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AN ABSTRACT OF THE THESIS OF John David Wood for the Master of Science in Geology presented April 30, 1976.

Title: The Geology of the Castle Rock Area, Grant, Harney and Malheur Counties, Oregon.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Paul E. Hammond

May 5, 1976

Gilbert T. Benson

May 4, 1976

Ansel G. Johnson

May 3, 1976

Richard R. Petersen, Graduate Office Representative

May 3, 1976

The geology of the Castle Rock area aids in the understanding of Cenozoic volcanic stratigraphy and structures in an area where these volcanic rocks thin near the margins of the pre-Tertiary basement rocks and structural trends are overlapping. The Castle Rock area is unique in several aspects and is important in understanding and interpreting the geology in adjacent regions which have all been studied, at least on a regional basis. Intrusive ash-flow bodies of the

Dinner Creek Ash-Flow Tuff, well-exposed sections of complexly interstratified volcanic rocks and well-exposed faults, and of high amount of erosional relief are features which make this area a unique and important addition to the understanding of the stratigraphy of eastern Oregon.

The Castle Rock area includes approximately 65 km² occupying the area of intersection of Grant, Harney and Malheur Counties of eastern Oregon. The products of this study are a geologic map of the area and stratigraphic and lithologic descriptions of the rock units within the area.

The "unnamed igneous complex" is the oldest rock unit exposed within the area. This complex consists of more than 670 m of flow-on-flow basaltic lava flows deposited in Late Miocene time. Faulting and intrusion of rhyolitic dikes resulted in the Castle Rock ridge being uplifted along numerous north-northwest-trending faults.

Eruptions of the Dinner Creek Ash-Flow Tuff from these rhyolitic dikes introduced numerous local volcanic structures and ultimately caused subsidence of the area around Black Butte. The resultant tuff sheet is more than 300 m thick locally.

Silicic lava flows and breccias, pumice lapilli-tuffs and basaltic lava comprising a section more than 700 m thick, were deposited over the Dinner Creek Tuff in very Late Miocene time. These rocks, the Strawberry Volcanics, were derived from sources primarily outside the Castle Rock area.

Following folding, continued faulting and extensive

erosion, the tuffaceous, lacustrine and fluviatile sediments of the Juntura and Drewsey Formations and associated volcanic rocks were deposited through Early and Middle Pliocene time, respectively. A thin rhyolitic welded ash-flow tuff was deposited during deposition of the Drewsey Formation.

During Pleistocene to Recent time faulting and folding have continued on a small scale and erosion of the lacustrine sediments has left stream deposits on pediment surfaces 470 m above the present stream level.

TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

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April 30, 1976

THE GEOLOGY OF THE CASTLE ROCK AREA,
GRANT, HARNEY AND MALHEUR COUNTIES, OREGON

by

JOHN DAVID WOOD

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
GEOLOGY

Portland State University
1976

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ABSTRACT

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GEOLOGIC PLATE

PLATE

1	Geologic Map of the Castle Rock Area	In Pocket
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INTRODUCTION

LOCATION AND ACCESSIBILITY

The Castle Rock area covers a region of about 65 km² occupying the area of intersection of Grant, Harney and Malheur Counties of eastern Oregon (Fig. 1). The area is a rugged volcanic upland with a topographic relief of about 1,170 m.

The nearest hard-surfaced road, U. S. Highway 20, is about 32 km to the south of the thesis area. From Highway 20, at the west end of the town of Juntura, a maintained gravel road leads to Beulah Reservoir near the southwest corner of the thesis area. From the reservoir three unimproved dirt roads traverse the area (Fig. 2). Two of these roads are within the thesis area, one paralleling the North Fork of the Malheur River and Little Malheur River Valleys to Black Butte where it degrades into a jeep trail on the western margin of the area. The other is a mountain road through the center of the thesis area, which eventually leads to the town of Ironside. A third road leading past the abandoned Hunter Ranch parallels the eastern boundary of the area. These dirt roads are all seasonably impassible in times of heavy rain or snow. In all weather, travel is easiest in a four-wheel drive, high clearance vehicle, though not always possible.

Figure 1. Index map of the Castle Rock area.

Figure 2. Topographic map of the Castle Rock area, showing main access roads.

PURPOSE OF INVESTIGATION

This thesis was undertaken as a detailed mapping project in order to fill in some unmapped terrain between previously mapped areas and supply more geologic information and stratigraphic control to a composite geologic map of regional scale prepared for Amax Exploration, Inc.

Beyond describing the lithology, geologic structure and development of landforms, an attempt has been made to comment on the work and ideas of previous investigators. Interpretations and correlations are minimal, but an effort is made to bring the geology of the area into a regional picture with respect to previous investigations.

PREVIOUS WORK

Geologic investigations around the Castle Rock area have been quite limited until recent years. The most recent mapping projects are summarized in Figure 3. Contributions by other workers are cited in the main body of the text and are listed in the reference section of the report.

FIELD WORK AND GENERAL PROCEDURE

Field work was begun in December 1974 after library investigations and construction of a regional geologic map from the literature. Field work was intermittent until June 1975. From June to late August field work was continuous. Final field work was completed by November 1975.

Figure 3. Index map of the Castle Rock area and nearby geologically mapped areas.

The topographic base for the geologic map was constructed from four U. S. Geological Survey preliminary sheets at a scale of 1: 24,000 with a contour interval of 40 ft. (13.3 m). These maps cover the southern half of the Castle Rock 15 min. quadrangle. Aerial photographs obtained from the U. S. Department of Agriculture greatly facilitated mapping. These photos were from a 1969 flight at a scale similar to the base map. Field map data was transferred to a base map in the field. Geologic contacts were located on the basis of topographic expression and rarely by triangulation. The completed geologic map (Plate 1, in pocket) is the foundation of this report and is referred to in later sections. About 40 thin sections were studied in order to refine hand specimen identifications. Glass-bead silica determinations were performed for correlation purposes and in order to obtain compositional control on black glassy lava flows for classification purposes.

GEOGRAPHIC SETTING

Physiography

The thesis area includes the southernmost extension of the Strawberry Mountains which border the Owyhee Upland to the southeast. Castle Rock at an elevation of 2,280 m is the highest point in the area and Beulah Reservoir at an elevation of 1,080 m is the lowest. Local relief in Jerry Canyon and the Canyon of the Little Malheur River may be over 130 m locally, with near vertical canyon walls.

The rugged topography of the Castle Rock area is the result of uplift accompanying volcanism, extensive faulting and erosion. High ridges and deep canyons reflect a north or northwest structural orientation. Lithology also plays an important part in controlling topography. Broad, gently sloping grassy plains have been formed on the dip slopes of lava flows. Soft volcanic and tuffaceous sediments of the southern part of the area form low, rounded hills, with a few prominent cliffs formed by interbedded ash flows and basalt flows.

All of the streams within the Castle Rock area are, at least in part, controlled by faulting. The main streams which skirt the eastern and western margins of the area have relatively low gradients and cause little erosion when not in flood stages. Streams draining the interior of the region have much higher gradients. Jerry Canyon, for instance, drops nearly 470 m in a distance of only 8.3 km, a gradient of over 5.7 percent. All of the interior streams are fed by springs which are commonly associated with faults, landslides or geologic contacts.

Geomorphic History

Evidence of erosion persists throughout the geologic record in the Castle Rock area. The irregular relief developed on the lava flows on the unnamed igneous complex and associated interbedded stream gravels are good examples. All rocks in the area show signs of past erosion or reworking by

sedimentary processes.

Evidence of the oldest lake existing within the area is the lacustrine sediments of the Juntura Formation. Erosion of these lacustrine sediments formed the irregular topography onto which the ash-flow tuff of the Drewsey Formation was deposited. This ash-flow sheet flowed into a wide valley very similar to that of the present valley of the North Fork of the Malheur River. Several small step-toes remained protruding through the sheet. This sheet probably flowed into the area from the south and its northward progress was stopped by the topographic barrier posed by the Castle Rock ridge system (Plate 1). A thin layer of lacustrine and fluvial sediments was deposited over the ash sheet and only erosional remnants of these are found today. This period of erosion probably began in Middle Pliocene time and has continued to the present. Extensive pediments of Pleistocene age were cut into the soft sediments in the southwest corner of the area (Fig. 4, Plate 1). Landslides developed in valley walls because of over-steepened slopes caused by erosion and faulting and a high water level. At least one erosional remnant of a Pleistocene alluvial fan exists today over 470 m above the present stream level southeast of Horse Flat. Uplift of the area and subsequent down-cutting of streams resulted in the formation of the present topography. Youthful landslides and alluvial fans have formed along the present streams at their new base level.

Figure 4. Pediments formed along the North Fork of the Malheur River looking westward from the base of Castle Rock. The low bench in the foreground is the upper surface of the Castle Rock landslide.

Culture

Several ranches prosper in the valleys of Warm Springs Creek and the North Fork of the Malheur River on the eastern and western margins of the thesis area. Agriculture is limited to the flat, easily irrigated areas, although dry farming techniques have been successful on the pediments above the valley floors. Elsewhere, agriculture is very limited due to steepness of terrain, insufficient water, poor soil conditions, or other factors. Water for irrigation comes from the permanent streams and reservoirs. Alfalfa is the major crop and is utilized as winter feed for cattle. Cattle raising is the dominant industry of the area. Most land is managed by the Bureau of Land Management, although much of the best agricultural land, near water sources, is privately owned. The total permanent population of the area is about 15 persons.

Climate

The climate of the Castle Rock area is generally cold and semi-arid. Low annual precipitation of about 25 cm is probably due to the rainshadow effect of the high mountain ranges to the west.

Castle Rock itself, being a 2,084 m tall peak surrounded by much lower lava plains, is effective at disturbing eastward moving weather fronts and receives slightly more precipitation and windy conditions. Storm systems in winter months

come predominantly from the northwest and in the summer from the southwest. Seasonal and diurnal temperature variations are large. The maximum yearly temperature variation is from about 43°C to about -34°C , a total of 77°C . Diurnal temperature variations are most extreme in the summer and may vary by as much as 43°C .

Most precipitation occurs from October to June in the form of snow. In summer months precipitation comes in the form of sudden heavy rains from thunder showers. In winter months temperatures often remain below freezing for many days and the large Beulah Reservoir commonly freezes over.

Vegetation and Wildlife

The vegetation of the Castle Rock area is controlled by soil type, availability of water, elevation and exposure to the sun. Vegetative cover ranges from flat laying grasslands to dense forests. Heavy forests of pine and fir are common on eastern mountain slopes, while only juniper and mountain mahogany can tolerate the intense heat and winds which make the western slopes sparsely vegetated. Dead juniper and mahogany within the pine and fir forest suggest that it is growing at their expense. Sage and wild grasses grow wherever heavy tree cover does not exist. Many species of lichen are present and are most apparent after thunder showers when they brighten in color and make footing quite slippery. Poplar trees, willows and other plants requiring considerable moisture serve as markers for springs and areas

of high water table.

Most of the animal population is active only in early morning and evening hours and may only be seen in midday by disturbing their natural routine. Mammals present in the Castle Rock area include deer, bear, wildcats, badgers, coyotes, porcupines, skunks, jack rabbits, numerous squirrels and small rodents. Birds represented include chukar, partridge, sage hen, dove, duck, quail, pheasant, red-winged blackbird, western meadowlark, Canadian goose, robin, buzzard, eagle, hawk, raven, western magpie and scrub jay. In summer months several types of lizards and snakes are abundant. Rattlesnake and milk boa are the most prevalent snakes.

STRATIGRAPHY

SYNOPSIS

The oldest rocks exposed in the Castle Rock area consist of a thick sequence of basaltic lava flows and related pillow palagonite breccias termed the "unnamed igneous complex" (Tuic). These rocks have a thickness of at least 670 m and an areal extent of about 5 km² within the thesis area (Fig. 5, Plate 1).

The Dinner Creek welded tuff (Tdc) unconformably overlies the "unnamed igneous complex" and was erupted from fissure vents represented by Castle Rock and Black Butte (Haddock, 1967; Fig. 6). At the base of this unit is a non-welded pumice-lapilli-tuff (Tdcp) which is restricted to one exposure southwest of Castle Rock. The Dinner Creek has a minimum thickness of 250 m and has an areal extent of greater than 7 km².

The Strawberry Volcanics is the most complex lithologic unit within the Castle Rock area and unconformably overlies the Dinner Creek Tuff. The Strawberry Volcanics are subdivided into four members: a rhyolitic breccia and flow member interbedded low in the section (Tsvr), the basaltic to dacitic lava flows comprising the bulk of the section (Tsv), a volcaniclastic member (Tsvv) which includes a pumice lapilli-tuff marker bed (Tsvm) that was also mapped separately, and three

Figure 5. Composite stratigraphic section of the Castle Rock area (and color key for figure 6.).

thin olivine basalt flows high in the section (Tsvb). The Strawberry Volcanics have a total aggregate thickness of at least 400 m and an areal extent of about 20 km² within the thesis area.

The Juntura Formation (Tj) unconformably overlies the Strawberry Volcanics in the southern part of the thesis area. This formation consists of more than 200 m of light-brown tuffaceous sediments and interbedded air-fall deposits (Tj), and basalt lava flows (Tjb) covering an area of about 20 km².

The Drewsey welded tuff (Tdt) and sedimentary strata of the Drewsey Formation (Td) overlie the Juntura Formation. These rocks have an areal distribution of about 4 km² in the southwest corner of the thesis area and have a thickness as great as 25 m locally.

REGIONAL CORRELATION

The stratigraphic units of the Castle Rock area are all of Late Miocene and Early Pliocene age, but less than 2 km to the north much older basement rocks are exposed. These basement rocks consist of Upper Paleozoic and Lower Mesozoic eugeosynclinal sedimentary and volcanic strata as described by Brown and Thayer (1966) and Lowry (1968). All of these pre-Tertiary rocks show signs of deformation by several orogenies and have been intensely metamorphosed in places, primarily adjacent to intrusions. The products of metamorphism are predominantly schists, slates and greenstones which resulted from emplacement of both silicic and mafic intrusions.

The "unnamed igneous complex" is the oldest rock unit exposed in the Castle Rock area and the adjacent regions to the west, south and east. In one of the earliest organized investigations, the "unnamed igneous complex" was included in a super unit termed the "Basement Complex," (Bowen, Gray and Gregory, 1963). The "Basement Complex" included such units as the Dinner Creek Ash-Flow Tuff, Littlefield Rhyolite, Hunter Creek Basalt, and other units which have since received formal formational status by Kittleman (1965). Flows of the "unnamed igneous complex" are those below the (Dinner Creek) welded ash-flow tuff marker bed of the "Basement Complex." Similarly, flows of this complex were included in the lower part Strawberry Volcanics, as mapped by Brown and Thayer (1966 and 1973) within the Castle Rock area. Lowry (1968) may have mapped the lower porphyritic flows and breccias of the "unnamed igneous complex" as Ring Butte andesite and the younger dark gray lavas as Columbia River Basalt where the Dinner Creek Marker Bed was not obviously overlaying both of them (Fig. 7).

The Dinner Creek Tuff was first mapped by Lowry (1943) with other rhyolitic lava flows and breccias as "Dooley Rhyolite." Bowen (1956) and Gray (1956) referred to it as the welded tuff member of the Owyhee Basalt, a designation which was changed to welded tuff within the "Basement Complex" by Bowen, Gray and Gregory (1963).

The older rhyolitic lavas of the Strawberry Volcanics as mapped in this report were included in with the "Dooley

Figure 7. Regional correlation chart of principal stratigraphic units and nomenclature used in this report and previous investigations.

Rhyolite" by Lowry (1968) and were mapped as Littlefield Rhyolite by Haddock (1967). Younger lava flows of the Strawberry Volcanics were included in the "Basement Complex" of Bowen and others (1963) and the Columbia River Basalt by Lowry (1968). The volcanoclastic member of the Strawberry Volcanics was mapped as "Goodwin Ranch Tuff Breccia" by Lowry (1968).

The Juntura Formation is equivalent to the lower part of the Idaho Group as mapped by Lowry (1968). The basalts interbedded within the lower part of the Juntura Formation are equivalent to the Tims Peak Basalt as mapped by Haddock (1967). The lower part of the Juntura Formation, below the basalt flows, is equivalent to the "Tims Peak volcanic and sedimentary unit" of Haddock (1967).

The welded tuff at the base of the Drewsey Formation may be correlative with Rattlesnake Tuff of the John Day Basin (Bowen and others, 1963) and was mapped as Rattlesnake Tuff by Lowry (1968), even though he recognized lithologic and stratigraphic differences.

"UNNAMED IGNEOUS COMPLEX"

DEFINITION

The interstratified mafic lava flows and breccias of the "unnamed igneous complex" (Tuic) were first described by Hagood (1963), and subsequently by Kittleman and others (1965) and Haddock (1967). The base of the "unnamed igneous complex" has never been described, but it is exposed a short distance north of the Castle Rock area overlying pre-Tertiary strata. Regionally this complex is exposed over an area in excess of 2,000 km² and within the Castle Rock area has a minimal thickness of 650 m. Since this unit has never attained formational status and no type section has been described, two correlated sections have been measured; either might make a suitable type section (Fig. 8). Both of these sections are over 350 m in thickness with relatively little structural complication.

The "unnamed igneous complex," Owhyee Basalt and the Steens Mountain Volcanic Series, while similar in age, may never be proven to be part of one continuous unit because of extensive erosion, vast amounts of overburden, and the stratigraphic and lithologic variability of the individual flows. These lava flow complexes are not composed strictly of flood basalts. Individual flows in the Castle Rock area are not traceable for more than a few kilometers and it is

Figure 8. A comparison of reference sections from Haddock (1967) measured in the SW 1/4 sec. 34, T. 20 S., R. 30 E. and the section measured at Hunter Campground of this report in sections 15 and 16, T. 18 S., R. 37 E.

believed they represent smaller pahoehoe flows, which were erupted from scattered central vents and fissures. Based on measurements in the Castle Rock area, flows average 15.3 m in thickness and may range from 10 to 150 km² in areal extent. The complex is formed from many such overlapping and interfingering pahoehoe flows. The limited areal extent, stratigraphic and petrologic variability of these flows precludes flow-by-flow correlation of outcrops separated by more than 45 km of exposureless area.

Formal naming of this unit in the future will foster more detailed stratigraphic work, standardize past terminologies and eliminate confusion as to the exact relationships between the mafic lava complexes of eastern Oregon. It is suggested that the term "igneous" is too broad and vague, and might be replaced with the term "volcanic" which is more precise. Due to the regional extent of this unit, it might be named after Malheur Gorge, where the best exposures are present and it was first described (e.g., Malheur Gorge Volcanic Complex).

DISTRIBUTION AND THICKNESS

Within the Castle Rock area strata of the "unnamed igneous complex" are restricted to the central and western portions of the mapped area (Plate 1) covering an area of about 5 km². In the central portion of the mapped area these rocks form a structural high, uplifted along fault zones. In

Figure 9. Lava flows of the "unnamed igneous complex" exposed at the south end of the Castle Rock ridge, where the reference section was measured (secs. 15 and 16, T. 18 S., R. 37 E.). The approximate traverse line appears on the left side of the photo. The pillow palagonite breccia (unit #3, Fig. 10 and App. A, Sec. 1) in the lower foreground was used as a marker bed.

the western regions these rocks are exposed in the walls of deep canyons. At the south end of the Castle Rock ridge, the "unnamed igneous complex" has a total thickness exceeding 650 m. Here, at Hunter Campground, a reference section of over 410 m, containing 25 individual flows, was measured (Fig. 9).

The base of the "unnamed igneous complex" is not exposed in the Castle Rock area, nor has it been described in the literature, but flows of this unit lap up against and overlie pre-Tertiary rocks exposed from 2 to 8 km to the north. The complex is unconformably overlain by the Dinner Creek Ash-Flow Tuff.

LITHOLOGY

In the Castle Rock area, the "unnamed igneous complex" consists of dense, porphyritic, palagonitic and vesicular basalt flows with two interstratified pillow palagonite breccias. These flows are similar to those described by Haddock (1967). The lower 265 m of Haddock's reference section consists of massive aphanitic basalt flows and two extensive palagonitic breccias (Fig. 8). The Castle Rock section is similar, but contains five porphyritic basalt flows and some coarser grained flows not described by Haddock. The upper 116 m of Haddock's section contains scoriaceous basalt flows and basaltic breccias, while the Castle Rock section is composed of dense aphanitic flows.

The pillow palagonite breccias in the lower part of the Castle Rock section are composed of fine-grained and glassy basalt fragments with lesser amounts of crystalline basalt fragments. Palagonitic pillows of nonvesicular basalt are commonly rimmed by black glass. These pillows range in size from 0.15 to 0.3 m in thickness and from 0.2 to 3 m in length and are generally surrounded by palagonitic breccia. Zeolite minerals, calcite and amorphous silica are present and well-developed foreset bedding indicate deposition from the southeast. The breccias of Haddock's section are similar and calcite and stilbite fillings and linings are common in cavities, but no depositional structures or pillows were described.

All of the flows observed in the Castle Rock area appear in this section to be basalts, although more detailed work may conclude that some are basaltic andesites. These flows can be divided into two representative groups to aid in petrographic description; namely, porphyritic and aphanitic. The Castle Rock Section (App. A, Sec. 1) consists of over 25 individual flows with porphyritic flows comprising about one in five (Fig. 10). Most porphyritic flows lie stratigraphically below the upper pillow palagonite breccia (Unit No. 13). These are generally hypocrystalline, and commonly have an intergranular groundmass. Phenocrysts commonly compose 20 percent of these rocks with plagioclase and olivine being most common. Plagioclase laths measure up to 1 cm in length, comprising about 75 to 90 percent of the phenocrysts with

Figure 10. Measured stratigraphic section of the "unnamed igneous complex", at the south end of the Castle Rock ridge (secs. 15 & 16, T. 18 S., R. 37 E.).

olivine and pyroxene making up the rest. Plagioclase phenocrysts have good crystal outlines but are badly cracked and show strained extinction. Similarly, pyroxene crystals are commonly altered to a fibrous mineraloid with sector zoning suggestive of augite, although optical properties are indeterminate. Zeolite, calcite, and amorphous silica are common in these flows. Plagioclase in the groundmass was determined to be about An_{58-63} and composes about 30 percent of the rock. A dark glassy groundmass makes up about 40 percent of the rock and over 5 percent may be made up of secondary minerals and alteration products. Ferromagnesian minerals such as magnetite, olivine, and pyroxene occur within the angular interstices between plagioclase laths in the groundmass. Modal compositions by Haddock (1967) are listed in Table 1, and their relative position within his section, and its relationship to the Castle Rock section is shown in Figure 8.

Aphanitic basalt flows are the most common rock type found within the "unnamed igneous complex." Three dense basalt samples have an average silica content of $44.5(\pm 2)$ percent (App. B, Table 2). Most commonly these are hypocrystalline and aphanitic, having intergranular to intersertal and sometimes subophitic textures with sparse phenocrysts. These flows are generally composed of about 40 to 50 percent plagioclase, 20 to 35 percent augite, 0 to 5 percent olivine, 5 to 10 percent opaque minerals, with the remainder being a fine matrix of glass, secondary minerals and alteration products.

TABLE I

MODAL COMPOSITION OF BASALTS FROM THE "UNNAMED IGNEOUS COMPLEX" (FROM HADDOCK, 1967)

Specimen number	Plagioclase An	Subcalcic Augite	Olivine	Opaque Minerals	Glass	Alteration products	Points Counted
10	46.0 ₅₁₋₅₈	31.4	Tr.	7.5	11.0	4.1	750
9	48.0 ₅₂₋₆₀	29.8	0.3	9.2	8.7	4.0	750
8	46.1 ₅₄	29.1	1.0	8.3	9.8	5.7	800
7	48.7 ₅₅₋₅₉	22.7	Tr.	4.1	10.9	13.5	750
6	51.9 ₅₀₋₅₆	31.3	3.9	6.4	5.6	0.9	750
5	48.4 ₅₅	32.5	0	7.7	3.2	7.6	750
4	39.2 ₅₂	28.1	0	6.5	17.1	9.1	750
3	41.4 ₅₆	34.8	0.2	5.3	6.5	12.7	850
2	45.1 ₅₇₋₅₈	22.9	0	3.3	9.6	18.6	750
1	50.6 ₅₃₋₅₉	32.8	1.0	5.6	5.6	4.6	500

AGE AND CORRELATION

The age of the "unnamed igneous complex" was tentatively established as no younger than Late Miocene by Kittleman and others (1965), who indicate that it is indirectly overlain by sediments containing Barstovian mammalian fossils. These Barstovian deposits, the Butte Creek Volcanic Sandstone, have been dated at 15.1 m y by potassium argon age determination (Evernden and others, 1964).

Regionally the "unnamed igneous complex" is possibly correlative with the Steens Basalt, Steens Mountain Volcanic Series, Owyhee Basalt and other lava complexes such as those of western Idaho, northern Oregon and southern Washington. These are very similar in age to the Columbia River Basalt, but their exact relationships are uncertain. In one of the earliest organized investigations, the "unnamed igneous complex" was included in a super unit termed the "Basement Complex." Flows of the "unnamed igneous complex" are those below the welded ash-flow tuff (Dinner Creek) marker bed of the "Basement Complex." Similarly, flows of this complex were included in the "Strawberry Volcanics" as mapped by Brown and Thayer (1966) within the Castle Rock area.

In general, flows of the complex dip towards the northwest, causing older flows to be exposed farther to the southeast. Beaulieu (1972) believes that about 330 m of intercalated autoclastic breccias and dense aphanitic basalts exposed in the Crowley area (Greene, 1962) represent the

lower part of the section. The middle part of the section is probably represented by 200 m of porphyritic olivine basalt flows overlain by 230 m of platy aphanitic andesite and andesitic basalts exposed in the Monument Peak area (Hagood, 1963). The uppermost part of the section is probably represented by the porphyritic to aphanitic flows and breccias exposed in the Castle Rock area, Malheur Gorge area and the Central Monument Peak area, comprising a section more than 670 m in thickness. Correlation is complicated by the fact that continuous stratigraphic markers within the complex are absent. However, the porphyritic flows are more common in the lower part of the section and mark a general stratigraphic position. Similar rocks, the Ring Butte andesite, as described by Lowry (1968) north of the Castle Rock area, may represent the base of the section.

DINNER CREEK WELDED ASH-FLOW TUFF

DEFINITION

The Dinner Creek Welded Ash-Flow Tuff (Tdc) was named by Kittleman and others (1965, p. 18) for exposures on Dinner Creek, southwest of Jonesboro, at the type locality in the NW 1/4 SE 1/4 sec. 30, T. 21 S., R. 39 E. The Dinner Creek was described by Dole and Corcoran (1954) and was referred to as the welded tuff marker bed in the Malheur Gorge. Bowen (1956) and Gray (1956) described this unit, referring to it as the welded tuff member of the Owyhee Basalt, but it was not mapped as a separate unit. This designation was changed to welded tuff within the "Basement Complex" by Bowen and others (1963). Haddock (1967) provides the most complete description of the unit, describing textural, chemical and physical characteristics as well as interpreting flow directions and possible source areas. Lowry (1968) described this unit and also named possible source areas, although he referred to it and local rhyolite flows as Dooley Rhyolite.

DISTRIBUTION AND THICKNESS

The Dinner Creek Welded Ash-Flow Tuff is found in scattered exposures totalling about 8 km² and is as thick as 470 m locally. The 470 m section at Black Butte (sec. 24, T. 17 S., R. 36 E.) is probably excessive due to its plug-

like nature. However, a section of almost 300 m is exposed in Jerry Canyon on the east side of the thesis area. From the Castle Rock area the tuff sheet extends over 65 km to southeast, where it thins to about 6 m (Haddock, 1967). An isopach map by Haddock (1967) shows this tuff to have a total areal extent of at least $2,560 \text{ km}^2$ and possibly as much as $5,000 \text{ km}^2$. If the tuff has a uniform distribution away from its source area its volume would be at least 80 km^3 and possibly as much as 185 km^3 . The base, where exposed, overlies lava flows of the "unnamed igneous complex" or a light gray pumice lapilli-tuff of about 20 m in thickness. The Dinner Creek Tuff is unconformably overlain by rocks of the Strawberry Volcanics and tuffaceous sediment of the Juntura Formation.

GENERAL LITHOLOGY

The Dinner Creek Welded Ash-Flow Tuff is a prominent marker bed around Castle Rock and adjacent areas. It is a densely welded sheet enclosed in an envelope of glassy and non-welded material. The densest welding took place in the center of the flow and decreased relatively uniformly towards the edges (Haddock, 1967). Within and near the vents the ash-flow nature of this flow might escape the most meticulous field investigator because of the high degree of welding, subsequent alteration and well-developed laminar viscous flow structures.

A fresh hand specimen appears dark violet or lavender to dark reddish-gray and weathers to a distinctive purplish-red. Away from vent areas the rock is finer grained and has a more reddish appearance. Less welded zones may be light-brown, very light purple or even greenish and weather to shades of red-brown. Flow layering is very prominent on a small scale, layers are about 1 mm apart, and impart a very distinctive fracture cleavage which causes hand specimens to split into plates about 4 mm in thickness. The rock consists of 4 to 5 percent pumice fragments, 1 to 4 percent sanidine and potassium feldspar and up to 5 percent xenolithic fragments in a matrix of purplish-gray glass.

ZONATION

The Dinner Creek tuff is divisible into seven major zones of welding and may be composed of three cooling units (Fig. 11). The basal and upper cooling units are composed of non-welded pumice lapilli-tuff, while the central zone is densely welded and complexly zoned. This central cooling unit is divisible into seven vertical zones of welding and causes the tuff to have several distinct outcrop patterns (Fig. 11). Within the Castle Rock area the exact relationship between these zones is not readily apparent because more than two zones are rarely exposed together.

At Castle Rock the base is a very irregular zone of 10 cm or more of black frothy to dense crystal rich glass

Welding Zones	Thickness		Relative Degree of Welding	Structures
	Central	Distal		
Upper nonwelded cooling unit	33.5 m	12.2 m	Low	Nonwelded pumice lapilli-tuff
Upper nonwelded zone	5 cm	90 cm		Upper glassy zones Zone of platy jointing
Upper partially welded zone	20 cm	50 cm		Upper lithophysal zone
Upper densely welded zone	40 cm	70 cm		Densely welded vesicular zone
Devitrified, vapor-phase crystallization zone	65 m	3 m	High	Zone of columnar and platy jointing
Lower densely welded zone	60 cm	90 cm	Low	Lower lithophysal zone
Lower partially welded zone	5 cm	60 cm		Spherulitic zones Lower glassy zones
Lower nonwelded zone	5 cm	90 cm		
Lower nonwelded cooling unit	17 m	5 m		Nonwelded pumice lapilli-tuff

Figure 11. Lateral and vertical zonation within the Dinner Creek Welded Ash-Flow Tuff, a multiple flow compound cooling unit (after Haddock, 1967).

resembling obsidian or pitchstone in places. This glassy chilled zone changes abruptly upward into densely welded dark-brown glassy tuff which in turn grades upward into the more characteristic grayish-red tuff. Elsewhere, the base includes a non-welded zone of medium to light-gray pumice-lapilli-tuff which was mapped individually as a separate cooling unit and is only exposed in the mapped area southwest of Castle Rock (Sec. 20 & 21, T. 18 S., R. 37 E.). The base in more distal areas has been described as non-welded ash which grades upward from light-gray non-welded tuff into dark-gray to black glass within a distance of 5 to 60 cm (Haddock, 1967). Cavernous weathering in the Castle Rock area may have resulted from the weathering out of a fine non-welded ash.

Above the non-welded and glassy zones is a densely welded devitrified zone resembling a purple-to-pinkish red rhyolite flow with phenocrysts of sanidine and small xenoliths. This devitrified zone consists of 30 percent or more vesicles, or vapor vugs, which may be over 6 cm in diameter, averaging about 2 cm in diameter. These vesicles decrease in size and number upward in the section. Much larger structures several meters in diameter show intricate wall and roof structures suggesting a primary origin, perhaps large vapor cavities or spiracles. Smaller vesicles are wholly or partially filled with white or bright blue secondary chalcedony. Zones of lithophysae and spherulites are common (Fig. 11). This zone grades upward into a zone of columnar jointing with a 0.5 m joint spacing. Columnar jointing is commonly obscured

by a well-developed platy fracture averaging 2 to 4 mm in thickness, oriented normal to the columnade. The columnar zone in turn grades upward into a lithophysal zone where lithophysae are uniform in size and comprise up to 50 percent of the rock. The lithophysae are filled with secondary amorphous silica but in distal regions have been described as being completely or partially filled with a spongy crystalline material of anorthoclase, tridymite, and cristobalite (Haddock, 1967).

The devitrified zone grades upward into a brownish red glassy zone of densely and finally lightly welded tuff. Above the upper glassy zones Haddock (1967) describes the remains of an upper non-welded zone as a stratified pumice-lapilli-tuff and pumiceous sandstone ranging from 13 to 37 m in thickness. Within the Castle Rock area several units fitting this description are found above the Dinner Creek tuff. Some of these units are definitely much younger and others have a still uncertain relationship. This upper non-welded zone therefore could have been included with the pumiceous units in the Lost Creek Volcaniclastics which overlie the Dinner Creek Tuff locally.

PETROGRAPHY

A vitroclastic texture predominates throughout the welded tuff in both glassy and devitrified zones. An axiolithic texture consisting of fibrous minerals which have grown elongated along shard boundaries, and a eutaxitic

structure around rims of lithophysae have been described in detail by previous investigators (Bowen, and others, 1963; and Haddock, 1967). Individual reddish colored glass shards compose about 95 percent of the rock in compact zones and show a wide degree of flattening and stretching. Flattening took place in the horizontal plane resulting from post-depositional settling and compaction of hot particles under the weight of overlying ash. Stretching was caused during actual flow and emplacement of the ash sheet, and is a linear feature oriented in the direction of movement. Haddock (1967) mentions that in and near the vent area at Castle Rock glass shards are extremely stretched and become decreasingly stretched away from the vent area. The numerous elongated vesicles and stretched glass shards suggest post-depositional movement of the ash-flow sheet in many areas. Devitrification of this ash sheet is more pronounced in the center of the flow and in near vent areas.

Phenocrysts of anorthoclase, sanidine and oligoclase and quartz comprise up to 4 percent of the rock (Bowen and others, 1963; and Haddock, 1967). Anorthoclase and sanidine are by far the most abundant, comprising over 80 percent of the phenocrysts. The number of potassium feldspar crystals increases upward in the section and their once euhedral outlines are embayed. Amorphous silica of various colors commonly fills fractures and gas cavities within the rock. Magnetite constitutes less than 1 percent of the rock; it

occurs primarily as dusty anhedral grains and rarely as euhedral crystals. Dusty hematite may be responsible for the reddish color of the glassy matrix (Gray, 1956). Other minerals are zircon, clinopyroxene and a small number of quartz crystals having the dipyramidal habit of beta quartz (Haddock, 1967).

Lithic fragments ranging from 0.1 mm to 6 cm in diameter increase in abundance near the top of the tuff sheet and seldom comprise more than one percent of the total rock (Fig. 12). Pumice and welded tuff fragments are much more abundant near the top of the section, while xenolithic foreign material is more disseminated throughout the tuff sheet. Basaltic xenoliths are by far the most common. Xenoliths of flow-layered rhyolite, sandstone and possibly some altered shale have been reported (Haddock, 1967). Xenoliths show almost no reaction rims and may be accentuated by coarser-grained, lighter-colored tuff surrounding them. These xenoliths apparently acted in places as nucleation points for early crystallization of the tuff, being most common in and near vents. Glass shards are commonly bent around lithic fragments and phenocrysts.

SOURCE AREAS

The most critical problem with extensive ash-flow deposits is the location and characteristics of their source areas, which are usually heavily buried by the sheets they

Figure 12. Basaltic xenolith and steeply inclined flow-layering in the southwest side of the Castle Rock dike (NE 1/4 SW 1/4 NW 1/4, sec. 9, T. 18 S., R. 37 E.). The xenolith is about 6 cm in length (paper clip indicates scale). Note hollow at upstream side of xenolith and arrow indicating flow direction.

produce. In fact, very few intrusive ash-flow bodies have been recognized as sources for tuff sheets. The Castle Rock area and Ironside Mountain quadrangle to the north are unique in that dikes and central vents representing the southernmost extension of a north-south trending dike system are exposed. Intrusive Dinner Creek Tuff bodies within the Castle Rock area are represented by Black Butte, possibly a central vent and Castle Rock, a 2 km-long dike.

Features in the vicinity of the Castle Rock dike suggestive of its intrusive nature are its geometric outline and isolated exposure (Fig. 13, Plate 1). Flow layering is steeply inclined in the southern end of the Castle Rock dike, but dips an average of 37 degrees to the northwest at the northern end. Flow layering and a rude joint set within the dike appear to fan outward near the top of the dike (Fig. 14). Joints have a 2 m spacing and surfaces are polished slickensided faces of light green to dark purple colored glass. Quartz-filled vesicles, highly elongated, vitric nodules and basaltic xenoliths are common within the dike. Brecciated flow remnants and glassy tuff are found locally near the base of the dike.

The lower slopes of the Castle Rock ridge are composed of a thick sequence of basalt flows which dip about 20 degrees to the northwest (Fig. 13, Plate 1). Erosional remnants of brecciated flow material of the Dinner Creek Tuff are common on the basaltic slopes below the Castle Rock dike.

Figure 13. View of the 2 km long Castle Rock dike looking southwestward. Note the isolated exposure on top of the basaltic ridge (trees at base of dike indicate scale).

Figure 14. View of the south end of the Castle Rock dike. This exposure is more than 180 m in height with a 2 m joint spacing.

These rocks may represent autobrecciated flow material or hot avalanche deposits deficient in nonwelded ash size material. This breccia consists of large angular blocks ranging in size from 0.5 to over 3 m in diameter, chaotically welded together. This brecciated Dinner Creek Tuff is believed confined to near-vent areas. Nowhere else were these large welded blocks found and Kittleman and others (1965), Haddock (1967) and Lowry (1968) described none in more distal parts of the flow. Ramping structures caused by viscous flowage are exposed in a canyon wall (SW 1/4 NE 1/4 SW 1/4 of sec. 6, T. 18 S., R. 37 E.) west of Castle Rock. These ramping structures appear as concentric joints with their convex sides facing away from the Castle Rock dike (Fig. 15). Ramping structures are excellent indicators of flow direction and two or more on the opposite sides of a vent may serve to locate it.

Flow-layering in the northern end of the Castle Rock dike dips in the direction of Black Butte, suggesting the two may be connected at a relatively shallow depth (Fig. 16).

Attitudes on flow-layering and the relative geographic closeness of these two intrusive features indicate they may be connected more shallow than subcrustal levels, but probably no shallower than 3000 to 4000 feet (100 to 1330 m). A contact at the south end of Castle Rock indicates that the dike occupied a topographically high position at the time of extrusion and flows traveled over basalts of the "unnamed

FLOW
DIRECTION

Figure 15. Ramping structures preserved within an erosional remnant of the Dinner Creek Tuff sheet (NE 1/4 SW 1/4 sec. 6, T. 18 S., R. 37 E.). These structures are approximately 15 m tall. The direction of flowage was from right to left, away from the Castle Rock dike.

Figure 16. Cross sections of the Castle Rock and Black Butte intrusions, showing the relative positions of flowage structures within the Dinner Creek Tuff sheet.

igneous complex" into valleys on both sides of the ridge. These valleys are traceable by the thick accumulations of Dinner Creek Tuff which roughly parallel the present valleys, and have been eroded off on higher slopes, exposing the pre-eruption paleotopography.

AGE AND CORRELATION

The Dinner Creek Welded Ash-Flow Tuff has been assigned an age of Late Miocene on the basis of its stratigraphic position above the "unnamed igneous complex" and below the Strawberry Volcanics and Juntura Formation. Radiometric ages of 14.3 to 14.9 m y have been reported for this unit (Walker and others, 1974).

STRAWBERRY VOLCANICS

DEFINITION

The Strawberry Volcanics comprise a complex series of silicic to mafic lava flows more than 2,700 m in thickness (Thayer and Brown, 1973), first described by Thayer (1957) in the area of Strawberry Mountain 55 km northwest of Castle Rock. The actual unit as originally mapped includes many units which have since received formal naming, making the exact lithology and extent quite vague. Brown and Thayer (1966) included all Late Miocene volcanic rocks of the Castle Rock area and the 30 min. Ironside Mountain quadrangle to the north within this unit. Thayer and Brown (1973, p. 492-493) described a generalized section at Ironside Mountain, part of which is similar to the reference section of this report (App. A, Sec. 2). The Strawberry Volcanics are a significant regional stratigraphic unit and will be more precisely described and redefined in the future with accumulation of more information.

In the map area, Plate 1, the Strawberry Volcanics consist of interstratified lava flows and volcaniclastics which are subdivided into four members on a lithologic basis. The base of the Strawberry Volcanics is defined locally as a series of rhyolitic flows and breccias (Tsvr), forming the lower member. This unit is in part correlative to the

Littlefield Rhyolite (Haddock, 1967). Stratigraphically above the rhyolitic lava flow and breccia member are a thick sequence of platy basaltic to dacitic lava flows (Tsv), which comprise the bulk of the formation. Interbedded with the basaltic to dacitic lava flow member is a volcanoclastic member (Tsvv) composed predominantly of pumice-lapilli-tuffs and minor sedimentary strata. Included within this volcanoclastic member is a pumice lapilli-tuff marker bed (Tsvm). Three relatively thin open-textured olivine basalts or basaltic andesite flows (Tsvb), forming the fourth member, overlie the volcanoclastic member and are interbedded with the basaltic to dacitic lava flow member high in the section. A reference section, including strata of all but the basal member, appears in Figure 17 and a detailed lithologic description of the formation is given in Appendix A, Section 2. Rocks of the Strawberry Volcanics unconformably overlie the strata of the "unnamed igneous complex" and Dinner Creek Ash-Flow Tuff and underlie strata of the Juntura Formation disconformably.

DISTRIBUTION AND THICKNESS

The rhyolitic lava flow and breccia member (Tsvr) covers an area of less than 0.5 km² and has a maximum thickness of 80 m. This unit is exposed primarily along the east wall of Jerry Canyon and 2 km southeast of the Castle Rock Ranch.

The basaltic to dacitic lava flow member (Tsv) covers

an area exceeding 15 km^2 and is more than 150 m thick. This member is thickest in the northern half of the Castle Rock area.

The volcaniclastic member (Tsvv) is exposed over an area of 12 km^2 and probably underlies an additional 36 km^2 of the thesis area. These strata have a thickness exceeding 200 m but tend to thin away from Lost Creek east of Black Butte. These beds have been described 30 km to the north (Lowry, 1968) and have a minimum regional distribution of about $1,600 \text{ km}^2$.

The upper open-textured basalt member (Tsvb) is exposed in scattered outcrops throughout the northern half of the Castle Rock area. These lava flows have a maximum thickness of 55 m.

LITHOLOGY

Rhyolitic Lava Flow and Breccia Member

A rhyolitic breccia, at the base of the formation, exposed in the southeast wall of Jerry Canyon, was mapped as Littlefield Rhyolite by Haddock (1967), indicating the two are correlative. This breccia is over 30 m thick and is closely associated with a dense dark-gray to black, fine-grained, silicic lava flow about 22 m thick, which apparently grades into the breccia. The breccia consists of large lava blocks over 2 m square to small angular fragments chaotically embedded in a fine, dark-brown to light-red sandy

matrix and commonly weathers into hoodoos or spires. The exact origin of the breccia is uncertain, but its association with a lithologically similar lava flow suggests subaqueous brecciation. Ramping structures indicate that the flow came from the north and entered a small lake. The flow may have had a sublacustrine origin, but lack of sedimentary material and abundant coarse angular fragments suggests a near vent source.

A terrestrial rhyolite breccia about 10 m thick is exposed southwest of Horse Flat (Plate 1). This breccia is light-red to pale orange in color with autobrecciated fragments embedded in a fine, welded vitric matrix. The breccia is generally light in color and shows distinctive red, gray, and yellow crenulated flow layering. The rock is composed of about 95 percent glass with 3 percent anhedral magnetite, minor pyroxene and feldspar crystal fragments, and has a silica content of 73 percent (App. B).

Basaltic to Dacitic Lava Flow Member

The lava flows of this member have such a similar outcrop appearance and are so intimately interstratified that further subdivision on the basis of composition was not justified. In general, the older flows are silicic and younger flows are basaltic. Many of the silicic flows are older than rocks of the reference section and are closely related to the rhyolitic breccias.

Silicic flows are very fine-grained, medium to dark-gray in color, although some are shades of light-brown.

Dark flows commonly have a green mineral banding and a fine platy jointing. This jointing is commonly undulating in outcrop and develops along incipient flow layering. In hand specimen these rocks weather light-brown in color and feldspar and pyroxene crystals are visible on a fresh surface. Other flows are highly scoriaceous with a coating of green alteration minerals. One flow with a 3 m thick autobrecciated zone at the top, pink glassy streaks, green mineral banding, a very glassy groundmass and numerous flow structures common to rhyolites, has a silica content of less than $53(\pm 2)$ percent. A much coarser grained, less silicic looking lava flow at the northwest end of Beulah Reservoir has a silica content of $64(\pm 2)$ percent (App. B, Table 2).

Basaltic lava flows are characteristically dark-gray to black, very fine-grained with platy jointing and greenish streaks of alteration minerals between flow laminations. These flows are hypocrystalline and microporphyritic, with intensely altered plagioclase and pyroxene phenocrysts about 1 mm in length. Fine plagioclase crystals, crystallites and microlites compose about 70 percent of the rock and are so well aligned and curved around larger crystals as to resemble glass shards in an ash-flow. About 2 percent of this rock is composed of phenocrysts at a ratio of about 4 plagioclase to one pyroxene. A very dark glass matrix forms 20 percent of the rock and dusty magnetite makes up almost 5 percent. Silica contents on these basaltic rocks range from 41.0 to $52.5(\pm 2)$ percent. These flows average about 15 m in thick-

ness, have very platy jointing but lack the viscous flow structures common to the older rhyolitic and dacitic flows. Platy jointing in younger flows is developed along flow layers which most commonly parallel the basal contact of the flow. Several flows, however, have highly undulating wave-like viscous flow structures (Fig. 18, Plates A and B). The extremely tight folds developed in some platy lavas may have resulted from lava being extruded at a slow rate and flowed across a broad, relatively flat, gently sloping plain. Another common structure is concentric jointing enclosed within a poorly developed vertical joint set (Fig. 18, Plate C). These structures may have formed within a cylinder of lava within the flow.

Volcaniclastic Member

The volcaniclastic member of the Strawberry Volcanics consists of more than 20 lithologically similar pumice lapilli tuff beds, one yellowish-brown volcanic conglomerate and two light-gray to brown ash beds (Fig. 17). The pumiceous tuffs are generally dull colored in shades of light-gray and brown and range in thickness from less than 2 m to more than 50 m. Fragments consist largely of flattened pumice lapilli and lesser amounts of lithic fragments as much as 15 cm long. Lithic fragments compose 5 to 10 percent of the rock, an ash matrix 30 to 70 percent, and pumice lapilli make up the rest. Other constituents include minor amounts of plagioclase, augite and hornblende crystals (Lowry, 1968).

Figure 18. Jointing in lava flows of the Strawberry Volcanics (see text for discussion).

Lowry (1968) measured the refractive indices of glass fragments of three tuffs as ranging from 1.482 to 1.506 ($\text{SiO}_2 = 72$ to 68 percent; App. B), indicating that these rocks are rhyolitic to dacitic in composition. A pumice lapilli-tuff marker bed (Tsvm) (Unit 9, App. A, Sec. 2) was mapped separately to aid in determining the relative position of other tuffs within the stratigraphic section. Deposits of this unit are characteristically lense-shaped where they have filled shallow basins. Lava flows occur both above and below as well as interstratified with this unit.

The tuffs range from nonwelded to partially welded. Angular fragments and a lack of bedding rule out appreciable reworking by sedimentary processes. The distribution and thickness of some units suggest possible source areas near Goodwin's Tomb. The marker bed may have been derived from the area near the road intersection 1 km south of the Castle Rock Fire Guard Station (W 1/4 sec. 33 T. 17 S. R. 37 E.). In this area the marker bed contains dense fragments of Dinner Creek Ash-Flow Tuff, more than 8 cm long, which are not found elsewhere within the tuff sheet and probably could not have traveled far from the source area. Lowry (1968, p. 42) describes the remnant of a central volcano or vent related to these tuffs on the east side of Rail Creek (NW 1/4 SW 1/4 sec. 14, T. 16 S., R. 38 E.) at an elevation of 1,750 m (5200 feet), north of the Castle Rock area.

Olivine Basalt Member

Three of the youngest flows of the Strawberry Volcanics

are medium-gray, medium to fine-grained, diktytaxitic, porphyritic olivine basalt flows averaging 8 m in thickness (App. A, Sec. 2). Plagioclase and olivine are clearly visible in hand specimen. These rocks have dominant intergranular and subophitic textures, although an ophitic texture is found sporadically, and contain about 50 percent plagioclase (An_{58}), 10 percent olivine, 18 percent augite, 2 percent opaque minerals and about 20 percent vesicles.

AGE AND CORRELATION

No vertebrate fossils have been found within strata assigned to the Strawberry Volcanics. Lowry (1968) found fossil leaves and fronds but they were of an unidentifiable age. The Strawberry Volcanics are assigned herein, an age of very Late Miocene on the basis of stratigraphic position above the Late Miocene Dinner Creek Ash-Flow Tuff (14.3 m y; Walker and others, 1974) and below the Late Miocene to Early Pliocene Juntura Formation (12.1 m y; Evernden and James, 1964). The older rhyolitic flows at the base of the Strawberry Volcanics are considered equivalent to the Littlefield Rhyolite of Kittleman and others (1965) and Haddock (1967).

JUNTURA FORMATION

DEFINITION

The Juntura Formation was named by Shotwell (Gray, 1956) and was first described by Bowen (1956) and Gray (1956). The Juntura Formation was formally named by Bowen, Gray and Gregory (1963) in the region south and southwest of the Castle Rock area. The type section has three parts: an upper member at a quarry 5 km south of Pete's Mountain, the middle member at Juniper Hill, and the lower member north of Scab Mountain (McClellan Mountain). Strata of the Juntura Formation disconformably overlies rocks of the Strawberry Volcanics and are overlain by the basal crystal rich tuff of the Drewsey Formation with minor disconformity.

DISTRIBUTION AND THICKNESS

The Juntura Formation covers approximately 16 km² in the southern half of the thesis area, has a minimal stratigraphic thickness of about 150 m and may be over 300 m thick in the southeastern part of the mapped area. Regionally this formation is exposed over an area of at least 300 km² and has a combined thickness of about 420 m (Bowen and others, 1963).

LITHOLOGY

The Juntura Formation, in the south and southwest parts

of the Castle Rock area, consists of well-bedded lacustrine sediments. These strata include volcanic sandstones, tuffaceous clayey beds, water-laid tuffs, minor diatomite and interbedded ash. Thin palagonitic basalt flows, at least two and as many as five, are interbedded in the sediments throughout the area. Strata are generally light in color, poorly consolidated, but well stratified, showing many sedimentary structures.

Sedimentary Strata

The oldest strata in this area are light-brown to yellow clay-stones. Manganese dioxide staining along bedding planes gives this rock a deceptive dark-brown to black appearance. These beds may be over 100 m in thickness and, where not capped by more resistant strata, weather into large, round hills with a characteristic covering of loose, clayey "popcorn" soil (Fig. 19).

Above these lacustrine strata is a relatively thin but widely distributed volcanic sandstone bed. This sandstone unit is about 5 m in thickness and is generally fine-grained, light-greenish gray in color, well sorted with well-developed cross-bedding. Joints parallel bedding planes locally and solution of some parts has formed cavities within the rock. Stratigraphically above the sandstone bed is about 20 m of more indurated or well-compacted, light-brown to greenish, tuffaceous, clayey lacustrine sediments which have a well-developed thin bedding.

Figure 19. Composite stratigraphic section of the sedimentary strata of the Juntura Formation (measured in the SW 1/4 sec. 28, T. 18 S., R. 37 E.).

Volcanic Strata

From two to five olivine basalt flows, totaling over 40 m in thickness where all are present, are exposed above the lacustrine strata. A light-colored claystone interbed separates the lower two flows from the others. This interbed increases in thickness towards the south, probably away from the margin of the depositional basin. Near Horse Flat these basalts have a flow-on-flow relationship. The basalts are fine to medium-grained, dark-gray to black with olivine phenocrysts. In thin section the basalt is hypocrystalline with intergranular textures. The rock consists of about 60 percent plagioclase, 10 percent olivine, 5 percent magnetite, minor amounts of altered augite and 15 percent brownish opaque mineraloid alteration products.

In the north and northeastern parts of the area the formation is more volcanic than sedimentary in nature. In Jerry Canyon light colored pumice lapilli-tuffs and related fluviatile sedimentary lenses are the dominant lithologic types (Figs. 20 and 21). These strata are commonly light shades of green, brown, gray or white and are composed predominantly of pumiceous air-fall tuffs and minor conglomerates (App. A, Sec. 3). A lithologic comparison of the Juntura Formation within the Castle Rock area with that of the neighboring Juntura Basin shows considerable variation. Deposition of this formation in the Castle Rock area (the northern extremity of the Beulah Basin), while contemporaneous with deposition in the Juntura Basin, shows variations

Figure 21. Measured stratigraphic section of the volcanic strata of the Juntura Formation at the southeast end of Jerry Canyon (SW 1/4 sec. 23, T. 18 S., R. 37 E.).

in both lithology and volume.

AGE AND CORRELATION

Fossil leaves of Late Miocene age have been found near Beulah, Oregon (Russell, 1903). Fossils reflecting a shallow water lacustrine depositional environment, namely, fresh water mollusks, turtles and fish, as well as mammalian fossils in tuffaceous clayey beds, have been described (Gray, 1956).

The lower part of the Juntura Formation is believed to be Barstovian (Late Miocene) in age and the upper part has been dated as Clarendonian (Early Pliocene) by mammalian chronology (Shotwell and Russell, 1963, p. 43). Bowen and others (1963) indicate that fossil mammals from the Poison Creek Formation of Idaho, Deer Butte Formation in eastern Oregon, The Dalles Formation in north central Oregon, and the Truckee Formation in Nevada, are all correlatives with the upper part of the Juntura Formation. Similarly, the Danforth Formation is correlative to the middle part of the Juntura Formation (Bowen and others, 1963). The Bully Creek Formation and the Tim's Peak sedimentary and volcanic unit, as described by Haddock (1967), correlates with the upper and lower members of the Juntura Formation, respectively. Floras and faunas from the Mascall Formation, Sucker Creek Formation, "Skull Springs beds," and the "beds at Beatty Butte" indicate that these beds are roughly correlative with the lower member of the Juntura Formation (Chaney, 1959; Downs, 1956).

DREWSEY FORMATION

DEFINITION

Strata of the Drewsey Formation were first described by Bowen (1956) and Gray (1956) and the formation was formally named by Bowen, Gray and Gregory (1963), who designated exposures near Table Mountain north of the town of Drewsey along Mule Creek as the type section. Haddock (1967) mapped the basal crystal-rich ash-flow tuff of this formation north and east of Juntura, Oregon. Strata of the Drewsey Formation are the youngest within the Castle Rock area and overlie the Juntura Formation with minor disconformity.

DISTRIBUTION AND THICKNESS

The ash-flow tuff which forms the base of the Drewsey Formation is exposed over an area of about 4 km² within the Castle Rock area and has an average thickness of about 4 m. The upper sedimentary unit may measure up to 50 m in thickness, but exists predominantly as erosional remnants above the ash-flow. This formation has a regional extent of at least 250 km² and a thickness in excess of 300 m (Bowen and others, 1963). The more extensive ash-flow sheet may have covered an area of over 11,500 km², averaging 12 m in thickness and reaching a total volume of almost 65 km³ (Greene, 1973).

STRATIGRAPHY

No well-defined stratigraphic break between the Drewsey Formation and the Juntura Formation is found in the Castle Rock area. For this reason, beds of the Drewsey Formation were mapped in this report on the basis of their stratigraphic position above the rhyolitic ash-flow which forms the base of the section. With the exception of scattered erosional remnants, exposures of the Drewsey Formation are limited to the southeast part of the Castle Rock area along the North Fork of the Malheur River between the elevations of 1200 m (3,600 feet) and 1330 m (4,000 feet).

Only the basal rhyolitic welded ash-flow tuff member of the Drewsey Formation is well exposed in the thesis area. This tuff is very resistant to erosion and commonly forms a steep ledge which protrudes from the incompetent sediments surrounding it. The Drewsey welded tuff ranges from light greenish to olive-gray in color, is generally compact with a densely welded central zone surrounded by a thin envelope of lightly welded ash, displays flattening of glass shards and pumice fragments and has a prominent platy jointing. In thin section this rhyolitic tuff has a vitroclastic texture and is composed of 80 to 90 percent glass shards, 8-12 percent flattened lithic and pumice fragments, 6-8 percent quartz crystals, 3-5 percent feldspar crystals and minor amounts of magnetite and augite.

The strata above this bed are heavily mantled by talus

and vegetation. These beds are similar lithologically to the strata of the Juntura Formation exposed directly below the flow. Rocks above the ash-flow are predominantly light-brown clayey tuffaceous sediments. These sediments weather very readily and characteristically form very poor outcrops.

AGE AND CORRELATION

The welded tuff of the Drewsey Formation has been radiometrically dated at 9.2 ± 0.6 million years in age (Greene, 1973). The Drewsey Formation has produced Hemphillian mammalian fauna, which indicates that it may be correlative with the Rattlesnake Formation of the John Day Basin to the northwest (Bowen and others, 1963). Perhaps for this reason, Lowry (1968) mapped the Drewsey welded tuff as Rattlesnake Tuff even though he recognized the major lithologic difference and minor stratigraphic difference. Bowen and others (1963) suggest that the similarity of the sequence of lithologies in the Drewsey Formation suggests that it may also be correlative with the upper part of the Danforth Formation in the Harney Basin to the southwest. It is believed by the author that the Drewsey tuff, the crystal-rich tuff of the Danforth Formation and the Devine Canyon tuff, as described by Greene (1963), are not only correlative in age, but all may be parts of the same eruptive phase.

PLIOCENE TUFF PROBLEM

Haddock (1967) mentions that there are a number of welded ash-flow tuffs which could easily be mistaken for the Drewsey welded tuff, which occur in isolated areas of low relief at elevations between 1,400 m (4,200 feet) and 1670 m (5,000 feet). In some areas these tuffs may be the Drewsey tuff, but in several areas they definitely are not. Haddock (1967) described one such tuff capping a hill one mile east of Juntura as having a modal composition of 94 percent devitrified glass shards, 4 percent sanidine, and 2 percent lithic fragments. The absence of quartz phenocrysts was used to distinguish it from the Drewsey tuff.

Lowry (1968) described a welded tuff in the upper Bendire Creek area which contains abundant crystals of potash feldspar. The section he described thickens towards the southeast corner of the Ironside Mountain 30-minute quadrangle and may be thicker than 65 m locally. Lowry attributes the greater thickness and greater degree of welding to the proximity to its source area, about 1 km east of the quadrangle along and north of the old Central Oregon Highway, between the Old Hunter (Wilson) Ranch and the town of Westfall (Lowry, 1968). Near the source area pieces of flattened pumice over 30 cm in length were described within larger blocks of dark-gray welded tuff. Phenocrysts of potash feldspar and a perlitic groundmass serve to distinguish this from Drewsey tuff. This perlitic welded tuff is similar to that

which occurs in Pliocene lake beds in the first cliffs west of Juntura on the north side of U. S. Highway 20, a unit mapped as Drewsey welded tuff by Bowen and others (1963) and Lowry (1968). Bowen and others (1963) mentioned the lack of plagioclase phenocrysts as characteristic of the Drewsey welded tuff except in inclusions. However, a few plagioclase phenocrysts were seen in thin sections of the Devine Canyon tuff, as mapped by Greene, Walker, and Corcoran (1972) in the northern portion of sec. 26, T. 18 S., R. 34 E. Other than these few phenocrysts, the rocks are nearly identical. Greene's (1973, p. 5 and 6) extensive study of the Devine Canyon welded tuff infers that it is part of the same ash-flow which formed the Drewsey welded tuff. The Drewsey (Devine Canyon) tuff sheet may be a multiple flow compound cooling unit derived from scattered vents between Castle Rock and the town of Burns, Oregon. Haddock (1967) mentions that welded tuffs very similar in lithologic characteristics and stratigraphic position occur as far north as Silvies Basin. Greene (1963) mentions that the variation in alkali feldspar and quartz phenocrysts is the outstanding feature of the welded tuff. Alkali feldspar phenocrysts are described as ranging from 1 to 29 percent, increasing stratigraphically upward within the flow and decreasing dramatically away from the source area. This variation has been used to recognize other similar crystal-rich tuffs, but more sophisticated methods such as trace element analyses may delineate other tuff sheets. However, no one has attempted to differentiate

between these tuffs or determine how many there might be. In the future, with accumulation of more data, the close lithologic and stratigraphic similarities and extreme lateral and vertical variations within the individual flows will be better understood, and discrimination of individual flows a less difficult task.

SURFICIAL DEPOSITS

ALLUVIAL FAN DEPOSITS

Alluvial fan deposits consist of unsorted or poorly sorted mixtures of gravel, sand and colluvium which accumulated in times of heavy runoff. The best developed fans are along the western side of the North Fork of the Malheur River Valley where small intermittent streams abruptly lose their gradient upon entering the flat alluvial valley. These fan deposits have caused the river's position to shift eastward and undercut the pediments (secs. 13, 18, & 19, T. 18 S., R. 37 E.). An older (possibly Pleistocene) alluvial fan formed when this river was at a level graded to the upper pediment surface southeast of Horse Flat.

LANDSLIDE DEPOSITS

Scarps caused by faulting and oversteepened slopes along water courses are responsible for landsliding within the Castle Rock area. A very prominent rotational landslide block has moved downslope on the west side of the Castle Rock ridge, disturbing an area exceeding 1 km² (Figs. 22 and 23). The head of the landslide characteristically has an arcuate scarp above a flat bench which dips back into the hillside. The toe of the slide is marked by hummocky terrain with many springs and undrained depressions. The upper pillow pala-

Formation as well as the Strawberry Volcanics are equally affected structurally. Most structural deformation appears to have occurred after deposition of the Juntura Formation.

Emplacement of the Dinner Creek dikes along north-trending fissures caused local faults adjacent to volcanic centers. Subsidence at Black Butte is marked by volcanic strata dipping inward as steeply as 18 degrees within an area of 5 km radius. Black Butte may have subsided as much as 2 km relative to Castle Rock.

GEOLOGIC HISTORY

In Late Miocene time numerous eruptions south of the Castle Rock area sent over 25 pahoehoe flows and breccias of the "unnamed igneous complex" to bury the pre-Tertiary strata to a depth of at least 650 m. While this complex of lava flows was building up, small streams were dammed and lava flows spilling into the temporary lakes formed palagonitic breccias. In some instances breccias displaced water or built barriers allowing the lava flows to flow across or around lakes and solidify as compact lava. Some of the pahoehoe flows may have reached the proportions of flood basalts in volume and other relatively thin flows ponded by filling depressions and solidified as lakes of lava, developing a contorted columnar joint pattern as the lava slowly moved during cooling. Time intervals between flows were not long enough for soil horizons to develop, although small deposits of stream gravels and diatomite accumulated locally. After volcanism ceased a period of quiescence allowed nearly 800 m of erosional and structural relief to develop within the "unnamed igneous complex."

Eruption of the rhyolitic Dinner Creek Ash-Flow Tuff from the areas of Castle Rock and Black Butte marked the beginning of a new volcanic episode. Air-fall pumice lapilli marked the resumed volcanic activity and was shortly followed by the eruption of the Dinner Creek Welded Ash-Flow Tuff

originated as a fiery cloud (nuée ardente) from the vent at Black Butte and zones of flank eruptions, one of which is represented by the dike at Castle Rock. Hot avalanche deposits indicate that several eruptions took place within a short time interval. Before or contemporaneous with extrusion, a north, north-south fault system developed within the older basaltic rocks. During this eruptive phase the basaltic flows between Black Butte and Castle Rock were uplifted and subsequently collapsed after volcanic activity ceased.

Considerable erosional and structural relief developed in the Dinner Creek Tuff sheet, re-exposing basaltic flows of the "unnamed igneous complex" in places. Thick accumulations of volcaniclastics, rhyolitic lava flows and breccias of the Strawberry Volcanics then filled a basin around Black Butte and Lost Creek Valley. These silicic volcanics were in turn capped by a succession of basalt and dacite lava flows. These volcanic strata were folded into a broad anticline and syncline with strata around Black Butte, dipping circularly inward, reflecting subsidence in that area. Faults also developed with continued tectonic adjustment.

A period of erosion and continued faulting preceded deposition of the tuffaceous sediments of the Juntura Formation, which restricted these Late Miocene to Early Pliocene lacustrine sediments to a basin in the southern half of the area. These strata are the only extensive sedimentary rocks exposed within the area.

By the Middle Pliocene age a volcanic eruption far to the south in the region around Burns sent the Drewsey Tuff ash-flow into the Castle Rock area (Greene, 1973). By the time the ash flow reached this region it was as thin as 4 m and its northward journey ended on the lower slopes of the mountains in the northern half of the area. After deposition of the Drewsey Tuff a minor lake formed in the southwest corner of the area where tuffaceous sediments were deposited on top of the ash-flow.

In Pleistocene time a river flowed across the southwest corner of the area. This stream had a very low gradient and planed the soft lacustrine sediments into a broad, flat valley. Along tributary streams alluvial fans formed and landslides developed and are exposed today on the southwest end of the Castle Rock ridge, stranded 470 m above the present stream level.

In recent times, the North Fork of the Malheur River has cut back down through most of the lacustrine sediments, exposing older volcanic rocks and leaving the Pleistocene pediments, landslides, and alluvial fans stranded high above the present stream level. New alluvial fans and landslides are developing along the present-day river. Faulting has probably continued to the present day and although no recent volcanism has occurred, the presence of hot springs and hydro-thermal alteration suggest it is only dormant.

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APPENDIX A

STRATIGRAPHIC SECTION DESCRIPTIONS

SECTION 1: UNNAMED IGNEOUS COMPLEX

SECTION 2: STRAWBERRY VOLCANICS

SECTION 3: JUNTURA FORMATION

APPENDIX A

SECTION 1: UNNAMED IGNEOUS COMPLEX

(Descriptions are below, section appears in Fig. 10 in text.)

CASTLE ROCK SECTION

(Secs. 15 & 16, T. 18 S., R. 37 E., at the southeast end of the Castle Rock ridge.)

Unnamed Igneous Complex

Meters

25. Dense fine-grained basalt:

Dark-gray to black, reddish where weathered; fine-grained, very dense basalt. Blocky-jointed. Upper 1.5 m of the flow is vesicular. ----- 7.6

24. Dark, fine-grained basalt:

Dark-gray to black; fine-grained, plagioclase rich basalt. This flow has a lower vesicular zone which grades upward into a zone of columnar jointing with a 0.3 m joint spacing. Within the columnade are vesicle tubes consisting of vertical three-dimensional tube-shaped structures which are highly vesicular and surrounded by dense lava. ----- 6.0

22. Dark, fine-grained olivine basalt:

Dark-gray to black; fine-grained, plagioclase

Unnamed Igneous ComplexMeters

clase and olivine rich basalt. A 1 m
thick vesicular zone at the base, over-
lain by a 5 m thick zone of columnar
jointing. ----- 8.0

21. Dark, fine-grained basalt:

Dark-gray to black, weathering reddish in
color; fine-grained basalt. An irregular
vertical columnade with a 1 m joint spa-
cing is common. Contacts are sharp. ---- 7.6

20. Dark, fine-grained basalt:

Dark-gray to black, weathering red in
color; fine-grained basalt. The lower
2 m of flow is dense with a poorly
developed platy jointing and a 1.5 m
vesicular zone is present below the upper
contact. This flow has a normal remnant
magnetic polarity. ----- 33.4

19. Dark, medium-grained basalt:

Dark-gray to black; medium-grained; pyro-
xene, olivine and plagioclase rich basalt.
Many plagioclase crystals have a bluish
cast, possibly indicating a labradoritic
composition. Nearly the entire flow
displays a highly irregular or contorted
columnar structure. Columns are horizon-
tal in places and end abruptly into a

Unnamed Igneous ComplexMeters

weathered surface at the top of the
flows. ----- 36.5

18. Covered interval:

Among basaltic talus, float from a
white crystal-lithic-tuff with black
glass fragments and a light-colored
porcelinite type rock was found. ----- 16.7

17. Olivine basalt:

Medium-gray; medium to fine-grained;
olivine, and plagioclase rich basalt.
Columnar jointing is well-developed. --- 25.8

16. Olivine basalt:

Medium-gray; fine-grained; dense,
olivine and plagioclase rich basalt.
This flow has a very well-developed
columnade which has a 0.6 m joint
spacing and is 32 m thick. The tops
of the columns are radially bent
towards the south and southwest. This
may represent the downslope direction
of the flow, indicating its source in
an east or northeast direction. This
flow might represent ponding of a
generally much thinner lava flow. The
upper 17 m of this unit is very poorly
exposed. ----- 49.0

Unnamed Igneous ComplexMeters

15. Dense, fine-grained basalt:

Medium-gray, weathering light-gray; fine-grained; dense, basalt. The central part of the flow is columnar jointed with flow laminations developed normal to the columns. The lower 2 m of the flow is a platy entablature. The upper contact is heavily mantled with talus. ----- 15.3

14. Olivine basalt:

Dark-gray to black; fine to medium-grained olivine basalt. The lower 1.5 m of this flow is a compact scoriaceous zone. This zone grades upward into 14 m of entablature. Above the entablature is a 4.6 m vesicular zone. ----- 19.8

13. Pillow-palagonite-breccia:

Dark to light-brown, weathering to a yellowish color; Pillows and basalt fragments are generally porphyritic, dense and palagonitic in the cores. Pillows are encased in a thick crust of dark glass and surrounded by a matrix of fine-grained palagonitic breccia. Pillows are commonly highly elongated or flattened, some measuring 3 m in length and only 0.3 m in thickness. Foreset

Unnamed Igneous ComplexMeters

bedding dipping about N10E may indicate a flow direction from the southwest. Fragments within the breccia have a weak normal remnant magnetic polarity. ----- 30.0

12. Fine-grained porphyritic olivine basalt:

Dark-gray to black; fine-grained, finely porphyritic olivine and plagioclase rich basalt. A well-developed 2.8 m thick columnade with a 0.5 m joint spacing is present at the base of the flow. This columnade becomes very irregular near the top of the flow. ----- 15.5

11. Fine-grained porphyritic olivine basalt:

Dark-gray to black; fine-grained basalt or basaltic andesite. Bright orange-red phenocrysts believed to be altered olivine form almost 2 percent of the hand specimen. Vesicularity increases toward the top of the flow. ----- 9.0

10. Dark, porphyritic olivine basalt:

Dark-gray to black; porphyritic, olivine and plagioclase rich basalt. This flow has a 1.5 m vesicular zone at its base and is amygdaloidal in places. Phenocryst and vesicle fillings decrease in

Unnamed Igneous ComplexMeters

number upward in the section. The phenocryst distribution is probably related to crystal settling during flow. Increased number of vesicle fillings is probably related to the permeable nature of the basal contact and the much lower permeability of the flow's interior. ----- 6.0

9. Olivine basalt:

Dark-gray to black; medium to fine-grained olivine basalt. The basal part of the flow is dense. The upper portion is highly vesicular and oxidized to a pale red color. Amygdales of a zeolite mineral are found scattered throughout the flow. ----- 6.1

8. Porphyritic basalt:

Dark-gray to black; fine-grained; porphyritic plagioclase and olivine rich basalt. Plagioclase phenocrysts may measure up to 6 mm in length and olivine crystals may measure up to 2 mm in diameter. Phenocrysts are noticeably more abundant lower in the flow, suggesting crystal settling. Columnar jointing is poorly developed. The lower 3 m of this flow is a palagonitic breccia which grades upward into dense,

Unnamed Igneous ComplexMeters

dark-colored porphyritic basalt. The transition zone, from palagonitic to fresh lava is oxidized to shades of lavender in places. This lava flow has a normal remnant magnetic polarity. ----- 15.2

7. Dark, fine-grained basalt:

Dark-gray to black; weathering to a light-brown color; aphanitic basalt. A poorly developed columnar joint set with a 0.6 m spacing is common. The flow breaks readily into blocks about 0.3 m³. ----- 14.0

6. Dark, fine-grained basalt:

Dark-gray to black; medium-grained to aphanitic basalt. Three zones of columnar jointing are present above a basal palagonitic zone. The zone contacts are sharp and columns 0.3 m in width become more irregular near the top of the flow. A basal 0.6 m thick vesicular zone underlies a columnade. In places the lower 1.5 m of the flow is a palagonitic breccia. ----- 13.9 .

5. Dark, fine-grained olivine basalt:

Black to dark-gray; fine-grained, plagioclase and olivine rich basalt. Columnar

Unnamed Igneous ComplexMeters

jointing with a 0.15 to 0.3 m spacing
 is poorly developed. A 0.3 m thick
 vesicular zone occurs near the basal
 and upper contacts of the flow. ----- 15.0

4. Light-colored, olivine basalt:

Medium to light-gray, weathering to
 small black to light-brown pellets;
 fine-grained, plagioclase and olivine
 rich basalt. An 8 cm joint spacing
 is prominent. ----- 14.0

3. Pillow palagonite breccia:

Basalt fragments are dark-gray; aphanitic
 and dense. Outcrops weather into blocks
 about 3 m³ in size related to an incon-
 sistent 3 m joint spacing. Basalt pillows
 are several feet in diameter; many are
 angular and broken and are surrounded by
 a relatively fine palagonitic breccia.
 Zeolitization is common in veins and cavi-
 ties. Well-developed foreset bedding
 indicating a flow direction on a bearing
 of about N30W suggests deposition from
 the southwest. The basal contact is deeply
 eroded and dusted with diatomite. The
 outcrop has an irregularly exposed upper
 contact which weathers into rounded spires

Unnamed Igneous ComplexMeters

or pinnacles locally. ----- 18.5 - 33.0

2. Dense, aphanitic to porphyritic basalt:

Black to dark-gray, weathering to a dark reddish brown; dense, fine-grained aphanitic to slightly porphyritic basalt. Outcrop displays a poorly-developed 10 cm joint spacing which decreases to 2.5 cm near the top, allowing the rock to fracture into small angular, platy fragments. The basal contact is deeply weathered below a 0.5 m vesicular zone. ----- 14.0

1. Dark, coarse-grained olivine basalt:

Black to dark-gray, weathering into black to light-brown pellets; medium to coarse-grained, almost diabasic, plagioclase and olivine rich basalt. The outcrop weathers into large bulbous masses about 1.m in diameter formed from deeper weathering along joints. A 0.3 m vesicular zone is exposed below the upper contact of the flow. ----- 9.0

- Poorly exposed lava flows of the "unnamed igneous complex."

Total

410.2
Meters

SECTION 2

STRAWBERRY VOLCANICS

(Descriptions are below, sections appear in Fig. 16 in text.)

Composite of Lost Creek Sections

(Secs. 19 and 20, T. 17 S., R. 37 E., along Lost Creek.)

Strawberry Volcanics

Meters

28. Dark, aphanitic basaltic lava flow:

Dark-gray to black; aphanitic basaltic
or more silicic lava flow, with a
poorly developed greenish mineral layer-
ing along platy jointing surfaces. ----- 22.5

27. Dark, aphanitic basaltic lava flow:

Dark-gray to black; very fine-grained
basaltic of more silicic lava flow.
Green mineral layering, probably altera-
tion products occur along a primary flow
layering. ----- 9.0

27. Dark, aphanitic basalt:

Dark-gray to black; aphanitic, basaltic
lava flow ($\text{SiO}_2 = 46 \pm 2$ percent, sample
75JW081, App. B, Tab. 3). The outcrop
shows some viscous flow structures common
to more silicic flows and green mineral
laminations along flow layering. A reddish

Strawberry VolcanicsMeters

- baked zone occurs below the basal
contact. ----- 21.0
25. Covered interval:
Heavy mantling of basaltic talus. ----- 6.5
24. Porphyritic basalt:
Medium-gray, weathering light-gray; open-
textured, porphyritic, olivine and plagio-
clase rich basalt. ----- 7.6
23. Porphyritic basalt:
Medium-gray, weathering light-gray; open-
textured, porphyritic olivine and plagio-
clase rich basalt. Plagioclase pheno-
crysts measure up to 3 mm in length.
This flow is very similar to unit 22. ---- 9.1
22. Porphyritic basalt:
Medium-gray, weathering light-gray; open-
textured, porphyritic, olivine and plagio-
clase rich basalt. A rudely developed
columnade with a 0.6 m to 1.2 m joint
spacing is common. The flow is finely
vesicular from top to bottom and displays
blue and green mineral coatings on some
vesicle interiors. ----- 9.1
21. Light-brown, pumice lapilli-tuff:
Light-brown, dark-brown when weathered;
pumice fragments measure up to 15 cm

in length but most are lapilli size.

The upper part of the tuff has been oxidized to a bright orange color, where it was baked by the overlying lava flow. -----

38.0

20. Light-brown, pumice lapilli-tuff:

Light-brown, dark-brown to dark-gray where weathered. Slightly elongated pumice fragments and obsidian-like glass fragments about 0.75 cm in length are common. The lower 6 m of this unit is incipiently welded and weathers into bulbous, hoodoo-like masses. The central 7.6 m part of this unit is lightly welded and grayer in color. This zone of light welding stands out in outcrop in a pseudo-columnade. -----

14.5

19. Covered interval:

Heavy soil cover. -----

5.0

18. Black, aphanitic andesite:

Black to dark-gray; glassy, aphanitic andesite ($\text{SiO}_2 = 52 \pm 2$ percent, App. B, Tab. 3). There is a 4.6 m basal vesicular zone with vesicles showing elongation due to flowage. Above this, is a 32 m thick zone of contorted jointing

Strawberry VolcanicsMeters

along mineral layering and ramping
structures. An upper auto-brecciated
zone about 3 m in thickness is also
present. ----- 38.0

17. Covered interval:

Heavy soil and talus. ----- 8.0

16. Brownish-gray pumice lapilli-tuff:

Light to medium brownish-gray; consisting of 10 percent elongated pumice fragments and 5 percent lithic fragments ranging from 0.5 to 2.5 cm in length. The matrix is a fine dark-brown pumiceous ash which gives the rock a dirty appearance. This unit is easily eroded due to its general incompetence and a widely spaced joint set. The upper part of the unit is more resistant but large cavities have been weathered into it. ---- 52.0

15. Covered interval:

Heavy soil cover. ----- 10.0 - 14.0

14. Pumiceous crystal lapilli-tuff:

Light brownish-gray; pumice fragments are orange, black, and gray, averaging about 4 mm in diameter. Feldspar crystals and glass fragments up to 4 mm

Strawberry VolcanicsMeters

- in length are present. A matrix of
light-gray ash comprises 70 percent
of the rocks. ----- 9.2
13. Covered interval:
Heavy soil cover. ----- 32.0
12. Pumiceous sedimentary ash:
Light brownish-gray to white; the lower
2 to 3 m is very fine and easily eroded
ash while the upper 2-3 m is composed of
reworked tuff, darker in color and much
more resistant to erosion. This upper,
coarser-grained zone has black glass and
lithic fragments about 4 mm in diameter. -- 4.5
11. Dark, fine-grained silicic lava flow:
Black to dark-gray; glassy, aphanitic with
pinkish glassy streaks and green mineral
banding along flow layering. -----10.5
10. Light, pumice lapilli-tuff:
Light to medium brownish-gray; lightly
welded and composed of orange, white, and
black pumice fragments and black obsidian-
like glass fragments in a matrix of brown
ash. ----- 10.7
9. Pumice lapilli-tuff marker bed (Tsvm):
Medium-gray; pumice fragments average
3 cm in diameter within a groundmass of

Strawberry VolcanicsMeters

smaller light-gray pumice and dark-glass fragments averaging 4 mm in diameter.

The unit has a poorly-developed vertical joint set and a horizontal platy jointing with a 0.6 m spacing. This unit is lightly welded and in places forms ledges. The lower 1.5 m is composed of white to light-gray sedimentary ash which readily weathers and is very uniform in thickness. ----- 18.0

8. Pumice lapilli-tuff:

Medium-gray, pumice fragments average 3 cm in diameter within a groundmass of smaller light-gray pumice and dark glass fragments averaging 4 mm in diameter, being very similar to unit 9. Fragments increase in size towards the top where they are about four times as large. This unit weathers into hoodoos or spires. ----- 15.0

7. Covered interval:

Heavy soil cover. ----- 7.0

6. Light, ashy pumice bed:

Light-gray, weathering to a light to medium-brown where weathered. This unit is rhythmically layered with fine and coarser pumice fragments with some larger

Strawberry VolcanicsMeters

lenses of white pumiceous ash. ----- 3.0

5. Volcanic conglomerate:

Yellow to brown; coarse-textured, volcanic conglomerate consisting of about 50 percent reworked tuff-breccia.

Elongated or flattened pumice fragments measure up to 15 cm in length. Basaltic and silicic lithic fragments comprise about 50 percent of the unit. These fragments are nonsorted and most commonly fall within a 0.5 to 7.5 cm size range. ----- 1.5

4. Volcanic sandstone:

Medium to light-gray; well compacted and moderately dense. Bedding structures are well-developed. ----- 4.6

3. Light, pumice lapilli-tuff:

Light-gray to brown; pumice fragments are elongated and flattened within a ground-mass of ash. Fragments decrease in size upward within the unit. Lenses of coarser material appear at the base of the unit and lithic fragments of basalt up to 5 cm in length are present. Bedding structures are well-developed near the top of the section. ----- 4.5

Strawberry VolcanicsMeters

2. Light, pumice lapilli-tuff:

Light to medium-gray; obsidian-like glass fragments and lithic fragments of pumice average about 4 mm in diameter within a matrix of fine medium-gray ash. This unit is nonwelded and the top 1.5 m shows fine bedding structures. ----- 3.0

Immediately above this unit a thin layer of white ash possibly mixed with some diatomite. This is a distinctive marker bed where exposed. ----- 0.3

1. Pumice lapilli-tuff:

Grayish-purple to white; composed of lapilli-size pumice fragments in a variety of colors with a few fragments of Dinner Creek Tuff and basalt. This unit shows signs of sedimentary reworking and has an irregular contact above the Dinner Creek Ash-Flow Tuff. ----- 3.0

- Dinner Creek Welded Ash-Flow Tuff

Total 379.1
Meters

SECTION 3

JUNTURA FORMATION

(Descriptions are below, section appears in Fig. 19 in text.)

Jerry Canyon Section

(NE 1/4 SW 1/4 sec. 23 T. 18 S., R. 37 E.; at the southeast end of Jerry Canyon.)

Juntura Formation

Meters

23. Light, pumice lapilli-tuff:

Light to medium-brown; dense, fibrous pumice fragments from 2 mm to 1 cm in size comprise about 30 percent of the rock. Lithic fragments and crystals are sparse and a matrix of fine ash forms about 65 percent of the rock. The upper 3 m of this flow has been completely reworked by sedimentary processes and bedding structures are

- well-developed. ----- 4.5

22. Light, tuffaceous sandstone:

Light to medium-gray; very fine-grained with interbedded layers of white to light-brown pumice and lithic fragments. ----- 3.0

Juntura FormationMeters

21. Light, welded ash-flow tuff:

Light brownish-gray; lightly to moderately welded, composed of welded and/or devitrified ash size pumice fragments with minor crystals and lithic fragments.

Some pumice fragments measure up to 1.5 cm in length, but 2 mm in diameter is the most common size. Light orange, brown, gray and reddish pumice fragments are welded densely enough to make this flow a good ridge former. ---- 7.5

20. Light, pumice lapilli-tuff:

Light to medium bluish-gray; well compacted. Medium to dark-gray pumice fragments averaging 5 mm in length comprise from 50 to 10 percent of this rock. These fragments show flattening in places and are well embedded in a bluish-gray coarse pumaceous ash. Ash fragments are 2 mm in diameter or smaller. ----- 4.5

19. Covered interval:

Heavy soil cover. ----- 6.0

18. Light, pumice lapilli-tuff:

Light to medium-brown; composed of dense

Juntura FormationMeters

fibrous pumice fragments ranging from 2 mm to 1 cm in size comprising up to 30 percent of the rock. Medium-gray and black lithic fragments averaging less than 2 mm in length comprise 3 to 5 percent of the rock and a fine, light-gray to buff-colored pumiceous ash forms the matrix. ----- 1.5

17. Porphyritic basalt:

Dark-gray to black; very fine-grained, dense porphyritic basalt. Plagioclase phenocrysts about 2 mm in length and olivine comprise over 10 percent of the rock. Locally the glassy groundmass has a lavender tinting in places. ----- 4.5

16. Olivine basalt:

Medium to dark-gray; weathering to a dark to medium-brown; fine-grained, and dense with a poorly developed platy jointing. This flow is poorly exposed and weathers to a sandy material in places. -----13.7

15. Covered material:

Heavy soil cover. ----- 7.5

14. Light, pumice lapilli-tuff:

Light-brown; lightly welded, ash-flow tuff. This rock is composed of 50 percent

Juntura FormationMeters

white fibrous pumice, 30 percent sanidine crystals within a matrix of light-colored ash and minor lithic fragments. --- 3.0

13. Dark, fine-grained basalt:

Dark-gray to black, fine-grained basalt. A columnar joint set with a 1 m spacing and a platy jointing developed normal to it are common. This flow is vesicular near the basal and upper contacts with a 0.3 m reddish oxidized baked zone at the base. ----- 3.0

12. Dark, fine-grained olivine basalt:

Dark-gray to black weathering light-brown; fine-grained, amygdaloidal olivine rich basalt. The rock itself is spotted with green alteration products and weathers to a fine-sand. The outcrop weathers to low profile bulbous masses about 0.3 m in width possibly reflecting deep weathering along joints. A 0.2 baked zone forms the base of this flow. ----- 7.6

11. Light-pumice lapilli-tuff:

Light to medium-gray; lightly welded, consisting of 40 percent large white flattened pumice fragments, ranging from 1 to 8 cm in length averaging about 2 cm in length, 2 percent black glass fragments averaging 2 mm

Juntura FormationMeters

in diameter, 2 percent red and black lithic fragments averaging 2 mm in diameter and minor sanidine and quartz crystals. Pink and gray pumice fragments averaging 1 cm in length comprise 10 percent of the rock and the remainder is a matrix of light-gray ash. Within the lower 3 m of the flow fragments are 50 percent smaller and the upper 3 m has been reworked and sorted by water action.--12.0

10. Light tuffaceous and volcanic sediments:

Alternating beds of light-gray and light-brown beds of reworked pumaceous air-fall material. Light-brown beds have an ashy texture, while light-gray beds have a more sandy texture. About 10 m above the base of this unit are 0.8 m thick lenses of pebble conglomerate, probably of fluvial origin. Lithic fragments with the conglome include quartzite, basalt, obsidian and pumice. Above the conglomerate lenses are 1.2 m of white very fine-grained tuffaceous sediments. -- 12.0

9. Pumiceous crystal-lithic tuff:

Light-brown to light-gray; loosely con-

Juntura FormationMeters

solidated, sanidine crystals are abundant. Lithic fragments comprise 15 percent of the rock and are red, green, gray, orange, and black in color. Lapilli-size pumice fragments up to 2 cm in length form the bulk of the rock. ----- 3.0

8. Porphyritic olivine basalt:

Dark-gray, medium-gray where weathered; medium to fine-grained, porphyritic olivine and plagioclase rich basalt. The lower 1.8 m of the flow is oxidized to a bright reddish color and is highly vesicular. The flow has another vesicular zone below the upper contact. ----- 5.0

7. Pumice lapilli-tuff:

Medium-brown, moderately dense, with pumice fragments measuring up to 4 cm in diameter. The rock is lightly welded and very tough with a fibrous texture. ---- 3.0

6. Light, pumice lapilli-tuff:

Light-gray, weathering white; fibrous pumice fragments average about 8 mm in length, form the bulk composition of the rock. Lithic fragments and black glass fragments comprise about 5 percent of the rock. ----- 1.2

Juntura FormationMeters

5. Light, pumice lapilli-tuff:

Light-brown; pumice fragments average
8 mm in length, surrounded by an ashy
matrix. ----- 1.2

4. Light, pumice lapilli-tuff:

Light to medium-gray; pumice fragments
measure up to 2.5 cm in length and
average about 8 mm in length. Less than
2 percent of this rock is composed of
lithic fragments. The basal contact is
sharp and the upper 10 cm of this unit
has been reworked, possibly due to
wind. ----- 5.0

3. Pumiceous lithic lapilli-tuff:

Light green to yellowish gray, yellowish
where weathered; incipiently welded, com-
posed of lithic and glass fragments com-
prising 5-10 percent of the rock, light-
brown and light-gray pumice fragments
compose 50 percent, and a fine greenish-gray
to yellow ashy matrix with minor sanidine
crystals comprise the remainder of the rock.
Pumice, glass and lithic fragments are
between 2 to 5 mm in length, generally much
smaller than pumice fragments. Decompo-
sition of light-colored pumice fragments

Juntura FormationMeters

and ashy groundmass into clays gives the
 rock a yellowish appearance. The basal
 contact is very sharp and conformable
 with unit 3. ----- 3.0

2. Light, pumiceous ash:

Light greenish-gray, incipiently welded,
 pumiceous ash. Light to dark-brown and
 gray to black pumice fragments about 2 mm
 in length comprise about 10 percent of
 the rock. Greenish-gray, pumiceous ash
 with small transparent crystals comprise
 the bulk of the rock. ----- 3.0

1. Dark, porphyritic basalt:

Black to dark-gray, weathers dark to medium
 brown in color. When weathered the flow
 forms large, rounded bulbous masses heavily
 mantled by a coarse, dark-brown, sandy
 decomposition products. ----- 9.0

- Rhyolitic breccia of the Strawberry Volcanics
 (Tsvr).

Total 123.7
 Meters

APPENDIX B

GLASS-BEAD SILICA DETERMINATION FOR A SUITE OF VOLCANIC ROCKS FROM THE CASTLE ROCK AREA, OREGON

INTRODUCTION

The refractive index of a volcanic glass is inversely proportional to its silica content; the higher the silica content, the lower the refractive indices (Stark, 1904; George, 1924; and others). For control purposes a correlation curve for a suite of volcanic rocks from the nearby Owyhee Plateau (Kittleman, 1963) was obtained in order to plot glass-bead samples from the Castle Rock area. This curve was experimentally derived, with refractive indices plotted against chemically determined silica (Fig. 26). These samples proved to fall along a near linear scale, with nearly all samples falling within a 1.8 percent error range believed adequate for this test (Mathew, 1951). Refractive indices for rocks of the Castle Rock area were plotted on this graph in order to determine their silica content (± 1.8 percent). For additional control, a basalt standard (USGS, W-1) and an obsidian standard (USGS, 0-16) of known silica content were analyzed and plotted. A sample of Littlefield Rhyolite of known silica content (Haddock, 1967) was also plotted. The two U. S. Geological Survey standards were close to falling within the 1.8 percent error range and

Figure 26. Glass-bead silica determinations for a suite of volcanic rocks from the Castle Rock area of eastern Oregon.

the Littlefield rhyolite proved to be within a 0.5 percent error range.

Additional glass-bead analyses plotted in Figure 27 show an uneven chemical distribution of volcanic rocks with four major groups being basalt, basaltic andesite, dacite and rhyolite. All analyses and the sample locations are listed in Table 2, with their exact locations plotted on Plate 1.

PRACTICAL APPLICATION

The glass-bead silica technique is simple, rapid, inexpensive and may be done in the field. This method is adequate for correlation purposes and obtaining compositional control on black, glassy lava flows for classification purposes. The method is useful within areas of basalt, andesite and rhyolite associations, where rocks may be too fine-grained for modal analysis and mineralogy is deceptive. This method can be of assistance in recognition of the approximate composition of a rock, enabling determination of volumetric and stratigraphic distributions without a large number of expensive chemical analyses or tedious and often uncertain microscope work. Besides correlating stratigraphic units, compositional variations within ash-flows may be determined.

THE METHOD

- a) A rock specimen (approximately 10 grams) is first

Figure 27. Scatter diagram showing the range in silica content of some volcanic rocks from the Castle Rock area. Four compositional groups are recognized, with intermediate rocks confined to two general regions on the diagram.

TABLE II

SUMMARY OF GLASS-BEAD DETERMINATIONS FOR THE CASTLE ROCK AREA

Sample Number	Formation	SiO ₂ (Percent)	Refractive Index	Sec.	Location Township	Range	Sample Description
74JW10	Tsv	73.0	1.490	30	T. 18 S.	R. 37 E.	Rhy. brec.
75JW02	Tsv	64.0	1.526	33	T. 18 S.	R. 37 E.	Sil. flow
75JW07	Tjb	47.5	1.597	33	T. 18 S.	R. 37 E.	Bas. flow
75JW07	Tjb	46.5	1.603	"	"	"	Repeat
75JW22	Tdc	71.5	1.495	9	T. 18 S.	R. 37 E.	Rhy. ash-flow
75JW25	Tuic	43.0	1.617	9	T. 18 S.	R. 37 E.	Bas. flow
75JW27	Tuic	45.0	1.610	9	T. 18 S.	R. 37 E.	Bas. flow
75JW31	Tsv	63.5	1.528	5	T. 18 S.	R. 37 E.	Sil. flow
75JW32	Tsv	46.0	1.605	4	T. 18 S.	R. 37 E.	Bas. flow
75JW35	Tsv	43.5	1.615	33	T. 17 S.	R. 37 E.	Bas. flow
75JW48	Tsv	52.5	1.574	31	T. 17 S.	R. 37 E.	And. flow
75JW50	Tsv	41.0	1.626	29	T. 17 S.	R. 37 E.	Bas. flow
75JW60	Tuic	45.0	1.607	21	T. 18 S.	R. 37 E.	Bas. flow
75JW73	Tsv	46.5	1.603	33	T. 17 S.	R. 37 E.	Bas. flow
75JW80	Tsv	45.5	1.608	11	T. 18 S.	R. 37 E.	Bas. flow
75JW81	Tsv	51.5	1.581	19	T. 17 S.	R. 37 E.	Bas. flow
75JW84	Tsv	45.0	1.607	19	T. 17 S.	R. 37 E.	Bas. flow
75JW93	Tsv	51.5	1.581	30	T. 18 S.	R. 37 E.	Bas. flow
75JW98	Tdt	73.0	1.489	13	T. 18 S.	R. 37 E.	Rhy. ash-flow

(See Plate I for exact locations)

finely powdered to a sieve size less than 80 mesh with a machined steel mortar. All of any given rock fragment was crushed and no size fraction was discarded. This prevents any error due to differential breakdown of the various mineral constituents.

b) A magnetic separation was done with a small magnet to remove iron filings. Use of too strong of a magnet may result in removal of magnetite and other ferromagnesian minerals, resulting in increased error. The later separation may be done by dragging the magnet across the under side of a piece of paper containing the sample.

c) The sample is then fused into glass beads to homogenize the sample by the elimination of water and bringing the iron to a uniform oxidation state. The significant changes brought about in the composition of rock as a result of melting are essentially loss of the most volatile constituents, notably water, and changes in the oxidation state of iron.

A small amount of powder (approximately 1 gram) was then placed on an asbestos sheet and fused with a (double electrode) carbon arch torch to produce the glass beads. The torch was powered by a Lincoln arch welder set at about 60 amperes. The resulting glass beads range from about 0.5 mm to 1 mm in diameter.

d) The beads were then crushed and glass fragments free of inclusions selected for measurement.

e) Measurement of refractive indices was done with immersion oils in monochromatic sodium illumination directly on the Zeiss refractometer. Some beads have a small range of indices, in this case an estimated mean was used. Contaminants seen as microscopic inclusions are occasionally observed, probably carbon (Kittleman, 1963), as well as incompletely fused mineral fragments.

GENERAL OBSERVATIONS

The scatter diagram of Figure 27 defines an approximately linear trend, such that the percent silica can be estimated with an error of ± 2 percent (Kittleman, 1963). The maximum departure from a smooth curve on the silica-refractive index diagram is 0.007 in index and 1.8 percent in silica content within rocks of the same volcanic suite (Mathews, 1951). On a graph prepared by Kittleman (1963) of samples taken throughout North America, nearly all samples (126 in all) fall within an error of 4.0 percent.

According to Tilley (1922) the refractive index rises at a rate of about 0.0033 for each additional percent water up to 3.3 percent. Water in small amounts can therefore have a significant influence on the refractive index. Differences in the degree of oxidation of lavas during and after extrusion may also create deviations from the composition and refractive index for a particular rock suite (Mathews, 1951). Observations made by Stark (1904) and George (1924) indicate two glasses with the same refractive

index might differ in silica content by as much as 14 percent, or may differ by only 0.065 percent. Indices are generally low if the silica content of the glass is high, and vice versa. The proportion of any one constituent, even the major constituents, do not alone determine the refractive index of a glass, but each constituent contributes according to its abundance and to its specific properties (Mathews, 1951). To examine the relative effect of iron on the refractive indices of the Castle Rock samples, the magnetic minerals were separated out of those samples with the suffix-s of Figure 27. It is interesting to note that the separation of magnetic minerals has little effect on the more silicic volcanic rocks but may cause a variation in silica content by as much as 2 percent in basaltic rocks. In general, loss of iron tends to reduce the refractive indices of the more mafic samples and slightly increases the refractive indices of the more silicic samples. The net result is a higher silica content for basalts and a lower silica content for more silicic rocks. It is believed that other constituents such as magnesium, titanium and trace elements play an important part in determining the refractive indices of the glass beads.

Harker (1909) selected groups of igneous rocks, of one general locality and age, and showed that within such groups of igneous rocks in the same petrologic province, there are distinct similarities in silica content and bulk composition. If glassy, these rocks can be expected to have similar re-

fractive indices. Mathews (1951) expands on this by suggesting rocks representing comparable degrees of magmatic differentiation would contain similar amounts not merely of silica, but also of alumina, iron, lime, and other essential constituents.

gonite breccia of the "unnamed igneous complex" formed the plane of movement for this slide. Other, smaller landslides of similar type occur throughout the area. Tuffaceous interbeds, brecciated flows or thin baked horizons may form slide planes within the lava flow complexes.

Sedimentary strata are more prone to minor slumping and soil creep. Irregular slumping within the Juntura Formation has caused displacement of the Drewsey welded tuff near the Castle Rock Ranch (Plate 1). The soft sediments show a continuous long-term soil creep at the Agency Valley Cemetery, where tombstones are cracked and tilted in random directions. Some of these tombstones are nearly 100 years old and their displacement indicates that soil creep is an important erosive process in the area.

COLLUVIUM

Colluvium mantles much of the Castle Rock area in the form of angular to rounded rock fragments, ranging in size from 2 cm to about 1 m in diameter. Cobble-size clasts of about 5 cm in diameter are most common. Colluvium is unsorted, clasts are angular and unevenly distributed. The Juntura Formation in the southern part of the area is covered with colluvium which acts as lag gravel or desert pavement, causing gently sloping benches to form, protecting the softer sediments from intense hoodoo weathering. These gravels are associated with minor deposits of rounded terrace gravels on the pediment surfaces along the east side of the

North Fork of the Malheur River Valley. The long, gently dipping slopes of the Juntura Formation in the southeast corner of the area are also heavily laden with these gravels and may represent an extensive pediment which has undergone considerable erosion.

Sources of colluvium appear to be early talus slopes of older lava flows, small alpine and valley glaciers which existed a short distance north of the Castle Rock area during the Pleistocene Epoch, and local talus slopes and alluvial fans. Sudden runoff from thunder storms has loosened the clayey regolith from around the gravels in places, causing channels to appear as long strips of cobble-size fragments. The pediments indicate that the ancient North Fork of the Malheur River once occupied a position almost 470 m above its present level during the Pleistocene Epoch.

ALLUVIAL AND LACUSTRINE DEPOSITS

Alluvial deposits are restricted to the flood plains of the major streams draining the area, namely, the North Fork of the Malheur River, the Little Malheur River and Lost Creek. This alluvium consists predominantly of cobble and gravel size detritus near stream banks with a heavy mantling of clays and silts deposited at flood stages along the flood plain. These deposits are usually located upstream from bedrock obstructions in the stream. Intermittent streams often have beds of cobbles and gravels which may be substituted for roads in times of fair weather.

Lacustrine deposits are restricted to the northern end of Beulah Reservoir which receives heavy runoff in the spring and late fall months. Since all of the runoff from the Castle Rock area and a much larger surrounding area must pass through Beulah Reservoir, heavy thunder storms fill the reservoir and back waters into the valleys of Warm Springs Creek and the North Fork of the Malheur River.

HYDROTHERMAL ALTERATION

An area of hydrothermal alteration covering about 1 km² was found 2 km southwest of Castle Rock (Plate 1). The most intense alteration occurs in the north-central portion of the alteration zone and decreases outward towards its margin. Within the zone lava flows of the "unnamed igneous complex" are decomposed and bleached to a light brown color and zeolitized with heulandite crystals measuring over 1 cm in length. Younger lava flows of the Strawberry Volcanics have been bleached to a light green color and consist of clay minerals, chlorite, zeolites and minor amounts of cinnabar. This alteration zone lies along a fault zone and may be attributed to the sulfataric action of hot springs. The youngest rocks within the zone are basalt flows of the Strawberry Volcanics, indicating that alteration was less than about 10 m y ago.

Further southeastward along the fault zone, in the SW 1/4 sec. 16, T. 18 S., R. 37 E., patches of bare ground are covered with white salts, possibly sulphates. Rocks of the Juntura Formation are locally silicified and siliceous sinter occurs over an area of 0.5 km² around two hot springs where Warm Springs Creek enters Beulah Reservoir. Another hot spring flows out of stream gravels on the east side of the North Fork of the Malheur River upstream from where it enters Beulah Reservoir. Spring temperatures are about 70°C. Although there are no recent volcanic rocks within the Castle Rock area, hot springs and hydrothermal alteration indicate that the region is not totally inactive.

STRUCTURAL GEOLOGY

INTRODUCTION

The Castle Rock area lies within a zone of changing structural trends. South of the area faults and folds trend north-south. Structural elements within the Castle Rock area and to the west have a well-developed north-northwest orientation. There is a less well-developed north-northeast orientation of some structural elements in the eastern part of the Castle Rock area. These elements become better developed towards the east.

The Castle Rock ridge is a major structural high which extends from Hunter Campground through the center of the area to Black Butte (Plate 1, Cross Sec. A & B). This ridge has been uplifted along faults on all sides to form a horst. Emplacement of the Castle Rock dike is believed to be related to this uplift. Major structural lows are: the valley of the North Fork of the Malheur River, the Beulah Reservoir area and the area of subsidence around Black Butte.

FOLDING

Two major north-northwest trending folds are represented by the Castle Rock anticline and the North Fork of the Malheur River syncline (Plate 1, Cross Sec. B). The anticline and syncline have widths of 6 km and 5 km, respectively, and

lengths exceeding 10 km extending outside of the mapped area to the northwest.

The Castle Rock anticline has an amplitude of about 430 m, and is asymmetric with an axial plane inclined steeply eastward. At Jerry Canyon the crest of the fold has formed along a longitudinal fault zone (Plate 1, Cross Sec. A & B). The western limb of the anticline dips 8 to 19 degrees; the eastern limb dips as steeply as 28 degrees; and the nose of the fold plunges about 35 degrees southward. North of the Castle Rock Fire Guard Station the anticline plunges about 15 degrees northward.

The North Fork of the Malheur River syncline is also asymmetrical with an axial plane steeply inclined eastward. The southwest and northeast limbs of the syncline have average dips of 10 to 15 degrees, respectively, and the fold plunges about 12 degrees to the southeast (Plate 1, Cross Sec. B). South of Castle Rock this syncline terminates in the fault-bounded basin occupied by Beulah Reservoir. This fault zone continues southward along the North Fork of the Malheur River, forming a graben-like structure, bounded on both sides by high angle normal faults. The fault zone continues into the Juntura Basin and extends southward along the South Fork of the Malheur River, forming a fault zone several kilometers wide (Haddock, 1967). This syncline merges or trends into a high angle normal fault about 15 km northwest of the Castle Rock area and extends northwestward

into the area of Prairie City, merging with the axis of the John Day Syncline (Lowry, 1968).

Folding within the Castle Rock area may predate some faulting and be contemporaneous with younger faulting. Attitudes change abruptly in the flanks of major folds where small-scale faulting disrupts bedding (Fig. 24; Plate 1, Cross Sec. B).

FAULTING

Normal faults are important structures within the Castle Rock area. Several northwest trending normal faults are exposed east of Goodwin's Tomb near Irish Spring, forming a series of stepped blocks (Fig. 25).

A reverse fault of uncertain displacement was mapped on the ridge northeast of Castle Rock in sec. 3, T. 18 S., R. 37 E. Two other faults on the same ridge across from Hunter Campground also appear to have reverse displacement.

Many faults within the Castle Rock area are gradational between normal faults and hinge faults. Faults with hinge displacement generally show a flexure at right angles to the fault plane, representing the axial trace of the hinge. Such faults are best exposed on the west side of the North Fork of the Malheur River and the southeast end of Jerry Canyon.

STRUCTURAL SYNTHESIS

Evidence separating structural events from deposition of volcanic formations was not found. The youngest Juntura

Figure 24. Small scale normal faulting disrupting strata of the Strawberry Volcanics along Lost Creek, looking southwestward with Black Butte in the background. Vertical displacement is about 5 m, west side down. Note the abrupt change in attitudes of beds at the fault plane.

Figure 25. A series of stepped fault blocks east of Goodwin's Tomb near Irish Spring, looking northward with Ironside Mountain in the distance. Strata of the Strawberry Volcanics are cut by normal faults inclined about 60 degrees northeastward. Displacement on each fault is about 40 m.