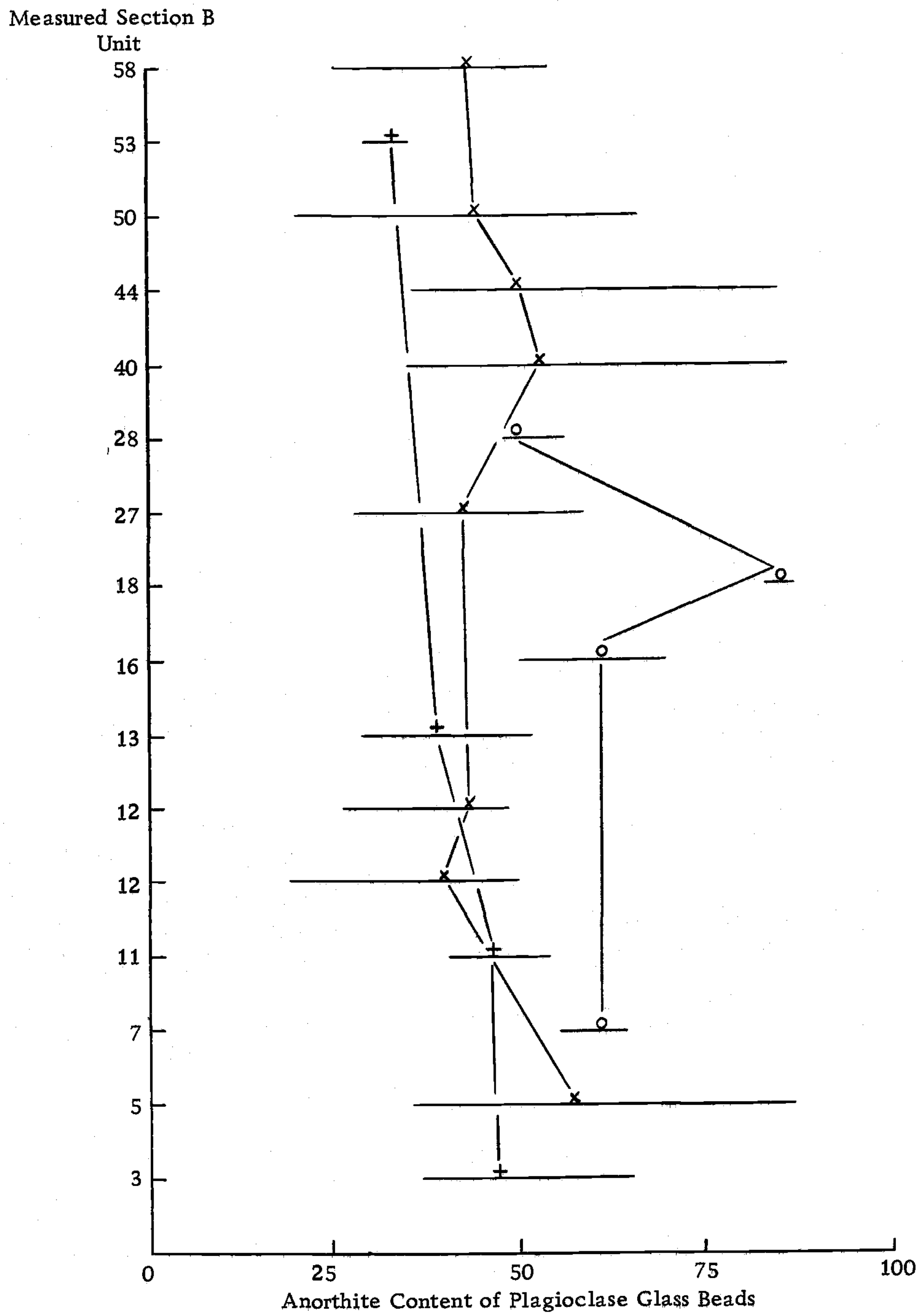
Composition of the Host Rock

The Colestin Formation is composed mainly of andesites and basalts, basic to intermediate ash-flows and volcanic lithic sediments. In addition, the middle member locally contains moderately sorted fine- to medium-grained sandstones high in either pyroclastic material or detrital feldspar.

The relatively close correlation between the plagioclase composition of the ash-flows and the volcaniclastic sediments (Table 24) suggests that the source of the plagioclase in the Colestin sediments is from pyroclastic material rather than lavas. This implies that pyroclastic glass, now altered beyond recognition, may have originally been abundant in most of the sediments of the Colestin Formation, Occasional relict shard texture visible in some of the sandstones supports this conclusion.

In the sediments of the Colestin Formation the plagioclase and opaques are relatively unaltered except near the bottom of the type section where plagioclase is partially albitized. Mafics and pyroclastic material are generally replaced or highly altered throughout the Formation. The dominant mafic observed in this formation is augite. Peck and others (1964) indicate the Colestin Formation contains mostly olivine, hypersthene and augite andesites. Table 25 is presented in order to visualize the relative abundance of the oxides in the materials which have been most susceptible to alteration (andestic glass and augite) in the Colestin Formation. Table 26 presents ideal chemical formulas taken from various sources for the authigenic minerals found in the Colestin Formation.

Table 24. Anorthite content of fused plagioclase glass beads from the Colestin Formation.



\+ Ash-flow tuffs

x Sediments

o Lavas

Horizontal lines indicate maximum anorthite range found in 2 to 10 glass beads per line. Symbols +, x, and o represent mean values of each line

Table 25. Chemical composition of a typical andesite and augite. The data for the rock is taken from Nockold, 1954, and from Deer and others, 1963 for the augite.

	Andesitic glass	Augite
SiO_2	54.2	50.7
TiO	1.31	0.95
Al_2O_3	17.17	2.98
Fe_2O_3	3.48	2.37
FeO	5.49	10.04
MnO	0.15	0.17
MgO	4.36	14.24
CaO	7.92	17.88
Na_2O	3.67	0.67
K_2O	1.11	
H_2O^+	0.86	0.20
P_2O_5	0.28	

Table 26. Ideal chemical formulas taken from various sources for the montmorillonite, chlorite, corrensite and heulandite.

Montmonrillonite	$Si_8Al_{3.33}Mg_{0.67}O_{20}(OH)_4$
	$M_{0.67}$
(Nontronite)	$Si_{7.33}Al_{0.67}Fe_4^{+3}O_{20}(OH)_4$
(Saponite)	$Si_{7.33}Al_{0.67}Mg_6O_{20}(OH)_4$
Chlorite	$Si_{8-x}Al_x(Mg, Fe^{++})_6O_{20}(OH)_4(Mg_{6-x}Al_x)(OH)_{12}$
Corrensite	$Mg_8Al_3Si_6O_{20}(OH)_{10}4H_2O$ + 1 exchange charge
Heulandite	$(Ca, Na_2)Al_2Si_7O_{18}\cdot 6H_2O$

Table 27 compares the cation content of andesitic glass with typical cation content occurring in authigenic minerals found in the Colestin Formation. Other factors being favorable it is apparent that andesitic glass could provide the necessary amounts of Al, Ca, Na, and K for the formation of the authigenic minerals but does not contain enough Si for the formation of clinoptilolite or Mg for the formation of chlorite or corrensite. The cation content of a typical andesitic augite is also plotted in Table 27. It is notable that augite would contribute significant amounts of Ca, Mg and Fe.

An alternative approach to this comparison is to consider Al as the least mobile cation in the system (Table 28). The more mobile cations can be thought of as leached or added to this system while the aluminum concentration remains essentially the same (in this case 17.2 percent, a typical Al_2O_3 value for an andesitic glass). When this comparison is made it is apparent that andesitic glass contains the necessary cations in sufficient quantities for the formation of the authigenic minerals except for the formation of clinoptilolite, chlorite and corrensite. The two clay minerals require appreciably more Mg than andesitic glass can provide.

Clinoptilolite is found as the sole zeolite in three units (units 53, 38 and 13) of the Colestin Formation. The average anorthite content of the plagioclase found in unit 13, an ash-flow tuff, is An_{39}, and in unit 53, an ash-flow tuff it is An_{33}. Both of these units contain quartz

Table 27. Typical cation content of andesitic glass and augite compared to cation content of authigenic minerals.

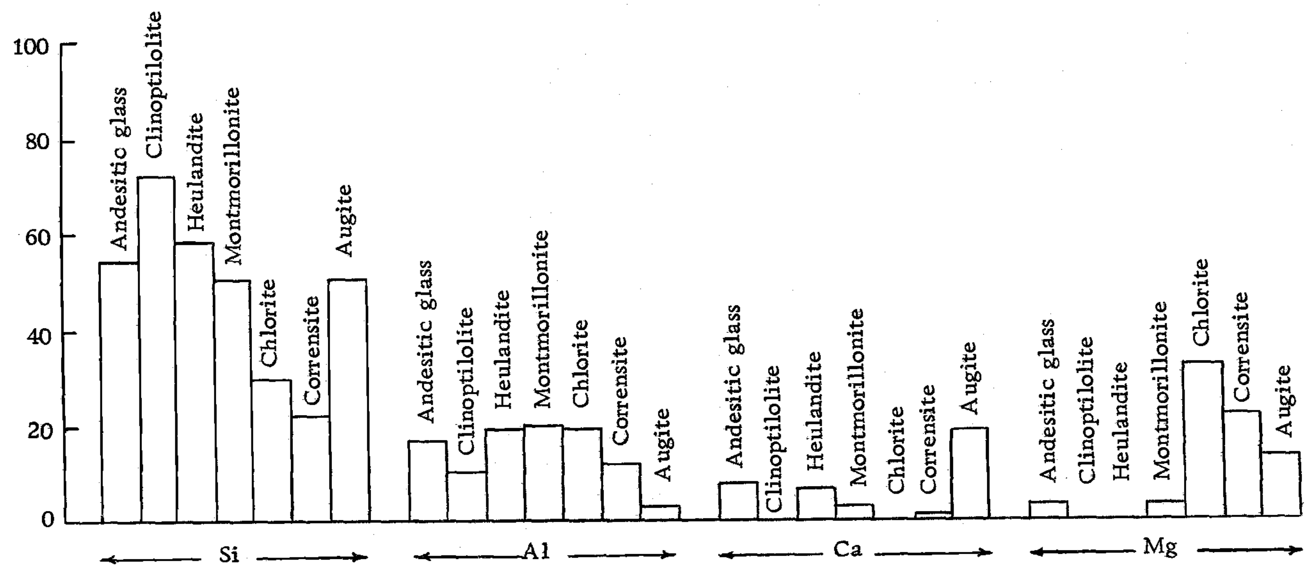
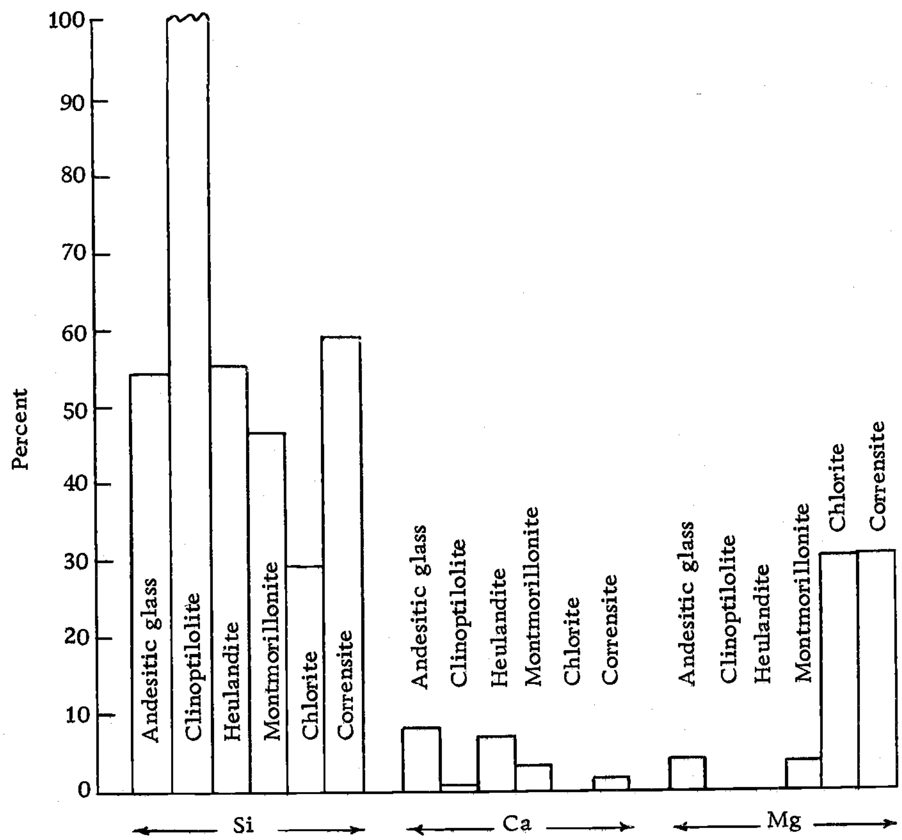


Table 28. Cation content of andesitic glass compared with the diagenetic minerals in the Colestin Formation. A constant Al content of 17.2% is maintained, based on the assumption that Al is the least mobile of the cations present in andesitic glass and that in order for the diagenetic minerals to form the glass, Si, Ca, and Mg have to be leached or concentrated.



phenocrysts. Unit 38 is an epiclastic rock containing significant amounts of authigenic quartz, so it appears that clinoptilolite is preferentially forming in the rocks with sufficient silica available to form clinoptilolite. Sufficient Mg for the formation of chlorite and corrensite probably came from dissolution of both andesitic glass and mafic minerals, particularly augite.

Composition of Hornbrook Formation

The Cretaceous Hornbrook Formation which lies directly beneath the Colestin Formation has been studied in detail by Elliott (1970, unpublished Ph. D. thesis, Oregon State University). He reports that the average composition of all sandstones studied from the Hornbrook Formation is about 30 % quartz, 18% plagioclase, 15% k-spar, 3% composite grains (only a few of which are volcanic), 5% mica, 4% mafics and 4% opaques. Cement averages 16% and matrix 21%. According to Elliott the only cement found in the Hornbrook Formation is calcite and matrix minerals are typically phyllosilicates (especially chlorite). The clay fraction is dominantly kaolinite with a trace of mica in the arenites whereas wackes contain chlorite, mica, and kaolinite. He suggests that much of the matrix is detrital but also feels that much is diagenetic and has altered from primary detrital grains. Elliott notes that chlorite is forming from biotite, amphibole and pyroxene, and that pyrite, limonite and hematite occur in considerable amounts as authigenic minerals.

The Hornbrook and Colestin Formations are obviously very different in composition. The only authigenic mineral which is relatively abundant in both formations is chlorite. Notably lacking in the Hornbrook Formation are zeolites, corrensite and montmorillonite. The absence of zeolites in the Hornbrook Formation is an interesting problem which has been encountered by other investigators dealing with zeolite rich rocks.

Brown and Thayer (1963) found only calcite and phyllosilicates in a calcareous graywacke and shale unit of Late Triassic age in the Aldrich Mountains of Oregon whereas less calcareous units above and below were characterized by minerals found in the prehnite-pumpellyite facies and the laumontite stage of the zeolite facies. They attributed the lack of zeolites in this rock to the high concentrations of calcium carbonate. Zen (1960) suggested that at constant temperature and total pressure, changes in chemical potentials of the mobile components, H_2O and CO_2 can account for two different mineral assemblages. A zeolitic facies can be obtained by increasing the chemical potential of H_2O relative to that of CO_2. However, many times conditions prevail where relative values of CO_2 activity are high enough to form alternative assemblages of calcite-kaolinite quartz or calcite pyrophyllite-quartz. These last two assemblages according to Zen (1960) rule out the zeolitic analcite-quartz assemblage under the same conditions. According to Elliott the Hornbrook sandstones contain a matrix composed mainly of kaolinite, chlorite, and mica and a cement of calcite. Hence the absence of zeolites in the Hornbrook Formation can be attributed to the higher chemical potential of CO_2 in this formation. Additional evidence that calcite precipitation can inhibit the growth of zeolites is present in the Klamath River measured section of the Colestin Formation. Here needle-like crystals of heulandite or possibly clinoptilolite are embedded in massive calcite cement. Apparently the chemical potential of CO_2 was low enough at first to allow precipitation of zeolites but gradually increased and finally was high enough to inhibit crystallization of zeolites.

Corrensite is found throughout the Colestin Formation and appears to increase in abundance with depth up to the contact with the Hornbrook Formation. Within the Hornbrook Formation corrensite is absent. The complete lack of corrensite may be due to lower chemical activities of Mg in the Hornbrook Formation which is a direct result of the less basic character of this formation.

Environmental Eh-pH and Temperature

Most of the Colestin Formation belongs in the "low grade" zeolite facies of Coombs and others (1957). In this facies pH and Eh are probably more important in determining which authigenic minerals will form than temperature and pressure (Packham and Crook, 1960).

It has been found that most beds buried to several thousand feet or more have been subjected after burial to groundwater solutions more saline than the water of the depositional environment (Hay, 1966; Garrels and Christ, 1965). The groundwater solutions of the Colestin Formation were probably alkaline and reducing except possibly in porous zones where high rates of flow may have occurred. The authigenic minerals reflect to varying degrees the salinity, and pH of the solutions from which they crystallized.

The Colestin Formation was believed to be about 2000 feet thick by Wells (1956) but studies connected with this thesis indicate at least 3000 feet of strata. Williams (1942) states that the strata in the Western Cascade Range at about the latitude of Crater Lake is 7000 to 10,000 feet thick. Using this data the top of the Colestin Formation at one time might have been buried by at least 4000 to 6000 feet of rock. If one considers that the Western Cascade Range was highly eroded at the time it was covered by the High Cascade lavas, then an even greater thickness can be assumed. For purposes of discussion the Colestin Formation within the thesis area will be considered to have been buried beneath at least 7000 feet of lavas and volcaniclastic rocks and to have been heated to no less than 30°C nor more than 125 C at the base (Fyfe and others, 1958).

Chlorite

Chlorite occurs under a wide range of environmental Eh-pH conditions. In the range of temperature found in the post-depositional environment of the Colestin Formation (30 to 125°C) chlorite could probably form in any reducing environment with a pH from 7 to 9 (Degens, 1965). An important factor in the consideration of the formation of chlorite in a reducing-alkaline environment is the activity of Mg. However, very little data concerning equilibria for the cation pair Mg/H is available (Grim and others, 1960). Garrels and Christ (1965) and Grim and others (1960) have presented tentative conclusions on the stability fields of chlorite. The former (Garrels and Christ) express chlorite stability at room temperature in the system involving pure magnesium chlorite, phlogopite, kaolinite, k-feldspar and k-mica. Chlorite appears to be stable in an aqueous environment with pH 7 to 9 if the activity of K is low and Mg high, but stable at only high pH values (around 8-1/2 to 9) with relatively low Mg activity.

Quartz

Quartz can form under a wide range of reducing alkaline conditions. The haphazard occurrence of this mineral within the Colestin Formation suggest that local conditions were largely responsible in controlling its precipitation.

Generally the quartz is best developed in or immediately adjacent to porous more permeable rocks. In these zones groundwater circulated more freely and flowed at greater rates (and possibly laterally rather than vertically). This water was probably less alkaline and less reducing than the surrounding groundwater. Degens (1965) suggests that connate waters containing silica in solution will gradually equilibrate with quartz and the excess of silica may crystallize as microcrystalline aggregates in the pores of the rock. Thus it is suggested that for the Colestin Formation, aggressive, vertically moving groundwater occasionally equilibrated with silica in fairly high pH environments where silica is relatively soluble, but upon encountering less alkaline water in highly permeable (possibly less tuffaceous) zones the groundwater became supersaturated and silica precipitated.

Corrensite

Corrensite from the Colestin Formation has formed both as a chemical precipitate in the pores of volcaniclastic rocks and as an alteration of chlorite. Indirect evidence also suggests this mineral formed from possible detrital montmorillonite in the Colestin Formation.

Grim, Droste and Bradley (1960) suggest detrital montmorillonite as the ultimate source of Mg for the corrensite from a Permian evaporite section. Lippman (1956) suggested detrital chlorite for the source of corrensite in his description of Triassic sediments and Peterson (1962) presents evidence of corrensite crystallization from highly saline seawater.

In their study of corrensite, Bradley and Weaver (1956) state, "It may be assumed that this well-defined complex originally must have been a chlorite, and that it has resulted from replacement of alternate charged 'brucite' layers by water and exchange bases," whereas Grim and others (1960) state that:

> "... observed subaerial alteration of chlorite to vermiculite indicates the relatively more acid (or less basic) character of vermiculite with respect to chlorite.
>
> Heterogeneous equilibrium at moderate pH in the liquid phase apparently requires the presence of both chlorite and vermiculite in the solid. In view of the success of the important Pauling principle that a complex solid structure tends to become electrostatically neutral in the smallest practical volume, it seems only natural its extension to neutrality in the acid-base sense is equally valid. For the articulated layer structures, best economy of space is achieved by regularly alternating intergrowth of the two species of layers."

Harvey and Beck (1950) found hornblende altered to corrensite in a hydrothermally altered andesite. Penninite is an intermediate stage.

Apparently corrensite is associated with chlorite, suggesting the two form under nearly the same environmental conditions. Corrensite from the Colestin Formation indicates, however, that chlorite is not necessarily an intermediate step in the formation of corrensite. It is unlikely that euhedral crystals of corrensite embedded in heulandite cement could ever have been chlorite.

Vivaldi and MacEwan (1960) have suggested the following reaction for the removal of hydroxide layers from chlorite:

$$2H^{+} + Mg(OH)_2 \text{-----} \quad Mg^{++} + 2H_2O$$

This reaction could only occur in an environment which was less acid than the environment in which the original chlorite formed.

This is supported in the Colestin Formation by supposedly higher pH values needed for the formation of heulandite relative to chlorite. Here heulandite and corrensite are found together suggesting the pH remained high or slightly increased from the time of formation of chlorite. Although no completely satisfactory explanation for the formation of corrensite has been discovered as yet, it appears that the relative concentration of Mg at a critical pH may be the vital factor in determining whether chlorite or corrensite will form.

<u>Heulandite-Clinoptilolite</u>

It is well established that zeolites generally form in alkaline environments (Deffeyes, 1959). Zeolites of various types have been found in normal marine waters with a pH of 7.5 to 8.1 and in alkali lakes in which the pH may reach 9.9 (Hay, 1966). Heulandite is rarely found in alkali lakes where the activity of Ca is extremely low, but is apparently one of the commonest low temperature zeolite alterations of silicic glass in sedimentary rocks of environments less saline than alkali lakes, and probably less alkaline than pH of 9.1 (Hay, 1964).

The pH exerts a strong control on the silica content of zeolites. Hay (1964) found that the silica activity was highest where the pH was lowest. If this is the case, and assuming other factors to be constant, clinoptilolite would be favored by lower pH values than heulandite.

The environment in which clinoptilolite forms is silica-rich according to Reynolds (1970). In the Colestin Formation it is found in ash-flow tuffs which contain quartz phenocrysts and in sediments in which quartz is present as an older cement. On the other hand, in the Colestin Formation, heulandite is not consistently associated with quartz.

Carbonates

The precipitation of carbonates require an alkaline environment, preferably one with pH at or above about 7.8 (Krumbein and Garrels, 1952). The conditions of formation of calcite in preference to heulandite have already been discussed, but essentially require a higher activity of CO_2 to H_2O.

AUTHIGENIC MINERALS VERSUS DEPOSITIONAL ENVIRONMENT

Table 29 depicts the number of occurrences of the major authigenic minerals with respect to the depositional environment in which the resultant rock is believed to have been deposited. It is immediately apparent that texture and rock type are intimately related to the depositional environment.

In the Colestin rocks channel lag and fill sediments are coarse grained sandstone and conglomerates containing relatively small amounts of matrix, and were probably extremely porous rocks before cementation. In these deposits the depositional environment was such that detrital fine-grained sediments were rarely deposited. The apparently frequent occurrence of montmorillonite is mostly the result of alteration of lithic fragments to montmorillonite. Quartz in the channel lag and fill deposits supports the suggestion that these sediments were highly permeable and allowed fresh groundwater to keep alkalinity low and favorable for the precipitation of quartz.

The sediments grouped in the less specific fluvial category are mostly fine-grained and were apparently once tuffaceous. They are believed to be flood plain deposits in which detrital clays should have accumulated. Data from Table 29 suggests detrital montmorillonite has partially altered to chlorite and corrensite in these sediments.

Table 29. Comparison of depositional environments with authigenic minerals and montmorillonite found in the Colestin Formation.

Environment	No. of deposits studied	No. of occurrences of selected min. Co.	Mo.	Ch. & Ch/K	Qtz	Zeol.
Channel lag and fill	10	3	9	8	8	4
Fluviatile	6	3	4	2	2	3
Channel bar?	5	4	0	5	0	0
Lacustrine	6	0	5	2	?	0
Graded Slurry	10	6	5	9	1	6
Non-graded Slurry	9	7	4	8	0	6

Co. = Corrensite
Mo. = Montmorillonite
Ch. = Chlorite
Ch/K = Chlorite-kaolinite group mineral undifferentiated
Qtz = Quartz
Zeol. = Zeolite

Channel bar? deposits have less lithics than the slurry deposits and are the best sorted sediments in the Colestin Formation. The porosity of channel bar? deposits was probably fairly high. These deposits are well sorted and generally contain more feldspars than sediments in the upper and lower member. It is reasonable to believe that the channel bar? sediments should contain about the same authigenic mineral assemblage as the lag and fill deposits. Data from Table 29 shows a fair similarity except in the montmorillonite content and in the quartz content. The lack of montmorillonite is expected since lithic fragments containing montmorillonite are subordinate to feldspar in the channel bars?. The authigenic quartz content of these sediments was not determined but should be high.

The slurry deposits are poorly sorted and, especially in the non-graded types, have a high content of both matrix and cement. Table 29 indicates that corrensite and chlorite and kaolinite group/ chlorite undifferentiated predominate in these sediments. Zeolites also are more common.

It is believed that the highly labile nature of the pyroclastic debris and mafic minerals in the slurry deposits led to the eventual formation of highly alkaline groundwater. These sediments, being more permeable than the lacustrine and fine-grained fluvial sediments, but less permeable than the channel lag and fill and bar? deposits tended to form and retain highly alkaline groundwater and to precipitate corrensite, chlorite, and zeolites.

The channel lag and fill, and bar? deposits are more permeable than the slurry deposits and contain less pyroclastics and mafic minerals (because of sorting and reworking). The former deposits, because of their relatively good permeability, were probably recharged more often with less alkaline groundwater than were the slurry deposits.

The lacustrine sediments are fine-grained and impermeable. Lacustrine deposits have probably undergone the least diagenesis due to their relative impermeability (Triplehorn, 1970). Thus the montmorillonite content of lacustrine sediments should be high and the corrensite, heulandite, and chlorite content low. This is borne out by the evidence in Table 29.

In one lacustrine sample the depositional environment evidently played an important role in the type authigenic minerals formed.

Unit 24 is an extensive ash-fall which came to rest directly in a large lake. It is the only example in this formation in which the evidence suggests the depositional environment was directly responsible for the authigenic minerals. The primary basis for assuming the depositional environment was the controlling factor is that the authigenic mineral assemblage is completely unlike the remaining authigenic mineral assemblages found in the Colestin Formation. The ash-fall forming this deposit was apparently intermediate in composition, yet Mg and Fe bearing authigenic minerals are rare suggesting extreme leaching of these cations from the ash-fall material. As burial and compaction of this deposit occurred, the permeability surely decreased, and it seems probable that more leaching occurred in the depositional environment than in the post-depositional environment.

Fragments of diatoms in this sediment suggests the water was rich in silica. Authigenic kaolinite group minerals and quartz with minor chlorite and mica suggest a slightly acid, leaching environment typical of fresh water lakes but atypical of the post-depositional environment postulated for the Colestin Formation.

The authigenic minerals found in unit 24 are not typical of those found in the majority of fine-grained sediments in the Colestin Formation. This is probably due to the fact that unit 24 is a result of a primary ash fall which was quickly altered in the depositional environment.

Triplehorn (1970) found that the low permeability of claystones apparently make them less susceptible to clay mineral diagenesis than sandstones. He concluded that in the study of provenance and depositional environments it would be most logical to emphasize the study of clay shales. The clay mineralogy of the claystones in the Hornbrook and Colestin Formations should reflect the source rocks and depositional environment to a greater degree than clays found in the coarser grained sediments. This conclusion is supported by the fact that authigenic corrensite is found in many of the sandstones and conglomerates but is almost completely absent from fine-grained rocks of similar composition. Thus most of the typical claystones in the Colestin Formation apparently have undergone little diagenesis and reflect detrital material brought in from the source area.

Table 30 represents 16 claystone and siltstone samples investigated during the course of this study. The location of the samples collected in Oregon are shown in Figure 7. Locations of three samples collected in California are not shown on the map but a written description of their location is provided.

Table 30. Age, depositional environment and clay mineralogy of 17 claystones and siltstones from the Colestin and Hornbrook Formations.

Sample	Age	Environment	Clay Minerals
105	Cretaceous	M?	Mont., Mica, Kaolinite group min.
154	Cretaceous	N	Mont.
168	Cretaceous	M	Mica, Chlor.
248	Eocene	F	Mont., Kaolin./Chlor.
248	Eocene	F	Mont., Kaolin./Chlor.
245	Eocene	F	Mont., Kaolin./Chlor.
225	Eocene	F	Mont., Kaolin./Chlor.
204	Eocene	F	Mont., Kaolin./Chlor.
115	Eocene	F	Verm., Chlor.
106	Eocene	F	Corrensite
125	Eocene	L	Mont., Mica, Kaolin./Chlor.
160	Eocene	L	Mont.-Mica
162	Eocene	L	Mont., Mica, Kaolin.
163	Eocene	L	Mont., Mica, Kaolin.
265	Eocene	L	Mont.
178	Eocene	L	Mica, Chlor., Kaolin.

N = Non-marine
M = Marine
F = Fluvial
L = Lacustrine

Mont. = Montmorillonite
Chlor. = Chlorite
Verm. = Vermiculite
Mont.-Mica = Regularly interstratified mont. and mica.
Kaolin./Chlor. = Kaolinite group mineral/ chlorite undifferentiated.

The claystones collected from the Cretaceous rocks by this author are apparently not representative of the Hornbrook Formation as a whole. Elliott (Unpublished Ph. D. thesis, 1970, Oregon State University) reports that the dominant clay in the Hornbrook Formation is a regularly interstratified mixed-layer mica-vermiculite. Lesser

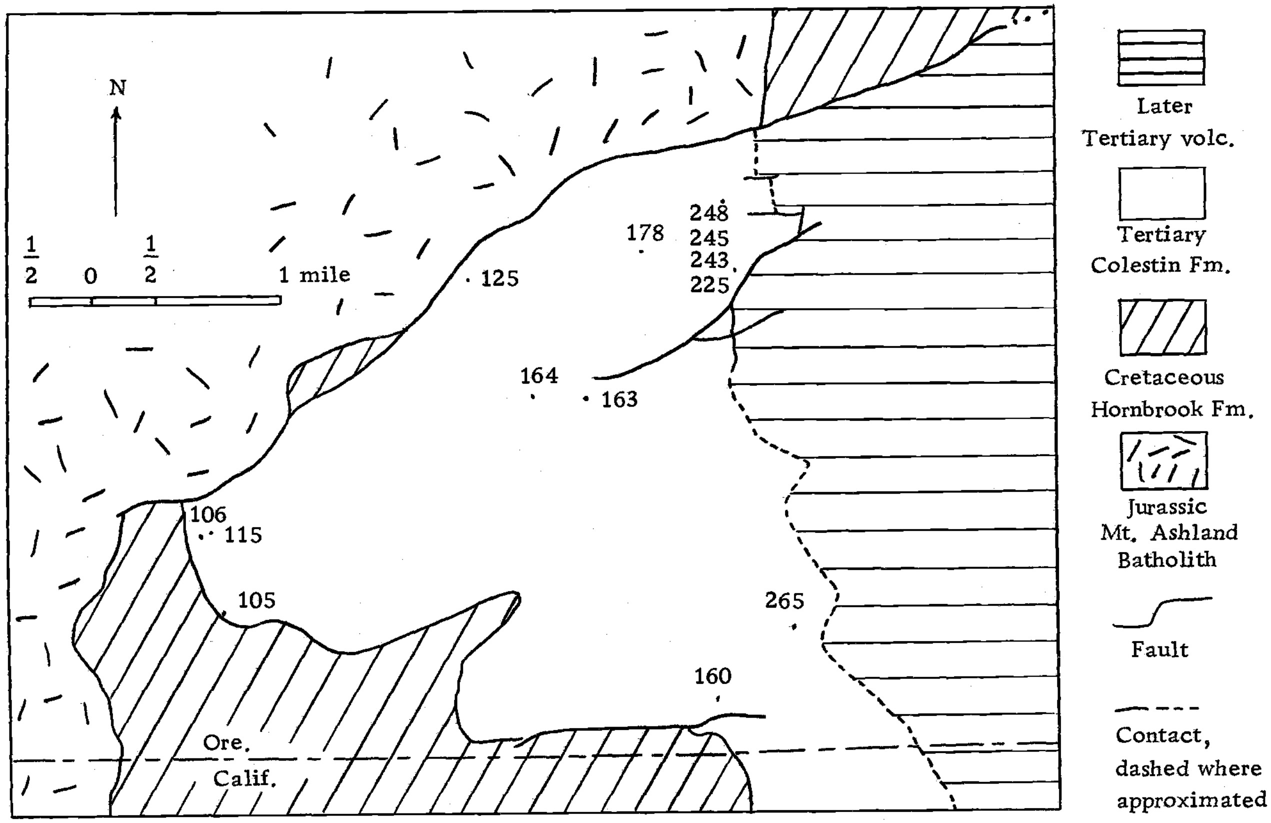


Figure 7. Sample locations of 17 claystones and siltstones from the Colestin and Hornbrook Formations.

<u>Location of samples in California:</u>

168 - North flank of Black Mt. Age - Cretaceous

154 - Shelton Creek measured section. Age - Cretaceous (non-marine)

204 - Klamath River measured section. Colestin Fm. claystone.

amounts of mica, vermiculite, chlorite and kaolinite are also reported. He does not mention montmorillonite which is found in two of the three Hornbrook samples studied in this thesis.

If one accepts Elliott's clay data as representative of the Hornbrook Formation there is a significant difference in the clay mineralogy of the two formations. The Colestin Formation claystones are composed mainly of montmorillonite whereas the Hornbrook Formation contains mostly mica-vermiculite mixed layer clay.

The source rock for the Hornbrook Formation is different from the source rock for the Colestin Formation. The Hornbrook Formation is derived primarily from acid plutonic rocks and a variety of metamorphic rocks while the Colestin Formation is derived mainly from intermediate pyroclastics and lavas. The depositional environment for the two formations is also different. The Hornbrook was deposited predominately in a near shore marine environment while the Colestin clays were deposited in fluvial and lacustrine environments. The importance of the depositional environment (marine versus nonmarine) between the Colestin and Hornbrook Formations is difficult to evaluate because of the difficulty in distinguishing detrital from authigenic constituents in fine-grained rocks. The major factor controlling the difference in the authigenic mineral assemblages of these two formations is the contrast in the composition of the host rocks.

BURIAL AND MINERAL ZONATION OF THE COLESTIN FORMATION

On the basis of Coombs' (1954) classic study of the alteration of deeply buried Triassic marine volcanic graywackes in southern New Zealand, Fyfe, Turner, and Verhoogen (1958) proposed a zeolitic facies for the lower 10,000 feet of altered sediments described by Coombs. Fyfe and others (1958) agree with Coombs' arbitrary line between diagenesis and metamorphism (upper limit of zeolitic facies is where albitization of plagioclase becomes extensive and the principal zeolite is laumontite). Later Coombs and others (1959) redefined the zeolite facies by subdividing it into a lower grade (heulandite-analcime-quartz) assemblage and a higher grade (laumontite-albite-quartz) assemblage which typically occurs in tuffs and volcanic graywackes. They also recognized a broad non-zeolitic transition stage separating the zeolitic rocks from the greenschist facies characterized by quartz-prehnite and quartz-pumpellyite assemblages.

In defining the zeolitic facies Turner (in Fyfe, Turner and Verhoogen, 1958) succinctly describes the metamorphic reactions and resulting mineral assemblages:

> The sequence of reaction in time as indicated by the downward sequence of mineral assemblages in place, is as follows:
>
> (1) Crystallization of glass to heulandite
> Reaction between glass and trapped sea water to give analcite
> Incipient albitization of plagioclase

These reactions took place independently and are classed as diagenetic rather than metamorphic. Water originally present in glass and connate water were now stored in great quantity in zeolitized glass.

(2) Extensive albitization of plagioclase, with release of CaO and Al_2O_3
Replacement of analcite by quartz-albite (in some cases pseudomorphs)
Replacement of heulandite, and in places analcite, by laumontite
Replacement of laumontite by quartz-albite-pumpellyite and quartz-adularia-pumpellyite
Complete destruction of calcium-bearing plagioclase.

These are localized but interdependent reactions. Lime and alumina, set free in one place by albitization of plagioclase, assisted elsewhere in replacement of heulandite and analcite by laumontite. Albitization of plagioclase was made possible by access of sodium set free elsewhere by destruction of analcite. ... The characteristic mineral assemblages of the zeolitic facies-products of stage (2) in the above sequence are as follows: Laumontite-albite-quartz(-sphene-celadonite); Quartz-albite-adularia-pumpellyite... Presence of laumontite instead of clinozoisite distinguished these assemblages from those of similar chemical composition in the greenschist facies. Upward transition to the zone of diagenesis is marked by prevalence of heulandite, rather than laumontite.

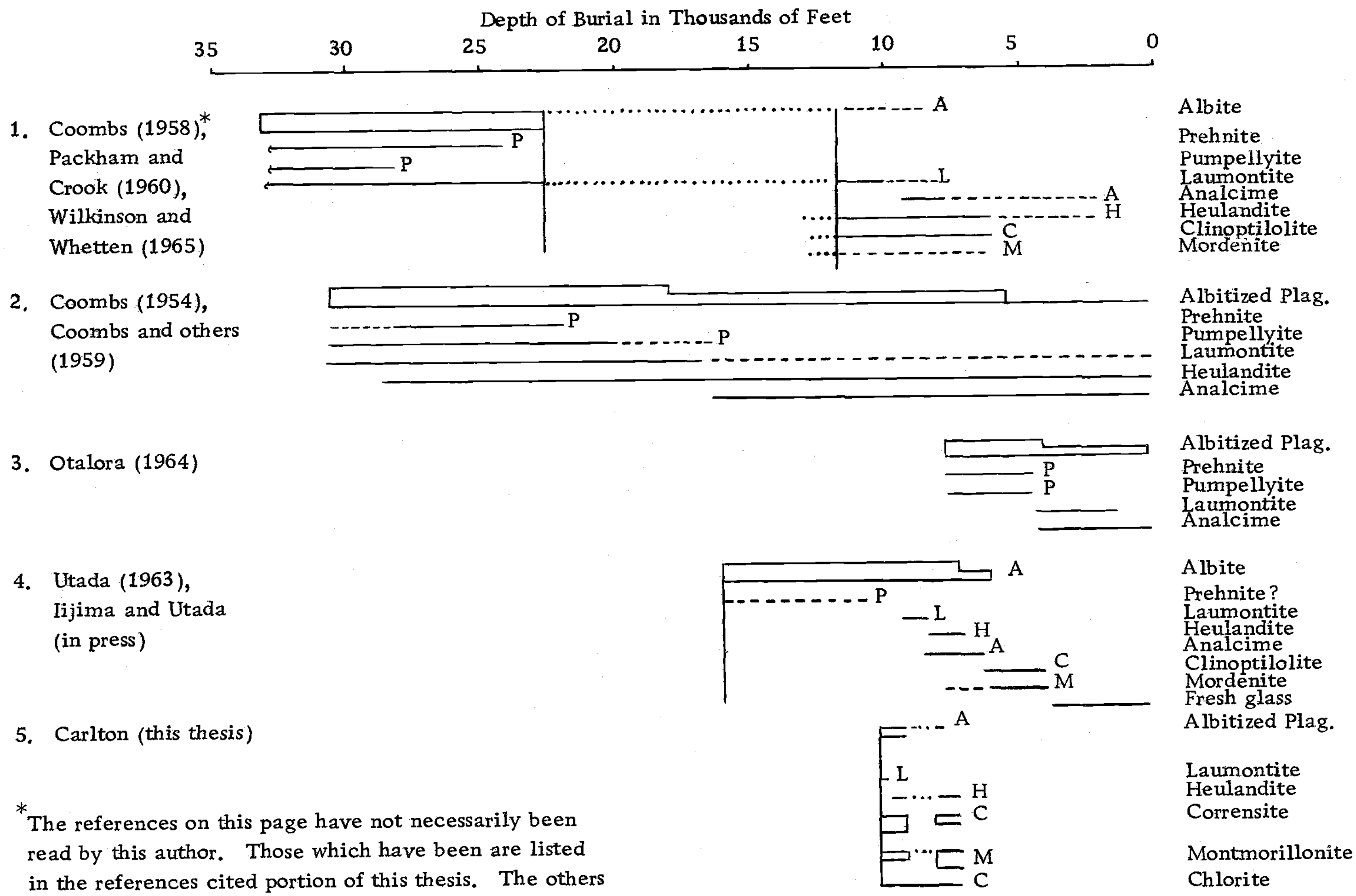
The sediments on which the zeolite facies was established are remarkably similar to those found in the Colestin Formation, that is, primarily andesitic volcanic sands containing much glass. However, two important differences between the Colestin Formation and the sediments described by Coombs exist. The Colestin Formation is nonmarine whereas the Tarangartura sediments are marine. Furthermore the sedimentary sequence described by Coombs is 28,000 feet thick and may have had at one time 10,000 feet of overburden. The Colestin Formation on the other hand only 3000 feet thick had at maximum 10,000 feet of overburden. The lowest unit within the Colestin Formation could not extend below 13,000 feet, while the New Zealand sediments may have extended to 38,000 feet at one time. Table 31 summarizes and compares the reactions which took place during diagenesis of these two sedimentary sequences.

The Colestin Formation at the type section is characterized by heulandite-clinoptilolite, chlorite, corrensite, montmorillonite and quartz. The heulandite and non-albitized plagioclase suggests most of the Colestin Formation belongs to the lower grade zeolite facies of Coombs (1954). The presence of albitized plagioclase in the lower member of the Colestin Formation and the presence of laumontite, new albite and quartz and the absence of heulandite in the lowest unit of the Colestin Formation indicate that the basal portion of this formation is nearly if not completely within the higher grade zeolitic facies as defined by Coombs. Table 32 shows a compilation by Hay (1966) of various mineral assemblages and their depth of occurrence found by various investigators. The Colestin Formation is given for the sake of comparison.

Table 31. Comparison of the diagenetic reactions which took place in the Colestin Formation with those occurring in Coombs' Tarangartura sediments.

Tarangartura sediments	Colestin Formation
Crystallization of glass to heulandite	Crystallization of glass to heulandite
Reaction between glass and trapped sea water to give analcite	Na activity probably not high enough to ppt. analcite
Incipient albitization of plagioclase	Incipient albitization of plagioclase
Extensive albitization of plagioclase with release of CaO and Al_2O_3	Moderate albitization with release of CaO and Al_2O_3
Replacement of analcite by quartz-albite	No activity reaches point where albite precipitates. Quartz precipitates but is rare.
Replacement of heulandite and in places analcite by laumontite.	Laumontite cement observed and possible replacement by laumontite of plagioclase.
Replacement of laumontite by quartz-albite-pumpellyite and quartz-adularia-pumpellyite	Not observed
Complete destruction of Ca-plagioclase	Not observed

Table 32. Vertical zonations of diagenetic minerals in sedimentary rocks compared with the vertical sequence of diagenetic minerals in the Colestin Formation. Modified from Hay, 1966.



*The references on this page have not necessarily been read by this author. Those which have been are listed in the references cited portion of this thesis. The others may be found in Hay (1966).

MODE OF OCCURRENCE OF CORRENSITE

Corrensite has not previously been reported, as far as this writer knows, in volcaniclastic sediments. Indeed phyllosilicates in general have received little attention in mineral zonation studies. Unfortunately the Colestin Formation sediments are not thick enough nor were they buried deeply enough for a regular sequential change of phyllosilicates to occur with temperature and pressure. Moreover the more common phyllosilicates such as montmorillonite, vermiculite, chlorite, and kaolinite apparently hold little promise as temperature-pressure indicators since they occur over such wide ranges of conditions. On the other hand corrensite like heulandite is rarely if ever found forming at the earth's surface. The apparent increase in corrensite with depth (Table 32) suggests, as does Harvey and Beck's investigation, that this mineral might be a useful temperature-pressure indicator when found in thick volcaniclastic sequences which have been buried to moderate depths.

Corrensite has been described in the literature a number of times. Table 33 lists most of the more important occurrences of this mineral and also includes several occurrences of regularly interstratified chlorite-montmorillonite.

It is apparent from Table 33 that corrensite has most commonly formed in highly saline, Mg rich environments. Other occurrences

Table 33. List of investigators and occurrences of corrensite.

Lippman (1954)	Middle Keuper of southern Germany. Marls show evidence of disiccation. Mineral - Swelling chlorite
Early and others (1956)	Yates Formation. Permian of West Texas. Chlorite-montmorillonite occurs as cement in argillaceous siltstone. Associated minerals include quartz, clay, feldspar, dolomite and mica.
Bradley and Weaver (1956)	Brazer Limestone. Upper Mississippian of Colorado. Corrensite occurs as insoluble residue in limestone. Quartz abundant.
Lippman (1956)	Rot member of the Trassic, near Gottingen, Germany. Corrensite sample comes from non-marine unit of mostly shale with some sandstone and siltstones. Lenticular beds of gypsum are present and indicates deposition in continental salt lake or salt flat environment. Associated minerals: Chlorite, illite, quartz, hematite, dolomite, calcite. Detrital chlorite altering to corrensite.
Harvey and Beck (1960)	Goldfield, Navada. Corrensite occurs as alteration product of hornblende in hydrothermally altered andesite. It is found in zone of least alteration. Penninite is an intermediate stage. Increased intensity of alteration results in disappearance of corrensite and development of montmorillonite.
Heystek (1956)	Chlorite-vermiculite occurs in south African shale.
Grim and others (1960)	Salado Formation, Permian of Carlsbad, New Mexico. Chlorite-vermiculite occurs as thin partings in potash ore beds (evaporites). Associated minerals: Halite, polyhalite, sylvite, magnesite, dolomite, carnallite. Environment since Permian has been high in Na, K and Mg activity.
Braitsch* (1960)	Stasfurtsalz, Permian, Reyershausen, Germany, Evaporite section.
Peterson (1961, 1962)	Upper Mississippian carbonate rocks, from Cumberland Plateau in Tennessee. Associated minerals: dolomite, chlorite-vermiculite, montmorillonite with mixed 10 A layers. Corrensite formed in saline marine depositional environment or shortly thereafter. Salinity caused by evaporative concentration of normal marine water.
Echle* (1961)	Keuper near Gottingen, Germany, dolomitic red bed sequence.
Flemal (1970)	Sespe Formation, a mid-Tertiary, non-marine red bed unit which crops out near Los Angeles, California. The corrensite occurs only in gypsiferous strata or in strata associated with gypsum-bearing beds. Usually associated with minor amounts of illite and chlorite.

* The original papers by Breitsch (1960) and Echle (1961) were not read by this writer but were taken from a list compiled by M. N. A. Peterson, 1961.

indicate it is apparently stable under normal marine conditions assuming the mineral formed in the depositional environment.

Keller (1964) concludes after a review of the occurrences of corrensite that an adequate chemical energy (activity) of Fe and Mg accompanied by adequately large amounts of those elements is probably the key to the authigenic formation of such minerals as chlorite, corrensite, and vermiculite.

Harvey and Beck's discovery of hydrothermally formed corrensite in andesites strongly suggests that corrensite is stable at temperatures higher than those normally found in sedimentary depositional environments, but alternatively has an upper temperature limit at which it alters to montmorillonite.

It is the opinion of this writer that the lack of reported occurrences of corrensite in unmetamorphosed andesitic volcaniclastic sequences may be due to problems involving identification of the phyllosilicates relative to other silicate phases rather than to the actual absense of the mineral in these rocks. In the light of the ubiquity of corrensite in the Colestin Formation it is felt by this writer that more precise studies of the clay minerals of coarse grained andesitic volcaniclastic rocks might show that corrensite is a more common mineral than previously thought.

SUMMARY

The Colestin Formation in the vicinity of the type area near Colestin Springs is informally divided into three members and consists of a minimum of 3030 feet of volcaniclastics and lavas. Southeast of the type area the Colestin Formation thins rapidly and in California forms a narrow, linear, discontinuous outcrop belt which pinches out in the vicinity of Black Mountain.

In the type area the lower member consists of 2124 feet of volcanic lithic arenites, conglomerates, breccias and ash-flow tuffs, and intermediate to basic lavas. The middle member contains mudstones, sandstones, intermediate to basic lavas and pyroclastic breccia. Because of poor exposures and complex faulting only 307 feet of strata were measured in the middle member. The measured portion of the middle member contains better sorted sandstones than the lower member which in general contains more feldspar grains and fewer volcanic lithics. The measured portion of the middle member includes a thick sequence of poorly exposed fossiliferous, reworked tuff of lacustrine origin. Poorly exposed, brown mudstones and highly weathered pebbly sandstones and siltstones make up most of the unmeasured portion of the middle member. Quartzite pebbles are common in most of the coarse sediments of the middle member and are found as float in many areas.

The upper member consists of 534 feet of siltstones, volcanic lithic sandstones, breccia and conglomerate and a single ash-flow unit. Pebbly volcanic lithic sandstone and bredcia are by far the most abundant rock types in the upper member. The ash-flow tuff present near the upper contact of the Colestin Formation varies from about 2 to 24 feet thick throughout most of the type area and can be used as a marker horizon.

The rock types found southeast of the type area in Oregon include ash-flow tuffs very similar and probably correlative to ash-flow tuffs in the lower member in the type area. Sedimentary rocks range from volcanic lithic arenites and plagioclase-rich, lithic poor sandstones similar to those found in the middle member sediments to lahars.

In California the Colestin Formation sediments are poorly sorted volcanic lithic arenites, epiclastic breccias and conglomerates. In places south of the Oregon border the Colestin Formation pinches out completely and Roxy Formation lavas directly overlie the Hornbrook Formation.

The late Eocene time of southwest Oregon was characterized by a subtropical to tropical cimate and vegetation. The depositional record during this time indicates that volcanism was occurring within and around the present site of Colestin Springs. Evidence suggests that the Colestin Formation within the thesis area is a non-marine, fluvial sequence of mostly volcaniclastic rocks deposited on a gently sloping flood plain which was occasionally devastated by lavas and ash-flows from nearby volcanism, but more often by slurry floods, and lahars. At other times the sediments of the Colestin Formation indicate streams and lakes existed along which dense vegetation probably grew. As volcanism increased, the Colestin sediments were finally covered by a thick sequence of lavas, flow breccia, and tuffs of the Roxy Formation.

Most of the Colestin Formation sediments are derived from an andesitic to basaltic source. Much of this volcanic material was probably pyroclastic debris which fell in the highlands surrounding the Colestin basin and was swept down after heavy rains. Supracrustal quartzite provenances and Cretaceous sandstones occasionally contributed significant amounts of detritus to the Colestin basin. Other rock types such as acid intrusives are very rare.

The Colestin Formation sediments have been moderately to highly altered since deposition in the late Eocene. The authigenic minerals of the Colestin Formation have formed in the depositional or post-depositional environment and include corrensite, chlorite, montmorillonite, mica, vermiculite, a kaolinite group mineral, heulandite, clinoptilolite, laumontite, opal, quartz, calcite, pyrite and albite.

Heulandite, clinoptilolite, montmorillonite, chlorite, and kaolinite group minerals have been identified replacing pyroclastic material but zeolites are by far the most common replacement of shards and pumice.

In the sediments detrital plagioclase ranges from completely fresh to clay mineral pseudomorphs and albitized grains. The most common minerals replacing plagioclase are albite, zeolites, clay minerals, carbonate and an unidentified substance. Albitization increases with increased depth in the Colestin Formation and commonly replaces 50 to 85% of individual plagioclase grains in the lower member. In the upper and middle member albitization is rare to completely absent.

Orthopyroxene was not discovered in any of the Colestin sediments and clinopyroxene, which is rare, varies from fresh to complete clay mineral or clay mineral-calcite pseudomorphs. The most common alteration product of pyroxene is a highly birefringent saponite-like mineral. Hornblende is found in the lavas and in some of the ash-flow tuffs but never in the epiclastic rocks of the Colestin Formation. The alteration product is usually a highly birefringent yellow montmorillonite. Lithic fragments, generally the most common component of the coarse Colestin clastics are usually fine-grained intermediate volcanic types. The mafics and glass portion of the lithics are generally altered to phyllosilicates leaving only the feldspars fresh or only slightly altered. The alteration of the mafic minerals and pyroclastic glass originally occurring in the Colestin Formation have undoubtedly greatly influenced the chemical environment of the Colestin Formation during diagenesis.

Heulandite is abundant in the upper and lower members of the Colestin Formation at the type locality but is rare or absent in middle member sediments and in the Shelton Creek and Klamath River measured sections. Most of the heulandite from the Colestin Formation when heated to 450 C either transforms to heulandite-B or becomes amorphous, but in several instances the heulandite when heated forms an unidentified phase. Clinoptilolite is essentially a "silica rich" heulandite, and the greater thermal stability of clinoptilolite over heulandite has been attributed by some investigators to be due to the additional structural silica in clinoptilolite. This suggests the different phases found in heulandite may also be due to variations in the amount of silica in different heulandites. Zoned heulandite from the Colestin Formation has rims with higher refractive indices than the cores whereas Hay (1962) found the opposite.

In two units refractive index determinations suggest both clinoptilolite and heulandite are present. The x-ray diffraction patterns in both units, although not precisely characteristic of either heulandite or clinoptilolite, seem to support the optical data and suggest both heulandite and clinoptilolite are present.

A third explanation indicates that Ca-rich clinoptilolite could account for the x-ray diffraction patterns found for the zeolite(s) in these two units.

The clay minerals of 86 samples taken from the Colestin and Hornbrook Formations were studied in detail. Corrensite was identified in 38 of the samples. Coarse, well crystallized corrensite ranges from dark green to bright golden yellow, and generally possesses strong to weak pleochroism. Fairly reliable optical data on one specimen indicated a high 0.054 birefringence, a negative optic sign, the cleavage traces parallel to the faster ray and the principal indices to be Alpha = 1.575, Beta = 1.625 and Gamma = 1.629. Corrensite appears to have crystallized directly from solution, by recrystallization of detrital matrix, and as an alteration product of chlorite and of mafic minerals within clastic lithic fragments.

Montmorillonite is a common mineral in the Colestin Formation but it is generally impossible to determine whether it is authigenic or detrital in the sedimentary rocks. Montmorillonite is the major authigenic mineral identifiable in the lavas, dikes and sills of the Colestin Formation.

Kaolinite group minerals are difficult to impossible to distinguish in the presence of chlorite. Dissolution of chlorite with HCl and heat treatments were attempted but results were only moderately successful.

Chlorite identified by optical and x-ray methods (14 A peak) occurs as epimatrix and phyllosilicate cement in many of the samples studied. An authigenic kaolinite group mineral makes up a large portion of a reworked tuff in the middle member of the Colestin Formation.

Vermiculite was found in two units in the lower member, one a tuff and the other a coarse epiclastic sandstone immediately overlying the tuff. Authigenic mica is found in an ash-flow tuff as clay mineral pseudomorphs after plagioclase? and as fine-grained material diseminated throughout a devitrified groundmass.

Regularly interstratified montmorillonite-mica clay occurs in a claystone of lacustrine origin in Oregon southeast of the type area. Authigenic quartz is present in the Colestin Formation rocks as a fine to coarse mosaic of anhedral grains and occasionally as fibrous chalcedony. A few occurrences of opal are found near the base of the type section. Authigenic albite occurs as small tabular crystals projecting inward toward the center of open cavities at the base of the Colestin Formation while anhedral masses of authigenic albite replaces much of the detrital plagioclase throughout the lower member sediments.

Laumontite is found only near the base of the Colestin Formation in the type area and is associated with corrensite, and authigenic albite when observed.

Carbonate minerals are found as cement and occasionally as partial pseudomorphs or small patches replacing plagioclase and pyroxene and as amygdules in lavas, sills and dikes. Sediments in the Klamath River and Shelton Creek measured sections contain most of the authigenic carbonate found in the thesis area. The carbonate appears to have formed in preference to heulandite and clinoptilolite. Authigenic pyrite occurs locally near the bottom of the Klamath River measured section.

Paragenetic sequences have been determined for the authigenic minerals. In general it appears that in the type area chlorite was one of the first authigenic minerals to form followed by crystallization of heulandite and corrensite. In the Colestin sediments in California chlorite followed by crystallization of corrensite and calcite are typical. Quartz when observed has formed later than heulandite and corrensite. Evidence for the time of formation of montmorillonite cannot be found but it is thought that much of the montmorillonite is detrital except for that found in the lavas and ash-flows.

Most of the authigenic mineral assemblages were formed under alkaline, reducing conditions. These conditions were influenced by the rock types in which the authigenic mineral occurred. Corrensite is restricted to sediments and montmorillonite is the primary alteration of the lavas. Since bulk chemical composition was probably similar for the sediments, lavas and ash-flows, the differences in authigenic mineral assemblages is probably due to permeability and mineralogy. In some cases the depositional environment may have influenced the authigenic mineral assemblage as in the large deposits of reworked tuff found in the middle member.

The underlying Cretaceous Hornbrook Formation and the Colestin Formation are very different in mineral and probably chemical composition. The only authigenic mineral which is relatively abundant in both formations is chlorite. Notably lacking in the Hornbrook Formation are zeolites, corrensite and montmorillonite. The absence of zeolites in the Hornbrook Formation may be due to high concentrations of calcium carbonate in the groundwater of the Hornbrook Formation at the time of diagenesis.

Corrensite is found throughout the Colestin Formation and appears to increase in abundance with depth up to the contact with the Hornbrook Formation. Its absence in the Hornbrook Formation is probably due to lower chemical activities of Mg which is a direct result of the less basic character of this formation.

Although no completely satisfactory explanation for the formation of corrensite has been discovered as yet, it appears corrensite forms under nearly the same environmental conditions as chlorite, the only difference being in the concentration of Mg at a critical pH.

Clinoptilolite in the Colestin Formation is associated with quartz which is in accord with the observations of many investigators that this mineral forms in silica-rich rocks.

In the Colestin rocks channel lag and fill sediments are coarse-grained sandstones and conglomerates containing relatively small amounts of matrix. The frequent occurrence of montmorillonite is the result of alteration of lithic fragments. Quartz occurs in these deposits probably because they were highly permeable and allowed fresh, silica-bearing groundwater to keep alkalinity low and favorable for the precipitation of quartz.

The flood plain deposits in which detrital clays were deposited contain montmorillonite partially altered to chlorite and corrensite. Channel bar? deposits contain less montmorillonite because of fewer lithics than in the other types of Colestin sandstones.

Zeolites, corrensite, chlorite and kaolinite group/chlorite minerals predominate in the graded and nongraded slurry flood deposits. The highly labile nature of the pyroclastic debris and mafic minerals in these deposits led to the eventual formation of highly alkaline groundwater, and the crystallization of corrensite, chlorite and zeolites.

The lacustrine sediments are believed to have undergone the least diagenesis due to their relative impermeability. Montmorillonite content is high in these and is probably detrital. In one instance a reworked tuff bearing fossil diatom test contains kaolinite and quartz as the major authigenic minerals. These minerals were probably formed in the depositional environment by leaching one of the more mobile cations.

The Colestin Formation is a minimum of 3030 feet thick and has been buried by at least 7000 feet of lavas and volcaniclastic rocks. Temperatures probably ranged from no less than 30 C to more than 125 C. Most of this formation belongs to the low grade zeolite facies of Coombs (1959). The presence of albitized plagioclase in the lower member and the presence of laumontite, euhedral albite crystals and quartz, and the absence of heulandite indicate that the basal portion of the Colestin Formation is nearly if not completely within the higher grade zeolite facies as defined by Coombs.

Diagenetic reactions which took place in the Colestin Formation in order of increasing depth are:

1. Crystallization of glass to heulandite
2. Incipient albitization of plagioclase
3. Moderate albitization of plagioclase
4. Albitization of plagioclase, formation of new albite and formation of laumontite as cement.

Corrensite has not previously been reported in volcaniclastic sediments. Corrensite increases in amount with depth in the Colestin Formation and may be useful as a temperature-pressure indicator when found in thick volcaniclastic sequences which have been buried to moderate depths.

All of the occurrences of corrensite have so far been associated with highly saline, Mg environments.

It is the opinion of this writer that the lack of reported occurrences of corrensite in unmetamorphosed volcaniclastic sequences may be due to problems involving identification of phyllosilicates compared to other silicate phases rather than to the actual absence of the mineral in these rocks. In the light of the common occurrence of corrensite in the Colestin Formation it is felt that more precise studies of the clay minerals of coarse grained andesitic volcaniclastic rocks might show that corrensite is a more common mineral than previously thought.

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APPENDICES

APPENDIX I

Clay Mineral Identification Procedures

Specimens of mudstone, volcaniclastic sandstone and igneous rock were broken by a mechanical crusher to particles about one centimeter in diameter. These rock chips were then soaked in distilled water overnight or longer. If the chips had not completely disaggregated by this time, which was the case for most of the sandstones and all the igneous rocks, they were gently crushed in distilled water using an iron mortar and pestle. The suspension thus obtained was centrifuged so that only the less than the 2 micron size fraction remained in suspension. This suspension was then divided into two equal parts. One part was Mg-saturated with 1 N $MgCl_2$ solution, and the other K-saturated using 1 N KCl solution. The clays were prepared for x-ray diffraction analysis by smearing the clay paste on petrographic slides (Theisen and Harward, 1962). Separate subsamples of the Mg-saturated clays were solvated with ethylene glycol and in some cases glycerine, and the K-saturated clays were heated to 300°C and 550°C for two hours when necessary. Relative humidity was partially controlled so that all the samples studied were x-rayed either at about six percent relative humidity or somewhere in the range of 40 to 54 percent relative humidity.

The clay mounts were x-rayed on a Norelco x-ray diffractometer using CuK radiation, a 0.006 inch receiving slit and one degree divergent-anti-scatter slits. Runs from 2° 2θ to $14^{\circ}2\theta$ were made at $2^{\circ}2\theta$ per minute on the goniometer and one inch per minute on the strip chart recorder. The KV and MA settings were both 35.

APPENDIX II

Zeolite Identification

Clinoptilolite and heulandite were identified from x-ray diffraction charts for whole rock samples ground to less than 200 mesh. In samples containing a small amount of zeolite, removal of magnetic material with a hand magnet enhanced the zeolite pattern. Oriented clay paste mounts used for clay mineral identification were found to be particularly useful in detecting very small amounts of zeolites. The tabular shape and well developed cleavage both parallel to the (010) face of clinoptilolite and heulandite are aligned just as the phyllosilicates are to well developed (001) cleavage thus giving strong (020) and (001) reflections, respectively. Key zeolite bearing powders were scanned from 6° to $36^{\circ}\theta$ for purposes of identification. The powders were then heated for 14 hours at 450 C and x-rayed again in order to distinguish clinoptilolite from heulandite (Mumpton, 1960).

APPENDIX III

Slab Point Count Procedures

For counting grains three millimeters or greater, one to three rock slabs were cut from specimens containing lithics larger than three millimeters in diameter. The slabs were roughly polished until saw marks were obliterated, and then sprayed with two to three coats of Krylon plastic (a Borden product), in effect giving the rock surface a polished appearance.

Particles three millimeters or larger were counted under a binocular microscope using a transparent sheet of acetate inscribed with a 5 mm grid system taped onto the rock slab. One hand was used to activate the point counter and the other to slowly slide the slab across the field of view of the microscope. The apparent diameter of particles near 3 mm were measured using an inscribed circle 3 mm in diameter. Table 34 describes how the thin section modal and rock slab analysis were combined.

Table 34. An example of a combined thin section and rock slab modal analysis.

On Rock Slab	On Thin Section
1. Matrix = all particles less than 3 mm.	1. Point counted in standard way, except points landing on lithics greater than 3 mm not counted.
2. Only particles greater than 3 mm counted on rock slab.	
Example	
Matrix = 65% Lithics greater than 3 mm = 35%	51% matrix (detrital grains less than 0. 04 mm) 36% lithics (less than 3 mm) 13% other (includes cement, mineral grains, pores)

All points counted in thin section can be considered as part of the "matrix" of the rock slab. The different percentages found in the thin section point count are thus based on 65% of the total rock. In order to obtain percentages of lithics, mineral grains, and "other" the following relationship was used.

$$\frac{51\%}{100\%} = \frac{A}{65\%}$$ where "A" = adjusted percent matrix less than 0. 04 mm.

$$\frac{36\%}{100\%} = \frac{B}{65\%}$$ where "B" = adjusted percent lithics less than 3 mm.

Total lithics found in rock = B + 35% (percent found in rock slab point count).

$$\frac{13\%}{100\%} = \frac{C}{65\%}$$ where "C" = adjusted percent of "other".

APPENDIX IV

Summary Table of Occurrences of Authigenic Minerals

Table 35. Summary of occurrences of authigenic minerals in the Colestin Formation. Identification is by x-ray and optical techniques for selected samples.

S.N.	Co.	M.	Ch.	K/Ch	V.	Mi.	A.Q.	A.A.	Ca.	Z.
270		X					X			H
260	X			X			X			H
259		X	X?							H
258		X		X?						C & H?
257		X	X?							H
246		X								C
247	X		X							H
248		X		X						H
249	X			X						H
250		X	X?							C/H
252	X	X								H
254	X?						X			C & H
255	X?	X							X	C & H
224		X		X			X			H
226		X		X						C/H
227	X	X		X						C/H
228		X		X						H
229		X		X						H
230		X								N. D.
232		X	X							H
233		X	X?							C/H
236		X		X?			X			C/H
237		X					X			C
238	X?	X		X			X			N. D.
239	X	X		X?			X			N. D.
241	X	X	X				X			N. D.
242	X	X	X				X			N. D.
243		X		X						N. D.
245		X	X?						X	H
161		X								N. D.
178			X	X		X?	X			
176			X?			X?				
33		X	X			X			X	

* Montmorillonite, although listed, is not necessarily authigenic.

S.N.	Co.	M.	Ch.	K/Ch	V.	Mi.	A.Q.	A.A.	Ca.	Z.
306		X								N.D.
309		X		X					X	
42	X		X?							N.D.
175	X		X				X?			N.D.
177	X	X							X	L?
310	X									N.D.
60	X			X						N.D.
104		X								N.D.
102	X		X					X		H
100		X				X		X		C/H
95						X	X			N.D.
93		X	X			X?		X?		C/H
92		X	X					X?		C
91	X		X							H
89	X		X							C/H
88	X		X							H
86	X	X								H
85	X	X								H
83	X		X			X				H
82	X		X						X	H
80		X								N.D.
118	X		X							H
115					X					H
112	X				X		X			N.D.
113					X		X			C & H
110	X						X	X		L
108	X	X	X?					X		N.D.
106	X		X?	X						N.D,
214	X			X					X	C/H
211			X						X	N.D.
210									X	C/H.
207	X?						X		X	N.D.
206			X							N.D.
205	X?		X						X	C/H.
204	X?	X		X						N.D.
201	X?		X?				X		X	N.D.
196	X		X?	X			X		X	C/H.
192		X		X						N.D.
191		X		X						N.D.
189			X						X	N.D.
140	X	X	X							N.D.
144	X		X						X	N.D.
147	X		X						X	N.D.

S. N. = Sample Number (see plate I for location)
Co. = Corrensite
M. = Montmorillonite
Ch. = Chlorite
K/Ch = Kaolinite - Chlorite undifferentiated
V. = Vermiculite
Mi. = 10 A mica
A. Q. = Authigenic quartz
A. A. = Authigenic albite
Ca. = Carbonate
Z. = Zeolites
L = Laumontite
H = Heulandite
C = Clinoptilolite
C/H = Clinoptilolite - Heulandite undifferentiated
C&H = Clinoptilolite and heulandite both present
N. D. = None detected (zeolites)

APPENDIX V

Description of Stratigraphic Sections

Partial stratigraphic section (see section A, plate I). Measured with Jacob staff on natural cliff in NW 1/4, sec. 29, T. 40 S., R 2 E.

Unit	Description	Thickness (feet) unit	Thickness (feet) Total
18	Basalt?: eroded remnants of Roxy Formation?		
17	Volcanic pebbly sandstone and sandstone: pale olive (10Y 6/2) on fresh surfaces to moderate yellowish brown (10YR 5/2) on weathered surfaces; upper 65 feet mostly weathered and partially covered; very coarse grained, subangular to subrounded (mostly pebble grade), very poorly sorted, contains some lenses of finer sandstones, lower contact erosional and sharp.	135	135
16	Ash-flow tuff: light olive gray (5Y 6/1), thins towards north, contains base of upright petrified tree which extends upward into overlying unit, dense, highly indurated, contains black mafic mineral, eutaxitic texture (formed by black flattened pumice), texture is mottled, groundmass is fine grained but appears to contain numerous fine grained lithic fragments.	2	137
15	Volcanic pebbly sandstone: yellowish gray (5Y 7/2), medium to coarse grained, poorly sorted, subangular to subrounded (many conspicuously subrounded pebbles), contains weathered pumice.	15	152
14	Ash-flow tuff: yellowish-gray (5Y 8/1), marker bed, ledge forming, contains 2 mm crystals of feldspar and black carbonized wood fragments and minor eutaxitic texture in a fine-grained groundmass, weathers to a block aggregate, lower contact sharp.	3	155

Unit	Description	Thickness (feet) Unit	Total
13	Volcanic sandstone: weathered throughout to a moderate yellowish brown (10YR 5/4), moderately well sorted, medium- to coarse-grained sandstone lenses, subangular.	2	157
12a & 12	Volcanic pebbly sandstone, conglomerate and epiclastic breccia: pale olive (10Y 6/2), very poorly sorted, subangular to subrounded, very thickly bedded, very coarse-grained sandstone grading into pebble conglomerate with very coarse sand matrix; pebbles subrounded to subangular, graded beds in unit (12), pores commonly filled with calcite and zeolite cement, lower contact undulatory and sharp.	43	200
11	Volcanic pebbly sandstone: light olive gray (5Y 6/2), thins toward south, differs from other pebbly sandstone by being very dense and hard, almost appears to be welded tuff at outcrop but thin sections reveal sedimentary nature by the wide variety of lithics and their roundness, contains carbonized wood, is poorly sorted, lower contact sharp and undulatory.	2	202
10	Volcanic pebbly sandstone: weathered surface is pale yellowish orange (10YR 8/6) to fresh light olive gray (5Y 6/1), subangular to subrounded, very poorly sorted, contains some zeolite cement, very coarse grained to fine and medium grained, graded beds, rare well rounded quartzite cobbles present, lower contact erosional and sharp.	15	217
9	Volcanic pebbly sandstone: yellowish gray (5Y 7/2), similar to unit 8, highly indurated, contains carbonized material, mottled luster, eutaxitic texture.	2	219

Unit	Description	Thickness (feet) Unit	Total
8	Volcanic pebbly sandstone: slightly weathered surface is grayish orange (10YR 7/4), poorly sorted, subangular, very coarse grained, grades upward into material with same general description but slightly finer grained on average, both contain zeolite cement, lower contact undulatory, and sharp, carbonized wood present along lower contact.	12	231
7	Ash-flow tuff: medium light gray (N6), dense, welded, fine-grained, porphyritic felsite lithic fragments present, poorly sorted, fine grained, rare black flattened pumice giving rock eutaxitic texture, semi-vitreous luster on fresh surface, pinches out toward north, lower contact undulatory and sharp.	1	232
6	Volcanic pebbly sandstone and conglomerate: yellowish gray (5Y 7/2), very poorly sorted, subangular to subrounded, very coarse grained, may be channel conglomerate locally, characterized by unusually high content of zeolite cement, thins gradually toward north but can be traced at least 0.75 miles, lower contact erosional and sharp with at least two feet relief.	4	236
5	Volcanic pebbly sandstone and breccia: pale olive (10Y 6/2), poorly sorted, subangular to subrounded, beds graded, beds range from 2 to 10 centimeters, lower contact undulatory and sharp, zeolite cement present.	8	244
4	Volcanic pebbly sandstone and sandstone: pale olive (10Y 6/2), poorly to moderately sorted, medium to very coarse grained, subangular to subrounded, this unit made up of many graded beds, a single graded bed usually less than 15 centimeters thick; is one of best examples of a graded unit in the Colestin Formation, can be traced for at least 1-1/2 miles, lower contact sharp and erosional but rarely exposed.	56	310

Unit	Description	Thickness (feet) Unit	Total
3	Volcanic pebbly sandstone: very poorly exposed and highly weathered in outcrop.	25	335
2	Volcanic conglomerate and sandstone: light olive gray (5Y 6/1), poorly sorted, pebbles to cobble conglomerate with some pebbly sandstone, pebble and cobbles vary from subrounded to well rounded, many quartzite pebbles and cobbles present, lower contact undulatory and erosional with only slight relief, this bed can be traced 0.75 miles before disappearing beneath cover, does not vary much in thickness.	5	340
1	Volcanic pebbly sandstone: yellowish gray (5Y 7/2), poorly sorted, subangular to subrounded, coarse to very coarse grained, very thickly bedded, beds are gradational into one another, four foot diameter upright petrified tree present in middle of unit.	23	363

Composite type section (see section B, plate I). This portion measured with Jacob staff along Interstate Highway 5 at Siskiyou Summit. (SE 1/4, sec. 29, T. 40 S., R. 2 E.)

59	Volcanic pebbly sandstone: yellowish gray (5Y 7/2), indurated, forms ledge, very coarse grained, poorly sorted, grains subangular to subrounded but most subangular; beds crudely graded and from 1/2 centimeter to greater than 3 centimeters thick; volcanic pebbles compose about 38 percent of the rock; unit thins rapidly to north; lower contact sharp, planar to undulatory, upper is eroded top of section.	2	2
58	Epiclastic volcanic breccia: grayish yellow green (5GY 7/2), indurated, forms ledge, massive, very coarse grained matrix, poorly sorted, volcanic pebbles subangular to subrounded but most subangular, and make up 65 percent of rock; lower contact erosional (15 feet relief); unit thins rapidly to north.	25	27

Unit	Description	Thickness (feet) Unit	Total
57	Volcanic pebbly sandstone: olive gray (5Y 4/1), indurated, forms ledge, very coarse grained, poorly sorted, grains subangular to subrounded; beds graded, each 1 to 2 centimeters thick; volcanic pebbles compose 25 percent of the rock; lower contact erosional (5 feet relief); this unit absent due to erosion farther south along outcrop.	10	37
56	Tuffaceous volcanic siltstone: within siltstone is thin lens of volcanic sandstone (5Y 5/2), indurated, coarse grained, poorly sorted, massive; contains small pieces of carbonized wood; eutaxitic-like texture developed from flattened pumice; yellow and orange stains on upper and lower contacts with siltstone.	10	47
55	Volcanic conglomerate: massive, subrounded to rounded pebbles and cobbles, pinches out laterally; cut into unit 54; lower contact erosional (8 feet relief), upper contact sharp but gradational over several inches.	6	53
54	Volcanic pebbly sandstone: pale olive (10 6/2), weathers yellowish gray (5Y 7/2), consolidated, massive, very poorly sorted, very coarse grained, contains about 26 percent pebbles, subangular; lower contact planar.	9	62
53	Ash-flow tuff: yellowish gray (5Y 8/1), consolidated used as marker bed; possesses slight eutaxitic texture, abundant carbonized wood and about ten percent phenocrysts averaging 1 millimeter diameter of quartz and plagioclase; lower contact erosional (14 feet relief).	6	68
52	Volcanic pebbly sandstone: greenish gray (5GY 6/1), consolidated, very poorly sorted, subangular to subrounded; silt to very coarse grained; graded beds ranging in thickness from 1 to greater than 6 centimeters; zeolite cement visible; lower contact planar and sharp.	8	76

Unit	Description	Thickness (feet) Unit	Total
51	Volcanic siltstone: olive gray (5Y 4/1), friable to consolidated, massive, lower contact planar and sharp.	3	79
50	Volcanic pebbly sandstone: pale olive (10 Y 6/2), consolidated, very poorly sorted, subangular to subrounded; very coarse grained, graded?, zeolite cement, carbonized wood present, lower contact planar and sharp.	15	94
49	Volcanic siltstone and sandstone: unconsolidated, contains weathered, rounded pebbles up to 1 centimeter diameter; also a thin five inch thick resistant bed near center of unit that is light olive gray (5Y 5/2), very thinly bedded to laminated, moderately sorted, fine-grained sandstone with pebble size inclusions of fine grained dark volcanic lithic fragments; lower contact of unit is planar and sharp.	5	99
48	Volcanic pebbly sandstone: greenish gray (5GY 6/1), consolidated, very poorly sorted, subangular, very coarse grained, approximately 2 to 3 percent pebbles, graded beds present, lower contact planar and sharp.	28	127
47	Tuffaceous(?) volcanic siltstone: contains thin discontinuous bed 4 inches thick of resistant rock which weathers pale yellowish brown (10YR 6/2) to dark yellowish brown (10YR 4/2), on fresh surfaces medium light gray (N 6), almost glassy-like luster, breaks with sharp hackly fracture and is fine-grained, massive; lower contact planar and sharp but gradational over few inches into friable tuffaceous siltstone which makes up remainder of 1-1/2 foot bed.	1.5	128.5

Unit	Description	Thickness (feet) Unit	Total
46	Volcanic pebbly sandstone: less resistant portion of outcrop weathers leaving more resistant knob-like projections several inches in diameter, but not concretionary; knobs are weathered pale yellowish brown (10YR 6/2) but are medium light gray (N6) on fresh surfaces, knobs are poorly sorted, coarse, subangular calcareous sandstone; this unit contains carbonized wood and thin coal seam 1 to 2 inches thick near base; lower contact is undulatory and sharp.	9	137.5
45	Siltstone to volcanic pebbly sandstone: upper two feet of siltstone grade downward into three feet of unconsolidated to slightly consolidated sediments. Siltstone also contains volcanic debris, probably mostly altered tuff which has been reworked. Lower contact planar and sharp.	5	142.5
44	Volcanic pebbly sandstone: light gray (N7), slightly friable, poorly sorted, subangular, coarse grained; contains 25 percent pebbles, massive, quartz cement. Lower contact is planar and sharp.	1	143.5
43	Volcanic siltstone (near top) to volcanic pebbly sandstone (near bottom): olive gray (5Y 4/1) near top to medium gray (N5) near bottom; entire unit is friable, poorly sorted, very coarse grained with subangular to subrounded pebbles; lower contact irregular, erosional and sharp.	15	158.5
42	Volcanic sandstone to pebbly sandstone: greenish gray (5GY 6/1), consolidated, ledge forming, poorly sorted, subangular, medium to very coarse grained, graded beds; outcrop has mottled appearance due to sharp contact between weathered and fresh surfaces; lower contact undulatory (1 foot relief) and sharp.	10	168.5

Unit	Description	Thickness (feet) Unit	Total
41	Reworked? tuff or tuffaceous volcanic siltstone: dusky brown (5YR 2/2), friable, mottled texture; lower contact covered.	10.5	179
40	Volcanic pebbly sandstone: upper portion-grayish yellow green (5GY 7/2), consolidated, poorly sorted, angular to subangular, massive; pumice slightly flattened giving eutaxitic texture; contains volcanic debris; pebble size lithics excluding pumice amount to 30 percent of rock. Lower portion-light greenish gray 5G 8/1) to light olive gray (5Y 6/1), consolidated, poorly sorted angular to subrounded, coarse grained, massive; pebbles amount to 23 percent of rock; locally this unit contains tree stumps in upright position and petrified logs; at base is 5 foot thick bed of moderately sorted, medium-grained volcanic sandstone; lower contact is planar and sharp.	40	219
39	Volcanic siltstone and claystone: color not determined; lower contact planar and sharp.	1	220
38	Volcanic cobble to boulder conglomerate; pale yellowish brown (10YR 6/2), consolidated, subangular to mostly subrounded to rounded, very poorly sorted, very coarse sandstone matrix, largest boulder seen is 1-1/2 feet diameter of porphyritic andesite or basalt; lower contact is undulatory and sharp.	6	226
37	Volcanic pebble conglomerate and epiclastic volcanic breccia: dark yellowish brown (10YR 4/2), consolidated, very poorly sorted, angular to subrounded, mostly subangular; pebbles amount to about 51 percent of rock; massive coarse grained sandstone matrix; lower contact undulating and sharp.	6	232

Unit	Description	Thickness (feet) Unit	Total
36	Volcanic boulder conglomerate and epiclastic volcanic breccia and pebbly sandstone near bottom of unit: lower portion-grayish yellow green (5GY 7/2), slightly friable, poorly sorted, subangular, very coarse grained; whole unit is ledge former and pinches out towards south; lower contact is planar and sharp.	10	242
35	Volcanic pebbly sandstone: light brownish gray (5YR 6/1) to light gray (N7), consolidated, moderately sorted to poorly sorted, subangular, medium to very coarse grained, beds graded, lower contact undulatory and sharp.	20	262
34	Volcanic siltstone to fine sandstone: dark gray.	1	263
33	Volcanic pebbly sandstone: light olive gray (5Y 6/1), consolidated, poorly sorted, subangular, very coarse grained, massive, pinches out to south where channel conglomerate removed it; lower contact sharp and planar.	3.5	266.5
32	Volcanic siltstone (upper part) to volcanic pebbly sandstone (lower part): Upper portion-medium dark gray (N4), friable, moderately sorted, silt size; lower portion-friable, poorly sorted, contains subrounded pebbles some of which are quartzite 1 centimeter diameter, in fine sand matrix; lower contact erosional (5 feet relief).	7.5	274
31	Volcanic pebble to boulder conglomerate: moderate yellowish brown (10YR 5/4), thoroughly weathered, and friable, subrounded to rounded, very poorly sorted, very coarse sand matrix; contains thin lens of volcanic siltstone (pinches out to north); largest boulder seen is 1 foot in diameter; contains rounded quartzite pebbles; this unit thins toward south; lower contact is planar and sharp.	10	284

Unit	Description	Thickness (feet) Unit	Total
30	Tuffaceous volcanic siltstone (possibly reworked tuff): brownish gray (5YR 4/1), friable, poorly sorted, sand size,vitreous, rounded particles may be glass in finer silt size matrix; stained in places with yellow iron oxide; contains 2 inch thick coal seam 10 feet in length at south end of outcrop; lower contact covered.	12	296

Continuation of section. This portion measured in the NW 1/4 sec. 29, T. 40 S., R. 2 E. Measured with tape and compass.

29	Covered area: float indicates volcanic pebbly sandstone and conglomerate; pebbles are volcanic and quartzite (rounded) interbedded with basalt and andesite flows in the lower part. Exposed locally in lower portion of covered zone are lavas with the following description: a. porphyritic basalt?: medium light gray (N6), contains about 4% mafic phenocrysts 2-1/2 mm long and very large (up to 1 cm) plagioclase phenocryst and making up about 45% of the rock. The plagioclase phenocrysts are vitreous with a slight yellowish alteration. The groundmass is fine-grained. Contacts are covered. b. porphyritic basalt?: contains thin laths of feldspar (1 mm long) and mafic phenocryst (2 mm long) totaling 15% of the rock. Mafic phenocrysts may be weathered to brown clay. Medium gray (N5). Contacts covered.	238	534
28a	Basalt?: light brownish gray (5YR 6/1), composed of 25% milk white plagioclase laths up to 3 mm long and about 5% mafics commonly weathered to brown material; the unit, where it fills channel immediately SW of west end of Siskiyou railroad tunnel is 80 feet thick but generally is about 10 feet thick; locally can be used as marker bed; usually poorly exposed, contacts covered.	10	544

Unit	Description	Thickness (feet) Unit	Total
28b	Basalt?: medium gray (N5), porphyritic, 10% phenocrysts of plagioclase and mafic minerals in a dense fine-grained groundmass; contacts covered but unit directly beneath this basalt? is pyroclastics described below. Thickness is variable from 0 to an estimated 50 feet.	10	557
28c	Pyroclastic debris: various types of pyroclastics ranging from coarse breccia composed of many types of volcanic blocks to fine tuff. Poorly exposed.	10	564
	Continuation of section: this portion measured NW 1/4 sec. 29, T. 40 S., R. 2 E. (see plate I) Measurement by Jacob staff.		
27	Volcanic pebbly sandstone: consolidated, poorly sorted, very thickly bedded (excess of 4 feet), subangular, coarse grained; pebbles make up 20 percent of rock; upper and lower contacts covered.	15	579
26	Covered area: float is a light tan very fine tuff or reworked tuff.	270	849
25	Sill: basic igneous rock, diabasic texture, medium gray (N5); phenocrysts of plagioclase 1/2 to 1 mm length, and mafic phenocrysts about 1 mm length; total phenocrysts equal about 15% of rock; baked zone above and below sill at contacts.	11	860
24	Tuff: bluish white (5B 9/1), reworked?, contains rare non-pyroclastic material, indurated, moderately to well sorted, small scale cross bedding, some horizontal laminae contain black carbonaceous matter.	3	863

Unit	Description	Thickness (feet) Unit	Total
23	Volcanic sandstone: yellowish gray (5Y 8/1), consolidated, moderately sorted, subangular, fine to medium grained, contains abundant plagioclase and conspicuous detrital biotite; lower contact planar, baked zone up to about 15 centimeters thick.	8	871
22	Sill: basic igneous rock, identical to unit 25	7	878
21	Volcanic sandstone: light olive gray (5Y 5/2), consolidated, massive, moderately sorted, coarse grained, subangular, plagioclase abundant, rare subrounded volcanic pebbles present; lower contact undulatory and sharp, upper contact has slight baked zone about 1 inch thick.	6	884
20	Volcanic cobble conglomerate: volcanic pebbles and cobbles subrounded, largest is 15 centimeters and andesitic?, this unit contains lenses of medium-grained sandstone up to 12 centimeters thick; no quartzite lithics seen.	12	896
19	Volcanic sandstone: yellowish gray (5Y 7/2), consolidated, moderately to poorly sorted, medium to coarse grained; lower contact covered.	5	901
	Covered area: valley fill and soil covers most of the Colestin Formation from this point to the valley floor.		

Continuation of section: this portion measured NW 1/4 sec. 11, T. 41 S., R. 1 E. on east side of Mill Creek. Unit 18 underlies unit 19 by an unknown thickness of Colestin Formation. Measurement by tape and compass.

Unit	Description	Thickness (feet) Unit	Total
18	Basalt: medium dark gray (N4), slightly porphyritic, phenocrysts are of olivine (10%), some altered to iddingsite; this basalt caps ridge in section 36; lower contact is covered.	135	1036
17	Partially covered area: this thick sequence as interpreted from local outcrops and float is composed of minor interbedded basic or intermediate lava flows, and large amounts of pebbly volcanic sandstones and conglomerates, many containing rounded quartzite pebbles.	1007	2043
16	Lava flows: basic or intermediate, porphyritic to almost non-porphyritic rocks; sample 104 (see plate I) collected near bottom is slightly porphyritic (plagioclase phenocryst), olive gray (5Y 4/1), fine-grained, dense groundmass; lower contact covered.	120	2163
15	Volcanic pebbly sandstone: very light gray to greenish gray (N7 to 5GY 6/1), partially covered by soil but where exposed is very poorly sorted, very coarse grained, subangular to subrounded, pebbles range from 33 to 42 percent of rock; eutaxitic-like texture from compaction of pumice, very steep slope former, lower contact covered.	135	2298
14	Covered area:	71	2369
13	Ash-flow tuff: lithology variable, samples described below. at 657 feet: grayish yellow green (5GY 7/2) to grayish green (10GY 5/2), consolidated, partially welded, massive, porphyritic, poorly sorted, eutaxitic (sample 101). at 650 feet: pale green 5GY 7/2), consolidated, poorly sorted, massive, partly welded, eutaxitic, porphyritic, sample 100.		

Unit	Description	Thickness (feet) Unit	Total
	at 620 feet: grayish yellow green 5GY 7/2, consolidated, poorly sorted, welded, plagioclase phenocrysts (milk white), faint to strong banding varying from purple to white bands running perpendicular to eutaxitic texture. Sample 99.		
	at 597 feet: pale blue (5PB 7/2), to light gray (N7) consolidated, poorly sorted, partly welded?, porphyritic (plagioclase), eutaxitic, sample 98. From 570 to 635 feet the rock weathers in plates one centimeter thick and parallel to depositional surface.		
	at 562 feet: pale red (5R 6/2) consolidated, poorly sorted, porphyritic (plagioclase phenocrysts), deep red bands less than 1/2 mm thick and spaced from 1/2 mm to 1/2 centimeter apart, bands are perpendicular to eutaxitic texture of rock.		
	from 546 to 519 feet: very pale orange (10YR 8/2) consolidated, poorly sorted, porphyritic (plagioclase), partly welded to non-welded?, may be separate ash flow from overlying tuff but more likely non-devitrified zone of same ash-flow.		
	at 503 feet: light gray (N7) to light olive gray (5Y 6/1) consolidated, poorly sorted, porphyritic (plagioclase phenocrysts), slight eutaxitic texture, chert fills some fracture zones, sample 93.		
	at 492 feet: light olive gray (5Y 6/1), consolidated, poorly sorted, porphyritic (plagioclase), sample 92, lower contact covered.	185	2554

Unit	Description	Thickness (feet) Unit	Total
12	Volcanic pebbly sandstone: light gray (N6) to medium dark gray (N4), consolidated, very poorly sorted, massive?, subangular to subrounded, pebbles range from 13 to 41% of the rock; may be very thickly bedded, and has eutaxitic-like texture as certain horizons; shard texture is visible in thin sections suggesting the rock is mostly water-worked pyroclastics; lower contact is undulatory and sharp.	106	2660
11	Ash-flow tuff: medium dark gray (N3), to dusky blue (5PB 3/2), highly indurated, fine grained with a few plagioclase phenocrysts, irregular planes of brown alteration approximately parallel to horizontal giving rock slightly platy character, in outcrop and handsample appears to be flow rock except for carbonized wood.	12	2672
10	Volcanic pebbly sandstone: medium gray (N5), consolidated, thickly? bedded, poorly sorted, subangular, fine grained to very coarse, eutaxitic-like texture present, pebbles make up 33 percent of rock; shard texture visible in thin section; lower contact covered.	11	2683
10a	Covered area:	46	2729
9	Volcanic pebbly sandstone: very light gray (N7), consolidated, very poorly sorted, subangular, coarse grained, lower 8 feet of outcrop is very hard and cemented with calcite and zeolites, knobby proturberances effervesce more vigorously than rest of outcrop; appears to be unsorted, contacts covered.	14	2743
8	Covered area:	67	2810
7	Basalt: dark gray (N3), fresh, porphyritic, phenocrysts mostly plagioclase, groundmass is fine grained and dense.	25	2835

Unit	Description	Thickness (feet) Unit	Total
6	Volcanic pebbly sandstone and breccia: light olive gray (5Y 6/1) to grayish yellow green (5GY 7/2), massive, well exposed ledge former, no bedding or structural features observed, pebbles are locally abundant and are subangular to angular, largest pebbles are of volcanic origin (5 centimeters in diameter) lower contact planar and gradational over a few centimeters.	45	2880
5	Volcanic sandy siltstone: brownish gray (5YR 4/1), moderately to poorly sorted, massive, eutaxitic-like texture; appears to have been tuffaceous at one time but now completely devoid of glass through alteration; lower contact planar and sharp.	15	2895
4	Volcanic pebbly sandstone: light gray (N6), consolidated, composed of a single bed, poorly sorted, subangular, very coarse grained, pebbles make up 29 percent of rock; lower contact planar and sharp.	1	2896
3	Ash-flow tuff: yellowish gray (5Y 7/2) to olive gray (5Y 6/1), consolidated, massive, poorly sorted, porphyritic with plagioclase phenocryst, eutaxitic-like texture; lower contact covered.	37	2932
2	Volcanic pebbly sandstone and breccia: very light gray (N7) to greenish gray (5GY 6/1), consolidated to slightly friable, poorly sorted, angular to subangular, very coarse grained, massive, pebble count in this portion resulted in 100 percent volcanic lithics of variable textures; lower one-half is an epiclastic breccia; lower contact is erosional and sharp.	44	2976

Unit	Description	Thickness (feet) Unit	Total
1	Volcanic siltstone and sandstone to pebbly sandstone: light to medium gray (N5 to N6), consolidated, center of unit is coarser than top and bottom, unit as whole is moderately to poorly sorted, very fine grained to silt size in lower and upper parts which are thin bedded; lower contact is covered but near Cretaceous contact.	54	3030

Minimum thickness of Colestin Formation at type section: 3030 feet.

Partial stratigraphic section (see section C, plate I) measured in the NW 1/4 NW 1/4 sec. 15, T. 41 S., R. 2 E.

Unit	Description	Unit	Total
4	Volcanic pebbly sandstone and sandstone: pale olive (10Y 6/2), medium to very coarse grained, subangular to subrounded, moderately sorted, beds graded.	8	8
3	Covered area: float indicates rock similar to unit 2.	57	65
2	Volcanic pebbly sandstone and sandstone: grayish orange (10YR 7/4) to pale olive 10Y 6/2, coarse to very coarse, subangular to subrounded, pebbles when they occur compose less than 1 percent of rock, moderately sorted, thick to thin bedded, apparently non-graded, lower contact is undulatory and sharp.	31	96
1	Ash-flow tuff: yellowish gray (5Y 7/2), poorly sorted, contains abundant light colored, slightly flattened pumice up to 3 centimeters long and black carbonized wood fragments up to 1 centimeter long in a finer matrix. A few vitreous phenocrysts less than 1 mm are visible.	24	120

Unit	Description	Thickness (feet) Unit	Total
	Shelton Creek stratigraphic section (see section D, plate I). Measured in the C. sec. 8, T. 47 N., R. 6 W., Hornbrook, California quadrangle.		
9	Andesite?: Roxy Formation, olive gray (5Y 4/1), porphyritic, plagioclase phenocryst make up 25 percent of the rock, groundmass is fine grained.	Not measured.	
	Volcanic sandstone: greenish gray (5GY 6/1), weathered, poorly sorted, very coarse grained, subangular, most of labile constituents have altered to greenish clay, fossil petrified tree in growth position present, thick bedded, non-graded, lower contact undulatory and sharp.	12	12
	Siltstone: sandy, appears to have been partly derived from tuffaceous material, lower contact undulatory.	1/2	12-1/2
8	Volcanic pebbly sandstone: greenish gray (5GY 6/1), weathered, poorly sorted, subangular, less than one percent pebbles in a fine sand matrix, thick bedded, lower contact undulatory and sharp.	8	20-1/2
	Siltstone: sandy, appears to have been partly derived from tuffaceous material.	1/2	21
	Volcanic pebbly sandstone and breccia: light olive gray (5Y 6/1), very poorly sorted, fine to very coarse grained, mostly medium grained, pebbles angular to subangular, pebbles constitute 20 percent of rock, some carbonate cement, lower contact covered.		
7	Volcanic sandstone: pale olive (10Y 6/2), moderately sorted, subangular, fine to medium grained, massive, lens shaped, lower contact covered.	3	36

Unit	Description	Thickness (feet) Unit	Total
	Volcanic pebbly sandstone: lenses of moderately to poorly sorted, medium to very coarse grained sandstone present, large carbonized fossil leaf fragments on bedding planes; unit as a whole is pebbly and very thickly bedded, petrified stump in growth position near base of unit, asymmetric ripple marks also present, lower contact covered.	38	74
6	Siltstone: rich with volcanic debris, contains lenses of black silty shale containing leaf fossils, lower contact sharp and planar.	1	75
	Volcanic pebbly sandstone and sandstone: light olive gray (5Y 5/2), poorly to moderately sorted, subangular to subrounded, medium to coarse grained with less than 1 percent pebbles, quartzite pebbles subrounded, unit contains black carbonized wood, lower contact covered.	5	80
5	Volcanic pebbly sandstone: light olive gray (5Y 6/1), poorly sorted, subangular to subrounded, medium to very coarse grained, pebbles mostly subangular and constitute 15 percent of rock, contains some carbonate cement, lower contact covered.	5	85
4 3 2	Igneous rock: intermediate to basic, porphyritic, mafic phenocrysts, rock is highly weathered, friable and separated into two layers by boulder to pebble volcanic conglomerate about 1-1/2 feet thick, very poorly exposed, contacts covered, and may be lava flows or sills.	29	114
1	Volcanic sandstone and conglomerate: olive gray (5Y 4/1), moderately sorted beds of medium sandstone interbedded with beds of poorly sorted pebbly conglomerate with subrounded pebbles, lower contact exposed locally and is angular unconformity with up to several hundred feet of relief, overlies Cretaceous sediments.	8	122

Unit	Description	Thickness (feet) Unit	Total
	Sandstone: volcanic, light olive gray (5Y 6/1), moderately sorted, subrounded to subangular, very thinly bedded to thin bedded, grains medium to coarse. Cretaceous.		

Klamath River partial stratigraphic section (see section E, plate I). Measured in the NW 1/4 sec. 26, T. 47 N., R. 6 W. with Jacob staff.

Unit	Description	Thickness (feet) Unit	Total
16	Lavas: Roxy Formation, medium dark gray (N4) porphyritic, 25 percent plagioclase phenocrysts, dense fine grained groundmass.		
15	Covered area: andesitic lava debris from overlying rock.	55	55
	Volcanic conglomerate: near top- poorly sorted, largest boulder two feet in diameter and is andesite or basalt; conglomerate contains ten foot thick lens of medium to coarse sandstone which is light olive gray (5Y 6/1)	70	125
14	Volcanic pebbly sandstone: yellowish gray (5Y 7/2), poorly sorted, pebbles are mostly subangular, matrix is fine to medium grained, lower contact is covered.	8	133
13	Volcanic sandstone, pebbly sandstone and conglomerate: pale olive (10Y 6/2) to dusky yellow (5Y 6/4), poorly sorted, subangular to subrounded, most of coarser materials subrounded, graded beds, this unit is partially covered but probably made up of thin to thick bedded graded units, lower contact covered.	33	166
12	Volcanic pebble conglomerate: no sample	5	171

Unit	Description	Thickness (feet) Unit	Total
11	Volcanic pebbly sandstone and sandstone: pale olive (10Y 6/2) to light olive gray (5Y 6/1), graded beds, each graded sequence thin to thick bedded, poorly sorted, subangular to a few subrounded pebbles, calcite cement.	70	191
10	Siltstone: yellowish gray (5Y 7/2), contains volcanic debris including altered pumice?, lower contact covered.	5	196
9	Volcanic pebbly sandstone: light gray (N7), poorly sorted, medium to very coarse grained, subangular to subrounded, beds graded, carbonate cement.	9	205
	Covered area: probably part of unit 8.	15	220
8	Shale: (5YR 3/4), weathered and friable, cleavage is poorly developed, contacts covered.	20	240
7	Volcanic pebbly sandstone and sandstone: major ledge forming unit in this stratigraphic section, color varies from pale olive (10Y 6/2) to light greenish gray (5GY 8/1), characterized by graded beds varying from 2 centimeters to 4 feet thick, coarser units are pebbly sandstone with carbonate cement and grade upward to siltstones containing pumice and eutaxitic-like texture, contains coal seams near bottom, carbonized wood and very fine authigenic pyrite, lower contact undulatory and sharp.	80	320
6	Volcanic conglomerate: highly weathered, moderate yellowish brown (10YR 5/4), cobble conglomerate, friable, stained yellow in places, may be regolith, poorly sorted, subrounded, to rounded cobbles, similar to unit 4, lower contact sharp and planar.	15	335

Unit	Description	Thickness (feet) Unit	Total
5	Volcanic conglomerate: pale olive (10Y 6/2), consolidated, ledge forming, cobble to boulders, rounded to well rounded, matrix medium to coarse grained, lower contact erosional, three feet of relief.	5	340
4	Volcanic conglomerate: moderate yellowish brown (10YR 5/4), highly weathered, friable, cobble conglomerate, cobbles subangular to subrounded, may be regolith, lower contact undulatory and sharp.	8	348
3	Volcanic conglomerate: pale olive (10Y 6/2), consolidated, pebbles and cobbles subrounded, matrix composed of medium to fine sand, poorly sorted, lower contact planar and sharp.	2	350
2	Volcanic pebbly sandstone: pale olive (10Y 6/2), poorly sorted, subangular, medium to coarse grained, pebbles make up about one percent of rock, lower contact covered.	8	358
1	Volcanic conglomerate: contains coarse sandstone lenses; cobbles are subangular to subrounded, matrix coarse grained, very poorly sorted and crudely graded from coarse below to fine above.	4	362
	Covered area: this interval is mostly covered, this interval contains at least one lava flow but is probably mostly volcaniclastics. Estimated thickness is 300 feet before reaching Cretaceous contact.		