Granite Inclusions in Lavas of Medicine Lake Volcano, California, USA
Clues to the Subsurface Geology

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Abstract

Two types of granitic clasts are found in Holocene rhyolite and basalt lava flows from Medicine Lake volcano, a Quaternary shield volcano that lies about 50 km east-northeast of Mt. Shasta, in northern California. Type I is enriched in $\delta^{18}O$ (whole-rock (WR) and quartz separates: 7.8 - 9.8 ‰: n=7) and $^{87}Sr/^{86}Sr$ (0.7046 - 0.7050). Most inclusions show evidence for incipient melting that occurred prior to or during their transport to the surface. Type II inclusions are lower in $\delta^{18}O$ (quartz separates: 5.1 - 7.5 ‰: n=8) and $^{87}Sr/^{86}Sr$ (0.7037 - 0.7041), and have been found in the Glass Mtn. domes and the basaltic Burnt Lava flow, the latter in which they are 30-50% melted and partly vesiculated. Both types are fine- to medium-grained; individual clasts may have hypidiomorphic granular or porphyritic textures, the latter usually with a micrographic groundmass. Mafic minerals include biotite and orthopyroxene, the latter more common where melting appears greatest. Primary, vapor-rich fluid inclusions are common, as are glassy melt inclusions, consistent with relatively rapid cooling in a shallow environment.

The clasts are not likely to have been tapped from depths < 3 km, as shown by core from geothermal drillholes sited near the Holocene rhyolites. These holes traverse through abundant altered silicic volcanic rocks before reaching granite similar to that found in Type I and II clasts. The granites are hydrothermally altered and have WR $\delta^{18}O$ values from -0.8 to -4.7 (n=4). The rarity of hydrothermally altered granitic clasts in Holocene lavas implies that magma storage, fractionation and attendant crustal melting occurred at depths slightly greater than 3 kms beneath the present-day surface.

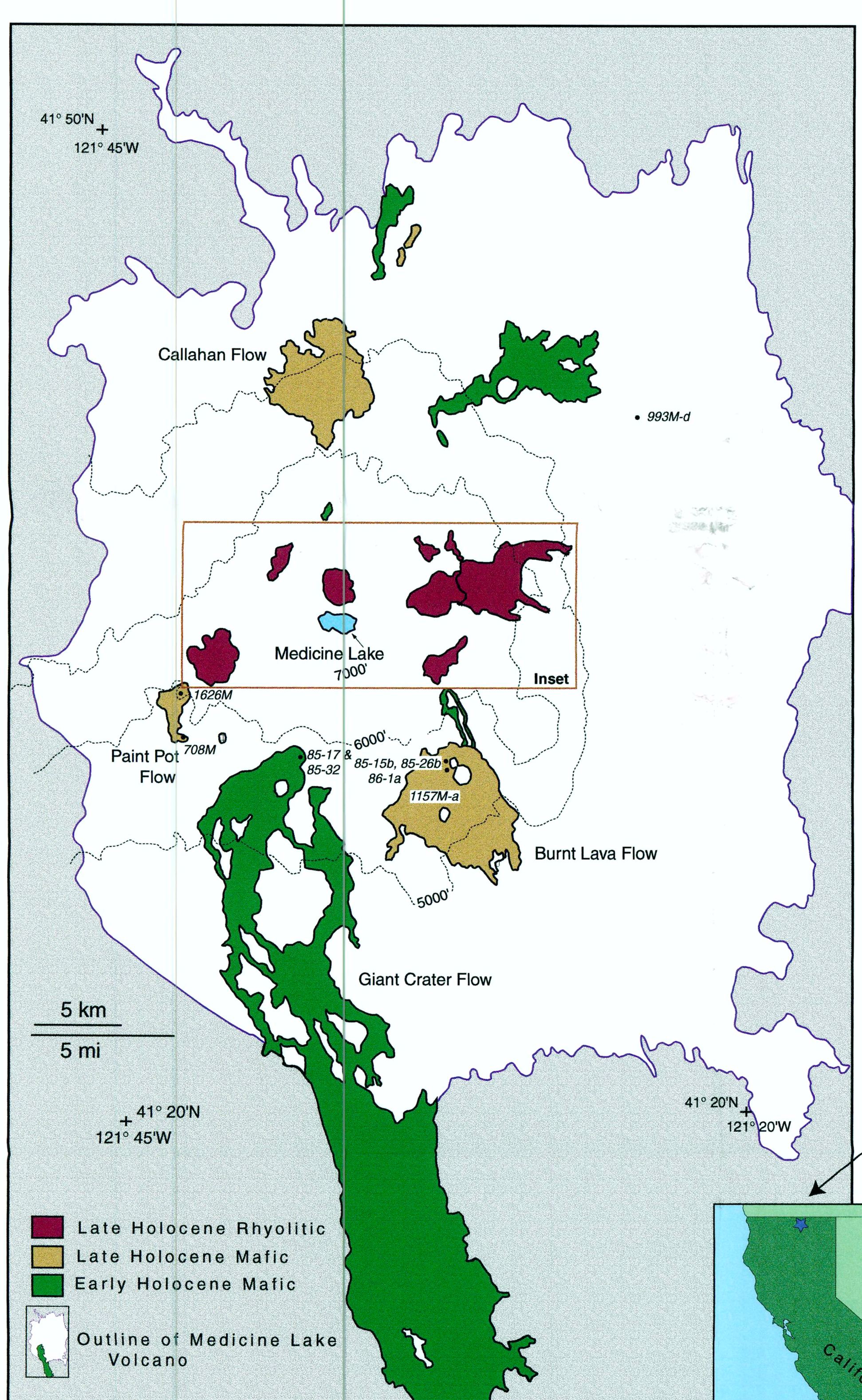
Two granitic inclusions in the Pleistocene Andesite Tuff are similar in texture to Type I and II, but are visibly altered in thin section and have WR $\delta^{18}O$ of 0.5. Pleistocene dacites and rhyolites are chemically different than those from the Holocene, and have lower $\delta^{18}O$, consistent with assimilation of more hydrothermally altered crust such as that found in drillcore and as lithics in Andesite Tuff.

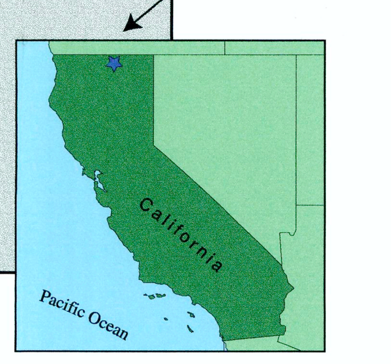
MEDICINE LAKE VOLCANO is a Quaternary shield volcano that lies about 50 km east-northeast of Mount Shasta, the largest of the Cascade stratovolcanoes. It is located east of the axis of the Cascade volcanic arc. Its low shield shape contrasts with the stratovolcanoes that dot the length of the Cascade chain. Medicine Lake volcano could be considered a Basin and Range volcano, but chemical and temporal similarities as well as close spatial association indicate that it is Cascadian. The predominant magma types erupted, in the past, and in the Holocene, are basaltic lavas and domes of rhyolitic obsidian, some as young as ~850 years old. The total amount of magma erupted has been estimated at ≤750 km³.

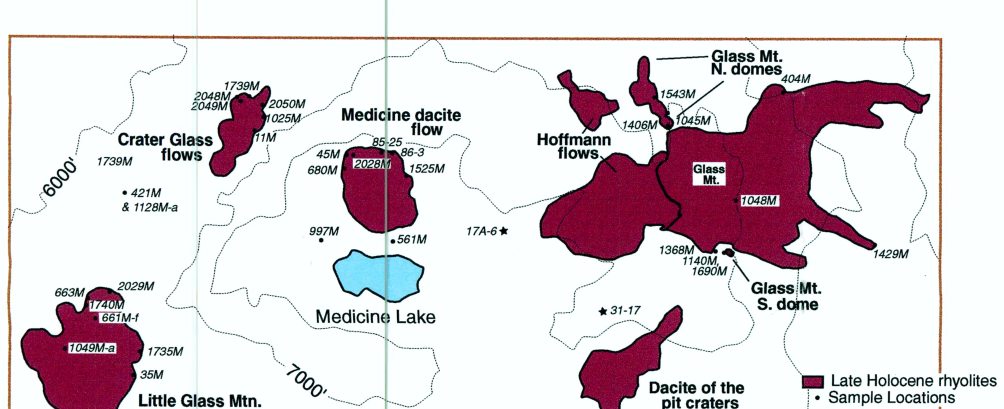
The basement beneath Medicine Lake volcano has been the subject of much speculation. It may include Sierran granites, Klamath terrain metamorphic and ophiolitic rocks and mid-Tertiary igneous and sedimentary units. Crustal thickness is estimated at 36-40 km.

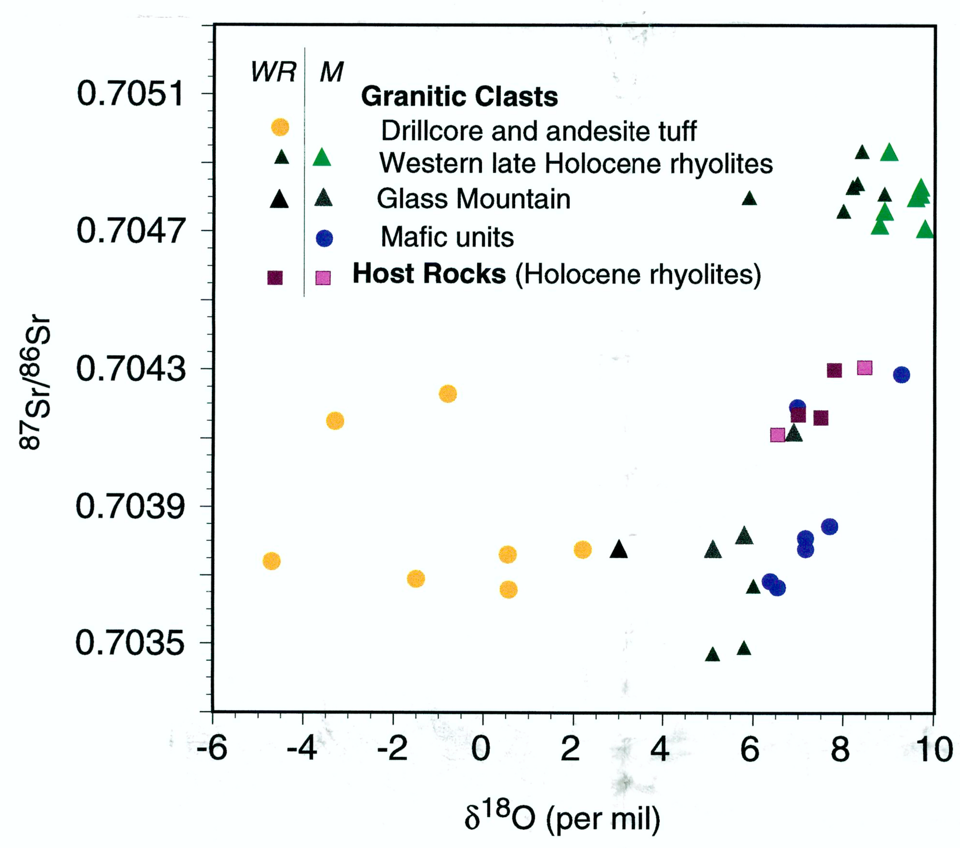
Granite inclusions in mafic and silicic volcanic units can provide information on the source region of Medicine Lake magmas, the depth at which they pond in the upper crust, and the lithologies that occur beneath the present-day volcano.

Granitic inclusions (clasts) are found in a wide variety of silicic and mafic lavas from Medicine Lake volcano, northern California. They range from unmelted to highly melted, and could potentially represent Sierran or Klamath basement, Pliocene or Pleistocene intrusions that predate the volcano, or crystallized equivalents of Pleistocene and Holocene lavas of the present-day volcano. This poster discusses how the granite clasts yield information about the volcanic architecture and history of Medicine Lake volcano.

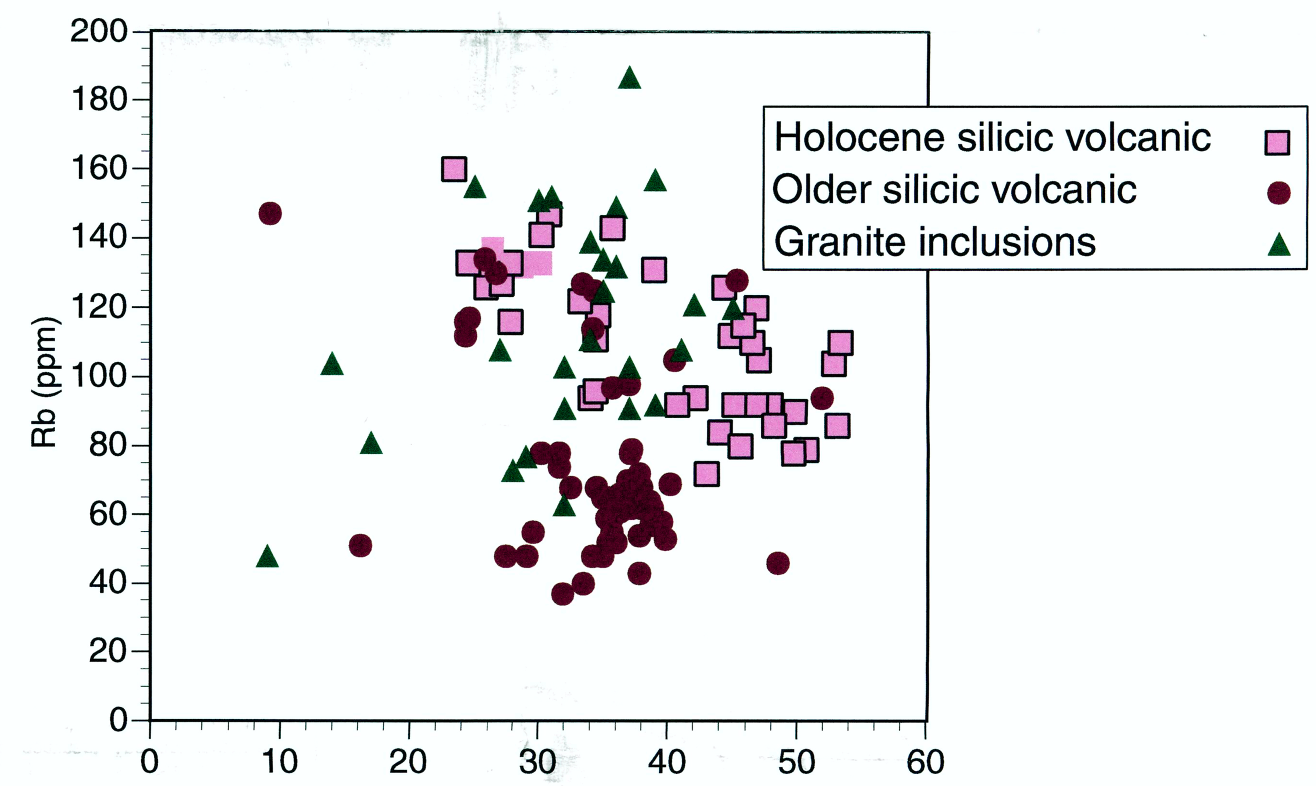




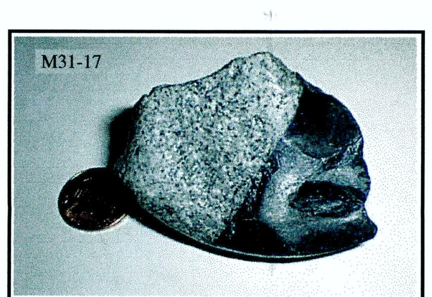




$\delta^{18}O$ vs. $^{87}Sr/^{86}Sr$ for granitic clasts and other rocks from Medicine Lake volcano. Granitic rocks from drillcore are hydrothermally altered, as are clasts within the Pleistocene andesite tuff. Granitic clasts in Holocene rhyolites form two general groups: one high in $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ and the other low in both. Granitic clasts in mafic Holocene lavas and the rhyolitic host rocks themselves plot in an intermediate region. *WR data are for whole rocks. M are for mineral separates, which were for quartz, except for the Host Rocks (feldspars).*



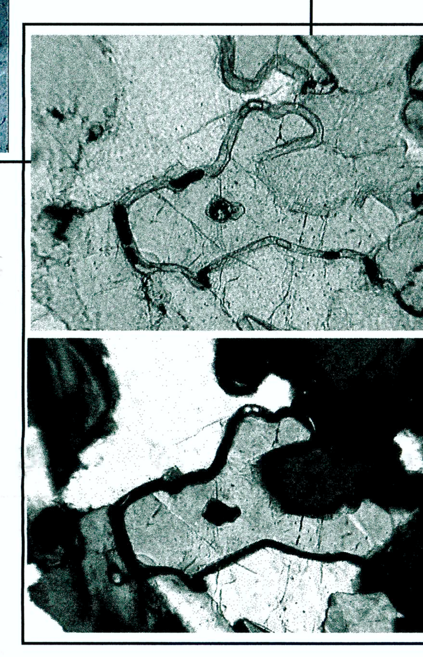
Plot of Mg# versus Rb for Holocene rhyolites and dacites, Pleistocene rhyolites and dacites and granite inclusions from all units. As noted by Donnelly-Nolan (in press), the Pleistocene silicic units are distinct from younger rhyolites in a variety of chemical and isotopic aspects. The granitic inclusions overlap the ranges of both groups.



Sample M31-17 consists of a granite that intruded an older basaltic rock. It comes from the bottom of drillhole 31-17. Both the granite and basalt are hydrothermally altered, as shown by oxygen isotope analyses and petrographic inspection.

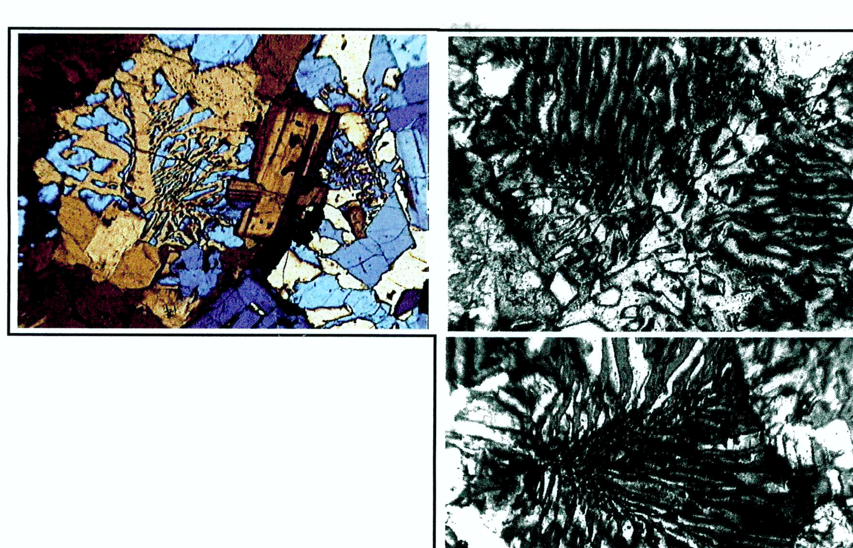
UNMELTED HYPIDIOMORPHIC GRANULAR. Sample 1045 M-a is an unmelted, sample with abundant biotite, opx and limited olivine and hornblende, the latter which are rare in the Medicine Lake granitic inclusions. The grains are intergrown and subequal in size.

SCALE: Each image is 2 mm across.



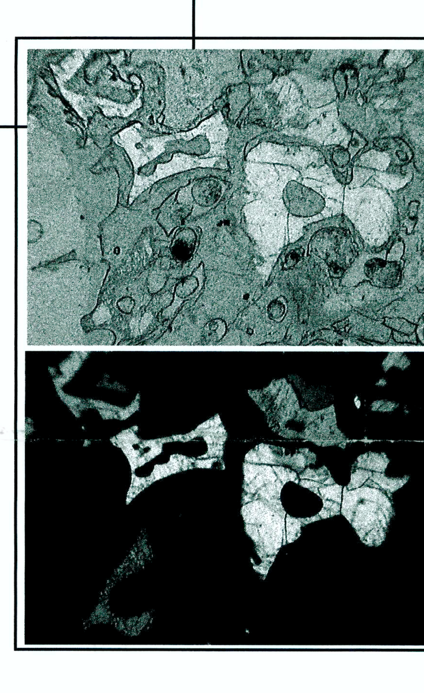
SINTERED INCLUSION Sample 1049M-a has started to melt around crystal edges. In this case, where grains of feldspar and quartz join, the edges have started to melt. The top image shows the sample in plane-polarized light. The bottom image is with crossed nichols. Note that the glass around the central crystal goes to extinction in the bottom image.

SCALE: Each image is 1 mm across.



GRANOPHYRE. Sample 2028M (right, top and bottom, photos with crossed nichols) is a well-developed granophyre, with micrographic textures and limited radiating fringes around pre-existing phenocrysts. All granophyres appear to be biotite dominant. They are unmelted, though melted samples would lose their granophyric groundmass upon initial melting, and evidence for granophyres may not survive in the melted samples. Sample 86-3 has smaller patches of granophyre (photo with crossed nichols and inserted gypsum plate).

SCALE: Top left image is 2 mm across. Other images are 1 mm across.



HIGHLY MELTED SAMPLES, such as 1543M from Glass Mtn., are composed of highly irregular grains of quartz and feldspar and vesicular glass, which is black in the bottom photo (crossed-nichols). Mafic minerals are usually absent.

SCALE: Each image is 2 mm across.

Nearly all the granitic clasts are full of fluid inclusions. By far the most abundant type is vapor-rich inclusions (to left in top frame), most commonly with <10% liquid by volume. These primary, low-density inclusions must have formed at low pressure, likely 1-2 kbars. Only one sample, 1140M-h, also contains halite-bearing inclusions, demonstrating that this sample formed also at low pressure, but in equilibrium with both vapor and a saline brine.

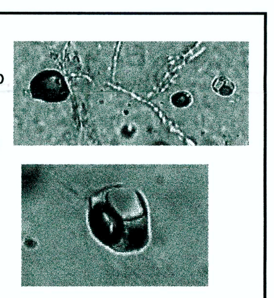


Table. Chemical and textural characteristics of Medicine Lake granite inclusions

Sample #	Location	$\delta^{18}O$ WR	$\delta^{18}O$ Min	G	M	$^{87}Sr/^{86}Sr$	Mafics	Host	Mg#	SiO_2	FeO*	MgO	Rb	Sr	Zr	Ba	U
Granitic Inclusions																	
85 -15b	Burnt Lava		7.1q		-	0.70378	-	Mh	27	73.42	1.82	0.34	108	103	241	685	4.75
85 -17	Chimney Crater		7.0q		-	0.70419	-	Mh	44	72.83	2.12	0.84					
85 -25	Medicine Dacite		9.8q	y	s	0.70471	bio	W	37	73.89	1.53	0.45	187	145	178	828	6.60
85 -26b	Burnt Lava				-	0.70382	-	Mh	43	74.99	1.87	0.72					
85 -32	Chimney Crater				m	0.70376	none	Mh	45	73.39	1.98	0.82	120	134	202	701	
86 -3	Medicine Dacite	7.8			u	0.70481	bio	W	34	72.58	1.88	0.49	139	177	158	850	3.06
86-1a	High Hole Crater		7.7q	y	m	0.70384	none	Mh		76.01	0.28	0.00	109	19	99	124	
421 M	andesite host				u		none	DA	22	74.62	1.51	0.22	111	51	205	551	4.88
561 M	Lake basalt		9.3q		s	0.70429	opx	o	39	71.03	2.38	0.77	92	234	182	887	3.76
661 M-f	L Glass Mtn				s	0.70404	opx	W	30	71.40	2.35	0.52	126	136	290	833	5.25
663 M-c	L Glass Mtn	8.2	9.7q	y	u	0.70483	bio>opx	W	36	73.63	1.46	0.42	149	157	161	727	5.90
680 M	Medicine dacite		8.8q		u	0.70472	bio (alt)	W	35	74.21	1.51	0.41	134	148	189	776	4.90
708 M	Paint Pot		7.1q		m	0.703812	none	Mh	32	74.25	1.60	0.38	63	170	150	1106	1.46
716 M-b	Burnt Lava		6.5q		-	0.70367	-	Mh	37	78.18	0.38	0.11	103	40	63	70	9.12
993 M-d	East Sand Butte				m		opx	o	41	70.82	2.58	0.90	108	239	195	826	3.95
997 M-c	Andesite Tuff	0.5			u		none	DA	17	71.99	2.09	0.22	81	167	315	1049	4.53
997 M-d	Andesite Tuff	2.2			u		none	DA	23	63.10	5.81	0.97	26	308	266	660	1.31
997 M-f	Andesite Tuff	0.5			u		none	DA	28	67.74	4.28	0.83	73	249	340	625	2.95
1025 M-a	Crater Glass	8.4	9.0q		u	0.704935	bio>opx	W	39	74.23	1.60	0.52	132	160	181	869	4.54
1045 M-a	Glass Mt. 7	5.1			u	0.703472	opx+bio	G	71	50.00	8.09	10.86	43	355	88	166	0.54
1049 M-a	L. Glass Mtn		9.9q		s		bio=opx	W	42	74.11	1.45	0.53	121	172	140	723	4.69
1128 M-a	andesite host				u		none	DA	14	74.64	1.56	0.13	104	67	199	593	4.20
1140 M-h	Glass Mtn s.		5.8q		s	0.70382	bio	G	26	75.43	1.50	0.26	123	103	183	861	4.10
1157 M-a	Burnt Lava		6.4q		-	0.70368	-	Mh	37	76.41	1.42	0.42	91	147	136	1259	4.24
1525 M	Medicine Dacite	8.0	8.9q	y	s	0.70476	bio	W	38	73.56	1.62	0.50	130	176	164	807	4.81
1543 M	Glass Mtn. 8		6.9q		m	0.70412	none	G	25	76.92	0.83	0.14	155	41	144	661	5.49
1626M	Paint Pot Crater				m		ox	Mh	9	65.57	3.79	0.19	48	31	587	216	
1690M	Glass Mtn S	3.0	5.1q		u	0.70378	bio	G	42	71.15	2.02	0.72	94	333	185	814	1.29
1735M	L Glass Mtn				s		bio>opx	W	30	73.25	1.78	0.42	151	189	171	771	5.47
1739M	Crater Glass		9.7q		s	0.70481	bio=opx	W	31	73.44	1.83	0.45	152	184	173	909	4.71
1740M	L Glass Mtn		9.6q		s	0.70480	bio>>opx	W	29	73.43	1.89	0.43	137	189	179	825	4.52
2028M	Medicine Dacite	5.9		y	u	0.70480	bio	W	31	73.71	1.74	0.43	141	153	168	750	4.26
2029M	L Glass Mtn	8.9			s	0.70481	bio=opx	W	30	73.75	1.74	0.42	123	169	149	803	5.55
2048M	Crater Glass	5.8			s	0.70349	opx	W	54	68.59	3.31	2.22	82	139	194	581	4.33
2049M	Crater Glass	8.3			s	0.70484	bio>opx	W	33	72.96	1.73	0.48	143	169	191	805	3.76
2050M	Crater Glass	6.0			s	0.70367	opx=ox	W	38	64.87	4.25	1.46	65	335	430	814	1.63
Samples from drillholes																	
31-17a	granite	-1.5			u	0.70369	chlorite		37	63.94	5.12	1.70					
31-17b	basalt	-4.7			u	0.70374	chlorite		53	50.26	9.00	5.74	84	568	85	308	0.49
17A6 8210	drillhole 8210'	-0.8			u	0.70423	chlorite		34	73.13	1.72	0.51	111	241	156	837	3.26
17A6 9620	drillhole 9620'	-3.3		y	u	0.70415	chlorite		34	72.67	1.60	0.46	94	238	153	892	3.37
Host rhyolites																	
1406 M	Glass Mtn.	7.0				0.70417		G	26	74.60	1.58	0.30	142	111	217	828	6.05
35 M	Little Glass Mtn.		6.6p			0.704114		W	28	73.70	1.73	0.38	150	118	223	858	6.15
45 M	Medicine dacite	7.8	8.5p			0.70430		W	47	68.50	3.17	1.55	110	270	183	747	4.31
404 M	Glass Mtn.	7.5				0.704162		G	27	73.80	1.70	0.35	154	115	230	865	5.69

$\delta^{18}O$. Oxygen isotopic composition (per mil) of whole rocks (WR) and mineral separates (q= quartz, f=feldspar). Analyses by L. Adami and P. Larson. Analyses relative to VSMOW.
G. Presence of granophyre (y=yes)
M. Amount of melting (u= unmelted, s = sintered crystal edges, m = >10% melted).
$^{87}Sr/^{86}Sr$. Sr isotopic ratio of whole rock. Analyses by M. Lanphere, J. Wooden and T. Bullen.
Mafics. Most abundant mafic mineral.
Host. Sample code for magma type in which inclusion was found (Mh = Holocene mafic unit, W=Western Holocene rhyolites such as Medicine Dacite, Crater Glass and Little Glass Mtn flows).
Mg# = 100 X molar Mg/(Mg+Fe)
SiO_2, FeO and MgO in wt. %.
Rb, Sr, Zr, Ba and U in ppm by weight.

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CONCLUSIONS

1. Granite inclusions are found in Holocene units and some earlier volcanic rocks. They can be melted, sintered or unmelted. Most are equigranular and contain two feldspars, quartz and opx and/or biotite.

2. Two primary groups of granite inclusions can be discriminated on a $\delta^{18}O$ vs. $^{87}Sr/^{86}Sr$ plot. The first group is low in both constituents. The other is high in both. Neither is hydrothermally altered. Neither group is the same as the Holocene rhyolitic hosts, demonstrating that the inclusions are not subvolcanic equivalents of Holocene rhyolites.

3. As shown in the Rb vs. Mg# diagram as well as many others, Holocene rhyolites are distinct from earlier rhyolites. They also are uniformly higher in $\delta^{18}O$ (7.4 vs. 5.6 ‰: Donnelly-Nolan, in press; *Bulletin of Volcanology*). Granite inclusions plot over a wider area than either group and likely have diverse origins.

4. Rocks from geothermal drillholes, down to 3,000 m. depth are hydrothermally altered and have $\delta^{18}O$ ranging from -5 to -1 ‰. Similar granitic rocks are found as lithics in some Pleistocene volcanic units. Because altered granites are not found as clasts in the Holocene units, recent rhyolitic magmas must have staged below 3 km. and did not interact with shallow granites on their way to the surface.

5. Fluid inclusions in the granites are primary, vapor-rich, and have densities of ~0.1 g/cc. Such low-density inclusions require low-pressure formation--- less than the >3000 m depths from which they likely came. Most likely, these shallow granites pre-date growth of the Medicine Lake volcano edifice and have subsequently been buried.