Potential Petroleum Reservoir Rocks of North-Central Oregon

Alfred J. Riddle

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ABSTRACT

POTENTIAL PETROLEUM RESERVOIR ROCKS
OF NORTH-CENTRAL OREGON

by

Alfred J. Riddle

Petroleum explorationists have commonly assumed, based on the presence of volcanic and/or volcaniclastic rock, that regions such as north-central Oregon do not hold potential as petroleum basins. The typical argument has been that volcanic flows have no effective porosity or permeability and poorly sorted volcaniclastic sediments contain a high percentage of mineralogically unstable grains which are too easily and rapidly altered into clays and zeolites for any significant or effective porosity to be retained.

The objective of this study was to determine if potential petroleum reservoir rocks do exist in north-central Oregon. Through field and laboratory study and by comparing this region with petroleum producing basins with volcanic and volcaniclastic reservoirs, I have determined that the potential volcanic and volcaniclastic reservoirs of this area cannot be entirely "judged" by the "rules" of average siliciclastic reservoirs. Secondary dissolution and fracture porosity is extremely important in these reservoirs and is the natural consequence of hydration reactions, the formation of organic acids during
thermal maturation of associated organic rich source rocks, high geothermal
gradients which increase the rate of dissolution of some grains, the flushing of
dissolution products out of the reservoirs during diagenesis, and the
development of fracture porosity in a tectonically active area. As a result of this
study, I have concluded that north-central Oregon does in fact have good
potential petroleum reservoir rocks.
LOMA LINDA UNIVERSITY
Graduate School

POTENTIAL PETROLEUM RESERVOIR ROCKS
OF NORTH-CENTRAL OREGON

by
Alfred J. Riddle

A Thesis in Partial Fulfillment
of the Requirements for the Degree Masters of Science
in Geology

August 1990
Each person whose signature appears below certifies that this thesis in his opinion is adequate, in scope and quality, as a thesis for the degree Master of Science.

Lanny H. Fisk, Ph.D., Associate Professor of Geology

H. Paul Buchheim, Ph.D., Professor of Biology/Geology

Ivan G. Holmes, Ph.D., Professor of Chemistry
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<tr>
<td>6.</td>
<td>Modal analysis (100 points) of thin sections of volcaniclastic sandstones from the Clarno Formation.</td>
<td>45</td>
</tr>
<tr>
<td>7.</td>
<td>Porosity and permeability measurements of Clarno Formation volcaniclastic sandstone samples.</td>
<td>62</td>
</tr>
<tr>
<td>8.</td>
<td>Modal analysis (100 points) of thin section of sandstone from the Columbia River Basalt Group.</td>
<td>67</td>
</tr>
<tr>
<td>9.</td>
<td>Porosity and permeability measurements of a tuffaceous, diatomaceous sandstone from an interbed in the Columbia River Basalt Group.</td>
<td>69</td>
</tr>
</tbody>
</table>
INTRODUCTION

The petroleum reservoir properties and potential of Cretaceous and Tertiary rocks in north-central Oregon have to date been only superficially treated in the literature. However, interest in the petroleum potential of the area (Figure 1) has recently been renewed, spurred in part by current drilling activity in the Columbia Basin by Shell, Arco, and Meridian oil companies.

Of the four requirements commonly believed necessary for an area to have petroleum potential:

1. thermally mature source rocks,
2. porous and permeable reservoir rocks,
3. traps for accumulation and concentration of oil and/or gas, and
4. seals to prevent their leakage and loss,

it is probably the absence of proven reservoirs that has created the greatest misunderstanding and low estimate of the petroleum potential of north-central Oregon. The source rock potential of the area has been demonstrated (Newton, 1979; Law and others, 1984; Summer and Verosub, 1987; Fisk and Fritts, 1987; Tennyson and Parrish, 1988), as has the presence of numerous potential structural and stratigraphic traps (Newcomb, 1969; Fritts and Fisk, 1985a, 1985b; Fisk and Fritts, 1987), and effective seals (Fisk and Fritts, 1987). However, potential petroleum reservoir rocks have received less attention than is needed to demonstrate the presence of a potential petroleum province.
Figure 1. Index map of north-central Oregon (modified from Fisk and Fritts, 1987).
The purpose of my thesis research was to expand our understanding and knowledge of the reservoir potential of formations in north-central Oregon by analyzing reservoir properties, discussing their significance, and comparing the results with data from petroleum producing reservoirs in other basins. The results of this study will help to accurately evaluate the petroleum potential of north-central Oregon.
GEOLOGIC SETTING

GENERAL STATEMENT

Potential reservoir rocks in north-central Oregon are exposed in inliers or windows (Figure 1) through the cover of Columbia River Basalts. Through study of the stratigraphic sequence (Figure 2) exposed in these inliers, previous workers have determined that petroleum reservoir rocks in north-central Oregon could include: submarine-fan sandstones of the "Mitchell Formation"; fluvial channel sandstones of the "Herren Formation"; volcaniclastic sandstones, conglomerates, and breccias of the Clarno and John Day formations; and interbeds of the Columbia River Basalt Group (Fritts and Fisk, 1985a; Fisk and Fritts, 1987; Tennyson and Parrish, 1988).

The interpretation of the depositional environment, as expressed by physical, chemical, and paleontological evidence, is especially important in assessing the reservoir rock potential of a stratigraphic sequence. Fortunately, much research has been completed by previous workers in north-central Oregon so that an accurate description of the stratigraphy and the related depositional environments of the formations is possible.

STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS

The stratigraphy of north-central Oregon has been discussed in detail by Merriam (1901), Swarbrick (1953), Taylor (1960), McKnight (1964), Wilkinson and Oles (1968), Oles and Enlows (1971), Oles (1973), Enlows and Oles (1973),
<table>
<thead>
<tr>
<th>Era</th>
<th>Formation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUATERNARY</td>
<td>Quaternary Deposits</td>
<td>Valley fill and flood-plain deposits; extensive landslides; remnants of high, older fans; basalt flows</td>
</tr>
<tr>
<td></td>
<td>Rattlesnake Dalles Group</td>
<td>Volcaniclastic siltstones, sandstones, conglomerates; some intercalated basalt flows and ignimbrites</td>
</tr>
<tr>
<td></td>
<td>Mascall Formation</td>
<td>Fluvial and lacustrine tuffs, coals, and volcaniclastic sandstones</td>
</tr>
<tr>
<td></td>
<td>Columbia River Basalt Group</td>
<td>Basalt flows with some interbedded fine-grained volcaniclastic sediments</td>
</tr>
<tr>
<td></td>
<td>John Day Formation</td>
<td>Fluvial and lacustrine tuffs, volcaniclastic sandstones, and ignimbrites</td>
</tr>
<tr>
<td></td>
<td>Clarno Formation</td>
<td>Andesite flows, lacustrine and fluvial tuffs, coals, and local mudflows of volcanic conglomerates and breccias</td>
</tr>
<tr>
<td></td>
<td>&quot;Herren Formation&quot;</td>
<td>Paludal black shales, siltstones, coals, and fluvial channel sandstones</td>
</tr>
<tr>
<td></td>
<td>&quot;Mitchell Formation&quot;</td>
<td>Marine mudstones, siltstones, and sandstones interbedded with channel sandstones and conglomerates</td>
</tr>
<tr>
<td></td>
<td>Basement Complex</td>
<td>Metasediments, metavolcanics, and plutonics</td>
</tr>
</tbody>
</table>

Figure 2. Generalized composite stratigraphic column from north-central Oregon (modified from Fisk and Fritts, 1987).
Robinson (1973 and 1975), and Fisk and Fritts (1987). The most recent stratigraphic nomenclature is included here as Figure 2.

The exposed stratigraphic sequence can be divided into the basement complex, "Mitchell Formation", "Herren Formation", Clarno Formation, John Day Formation, and Columbia River Basalt Group. The depositional setting evidenced by this stratigraphic sequence has evolved from a deep-sea paleoenvironment in the Paleozoic and Mesozoic to an environment of continental volcanism through the Tertiary. The deep-sea fan deposits of the Cretaceous "Mitchell Formation" (as reinterpreted by Kleinhans and others, 1984) lie below the deltaic sands of the Paleogene "Herren Formation" (interpreted by Shorey, 1976, and Fisk, manuscript in preparation), which are in turn overlain by the volcanic and volcaniclastic deposits of the Eo-Oligocene Clarno Formation, Oligo-Miocene John Day Formation, and Miocene Columbia River Basalt Group.

Tectonically, the study area has been very active and local faults, intrusions, and paleohighs have controlled deposition. Davis (1977), Davis and others (1978), Brooks (1979), Dickinson (1979), Kleinhans and others (1984), Fritts and Fisk (1985a), and others have presented models of tectonic activity and/or depositional environments. The deposition of potentially good petroleum reservoirs is easily envisioned in these previously proposed tectonic and paleoenvironmental settings.
Basement Complex

The exposed basement rocks in the study area consist of Permo-Triassic metasediments, chert, phyllite, schist, crystalline limestone, and various melange and forearc basin sequences (Oles and Enlows, 1971; Beaulieu, 1972). The high-pressure, low-temperature glaucophane-lawsonite metamorphic mineral facies near the town of Mitchell suggest that the basement originated as a result of compressional forces associated with subduction at a plate margin (Hamilton and Myers, 1966; Novitsky-Evans, 1974).

"Mitchell Formation"

Unconformably overlying the basement complex is the Cretaceous "Mitchell Formation". It consists of a basal unit composed of thin sandstones and conglomerates, a middle unit of thick mudstones and siltstones, and an upper unit of mudstones and conglomerate-sandstone "tongues" (Wilkinson and Oles, 1968). Because of the complexity of the interfingering lithologies, controversy has surrounded the interpretation of its depositional environment and the naming of its subunits.

Though first described by Merriam in 1901, the Cretaceous rocks of north-central Oregon were not named, and were referred to by various workers (Packard, 1928; Chaney, 1933; Hodge, 1932, 1942; Wilkinson, 1959; Popenoe and others, 1960) only as the "Cretaceous rocks of Central Oregon". The first attempts to informally name the Cretaceous rocks were made by Swarbrick
(1953), Bowers, (1953), and McIntyre (1953). Swarbrick (1953), showing a clear understanding of the relationship of the units, named the Cretaceous rocks the "Mitchell Formation" with two members. Both Bowers (1953) and McIntyre (1953) used variations on this theme. McKnight (1964) reclassified and renamed what were essentially the two "members" of Swarbrick's (1953) informally named "Mitchell Formation" as separate formations.

Wilkinson and Oles, in 1968, formally described and named the Cretaceous rocks of the Mitchell area using the lithologic subdivisions of McKnight (1964). However, his thesis and informal nomenclature, as well as those of Swarbrick (1953), Bowers (1953), and McIntyre (1953), were not referenced.

Fisk and Sandefur (manuscript in preparation; Sandefur, 1986) have proposed that the mudstones and siltstones named the Hudspeth Formation by Wilkinson and Oles (1968) be called the "Hudspeth mudstone facies", and that the conglomerates and sandstones named the Gable Creek Formation be called the "Gable Creek sandstone-conglomerate facies", both within the newly renamed "Mitchell Formation". Fisk and Sandefur argue that, since both the Hudspeth and the Gable Creek Formations were deposited contemporaneously as part of the same depositional system (i.e., a deep-sea-fan complex), they should be considered facies within the same formation.

The "Mitchell Formation" was originally interpreted to be deposited in a shallow marine/fluvial-deltaic environment (Swarbrick, 1953; Walker, 1967; Wilkinson and Oles, 1968). McKnight (1964) interpreted the depositional
environment to be deeper marine with evidence of a high energy sediment dispersal system. In 1984, Kleinhans and others formally reinterpreted the Cretaceous rocks as originating from deep-sea-fan sedimentation.

"Herren Formation"

In erosional windows through the volcanic cover in Umatilla and Morrow counties (Figure 1) is exposed a Paleocene to early Eocene unit informally named the "Herren Formation" (Shorey, 1976). It is composed of arkosic sandstone, coals, and organic-rich shales. The latter contain an abundance of plant macro- and microfossils including a flora of leaves, pollen, spores, and wood (Hergert, 1961; Elemendorf, 1978; Gordon, 1985; Fisk, manuscript in preparation). The "Herren Formation" is interpreted to be deposited in a proximal deltaic environment, with sediment transport being toward the northwest into the thermally subsiding Columbia Basin (Fritts and Fisk, 1985a).

Based on the areal extent, volume of sand, and its relative cleanness, the "Herren Formation" has been described as holding high potential as a petroleum reservoir (Fritts and Fisk, 1985b; Fisk and Fritts, 1987; Tennyson and Parrish, 1988).

Clarno Formation

The Clarno Formation unconformably overlies the basement complex, "Mitchell Formation", or "Herren Formation" (Figure 2). As described by
Merriam (1901), Calkins (1902), Waters and others, (1951), Hay (1963), Rogers (1966), and others, it consists of quartz-rich sandstones, mudflows, fossiliferous lacustrine deposits, flows of basaltic and andesitic composition, tuffaceous sandstones and siltstones, and volcanic conglomerates and breccias. These deposits accumulated in volcanically active rift basins (Fritts and Fisk, 1985a, 1985b) to thicknesses of 3200 feet near Clarno (Taylor, 1960), 5800 feet in the Horse Heaven Mining District (Waters and others, 1951), and approximately 6360 feet in the vicinity of the Steele Energy Keys 1-28 well (Figure 1; Fisk, personal communication, 1988). The fossil-rich lacustrine deposits and abundant flora and fauna found in the "Clarno Nut Beds" (Manchester, 1981) and elsewhere show the importance of water in the deposition of these sediments (Taylor, 1960; Fisk and Fritts, 1987). The reactivation of rifting in the area during Eocene time caused the formation of large scarps and grabens creating the potential for the deposition of voluminous sandstone reservoirs along graben margins (Fritts and Fisk, 1985b).

**John Day Formation**

The Clarno Formation is unconformably overlain by the John Day Formation (Figure 2) which consists of vari-colored tuffs and tuffaceous sedimentary rocks deposited primarily in fluvial or lacustrine environments. Also included in the John Day Formation are sub-aerial ash falls, welded ash-flow tuffs (ignimbrites), rhyolite flows, and trachyandesite flows (Waters, 1954; Hay,
1962, 1963; Peck, 1964; Fisher, 1966a; Fisher and Rensberger, 1972). Like the Clarno Formation, the John Day Formation also contains an abundant fossil flora and fauna. The claystone deposits of the John Day Formation are potentially good seals for tectonically formed traps (Fisk and Fritts, 1987).

**Columbia River Basalt Group**

The dominate rock type exposed in north-central Oregon is the mid- to late Miocene tholeiitic flood basalts of the Columbia River Basalt Group. The sequence of flows has an average thickness of 2000 to 3000 feet in north-central Oregon (Beaulieu, 1972; Swanson and others, 1979; Swanson and others, 1981). The Columbia River Basalt Group rests unconformably on the John Day Formation, the Clarno Formation, the "Herren Formation", and/or the basement complex (Figure 2). The extrusion of the Columbia River Basalts was probably related to extension caused by back-arc spreading behind the newly formed Cascade magmatic arc. Interbedded with the basalt flows are often found tuffaceous and diatomaceous lacustrine sediments, such as the Mascall Formation, that are often significant as water reservoirs (Fisk and others, 1977; Gonthier, 1985).
FIELDWORK

The majority of the field research for this thesis was completed during the Summer of 1985 and followed with shorter periods of fieldwork during 1986-1989. Sixty five (65) outcrop rock samples were collected from locations throughout the study area; thirty (30) from the Clarno Formation and the remainder from the "Mitchell Formation", the "Herren Formation", the John Day Formation, and the Columbia River Basalt Group (Table 1). The samples collected were approximately twenty centimeters long by ten centimeters wide by six centimeters thick (20 cm X 10 cm X 6 cm). In the field samples were labeled, catalogued, and bagged for future laboratory studies. A brief description of the sample, sample location, and outcrop characteristics was entered into my field notebook.

In an attempt to have stratigraphic control over the Clarno Formation samples, a stratigraphic section was measured near the community of Clarno (Figure 1). Measurement was done with a Brunton compass, meter tape, and Jacob staff. Since the cliff faces and slopes of the exposed beds were approximately perpendicular to the local dip of the bedding planes, measurements of thickness could be taken directly.
Table 1. List of outcrop samples collected from formations in north-central Oregon.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>COLUMBIA RIVER BASALT GROUP</td>
<td>2</td>
</tr>
<tr>
<td>JOHN DAY FORMATION</td>
<td>3</td>
</tr>
<tr>
<td>CLARNO FORMATION</td>
<td>30</td>
</tr>
<tr>
<td>&quot;HERREN FORMATION&quot;</td>
<td>17</td>
</tr>
<tr>
<td>&quot;MITCHELL FORMATION&quot;</td>
<td>13</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>65</strong></td>
</tr>
</tbody>
</table>

LABORATORY STUDIES

Laboratory studies of field samples were performed during the Fall of 1986 and Winters of 1987 and 1988. The studies included: 1) thin-section preparation and description, 2) scanning electron microscopy (SEM), and 3) porosity and permeability determinations.

Samples from the "Mitchell Formation", "Herren Formation", Clarno Formation, and Columbia River Basalt Group were studied in depth. However, since no potential reservoir sandstones were seen in the field, the John Day Formation was studied only in outcrop and no samples were studied in the laboratory.

Thin-section Preparation and Description

Twenty-one (21) thin-sections of field samples were prepared commercially by Thin Sections Incorporated. All thin-sections were impregnated using
blue epoxy for ease in point-count porosity determinations. Thin-sections were ground to a thickness of 30 microns. Six (6) of the samples were prepared with an orientation perpendicular to the bedding plane. In addition to the thin sections prepared by Thin Sections Incorporated, six (6) thin sections of rock samples collected by Lanny H. Fisk and Don Rasmussen and prepared by Reservoirs Incorporated for Davis Oil Company, and two (2) thin sections of samples collected by Lanny H. Fisk and Craig Sandefur and prepared by Reservoirs Incorporated for F & F GeoResource Associates were made available for this study.

Thin-sections were described using a Zeiss monocular, cross-polar, petrographic microscope with rotating stage and 2.5X, 10X, and 40X objectives. Initial descriptions were made using Blatt's (1982) "Checklist for Petrographic Description of Thin Sections of Sandstones". Emphasis was put on the nature of the feldspars, relative abundance of quartz, and porosity development. Modal analyses of the composition of each sample were made using a 100-point grid at a magnification of 20X. A Swift and Sons semiautomatic electronic point counting stage was used to record the modal distribution. In addition, percentage counts of the porosity present, as exhibited by the impregnating blue epoxy, were performed on all thin sections. Thin-section descriptions were written using Miller and Orr’s (1986) descriptions as a model.
Porosity and Permeability Measurements

Sixteen (16) samples were delivered to Core Laboratories for measurements of porosity and permeability to air. One-inch diameter plugs were drilled with tap water from each of the samples. The plugs were dried in a convection oven at 105°C for 16 hours and allowed to cool in a desiccator. Porosity determinations were made using Boyle’s Law methods. Permeability measurements were taken at a minimum confining pressure of 400 psig in a Hassler-type core holder.

In addition to these sixteen (16) samples, the data from 41 additional samples were made available for this study including fifteen (15) samples collected by Lanny Fisk, Craig Sandefur, and Steve Fritts and prepared by Core Laboratories for Barrick Exploration, seven (7) samples collected by Lanny Fisk and prepared by Core Laboratories for Amoco Production Company, nine (9) samples collected by James Kolb and prepared by Omni Petroleum Services for Texlan Oil Incorporated, six (6) samples collected by Lanny Fisk and Don Rasmussen and prepared by Reservoirs Incorporated for Davis Oil Company, two (2) samples collected by Lanny Fisk and Craig Sandefur and prepared by Reservoirs Incorporated for F & F GeoResource Associates, and two (2) samples collected by Greg Cable and prepared by Conoco.
Scanning Electron Microscopy

Scanning electron microscope work was done on an AMR Model 1000 Scanning Electron Microscope with a tungsten filament and magnifying powers ranging from 20k to 100k. Sample size was approximately five millimeters by ten millimeters by ten millimeters (5 mm X 10 mm X 10 mm). Samples corresponding to prepared thin-sections were used to determine mineralogy, especially clays, and types of porosity present. Reference material to aid in the identification of the minerals, clays, and porosity development included "SEM Petrology Atlas" by Welton (1984).
RESULTS AND DISCUSSION

GENERAL STATEMENT

This field and laboratory study of potential petroleum reservoir rocks outcropping in north-central Oregon has yielded results that are perhaps surprising, particularly for those not acquainted with the complete stratigraphic sequence of rocks exposed in the area. Outcrop studies revealed the presence of porous and permeable rocks in nearly all stratigraphic units. Petrographic analyses of thin sections from outcrop samples demonstrated the presence of surprising amounts of visual porosity, while SEM work revealed extensive development of secondary porosity in some samples. Porosity and permeability measurements provide quantitative documentation that these rocks are potential petroleum reservoirs. Both the qualitative and quantitative data resulting from my study are provided below organized by stratigraphic unit. These results will be important to continuing petroleum exploration in this area and in other basins containing volcanioclastic reservoirs.

"MITCHELL FORMATION"

Petrography

In outcrop, potential sandstone reservoirs of the Cretaceous "Mitchell Formation" appear to be tightly cemented and impermeable. However, in the subsurface where physical and chemical conditions may have been different, these siliciclastic sandstones still hold some potential as reservoirs. In fact, they
contain many of the elements that are often found in good reservoir rocks. Typical "Mitchell Formation" sandstones are moderately to well-sorted, moderately to well-rounded, fine to coarse-grained, lithic sandstones, which are interbedded with poorly sorted, moderately to poorly rounded conglomerates (Figure 3 and Figure 4). The quartz content is significant and quartz is an important stable grain in samples where other grains have been altered. In the absence of pore-filling cements or in the event of the migration and accumulation of hydrocarbons in pore spaces prior to cementation, the "Mitchell Formation" sandstones could retain good porosity and permeability.

Locally the "Mitchell Formation" is highly fractured and does not show evidence of second generation recementation of these fractures. These fracture systems could have played an important role in the migration of hydrocarbons out of, into, and through the "Mitchell Formation".

In thin section most "Mitchell Formation" sandstones are very fine- to coarse-grained, angular to round, poorly sorted litharenites, although some samples are better classified as lithic arkoses (McBride, 1963; Folk, 1968). The average bulk composition and detrital mineralogy, determined from 100-point counts, is shown in Table 2. Detailed petrographic descriptions of individual samples are found in Appendix A.

The dominate framework grains making up "Mitchell Formation" sandstones are quartz, feldspar, metamorphic rock fragments (MRFs), and volcanic rock fragments (VRFs). Some framework grains are highly altered, especially
Figure 3. Sandstone outcrop of the Cretaceous "Mitchell Formation" near the town of Mitchell.

Figure 4. Conglomerate outcrop of the Cretaceous "Mitchell Formation" near the town of Mitchell.
Table 2. Modal analysis (100 points) of thin sections of sandstones from the "Mitchell Formation".

<table>
<thead>
<tr>
<th></th>
<th>WHOLE ROCK 100%</th>
<th>GRAINS 100%</th>
<th>POROSITY 100%</th>
<th>INTERGRANULAR</th>
<th>INTRAGRAIN</th>
<th>MICROPOROSITY</th>
<th>FRACTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GRAINS</td>
<td>MATRIX CEMENT CLAY POROSITY</td>
<td>QUARTZ</td>
<td>PLAGIOCLASE</td>
<td>K-FELDSPAR</td>
<td>CHERT</td>
<td>SRF</td>
</tr>
<tr>
<td>HUD-101</td>
<td>95 0 1 4 0</td>
<td>55 12 8 0 5 19 0 1</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GCC-18A</td>
<td>90 0 1 9 0</td>
<td>42 13 8 0 7 25 3 1</td>
<td>0 0 0 0</td>
<td>0 0 0 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HUD-R2</td>
<td>85 2 6 6 2</td>
<td>56 10 8 1 7 12 4 2</td>
<td>Tr Tr 0 100</td>
<td>0 0 0 0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MRFs and VRFs. Many lithic fragments show compaction compression into intergranular pores forming a pseudomatrix (Figure 5). Associated with these fragments are clay alteration products which also occlude porosity. Some framework grains are altered beyond identification. They still act as pseudo-framework grains, but consist of clay alteration products or are replaced by siliceous cements, including chalcedony and limonite.

Quartz grains are subangular to round and are predominately polycrystalline (Figure 6). This may indicate a predominately metamorphic provenance (Folk, 1968). Examples of quartz overgrowths and pressure solution (Figure 7)
Figure 5. Photomicrograph showing pseudomatrix, formed by the compaction of lithic fragments into the intergranular pore space, in a "Mitchell Formation" sandstone (crossed nicols, 40X).

Figure 6. Photomicrograph of a polycrystalline quartz grain in a "Mitchell Formation" sandstone (crossed nicols, 100X).
Figure 7. Photomicrograph showing quartz grains which exhibit pressure solution in a "Mitchell Formation" sandstone (crossed nicols, 40X).
may occasionally be seen but are insignificant to the reservoir quality of the rock compared with the effects of altered lithic fragments (Figures 5 and 7).

Feldspars are primarily orthoclase. Individual grains are not highly altered (Figure 8) and have not undergone dissolution to create significant secondary porosity.

**Porosity and Permeability**

Primary porosity is not evident in "Mitchell Formation" sandstone samples (Figures 5 through 8). Intergranular pore space is filled with siliceous cements, deformed rock fragments, and clays. Samples studied with SEM show a singular lack of porosity retention due to the clogging effect of these constituents (Figures 9 and 10).

In spite of the loss of primary porosity, secondary porosity developed as a result of leaching of grains such as feldspars is sometimes seen (Figure 11), although dissolution porosity is not common. Microporosity is developed to some extent in many samples. Microfracture porosity is also present in many samples and may be even more common than seen in thin section which would explain the poor correlation between visual porosity (Table 2) and measured porosity and permeability (Table 3).

Porosity and permeability determinations (Table 3) confirm the "clogging" effect that cements and clays have had on the "Mitchell Formation" sandstones. Measured porosities of eighteen (18) samples range from only 3.8% to 11.1%
Figure 8. Photomicrograph showing an unaltered feldspar grain in a "Mitchell Formation" sandstone (crossed nicols, 40X).

Figure 9. Photomicrograph showing pore clogging clays in a "Mitchell Formation" sandstone (uncrossed nicols, 100X).
Figure 10. Photomicrograph showing siliceous cement filling pores in a "Mitchell Formation" sandstone (crossed nicols, 200X).

Figure 11. SEM photomicrograph showing partially leached feldspar in a "Mitchell Formation" sandstone (500X).
Table 3. Porosity and permeability measurements of "Mitchell Formation" sandstone samples.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Formation</th>
<th>Porosity (%)</th>
<th>Permeability (md)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HUD-101</td>
<td>&quot;MITCHELL&quot;</td>
<td>3.8</td>
<td>0.09</td>
</tr>
<tr>
<td>GCC-18A</td>
<td>&quot;MITCHELL&quot;</td>
<td>6.9</td>
<td>9.80</td>
</tr>
<tr>
<td>HUD-R2</td>
<td>&quot;MITCHELL&quot;</td>
<td>4.7</td>
<td>0.06</td>
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<tr>
<td>1</td>
<td>&quot;MITCHELL&quot;</td>
<td>8.9</td>
<td>Tr</td>
</tr>
<tr>
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<td>4.8</td>
<td>Tr</td>
</tr>
<tr>
<td>3</td>
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<td>6.60</td>
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<td>10</td>
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</tr>
<tr>
<td>1B</td>
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<td>4.4</td>
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<td>2B</td>
<td>&quot;MITCHELL&quot;</td>
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</tr>
<tr>
<td>5B</td>
<td>&quot;MITCHELL&quot;</td>
<td>7.2</td>
<td>0.02</td>
</tr>
</tbody>
</table>

**MEAN** 6.93 % **MEAN** 1.37 md

with an average of 6.93%. Permeabilities range from 0.01 millidarcies to 9.8 millidarcies, with a mean of 1.37 millidarcies.

**Discussion**

The "Mitchell Formation" at the surface exhibits poor to moderate sorting with destructive cementation by either silica cement or clay alteration products. With the exception of fractures, useful secondary porosity development is not
seen in surface samples. This is not to say that the formation is completely tight since, as expressed earlier, the sandstones in outcrop may be more or less altered than those in the subsurface. McLean (1981) reported that petrography and SEM studies indicate that most sands deposited in subma-
rine-fan environments are originally porous and permeable. Diagenetic processes and the amount of shale versus sand present are parameters affecting the ultimate porosity and permeability. Submarine-fan sandstones from the Stevens Sandstone of the San Joaquin Valley Sequence of California are composed of arkosic and lithic arkose sandstones which have produced over 400 million barrels from 15 fields. The reservoir quality of these sandstones is attributed to both primary intergranular porosity and secondary dissolution porosity developed in feldspars (Biederman, 1986a, 1986b). The "Mitchell Formation" sandstones are similar in mineralogy and depositional history to the Stevens sandstones. However, their diagenetic histories may be quite different. If the pervasive cementation of the "Mitchell Formation" outcrops is also present in the subsurface, unfractured sandstones could only serve as poor reservoirs for oil but possibly still good reservoirs for gas.

"HERREN FORMATION"

Petrography

The "Herren Formation" contains sandstones that are moderately clean and sorted, and in outcrop appear to be good to excellent reservoir rocks.
Even at a cursory glance (Figure 12), these sandstones appear to hold great potential as petroleum reservoirs. Closer examination of the Herren sandstones shows that they do have many of the elements that are found in good reservoir rocks. Herren sandstones are moderately to well sorted; framework grains are subangular to rounded, and consist of quartz, feldspars, and mica. Some rock samples exhibit good permeability when tested in the field. Fracture systems are common and may be important in the subsurface.

Thin sections from eight (8) samples of the "Herren Formation" were studied to aid in characterization of reservoir quality. The average bulk composition and detrital mineralogy for each thin section, determined from 100 point counts, is shown in Table 4 and individual petrographic descriptions are found in Appendix A. The "Herren Formation" sandstones range in classification from feldspathic litharenites to lithic arkoses and arkoses (McBride, 1963; Folk, 1968). In general, the "Herren Formation" sandstones are fine- to medium-grained, angular to subrounded, poorly sorted, lithic arkose. Framework grains include quartz, plagioclase feldspars, alkali feldspars (microcline and orthoclase), volcanic rock fragments (VRFs), sedimentary rock fragments (SRFs), metamorphic rock fragments (MRFs), biotite and muscovite micas, chert, and organic fragments.

Quartz grains are the dominate constituent (averaging 51%) of "Herren Formation" sandstones. They are subangular to rounded and both monocrystalline and polycrystalline grains are present. The polycrystalline grains are
Figure 12. Outcrop of "Herren Formation" sandstone in the Blue Mountains near Heppner.
Table 4. Modal analysis (100 points) of thin sections of sandstones from the "Herren Formation".

<table>
<thead>
<tr>
<th>WHOLE ROCK 100%</th>
<th>GRAINS 100%</th>
<th>POROSITY 100%</th>
</tr>
</thead>
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<tr>
<td></td>
<td>GRAINS</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
<td>---------</td>
</tr>
<tr>
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</tr>
<tr>
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<td>0</td>
</tr>
<tr>
<td>HER-SS-5</td>
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<td>0</td>
</tr>
<tr>
<td>SDS-100</td>
<td>88</td>
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<td>88</td>
<td>0</td>
</tr>
<tr>
<td>NO. 1</td>
<td>86</td>
<td>1</td>
</tr>
<tr>
<td>NO. 2</td>
<td>81</td>
<td>10</td>
</tr>
</tbody>
</table>

smooth to crenulated. Quartz overgrowths are not uncommon (Figure 13). Compaction has resulted in the development of pressure solution features along quartz grain boundaries. The rounded grains and sorting are evidence of considerable water transport prior to deposition.

Plagioclase feldspars are generally leached and altered. As a result, secondary porosity is common in most sandstone samples (Figure 14). The formation of illite, kaolinite, and the production of chlorite is a result of leaching and alteration. Some samples show plagioclase entirely altered and replaced
Figure 13. Photomicrograph of a "Herren Formation" sandstone showing quartz overgrowths (s) bridging grains (uncrossed nicols, 160X).

Figure 14. Photomicrograph of a "Herren Formation" sandstone showing secondary porosity demonstrated by blue epoxy filled pores (uncrossed nicols, 100X).
by clay minerals. Alkali feldspars are less altered, but generally exhibit some alteration and replacement by sericite, illite, and/or other clay minerals.

All types of lithic fragments are seen. MRFs contain sutured contacts and uneven extinction. VRFs consist of quartz, alkali feldspars, and glass. Most VRFs are highly altered so that clays are the predominate constituent. Some SRFs are present in the form of siltstone clasts.

Both biotite and muscovite micas are present and generally show early stages of deformation (Figure 15). Chert is present as reworked grains that are moderately rounded (Figure 16); this may be important for provenance determinations. Limonite, hematite, silica, calcite, and various clays are present as cements. These cements clog both intergranular and intragranular pore spaces in some samples.

**Porosity and Permeability**

The porosity present in "Herren Formation" samples is both primary and secondary. Figure 17 shows porosity as evidenced by blue epoxy filling intergranular pores. Primary porosity is often clogged with deformed micas and lithic fragments, quartz overgrowths, and clays, especially kaolinite. Secondary porosity has developed in many feldspars; dissolution of grains is seen in Figure 18.

In SEM "Herren Formation" samples revealed characteristics which are commonly found in good reservoirs, such as primary porosity retention and
Figure 15. Photomicrograph of a "Herren Formation" sandstone showing mica grains in early stages of deformation (crossed nicols, 100X).

Figure 16. Photomicrograph of a "Herren Formation" sandstone showing a chert grain rounded by transport (crossed nicols, 35X).
Figure 17. Photomicrograph of a "Herren Formation" sandstone showing primary porosity retention as blue epoxy (uncrossed nicols, 135X).

Figure 18. Photomicrograph of a "Herren Formation" sandstone with blue epoxy showing dissolution of feldspar grains (uncrossed nicols, 135X).
secondary porosity development. Primary porosity is retained in many samples in spite of the alteration and deformation of micas, alteration and/or dissolution of feldspars, and formation of kaolinite. Figures 19 and 20 show primary intergranular porosity retention.

Secondary intragranular porosity has been developed primarily by the dissolution of feldspar grains. Figures 21 and 22 show a feldspar grain which has undergone extensive dissolution, with the development of secondary intragranular porosity.

Kaolinite has filled some of the intergranular pore space as is seen in Figure 23. Chlorite also acts as an intergranular pore-clogging agent. Authigenic clays, silica cement, and carbonate cement fill other intergranular pores. Figures 24 and 25 show examples of these pore-filling cements.

In the twenty-four (24) samples of Herren sandstone for which measurements of data are available, porosities averaged 12.27% and ranged from a low of 8% to a high of 21.3%. Permeabilities averaged 8.42 millidarcies (md) and ranged from 0.04 to 73.0 md (Table 5). Low permeability in some Herren sandstones is a result of the abundance of authigenic clays which plug pore throats. However, this condition may be due, at least in part, to surface weathering.
Figure 19. SEM photomicrograph showing primary porosity retention in "Herren Formation" sandstone (50X).

Figure 20. SEM photomicrograph of a "Herren Formation" sandstone showing primary porosity retention (150X).
Figure 21. SEM photomicrograph showing secondary dissolution porosity in a reabsorbed potassium feldspar in a "Herren Formation" sandstone (50X).

Figure 22. SEM photomicrograph showing greater magnification of partially reabsorbed feldspar grain shown in Figure 21 (200X).
Figure 23. SEM photomicrograph of a "Herren Formation" sandstone showing pores clogged with kaolinite (500X).

Figure 24. SEM photomicrograph of a "Herren Formation" sandstone showing siliceous pore-filling cement (100X).
Figure 25. SEM photomicrograph of a "Herren Formation" sandstone showing laumonite and calcite pore-filling cements (50X).
Table 5. Porosity and permeability measurements of "Herren Formation" sandstone samples.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Formation</th>
<th>Porosity (%)</th>
<th>Permeability (md)</th>
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<td>SAMPLE 2</td>
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**MEAN**  
12.27 %  
8.42 md

Discussion

"Herren Formation" sandstones appear to hold good to excellent potential as petroleum reservoir rocks. The fine- to coarse-grained, moderately
sorted sandstones exhibit good primary porosity retention, secondary porosity formation as a result of feldspar dissolution, and fracture development.

Subsurface data confirms that sandstones similar to "Herren Formation" sandstones seen in outcrop have excellent potential as reservoirs. The Texaco Federal well in Crook County penetrated strata containing quartzose sandstones, some of which are Paleogene in age (Thompson and others, 1984) and probably Herren equivalent. Log data indicate excellent reservoir potential (Fritts and Fisk, 1985b).

**CLARNO FORMATION**

**Petrography**

Most outcrops of Clarno Formation volcanioclastic sandstones are composed of poor to moderately sorted sand, consisting of angular to subangular grains that are partially cemented and often highly altered or weathered (Figure 26). Large clasts (4 mm to 30 cm) of volcanioclastic materials consisting of feldspar fragments and tuffaceous mud are often present as well (Figure 27). The formation contains fluvial channels, sheet flows, mud flows, and laminated lacustrine deposits. Many of these depositional units are laterally continuous in outcrop for at least a kilometer (Figure 28). In addition to the sandstones and mudstones, also present are mudflows, basalt and andesite flows, conglomerates and breccias, and andesite and rhyolite intrusions (Figure 29).
Figure 26. Outcrop of Clarno Formation sandstone near the community of Clarno.

Figure 27. Outcrop of a Clarno Formation mud flow near the community of Clarno.
Figure 28. Outcrop of tuffaceous sandstone from the Clarno Formation near the community of Clarno.

Figure 29. Andesite flow from the Clarno Formation located near the town of Clarno.
Thin sections of eighteen clastic sandstones from throughout the Clarno Formation were analyzed. The average bulk composition and detrital mineralogy for each thin section, determined from 100 point counts, is shown in Table 6 and petrographic descriptions of individual samples are found in Appendix A. The Clarno Formation sandstones are predominately lithic arkoses in the classifications of McBride (1963) and Folk (1968), although feldspathic litharenites, arkoses, and litharenites are also present. Typical Clarno sandstones are fine- to medium-grained, angular to subround, poorly sorted, lithic arkoses. Framework grains include plagioclase (An$_{60}$), volcanic rock fragments (VRFs), alkali feldspars (anorthoclase, sanadine, orthoclase, or microcline), quartz, amphiboles (primarily hornblende), mica (biotite and muscovite), and sedimentary rock fragments (SRFs) including chert and clay-rich mudstone.

Plagioclase feldspars are abundant in all samples, as would be expected in volcanically derived sediments, and have an average anorthite content of An$_{60}$. Individual feldspar grains are often altered and replaced by clay minerals and clay mineral complexes, including chlorite, illite, smectite, kaolinite, and sericite (Figure 30). Some plagioclase grains have also been replaced by calcite, chalcedony, or zeolites (Figure 31). In some thin sections, plagioclase grains have also undergone dissolution with the development of extensive secondary porosity (Figure 32 and Figure 33).

The alkali feldspars, which include anorthoclase, sanadine, and, much less abundant, orthoclase and microcline, show replacement of portions of
Table 6. Modal analysis (100 points) of thin sections of volcaniclastic sandstones from the Clarno Formation.

<table>
<thead>
<tr>
<th>GRAINS</th>
<th>WHOLE ROCK 100%</th>
<th>GRAINS 100%</th>
<th>POROSITY 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MATRIX CEMENT CLAY POROSITY</td>
<td>QUARTZ PLAGIOCLASE K-FELDSPAR CHERT SRF VRF MRF MICA</td>
<td>INTERGRANULAR INTRAGRAIN POROSITY MICROPOROSITY FRACTURE</td>
</tr>
<tr>
<td>CLR-2M</td>
<td>90 2 2 3 3</td>
<td>11 30 6 3 5 46 0 5</td>
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<tr>
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<td>15 30 4 3 0 45 3 5</td>
<td>Tr 99 0 1</td>
</tr>
<tr>
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<td>3 62 15 0 0 31 1 10</td>
<td>Tr Tr 0 99</td>
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<tr>
<td>CLR-R2</td>
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<td>65 10 5 10 3 2 0 3</td>
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<td>30 25 13 8 2 18 0 6</td>
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<tr>
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<td>1 10 9 3 5 71 0 1</td>
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<tr>
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<td>3 34 2 0 0 63 0 0</td>
<td>45 45 5 5</td>
</tr>
</tbody>
</table>

grains with chlorite, illite, sericite, smectite, and calcite (Figure 34). The dominate alkali feldspars consist of high temperature anorthoclase and
Figure 30. Photomicrograph of a Clarno Formation volcaniclastic sandstone showing replacement of a plagioclase feldspar by clay minerals (crossed nicols, 100X).

Figure 31. Photomicrograph of a Clarno Formation volcaniclastic sandstone showing replacement of a plagioclase feldspar with chalcedony and calcite (crossed nicols, 100X).
Figure 32. Photomicrograph showing development of secondary porosity evidenced by blue epoxy in a feldspar grain from a Clarno Formation volcaniclastic sandstone (uncrossed nicols, 100X).

Figure 33. Photomicrograph showing development of secondary porosity evidenced by blue epoxy in a feldspar grain from a Clarno Formation volcaniclastic sandstone (uncrossed nicols, 100X).
Figure 34. Photomicrograph of a Clarno Formation sandstone showing alkali feldspars replaced by clays (crossed nicols, 100X).
sanadine probably derived from a volcanic source. The smaller proportion of microcline and orthoclase may indicate a lower influx of grains from a metamorphic source (Folk, 1974). The alkali feldspars are much less abundant than plagioclase feldspars.

Volcanic rock fragments consist of agglomerates of felted microcrystalline feldspars, tuffaceous clasts and lapilli, minor amounts of high temperature quartz, and pyroclastic andesite clasts. The rock fragments were derived from explosive volcanic sources but often show rounding due to water transport.

Quartz grains are predominately monocry stalline, exhibiting uniform extinction, though some polycrystalline grains with undulatory extinction are also present. Polycrystalline grains are smooth to crenulated. The presence of metamorphically derived quartz grains that show evidence of working by the action of water (Figure 35) again supports the conclusion that water was very much involved in the deposition of at least parts the Clarno Formation. This implies that the Clarno may have cleaner sands than more typical volcaniclastic deposits.

Amphiboles (primarily hornblende) are present in some samples and ghosts of hornblende grains remain in others (Figure 36). The percentage of chlorite is probably increased as a direct result of the alteration of hornblende.

Micas present include both biotite and muscovite, as well as variations of the muscovite - lepidolite and biotite - phlogopite series. Micas have also
Figure 35. Photomicrograph of a Clarno Formation volcanioclastic sandstone showing quartz grains rounded from transport (crossed nicols, 100X).

Figure 36. Photomicrograph of a Clarno Formation volcanioclastic sandstone showing partially dissolved grains and ghosts of hornblende (crossed nicols, 100X).
added to the chemical production of chlorite clay complexes (Figure 37; Blatt, 1982).

SRFs include chert and tuffaceous mud clasts. Again, many samples show evidence of working by water by exhibiting rounding.

As would be expected in volcaniclastic rocks of the Clarno Formation, in SEM kaolinite books (Figure 38), quartz overgrowths (Figure 39), feldspar overgrowths (Figure 40), smectite, illite-smectite complexes, chlorite (Figure 41), and clay alteration products (Figure 42) are all seen.

**Porosity and Permeability**

Outcrop samples of Clarno Formation sandstones exhibit varying degrees of porosity and permeability. Some rocks with high ash content have surprisingly high porosities and permeabilities, similar to those normally associated only with much cleaner, quartz-rich sands.

Most thin sections show that primary intergranular porosity is not very well retained. Intergranular pore spaces are choked with either clays, chalcedony cement, or a pseudomatrix of squeezed lithic fragments (Figure 43). Stable grains such as quartz are rimmed by clays which effectively close the pore space between framework grains (Figure 44). Cements, which include calcite, chalcedony, and clay minerals, also close primary pore space.

However, secondary porosity is very extensively developed in Clarno Formation sandstones. The most common occurrence of porosity development
Figure 37. Photomicrograph of a Clarno Formation volcanioclastic sandstone showing mica which has undergone alteration and produced chlorite (uncrossed nicols, 100X).

Figure 38. SEM photomicrograph of a Clarno Formation volcanioclastic sandstone showing intergranular pore-filling rubble composed of kaolinite (600X).
Figure 39. SEM photomicrograph of a Clarno Formation volcaniclastic sandstone showing quartz overgrowths (1200X).

Figure 40. SEM photomicrograph of a Clarno Formation volcaniclastic sandstone showing feldspar overgrowths (6000X).
Figure 41. SEM photomicrograph of a Clarno Formation volcaniclastic sandstone showing the development of smectite and illite-smectite complexes (1200X).

Figure 42. SEM photomicrograph of a Clarno Formation volcaniclastic sandstone with pore clogging clay alteration products (600X).
Figure 43. Photomicrograph of a Clarno Formation volcaniclastic sandstone showing squeezed lithic fragments occluding pore spaces (crossed nicols, 200X).

Figure 44. Photomicrograph of a Clarno Formation volcaniclastic sandstone showing clay rims around quartz grains (uncrossed nicols, 100X).
is found in plagioclase feldspar. Figure 45 and Figure 46 show that some feldspar grains have almost completely leached away leaving only a ghost of the original grain shape. This dissolution is probably the result of the production of organic acids and hydration reactions (Huang and Keller, 1972; Surdam and others, 1982). The resulting products of dissolution have either been flushed out of the open system with migrating fluids or deposited in intergranular pore spaces.

Scanning electron microscopy of samples of Clarno sandstones reveals a number of characteristics that are not typically associated with volcaniclastic rocks. Tremendous feldspar dissolution, microporosity development, and some intergranular porosity retention were all revealed in SEM. Examples of intragranular porosity are seen in Figures 47 through 50. Primary intergranular porosity is also retained in some samples (Figure 51). Microporosity is a constant in most samples (Figure 52).

Another important element the Clarno Formation exhibits is its fractured condition (Figure 53). The horizontal, vertical, and conjugate fractures seen in both outcrops and thin sections greatly enhance the reservoir potential of Clarno sandstones and could also result in the formation of reservoirs out of pyroclastic flows.

Measurements of porosity and permeability give a clear picture of how Clarno sandstones could act as a petroleum reservoir. Table 7 shows the results of porosity and permeability determinations for 14 samples. Porosity
Figure 45. Photomicrograph of a Clarno Formation volcanioclastic sandstone showing ghost of feldspar grain after dissolution (uncrossed nicols, 100X).

Figure 46. Photomicrograph of a Clarno Formation volcanioclastic sandstone with feldspar evidenced only by a ghost (uncrossed nicols, 100X).
Figure 47. SEM photomicrograph of a Clarno Formation volcaniclastic sandstone showing a reabsorbed potassium feldspar (600X).

Figure 48. SEM enlargement of feldspar grain in Figure 47 showing secondary porosity (1200X).
Figure 49. SEM photomicrograph of a Clarno Formation volcanioclastic sandstone showing a feldspar that has undergone extensive dissolution (600X).

Figure 50. SEM enlargement of feldspar grain seen in Figure 49 (1200X).
Figure 51. SEM photomicrograph of a Clarno Formation volcaniclastic sandstone showing the retention of primary intergranular porosity (600X).

Figure 52. SEM photomicrograph of a Clarno Formation volcaniclastic sandstone with microporosity exhibited in grains (600X).
Figure 53. Outcrop of Clarno Formation near the community of Clarno showing fractured condition of sandstones.
Table 7. Porosity and permeability measurements of Clarno Formation volcanioclastic sandstone samples.

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<th>Sample</th>
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<td>CLARNO</td>
<td>8.8</td>
<td>0.36</td>
</tr>
<tr>
<td>CLR-R2</td>
<td>CLARNO</td>
<td>18.0</td>
<td>7.80</td>
</tr>
<tr>
<td>CLR-R4</td>
<td>CLARNO</td>
<td>16.9</td>
<td>0.64</td>
</tr>
<tr>
<td>CLR-R5</td>
<td>CLARNO</td>
<td>23.4</td>
<td>8.00</td>
</tr>
<tr>
<td>CLR-R7</td>
<td>CLARNO</td>
<td>25.4</td>
<td>43.00</td>
</tr>
<tr>
<td>CLR-R7A</td>
<td>CLARNO</td>
<td>37.9</td>
<td>12.00</td>
</tr>
<tr>
<td>CLR-11A</td>
<td>CLARNO</td>
<td>22.2</td>
<td>7.60</td>
</tr>
<tr>
<td>CLR-R12</td>
<td>CLARNO</td>
<td>8.6</td>
<td>0.29</td>
</tr>
<tr>
<td>CLR-R12A</td>
<td>CLARNO</td>
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<td>0.35</td>
</tr>
<tr>
<td>CLR-R15</td>
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<td>0.04</td>
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<tr>
<td>CLR-R19</td>
<td>CLARNO</td>
<td>11.9</td>
<td>12.00</td>
</tr>
<tr>
<td>CLR-R20</td>
<td>CLARNO</td>
<td>16.4</td>
<td>5.70</td>
</tr>
<tr>
<td>CLR-R21</td>
<td>CLARNO</td>
<td>27.0</td>
<td>16.0</td>
</tr>
<tr>
<td><strong>MEAN</strong></td>
<td></td>
<td><strong>17.4 %</strong></td>
<td><strong>8.13 md</strong></td>
</tr>
</tbody>
</table>

ranged from 4% to 38% and averaged 17.4%. Permeability values ranged to 43 millidarcies with an average of 8.13 millidarcies.

**Discussion**

It has generally been assumed in the petroleum industry that volcanioclastic rocks are too impermeable to be of interest as petroleum reservoirs. However, my research indicates that the volcanioclastic sandstones of the Clarno Formation may be an exception. The evidence from outcrops, thin sections, and SEM samples suggests that Clarno Formation volcanioclastic sandstones
may well be good reservoirs due to the preservation of some primary inter-
granular porosity and the creation of secondary dissolution and fracture
porosity. The unexpectedly high porosity and permeability values are primarily
the result of the formation of secondary intragranular porosity (Table 6) by
dissolution of feldspars.

Porosity and permeability may be enhanced further in the subsurface by
fracturing. The presence of extensive fracture systems in the Clarno Formation
explains the loss of over 175,000 barrels of drilling fluid and more than 2,500
sacks of lost circulation materials in the Steele Energy Keys 1-28 well (Fisk,
personal communication, 1988). Electric logs from the Standard Oil Kirkpatrick
#1 well (Figure 1) indicate that some subsurface volcanic breccias and sand-
stones of the Clarno Formation are also permeable, probably due to fractures,
and are potential reservoirs.

In his hydrological study of Central Oregon rocks, Gonthier (1985)
classified the Clarno Formation as an aquifer unit with low permeability, but
having permeability none-the-less. The low permeability of these rocks
(Table 7) is in part due to weathering and to alteration of feldspar minerals to
clays. However, under the right conditions, the permeability of Clarno sand-
stones may be greatly enhanced through the flushing of these alteration
products out of the sandstones and by fractures.

Enhanced permeability is evident from water production records of two
recent wells that produce from the Clarno Formation. The Steele Energy Keys
1-28 well recorded a flow rate of up to 2650 barrels of water per day (Vannoy, 1988) from highly fractured Clarno sandstones. Evidence of this fracturing is seen on sonic logs from the Steele Energy Keys 1-28 well (Figure 54). A water well drilled into a highly fractured welded tuff of the Clarno Formation on the Muddy Ranch (formerly Rancho Rajneesh) produced at 100 gallons per minute (State of Oregon Water Well Report, 1983). Many people in the John Day Basin rely on the Clarno Formation as their sole source of water (Young and others, 1986).

**JOHN DAY FORMATION**

**Petrography**

The John Day Formation is composed primarily of varicolored, andesitic to dacitic claystones and siltstones and welded ash-flow tuffs (ignimbrites). For the most part it is a very fine-grained, clay-rich unit but it does have some isolated sequences of ash-flow tuffs and flows that can contain relatively good permeability and porosity (Young and others, 1986). Other than fractured ignimbrites, no potential petroleum reservoir rocks were observed during my fieldwork, so further work was not conducted.

**Discussion**

Because of its high clay content, the John Day Formation probably has more potential as a seal for other reservoirs (Fisk and Fritts, 1987) than as a
Figure 54. Portion of the sonic log from the Steele Energy Keys 1-28 well near Service Creek showing evidence of fractures.
reservoir itself. However, because of the presence of extensive fractured ignimbrites (such as the Picture Gorge Ignimbrite; Fisher, 1972), the John Day Formation cannot be completely discounted as a possible reservoir. Fractured ignimbrites in Nevada (Dolly, 1979; Duey, 1983) and Argentina (Baldwin, 1944) have produced significant volumes of hydrocarbons.

COLUMBIA RIVER BASALT GROUP

Petrography

The basalt flows and extensive sedimentary interbeds of the Columbia River Basalt Group have always held some lure as potential petroleum reservoirs. The interbeds exposed in north-central Oregon consist of poorly to moderately sorted, fine- to coarse-grained sandstones, as well as tuffaceous siltstones, paleosols, laminated lacustrine deposits, diatomites, breccias, and scorias. Sandstone, breccia, and scoriaceous interbeds show some porosity and permeability when examined in the field. However, clays and other alteration products appear to clog much of the pore space. Tuffaceous sediments and diatomites appear to be slightly permeable until infused with fluids; swelling clays appear to choke the pore throats very quickly.

Only one interbed in the Columbia River Basalt Group was studied in detail. The bulk composition and detrital mineralogy of this sample are in Table 8; a detailed petrographic description is found in Appendix A. This interbed consists of fine-grained, poorly to moderately sorted, tuffaceous and
Table 8. Modal analysis (100 points) of thin section of sandstone from the Columbia River Basalt Group.

<table>
<thead>
<tr>
<th></th>
<th>WHOLE ROCK 100%</th>
<th>GRAINS 100%</th>
<th>POROSITY 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRAINS</td>
<td></td>
<td>QUARTZ</td>
<td></td>
</tr>
<tr>
<td>MATRIX</td>
<td></td>
<td>PLAQUEOCLASE</td>
<td></td>
</tr>
<tr>
<td>CEMENT</td>
<td></td>
<td>K-FELDSPAR</td>
<td></td>
</tr>
<tr>
<td>CLAY</td>
<td></td>
<td>CHERT</td>
<td></td>
</tr>
<tr>
<td>POROSITY</td>
<td></td>
<td>SRF</td>
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<tr>
<td></td>
<td></td>
<td>VRF</td>
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<tr>
<td></td>
<td></td>
<td>MRF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MICA</td>
<td></td>
</tr>
<tr>
<td>CRB-R2</td>
<td>20 60 5 10 5</td>
<td>0 10 0 0 90</td>
<td>0 0 1 0 0 99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

diatomaceous sandstone. Feldspar laths, volcanic rock fragments (VRFs), lapilli, glass, zeolites, and kaolinite clays are present (Figure 55). The feldspar laths have not undergone any extensive dissolution or alteration. However, many of the VRFs have undergone extensive alteration, as has the glass (Figure 56). Clays and zeolites have developed as a result.

**Porosity and Permeability**

Porosity is developed in microfractures, diatoms, and in the coarser-grained sediments. The breccia and scoria interbeds can contain surprisingly high porosity and permeability. The one tuffaceous and diatomaceous sample studied contains 54.8% porosity but only 2.10 millidarcies of permeability (Table 9). The low permeability value can be attributed to the high clay content
Figure 55. Photomicrograph of a Columbia River Basalt interbed showing altered states of glass and feldspars (crossed nicols, 200X).

Figure 56. Photomicrograph showing altered lithic fragments from an interbed in the Columbia River Basalt Group (crossed nicols, 200X).
Table 9. Porosity and permeability measurements of a tuffaceous, diatomaceous sandstone from an interbed in the Columbia River Basalt Group.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Formation</th>
<th>Porosity (%)</th>
<th>Permeability (md)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRB-R2</td>
<td>COLUMBIA</td>
<td>54.8</td>
<td>2.10</td>
</tr>
</tbody>
</table>

of the sample, clogging pore throats. Interbeds similar to this one contain moderate to excellent porosity and questionable permeability. However, breccia and scoria interbeds contain not only excellent porosity but excellent permeability as well.

Discussion

The Columbia River Basalt Group may hold the most under-estimated reservoirs of any of the formations in north-central Oregon. In terms of shear volume, the interbeds found between the basalt flows could form tremendous reservoirs.

The Columbia River Basalt Group contains important aquifers throughout the Columbia Basin (Newcomb, 1959; Walters and Grolier, 1960; Newcomb, 1961a; Hogenson, 1964; Mac Nish and others, 1973; Luzier and Burt, 1974; Young and others, 1986). Gonthier (1985) confirms that stratigraphic units in the group supply substantial irrigation water. This indicates significant porosity and lateral permeability. The Columbia River Basalt Group is the most
extensive and the most hydrologically important aquifer in the John Day Basin (Gonthier, 1985). Diatomaceous lacustrine sediments of the partially inter-fingering Mascall Formation are also significant water reservoirs (Gonthier, 1985). Lateral permeability is particularly high in Columbia River Basalt inter-beds because water can move easily through the brecciated and scoriaceous zones between flows (Young and others, 1986).

The Columbia River Basalt Group interbeds are, in fact, proven hydrocarbon reservoirs. The Rattlesnake Hills Gas Field located in south-central Washington produced 1.3 billion cubic feet of methane gas between 1930 and 1940 (Hammer, 1934). The gas occurred in interbeds between basalt flows and fracture zones within flows. Hydrocarbons are assumed to have been produced from Eocene or Miocene rocks below the basalts (Hammer, 1934).

**VOLCANICLASTIC SANDSTONES AS PETROLEUM RESERVOIRS**

In the past, petroleum explorationists have tended to ignore many regions as potential petroleum basins because of the high volcaniclastic content of the basin fill. The standard argument has been that minerals in volcaniclastic sediments are too easily and too rapidly altered into clays, mixed-layer clay complexes, and zeolites for any significant or effective porosity to be retained.

Some of the concerns explorationists have voiced about the character-istics of volcaniclastic reservoirs include the following:
1) Volcaniclastic sandstones typically are not well sorted and may contain a high percentage of fine particles filling potential primary pore space.

2) Volcaniclastic sandstones may contain a high percentage of mineralogically unstable grains, such as feldspars, micas, glass, pyroxenes, amphiboles, olivine, and heavy minerals including magnetite and ilmenite. These unstable grains may be readily dissolved and their products precipitated in primary pore spaces early in the diagenetic process. Depending on physical and chemical conditions, pore-filling minerals precipitated from these mineralogically unstable grains may include clay minerals (kaolinite, smectite, illite, chlorite and mixed-layer chlorite/smectite), sericite, zeolites (laumonite), and cements such as calcite, dolomite, hematite and various iron oxides, anhydrite, pyrite, chalcedony, and quartz.

3) Compaction as a result of burial may have a greater influence on the loss of primary porosity and permeability in volcaniclastic than in siliciclastic sandstones since the percentage of unstable, ductile, and altered framework grains, and the potential for deterioration of these grains is greater (Seeman and Scherer, 1984; Surdam and Boles, 1979);

4) Higher geothermal gradients associated with volcanic activity may decrease porosity at a faster rate than lower geothermal gradients (Galloway, 1979). This may be significant for volcaniclastic reservoirs forming in geothermally active areas;
5) At equal geothermal gradients, porosity in volcaniclastic sandstones may decrease more rapidly than in siliciclastic sandstones (Galloway, 1979) due to the presence of more easily altered grains.

While these are valid concerns and cautions that any explorationist must be aware of, one must also keep in mind the complex variables which affect volcaniclastic sandstone diagenesis. There is a real danger of missing important reservoirs when applying the "rules" of siliciclastic diagenesis (McBride, 1984) to volcaniclastic-rich basins. The diagenetic processes that could potentially destroy a typical siliciclastic reservoir may be the very processes that allow dissolution of minerals and the retention and/or formation of porosity in a volcaniclastic reservoir. As more and more explorationists see the possibilities of volcaniclastic reservoirs, new "rules" of diagenesis that take into account the complexity and variability of these reservoirs may be necessary.

Some of the characteristics of volcaniclastic sandstone which make them good potential reservoirs include the following:

1) Volcaniclastic sediments are composed of a more varied mineralogical suite, with many more grains susceptible to dissolution processes than in siliciclastic sediments, suggesting that volcaniclastic reservoirs hold a greater potential for the development of secondary porosity (Seeman and Scherer, 1984).
2) It has been noted by various workers (Boles, 1988; Hays and Tieh, 1986; Marshall, 1988) that acids associated with and perhaps moving in front of migrating hydrocarbons effectively create a substantial part of the reservoir porosity. The resulting potential for porosity development may be greater in volcaniclastic sediments which contain more grains susceptible to dissolution.

3) Volcaniclastic sediments deposited in some settings, such as rift basins, are often associated with organic-rich sediments, such as lacustrine shales and coals which during thermal maturation produce organic acids that create secondary porosity.

4) Significant porosity and permeability can develop in volcaniclastic sandstones as a result of early silicate dissolution due to hydration reactions in volcaniclastic basins during shallow burial diagenesis. Early dissolution occurs due to elevated pH and salinity often found in non-marine volcaniclastic basins (Mathisen, 1984).

5) Reworked volcaniclastic sands, as those found in the volcaniclastic Tobifera Formation offshore Patagonia (Seeman and Scherer, 1984), have increased porosity and permeability compared to their original composition. The subsequent reservoir quality was less severely affected by burial diagenesis.
By recognizing the complex physical and chemical reactions that take place in volcanioclastic reservoirs, petroleum explorationists may be able to develop greater predictability during new basin analysis. Explorationists throughout the world have just begun to recognize the potential that volcanioclastic reservoirs hold.

**COMPARISONS WITH OTHER BASINS**

It is becoming increasingly clear that deposits of volcanioclastic materials do hold potential as important petroleum reservoirs (Seeman and Scherer, 1984). The thick volcanic and volcanioclastic deposits of north-central Oregon, such as the Clarno Formation, compare favorably with petroleum producing volcanic and volcanioclastic reservoirs elsewhere in the world.

An example of volcanioclastic deposits similar to those in north-central Oregon which produce hydrocarbons is the extensive Permian back-arc basins of eastern Australia. Oil and gas production has been established in tuffaceous rocks in these provinces (Conolly and Ferm, 1985). The producing reservoirs are interbedded with subbituminous to bituminous coal seams and consist of quartz-poor sandstone, conglomerate, and siltstone, derived from a volcanic arc. The tuffaceous rocks of the Clarno Formation compare closely to this sequence. Both contain coals and abundant organic material (Collier, 1914; Fisk and Fritts, 1987) that may be important in the production of organic acids and in the creation of subsequent dissolution of cements and/or framework
grains. Organic acids produced from the thermal alteration of these humic materials can also act to inhibit the precipitation of carbonate and other cements by lowering the pH of formation fluids (Mount and others, 1986).

Two formations that compare even more closely to the Clarno Formation in depositional environment and volcanioclastic basin content are the Ilagan and Awidon Mesa Formations of the Cagayan Basin in the Philippines. These non-marine Cenozoic formations consist of 400 meters of interbedded fluvial and pyroclastic deposits, similar to the Clarno Formation. Mathisen (1984) has shown that the non-marine volcanioclastic sandstones in the Cagayan Basin have been significantly altered by early dissolution and cementation processes. "Dissolution of plagioclase, heavy minerals, and volcanic rock fragments has occurred in nearly all samples, dissolving up to one-half the framework grains and increasing thin-section porosity to as much as 40%" (Mathisen, 1984). This early silicate dissolution occurred during shallow burial diagenesis and greatly increased the secondary porosity. The extensive research by Mathisen (1978, 1981, 1983, 1984) on sandstones of the Cagayan Basin gives an excellent example of the development of secondary porosity in a basin composed largely of volcanioclastic sediments.

Another example of the tendency of volcanioclastics to develop secondary porosity can be seen in the Tertiary volcanioclastics of the Texas Gulf Coast. Porosities in excess of 30% at a burial depth of 15,000 feet have been reported
Figure 57. Photomicrograph of partially consolidated Mazama Ash showing tremendous porosity as evidenced by the blue epoxy (uncrossed nicols, 100X).
(Loucks and others, 1979). These authors suggested that most of this porosity is the result of dissolution of volcanic detritus at depth.

Many volcanioclastic sediments, when first deposited, form an extremely open system. Large amounts of snowmelt and precipitation readily infiltrate Recent volcanioclastic sediments from the Cascades eastward in Oregon, recharging jointed basalt and older volcanioclastic reservoirs with ground water (Gonthier, 1985). Porosity and permeability measurements of a semi-consolidated Mazama Ash collected from my study area showed the fantastic porosity of 63.1% and permeability of 1478 millidarcies (Figure 57). During burial diagenesis, such an open system with free flowing meteoric and connate waters could be important in flushing products of dissolution, such as clays, from developing reservoirs. A similar open system in the Cagayan Basin has allowed pore fluids to remove dissolved material (Mathisen, 1984), and this may have also been the case in the early burial history of the Clarno Formation as well.

In addition to secondary porosity and permeability resulting from grain dissolution, fracture porosity and permeability may be very important in creating oil and gas reservoirs out of volcanic and volcanioclastic rocks. In outcrop, some Clarno Formation sandstones and flows are highly fractured. In the subsurface, similar conditions could form excellent reservoirs. As mentioned earlier, the Steele Energy Keys 1-28 well encountered massive fracture systems in the Clarno (Fisk, personal communication, 1989). As also mentioned above,
the highly fractured condition of welded tuffs allows the Clarno to be a good aquifer (Oregon State well records).

The Dineh-Bi-Keyah Oil Field in Arizona produces from similar fractured volcanics (Biederman, 1986). Porosities in this fractured syenite sill range from 10 to 25% and permeabilities from 0 to 25 millidarcies. According to Biederman (1986), the fractured nature of the sill allowed warm mineralized fluids to leach out or alter the original minerals. Oil was emplaced as cooling took place. Thus, the fractures in the Dineh-Bi-Keyah sill serve a two-fold purpose of enhancing both its porosity and permeability (Biederman, 1986).

Another area where production comes from fractured volcanics, not unlike those of the Clarno Formation, is the Eagle Springs Oil Field in Nye County, Nevada. In this field oil is produced from the Garrett Ranch Ignimbrite at rates as high as 343 barrels of oil per day. Exploration continues to reveal the importance of volcanic deposits to the recovery of hydrocarbons in Nevada (Berrong, 1974; Berrong and Vreeland, 1978; Bortz and Murray, 1979; Dolly, 1979; Duey, 1983; Foster, 1979; Foster and others, 1985; Guion and Pearson, 1979; Poole and Sandberg, 1977; Poole and others, 1983; Veal and others, 1988; Vreeland and Berrong, 1979). In describing the Nevada discoveries Dolly (1979) wrote: "Ignimbrites may form excellent, predicable reservoirs." In north-central Oregon similar fractured ignimbrites are common in both the Clarno and John Day formations.
Still another area containing lithologies similar to those found in the Clarno Formation is the Tupungato Oil Field in Argentina. According to Baldwin (1944), oil is produced in this field from both fractures and pores in the upper part of a thick series of volcanic tuffs. The fractures are believed to be the causative agent allowing production (Baldwin, 1944).

The producing reservoirs in the Jatibarang Oil Field in northern Java are also similar to the Clarno Formation in many ways. The Jatibarang volcanic sequence consists of andesitic lavas overlain by dacitic basalt lavas interbedded with clays, sandstones, conglomerates, and pyroclastics. Most of the effective porosity comes from fractures, though porosity of agglomerate-conglomerate lenses and vesicular porosity of the lavas also contribute as well (Nutt, 1985).

A case example which may also compare in some ways to the Clarno Formation is production from the Green Tuff Formation in the Minami Nagoaka Gas Field in Japan. Rhyolite reservoirs, having a total thickness of 1,000 meters and a gas column of more than 800 meters, occur at depths of 3,800 meters and deeper. The rhyolite rock facies include lavas, pillow breccia, and hyaloclastite. The lava and pillow facies are the favorable facies for producing gas. Meso- and micro-vugs are important for porosity while microfractures affect permeability (Komatsu and others, 1984; Sato, 1984; Sekiguchi, 1984).

Other examples of petroleum production from volcanic and/or volcaniclastic reservoirs are described by Horton (1965), Rateyev and others (1967),
Carroll (1968), Sutan-Assin (1972), Khatchikian and Lesta (1973), Brobst and Tucker (1974), Davies and William (1978), Helmhold (1979), Surdam and Boles (1979), Fletcher (1982), and Seeman and Scherer (1984). These numerous examples, along with my porosity and permeability measurements from the Clarno Formation, illustrate that the volcanic and volcanioclastic deposits of north-central Oregon do have potential to be important petroleum reservoirs.
CONCLUSIONS

GENERAL STATEMENT

The characterization of a petroleum reservoir is the result of many workers gathering data concerning the petrology, porosity and permeability, the nature of fracture development, areal extent and volume, diagenetic history, and other appropriate data from both outcrops and wells. When these data are compiled and reported, over a period of time a picture of the true character of the reservoir begins to emerge. However, at any given moment in the research and development of a basin reservoir, explorationists may need to make a conclusion on the character of a reservoir, based on an interpretation of only the data at their disposal at that moment. Thus, though the data reported in the research and development of a new potential petroleum reservoir is necessarily limited and even general in nature, an educated interpretation of that data may have to be made. Once that interpretation is made, further research will refine and, if necessary, modify the interpretation so that a more and more accurate description of the character of the reservoir will result.

The data recorded in this thesis are from new potential petroleum reservoirs. Following Keighin's (1982) warning that "Great caution should be used before generalizing about vast quantities of rock from limited data...", I have made every attempt to obtain all the data possible from surface outcrops, from thin sections, scanning electron microscopy, and porosity and permeability measurements. My conclusions, based on the data available, are sometimes
general in nature; yet they give an accurate picture of the potential petroleum reservoir rocks of north-central Oregon as I see them at present. Further research and the results of future exploration drilling will refine and possibly redefine the conclusions made here.

**RESERVOIR ROCK POTENTIAL**

Cretaceous and Tertiary strata in north-central Oregon show surprisingly good potential as petroleum reservoirs with porosity and permeability values not generally associated with volcaniclastic rocks. The development of secondary dissolution and fracture porosity and permeability makes these formations significant as potential reservoirs.

Sandstones of the "Mitchell Formation" at the surface are poorly sorted, tightly cemented, clay rich, and have low porosity and permeability. However, in the subsurface where not cemented, such as in reservoirs that accumulated petroleum prior to cementation, porosities and permeabilities may be adequate, particularly for gas. In addition, secondary porosity created by fracturing and dissolution of cements and detrital framework grains may also be present.

The fluvial channel sandstones of the Paleocene-Eocene "Herren Formation" are potentially good reservoirs with porosity values averaging nearly 12% and permeability values averaging five millidarcies. The presence of authigenic clays, siliceous overgrowths, and dissolution products plugging some of the intergranular porosity may at least in part be a surface weathering effect. As
Keighin (1984) has cautioned in the interpretation of subsurface reservoirs from outcrop samples, Herren sandstones in the subsurface could have much higher or lower porosity and permeability.

The volcaniclastic sandstones of the Eo-Oligocene Clarno Formation show surprisingly high porosity. Porosity values averaging 17.5% and permeability values averaging 8 millidarcies indicate that Clarno sandstones are potential reservoirs. The development of secondary porosity is the most important factor in raising the porosity and permeability values. The development of this secondary dissolution porosity, in rocks that are not usually thought of as having reservoir potential, can be attributed to at least four factors: 1) the presence of hydration reactions; 2) the formation of organic acids from the decomposition and thermal maturation of organic matter causing silicate dissolution; 3) high geothermal gradients which increase the rate of dissolution of some silicates; and 4) the flushing of dissolution products out of the reservoirs during diagenesis.

The presence of hydration reactions, which are ubiquitous in volcanicogenic terrains, may be the primary cause of dissolution (Surdam and Boles, 1979). Hydration reactions cause a pH increase in the interstitial fluids resulting in cations being released into solution. The further increase in Ph and salinity affects subsequent diagenetic reactions (Mathisen, 1984). In Hay’s (1966) study of sedimentary rocks, he noted that plagioclase dissolution is found in saline, alkaline, nonmarine environments. Hay also found that the rate of
plagioclase dissolution is increased as salinity and pH is increased. This increase in pH and salinity also has a direct effect on dissolution of volcanic rock fragments. Hydration reactions would be expected to occur as an early diagenetic event taking place before extensive thermal maturation and the release of pH lowering organic acids.

The formation of organic acids from the decomposition and diagenesis ("maturation") of organic matter may also cause silicate dissolution (Huang and Keller, 1972; Surdam and others, 1982). Abundant organic matter does exist in the Clarno Formation, including coals, fossil leaves and other plant fragments, and kerogen-rich lacustrine shales (Collier, 1914; Cavender, 1968; Fisk and Fritts, 1987). Porosity development is a natural consequence of thermal maturation of associated kerogen-rich source rocks and the production of organic acids. The organic acids produced from organic-rich facies in the Clarno Formation have no doubt contributed to the dissolution of plagioclase and volcanic rock fragments.

High temperature gradients may also have been an important factor in the dissolution of some silicates in Clarno sandstones since the increase in temperature may increase the silicate dissolution rate (Blatt, 1979; Galloway, 1979; Mathisen, 1984). The abundant intrusions, pyroclastic flows, and other volcanogenic deposits of the Clarno Formation suggest that the geothermal gradient was elevated and that the deposits were subjected to increased dissolution reaction rates during diagenesis.
The increased temperature gradient could have also been an important factor in the flushing of the dissolution products out of sandstone reservoirs during diagenesis. The accelerated movement of connate and meteoric waters due to an increased temperature gradient could be especially important in a formation such as the Clarno, where the dissolution products are predominately unstable clays, chlorite, and zeolites.

It is apparent from these four factors, that though hydration reactions and production of organic acids do cause dissolution and subsequent precipitation of authigenic silicate cements (Mathisen, 1984; Surdam and Boles, 1979), portions of the Clarno Formation must have been an open system with free flowing connate and meteoric waters which flushed out of the system the products of dissolution. Hence, secondary dissolution porosity was developed and contributes to the secondary porosity seen in the Clarno Formation. The secondary porosity is further increased by the presence of tremendous secondary fracture porosity seen in both outcrop and the subsurface.

Much of the John Day Formation is very clay-rich but fractured ignimbrites in the formation could act as important reservoir rocks. Fractured ignimbrites similar to those of the John Day Formation are known hydrocarbon producers in Nevada and Argentina. In addition to potential reservoirs in the "Mitchell", "Herren", Clarno, and John Day formations, the Columbia River Basalt Group has many interbeds that act as good reservoirs. The interbeds consist of scoria, breccia, tuff, sandstone, diatomite, and lacustrine deposits. The now
abandoned Rattlesnake Hills Gas Field has produced commercial amounts of gas from these interbeds. In terms of shear volume, the Columbia River Basalt Group may be very significant as a reservoir.

CONCLUDING STATEMENT

Potential petroleum reservoirs do exist in north-central Oregon. Outcrop and laboratory studies show that potential reservoirs include submarine-fan sandstones of the "Mitchell Formation", fluvial channel sandstones of the "Herren Formation", volcaniclastic sandstones and fractured flows of the Clarno Formation, fractured ignimbrites of the John Day Formation, and tuffaceous, diatomaceous, scoriaceous, and brecciated interbeds of the Columbia River Basalt Group. Proven reservoirs, similar in lithology and depositional environment to these formations in north-central Oregon, are being produced successfully around the world.
LITERATURE CITED


Beaulieu, J.D., 1972, Geologic formations of eastern Oregon (east of longitude 21° 30’): Oregon Department of Geology and Mineral Industries Bulletin 73, 80 p.


Horton, R.C., 1965, Eastern Nevada is a gamble, but production is rising: World Oil, v. 160, p. 84-89.


Newton, V.C., Jr., 1979, Oil and gas exploration in Oregon for 1978: Oregon Geology, v. 41, p. 47-49.

Newton, V.C., Jr., 1979, Oil and gas exploration in Oregon: Oregon Department of Geology and Mineral Industries, Miscellaneous Paper 6, 41 p.


APPENDIX A

PETROGRAPHIC DESCRIPTION OF SAMPLES

HUD-101: "Mitchell Formation"

NAME: Lithic Arenite Sandstone

LOCATION: Streamside outcrop on south side of Highway 26, 6.5 km northwest of the town of Mitchell in SW SE 21, T11S R21E.

PETROGRAPHIC DESCRIPTION: This very fine- to medium-grained, subangular to subround, poorly sorted rock is a lithic arenite (see Figure 58). Framework grains include quartz, feldspars, volcanic rock fragments (VRFs), and metamorphic rock fragments (MRFs). A relatively high amount of clay cement is present. Both VRFs and MRFs are highly altered. Some altered lithic fragments have filled pore space, forming a pseudomatrix. Clay alteration has occurred. Limonite-rich areas are present. Many grains have been compacted, thus filling intergranular pore space.

Scanning electron microscope work (see Figure 59) shows the relative lack of intergranular porosity. The intergranular pore space has been completely filled with clay. Some grains exhibit dissolution features related to alteration. Relatively small amounts of microporosity are associated with the clay in this sample.
Figure 58. Photomicrographs of "Mitchell Formation" sample HUD-101, a very fine- to coarse-grained, subangular to subround, poorly sorted, lithic arenite, shown in views: A. (uncrossed nicols, 12.8X); and B. (crossed nicols, 12.8X).

A. This photomicrograph shows the tightly packed nature of the "Mitchell Formation". Altered lithic fragments fill pore space, forming a pseudomatrix. Only minor porosity is seen (uncrossed nicols, 12.8X).

B. This photomicrograph shows the mineral assemblage of a typical "Mitchell Formation" sandstone, including quartz, feldspars, volcanic rock fragments (VRFs), and metamorphic rock fragments (MRFs). Limonitic rich areas are present (crossed nicols, 12.8X).
Figure 59. SEM photomicrographs of "Mitchell Formation" sample HUD-101, a fine- to medium-grained, subangular to subrounded, moderately sorted, lithic arenite, at increasing magnifications: A. (35X); B. (500X); and C. (750X).

A. This view shows a fine- to medium-grained, subangular to subrounded, moderately sorted sandstone. Intergranular porosity in this sample has been completely filled with clay. Some grains exhibit a grain coating clay (35X).

B. This view shows clay completely surrounding grains. Note the relative lack of intergranular porosity. Also visible is some microporosity associated with the clays. A number of grains in this sample exhibit dissolution (500X).

C. Higher magnification shows a mixture of mixed layer clay types. Intergranular porosity is not present and relatively small amounts of microporosity are associated with the clay in this sample (750X).
GCC-18A: "Mitchell Formation"

**NAME:** Lithic Arenite Sandstone

**LOCATION:** Outcrop located near junction of Highway 26 and Highway 207, in SW NW 36, T11S R21E

**PETROGRAPHIC DESCRIPTION:** This sample is a very fine- to coarse-grained, subangular to subround, poorly sorted lithic arenite (see Figure 60). Framework grains consist of quartz, feldspars, volcanic rock fragments (VRFs), and metamorphic rock fragments (MRFs). Some framework grains have been altered. Large amounts of clay alteration products are also present. Some altered framework grains have been squeezed into adjacent pore spaces. Virtually no pore space is visible in thin section. Some of the VRFs and MRFs exhibit partial alteration to clays.

The scanning electron microscope (see Figure 61) shows a lack of intergranular pore space. Some microporosity is seen associated with mixed layer clays. Mixed layer clays are seen coating entire grains. Intergranular porosity is clogged with clays and shows only small amounts of microporosity.
Figure 60. Photomicrographs of "Mitchell Formation" sample GCC-18A, a very fine- to coarse-grained, subangular to subround, poorly sorted, lithic arenite, shown in views: A. (uncrossed nicols, 12.8X); and B. (crossed nicols, 12.8X).

A. Photomicrograph showing some of the volcanic rock fragments (VRFs) and metamorphic rock fragments (MRFs) partially altered to clays. Virtually no pore space is visible in thin section (uncrossed nicols, 12.8X).

B. Photomicrograph showing the typical mineral assemblage of a "Mitchell Formation" sandstone, including quartz, feldspars, VRFs, and MRFs (crossed nicols, 12.8X).
Figure 61. SEM photomicrographs of "Mitchell Formation" sample GCC-18A, a very fine- to coarse-grained, subangular to subround, poorly sorted, lithic arenite, at increasing magnifications: A. (35X); B. (250X); and C. (750X).

A. This is a very fine- to coarse-grained, subangular to subround, poorly sorted sandstone. Framework grains are quartz, feldspars, volcanic rock fragments (VRFs), metamorphic rock fragments (MRFs), and occasional igneous lithic fragments. Intergranular pore space is lacking in this sample (35X).

B. Increased magnification shows the lack of intergranular pore space associated with this sample. Relatively small amounts of microporosity are associated with mixed layer clays (250X).

C. This high magnification view shows the lack of intergranular pore space and minor amounts of microporosity (750X).
HUD R2: "Mitchell Formation"

NAME: Arkosic Sandstone

LOCATION: Roadcut 6 km north of the town of Mitchell on Highway 207, in SW SE 21, T11S R21E.

PETROGRAPHIC DESCRIPTION: This sample consists of a fine-grained, poorly sorted arkose (see Figure 62). The framework grains consist of chert, quartz, metamorphic rock fragments (MRFs), and sedimentary rock fragments (SFRs). The cement appears to be siliceous and contains a high percentage of chalcedony. Clay also appears to act as a cement and pore-clogging agent. The sample is well compacted and shows no porosity.
Figure 62. Photomicrographs of "Mitchell Formation" sample HUD-R2, a fine-grained, moderately sorted arkose, shown in views: A. (uncrossed nicols, 12.8X); and B. (crossed nicols, 12.8X).

A. This view shows a fine-grained, poorly sorted arkose. The clay content is high, and the rock appears to be nearly completely "tight". Minor porosity is seen between two feldspar grains (uncrossed nicols, 12.8X).

B. Chalcedony and altered lithic fragments are seen here. A quartz grain with inclusions is seen (crossed nicols, 12.8X).
HER-R10: "Herren Formation"

NAME: Arkosic Sandstone

LOCATION: Streamside outcrop 1/2 mile north of Well's ranch house in SW NW 7, T2S R33E.

PETROGRAPHIC DESCRIPTION: The sample consists of a fine- to medium-grained, subangular to round, moderately sorted arkose (see Figure 63). Framework grains consist of quartz, plagioclase feldspars, alkali feldspars (microcline and orthoclase), volcanic rock fragments (VRFs), biotite and muscovite micas, chert fragments, and organics. The quartz grains are moderately worked and subangular to subround. Both monocrystalline and polycrystalline grains can be seen. Many of the polycrystalline grains are stretched indicating possible metamorphic source. The plagioclase grains have undergone alteration to illite and chlorite. Many are entirely altered and replaced by clay minerals. The alkali feldspars are less altered, but exhibit alteration product replacement by sericite, illite, and other clay minerals. Feldspar grains are subangular to subround. Chert is present as fragments that show some reworking by their subround shape. Cement appears to be predominantly silica, but limonite and clay minerals also act as cementing agents. Clay rims are developed around many of the grains, and pore space is often completely clogged by clay development. Deformed altered lithic grains also clog some pores. This leaves only minor amounts of primary porosity. A small percentage of secondary porosity is present (6% by point count analysis) in the form of dissolution of plagioclase feldspar grains, though strong dissolution development is absent.
Figure 63. Photomicrographs of "Herren Formation" sample HER-R10, a fine- to medium-grained, subangular to round, moderately sorted arkose, shown in views: A. (uncrossed nicols, 12.8X); and B. (crossed nicols, 12.8X).

A. Photomicrograph showing small amounts of porosity as evidenced by the blue epoxy. Clay rims are seen around many of the grains (uncrossed nicols, 12.8X).

B. Photomicrograph showing the typical mineral assemblage of a "Herren Formation" sandstone, including quartz, plagioclase feldspars, alkali feldspars (microcline and orthoclase), volcanic rock fragments (VRFs), biotite and muscovite micas, chert fragments, and trace organics. The quartz consist of both monocrystalline and polycrystalline grains (crossed nicols, 12.8X).
**NAME:** Lithic Arkose

**LOCATION:** Small outcrop with spectacular planar cross bedding in SW NW 20, T4S R29E

**PETROGRAPHIC DESCRIPTION:** This is a fine- to coarse-grained, subround to angular, moderately to poorly sorted, weakly laminated lithic arkose (see Figure 64). Framework grains are mono- and polycrystalline quartz, potassium feldspars (orthoclase and microcline), plagioclase feldspar, biotite, and volcanic rock fragments (VRFs). Minor amounts of metamorphic rock fragments (MRFs), chert, sandstone rock fragments and hornblende are also present. Many of the unstable grains have been partially replaced by impure illitic clays, making the grains more susceptible to deformation. Compaction has resulted in the development of pressure solution features, such as interpenetrating grain boundaries. Primary intergranular and dissolution-enhanced porosity is present, as indicated by the blue epoxy in thin-section. Calcite cement is seen as well as siliceous cement.

Scanning electron microscope study (see Figure 65) shows the presence of quartz overgrowths filling some of the intergranular pore space. Chlorite and illite clays also coat many of the grains. Partial leaching of feldspar grains is evident.
Figure 64. Photomicrographs of "Herren Formation" sample HER SS-3, a fine- to coarse-grained, subround to angular, moderately to poorly sorted, lithic arkose, shown in views: A. (uncrossed nicols, 35X); and B. (crossed nicols, 35X).

A. Photomicrograph showing primary intergranular and dissolution-enhanced porosity, as indicated by the blue epoxy. Clay rims are seen around some of the grains (uncrossed nicols, 35X).

B. Photomicrograph showing the typical mineral assemblage of a "Herren Formation" sandstone, including quartz, plagioclase feldspars, alkali feldspars (microcline and orthoclase), volcanic rock fragments (VRFs), biotite and muscovite micas, chert fragments, and hornblende. Compaction has resulted in the development of pressure solution features, such as interpenetrating grain boundaries (crossed nicols, 35X).
Figure 65. SEM photomicrographs of "Herren Formation" sample HER SS-3, a fine- to medium-grained, subangular to subround, moderately sorted, lithic arkose, at increasing magnifications: A. (50X); B. (100X); and C. (500X).

A. This is a fine- to medium-grained, subangular to subround, moderately sorted sandstone. Framework grains are quartz and lithic fragments. Much of the intergranular porosity has been partly to completely filled by silica cement in the form of quartz overgrowths. However, some good intergranular porosity is visible (P). Note the scattered grain-coating clays (50X).

B. Intergranular pore space is visible in center of sample (100X).

C. Increased magnification shows the chlorite and illite clays partially filling the intergranular pore space (500X).
HER SS-5: "Herren Formation"

NAME: Lithic Arkose

LOCATION: Sandstone cliff in NE SE 19, T4S R29E

PETROGRAPHIC DESCRIPTION: This sample is a fine- to coarse-grained, subangular to subrounded, moderately to poorly sorted, lithic arkose (see Figure 66). Framework grains are mono- and poly-crystalline quartz, potassium feldspars (orthoclase and microcline), plagioclase feldspar, biotite, and volcanic rock fragments (VRFs). Some metamorphic rock fragments (MRFs), chert, sandstone rock fragments and hornblende are also present. The predominate cements are silica and a cherty-clayey matrix. Dissolution enhanced porosity is prevalent, forming significant intragranular porosity. Organic material lines intergranular pores in some areas.

Scanning electron microscope study (see Figure 67) shows the intergranular pore space has been largely filled by silica cement, carbonate, or interlayered chlorite/smectite. Quartz overgrowths are present on some grains. Authigenic clays coat many of the grains, and chlorite rims some grains. Dissolution features appear on many of the framework grains.
Figure 66. Photomicrographs of "Herren Formation" sample HER SS-5, a fine- to coarse-grained, subangular to subround, moderately to poorly sorted, lithic arkose, shown in views: A. (uncrossed nicols, 12.8X); and B. (crossed nicols, 12.8X).

A. Photomicrograph showing prevalent dissolution enhanced porosity forming significant intragranular porosity. Organic material lines intergranular pores in some areas (uncrossed nicols, 12.8X).

B. Photomicrograph showing the typical mineral assemblage of a "Herren Formation" sandstone, including mono- and poly-crystalline quartz, potassium feldspars (orthoclase and microcline), plagioclase feldspar, biotite, and volcanic rock fragments (VRFs). Some metamorphic rock fragments (MRFs), chert, sandstone rock fragments, and hornblende are also present. The predominate cements are silica and a cherty-clayey matrix (crossed nicols, 12.8X).
Figure 67. SEM photomicrographs of "Herren Formation" sample HER SS-5, a fine- to coarse-grained, subangular to subround, tightly cemented, lithic arkose, at increasing magnifications: A. (75X); B. (500X); and C. (1500X).

A. This is a fine- to coarse-grained, subangular to subround, tightly cemented sandstone. Intergranular porosity has been filled by a combination of silica and carbonate cements, and pore-filling, authigenic kaolinite. The smooth crystal faces in this view are quartz overgrowths. Note the dissolution that has taken place in some grains (75X).

B. Increasing detail shows the authigenic kaolinite platelets and booklets. Chlorite rims some grains as seen at (CH). Note the dissolution of grain at left of view (500X).

C. Higher magnification shows the kaolinite morphology (1500X).
SDS-100: "Herren Formation"

NAME: Arkosic Sandstone

LOCATION: Along Smith Ditch in NE SE 19, T4S R29E

PETROGRAPHIC DESCRIPTION: This is a fine- to coarse-grained, subangular to subround, poorly sorted, arkosic sandstone (see Figure 68). Framework grains are mainly monocrystalline quartz, potassium feldspar (orthoclase and microline), plagioclase feldspar, volcanic rock fragments (VRFs), and chert. Lesser amounts of sandstone rock fragments, metamorphic rock fragments (MRFs), and biotite are also present. Illitic clay has partially replaced some framework grains, making them ductile and susceptible to deformation. Compaction has squeezed some of these grains into adjacent pore spaces forming a "pseudomatrix". Extensive leaching has formed intragranular porosity in the more unstable framework grains. Dissolution-enhanced pores formed by the almost complete removal of feldspar grains are common. Pyrite is seen in some samples and hematite is occasionally seen as a cement as well. Silica and pyrite cements also occur and are present as quartz overgrowths and intergranular material respectively. Well crystallized kaolinite partially fills some intergranular pore space and replaces some feldspars.

In scanning electron microscope study (see Figure 69), the intergranular pore space has been largely filled by silica cement, or interlayered chlorite/smectite. Authigenic clays coat many of the grains. Dissolution features appear on many of the framework grains.
Figure 68. Photomicrographs of "Herren Formation" sample SDS-100, a fine- to coarse-grained, subangular to subround, poorly sorted, arkosic sandstone, shown in views: A. (uncrossed nicols, 12.8X); and B. (crossed nicols, 12.8X).

A. Photomicrograph shows that extensive leaching has formed intragranular porosity in the more unstable framework grains. Dissolution-enhanced pores formed by the almost complete removal of feldspar grains, seen here, are common (uncrossed nicols, 12.8X).

B. Photomicrograph showing the mineral assemblage of this "Herren Formation" sandstone, which includes monocrystalline quartz, potassium feldspar (orthoclase and microcline), plagioclase feldspar, volcanic rock fragments (VRFs), and chert. Illitic clay has partially replaced some framework grains, making them ductile, and compaction has squeezed some of these grains into adjacent pore spaces forming a "pseudomatrix" (crossed nicols, 12.8X).
Figure 69. SEM photomicrographs of "Herren Formation" sample SDS-100, a medium- to coarse-grained, subangular to subround, moderately sorted, arkosic sandstone, at increasing magnifications: A. (50X); B. (150X); and C. (750X).

A. This view shows a medium- to coarse-grained, subangular to subround, moderately sorted sandstone. Intergranular porosity has been largely filled by silica cement. However, some good intergranular porosity is visible. Also note the grain-coating clay in the upper right corner (75X).

B. Increasing detail of a leached biotite grain (150X).

C. Note the leaching that has occurred along the cleavage planes of the biotite grain (750X).
NAME: Lithic Arkose

LOCATION: Along Smith Ditch measured section at level 184 feet, in SE SW 34, T4S R29E.

PETROGRAPHIC DESCRIPTION: The sample is a fine- to coarse-grained, subround to angular, moderately to poorly sorted lithic arkose (see Figure 70). Framework grains are monocrystalline quartz, potassium feldspar (orthoclase and microcline), plagioclase feldspar, volcanic rock fragments (VRFs), and chert. Lesser amounts of sandstone rock fragments, metamorphic rock fragments (MRFs), and biotite are also present. Detrital mica has been squeezed into adjacent pore space, forming a "pseudomatrix." Extensive dissolution of other unstable framework grains has formed dissolution-enhanced and intragranular porosities as shown by the blue impregnating epoxy. Feldspar grains have been extensively leached, distinctly adding to the secondary porosity. Some intragranular pore space is filled with well crystallized kaolinite. Many framework grains are rimmed by a combination of organic material and clay. Hematite and pyrite are present in some areas.

The scanning electron microscope (see Figure 71) reveals the presence of intergranular porosity that has been partially filled by silica cement and authigenic clays. The leaching of feldspar grains is readily apparent as well. Grain coating chlorite and illitic clays, as well as booklets of authigenic kaolinite are present to some degree in much of the pore space. Carbonate cement is also a cementing agent seen in some locations.
Figure 70. Photomicrographs of "Herren Formation" sample SDS-184, a fine- to coarse-grained, subround to angular, moderately to poorly sorted, lithic arkose, shown in views: A. (uncrossed nicols, 12.8X); and B. (crossed nicols, 12.8X).

A. Photomicrograph showing that extensive dissolution of unstable framework grains has formed dissolution-enhanced and intra-granular porosities seen here as blue impregnating epoxy (uncrossed nicols, 12.8X).

B. Photomicrograph showing the mineral assemblage of this "Herren Formation" arkose, which includes monocrystalline quartz, potassium feldspar (orthoclase and microcline), plagioclase feldspar, volcanic rock fragments (VRFs), and chert. Illitic clay has partially replaced some framework grains, making them ductile, and compaction has squeezed some of these grains into adjacent pore spaces forming a "pseudomatrix" (crossed nicols, 12.8X).
Figure 71. SEM photomicrographs of "Herren Formation" sample SDS-184, a medium-grained, moderately sorted, subangular to subround, lithic arkose, at increasing magnifications: A. (50X); B. (150X); and C. (500X).

A. The SEM photomicrograph shows a medium-grained, moderately sorted, subangular to subround sandstone. Some intergranular porosity is visible, but much of it has been partly filled by silica cement and authigenic clays. Also note the leaching of the feldspar grain (F) in the upper left quadrant (50X).

B. Increased detail shows grain-coating and pore-filling kaolinite (K). This clay is pervasive and extremely well-crystallized (150X).

C. Note the extensively leached feldspar grain in the lower left quadrant and the poorly crystallized, grain-coating, chloritic and illitic clay (CL) (500X).
SAMPLE 1: "Herren Formation"

NAME: Lithic Arenite

LOCATION: North facing road cut at the west edge of Smith Ditch in SW SW 34, T4S R29E

PETROGRAPHIC DESCRIPTION: This sample is a medium- to very coarse-grained, subangular to subrounded, moderately sorted, lithic arenite (see Figure 72). Framework grains include polycrystalline quartz, feldspar, chert, lithic fragments including sandstone rock fragments, and muscovite. Limonite is also seen. Rock fragments have been altered, making them more susceptible to ductile deformation. Intergranular and intragranular porosity is seen as indicated by the blue impregnating epoxy. Feldspar grains show the most leaching and dissolution. In some cases, grains have undergone almost complete dissolution, creating tremendous secondary porosity.

Scanning electron microscope work (see Figure 73) reveals authigenic clays and carbonate cement filling some intergranular pore space. The significant dissolution of feldspar grains is readily seen in all samples, showing the development of secondary porosity.
Figure 72. Photomicrographs of "Herren Formation" Sample 1, a medium- to very coarse-grained, subangular to subround, moderately sorted, lithic arenite, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This is a medium- to coarse-grained, subangular to subround, poorly to moderately sorted sandstone. Framework grains include quartz, feldspar, chert, lithic fragments, and muscovite. The opaque inter- and intragranular material is limonite. Note the intergranular and dissolution-enhanced porosity (uncrossed nicols, 40X).

B. Cross nicol view of the previous photo showing the polycrystalline nature of some of the quartz grains. The birefringent mineral in the upper right corner is muscovite. Also note the abundance of chert (crossed nicols, 40X).
Figure 73. SEM photomicrographs of "Herren Formation" Sample 1, a medium-grained, subangular to subround, lithic arenite, at increasing magnifications: A. (50X); B. (200X); and C. (750X).

A. This view shows a medium-grained, subangular to subround sandstone. Intergranular porosity has been filled by authigenic clays and carbonate cement. Note the dissolution of the feldspar grains (f) (50X).

B. Increasing detail of the dissolution features of the feldspar. Note the intragranular porosity resulting from this dissolution (200X).

C. Higher magnification shows how extensive the dissolution is in feldspar grains (750X).
SAMPLE 2:  "Herren Formation"

NAME: Lithic Arenite

LOCATION: Along Smith Ditch in SE SW 34, T4S R29E

PETROGRAPHIC DESCRIPTION: This sample is a very fine- to coarse-grained, subangular to subround, poorly sorted, chert-rich sandstone (see Figure 74). Framework grains include polycrystalline quartz, feldspar, chert, lithic fragments, and muscovite. Scattered glauconite is present as well. Illite has replaced many of the unstable grains, and kaolinite is seen in association with and replacing feldspars. Feldspars have been highly leached. Mica grains often show deformation as a result of compaction. Dissolution enhanced porosity is prevalent throughout the sample. Cements include silica and clay.

Scanning electron microscope study (see Figure 75) shows the clogged intergranular pore space filled with such agents as kaolinite, silica cement and carbonate cement. Dissolution-enhanced porosity is also present in feldspars.
Figure 74. Photomicrographs of "Herren Formation" Sample 2, a very fine- to coarse-grained, subangular to subround, poorly sorted, chert-rich sandstone, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This very fine- to coarse-grained, subangular to subround, poorly sorted, chert-rich rock is a sandstone. Framework grain mineralogy includes quartz, feldspar, chert, lithic fragments, and muscovite. Note the leaching of the feldspar (f). Scattered intergranular and dissolution-enhanced porosity is visible (uncrossed nicols, 40X).

B. Crossed nicol view of the previous photo. Notice the fractured and dissolved condition of the grains (crossed nicols, 40X).
Figure 75. SEM photomicrographs of "Herren Formation" Sample 2, a fine-grained, well cemented, subangular to subround, lithic arenite, at increasing magnifications: A. (100X); B. (500X); and C. (1500X).

A. This is a fine-grained, well cemented, subangular to subround sandstone. Intergranular porosity has been filled by kaolinite, and silica and carbonate cements. Note the leached feldspar grain in lower center (100X).

B. This view shows the increasing detail of the pore filling kaolinite typical of this sample. Note the carbonate cement (probably dolomite) in the upper left corner of this view (500X).

C. Scattered chlorite blades are seen in some locations next to the pore filling kaolinite books (1500X).
NAME: Feldspathic Litharenite

LOCATION: Near base of measured section in NE NW 10, T8S R19E.

PETROGRAPHIC DESCRIPTION: This sample is a fine- to medium-grained, angular to subangular, poorly sorted, tight, feldspathic litharenite (see Figure 76). Framework grains include volcanic rock fragments (VRFs), alkali feldspars (sanadine, orthoclase, and microcline), plagioclase (An $\infty$), quartz, and sedimentary rock fragments (SFRs). Detrital biotite and muscovite is also present. VRFs consist of agglomerates of felted microcrystalline feldspars, tuffaceous clasts, and pyroclastic andesite clasts. Plagioclase feldspars are altered to clay minerals while the alkali feldspars show replacement of portions of grains with chlorite and calcite. Quartz grains are predominately monocrytalline exhibiting uniform extinction, though some polycrystalline undulatory grains can be seen. The polycrystalline grains are smooth to crenulated. SFRs include chert pebbles and tuffaceous mud clasts. Intergranular porosity is not well developed in this sample and is choked with clays, chalcedony or a pseudomatrix of squeezed lithic fragments. Stable grains such as quartz are rimmed by clays. Cements present include calcite, clay minerals, and chalcedony. Intragranular porosity is filled with calcite and chlorite or other clay minerals.

In SEM study (see Figure 77) the intergranular pore space is partially blocked by feldspar overgrowths. Illitization of many of the feldspars has taken place. Microporosity is present and some pores are very clean. As a result of dissolution, intragranular pore space is significant in this sample.
Figure 76. Photomicrographs of Clarno Formation sample CLR-2M, a fine- to medium-grained, angular to subangular, poorly sorted, tight, feldspathic litharenite, shown in views: A. (uncrossed nicols, 12.8X); and B. (crossed nicols, 12.8X).

A. This is a fine- to medium-grained, angular to subangular, poorly sorted sandstone. Scattered microporosity is visible, as shown by blue epoxy, in leached feldspars in some locations. The bright blue replacement mineral in the leached feldspar is amphibole (uncrossed nicols, 12.8X).

B. The grains are tightly packed, and the varied mineral assemblage is readily apparent. Note the feldspars that have undergone dissolution (crossed nicols, 12.8X).
Figure 77. SEM photomicrographs of Clarno Formation sample CLR 2M, a fine-to coarse-grained, subangular to subround, feldspathic litharenite, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. This view shows a fine-to coarse-grained, subangular to subround sandstone. Framework grains include potassium and alkali feldspars and volcanic rock fragments. Many grains exhibit potassium feldspar overgrowths. Intergranular porosity is evident, though the potassium feldspars have closed some pores. Intragranular porosity is also an important factor in this sample (600X).

B. In this magnification, note the clean pore space, as well as the microporosity. The large grain in the center is an alkali feldspar (1200X).

C. Note the intragranular pore space developed in this alkali feldspar through dissolution. Illitization of the potassium feldspar overgrowths has also taken place (6000X).
NAME: Lithic Arkose

LOCATION: Massive brecciated outcrop in measured section about 10 meters up from blue marker bed at base, in NE NW 10, T8S R19E.

PETROGRAPHIC DESCRIPTION: This is a fine- to very fine-grained, subrounded to angular, moderately sorted, slightly laminated, lithic arkose (see Figure 78). Framework grains include plagioclase (An₃₅), volcanic rock fragments (VRFs), quartz, alkali feldspars (sanidine and orthoclase), biotite and muscovite mica, metamorphic rock fragments (MRFs), and chert fragments. Plagioclase grains show varying degrees of alteration, with replacement by authigenic calcite, sericite, or other clay type minerals. The altered plagioclase grains along with the VRFs are slightly deformed and smashed. VRFs consist of finely felted feldspar laths, tuffaceous fragments and clays, and agglomerates of volcaniclastic lapilli. The rock fragments tend to form a pseudomatrix due to their easily deformed qualities. The quartz grains are predominately monocrystalline and exhibit uniform extinction; most are angular in shape. Much of the intergranular porosity is effectively destroyed by the pseudomatrix of easily deformed grains and by the development of clay rims around the grains. However there are numerous examples of clean grain separation and preservation of primary porosity. An unusual feature is the development of intergranular/intragranular porosity between the clay rims and a number of the plagioclase grains. Secondary micro-fracture porosity is also developed throughout the sample. Secondary dissolution formed porosity in feldspars is not well developed or is completely clogged with calcite or clay minerals. The sample contains possible organic material. The cement appears to be calcite with some clay minerals acting as a cementing agent as well.
Figure 78. Photomicrographs of Clarno Formation sample CLR-DA, a fine- to very fine-grained, subround to angular, moderately sorted, slightly laminated, lithic arkose, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This view shows a fine- to very fine-grained, subround to angular, moderately sorted, lithic arkose. Feldspar, lithic fragments, and hornblende are visible. Note the blue epoxy stained primary pore space around many of the grains, as well as the secondary porosity in some of the dissolved feldspars (uncrossed nicols, 40X).

B. The cementing agents, chalcedony and some calcite, are visible in this view. Note the deteriorated condition of many of the grains (crossed nicols, 40X).
CLR-R1: Clarno Formation

NAME: Subarkose Sandstone

LOCATION: Low road cut 1/4 mile west of Kelly Prairie on Ukiah Highway in SE NW 1, T5S R28E.

PETROGRAPHIC DESCRIPTION: This sample is described as a fine-grained, subrounded to angular, poorly sorted, subarkose (see Figure 79). Framework grains consist of plagioclase (An 78), volcanic rock fragments (VRFs), alkali feldspars, amphibole (hornblende), muscovite mica, and trace quartz. Much of the plagioclase is highly altered and replaced with calcite, chlorite, various clays, and other alteration products. Many of the grains are represented only by ghost forms. The less altered mica does show partial alteration to chlorite. Alkali feldspars are less altered. The quartz grains are monocrystalline and are rarely seen. Porosity is only developed in micro-fractures. Deformation of altered grains has destroyed all primary porosity.

SEM study (see Figure 80) shows that porosity and microporosity is present. The intergranular porosity appears to be partially clogged with feldspar overgrowths. The sample has a general lack of pore filling clays and clay complexes.
Figure 79. Photomicrographs of Clarno Formation sample CLR-R1, a fine-grained, subround to angular, poorly sorted, lithic arkose, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This photomicrograph shows a fine-grained, subround to angular, poorly sorted, lithic arkose. Lithic fragments are compressed into pores creating a pseudomatrix. Porosity fractures have developed in the lithic fragments as shown by the blue epoxy. Clay development is profuse. Note the microporosity in some cleavage planes of feldspar (uncrossed nicols, 40X).

B. The lithic fragment deterioration is seen here. Evidence of feldspar dissolution is also seen in some grains (crossed nicols, 40X).
Figure 80. SEM photomicrographs of Clarno Formation sample CLR-R1, a coarse-grained, subround to angular, poorly sorted, lithic arkose, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. This is a coarse-grained, subround to angular, poorly sorted sandstone. The framework grain is a large plagioclase feldspar that has undergone partial dissolution. Microporosity is present. Intergranular porosity appears to be partially clogged with feldspar overgrowths (600X).

B. Higher magnification shows the contact between the feldspar grain and the feldspar overgrowth. Note the microporosity and the general lack of pore filling clays and clay complexes (1200X).

C. The contact between the plagioclase grain and the feldspar overgrowth is clearly visible at this magnification. The lack of pore filling clays is also evident (6000X).
CLR-R2: Clarno Formation

NAME: Subarkose Sandstone

LOCATION: Low roadcut 1/4 mile west of Kelly Prairie on Ukiah Highway in SE NW 1, T5S R28E.

PETROGRAPHIC DESCRIPTION: This sample is described as a medium- to coarse-grained, angular to subangular, moderately sorted, quartz-rich subarkose (see Figure 81). Framework grains consist of quartz, plagioclase feldspars, alkali feldspars (orthoclase), biotite and muscovite mica, chert, rock fragments, and scattered pyroxenes. Quartz grains are both monocrystalline and polycrystalline, showing undulatory and nonundulatory extinction. The polycrystalline borders are smooth to crenulated and stretched. The apparent source of quartz is mixed volcanic and metamorphic. The plagioclase feldspars are all leached so that good dissolution porosity is developed (20% by point count analysis). Porosity is also present as primary interparticle pore space retention. Some illitization and sericitization is present where alteration instead of dissolution has taken place. Authigenic chert is present in abundance, and some lithic fragments are composed of chert. Lithic fragments are also composed of volcanic rock fragments (VRFs) and clay clasts. Thin clay rims are present around most grain boundaries, but may be a result of surface weathering. Silica appears to be the predominate cementing agent.

SEM (see Figures 82 and 83) shows the intergranular porosity clogged with kaolinite books. Some intragranular porosity is seen in the dissolved feldspars present in the sample. The alkali feldspar has undergone dissolution/weathering to form the kaolinite.
Figure 81. Photomicrographs of Clarno Formation sample CLR-R2, a medium- to coarse-grained, angular to subangular, moderately sorted, quartz-rich subarkose, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This is a medium- to coarse-grained, angular to subangular, moderately sorted, quartz-rich sandstone. The significant porosity development in the center of the photo is secondary dissolution of a feldspar grain. Quartz overgrowths are spanning many of the surrounding quartz grains (uncrossed nicols, 40X).

B. By comparing the grains in this view to the previous, the presence of quartz overgrowths, as well as the nature of the grain contacts, can be seen (crossed nicols, 40X).
Figure 82. SEM photomicrographs of Clarno Formation sample CLR-R2A, a fine-to coarse-grained, lithic arkose, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. This view shows a fine- to coarse-grained sandstone. Framework grains are completely surrounded and covered with books of kaolinite. The only grain visible is a large alkali feldspar that has probably undergone dissolution/weathering to form the kaolinite. Pore space characteristics are not classifiable (600X).

B. Increased magnification shows the distinct kaolinite books (1200X).

C. Kaolinite books (6000X).
Figure 83. SEM photomicrographs of Clarno Formation sample CLR-R2B, a medium- to coarse-grained, angular, weathered subarkose, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. This is a medium- to coarse-grained, angular, weathered sandstone. Framework grains include quartz grains exhibiting quartz over-growths and dissolved alkali feldspars. Intergranular porosity is clogged with kaolinite books. Intragranular porosity is evident through dissolution of the feldspars (600X).

B. Further magnification shows a pore in the lower portion of the quartz overgrowth (1200X).

C. View of typically unorganized kaolinite books (6000X).
CLR-R4: Clarno Formation

NAME: Subarkose Sandstone

LOCATION: 1/4 mile west of Kelly Prairie on USFS Road 53 (Ukiah Road) in SE NW 1, T5S R28E.

PETROGRAPHIC DESCRIPTION: This sample is a medium-grained, quartz-rich, angular to subangular, moderately sorted, subarkose (see Figure 84). Framework grains consist of quartz, plagioclase feldspars (An₃₅), orthoclase feldspars, biotite and muscovite micas, chert, and rock fragments. Quartz grains are both monocrystalline and polycrystalline, showing undulatory and nonundulatory extinction. The polycrystalline borders are smooth to crenulated and stretched. The apparent source of quartz is mixed volcanic and metamorphic. The plagioclase feldspars are all leached so that good dissolution porosity is developed (15%), though some illitization and sericitization is present. Porosity is also present as primary partake pore space retention. Authigenic chert is present in abundance and some lithic fragments are composed of chert. Lithic fragments are also composed of volcanic rock fragments (VRFs) and clay clasts. Thin clay rims have formed around most grain boundaries, but may be a result of surface weathering. Silica appears to be the predominate cementing agent.

Chlorite and kaolinite resulting from the alteration of volcanic rock fragments is seen in SEM study (see Figure 85). The character of the intergranular pore development is one of dissolution then overgrowth. Kaolinite books and chlorite complexes are present.
Figure 84. Photomicrographs of Clarno Formation sample CLR-R4, a medium-grained, quartz-rich, angular to subangular, moderately sorted subarkose, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This is a medium-grained, quartz-rich, angular to subangular, moderately sorted sandstone. Significant porosity is seen in the dissolved feldspar grain. Clay development is in evidence by the brown agglomerations (uncrossed nicols, 40X)

B. Cementing agents include silica, chalcedony, and clay complexes (crossed nicols, 40X).
Figure 85. SEM photomicrographs of Clarno Formation sample CLR-R4, a coarse-grained, angular subarkose, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. This view shows a coarse-grained, angular sandstone. Framework grains consist of potassium feldspars and volcanic rock fragments. The large reabsorbed potassium feldspar in the center of the photo has undergone extensive dissolution and alteration. Products of alteration coat some areas of the grain. Chlorite and kaolinite are present as a result of the alteration of volcanic rock fragments (600X).

B. In this view, the character of the intergranular pore development is apparent. Kaolinite books and chlorite complexes are seen (1200X).

C. The "clean" character of a potassium feldspar grain is seen in this view (6000X).
CLR-R5: Clarno Formation

NAME: Lithic Arkose Sandstone

LOCATION: Roadcut on USFS Road 53, 100 meters west of mile marker 29 in NE NE 4, T5S R28E.

PETROGRAPHIC DESCRIPTION: This is a medium-grained, angular to subangular, poorly sorted, lithic arkose (see Figure 86). Framework grains consist of plagioclase feldspar, alkali feldspars (sanadine, orthoclase, and trace microcline), quartz, muscovite and biotite mica, chert rock fragments, and abundant clays. The plagioclase feldspars exhibit good secondary porosity (10% by point count analysis) as a result of dissolution and leaching. Twinning present indicates a volcanic origin to the plagioclase feldspars. The alkali feldspars are partially altered to clay minerals. The quartz grains are predominately monocrysaline though some polycrystalline grains are evident. They exhibit undulatory and nonundulatory extinction. Chert is present as a cement replacement of some dissolved fragments and is therefore authigenic. The sample is closely packed and shows very little primary porosity. Secondary porosity is developed by the leaching of feldspars and volcanic rock fragments. Clay accumulation not related to grain alteration appears to be present in local areas and is probably detrital in nature. The silica cement appears to have taken a microcrystalline cherty nature.

SEM work (see Figures 87 and 88) gives evidence that smectite, illite-smectite complexes, and chlorite are all present as alteration products of feldspars. Intergranular pore space is present, especially around the quartz grains. The pore space is partially clogged with mixed illite-smectite. Intragranular microporosity is seen occasionally; however, illite-smectite complexes bridge the pore space between feldspars.
Figure 86. Photomicrographs of Clarno Formation sample CLR-R5, a medium-grained, angular to subangular, poorly sorted, lithic arkose, shown in views: A. (uncrossed nicols, 80X); and B. (crossed nicols, 80X).

A. A medium-grained, angular to subangular, poorly sorted, lithic sandstone is seen here. The clay content is high, but the dissolved feldspars, creating secondary porosity, are significant in the overall porosity values (uncrossed nicols, 80X).

B. Chert is visible here, as well as the dissolved feldspars. Clay agglomerations are also seen (crossed nicols, 80X).
Figure 87. SEM photomicrographs of Clarno Formation sample CLR-R5, a fine-to coarse-grained, angular to sub-angular, lithic arkose, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. This view is of a typical fine- to coarse-grained, angular to sub-angular, lithic arkose. Framework grains include alkali and potassium feldspars and detrital quartz. Smectite, illite-smectite complexes, and chlorite are all present as alteration products of feldspars. Intergranular pore space is present, especially around the quartz grain. The pore space is partially clogged with mixed illite-smectite. Intragranular microporosity is seen occasionally (600X).

B. This magnification shows the chlorite and smectite in close association. Note the presence of small pores (1200X).

C. Note the pore in the center of the plagioclase grain. The surrounding clays are smectite (6000X).
Figure 88. SEM photomicrographs of Clarno Formation sample CLR-R5B, a fine-to coarse-grained, angular to sub-angular, lithic arkose, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. A fine- to coarse-grained, angular to subangular sandstone is shown. Framework grains include alkali and potassium feldspars and detrital quartz. Smectite, illite, and kaolinite are all present as alteration products of feldspars. The pore space is partially clogged with kaolinite. Intrgranular microporosity is seen occasionally (600X).

B. This magnification shows the microporosity. Note the clogging kaolinite debris (1200X).

C. Kaolinite debris in close association with feldspar overgrowths (6000X).
CLR R7: Clarno Formation

NAME: Volcaniclastic Sandstone

LOCATION: A yellow to gray water-lain tuff in the measured section, 11 meters above blue marker bed at base, in NE NW 10, T8S R19E.

PETROGRAPHIC DESCRIPTION: This sample is described as a holo-crystalline, volcaniclastic sandstone, made of phaneritic crystals in an aphanitic groundmass (see Figure 89). The phaneritic plagioclase feldspars are partially altered, showing illitization. Some dissolution has taken place in feldspars creating a surprising amount of secondary porosity (as high as 15% by point count analysis) as evidenced by the epoxy. Numerous fractures and microfractures also create porous zones. The feldspars show zoning, a common characteristic of volcanic feldspars. Sericite has replaced some of the unzoned plagioclase grains. Many of the feldspars are replaced with chlorite, sericite, and calcite. Phaneritic hornblende, as well as altered biotite, is also present. The groundmass, which accounts for almost 70% of the sample, includes feldspar microlites, clays, iron and titanium oxides, and some isotropic grains. Illite is the predominate clay as an alteration product of feldspars. Chlorite is altered from the micas and shows a pleochroic green shade. Montmorillonite is present in many of the original pores, completely lining the pores. Epimatrix may be a useful term in describing the clay and mineral assemblage seen in this sample (see Dickinson (1970) classification of volcaniclastic rocks).

SEM (see Figure 90) shows intergranular pore space present, but it is often clogged with clay alteration products. Smectite lines many of the pores, effectively closing some pores. Casts of feldspar grains that have undergone total dissolution are present.
Figure 89. Photomicrographs of Clarno Formation sample CLR-R7, a holocrystalline, volcaniclastic sandstone, made of phaneritic crystals in an aphanitic groundmass, shown in views: A. (uncrossed nicols, 12.8X); and B. (crossed nicols, 12.8X).

A. This is a holocrystalline, volcaniclastic sandstone, made of phaneritic crystals in an aphanitic groundmass. Note the porosity development in both the feldspar grain and in the large fracture (uncrossed nicols, 12.8X).

B. The altered state of the large feldspar grain is very apparent. The bright mineral on the side is pyroxene (crossed nicols, 12.8X).
Figure 90. SEM photomicrographs of Clarno Formation sample CLR-R7, a fine-to medium-grained, angular sandstone, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. This is a fine- to medium-grained, angular sandstone. Framework grains include potassium feldspar, alkali feldspar, quartz, and volcanic rock fragments. Intergranular pore space is present but clogged with clay alteration products. Casts of feldspar grains that have undergone total dissolution are present. Sample appears very "dirty" (600X).

B. This view shows the character of the pore left from the dissolution of a feldspar grain. Also a partially dissolved feldspar grain is seen next to the pore opening in the center of the photo (1200X).

C. Further magnification shows the pore space lined with smectite causing almost total closure (6000X).
NAME: Volcaniclastic Sandstone

LOCATION: A sandstone channel in the measured section, 13 meters above blue marker bed at base, in NE NW 10, T8S R19E

PETROGRAPHIC DESCRIPTION: This sample is a holocrystalline, volcaniclastic sandstone, made of phaneritic crystals in an aphanitic groundmass (see Figure 91). The phaneritic plagioclase feldspars are partially altered, showing illitization and dissolution. The dissolution has created a surprising amount of secondary porosity (as high as 14%) as evidenced by the impregnating epoxy. Numerous fractures and microfractures also create porosity. The feldspars show zoning, a common characteristic of volcanic feldspars. Many of the feldspars are replaced with chlorite, sericite, and calcite. Phaneritic hornblende as well as altered biotite, is also present. The groundmass, which is less abundant than the previous sample, includes feldspar microlites, clays, iron and titanium oxides, and some isotropic grains. Illite is the predominate clay as an alteration product of feldspars. Chlorite is altered from the micas and shows a pleochroic green shade. Montmorillonite is present in many of the original pores, completely lining the pores. Epimatrix may be a useful term in describing the clay and mineral assemblage (Dickinson (1970) classification for volcaniclastic rocks).

SEM study (see Figure 92) shows the presence of intergranular pore space and the dissolution of quartz grains which has enhanced the intragranular pore space. Smectite clays appear to coat some surfaces.
Figure 91. Photomicrographs of Clarno Formation sample CLR-R7A, a holocrystalline, volcaniclastic sandstone, made of phaneritic crystals in an aphanitic groundmass, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This is a holocrystalline, volcaniclastic sandstone, made of phaneritic crystals in an aphanitic groundmass. In spite of its volcanic mineral assemblage, porosity is seen (uncrossed nicols, 40X).

B. Large feldspar grains are the dominate lithology (crossed nicols, 40X).
Figure 92. SEM photomicrographs of Clarno Formation sample CLR-R7A, a fine-to medium-grained, subangular to round sandstone, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. This view shows a fine- to medium-grained, subangular to round sandstone. Framework grains include quartz and potassium feldspars. Intergranular pore space is present and the dissolution of quartz grains has enhanced the intragranular pore space. Smectite clays appear to coat some surfaces (600X).

B. Magnification shows the character of the pores and the rimming smectite clays (1200X).

C. Further magnification a highly dissolved quartz grain with smectite clays rimming it. Also note the microporosity (6000X).
CLR-R10: Clarno Formation

NAME: Litharenite Sandstone

LOCATION: A poorly sorted conglomeratic sandstone outcrop in NW NW 30, T11S R21E.

PETROGRAPHIC DESCRIPTION: This highly altered, coarse-grained, angular to subrounded, poorly sorted rock is a litharenite (see Figure 93). The framework grains consist of fragments of volcaniclastic material or volcanic rock fragments (VRFs). It may be better described as the accumulation of tuffaceous lapilli. The grains are closely packed and nearly indistinguishable in cross-nicols. The VRFs consist of large feldspars set in a felted matrix of plagioclase laths, tuffaceous materials, and clays. Porosity is developed in minute fractures. Total point count porosity is less than 7%.
Figure 93. Photomicrographs of Clarno Formation sample CLR-R10, a highly altered, coarse-grained, angular to subround, poorly sorted litharenite, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This is a highly altered, coarse-grained, angular to subround, poorly sorted sandstone. Porosity is associated with desiccation cracks in the chalcedony cement lining the pores (uncrossed nicols, 40X).

B. The altered state of this lithic-rich rock is evident (crossed nicols, 40X).
CLR-R11A: Clarno Formation

**NAME:** Lithic Arkose Sandstone

**LOCATION:** 1/4 mile west of Ochoco National Forest sign on east side of Ochoco Pass in large roadcut on Highway 26. Sample was taken near top of outcrop in SW NW 17, T12S R20E.

**PETROGRAPHIC DESCRIPTION:** This sample is a fine- to medium-grained, angular, poorly sorted, highly altered, tuffaceous, lithic arkose (see Figure 94). The minerals present include plagioclase (An 70), alkali feldspars (orthoclase and sanadine), volcanic rock fragments, quartz, amphibole and trace micas. The plagioclase is highly altered and replaced with illite, chlorite, and other clay minerals. The VRFs are composed of volcaniclastic material, including feldspars, clays, hornblende, iron oxides and quartz. The hornblende shows twinning and some alteration but has held up better than the feldspars. Porosity is seen only in a few areas. Alteration of feldspars to clays, as well as compaction, has gone far in closing the pores. Secondary porosity is not readily apparent. Illite and chlorite are the dominate clays. Cement is siliceous and clays and tuff contribute as a bonding agent. Zeolites are also present, probably analcite. Alteration types include: 1) Illitization that has affected most of the feldspars; illite is the largest component of the groundmass; 2) Sericitization that has affected the plagioclase; 3) Possible kaolinization; 4) Calcite replacement of plagioclase.
Figure 94. Photomicrographs of Clarno Formation sample CLR-R11A, a fine- to medium-grained, angular, poorly sorted, highly altered, tuffaceous, lithic arkose, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This view shows a fine- to medium-grained, angular, poorly sorted, highly altered, tuffaceous, lithic arkose. The rock is a "dirty" combination of clay and clay complexes, altered lithic fragments, altered feldspars, and the lone amphibole. Minute porosity is in evidence by blue epoxy (uncrossed nicols, 40X).

B. Altered lithic fragments and clay complexes are visible in this view. The sample is highly altered (crossed nicols, 40X).
CLR-R11B: Clarno Formation

NAME: Lithic Arkose Sandstone

LOCATION: 1/4 mile west of Ochoco National Forest sign on east side of Ochoco Pass in large roadcut, on Highway 26, in SW NW 17, T12S R20E. Sample was taken beneath sill in a channel feature.

PETROGRAPHIC DESCRIPTION: This is a fine- to medium-grained, angular, poorly sorted, highly altered, tuffaceous, lithic arkose (see Figure 95). The minerals present include, plagioclase (An₆₅), alkali feldspars (orthoclase and sanidine), volcanic rock fragments (VRFs), quartz, amphibole, and trace micas. The plagioclase is highly altered and replaced with illite, chlorite, and other clay minerals. The VRFs are composed of volcaniclastic material, including feldspars, clays, hornblende, iron oxides, and quartz. The hornblende shows some alteration but has held up better than the feldspars. Porosity is seen in only a few areas. Secondary porosity is not readily apparent. Cement is siliceous and clays and tuff contribute as a bonding agent. Zeolites are also apparent and are probably analcite. Alteration types include: 1) Illitization that has affected most of the feldspars; illite is the largest component of the groundmass; 2) Sericitization that has affected the plagioclase; 3) Possible kaolinization; 4) Calcite replacement of plagioclase. Alteration of feldspars to clays, as well as compaction, has closed nearly all primary pores. Illite is the dominate clay, though chlorite is abundant. Total point count porosity is less than 5%. 
Figure 95. Photomicrographs of Clarno Formation sample CLR-R11B, a fine- to medium-grained, angular, poorly sorted, highly altered, tuffaceous, lithic arkose, shown in views: A. (uncrossed nicols, 12.8X); and B. (crossed nicols, 12.8X).

A. This is a fine- to medium-grained, angular, poorly sorted, highly altered, tuffaceous, lithic sandstone. The rock is composed of clay and clay complexes, altered lithic fragments, and altered feldspars. Porosity is in evidence by blue epoxy in a dissolved amphibole (uncrossed nicols, 12.8X).

B. The altered state of this rock is evident in this view (crossed nicols, 12.8X).
NAME: Lithic Arkose Sandstone

LOCATION: 1 mile northeast of Ochoco National Forest sign on Highway 26 in a massive roadcut in NE SW 8, T12S R20E.

PETROGRAPHIC DESCRIPTION: This is a medium- to coarse-grained, angular to subrounded, poorly sorted, lithic arkose (see Figure 96). Framework grains include plagioclase feldspars, volcanic rock fragments, alkali feldspars (orthoclase and microcline), amphibole (hornblende), biotite mica, and trace quartz. Plagioclase and alkali feldspars are highly altered and show replacement by chlorite, illite, sericite, and other clay complexes. The large volume of altered hornblende present has no doubt contributed to the high clay content. Primary porosity is essentially destroyed and potential secondary porosity is clogged with replacement minerals. However, this mineral replacement may be a surface weathering effect, and may be remedied in the subsurface with the right fluid solution. The extent of dissolution is large. Total point count porosity is less than 5%.
Figure 96. Photomicrographs of Clarno Formation sample CLR-R12, a medium- to coarse-grained, angular to subround, poorly sorted, lithic arkose, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This is a medium- to coarse-grained, angular to subround, poorly sorted, lithic sandstone. Feldspars have undergone extensive dissolution. Note the porosity in one of the feldspars (uncrossed nicols, 40X).

B. The fractured nature of the feldspar grains is apparent here (crossed nicols, 40X).
CLR-R12A: Clarno Formation

NAME: Feldspathic Litharenite Sandstone

LOCATION: 1 mile northeast of Ochoco National Forest sign on Highway 26 in a massive roadcut in NE SW 8, T12S R20E. Sample taken near base of 12 foot sandstone sequence.

PETROGRAPHIC DESCRIPTION: This is a fine- to medium-grained, angular to subangular, poorly sorted, feldspathic litharenite (see Figure 97). Framework grains include volcanic rock fragments (VRFs), alkali feldspars (sanadine, orthoclase, and microcline), plagioclase (An₂₅), quartz, and sedimentary rock fragments (SFRs). Detrital biotite and muscovite are also present. VRFs consist of agglomerates of felted microcrystalline feldspars, tuffaceous clasts, and pyroclastic andesite clasts. Plagioclase feldspars are altered to clay minerals and many show dissolution. Most of the grains that have undergone dissolution are filled with clays. The alkali feldspars show replacement of portions of grains with chlorite and sericite. Quartz grains are rare and those seen are predominantly monocristalline exhibiting uniform extinction. SFRs include chert pebbles and tuffaceous mud clasts. Intergranular porosity is choked with clays, chalcedony or a pseudomatrix of squeezed lithic fragments. Porosity is found in micro fractures and some dissolved plagioclase grains. Rock fragments, feldspars, and quartz grains are rimmed by clays. Cements present include sericite, clay minerals, and chalcedony. Intragranular porosity is filled with calcite and chlorite, kaolinite, or other clay minerals.

Alteration of plagioclase grains have helped in development of intragranular pore space. The SEM work (see Figure 98) also shows quartz grains exhibiting some microporosity. Chlorite and smectite is present as well. Clay rims are developed at the borders of feldspar and quartz grains.
Figure 97. Photomicrographs of Clarno Formation sample CLR-R12A, a fine- to medium-grained, angular to subangular, poorly sorted, feldspathic litharenite, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This is a fine- to medium-grained, angular to subangular, poorly sorted, feldspathic litharenite. Note the chalcedony lining the pore spaces. Intergranular porosity surrounds some grains, and some secondary porosity is seen in dissolved feldspar grains (uncrossed nicols, 40X).

B. The lithic fragments, as well as the feldspars, are highly altered. The chalcedony is readily apparent in the pores here (crossed nicols, 40X).
Figure 98. SEM photomicrographs of Clarno Formation sample CLR-R12A, a medium-grained, subangular to round, feldspathic litharenite, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. This view shows a medium-grained, subangular to round sandstone. A large quartz grain and feldspars compose the framework grains. The altered plagioclase grain has developed intergranular pore space. The quartz grain exhibits some microporosity. Chlorite and smectite is present (600X).

B. The presence of a clay rim, between the feldspar and quartz grain, can be distinguished at this magnification (1200X).

C. The clay rim is clearly visible as a smectite convoluted form (6000X).
CLR-R13: Clarno Formation

NAME: Feldspathic Litharenite

LOCATION: A red sandstone interbed between Clarno Formation basalts near Steele Energy I-28 well in NW NW 28, T9S R23E.

PETROGRAPHIC DESCRIPTION: This sample is a very fine-grained, angular, poorly sorted, feldspathic litharenite (see Figure 99). The framework grains consist of plagioclase laths (An$_{30}$) surrounded by a cement matrix of iron oxides and sub-microscopic particles. The thin section contains large pores (1-6 mm) that are partially filled with gypsum. The cavities are rarely connected to other cavities, due to pore throats that are filled with gypsum. Total point count porosity is less than 5%.
Figure 99. Photomicrographs of Clarno Formation sample CLR-R13, a very fine-grained, angular, poorly sorted, feldspathic litharenite, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This sample is a very fine-grained, angular, poorly sorted, feldspathic litharenite. The volcanic debris is predominately plagioclase laths in a herring-bone pattern (uncrossed nicols, 40X).

B. The plagioclase laths are very apparent here (crossed nicols, 40X).
CLR R15: Clarno Formation

NAME: Feldspathic Litharenite

LOCATION: 1/2 mile southeast of Shelton State Park on Highway 19, north of Service Creek, in SE SW 3, T8S R22E.

PETROGRAPHIC DESCRIPTION: The sample consists of a fine- to medium-grained, angular to subrounded, poorly sorted, feldspathic litharenite (see Figure 100). Framework grains include plagioclase feldspar, volcanic rock fragments (VRFs), alkali feldspar (orthoclase), mica, and quartz. Plagioclase and alkali feldspars are highly altered and show replacement by chlorite, illite, sericite, and other clay complexes. VRFs consist of agglomerates of felted microcrystalline feldspars, tuffaceous clasts, and pyroclastic andesite clasts. Some intergranular pore space is filled with a zeolite (possibly analcite), chalcedony, and clays. Porosity is low and only present as secondary dissolution of feldspars or an occasional primary pore. Total point count porosity is less than 5%.

SEM study (see Figure 101) shows the illite-smectite complexes surrounding small weathered pieces of feldspar. Zeolites are present as well. This sample is particularly weathered.
Figure 100. Photomicrographs of Clarno Formation sample CLR-R15, a fine- to medium-grained, angular to subround, poorly sorted, feldspathic litharenite, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. The sample consists of a fine- to medium-grained, angular to subround, poorly sorted sandstone. The grains have been highly leached, but clay and clay complexes clog most of the developed pores. Some microporosity is visible in the dissolved feldspars (uncrossed nicols, 40X).

B. The leaching of the feldspars is apparent here. Clay complexes and other minerals clog the pore spaces surrounding grains (crossed nicols, 40X).
Figure 101. SEM photomicrographs of Clarno Formation sample CLR-R15, a fine-to coarse-grained, angular, feldspathic litharenite, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. This view shows a fine- to coarse-grained, angular sandstone. Illite-smectite complexes surround small weathered pieces of feldspar. The "fuzzy" material in the center is an unidentified zeolite. Sample is particularly weathered (600X).

B. Greater magnification shows the unusual structures seen in this sample (1200X).

C. Higher magnification of previous views (6000X).
CLR R19: Clarno Formation

NAME: Lithic Arkose Sandstone

LOCATION: 1 meter above blue marker bed at base of measured section in SE NW 10, T8S R19E.

PETROGRAPHIC DESCRIPTION: This is a fine- to coarse-grained, angular to subrounded, poorly sorted, lithic arkose (see Figure 102). The framework grains include plagioclase feldspars (An₆), volcanic rock fragments (VRFs), alkali feldspars (microcline and orthoclase), amphibole (hornblende), and quartz. The plagioclase and alkali feldspars are highly altered. The replacement products from feldspar alteration include clays, calcite, and zeolites. Some of the feldspar grains with higher anorthite content are subrounded and indicate working before deposition. The VRFs are highly altered as well and are slightly deformed so that some create a pseudomatrix. The amphiboles are also altered and contribute to the chlorite content present in the sample. Matrix replacement by clays is dominate throughout the sample. Pores are closed completely except in scattered locations where calcite has been leached. Secondary porosity is not well developed, but is found in some VRFs, and individual feldspars. Porosity is also developed in some fractures and microfractures. Total point count porosity is about 5%.

SEM study (see Figure 103) shows that pore space is both intergranular and intragranular. Extensive dissolution has affected the feldspars leaving only shells of the grains. Coating smectite and feldspar overgrowths line some of the pore spaces. The porosity development is good despite the potential clogging agents.
Figure 102. Photomicrographs of Clarno Formation sample CLR-R19, a fine- to coarse-grained, angular to subround, poorly sorted, lithic arkose, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. A fine- to coarse-grained, angular to subround, poorly sorted, lithic arkose is seen in this view. The large feldspar grain is surrounded by blue epoxy indicating porosity. Alteration products are prevalent (uncrossed nicols, 40X).

B. Note the altered condition of the feldspar. Dissolution porosity is significant (crossed nicols, 40X).
Figure 103. SEM photomicrographs of Clarno Formation sample CLR-R19, a coarse-grained, subangular, lithic arkose, at increasing magnifications: A. (240X); B. (500X); and C. (1200X).

A. Seen at this magnification is a coarse-grained, subangular sandstone. Framework grains consist of potassium feldspar, alkali feldspar, and volcanic rock fragments. Pore space is both intergranular and intragranular. Extensive dissolution has affected the feldspars leaving only a shell of some grains. Coating smectite and feldspar overgrowths line the pore spaces (240X).

B. Greater magnification shows the presence of pore-lining smectite and feldspar overgrowths (600X).

C. The porosity development is good despite the potential clogging agents (1200X).
CLR-R20: Clarno Formation

NAME: Feldspathic Litharenite

LOCATION: 1 1/2 mile north of Fran Cherrie's ranch in roadcut along Highway 207 near gate, in NW SE 32, T10S R22E.

PETROGRAPHIC DESCRIPTION: This is a fine- to coarse-grained, angular, poorly sorted, tight, feldspathic litharenite (see Figure 104). Framework grains include volcanic rock fragments (VRFs), plagioclase feldspars ($\text{An}_{70}$), and alkali feldspars. VRFs consists of welded tuff, tuffaceous agglomerates, and felted feldspathic breccia. Plagioclase is highly zoned but also shows carlsbad twinning. Alkali feldspars are highly altered to clay minerals and probably zeolites. The matrix is made of tuffaceous mud and very fine VRFs. Intergranular porosity is not developed due to this matrix. Calcite cement is found in some of the vugs. Some plagioclase grains are leached so that some intragranular porosity is developed. Some VRFs also exhibit intragranular porosity.

Pore space is both intergranular and intragranular as evidenced by SEM study (see Figure 105). Extensive dissolution has affected the feldspars leaving only a shell of some grains. Coating smectite and feldspar overgrowths line the pore spaces. Coating clays are visible on surrounding weathered VRFs. Classic examples of reabsorbed potassium feldspar are present, showing excellent secondary porosity. Kaolinite debris is seen on some grains.
Figure 104. Photomicrographs of Clarno Formation sample CLR-R20, a fine- to coarse-grained, angular, poorly sorted, tight, feldspathic litharenite, shown in views: A. (uncrossed nicols, 12.8X); and B. (crossed nicols, 12.8X).

A. This is a fine- to coarse-grained, angular, poorly sorted sandstone composed predominately of volcanic lithic fragments. Note porosity associated with the zoned feldspar on the right edge of the photo (uncrossed nicols, 12.8X).

B. Zoned feldspars rest in an aphanitic groundmass (crossed nicols, 12.8X).
Figure 105. SEM photomicrographs of Clarno Formation sample CLR-R20, a coarse-grained, subangular, feldspathic litharenite, at increasing magnifications: A. (600X); B. (1200X); and C. (6000X).

A. This photo shows a coarse-grained, subangular sandstone. Framework grains consist of potassium feldspar, alkali feldspar, and volcanic rock fragments. Pore space is both intergranular and intragranular. Extensive dissolution has affected the feldspars leaving only a shell of some grains. Coating smectite and feldspar overgrowths line the pore spaces. Coating clays are visible on surrounding weathered volcanic rock fragments (600X).

B. Greater magnification shows a reabsorbed potassium feldspar with its developing secondary porosity. Kaolinite debris is seen on surrounding grains (1200X).

C. The porosity development is good. Small areas of feldspar overgrowths and smectite-illite growth are seen (6000X).
CLR-R21: Clarno Formation

**NAME:** Feldspathic Litharenite Sandstone

**LOCATION:** Outcrop at Indian Cave in NE SE 26, T7S R19E in John Day Fossil Beds National Monument, Clarno Unit.

**PETROGRAPHIC DESCRIPTION:** This sample is a fine- to medium-grained, angular to subrounded, poorly to moderately sorted, feldspathic litharenite (see Figure 106). The framework grains include volcanic rock fragments (VRFs), plagioclase feldspar, alkali feldspar (orthoclase and microcline), and amphibole. The VRFs consist of felted plagioclase set in a finer matrix of tuff and other volcanic sediments. They have undergone extensive dissolution and alteration with transport of generated alteration products out of the immediate area. Porosity is developed in these fragments in surprising percentages (at least 15% by point count analysis). Plagioclase has also undergone extensive dissolution so that many grains exhibit extensive secondary pore space. Primary pore space is not present.

In SEM study (see Figure 107) the reasons for the tremendous porosity becomes readily apparent. The reabsorbed potassium feldspar grains have undergone massive dissolution. Illite appears to be a significant by-product of the dissolution/weathering process. Feldspar overgrowths are very visible as well but the dissolution of the feldspar grain is the significant aspect.
Figure 106. Photomicrographs of Clarno Formation sample CLR-R21, a fine- to medium-grained, angular to subround, poorly to moderately sorted, feldspathic litharenite, shown in views: A. (uncrossed nicols, 40X); and B. (crossed nicols, 40X).

A. This sample is a fine- to medium-grained, angular to subround, poorly to moderately sorted sandstone. Various minerals have been dissolved, including feldspar and amphibole, creating surprising porosity for a "dirty" rock (uncrossed nicols, 40X).

B. The apparent porosity of the rock seen here belies the actual porosity found in this sample (crossed nicols, 40X).
Figure 107. SEM photomicrographs of Clarno Formation sample CLR-R21, a fine-to medium-grained, angular to subround, poorly to moderately sorted sandstone, at increasing magnifications: A. (240X); B. (600X); C. (1200X); and D. (6000X).

A. This view shows a fine- to medium-grained, angular to subround, poorly to moderately sorted sandstone. The framework grains are predominately feldspar. This potassium feldspar grain has undergone massive dissolution. Illite appears to be a significant by-product of the dissolution/weathering process (240X).

B. Feldspar overgrowths are very visible but the dissolution of the feldspar grain is the significant aspect. Notice the development of pores and micropores (600X).
Figure 107, (cont...). SEM photomicrographs of Clarno Formation sample CLR-R21, a fine- to medium-grained, angular to subround, poorly to moderately sorted sandstone, at increasing magnifications: C. (1200X); and D. (6000X).

C. The excellent development of secondary porosity is very apparent (1200X).

D. Further magnification shows the extensive leaching that has taken place (6000X).
CRB-R2: Columbia River Basalt Interbed

NAME: Tuffaceous Siltstone

LOCATION: Roadcut 3 miles west of US Highway 395 near Ukiah turn off on Forest Service Road 53 in SE NW 7, T5S R31E. Outcrop is a diatomaceous interbed capped by Columbia River Basalt.

PETROGRAPHIC DESCRIPTION: The sample is a fine-grained, poorly sorted, diatomaceous, tuffaceous siltstone (see Figure 108). The rock consists of fine feldspar laths and finer clays and volcanic rock fragments. Porosity is developed only in microfractures. Interbeds such as this sample could develop moderate porosity and permeability if the plagioclase laths undergo dissolution.
Figure 108. Photomicrographs of Columbia River Basalt sample CRB-R2, a fine-grained, poorly sorted, tuffaceous siltstone, shown in views: A. (uncrossed nicols, 80X); and B. (crossed nicols, 80X).

A. This view shows a fine-grained, poorly sorted, tuffaceous siltstone. Note the fractured nature of the rock. Diatom structures are evident in several locations. The sample is highly altered (uncrossed nicols, 80X).

B. The brown glaze is mud developed during thin section preparation. The fracture is a natural part of the rock system (crossed nicols, 80X).
APPENDIX B

DESCRIPTION OF A PRINCIPAL REFERENCE SECTION OF THE CLARNO FORMATION

Merriam (1901) referred to rocks near the town of Clarno as the those typical of the Clarno Formation. However, no type section was ever measured or described. As an important part of this thesis, I have described a principal reference section for the Clarno Formation. Following Merriam's (1901) reference to rocks near Clarno, I chose the bluffs to the east of the original post office as a logical place to do the measured section. The thick sequence of volcanioclastics and volcanic flows in this area is well exposed, with large bluffs and cliffs sometimes exceeding seventy-five (75) meters.

The section is located in T8S R19E in the northeast quarter of the northwest quarter of Section 10 (Figure 109). Access to the section is from Highway 218, on the Bureau of Land Management Road beginning south of U.S.G.S. Bench Mark 1356. The measured section (Figure 110) is 250 meters, consisting of cliffs and partially covered slope (Figures 111 through 114), and begins east of the Bureau of Land Management Road on the east side of the John Day River, approximately 5 km south of Highway 218. The section starts approximately 100 meters northeast of U.S.G.S. bench mark 1342 on the north edge of a series of 8 to 10 meter, north-south trending outcrops, that are nearest the road and river. A blue tuffaceous marker bed at the base of these outcrops identifies the base of the section.
From the tuffaceous blue marker bed, the section proceeds up a shallow
draw, consistently trending east and up, on the southward facing slope that
culminates in a 37 meter cliff-forming basalt and andesite flow unit. Vari-colored
tuffs and welded tuffs, tuffaceous siltstones, tuffaceous sandstones, channel
sandstones, channel conglomerates, breccias, and scoriaceous andesite and
basalt flows comprise the lithologic section. The section is described in detail in
the measured section located on the inner back cover.
Figure 109. Portion of topographic map (Clarno Quadrangle, 1:62,500) showing location of proposed Clarno Formation principal reference section.
Figure 110. Detailed principal reference section for the Clarno Formation.
Figure 111. Thick stratigraphic section of Clarno Formation volcaniclastic sandstones, welded ash-flows, andesite flows, and tuffs.

Figure 112. Blue marker bed (arrow) at base of principal reference section of Clarno Formation below prominent volcaniclastic sandstone cliff.
Figure 113. Cross-bedding in a volcaniclastic sandstone in the Clarno Formation measured section.

Figure 114. Porous volcaniclastic sandstone from the Clarno Formation measured section.