# LHERZOLITE INCLUSIONS AND MEGACRYSTS FROM THE GERONIMO VOLCANIC FIELD, SAN BERNARDINO VALLEY, SOUTHEASTERN ARIZONA

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The Geronimo volcanic field of the San Bernardino Valley, southeastern Arizona is one of a number of upper Cainozoic basalt fields in the southwestern U.S.A. and northern Mexico. The lava flows and cinder cones of the Geronimo field are composed of mildly silica-undersaturated alkali olivine basalts with Mg/(Mg+Fe) ratios in the range 0.65 to 0.55, comparable with the other Cainozoic basalt fields. The basalts contain forsteritic olivine, calcic augite and occasionally plagioclase phenocrysts, and magnetite in addition to these phases in the groundmass (Analysis, Table 1).

These are apparently two distinct periods of volcanism in the San Bernardino Valley. The dissected "older" basalts are distributed on the flanks of the valley and are perched above the valley floor. These older flows were erupted prior to substantial north-south faulting on valley boundary faults. The "younger" cinder cones and flows are well preserved morphologically and a K-Ar age of approximately 50,000 years has been obtained for one of the largest cones (D. J. Lynch, pers. comm.). Several maars are present and the largest of these is approximately 1.5 km in diameter, 150 m deep and is rimmed by 30 m of basaltic tuff. In the vicinity of Palaeozoic limestone outcrops, a control on the distribution of vents by basement structure is apparent but elsewhere the structural control is not obvious.

Spinel lherzolite and megacrysts of calcic augite, kaersutite, feldspar, spinel and magnetite are present in the majority of the flows and cinder cones, but the absolute amounts and proportions of megacryst species and nodules varies considerably. Mineralogically the lherzolites are composed of olivine ($Fo_{91-88}$), calcic augite ($Ca_{45.5}$, $Mg_{49.5}$, $Fe_{5.0}$), orthopyroxene ($Ca_{1.5}Mg_{89.0}Fe_{9.5}$) and spinel. The spinel varies in colour from light brown and green through to dark red-brown, and also in composition but is predominantly a chromian spinel. Representative analyses of the lherzolitic phases are included in Table 1. Some of the nodules show signs of reaction with the host basalts. For example, the Cr-Al-rich spinels show an increasing magnetite component and are darker in colour where in close contact with the host. Also potassic feldspars are present in veins and cracks probably from host contamination.

Clinopyroxene megacrysts range in composition from those similar to lherzolite pyroxene to more Fe and Ca-rich varieties (Table 1). The megacrysts probably represent both disaggregated nodule material and high-pressure cognate phenocrysts. Banks of rods and spherules of pyrrhotite are present in some of the cognate megacrysts. It is conceivable that the sulfide globules were trapped during crystal growth although injection along annealed cracks is also a possibility.

Feldspar megacrysts range from potash oligoclase through lime anorthoclase to anorthoclase in composition and are similar to feldspar megacrysts in other Cainozoic basalt fields. Possible equilibria that may be involved in the genesis of these alkali feldspars are currently under experimental study at NASA-JSC and ANU-RSES. Preliminary results suggest an expansion of the primary phase field of feldspar in the presence of $CO_2$ relative to the volatile-free systems in the following equilibria studied at 7 and 15 kbar:-

$6NaAlSi_2O_6 + CaMgSi_2O_6 + 2CO_2 \rightleftarrows 4NaAlSi_3O_8 + CaAl_2Si_2O_8 + Na_2CO_3 + MgCO_3$;
$6KAlSi_2O_6 + CaMgSi_2O_6 + 2CO_2 \rightleftarrows 4KAlSi_3O_8 + CaAl_2Si_2O_8 + K_2CO_3 + MgCO_3$.

Spinel megacrysts exhibit a wide range of composition and include some complex assemblages that permit estimates of T and $f_{O_2}$ of equilibration. For example, some spinels included in augite megacrysts contain magnetite exsolved on {111} planes, ilmenite blebs and globular pyrrhotite. In rare samples, corundum is also present typically in veins and cracks. In one spinel inclusion, coexisting pyrrhotite and pyrite has been analyzed but this assemblage does not appear to be common.

If the assumption is made that the magnetite and ilmenite solid solutions have remained in equilibrium together with the host spinel, then the T and $f_{O_2}$ of the last equilibration can be calculated (Buddington and Lindsley, 1964). Assuming this temperature also applies to the pyrrhotite compositions, then $f_{S_2}$ can also be determined (Toulmin and Barton, 1964). The assemblage $spinel_{ss}$ and titaniferous magnetite requires that $x^{spinel}_{Fe_3O_4}$ and $x^{mt}_{spinel}$ be calculated from microprobe analyses with total Fe as FeO. The usual procedure for recalculating magnetite compositions(Carmichael, 1967) has been modified to group MgO (+ FeO) with $Al_2O_3$ in the ratio given by the host spinel. Excess FeO is then computed firstly as $2FeO{\cdot}TiO_2$ and then as $Fe_3O_4$. Both the magnetites and ilmenites are aluminous and uncertainty may be attached to the application of the Buddington-Lindsley geothermometer/geobarometer, but temperatures in the range 830-700°C at log $f_{O_2}$ of $10^{-12}$ to $10^{-15.5}$ are calculated ignoring any pressure effect. The lack of detectable Ti in the host spinel implies that the activity coefficients for $Fe_2TiO_4$ in magnetite are large and that the solvus between $(Mg,Fe)Al_2O_4$ - $(Fe_2TiO_4{\cdot}Fe_3O_4)$ spinels is not regular.

The pyrrhotite compositions give log $f_{S_2}$ in the range -1 to -0.5 and the pyrrhotite-pyrite pair appears to confirm the lower temperature limit (700°C) calculated from the host spinel plus Fe-Ti oxides. Some of the homogeneous Ti-Al-Mg-rich magnetite megacrysts may be cognate with the host lava but the more complex assemblages are apparently unrelated to the host.

The cause of the Upper Cainozoic basaltic volcanism in the southwestern U.S.A. has lately been related to the change in plate motions from compressional to tensional plus shear associated with the collision of the proto-East Pacific Rise with the Americas Plate (e.g. Christiansen and Lipman, 1972). It is suggested that a possible eruption trigger is through mantle diapirism following the eastward passage of the trailing edge of subducted Farallon Plate (Snyder et al., 1976), contemporaneous with Basin and Range Faulting.

## References


Buddington, A.F. and D.H. Lindsley, Iron-titanium oxide minerals and synthetic equivalents, J. Petrol. 5 (1964) 310-357.

Carmichael, I.S.E., The iron-titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates, Contrib. Mineral. Petrol. 15 (1967) 36-64.

Christiansen, R.L. and P.W. Lipman, Cenozoic volcanism and plate-tectonic evolution of the western United States, Pt. 2, Late Cenozoic, Phil. Trans. R. Soc. London A. 271 (1972) 249-284.

Snyder, W.S., W.R. Dickinson and M.L. Silberman, Tectonic implications of space-time patterns of Cenozoic magmatism in the western United States, Earth Planet. Sci. Lett. 32 (1976) 91-106.

Toulmin, P. III and P.B. Barton, Jr., A thermodynamic study of pyrite and pyrrhotite, Geochim. Cosmochim. Acta 28 (1964) 641-671.

Table 1. Analyses of host basalt, individual lherzolite phases and megacrysts

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 44.41 | 40.96 | 51.35 | 54.71 | 0.00 | 48.30 | 64.52 |
| $TiO_2$ | 2.50 | 0.00 | 0.30 | 0.00 | 0.00 | 0.98 | 0.00 |
| $Al_2O_3$ | 15.50 | 0.00 | 6.56 | 4.50 | 58.94 | 9.25 | 21.09 |
| $Cr_2O_3$ | 0.00 | 0.00 | 0.88 | 0.27 | 9.03 | 0.13 | 0.00 |
| $FeO^*$ | 10.06 | 9.98 | 2.63 | 6.42 | 9.96 | 6.75 | 0.00 |
| MnO | 0.22 | 0.00 | 0.00 | 0.11 | 0.00 | 0.00 | 0.00 |
| MgO | 9.36 | 49.17 | 15.44 | 33.18 | 21.56 | 13.86 | 0.00 |
| CaO | 10.05 | 0.00 | 19.96 | 0.78 | 0.00 | 18.81 | 1.74 |
| $Na_2O$ | 3.75 | 0.00 | 1.48 | 0.00 | 0.00 | 1.18 | 8.16 |
| $K_2O$ | 1.94 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4.01 |
| Total | 98.35 | 100.11 | 98.60 | 99.97 | 99.49 | 99.26 | 99.52 |

*Total Fe as FeO. Analyses are by TPD microprobe except for column 1 by XRF. Total in column 1 includes 0.56 wt.% $P_2O_5$ in host basalt; 2 = ol. in lherz.; 3 = cpx in lherz; 4 = opx in lherz; 5 = spinel in lherz; 6 = cpx megacryst; 7 = feldspar megacryst.