Subduction-related origin of the volcanic rocks of the Eocene Clarno Formation near Cherry Creek, Oregon

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ABSTRACT

Terrestrial calc-alkaline volcanic rocks of the Eocene Clarno Formation in north-central Oregon appear to be a good example of subduction-zone magmatism. Mapping of an area along the John Day River near Cherry Creek showed that the many individual flows could be placed into three petrographic types. The earliest lavas are highly porphyritic two-pyroxene basaltic andesites. The key feature of the middle portion of the Clarno Formation is a group of nonporphyritic, quartz-bearing basaltic andesites which have also been noted as single units in other stratigraphic columns throughout the Clarno. The nature of their origin suggests they may be correlated as a time horizon across the Clarno. An angular unconformity and thick saprolite separate the gently folded lower Clarno beds from the much less voluminous upper Clarno volcanic rocks. A dome of hornblende andesite is the most notable feature of these later flows.

Textural and chemical evidence suggests that the porphyritic lavas formed as hydrous melts that rose from a subducted slab and interacted with the overlying mantle, whereas the nonporphyritic lavas formed by partial melting of anhydrous quartz eclogite followed by rapid ascent. New age data (Robinson, 1979, personal communication) suggest that the Clarno is older than 40-42 m.y. Subduction during this time was fairly rapid and at about a 30° angle. Estimated temperatures on the surface of this plate match temperatures at which the Clarno andesites could have formed. A model of magmatism arising from a shallowly dipping hydrous portion of the subducted plate, with one brief increase in dip (about 5°) generating the quartz lavas, can explain the general characteristics of Clarno volcanism.

INTRODUCTION

The Eocene Clarno Formation is located in north-central Oregon (Figure 1). It is a sequence of dominantly andesitic volcanic rocks that range in composition from basalt to rhyolite. Besides lava, the formation includes many intrusive feeders, volcanic breccias, mudflows, ash flows, and tuffaceous sediments of fluvial and lacustrine origin. Many of these units are characterized by rapid lateral and vertical variation. Previous workers on the Clarno Formation have concentrated on localized descriptions, as no regionally extensive unit that can be used for correlation had been found.

One of the thickest sequences of volcanic flows, intrusives, and sediments occurs between Cherry Creek and the mouth of Bridge Creek on the John Day River (Figure 1). The volcanic stratigraphy of this area was studied in detail by field mapping, petrography, and petrochemical analysis. One of the mapped units, the nonporphyritic quartz-bearing andesite, may prove to be a time horizon throughout the Clarno when its probable origin on a subducted plate is considered.

PREVIOUS WORK

The Clarno Formation lies unconformably on the Cretaceous marine Hudspeth and deltaic Gable Creek Formations (Oles and Enlows, 1971) and marks the end of marine deposition in central Oregon. Overlying the Clarno Formation are the more silicic fluvial and lacustrine tuffs of the John Day Formation and basalt flows of the Columbia River Basalt Group (Figure 2).

Summaries of Clarno lithology (Steere, 1954; Beaulieu, 1972) and reconnaissance mapping by Swanson (1969) present a picture of late Eocene terrestrial calc-alkaline volcanism. Petrochemical work (Rogers and Ragland, 1980) suggests that the Clarno Formation formed on thin continental crust and may be related to partial melting in the mantle.

Merriam (1901) first described Clarno rocks from typical exposures at Clarno's Ferry (present-day town of Clarno). He estimated that there were over 400 ft of dominantly eruptive materials, particularly rhyolite and andesite, with characteristic ashy shale and other tuffaceous sediments.

One of the thickest sequences of Clarno rocks was described by Waters and others (1951) in their investigations of the Horse Heaven mining district, situated alongside Cherry Creek. They established four units comprising 5,800 ft of section. Unit 1 consists of 600 ft of platy andesite interbedded with clays. Unit 2 contains 1,350 ft of tuffs, volcanic mudflows, and a few thin andesite flows and is partially equivalent to the lower sedimentary group of this study. Unit 3 has 1,750 ft of tuffaceous clay with a few andesite flows. Unit 4 is the 3,100-ft rhyolitic tuff layer. It includes 150 ft of andesite flows, one of which is equivalent to this study's nonporphyritic flows. A thick saprolite was developed on these units, and they were subsequently overlain unconformably by a second sequence of lavas considered post-Clarno by Waters and others (1951) but since placed in the Clarno Formation by Swanson and Robinson (1968).

Sporadic outcrops of Clarno-type rocks occur farther to the east, in the Canyon City quadrangle (Brown and Thayer, 1966). The northernmost Clarno exposure (Umatilla-Pilot Rock, Heppner district) is dominated by carbonaceous sediments and some andesite (Collier, 1914; Wagner, 1954; Hogenson, 1964).

AGE

One of the more interesting problems of the Clarno is its age. K-Ar ages range from 46 m.y. to 33 m.y. (see Walker and others, 1974, for a compilation). However, a date of 41.0 ± 1.2 or 43.0 ± 0.6 was obtained on a rock that is from one of the youngest flows from the upper portion of the Clarno Formation (Swanson and Robinson, 1968). Robinson carefully redated some of the "younger" Clarno rocks which appeared to be lower Clarno lavas and discovered they were actually about 50 m.y. old (1979, personal communication). In no case has a sample been younger than 41 m.y. This Eocene age fits well with the tectonic history as described in a later section.

DESCRIPTION OF ROCK UNITS

Near the confluence of Cherry Creek and the John Day River, the Clarno Formation is divisible into two groups of rocks separated by a thick saprolite and an angular unconfor-

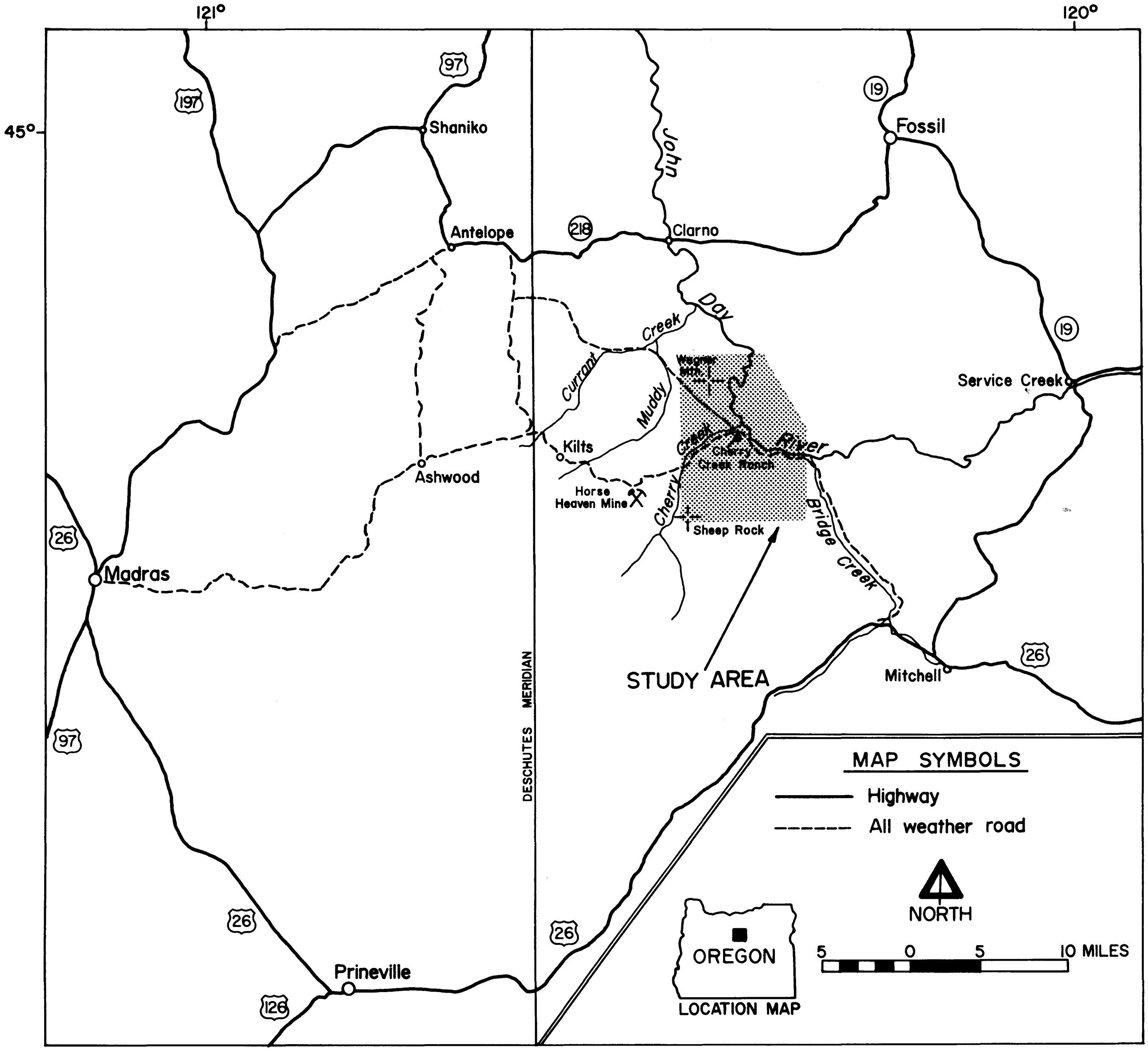

Figure 1. Map showing location of study area in north-central Oregon.

mity. The lower group, about 1 mi thick, comprises mudflows, andesitic lavas, and thick sedimentary clay and tuff sequences. The upper group is limited in extent to several basaltic and andesitic flows and domes. In this study, emphasis was on the petrography of volcanic rocks, and very little work was done on the sedimentary units. Major problems in identifying and mapping individual units were their extremely local and patchy nature and their frequently fine-grained textures, which made it necessary to use thin-section analysis to identify rocks from different units. With the exception of an extensive mudflow, few units extended for more than half a mile.

The terms "porphyritic" (greater than 10 percent phenocrysts), "subporphyritic" (6-10 percent phenocrysts), and "nonporphyritic" (less than 6 percent phenocrysts) are useful in classifying Clarno lavas into broad groups. Generally, porphyritic andesites have 25-30 percent phenocrysts of plagioclase and pyroxene. The nonporphyritic rocks have 2-3 percent phenocrysts usually of resorbed quartz and plagioclase. Division of these lavas into two petrographic types is most useful for discussing the origin of Clarno andesite. Characteristics of several of the prominent units are discussed below in stratigraphic sequence, beginning with the oldest unit (see Noblett, 1979, for details). A list of the Clarno units discussed in this paper appears in Table 1.

LOWER PORTION OF THE CLARNO FORMATION

The lowest unit, a 140-ft-thick basal sedimentary unit, includes a mudflow and conglomeratic sandstones which contain altered andesite fragments. This unit lies on the axis of an anticline and may not be the true base of the Clarno.

The basal unit is overlain by the first major outpouring of porphyritic andesite which occurs throughout the lower portion of the Clarno as a series of five units with an accumulated thickness of over 1,500 ft. These are holocrystalline lavas

Table 1. *Clarno Formation units discussed in this paper. A complete list of units and a geologic map showing their areal extent are found in Noblett (1979). Oldest units are at the bottom of the list; youngest units are on top.*

Nonporphyritic basaltic andesite
Hornblende andesite
Basaltic andesite
—Angular unconformity—
Thick saprolite
Subporphyritic basaltic andesites
Porphyritic andesite
Upper sedimentary unit (largely tuffaceous sandstone)
Nonporphyritic felsic hypersthene andesite
Nonporphyritic quartz-bearing andesite
Nonporphyritic olivine augite andesite
Nonporphyritic felsic glassy andesite
Middle sedimentary unit (varicolored tuffs, sandstone, local thin andesite flow, and local red and white basal tuff)
Middle porphyritic andesite
Lower sedimentary unit (tuffaceous sandstones and conglomerates, andesite and basalt flows, Cherry Creek fossil bed, pumiceous tuff)
Bouldery, hoodoo-forming mudflow
Porphyritic andesite
Porphyritic andesite
Altered tuff
Lowest porphyritic andesite
Basal sedimentary unit (mudflow and conglomeratic sandstones)

(about 30 percent phenocrysts), with phenocrysts of normally zoned plagioclase (An_{54-40}) that is often replaced by calcite and a clay, fresh augite, and hypersthene altered to either biotite or chlorite (Figure 3). Euhedral to stringy blebs of magnetite occur as phenocrysts. The groundmass is dominantly plagioclase, remnant pyroxene, and dusty magnetite, largely obscured by clay alteration. An extensive 100-ft-thick, altered red and white tuff unit lies between the two lowest flows.

A bouldery, 100-ft-thick, 3.5-mi-long, hoodoo-forming mudflow which proved to be the most useful unit for mapping was traced to an intrusion by the Cherry Creek ranch house (W¼ sec. 25, T. 9 S., R. 19 E.). The intrusion is the only hornblende andesite positively placed in the lower portion of the Clarno.

Stratigraphically above the mudflow are three tuffaceous fluvial and lacustrine sedimentary units, with a total thickness of over 2,000 ft, which were deposited throughout early Clarno time. The lowest sedimentary unit is an agglomeration of many tuffaceous sandstones and conglomerates and local andesite and basalt flows, and includes the famous fossil-leaf locale on Cherry Creek (Hergert, 1961) and the only patch of pumiceous tuff in the area. Either a local red and white tuff layer or a porphyritic andesite separates the lower from the middle sedimentary unit, which typically contains varicolored tuffs, sandstones, and local thin andesite flows.

Four nonporphyritic andesite flows with an accumulated thickness of over 1,000 ft (Figure 4) were erupted in rapid succession; this sequence contains no interbedded sediments and was probably contemporaneous with the middle sedimentary unit. Although these four flows are not covered by later Clarno lavas, their 20° dip and the lack of a thick saprolite beneath them places them in the lower portion of the Clarno. The oldest of these four, a felsic andesite unit, was erupted from the vent at Sheep Rock (SW¼ sec. 16, T. 10 S., R. 19 E.)

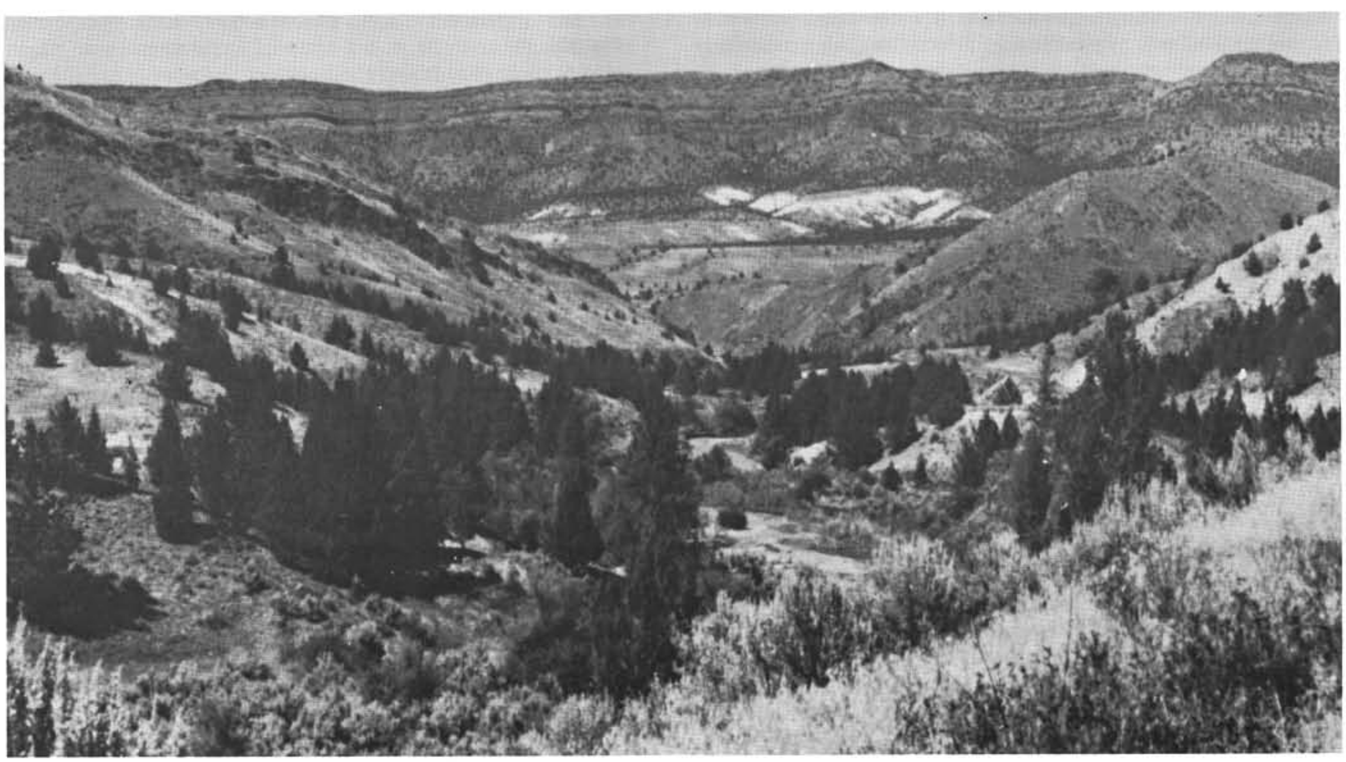

Figure 2. View northwest of Mitchell, Oregon, showing typical Clarno Formation lavas in foreground overlain by light-colored John Day Formation tuffs, which are in turn overlain by horizontal flows of the Columbia River Basalt Group.

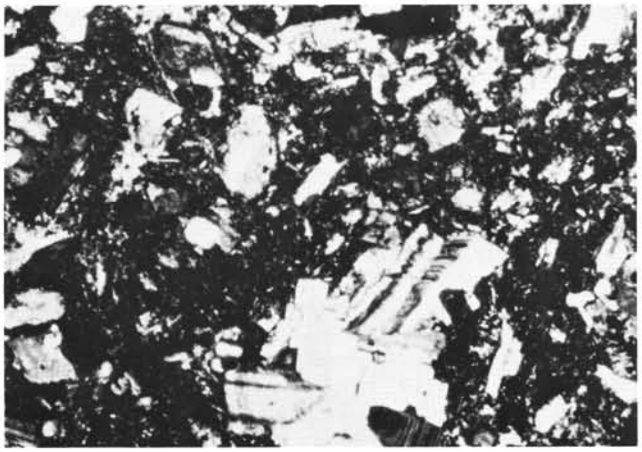

Figure 3. Photomicrograph of porphyritic two-pyroxene basaltic andesite with zoned plagioclase. View is 2 mm across.

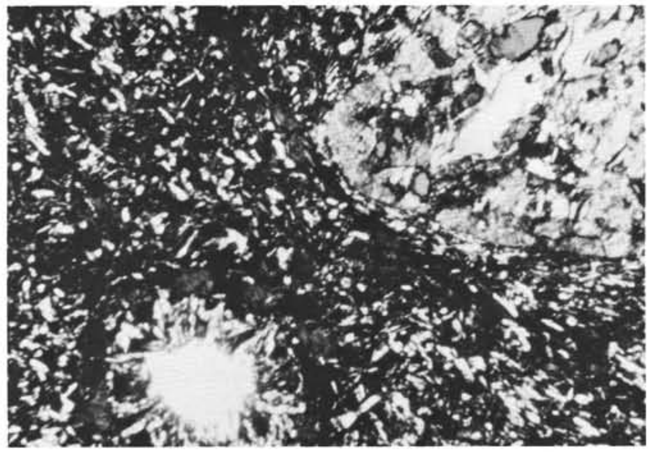

Figure 4. Photomicrograph of nonporphyritic basaltic andesite with quartz crystal showing augite reaction rim. View is 2 mm across.

and, unlike the earlier porphyritic lavas, must have been fairly fluid to be so widespread and thin. It is a fine-grained pilotaxitic felsic andesite with a trace of spongy plagioclase phenocrysts and embayed quartz crystals set in a matrix of plagioclase (An_{49}), augite, and minor glass.

The next of these nonporphyritic andesite flows, an olivine-bearing andesite, is probably related to the intrusion on the west side of John Day Gulch (E½ sec. 12, T. 10 S., R. 19 E.) and is a fine-grained, platy, pilotaxitic andesite with sparse phenocrysts of plagioclase, minor hypersthene, augite, and nontronized olivine in a matrix of plagioclase (An_{48}), augite, magnetite, and minor glass. Identifying features of this unit are nontronized olivines and the small but abundant augite phenocrysts. The third nonporphyritic andesite flow lacks pyroxene phenocrysts and contains more quartz with reaction rims of augite. The uppermost of the four flows is a more felsic andesite with fresh hypersthene and ferric augite phenocrysts.

The three units that stratigraphically overlie the nonporphyritic flows are similar to units that underlie the nonporphyritic units. One of these three units, a more porphyritic andesite that is 110 ft thick, was extruded into the upper sedimentary unit. The uppermost of these three units is subporphyritic basaltic andesite composed of phenocrysts of plagioclase, augite, and hypersthene in a matrix of plagioclase (An_{40}), augite, minor orthopyroxene, and magnetite.

Overlying this entire lower portion of the Clarno Formation is a thick saprolite that represents an ancient soil horizon (Waters and others, 1951) and forms a popcornlike surface on the tilted lower Clarno rocks. Although locally there are other saprolites in the Clarno Formation, the 10-20-ft thickness and the overlying horizontal beds were used to define this particular unit.

UPPER PORTION OF THE CLARNO FORMATION

The division of the Clarno Formation into upper and lower parts is based on the presence of the thick saprolite and angular discordance. The saprolite has been recognized in the Mitchell area (Oles and Enlows, 1971), in the Horse Heaven area (Waters and others, 1951; Swanson and Robinson, 1968), and in the Ashwood area (Peck, 1964). Horizontally bedded volcanic rocks (basaltic andesite, andesite, rhyolite tuff) lie on top of the saprolite. The petrographic similarity of these rocks to lower Clarno volcanic rocks, the 41-m.y. age on an upper Clarno flow (Swanson and Robinson, 1968), and the lack of the recognized welded tuffs that form the base of the John Day Formation in various places (Peck, 1964; Swanson and Robinson, 1968) argue for the inclusion of this volumetrically small group of lavas in the Clarno Formation.

One of the upper Clarno units, a fresh, 100-ft-thick, pilotaxitic basaltic andesite, forms a ridge crest on the saprolite. Olivine phenocrysts are commonly triangular skeletal crystals. The groundmass contains both augite and hypersthene, minor magnetite, and plagioclase (An_{54}).

The most notable upper Clarno event was a huge outwelling of a hornblende andesite dome that forms Wagner Mountain (E½ sec. 10 and all of sec. 11, T. 9 S., R. 19 E.). The eastern margin of the dome has nearly vertical 400-ft-long columnar joints. Phenocrysts in this andesite include oxidized hornblende, hypersthene, and plagioclase (zoned and twinned, with albitic rims).

The uppermost Clarno unit is a 60-ft-thick, nonporphyritic basaltic andesite with a trace of hypersthene and plagioclase phenocrysts. It and the hornblende andesite are the only units with extensive columnar joints.

GENERAL PETROLOGY OF THE CLARNO FORMATION

Except for a few basalts, the flows in this study are either andesites or basaltic andesites. Ignoring the late-stage hornblende andesites for the moment, we can identify two groups of petrographically distinct basaltic andesite lavas (Table 2). The first group contains highly porphyritic plagioclase-clinopyroxene-orthopyroxene rocks. The second group includes the nonporphyritic andesites containing only resorbed quartz and plagioclase crystals and sparse phenocrysts of olivine.

Subhedral to euhedral andesine to labradorite plagioclase crystals 1-5 mm in diameter are the most common phenocrysts in the porphyritic rocks. The most distinguishing feature of the plagioclase is the presence of numerous thin zones, some of which are normal, others oscillatory. Taylor (1960) argued that these zones are responses in a shallow melt to surface eruptions that caused rapid pressure changes. An alternative explanation is that zoning and related resorption features are caused by crystallization of a hydrous melt in which the escape of water at temperatures below the anhydrous liquidus but above the liquidus for that water content forces crystallization (Ringwood, 1975). Repetition of these conditions would lead to the zones.

In the porphyritic lavas, the next two common pheno-

Table 2. *Modal analyses of the three main petrographic Clarno lava types.*

Component	Porphyritic andesite* (%)	Nonporphyritic andesite* (%)	Hornblende andesite** (%)
Phenocrysts			
Plagioclase	26	4	5
Clinopyroxene	3	1	–
Orthopyroxene	9	Tr***	–
Hornblende	–	–	8
Olivine	–	Tr***	–
Quartz	–	1	–
Groundmass			
Plagioclase	47	58	71
Clinopyroxene	7	30	1
Orthopyroxene	1	Tr***	–
Hornblende	–	–	15
Magnetite	7	6	–
Total	100	100	100

* Average of six analyses.
** One analysis.
*** Tr = Trace.

Table 3. *Chemical analyses of the three main petrographic Clarno lava types.*

	Porphyritic andesite*	Nonporphyritic andesite*	Hornblende andesite**
	(wt. %)	(wt. %)	(wt. %)
SiO_2	60.8	61.3	63.3
Al_2O_3	17.3	16.4	17.4
Fe_2O_3	5.9	6.5	5.0
MgO	3.1	2.9	1.9
CaO	5.4	5.8	4.8
Na_2O	3.9	3.3	4.0
K_2O	1.4	1.8	1.9
TiO_2	1.0	.9	.7
Total	98.8	98.9	99.0
	(ppm)	(ppm)	(ppm)
Rb	20.1	42.3	35.5
Sr	474.4	207.1	369.7
Y	11.0	21.0	11.7
Zr	114.8	120.6	97.2
Nb	9.8	11.1	8.7
Ni	32.7	28.1	11.9

* Average of six analyses.
** One analysis.

crysts are fresh, infrequently twinned augite and laths of orthopyroxene, generally hypersthene, replaced by biotite or chlorite. The groundmass consists largely of albite-twinned plagioclase laths (about An_{45}) in flow alignment.

One possible explanation for the texture of the porphyritic lavas could be the shallow emplacement of a magma chamber which was tapped by frequent eruptions during crystallization. As the lavas themselves show no vertical textural or chemical variations, either typical processes of shallow chambers were not operative or the magmas were not derived in this manner.

Alternatively, under hydrous conditions, plagioclase and the two pyroxenes crystallize together over a much narrower temperature interval. Thus, the presence of these three phenocrysts and the zoned feldspar could indicate that the porphyritic lavas were derived from an initially hydrous andesite melt which lost water on rising from some depth.

The nonporphyritic lavas are very similar chemically to the porphyritic rocks (Table 3). Their similarity and proximity in time and space suggest that they had a common source. The key feature of the nonporphyritic lavas is the presence of resorbed quartz phenocrysts. The quartz is clear and occurs as embayed rounded crystals with reaction rims of tiny augites. Quartz has been noted in the volcanic rocks of many island arcs and continental margins across the world (Carmichael and others, 1974; Ringwood, 1975), so its presence here is taken to be primary, not xenocrystic.

The lava probably originated at great depth as a superheated liquid (shown by lack of phenocrysts) and rose rapidly enough so that the ascent was adiabatic. In Marsh and Carmichael's (1974) model, the conditions for formation of such a lava by partial melting of quartz eclogite at the Benioff zone are fairly restricted; consequently, a major outpouring of quartz-bearing basaltic andesite may well represent one time-equivalent event. This relation is particularly suitable to the Clarno Formation, where most stratigraphic columns include nonporphyritic quartz-bearing lavas that apparently occurred during one short span of time (Merriam, 1901; Wilkinson, 1932; Waters and others, 1951; Wagner, 1954; Taylor, 1960; Pigg, 1961; Peck, 1964; Oles and Enlows, 1971; Novitsky-Evans, 1974).

The hornblende andesites present a distinct problem. The role of amphibole in andesite generation has been discussed by several authors (Carmichael and others, 1974; Allen and others, 1975; Ringwood, 1975). The major difficulty in applying present models to the origin of amphibole in the Clarno lavas is the requirement of an extremely shallow Benioff zone (less than 60-80 km). The chemistry of the lavas indicates that there may have been a change in position of the trench or dip of the subduction zone that could account for a change from quartz eclogite melting (nonporphyritic lavas) to a much shallower amphibolite melting. Most of the mudflows in the area are associated with hornblende intrusives; thus, the presence of water may be important in explaining these lavas.

CLARNO SUBDUCTION TECTONICS

Plate-tectonic framework

Dickinson (1979) has placed the Eocene units of the Pacific Northwest within a coherent plate-tectonic framework (Figure 5). Starting in the east, a foreland basin developed across Montana by 65 m.y. ago. Local uplifts and basins were forming throughout Wyoming. The Challis Arc swept westward from Idaho and Montana across central Oregon between 65 and 40 m.y. ago, resulting in Clarno volcanism. To the west, a seamount province (Siletz River and Crescent Formations) that was not originally a part of the North American plate was underthrust and accreted onto the continent as part of a subduction complex. Finally, during Clarno times, a forearc basin developed on top of the seamount province, creating the present-day Oregon coast (Tyee, Nestucca, Cowlitz, and other formations). The Clarno Formation was probably erupted onto the edge of the Eocene continental margin.

Experimental work on the generation of andesitic magmas has placed some limits on the temperature and pressure under which lava can be generated. Theoretical work on the thermal regimes of subduction zones has resulted in a variety of models of temperature versus depth in the subduction region. To hypothesize a subduction origin for a given magma, it is necessary to show that the lavas could have been

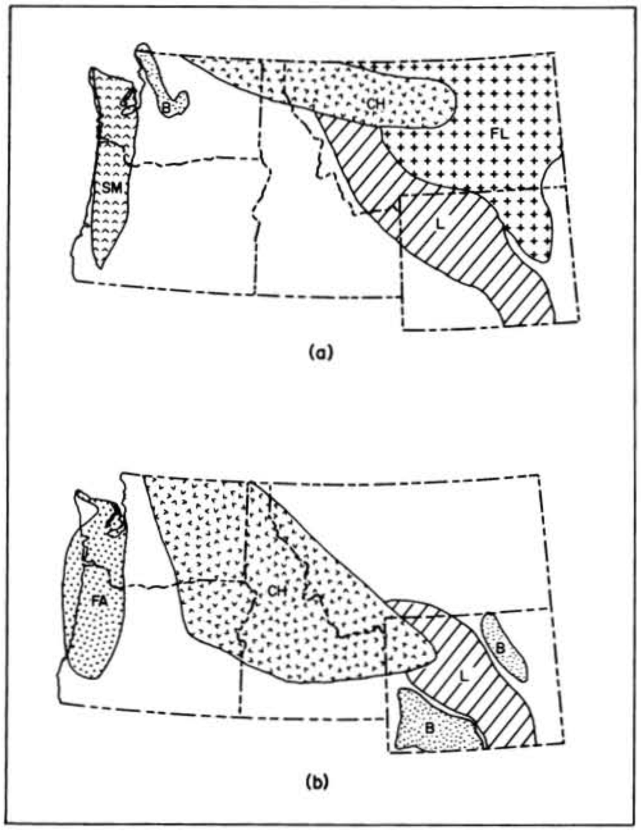

Figure 5. Paleotectonic map of the (a) Paleocene (60 m.y.) and (b) Eocene (45 m.y.) from Dickinson (1979). CH = Challis Arc; FA = Forearc Basin; SM = Seamount Province; B = Basin; L = Laramide Orogeny; FL = Foreland Basin.

melts either on the plate surface or nearby in the overlying mantle. In this study, thermal models from the literature were modified to fit the specific conditions of Clarno time.

Geometry of the Clarno-time plate system

The framework for plate tectonics in the Pacific Northwest was described by Atwater (1970) and augmented by Carlson (1976). In Eocene times, the subduction of the northeastern Pacific Farallon Plate under the North American Plate was presumably the cause of Clarno volcanism. The location of the associated trench has never been precisely determined because of later deposition. However, Simpson and Cox (1977) presented evidence that the coastal seamount province (Siletz River Volcanics) was rotated into its present position clockwise, possibly about a pivot at its southern end, which would suggest that the location of the trench was very close to the location of the present-day Willamette Valley.

Several episodes of Cenozoic sea-floor spreading with different plate motions have been distinguished (Carlson, 1976). Two episodes, one ending at about 42-44 m.y. ago and the second beginning at that time, are relevant to the Clarno. Before that time, plate convergence in the Northwest was oblique at the extremely rapid rate of 14 cm/yr (Carlson, 1976). This convergence may account for the northwest-southeast compression observed in Clarno rocks (Taylor, 1977). After that time, convergence was perpendicular at a rate of 6 cm/yr (Carlson, 1976). These changes in angle and rate of convergence can be correlated with the rearrangement of the Pacific plate system at about 42-44 m.y. ago, as recorded by the break in angle between the Emperor Island chain and the Hawaiian Island trend (Morgan, 1972).

New work by Robinson (1979, personal communication) dates the Clarno Formation between 50 and 40 m.y. Clarno volcanism, then, is a response to the rapid convergence of the plates. The reorganization of the plates marked the cessation of Clarno-type volcanism and the commencement of John Day volcanism. Because the changes in plate motion and the changes in volcanism took place so nearly at the same time (allowing for some lag in the response of the subduction system to these changes), a genetic relation between the events is suggested.

It is important to note that the trench was probably located along the Willamette Valley in western Oregon and the normal component of velocity of the subducted plate was approximately 10 cm/yr.

Depth to the Benioff zone

Various K-h diagrams can be used to determine the depth to the Benioff zone (Nielson and Stoiber, 1973). Rogers and Novitsky-Evans (1977) have shown that the Central American or Aleutian continental margin suites may be most similar to the Clarno. Using an overall average value in the Clarno of 0.95 weight percent for K_{55} (weight percent of K_2O at 55 weight percent of SiO_2) and 1.50 weight percent for K_{60} (Noblett, 1979), one gets depths to the subduction zone of about 105 km. The Clarno Formation lies approximately 200-220 km from the postulated trench. The calculated angle of dip of the subduction zone is thus about 30°. For the slightly higher K_{60} values of the nonporphyritic unit, depths were about 120-130 km, with about a 35° dip.

GENERATION OF CLARNO-TYPE ANDESITIC MAGMA

Proposals for the generation of andesitic magma above subduction zones have included fractionation of basaltic magma; direct partial melting of peridotite; interaction of overlying mantle peridotite with melts rising from the subducted slab; partial melting of either amphibolite or quartz eclogite in the diving slab; and contamination of basalt by sialic crust, subducted sediments, or sea water. Two of the above models seem relevant to the andesitic rocks of the Clarno Formation: (1) interaction of an initially hydrous andesitic melt derived from the subducted plate with mantle peridotite, followed by subsequent fractionation (Ringwood, 1975), and (2) partial melting of quartz eclogite.

As discussed above, the mineral assemblage and textures of the porphyritic lavas can be explained more satisfactorily by the rising of a deep-seated hydrous magma than by formation in a shallow magma chamber. If the porphyritic lavas ever occupied a shallow magma chamber, they probably did so as andesitic lava. The low Ni contents and Ni/Co ratios of the Clarno Formation argue against shallow fractionation from basalt, particularly from a high-alumina basalt, which has similar contents of these elements (Taylor and others, 1969). The large decrease in K/Rb values of over 150 from the base to the top of the porphyritic lavas suggests that fractionation of a hydrous phase was involved in these magmas, supporting the argument that they were hydrous at depth (Table 3; see also Noblett, 1979, for details of chemical analyses). It seems likely that these andesites initially formed from melts on a subducted slab and interacted with peridotite on rising. Fractionation from deep-seated basalt along with the loss of water during ascent would be a viable mechanism for explaining the por-

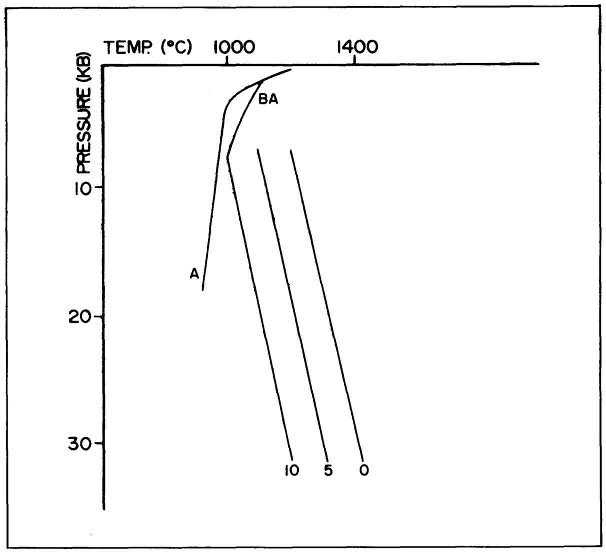

Figure 6. Plot of experimentally determined andesite liquidi. Water-saturated curves for andesite (A) and basaltic andesite (BA) from Nicholls (1974). Curves for andesite with 0, 5, and 10 weight percent water from Green (1972).

phyritic Clarno andesites.

Nicholls (1974) plotted the liquidi of several lavas of andesitic composition (Figure 6). Temperatures of 950°-1,000°C on the surface of the diving slab would be adequate to generate the porphyritic Clarno rocks if they were initially hydrous.

The nonporphyritic quartz-bearing lavas, however, require a different crystallization history. Marsh and Carmichael (1974) and Ringwood (1975) presented many of the arguments relating the presence of quartz to partial melting of anhydrous quartz eclogite.

Marsh and Carmichael (1974) showed that a basaltic andesite magma with less than 0.75 weight percent water at 155-km depth and at 1,400°C would crystallize coesite (which later inverts to quartz). Similarly, Green and Ringwood (1968) found that at 50 kb (about 100 km) 1,400°C would be the liquidus temperature for dry andesite.

Derivation from quartz eclogite appears to explain the textures of the nonporphyritic lavas. With decreasing pressure, quartz is resorbed, and plagioclase lies on the liquidus. The low Zr and Nb contents suggest crustal contamination was not a major process in forming these lavas (Taylor and others, 1969). Nearly constant values of K/Rb in the nonporphyritic units suggest that hydrous phases were not involved in these magmas. Also, the greater depth to the plate for these lavas is below the probable limit of stability for hydrous phases. The element yttrium, which is thought to reflect values of the light rare-earth elements, is enriched in the nonporphyritic rocks relative to the porphyritic andesites (Table 3). This would fit a model of garnet occurring as a residual fractionate. The lack of phenocrysts in these rocks argues against fractionation playing a major role in their development, such as is proposed for the porphyritic lavas. The quartz-bearing basaltic andesites would have to have risen from the surface of the plate without interacting with the mantle peridotite. This implies a rapid adiabatic ascent, which is in agreement with calculations by Marsh (1976).

This review indicates that the Clarno lavas could have originated on the surface of a subducted plate. The early porphyritic lavas would require higher water content, shallower depths, and lower minimum temperatures (about 900°-1,000°C). The later nonporphyritic lavas could have come from deeper than 100 km, from an anhydrous, hotter (1,100°-1,400°C) part of the plate. In the following section, these two sets of conditions are matched with temperatures calculated for the surface of the subducted Farallon Plate in Eocene times.

ORIGIN OF CLARNO VOLCANISM

A thermal model of the subducted plate in Eocene times should approximate the 30° dip and 10-cm/yr velocities as well as incorporate reasonable values of heat sources. Minear and Toksöz (1970) and Oxburgh and Turcotte (1970) presented the best models with a high velocity, while Sydora and others (1978) offered models with 27° and 45° angles of subduction (Figure 7).

Between depths of 100 and 200 km, a plate dipping 30° is about 150°-200°C hotter than one dipping 45°. At 105-km depth, Minear and Toksöz (1970) calculated a temperature of 1,000°C, and Oxburgh and Turcotte (1970) obtained 1,300°C. So the temperature on the plate at the depth where the porphyritic Clarno lavas are thought to have originated was probably between 1,150°C and 1,450°C.

If the plate were 20 km deeper, the temperature would be 75°-125°C greater. This would place the temperature between 1,250°C and 1,550°C, at which point the nonporphyritic lavas could form.

Clarno volcanism, then, can be explained generally in terms of two changes in dip of the subducted slab. The early porphyritic Clarno rocks probably formed about 100 km deep on the surface of a shallowly dipping slab. This is about the greatest depth at which water may still occur on the slab. Rogers and Novitsky-Evans (1977) showed that the crust underlying the Clarno was probably about 20-30 km thick, so a rising hydrous magma could readily have interacted with mantle peridotite and formed the porphyritic rocks.

This was followed by a small increase in dip of the plate (about 5°), which resulted in the anhydrous, hotter conditions needed to form the nonporphyritic lavas. Apparently, the

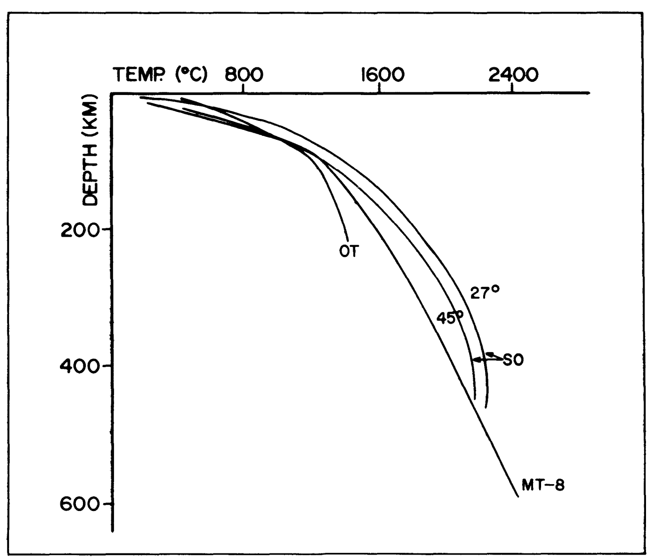

Figure 7. Plot of temperature versus depth on upper surface of slab which is being subducted. Models are from the following sources: OT= Oxburgh and Turcotte (1970); MT-8=Minear and Toksöz (1970), at 8 cm/yr velocity; SO= Sydora and others (1978), at dip angles of 27° and 45°.

plate then readjusted itself to a shallower dip, limiting the nonprophyritic lavas to a brief time interval of extrusion. This shallower dip could lead to hydrous melts again. Such melts could be amphibole-bearing andesites or dacites to rhyolites, as are common in younger Clarno rocks.

With all the variables involved (plate velocity, trench location, all the thermal model parameters, the assumptions involved in estimating the depth of the plate, the experimental data, and the interpretation of the textures of the rocks), this agreement between thermal and experimental models is gratifying. The key variable in the proposed variable dip model is the calculated depth to the Benioff zone. If the plate is much deeper than 100 km, a hydrous melt could not form, and only the partial melting of anhydrous quartz eclogite could occur. It would then be difficult to explain how the early porphyritic or later amphibolitic and silicic lavas might have formed in relation to the subduction system.

CONCLUSIONS

While the stratigraphy of the Clarno Formation in the study area is variable over distances of several miles, the formation can be divided into a few typical lava types. Porphyritic augite-hypersthene basaltic andesites occur throughout the sequence, while nonporphyritic quartz-bearing basaltic andesites occur at one stratigraphic level. This second group of flows is probably equivalent across most other areas of the Clarno Formation. Younger silicic rocks occur in several localities: Horse Heaven (Waters and others, 1951); Mitchell area (Taylor, 1979, personal communication); and Clarno basin (Taylor, 1960). The upper portion of the Clarno, which lies horizontally on a thick saprolite, comprises various thin basalt flows and a hornblende andesite.

The regional geologic setting and its relation to plate-tectonic models of the Pacific Northwest suggest that the Clarno Formation was largely derived from subduction volcanism. The minerals and textures of the lavas as well as the chemical compositions support this hypothesis. For this study, calculated temperatures on the subducted slab of Eocene times were compared with experimentally estimated temperatures to demonstrate that basaltic andesites of the Clarno Formation could have been produced by melting of the subducted slab. The proposed model for generating Clarno rocks suggests that most of the lavas were generated under hydrous conditions at depths of about 100 km. One brief change in the dip of the subducting plate can explain the origin of the nonporphyritic lavas. The key conclusion of interest to Clarno stratigraphy is that the nonporphyritic quartz-bearing lavas were extruded in one short pulse and probably could be correlated across the Clarno as a time horizon.

Certainly, a great deal more work is needed on the Clarno Formation if its origin is to be clarified. The quartz-bearing unit should be traced to see how widespread it is. If alteration has not completely obscured the patterns of distribution of rare-earth elements, such data would be helpful in determining whether partial melting of a quartz eclogite is a possible origin. More radiometric ages and further paleomagnetic data would be useful in improving the tectonic models.

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Mount St. Helens post-eruption map available

A new post-eruption map of Mount St. Helens and vicinity that includes color photographs of the major eruption and shows the aftereffects of the eruption has been published by the U.S. Geological Survey (USGS), through a cooperative effort with the USDA Forest Service and the Washington State Department of Natural Resources. Copies of the topographic map may be purchased by the public from any of the three agencies.

The 36- × 40-in. topo map is being printed in a first edition of nearly a half million copies, the single largest printing ever made by the USGS. The map shows how the area appears in the wake of the violent eruption of May 18, 1980, and clearly depicts the newly-formed crater and dome, the eruption-impact area, landslide-debris flow, and the mudflows on the Muddy, Toutle and Cowlitz Rivers.

Changes in topography and bodies of water, including Spirit Lake, are readily seen when compared to the earlier USGS pre-eruption special edition "Mount St. Helens and Vicinity" map of April 1980 or the Forest Service map, "Mount St. Helens-Spirit Lake" of 1973.

Presented at a scale of 1:100,000 (1 in. equals about 1.68 mi), the map has been updated from aerial photography taken June 19, 1980. The map denotes land managed by federal and state agencies and includes numerical designations for roads within the Gifford Pinchot National Forest, viewpoints, campgrounds, picnic areas, visitor centers, and points of interest.

On the reverse side of the map, the Forest Service has presented text and color photographs providing a narrative of recent Mount St. Helens volcanic activities. Included are before and after panoramic views of the devastated area, history and legends of the mountain and a glossary of volcanic terms.

In the joint federal-state effort, USGS cartographers at the Western Mapping Center, Menlo Park, Calif., mapped the new topographical features; the Washington State Department of Natural Resources delineated the eruption impact and mudflow areas and, with the Forest Service, depicted land management patterns.

Maps may be purchased by mail from the Branch of Distribution, U.S. Geological Survey, Box 25286, Federal Center, Denver, Colo. 80225, as well as from most USGS map dealers. Orders by mail to the USGS Branch of Distribution must specify map title ("Mount St. Helens and Vicinity, March 1981") and include check or money order payable to the U.S. Geological Survey.

Copies of the map also may be obtained over the counter or by mail from the Forest Supervisor, Gifford Pinchot National Forest, 500 West 12th St., Vancouver, Wash. 98660. Mail orders must include check or money order ($1.00 per map) made payable to the USDA Forest Service.

Maps also are available from the Washington State Department of Natural Resources, Resources Inventory Section, Olympia, Wash. 98504. Orders by mail should include check or money order payable to Department of Natural Resources. □

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