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Rb-Sr SYSTEMATICS IN LAVA FLOWS OF THE CLARNO FORMATION IN NORTH-CENTRAL OREGON—CHRONOLOGIC AND PETROLOGIC SIGNIFICANCE

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This paper presents Rb and Sr isotopic data for ten lava samples from the Clarno Formation in north-central Oregon (fig. 1) and discusses their chronologic and petrologic significance.

The Clarno Formation (Merriam, 1901) forms the Eocene-Oligocene section in north-central and eastern Oregon (fig. 1). The formation is dominated by andesitic flows, mudflows and breccias as well as moderate to large volumes of andesitic to rhyolitic volcaniclastic rocks and tuffaceous sedimentary rocks invariably intruded by minor dikes and plugs. It is correlatable in part with the calc-alkaline Challis and Absaroka volcanic rocks in Idaho, Montana and northwest Wyoming (Lipman and others, 1972; Armstrong, 1978; Dickinson, 1979).

The formation lies unconformably above Cretaceous sedimentary strata defined by two intertonguing sequences, the shallow-marine Hudspeth Formation and the deltaic Gable Creek Formation (Wilkinson and Oles, 1968; Oles and Enlows, 1971). The Clarno is overlain in part by the silicic volcanic and volcano-sedimentary rocks of the late Oligocene-Miocene John Day Formation (Robinson and Brem, 1981; Robinson and others, 1990), and in part by the mafic lava flows of the Miocene Columbia River Basalt Group (Waters, 1961; Hooper, 1982; Hooper and Swanson, 1990). Rapid variability in thickness and lithology, both laterally and vertically, and post-depositional structural dismemberment have complicated the geology and stratigraphy of the Clarno Formation. No complete stratigraphic sections of the Clarno can be found, but a minimum estimate of exposed Clarno rocks indicates an aggregate thickness of 1,825 meters (Waters and others, 1951; Swanson and Robinson, 1968; Walker and Robinson, 1990).

The Clarno rocks range in composition from basalt to rhyolite. They are typically calc-alkaline (Rogers and Novitsky-Evans, 1977a, Rogers and Ragland, 1980; Noblett, 1979, 1981; Suayah and Rogers, in press), and presumably represent subduction-related volcanism above a thin (Aleutian-type) continental crust (Rogers and Novitsky-Evans, 1977b).

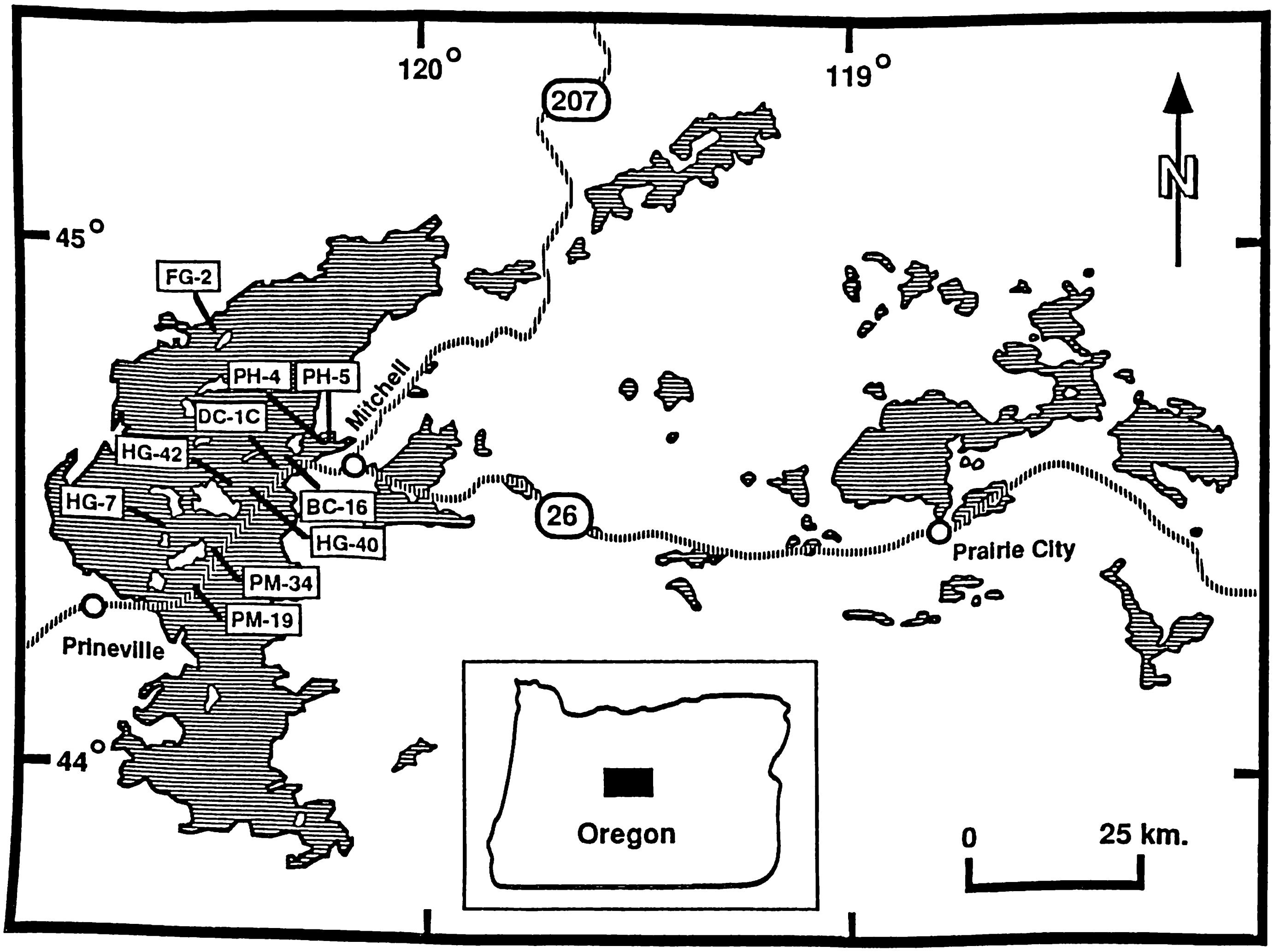

FIGURE 1. Outcrop map of the Clarno Formation modified from Walker (1977). Numbered thick lines point to sample locations.

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AGE OF THE CLARNO VOLCAN1SM

The Eocene-Oligocene age of the Clarno Formation has been established by three different sources of data: 1) the floral studies of Knowlton (1902), Merriam and Sinclair (1907), Chaney (1927, 1936), Pabst (1948), Arnold (1952), Scott (1954, 1955), Hergert (1961), Gregory (1969a, 1969b), McKee (1970), Andrews and Basley (1971) and Manchester (1981); 2) the fauna studies of Stirton (1944), Cavender (1968), Anderson (1971) and Hanson (1973); and 3) the K-Ar radiometric dating of Everenden and others (1964), Everenden and James (1964), Swanson and Robinson (1968), Enlows and Parker (1972) and Dalrymple and Lanphere (1974). Compilations of radiometric ages are given by Walker and others (1975), Larson and Hammond (1974 and 1978) and Fiebelkorn and others (1983).

K-Ar dating of Clarno volcanogenic rocks (Evernden and others, 1964) suggested ages of 35.5 and 36.5 ± 0.9 m.y. for a sample collected from the locality of Scott's (1954) Nutbed flora. An age of 41.0 ± 1.2 m.y. is given by a rhyolite sample from the top of the Clarno section in the Horse Heaven Mining District (Swanson and Robinson, 1968). Samples collected from the vicinity of Mitchell yield K-Ar dates ranging from 30.0 to 46.0 m.y. for the Clarno Formation (Enlows and Parker, 1972). An age as young as 28.8 ± 0.8 m.y. was published by Walker and others (1974) and Laurson and Hammond (1978). Ages as old as 50.0 and 53.7 ± 1.0 m.y. are cited as unpublished data by Noblett (1979) and Fiebelkorn and others (1983). Walker and Robinson (1990) concluded that ages younger than 37 m.y. are highly questionable, representing rocks of the overlying John Day Formation that are compositionally similar to Clarno rocks.

PETROGRAPHIC DESCRIPTION OF ANALYZED SAMPLES

All samples examined are lava flows with compositions ranging from basalt to rhyolite. Examination of at least two thin sections from each sample revealed two groups. The first group (Group I) consists of four samples showing no evidence of disequilibrium between their phenocrysts and the liquids in which they reside. The second (Group II) consists of the remaining six samples, each containing at least one mineral phase showing textural disequilibrium with its host liquid. Group II samples are similar to the R-type lavas of Sakuyama (1981), which were proposed to have formed by magma mixing.

Group I:

Sample #HG-7 is an aphyric basalt with a few microphenocrysts of olivine, plagioclase and minor augite in an intergranular groundmass composed of plagioclase, olivine, clinopyroxene and Fe-Ti oxides. Olivine is partially altered to iddingsite.

Sample #FG-2 is a porphyritic/glomeroporphyritic dacite with phenocrysts of plagioclase, hypersthene, lesser augite and minor Fe-Ti oxides. The groundmass is cryptocrystalline and composed of plagioclase, pyroxenes, Fe-Ti oxides and devitrified glass. The sample contains only a few grains of sieve-textured plagioclase, which have no clear core and thin or no clear overgrowth rims.

Sample #PM-19 is a porphyritic/glomeroporphyritic dacite with large plagioclase, augite and hypersthene grains in a hyalopilitic groundmass composed mostly of brown glass and minor amounts of plagioclase laths and Fe-Ti oxides.

Sample #BC-16 is a nearly hyalopolitic (obsidian-like), clinopyroxene-bearing rhyolite. A very small proportion of the rock consists of plagioclase and lesser amounts of Fe-rich augite, hornblende and Fe-Ti oxide microphenocrysts. A few plagioclase grains are ophitic, enclosing smaller clinopyroxenes. The groundmass is vitrophyric and consists entirely of colorless glass showing flow-like texture.

Group II:

Sample #PH-5 is a porphyritic basaltic andesite with microphenocrysts of plagioclase, olivine, augite and minor Fe-Ti oxide. Xenocrysts are quartz with thin or no resorption coronas, completely resorbed plagioclase with clear overgrowth rims, and a minor proportion of sieve-textured orthopyroxene with clear overgrowth rims. The groundmass is cryptocrystalline and is composed of plagioclase, olivine, clinopyroxene and Fe-Ti oxides. Olivine is variably altered to amphibole.

Sample #PH-4 is a porphyritic/glomeroporphyritic andesite with phenocrysts of plagioclase, augite, and minor amounts of hypersthene and Fe-Ti oxides in a pilotaxitic groundmass composed of plagioclase, clinopyroxene, Fe-Ti oxides, and a small proportion of interstitial brown glass. Xenocrysts include plagioclase.and rare orthopyroxene. Almost total resorption of quartz is seen as radially arranged clinopyroxene (augite) embedded in a pool of brown glass with local quartz remnants.

Sample #HG-40 is a porphyritic andesite with microphenocrysts of plagioclase, augite, hypersthene, and rare Fe-Ti oxide. Xenocrysts are abundant and include quartz (up to 5 mm long), plagioclase (large, blocky, spongy, up to 4 mm wide and 5 mm long, and showing variable degrees of resorption, as well as variably wide, clear overgrowth rims), and rare orthopyroxene. Large brown glass inclusions are present in both quartz and plagioclase. The groundmass is pilotaxitic to hyalopilitic and composed of plagioclase, orthopyroxene, clinopyroxene, Fe-Ti oxides, and interstitial glass.

Sample #HG-42 is a porphyritic andesite with microphenocrysts of plagioclase and augite and xenocrysts of quartz in a pilotaxitic to hyalopilitic groundmass similar in composition to HG-40. The sample contains partially to totally resorbed plagioclase.

Sample #PM-34 is a porphyritic, hornblende-bearing andesite with phenocrysts of plagioclase, hornblende, and hypersthene (commonly rimmed by augite) embedded in a pilotaxitic groundmass of plagioclase, clinopyroxene, orthopyroxene, Fe-Ti oxides, and glass. Hornblende and plagioclase are commonly glomerocrystic. Xenocrysts are quartz, seived plagioclase, and minor orthopyroxene. Xenoliths are equigranular, gabbroic, and consist of plagioclase, pyroxene, and hornblende.

Sample #DC-1C is a glomeroporphyritic dacite with phenocrysts of plagioclase and hypersthene and minor microphenocrysts of Fe-Ti oxide The orthopyroxene is commonly ophitic. Xenocrysts are sieve-textured clinopyroxene and orthopyroxene, sieve-textured plagioclase, and lesser resorbed quartz. Xenoliths include earlier volcanic rocks and gabbroic to noritic rocks.

ANALYTICAL PROCEDURES AND RESULTS

Rb and Sr isotopic analyses were done at the University of North Carolina using a Nuclide, 90°-sector, 30-cm radius, thermal-ionization mass spectrometer. Ten samples were selected on the basis of variations in their Rb/Sr ratios. Approximate locations of the samples are given in figure 1. Accurate locations are available from the author upon request.

TABLE 1. Rubidium and strontium isotopic analyses.

Sample	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$\pm 2\sigma$ sd (10^{-6})
Group I:					
HG-7	18	356	0.14	0.703661	24
FG-2	81	267	0.88	0.704163	25
PM-19	108	190	1.65	0.704671	65
BC-16	128	94	3.93	0.706396	37
Group II:					
HG-42	55	333	0.48	0.704294	33
PH-5	41	411	0.29	0.703934	37
PH-4	43	338	0.37	0.704237	34
HG-40	111	271	1.19	0.704366	29
PM-34	36	376	0.28	0.704044	41
DC-1C	63	277	0.65	0.704321	55

Rb and Sr are measured by isotope dilution.
sd = standard deviation.

Powdered samples were dissolved, then spiked for both Rb and Sr. The Rb and Sr fractions were separated using standard ion-exchange chromatography. The Rb fraction of each sample was loaded onto a single, degassed Ta filament, and the Sr fraction was loaded onto triple, degassed Re filaments. All measured $^{87}Sr/^{86}Sr$ ratios were normalized for within-run isotopic fractionation to a $^{86}Sr/^{88}Sr$ value of 0.1194. $^{87}Sr/^{86}Sr$ values are reported relative to an Eimer and Amend standard value of $^{87}Sr/^{86}Sr$ of 0.70800. The two-sigma estimate of the precision on Sr is within 0.0002, based on multiple analyses of N.B.S. standard SRM987 $SrCO_3$.

Isotopic ratios and Rb and Sr contents of the samples are given in table 1. The isotopic ratios are also displayed on a conventional isochron plot in figure 2. Data for all samples fall along a linear array that regresses (York, 1969) to an age of 47 ± 5 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70372 ± 0.00010, with MSWD value of 0.63. Separate treatment of the two groups shows that regression of Group I yields an age of 51 ± 6 m.y. and initial $^{87}Sr/^{86}Sr$ ratio of 0.70354 ± 0.00014, with a MSWD value of 0.02. With the exception of the dacite sample DC-1C, which is co-linear with Group I, samples of Group II scatter above the least-squares regression line defined by Group I.

DISCUSSION

Rb-Sr isotopic systematics could potentially be used to date Tertiary volcanic rocks providing that: 1) the suite of samples chosen is co-magmatic; 2) some degree of differentiation has occurred within the suite to cause variability in the Rb/Sr ratios between samples; and 3) the suite has remained a closed system with respect to Rb and Sr, both during differentiation and after emplacement. The term co-magmatic is generally used to describe suites of

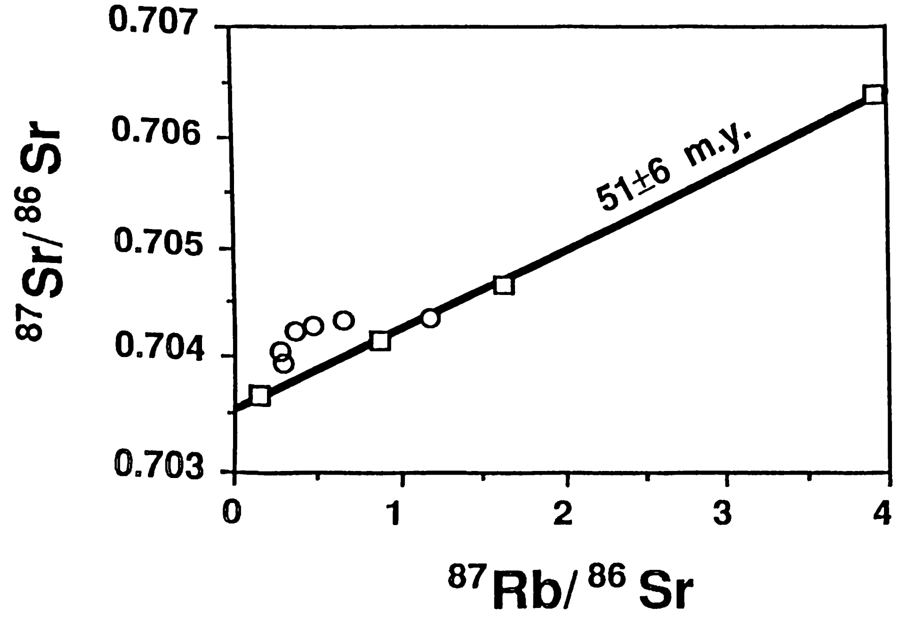

FIGURE 2. Isochron plot of Clarno lavas. Squares are Group I samples and circles are Group II samples. Thick line is the isochron of Group I.

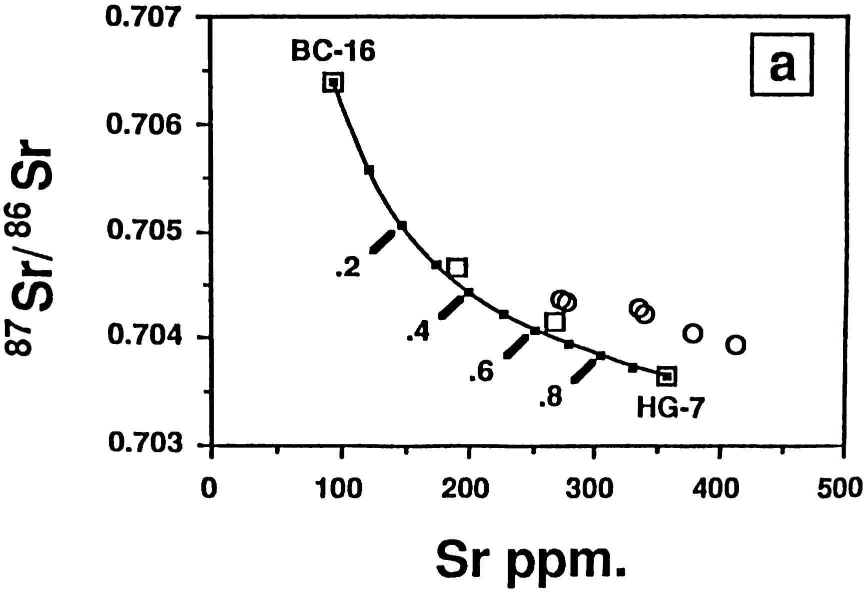

FIGURE 3a. Variation of ^{87}Sr/^{86}Sr with Sr (curved line is the basalt-rhyolite mixing hyperbola).

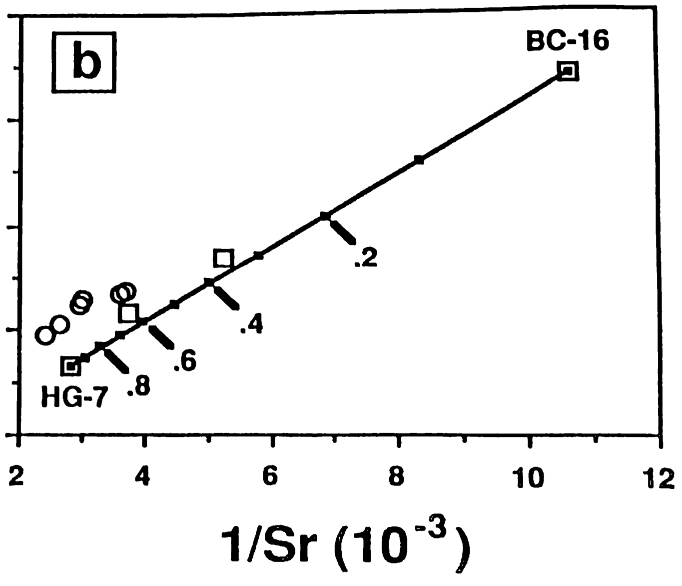

FIGURE 3b. Variation of ^{87}Sr/^{86}Sr with 1/Sr (straight line is the equivalent basalt-rhyolite mixing line). Remaining symbols are the same as in figure 2.

rocks that were formed solely by fractional crystallization from a single parent magma. In this restricted sense, the Clarno rocks are not comagmatic because they are also partly the product of magma mixing and assimilation (Suayah and Rogers, in press). This conclusion undermines the first assumption but not the second, because hybridization processes can lead to differentiated suites.

The scatter shown by the low-Rb/Sr rocks (all andesites) in figure 2 supports the argument that Clarno lavas are not co-magmatic. It also indicates that andesitic magmas/ rocks have undergone isotopic disequilibrium, which is possibly the result of open exchange of Rb and Sr between magmas and assimilated wallrock or interaction among magmas during differentiation. This conclusion is contrary to the third assumption, in which case careful examination of the selected samples is necessary to obtain plausible isochron ages.

Many Tertiary volcanic rocks show correlations between $^{87}Sr/^{86}Sr$ and $87Rb/^{86}Sr$ ratios. These correlations yield isochron ages that are commonly much older than Tertiary and are interpreted as ages of fractionation events within the mantle from which the magmas formed and subsequently evolved (Dickinson and others, 1969; James and others, 1976; Brooks and others, 1976). These isochrons are also interpreted as binary mixing lines between young, mantle-derived basaltic magmas and old radiogenic crust (Francis and others, 1980).

The age of the Clarno Formation determined either by the regression of all samples or the regression of Group I is in agreement with some Clarno K-Ar ages and is definitely within the 40- to 55-m.y. age interval of most Clarno measurements. I conclude that the isochron-age of Group I is a true age of a Clarno magmatic event. In order to examine the petrogenetic nature of this event, $^{87}Sr/^{86}Sr$ values are plotted against Sr (fig. 3a) and 1/Sr (fig. 3b) (Langmuir and others, 1978; Faure, 1986). Samples of Group I define a mixing hyperbola on figure 3a and an equivalent mixing line on figure 3b. Using the binary mixing equation (Faure, 1986, p. 142), the theoretical basalt (sample HG-7)-rhyolite (sample BC-16) mixing hyperbola (fig. 3a) was generated and translated into the equivalent mixing line (fig. 3b). The two dacite samples are consistent with a mixing model.

The preceding observations indicate: 1) at least some of the Clarno dacitic lavas are binary mixtures of basalt and rhyolite; 2) the isochron age calculated from Group I is an age of a mixing event; and 3) the end members and mixture must have remained a closed system to Rb and Sr during mixing and after solidification. The absence of xenocrysts from the dacites suggests that either the mixing end-members were nearly liquids during the mixing process or that the crystalline components of the mixing magmas were completely dissolved under the new magmatic conditions.

Initial $^{87}Sr/^{86}Sr$ values of all samples were calculated using a model age of 50 m.y. These values range from 0.70350 to 0.70379, which indicates that Clarno magmas originated mostly in the mantle with little or no incorporation from older radiogenic crust. The absence of such crust in the region is supported by the Sr and Nd isotopic composition of granitic rocks (Kistler and Peterman, 1973; Armstrong and others, 1977; Kistler and Peterman, 1978; Farmer and DePaolo, 1983). Consequently, the silicic end-member of the Clarno mixed magmas (sample BC-16 of Group I) must be either an extreme differentiate of a mantle-derived magma or a minimum melt of a nonradiogenic young crust, (possibly an earlier island-arc component).

The petrographic data and the Rb-Sr isotopic systematics presented here indicate that Group II samples (mostly andesitic lavas) had interacted with crystalline components from young, isotopically heterogeneous, crustal lithologies. The solid components could have been either partially fused wall rocks or solid phases of interacting batches of isotopically heterogeneous magmas. This open-system behavior resulted in Sr isotopic disequilibrium, causing the scatter shown in figures 2 and 3. Assimilation of such lithologies is shown by the xenocrysts and lesser xenoliths in all samples of Group II. None of these components show deformation nor other criteria that would indicate assimilation of metamorphic or granitic crustal material.

CONCLUSIONS

Petrographic examination of Clarno lavas allowed the separation of Clarno rocks into tow groups—one group (Group II) contains disequilibrated minerals and the other (Group I) is devoid of them. This grouping and the presence of abundant disequilibrium textures indicates that Clarno rocks are partly hybrids and therefore not strictly comagmatic. Model initial $^{87}Sr/^{86}Sr$ ratios of all samples (corrected for 50 m.y. age) indicate mantle sources with little or no involvement of the crust. Hybrid rocks, therefore, are largely mixtures of mantle-derived magmas and earlier-formed rocks of the Clarno magmatic suite.

Whole-rock Rb-Sr isotopic data shows that Group I defines an isochron with an age of 51 ± 6 m.y., within the range of K-Ar ages of Clarno rocks. Variation of $^{87}Sr/^{86}Sr$ ratios with Sr and 1/Sr indicate that the age determined is the time of production of dacitic magmas by binary mixing of a mantle-derived basaltic melt and a rhyolitic melt derived either from the mantle or a nonradiogenic crustal source. The low MSWD value (0.02) of the isochron for Group I indicates that the samples must have remained a closed system with respect to Rb and Sr during and after mixing.

This study shows that whole-rock Rb-Sr isotopic data of Clarno lavas provide meaningful ages and important petrologic information concerning the origin and evolution of Clarno magmas. Although isochron ages generally require that the suite of rocks under investigation must be comagmatic, and therefore represent ages of fractionation events, this assumption is not required for the conclusions drawn for Clarno magmatism. The uniformity of compositions of the andesites of Group II, however, makes age determination difficult.

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