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**FINAL TECHNICAL REPORT
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INVESTIGATION OF A FOSSIL GEOTHERMAL SYSTEM,
HAMBLIN-CLEOPATRA VOLCANO, CLARK COUNTY, NEVADA**

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INVESTIGATION OF A FOSSIL GEOTHERMAL SYSTEM, HAMBLIN-CLEOPATRA VOLCANO, CLARK COUNTY, NEVADA

Goals:

The two aims of this project have been to describe the physical and chemical parameters of growth of a large volcano throughout its activity and to reconstruct the geothermal system that acted within the volcanic pile. The Hamblin-Cleopatra volcano in southern Nevada (Figure 1) was selected for study because erosion since cessation of eruptions in Miocene time, combined with fault displacement, has exposed the entire volcanic succession, as well as the intrusive core, a radial dike system, and sedimentary and volcanic rocks that predate and postdate the volcano (Anderson, 1973). This unusual combination of preservation and dissection allowed a rare opportunity to estimate the proportions of igneous materials forming lava flows, pyroclastic deposits, intrusive bodies, and reworked debris in an average-size (60 km^3) stratovolcano of very common (andesite and dacite) composition. In addition, the unusually complete preservation of the eruptive sequence allowed documentation of chemical changes in the magma throughout the active time span of the volcano. Hydrothermal alteration increases in intensity toward the center of the volcanic pile and represents a fossil convective geothermal system. The high proportion of exposed rock and the stratigraphic continuity of units through differing degrees of alteration suggested that temperature gradients and flowline patterns could be reconstructed for this convective system.

Methods:

Geologic mapping on a scale of 1:12,000 of the largest and best preserved segment of the volcano was completed before the contract began, and 275 rock samples were collected during the mapping and subsequent field work. Petrographic thin sections were prepared from 266 of these samples. After petrographic study, 29 samples were analyzed for major and trace elements, 9 were dated by $^{40}\text{K}/^{40}\text{Ar}$ geochronology, and $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios were measured for 5 samples. Electron probe microanalysis was performed on minerals in 25 of the 29 rock samples for which whole-rock major and trace element analyses had been made. Least-squares mixing calculations were performed using whole-rock major element analyses as assumed parent and daughter liquids, with probe analyses of phenocrysts as compositions of fractionated phases, to test models of magma mixing and fractional crystallization.

Figure 1. Location of the Hamblin-Cleopatra volcano, Nevada

Results:

1) Volcanic stratigraphy and structure

Hamblin-Cleopatra lavas yield K-Ar ages of 13.1 ± 0.8 to 12.5 ± 0.9 million years, and are underlain and overlain by lavas with ages of 14.2 ± 0.5 and 11.5 ± 0.5 million years, respectively. The Miocene stratovolcano was bisected by a left-lateral strike-slip fault with displacement of 20 km, and further segmented by other strike-slip and normal faults (Figure 2). Volcanic units dip outward from the focus of a radial dike array (Fig. 3). Many lava flow, pyroclastic, and mudflow breccia units are continuous through more than 180 degrees of arc in the Cleopatra Wash segment, although many thicken where they filled valleys on the flanks of the volcano and thin over intervening ridges.

The Hamblin-Cleopatra volcanic edifice was constructed of lava flows (30 volume percent), pyroclastic breccias (16 volume %), reworked mudflow (lahar) deposits (38 volume %), and small intrusive bodies, mostly dikes (16 volume %). The volcanic products comprise two sequences separated by an erosional unconformity. The earlier, eroded and locally domed, sequence contains lavas of intermediate compositions (andesites and quartz latites). Among the non-lava units, mudflow breccias are strongly dominant over pyroclastic deposits in the earlier sequence. The second sequence is distinctly bimodal in composition; thin lava flows, commonly more mafic than those in the first sequence, occur with more felsic (dacitic) pyroclastic layers, which dominate the youngest part of the section. Mudflow breccias are much less abundant in the second sequence. Strike-slip and normal faults in the volcanic pile probably became active during the time interval represented by the unconformity, and fault displacement continued during accumulation of the second sequence.

2) Petrology

Analyzed lavas of the first sequence tend to be richer in Si, Na, and K, and poorer in Ti and P, than lavas of the second sequence. Phenocrysts in lavas of the first sequence are sparse but large, and constitute the assemblages plagioclase + clinopyroxene + orthopyroxene and plagioclase + clinopyroxene + biotite. In contrast, phenocrysts in second-sequence lavas tend to be smaller but more numerous; olivine and amphibole are more common, orthopyroxene and biotite less common, than in the first sequence. Crystallization temperatures estimated from compositions of plagioclase, pyroxenes, and iron-titanium oxides are in general higher in the second sequence, and phenocryst compositions vary through narrower ranges than in the first sequence. Changes in lava composition and crystallization temperatures during growth of the Hamblin-Cleopatra volcano are summarized in Figures 4 through 7; lines indicate running averages of three successive samples (a method used in similar plots by Rose and others, 1977).

Figure 2. Map showing the three faulted segments of the Hamblin-Cleopatra volcano.

Figure 3. Map showing faults and dips in volcanic units in the Cleopatra Wash segment of the Hamblin-Cleopatra volcano.

Figure 4. Variations in wt % SiO₂, Al₂O₃, total iron as FeO, MgO, and TiO₂ in lavas plotted as functions of stratigraphic position.

Figure 5. Variations in wt % CaO, Na₂O, K₂O, P₂O₅, and MnO in lavas plotted as functions of stratigraphic position.

STRATIGRAPHIC ORDER

Figure 6. Variations in ppm Ni, Nb, Y, Rb, Sr, and Zr in lavas plotted as functions of stratigraphic position.

Figure 7. Estimated crystallization temperatures in lavas plotted as functions of stratigraphic position. Triangles are temperatures estimated from compositions of coexisting orthopyroxene and clinopyroxene (Lindsley, 1983). Dots are temperatures estimated from compositions of coexisting magnetite and ilmenite (Spencer and Lindsley, 1981). Filled and open squares are the highest and lowest temperatures, respectively, for plagioclase phenocryst-whole rock pairs (Kudo and Weill, 1970; Mathez, 1973).

The diversity of phenocryst phases, their wide ranges of compositions, and their common resorbed outlines, suggest that mixing of mafic magma with more highly fractionated liquid may explain the cyclical compositional changes shown by Hamblin-Cleopatra lavas, especially in the first sequence. Amphibole phenocrysts in the lavas are kaersutite (high-titanium, calcic, silica-undersaturated amphiboles) and almost certainly are xenocrystic, being typical of mafic alkalic magmas. Clinopyroxene forms two populations; the less abundant, present in nearly every sample, is less euhedral, more resorbed, and richer in Al, Ti, and Ca. Like the amphibole, this clinopyroxene appears to be xenocrystic and derived from mafic alkalic magma.

Mafic alkalic (hawaiite) lava did erupt on the flanks of the Hamblin-Cleopatra volcano after the stratovolcano ceased its activity; its composition is that of the most mafic endmember required in mixing models. Least-squares modelling to derive a mafic andesite of the first sequence from hawaiite requires, in the best-fit solution, removal of 51% amphibole and 16% olivine, but addition of 8% clinopyroxene. The best-fit solution for derivation of an andesite from the mafic andesite requires removal of 23% olivine, 20% clinopyroxene, 13% plagioclase, and 7% magnetite, but addition of 35% orthopyroxene and a trace of ilmenite. In both of these models, no solution was possible without simultaneous addition of at least one phenocryst phase and the removal of others, demonstrating that fractional crystallization alone cannot account for the changes in magma compositions; magma mixing, combined with fractionation, is likely. The best-fit solution for deriving a dacite from andesite requires fractionation, in more reasonable proportions, of 27% plagioclase, 6% biotite, 2% magnetite, 2% clinopyroxene, and 0.1% ilmenite; no phase need be added. The model for this third step indicates that fractional crystallization, without mixing, can account for the diversity in shallow, more felsic, magma bodies that supplied the pyroclastic breccias of the second sequence in the Hamblin-Cleopatra volcano. Nevertheless, some mixing is shown by the presence of mafic glass blebs in the dacite blocks of these breccias, but this mingling did not result in a homogeneous product.

Hamblin-Cleopatra lavas yield initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.70455 ± 0.00004 to 0.70548 ± 0.00003 , and the later hawaiite gives 0.70536 ± 0.00004 . The isotopic data, the least-squares models, and the xenocrysts of kaersutite and clinopyroxene rich in Al and Ti, indicate that the alkali-calcic magmas of the Hamblin-Cleopatra volcano could be derived by fractionation from a mafic alkalic parent, with some mixing of differentiated magmas with mafic liquid which occasionally replenished the reservoirs.

The intrusive core of the volcano is elongated along faults and consists of biotite dacite, of the same composition as the most abundant radial dikes and the blocks in the pyroclastic breccias of the second sequence. The coexistence, but incomplete mixing, of dacitic and mafic liquids in the bimodal suite, combined with geothermometry of phenocryst and groundmass phases, suggests that magmas feeding the second sequence could move more freely along faults, and had shorter residence times in shallower reservoirs, than the more intimately mixed intermediate magma erupted in the first sequence.

The lithologies of 725 dikes and 253 lava flows were recorded in the field; this data base gave the opportunity to compare the abundances of extruded and shallow intrusive rock types in the same volcanic edifice, an attempt not previously recorded in the literature, to our knowledge. Dikes containing biotite phenocrysts are the widest, longest, and most abundant (59% of the dikes counted); biotite-bearing lava flows are also the most abundant (33% of the flows counted). In contrast, olivine-bearing rocks make up 24% of the flows, but only 2% of the dikes, and these are mainly in the outer fringes of the edifice, where olivine-bearing lava flows dominate. Flow lineations and dike morphologies (pinched-out tops and bottoms) indicate that magma transport through dikes was dominantly horizontal. Biotite crystallized in very shallow reservoirs near the summit of the volcano, but olivine crystallized at greater depth, and may have been carried in more dense magma that did not ascend to the summit but moved laterally into the lower parts of the volcanic pile. The relatively low proportion of olivine-bearing dikes to flows may also be due to re-use of the same dikes by later magma pulses. The proportions of amphibole-bearing dikes and flows are nearly the same (12 and 15%, respectively). Dikes and flows lacking olivine, biotite and amphibole have effectively the same proportions (27 and 28%, respectively).

3) The fossil geothermal system

Reconnaissance indicated a concentric pattern of hydrothermal alteration, increasing in intensity toward the center of the volcano, coincident with the focus of the radial dike system. Hydrothermal alteration products were sought in each of 266 thin sections; their distributions are shown in Figure 8. Quartz veins, sericite replacing plagioclase, and smectite patches replacing groundmass, mark the innermost part of the alteration pattern. Ankerite and siderite veins, analcime, zeolites, and smectite lining vesicles, form an intermediate zone. In the outer zone, iddingsite survives as an early deuteric alteration product of olivine, but is replaced by smectite toward the center of the volcanic pile. Low-iron carbonate veins, and calcite replacement of plagioclase, are most widely and uniformly distributed. Aqueous solutions containing carbonate were apparently active throughout the activity of the convecting geothermal system, and late, low-temperature effects were superimposed on early, high-temperature alteration.

Figure 8. Distribution of alteration products in the Cleopatra Wash segment of the Hamblin-Cleopatra volcano. Solid dots indicate presence, hollow circles absence, of the products indicated at the top of each map.

Figure 8, continued

The paragenetic sequence of alteration products is still under study, and probe study of carbonates, layer silicates, and zeolites (largely clinoptilolite followed by mordenite) is in progress. Displacement along faults during volcanism and geothermal circulation has complicated the alteration pattern by juxtaposing rocks with different degrees of alteration, and by providing channelways of high permeability, along which alteration is more intense than in intervening rock volumes. Fluid inclusions suitable for study were found only in quartz veins.

Although the hydrothermal alteration pattern in space and time proved to be more complex than had been first envisioned, textural and probe studies of the alteration phase assemblages are providing useful data which will be needed before oxygen isotope analysis of the carbonate phases can be performed.

Publications, and manuscripts in preparation, resulting from this contract are listed on the next page.

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MANUSCRIPTS IN PREPARATION

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