Petrology of Latite Ridge Latite in the East Tintic Volcanic Field, Utah in U.S.A.

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ABSTRACT : The Latite Ridge Latite in the East Tintic volcanic field, Utah in USA occurs as a welded ash-flow tuff, has 63.7-66 wt% SiO_2 on an anhydrous basis, and shows calc-alkaline affinities. The rocks fall in the trachyte field of IUGS classification. It is characterized by unusally high K_2O content (5.9-7.6 wt%), relatively high equilibration temperature (950-973°C), and biotites with high TiO_2 content (7.4-8.2 wt%). Various differentiation processes were tested using the XLFRAC program to infer the origin of the Latite Ridge Latite. The result suggests that crystal fractionation from shoshonite is one possible process to generate the Latite Ridge Latite. Shoshonite of the East Tintic volcanic field was possibly formed by crystal fractionation from a subduction-related K-, Mg-rich mafic magma.

Key words : Latite Ridge Latite, East Tintic volcanic field, crystal fractionation, shoshonite.

INTRODUCTION

The East Tintic volcanic field is located in the East Tintic Mountains of central Utah, which is near the eastern margin of the Great Basin of the western United States. The East Tintic Mountains are an uplifted, north-trending fault-block range of Proterozoic and Paleozoic sedimentary rocks and Tertiary igneous rocks. The folded and faulted Paleozoic sedimentary rocks (mostly carbonate rocks) are covered by a thick volcanic sequence which were produced by early to middle Oligocene magmatism (Morris and Lovering, 1979). The volcanic field consists of intermediate to silicic volcanic and shallow intrusive rocks produced by composite volcanoes and small calderas (Hannah *et al.*, 1991; Keith *et al.*, 1991; Kim, 1992; Moore, 1993). Moore (1993) suggested that at least 100 km³ of magma were erupted during the life span (35-32 Ma) of the volcanic field. Volcanic rocks range in composition from shoshonite to trachyte, with latitic lavas representing the dominant ones.

The result of mapping, combined with previous work (Morris and Lovering, 1979; Kim, 1988) and radiometric age determinations (Keith *et al.*, 1989, 1991) yielded a revised volcanic sequence for the central part of the East Tintic volcanic field (Table 1). Volcanic rocks in the area consist of eight different eruptive units, and they generally occur as thick flows, ash-flow tuffs, and small amounts of flow breccia, but occasionally as vent-facies rocks.

Latite Ridge Latite (LRL), named by Morris and Lovering (1979) after the Latite Ridge in the central part of the East Tintic Mountains, is a distinctive brick-red welded, crystal vitric tuff. It has an unsually high K_2O content compared to the high-K salic eruptives of western USA (Ewart, 1979) and to the associated igneous rocks in the East Tintic volcanic field (kim, 1992). It is also characterized by relatively high equilibration temperature and biotites with high TiO_2 content.

In this paper, various differentiation processes will be discussed to infer the origin of the strongly potassic Latite Ridge Latite. And it will be shown that crystal fractionation from shoshonite is one possible process to generate

Table 1. Volcanic stratigraphy of the central part of the East Tintic volcanic field

Geologic age	Volcanic Units	
Quaternary	Alluvium	
Oligocene	Latite of Rock Canyon	Laguna Springs Volcanic Group
		Big Canyon Latite
	Latite Ridge Latite	
	Andesite of Dry Herd Canyon	
	Latite of Sunrise Peak	Packard Quartz Latite
	Copperopolis Latite	
Paleozoic	Sedimentary rocks	

the Latite Ridge Latite.

PETROGRAPHY

The LRL occurs as a welded ash flow tuff along Latite Ridge and south, and in the north of Silver Pass, overlying either Latite of Sunrise Peak, Packard Quartz Latite, or Andesite of Dry Herd Canyon (Fig. 1).

The LRL welded tuff is readily recognized in the field because of its characteristic brownish red color and eutaxitic texture; however, the tuff is argillized and/or silicified over wide areas. Where strongly argillized, the tuff is generally pale pinkish brown to white and little or

Fig. 1. Index map and simplified geologic map of the central East Tintic Mountains, Utah. S.P.: Silver Pass, L.R.: Latite Ridge, 1: Quarternary alluvium, 2: Silver City Stock Monzonite, 3: Monzonite Porphyry Plugs and Dikes, 4: Latite of Rock Canyon, 5: Latite Ridge Latite, 6: Andesite of Dry Herd Canyon, 7: Latite of Sunrise Peak, 8: Packard Quartz Latite, 9: Paleozoic sedimentary rocks

no relict texture remains. A thin basal vitrophyre is present in some places around the base of the welded tuff. The vitrophyre horizon is underlain by thin sediments.

The welded tuff probably consists of several different cooling units which are represented by different crystal contents. However, the lack of consistent lateral continuity makes it impossible to map separate cooling units. A mixed lithology is found in several places above the welded tuff and occurs as tuff breccia which contains large blocks of crystal-rich tuff, crystal-poor tuff, and dark scoriaceous material in a matrix of welded tuff. This mixture of heterogeneous lithology suggests mixing of crystal-rich magma and crystal-poor magma during eruption. The mixed unit is particularly well exposed at the top of Silver Pass and nearby area along the Silver Pass Road. The mixed unit exposed at Silver Pass may mark the end product of LRL eruption.

The basal vitrophyre of the LRL welded tuff is composed of 81-92% pale brown glassy matrix, 2-6% lithic fragments, and 6-14% phenocrysts. Phenocrysts include plagioclase, biotite, clinopyroxene, and Fe-Ti oxides in decreasing order (Table 2). Most phenocrysts are broken or resorbed, but they are fresh and unaltered. Plagioclase is up to 3 mm in length, but most are 2 mm or smaller. Plagioclase constitutes 58-76% of phenocrysts. Many of the plagioclase phenocrysts show oscillatory zoning. Biotite is up to 5 mm in length and constitutes 15-19% of phenocrysts. They are commonly resorbed and some of them have deeply embayed out-
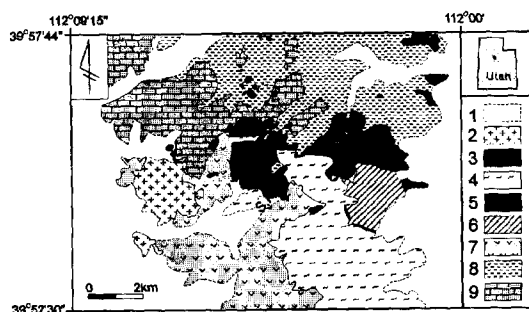
Table 2. Point-counting modal analyses of Latite Ridge Latite

	ET198A vtr	ET198B vtr	TJ198B vtr	ET153 tuff
plagioclase	10.2	3.6	8.2	2.9
biotite	2.3	1.2	1.7	1.2
clinopyroxene	0.5	0.5	0.4	
opaque	0.5	0.7	0.9	0.5
lithic fragment	5.2	2.2	6.1	5
groundmass	81.3	91.6	82.8	90.5
no. of points	1944	2336	2264	1959

vtr=vitrophyre

lines. Clinopyroxene constitutes only about 0.5% of the vitrophyre and is absent in some samples. The clinopyroxene grains in a crystal-poor vitrophyre are generally smaller than 0.5 mm in size. Fe-Ti oxides constitutes 0.5-0.9% of phenocrysts. Lithic fragments consist of at least four different lithologies, and are on the average 5 to 6 mm in diameter, but range up to 20 mm. The groundmass of the vitrophyre is composed of weakly to moderately welded glass shards, and pumice and scoria fragments. Pumice fragments are unflattened or moderately flattened, and some of them are devitrified.

Perlitic textures are shown in some samples. The basal vitrophyre can be divided into two lithologies on the basis of crystal contents, i.e. crystal-rich (about 14% phenocrysts) and crystal-poor (about 6% phenocrysts) vitrophyre. The crystal-rich vitrophyre has generally larger phenocrysts and lithic fragments than the crystal-poor vitrophyre.

The welded ash-flow tuff of the LRL consists of welded glassy matrix, lithic fragments, and phenocrysts. Phenocrysts are fragmental and composed dominantly of plagioclase and biotite with minor amounts of sanidine and Fe-

Table 3. Whole-rock composition of Latite Ridge Latite and shoshonite of Buckhorn Mt.

	LRL ET198A	LRL ET198B	LRL TJ198B	LRL ET153	LRL ET182	LRL TD26	shosh TJ18	shosh TJ83	shosh TD38	shosh TD41
SiO_2	63.86	65.71	63.75	65.96	65.92	63.65	54.27	56.41	54.06	54.65
TiO_2	0.87	0.68	0.85	0.69	0.68	0.84	1.16	1.16	1.23	1.20
Al_2O_3	16.72	17.10	17.15	16.97	16.28	17.30	17.72	16.30	17.10	17.83
Fe_2O_3	4.39	3.55	4.76	4.09	4.37	4.57	8.47	8.14	8.90	8.43
MnO	0.26	0.09	0.11	0.05	0.03	0.06	0.14	0.12	0.15	0.15
MgO	1.08	0.75	1.24	0.90	0.72	0.80	2.57	3.32	3.76	3.12
CaO	2.74	1.88	2.88	1.42	1.12	2.42	7.70	5.86	6.85	7.41
Na_2O	3.05	2.63	3.04	3.08	3.09	3.69	3.46	3.47	2.93	2.25
K_2O	6.76	7.40	5.93	6.64	7.57	6.41	3.93	4.68	4.39	4.34
P_2O_5	0.28	0.21	0.29	0.19	0.22	0.26	0.57	0.54	0.63	0.63
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
normative minerals										
Q	11.06	15.59	13.53	16.46	13.70	9.55				
Or	39.98	43.77	35.08	39.44	44.78	37.91				
Ab	25.77	22.23	25.69	26.14	26.12	31.19				
An	11.90	8.10	12.59	5.96	4.27	10.49				
C	0.00	1.77	1.09	2.53	1.42	0.43				
Hy	8.02	6.02	8.74	7.44	6.99	7.27				
Mt	0.96	0.77	1.03	0.31	0.96	1.00				
Il	1.65	1.29	1.62	1.32	1.29	1.60				
Ap	0.61	0.46	0.63	0.42	0.48	0.57				
trace elements (in ppm)										
Nb	30	26	24	22	21	24	13	13		
Zr	466	506	454	472	465	506	236	281		
Y	35	37	36	36	36	38	28	28		
Sr	634	337	542	314	192	463	964	781		
Rb	294	357	270	282	314	240	103	159		
Ba	1555	1309	1450	1286	1400	1420	1456	1416		
U		11					11	5	7	
Th		45					48	19	25	
Cu							11	73		
Ni							4	11		
Cr		7							17	
La		92.60				75.00	50.00	62.40		
Ce		162.00				157.00	100.00	118.00		
Nd		64.00				49.00	35.00	50.00		
Sm		10.50				5.00	4.00	8.80		
Eu		2.58						2.30		
Tb		1.50						0.90		
Yb		3.09						2.10		
Lu		0.42						0.30		

shosh=shoshonite

Ti oxides (Table 2). Only a few remnants of clinopyroxene grains are found in one sample. In unaltered rocks, plagioclase commonly exhibits an oscillatory zoning. Plagioclase is wholly or partly altered to aggregates of quartz, calcite, or sericite in many rocks. Biotite phenocrysts are oxidized. Lithic fragments are up to 15 mm in diameter and consist of lava flows with felty texture, a lava flow similar to the Latite of Sunrise Peak, shoshonite, and quartzites. The glassy matrix is composed of welded glass shards and pumice fragments and is devitrified to some degree.

WHOLE-ROCK CHEMISTRY

Unaltered, fresh samples of LRL were analysed for whole-rock major and selected trace elements using a Philips X-ray fluorescence spectrometer at Brigham Young University. The method of Norrish and Hutton (1969) was employed for matrix corrections. The precision and accuracy of the method has been determined by multiple analyses of international standards and is approximately ±1% for major elements except Na and P and ±5% for Na, P, and trace elements. Rare earth elements were analyzed for one sample by INAA at the XRAL Activation Services Inc., Michigan. For purposes of plotting and modelling, all samples have been normalized to 100% on an anhydrous basis (Table 3). The position of bulk compositions on the A-F-M diagram and the presence of normative quartz and hypersthene indicate that LRL is calc-alkaline.

The LRL has 63.7-66 wt% SiO_2 on an anhydrous basis and falls in the trachyte field of TAS (Toral alkali-silica) diagram of Le Bas et al. (1986) (Fig. 2). Compared to the average composition of high-K salic volcanic rocks (with 63-66 wt% SiO_2) of the eastern zone of western USA (Ewart, 1979), the LRL is significantly richer in K_2O, Rb, Nb, Y, Zr, and lower in Sr, but is similar in Ba content (Fig. 3). The K_2O content of LRL ranges from 5.9 to 7.6 wt%, whereas the average K_2O content of high-K sal-
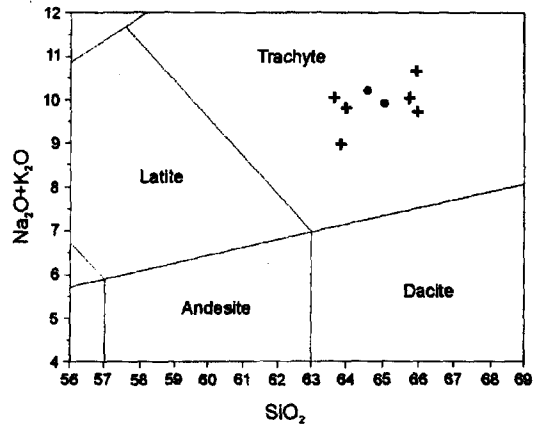

Fig. 2. Total alkali-silica (TAS) diagram of Le Bas et al. (1986) for the Latite Ridge Latite. The data of two samples marked by solid circles are from Morris and Lovering (1979).
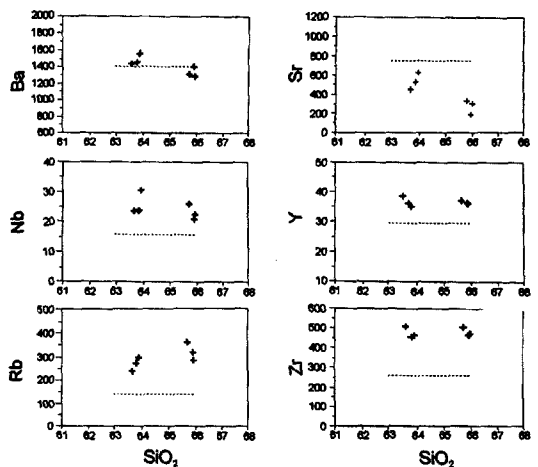

Fig. 3. Harker variation diagrams for the selected trace elements of the Latite Ridge Latite. The dotted line represents the average composition of high-K salic volcanic rocks (with 63-66 wt% SiO_2) of the eastern zone of western USA (Ewart, 1979).

ic eruptives is 3.92 wt%. The K_2O/Na_2O ratio of LRL ranges from 1.7 to 2.8 (2.1 in average), which is considerably higher than the average (less than 1) of intermediate calc-alkaline volcanic rocks. The LRL characteristically has normative corundum ranging from 0.1 to 2.5 wt%.

MINERAL CHEMISTRY

Mineral compositions were determined by

wavelength dispersive electron microprobe analyses using the JEOL JXA-8600 Superprobe at the University of Georgia. All analyses were done at an accelerating potential of 15 KeV and a sample current of 15 nA. The beam width was 1 or 5 microns, depending on the mineral phases analysed. Counting times were 40 seconds for standards and 20 seconds for unknowns. Data were reduced on-line using the correction procedure of Bence and Albee (1968). The accuracy of analyses were checked by comparision with in-house standards.

Plagioclase is the dominant phenocryst phase in LRL, and its composition is andesine. The phenocrysts are normally zoned. The core compositions of plagioclase phenocrysts are An_{40-49} and the rim compositions are An_{34-40} (Table 4). Plagioclase has a high Sr content (0.51-0.54 wt% SrO).

Titanomagnetites occur as microphenocrysts and inclusions in other phenocrysts. Micro-phenocrystic magnetites commonly exhibit oxidation to maghemite around cracks and rim of grains, or they have ilmenite lamellae as oxidation/exsolution products. Unoxidized grains are generally found as inclusions in plagioclase

phenocrysts. Only unoxidized grains without exolution lamellae were analyzed. Titanomagnetite compositions of LRL are Usp_{45-47} (Table 4). Titanomagnetite core compositions within the rock unit vary by less than 5 mole% Usp.

Ilmenite is much less abundant and smaller than the titanomagnetite. Ilmenite is most commonly found as inclusions in the biotite phenocrysts. Ilmenite compositions of LRL is Ilm_{84}. Mn contents of ilmenite is less than 1% MnO.

The composition of clinopyroxene phenocrysts in LRL is augite ($Wo_{42}En_{41}Fs_{17}$) (Table 4). Individual clinopyroxene phenocrysts are very weakly zoned or unzoned. The Mg# of clinopyroxenes is 70-73.

Biotite of LRL has unusually high TiO_2 content ranging from 7.42 to 8.23 wt%, and averaging in 7.82 wt% (Table 4). The X_{Mg}, X_{sid}, and X_{ann} of biotite is 0.51, 0.23, and 0.26, each. Biotite is homogeneous in each grain and zoning is very weak or nonexistent.

TEMPERATURE AND OXYGEN FUGACITY

Oxide analyses were recalculated by the

Table 4. Representative analyses of minerals in the Latite Ridge Latite

	Pl (ET198A)		Pl (ET198B)		Mt	Ilm	Cpx	Biot TJ199B	Biot ET198B
	core	rim	core	rim					
SiO_2	55.43	57.90	56.73	57.98	0.17	0.11	51.38	35.94	35.54
TiO_2					14.95	45.68	0.45	7.90	7.73
Al_2O_3	26.93	25.49	26.08	25.11	3.87	0.16	1.53	14.01	14.09
FeO	0.37	0.39	0.41	0.40	40.88	33.35	10.65	15.08	14.90
Fe_2O_3					35.10	14.89			
MnO					0.72	0.96	0.71	0.18	0.16
MgO	0.04	0.03	0.04	0.05	1.94	3.46	14.15	13.21	13.12
CaO	9.42	7.57	8.58	7.34	0.46	0.55	20.41	0.02	0.01
BaO	0.23	0.23	0.18	0.24				1.57	1.80
Na_2O	5.50	6.26	5.96	6.22			0.32	0.63	0.62
K_2O	0.98	1.52	1.28	1.67				8.13	8.04
NiO					0.02	0.00			
SrO	0.54	0.46	0.51	0.46					
Cr_2O_3					0.00	0.05	0.03		
ZnO					0.16	0.02			
Cl								0.03	0.02
F								1.13	1.15
Total	99.45	99.84	99.76	99.47	98.27	99.23	99.64	97.83	97.21
mole%	An=45.86	An=36.6	An=41.1	An=35.7	Usp=47.1	Ilm=84.7	Fs=17.2		
mole%	Ab=48.50	Ab=54.7	Ab=51.6	Ab=54.7			En=40.7		
mole%	Or=5.70	Or=8.7	Or=7.3	Or=9.6			Wo=42.2		

For magnetite and ilmenite, ferric iron and mole fraction of ulvospinel (usp) and ilmenite (ilm) components are calculated according to the method of Stormer (1983)

method of Stormer (1983) to obtain the mole fraction of ulvospinel and ilmenite components. Temperatures were obtained using the Fe-Ti oxide geothermometer of Andersen and Lindsley (1988) at 1 atm. Magnetite-ilmenite pairs most proximal to each other have been used to yield a range of estimated temperature. An equilibrium was tested for the oxide pairs with Mg/Mn partitioning relations between coexisting Fe-Ti oxides (Bacon and Hirschmann, 1988). All temperatures obtained are within the T-f_{O_2} limit of the applicability of the geothermometer. The temperature of LRL obtained from the compositions of coexisting Fe-Ti oxides is 950-973℃ (Fig. 4), and it appears to be too high, compared to its mineral constitutents which are mainly plagioclase and biotite. Previous studies (Luth, 1967; Naney, 1977) have shown that biotite is limited in stability to below about 850℃ in the presence of quartz, or slightly higher in the presence of high silica activity in the magma. However, this seemingly high temperature of LRL compared to its mineral constitutents can be explained by the high Ti content of the biotite. The experimental data of Patino-Douce (1993) show that the crystallization temperature of biotite is propotional to its Ti content, that is, the equilibrium
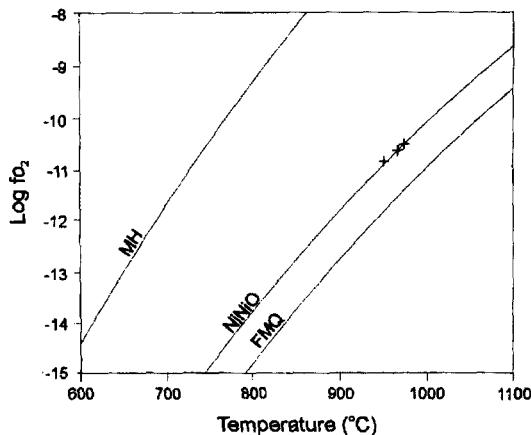
temperature increases with higher Ti content in biotite. Biotite of LRL has unusally high TiO_2 content (7.9 wt% in average, Table 4) and this high TiO_2 content made it possible for LRL biotite to exist at the high equilibration temperature of LRL (950-973℃) which is far above the thermal stability limit of common biotite (Patino-Douce, 1993). Luhr et al. (1984) formulated a biotite geothermometer based on the coupled exchange of Ti and Fe^{+2} in biotites from silicic volcanic rocks where temperatures are known from Fe-Ti oxides. The expression of this geothermometer is: $T(°K)=838/(1.0337-Ti/Fe^{+2})$. The average composition of LRL biotite (TJ199B, Table 4), assuming no Fe^{+3} in biotite, gives a temperature of 1216℃, according to this geothermometer. This unreasonably high temperature may be related to a Ti content which is well beyond the limit of the applicability of the geothermometer. If Fe^{+3} content in biotite is considered in the calculation, which could be up to 20% of the total Fe, the temperature obtained from the geothermometer will be even higher.

Oxygen fugacity is estimated from the compositions of coexisting Fe-Ti oxides by the oxybarometer of Andersen and Lindsley (1988). The LRL yields oxygen fugacities about 0.9 log units above that of FMQ buffer (Fig. 4). Calc-alkalic rocks generally crystallize at oxygen fugacities about 1 to 2 log units above that of the FMQ buffer (Frost and Lindsley, 1991).

PETROGENESIS OF LATITE RIDGE LATITE

Crystal Fractionation

The XLFRAC program of Stormer and Nicholls (1978) was used to test if LRL could be produced by crystal fractionation. The major element composition of LRL was successfully modelled with crystal fractionation using the shoshonite of Buckhorn Mountain (Keith et al., 1991; Moore, 1993) as a parent rock. The shoshonite of Buckhorn Mountain (Table 3) is

Fig. 4. Temperature and oxygen fugacity conditions of Latite Ridge Latite calculated from the coexisting Fe-Ti oxides. MH=Magnetite-Hematite, FMQ= Fayalite-Magnetite-Quartz, NiNiO= Ni-NiO

the most mafic volcanic rock in the East Tintic Mountains and is not obviously associated with LRL according to field relations. Shoshonite crops out in the vicinity of Buckhorn Mountain about 6.5 Km due south of Silver Pass. Shoshonite is composed of phenocrysts of plagioclase, clinopyroxene, and olivine in the holocrystalline groundmass of plagioclase and possibly sanidine (Keith, *et al.*, 1989). For modelling, mineral phases were selected from the parent rock (shoshonite) based on the observed phenocryst assemblages. The compositions of plagioclase and clinopyroxene were obtained from a relatively fresh sample (TJ-94) of shoshonite collected 0.75 km south of Buckhorn Mountain. No olivine compositions from this unit are yet available, so olivine composition of Fo80 was assumed. Whole-rock compositions of three samples of shoshonite with slightly different compositions were tested as a parent rock for crystal fractionation, and all of them reproduced LRL composition satisfactorily with the sum of squares of residulals (SSR) less than 1.

Table 5 shows the result of least-squares calculation which used the most mafic sample (TD-38) of shoshonites as a parent and the most felsic sample (ET-198B) of LRL vitrophyre as a daughter rock. The major element model involves removal of 48 wt% crystals, which include about 28 wt% plagioclase, 7 wt% clinopyroxene, 5 wt% olivine, 6 wt% magnetite, and 2 wt% apatite. The SSR of the calculation is 0.35 (Table 5). The mineral proportions resulting from the the least-squares calculation are in good agreement with the observed proportion of phenocrysts. The large residual of Na_2O possibly reflects the high mobility of this alkali during post-solidification process or a slightly inaccurate determination of the composition of fractionated plagioclase phenocryst. To check preferred Na_2O/K_2O ratio of this fractionation path, end-member anorthite (An) and albite (Ab) were used instead of the actual shoshonite plagioclase composition (An_{57}). The calculation with An and Ab yielded the same result as the previous one, with a little higher

Table 5. Major element crystal fractionation modelling for the Latite Ridge Latite using XLFRAC program (Stormer and Nicholls, 1978)

	initial TD-38	final ET-198B	observed difference	calculated difference	obs - calc (=residual)	phase	wt% removed
(1) using shoshonite plagioclase composition (An 57)							
SiO_2	54.54	65.94	11.4	11.24	0.2	Ol (Fo 80)	5.22
TiO_2	1.24	0.68	-0.56	-0.72	0.16		
Al_2O_3	17.25	17.16	-0.09	-0.16	0.07	Cpx (En 43)	7.3
FeO	8.09	3.21	-4.88	-4.95	0.07		
MnO	0.15	0.09	-0.06	-0.05	-0.01	Pl (An 57)	27.55
MgO	3.79	0.75	-3.04	-3.06	0.02		
CaO	6.91	1.89	-5.02	-4.98	-0.04	Mt (Usp 48)	6.09
Na_2O	2.96	2.64	-0.32	-0.02	-0.3		
K_2O	4.43	7.43	3	3.37	-0.38	Ap	1.8
P_2O_5	0.64	0.21	-0.42	-0.67	0.25	total	47.97
sum of the squares of the residuals (SSR)=0.35							
(2) using An and Ab instead of actual plagioclase composition (An 57)							
SiO_2			11.4	11.21	0.19	Ol (Fo 80)	5.29
TiO_2			-0.56	-0.76	0.2		
Al_2O_3			-0.09	-0.17	0.07	Cpx (En 43)	7.02
FeO			-4.88	-4.96	0.08		
MnO			-0.06	-0.05	-0.01	An	16.16
MgO			-3.04	-3.07	0.03	Ab	9.5
CaO			-5.02	-4.98	-0.05		
Na_2O			-0.32	0.06	-0.38	Mt (Usp 48)	6.25
K_2O			3	3.43	-0.43	Ap	1.91
P_2O_5			-0.42	-0.72	0.29	Total	46.13
sum of the squares of the residuals (SSR)=0.51							

Cpx and Pl composition from TJ-94, Mt composition from TJ181, and Ap composition from Deer *et al.* (1966).

SSR (0.5) (Table 5). The amount of An and Ab removed is 16.16 wt% and 9.5 wt%, each, and thus the ratio of An/(An+Ab) is 0.63, which is very close to the plagioclase composition (An_{57}) of the shoshonite. The average composition of shoshonite and LRL plagioclase were also used in calculation instead of the shoshonite plagioclase composition; the calculation yielded the satisfactory results with 51 wt% crystals removed.

The variation of chondrite-normallized REE patterns and of Cr and Sr abundances between the shoshonite of Buckhorn Mountain and LRL also supports the idea that LRL was evolved from the shoshonite by crystal fractionation. The REE patterns are subparallel, and normallized abundances increase from the shoshonite to LRL (Fig. 5). This is to be expected, as the REE are incompatible with respect to the major phases crystallizing (olivine, clinopyroxene, plagioclase, and magnetite) and therefore become increasingly concentrated in the more evolved liquid. The negative Eu anomaly in LRL (Fig. 5) and the decrease in Sr content from shoshonite to LRL (Table 3) is consistent with fractionation of significant amounts of plagioclase. The fall in Cr content from shoshonite (17 ppm) to LRL (7 ppm) supports the fractionation of clinopyroxene.
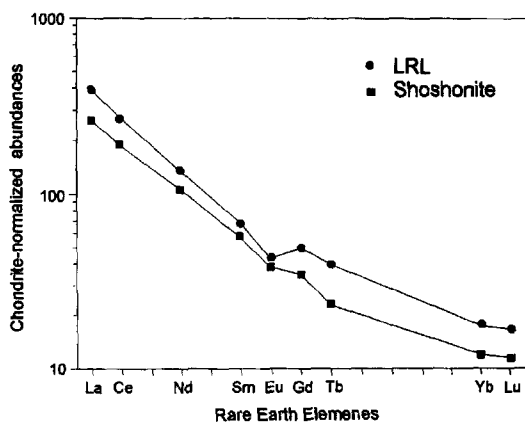

Fig. 5. Chondrite-normalized (Sun and McDonough, 1989) rare earth element patterns of the shoshonite of Buckhorn Mountain (TJ83) and the Latite Ridge Latite (ET198b).

Crystal fractionation tests using other parents (than the shoshonite) show that LRL composition cannot be produced by crystal fractionation process from other parents. These parents either have too low K_2O content to produce the K_2O content of the LRL or have lower magmatic temperatures than LRL.

Mixing of Magma

There is no evidence that LRL could have formed by mixing of any observed compositions in the East Tintic volcanic field. In the field, LRL is very homogeneous in composition, regardless of its occurrence as basal vitrophyre, welded tuff, or tuff breccia. The only heterogeneity observed in LRL is different crystal content between different cooling units. Petrographically, LRL shows no disequilibrium features suggestive of magma mixing in texture and mineralogy. Plagioclase phenocrysts show strong oscillatory zoning, but the composition ranges are relatively narrow (An_{40-49} in the core and An_{34-40} in the rim) and plagioclase compositions typical of basaltic or rhyolitic lavas are absent. In terms of magma chemistry, mixing is a linear process and a hybrid magma should thus be a linear combination of end-members. However, a linear combination of possible end-members of the East Tintic volcanic field (shoshonite as a mafic end-member and Packard Quartz Latite as a silicic end-member) cannot yield the K_2O content of LRL (Fig. 6). From the above considerations, it is unlikely that LRL formed by magma mixing.

Partial Melting

Least-squares calculations of Stormer and Nicholls (1978) were used to test if the major element composition of LRL could be produced directly by partial melting of the enriched lithospheric mantle material. For the partial melting calculation, high-K, metasomatized spinel lherzolite of Hartmann and Wedepohl (1990) was used as a mantle source material composi-
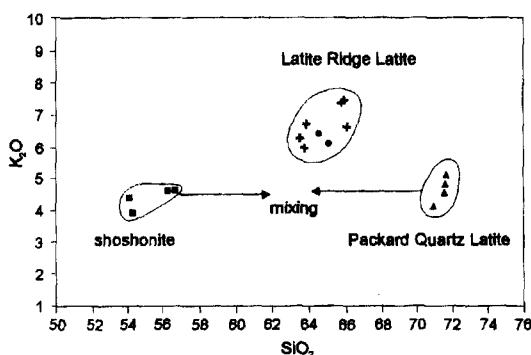
Fig. 6. A plot of K_2O vs. SiO_2 illustrating the effects of mixing between the shoshonite of Buckhorn Mountain and Packard Quartz Latite. The data of two LRL samples marked by solid circles are from Morris and Lovering (1979).

tion. Olivine and orthopyroxene were chosen as residual mineral phases and the composition of olivine and orthopyroxene of typical spinel lherzolite (data from Basaltic Volcanism Study Project, 1981) was used. The result of these calculations suggest that the major element composition of LRL cannot be derived directly by partial melting of metasomatized peridotites. The partial melting calculation resulted in either unreasonably high residual of FeO and CaO or an unreasonable melting ratio (eg. -2.3% melting). The very low Ni (<10 ppm) and Cr (7 ppm) contents and the absence of olivine in LRL also indicate that LRL is not a primary magma.

Assimilation

One likely process which could produce the enrichment in K_2O and the depletion in MgO shown by LRL is assimilation of crustal material. The presence of xenoliths in LRL might be an evidence that assimilation took place. However, most xenoliths are fragments of lava flows of intermediate composition and rare quartzite. Melting or assimilation of these rocks is not likely to produce the high-K LRL. The only other country rocks in Tintic area which might have been involved in assimilation to generate LRL are acid volcanic rocks such as Packard Quartz Latite or K-rich sediment-

ary rock.

To evaluate the plausibility of this process for the origin of LRL, a least-squares calculation (Stormer and Nicholls, 1978) was performed. The result of least-squares calculation using major elements may not reflect exactly the effect of assimilation. The calculation assumes assimilation of all the components of country rock, but in reality, not all mineral components of the country rock would be undersaturated in the magma. However, the result of this calculation at least helps in judging the approximate results of assimilation process. The composition of mica-rich minettes (WAT-12, SCO-1; Tingey et al., 1991) which occur in the Wasatch Mountain 20 miles east of East Tintic Mountain was selected as the parent magma, because the mica-rich minettes are the only rock which contain comparable amounts of zirconium (441-682 ppm) to the LRL (456-506 ppm). Packard Quartz Latite was chosen as the assimilated country rock, because it is the most felsic rock in Tintic volcanic field. The result of these calculations indicate that assimilation is not likely to produce the LRL. Considering the possible increase of Zr by concurrent fractional crystalization which would accompany assimilation, the shoshonite was also chosen as a parent magma composition. The calculation using shoshonite (Table 3) and Packard Quartz Latite (Table 6) also would not yield the composition of LRL.

Selective contamination of magma by potassium during wall-rock interaction (due to its high chemical diffusivity; Watson, 1982) might operate to enrich the LRL in K_2O, but there is no tenable way to test this hypothesis.
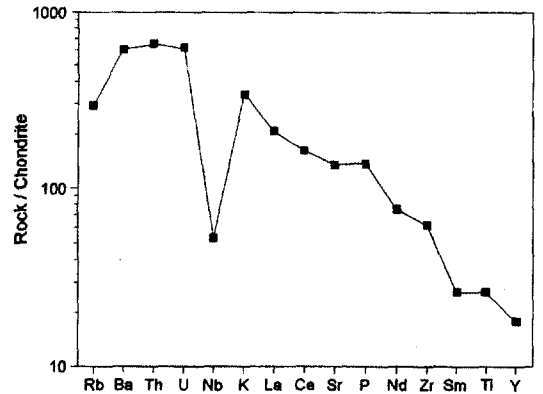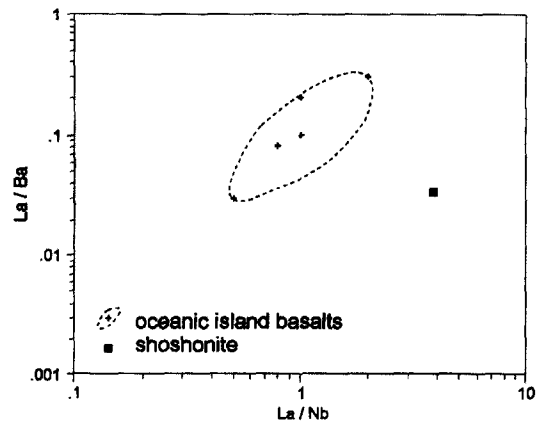
ORIGIN OF THE SHOSHONITE OF BUCKHORN MOUNTAIN

Meen (1987) studied the rocks from the Independence Volcano, Montana, a major center of the Absaroka volcanic field of Montana and Wyoming which is the type area for absarokite, shoshonite, and banakites. Based on the whole-

Table 6. Whole-rock compositions of the Packard Quartz Latite (from Morris and Lovering, 1979)

	D102203	D102204	D101864	D101871	D101872
SiO_2	67.68	70.87	69.76	69.27	69.33
TiO_2	0.38	0.38	0.36	0.34	0.35
Al_2O_3	14.73	14.36	14.75	14.52	14.99
Fe_2O_3	1.71	1.91	2.16	1.64	1.63
FeO	0.59	0.49	0.22	0.52	0.53
MnO	0.06	0.03	0.04	0.06	0.06
MgO	0.67	0.46	0.50	0.59	0.59
CaO	2.50	1.62	2.20	2.08	2.05
Na_2O	3.05	2.61	3.02	2.96	2.89
K_2O	3.98	5.95	4.50	4.67	4.79
P_2O_5	0.13	0.18	0.11	0.10	0.10
H_2O^+	3.47	0.44	0.76	2.51	2.52
H_2O	0.65	0.03	1.11	0.14	0.10
Total	99.70	99.42	99.73	99.55	99.57

Fig. 7. Chondrite-normalized (except for Rb, K, and P [Sun and McDonough, 1989]) trace element patterns for the shoshonite of Buckhorn Mountain (TJ18).

Fig. 8. La/Ba and La/Nb ratios of the shoshonite of Buckhorn Mountain (TJ18) compared to the field for ocean island basalts (Fitton et al., 1991).

rock chemistry, Sr-Nd isotopic compositions, and experimental data, he concluded that the shoshonite magma formed from high alumina basaltic andesitic magma by high-pressure (10 kbar) crystal fractionation of phenocryst phases (plagioclase, hypersthene, augite, and magnetite) and without interaction with crustal rocks. This model of shoshonite formation is not applicable to the shoshonite of Buckhorn Mountain because the high alumina basaltic andesite which acts as a parent for crystal fractionation is not found in the central East Tintic Mountains.

Major and trace element compositions of the shoshonite of Buckhorn Mountain (Table 3) suggest that the shoshonite probably formed by crystal fractionation from a Mg-, K-rich mafic magma. The shoshonite of the Buckhorn Mountain has high total alkalies (Na_2O+K_2O=7.1 wt% in avg.), high K_2O (4.5 wt% in avg.), and high P_2O_5 (0.6 wt% in avg.) compared to the basaltic andesitic rocks of the same SiO_2 content (54-56 wt%). The shoshonite is enriched in large ion lithophile elements (Rb, Sr, Ba, Th, and light REE) in accord with potassium enrichment (Fig. 7). The low Mg# (55-62), very low contents of Cr (~17 ppm) and Ni (11 ppm), and high SiO_2 (exceeding 50 wt%) of the shoshonite (Table 3) indicate that the shoshonite is not a primary magma but an evolved magma formed by fractional crystallization from a mafic magma which was probably generated by partial melting of peridotite. The negative Nb

anomaly of shoshonite on a chondrite-normalized abundance diagram (Fig. 7) and the higher La/Nb and lower La/Ba ratios of the shoshonite compared to the field for oceanic island basalts (Fig. 8) suggest that the magmatism which produced shoshonite is subduction-related (Wilson, 1989; Fitton et al., 1991). The negative Nb anomaly, which is generally considered to be a subduction zone signature (Wilson, 1989), may be caused by hydrous fluids or magmas with higher concentrations of K and LREE (as compared to less soluble Nb, Ta, and Ti) reacting with overlying mantle to produce magma or metasomatized mantle (Tingey et al., 1991).

From the above considerations, it is most likely that the shoshonite of Buckhorn Mountain formed by crystal fractionation from a subduction-related, K-, Mg-rich mafic magma.

Possible magmatic parents for the shoshonite of Buckhorn Mountain occur near the Bingham mining district (about 60 km north of the Tintic district) and in the vicinity of Salt Creek in the Southern Wasatch Mountains (30 km east of East Tintic Mountains) (Best, unpublished data; Keith, unpublished data; Moore, 1973). These parents include nepheline basalt flows and melanephelinite.

CONCLUSION

1. The Latite Ridge Latite in the East Tintic volcanic field occurs as a welded ash-flow tuff, has 63.7-66 wt% SiO_2 on an anhydrous basis, and shows calc-alkaline affinities. The rocks fall in the trachyte field of IUGS classification (Le Bas *et al.*, 1986).

2. The Latite Ridge Latite is characterized by unusally high K_2O content (up to 7.5 wt%), relatively high equilibration temperature (950-973℃), and biotites with high TiO_2 content (up to 8.23 wt%). The Latite Ridge Latite was probably generated by crystal fractionation from the shoshonite of Buckhorn Mountain or similar magma.

3. Shoshonite, which played an important role in generating the Latite Ridge Latite, was possibly formed by crystal fractionation from a subduction-related K-, Mg-rich mafic magma.

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미국 유타주 이스트틴틱 화산지대에 분포하는
Latite Ridge Latite에 대한 암석학적 연구

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요   약 : 미국 유타주의 이스트틴틱 화산지대에 분포하는 Latite Ridge Latite는 용결회류응회암으로 산출되며, 실리카 함량이 63.7-66 wt%이고, 칼크알칼리계열에 속한다. 본암은 IUGS분류에 따르면 조면암에 해당한다. Latite Ridge Latite는 비정상적으로 높은 K_2O 함량 (5.9-7.6 wt%)과 비교적 높은 평형온도(950-973℃), 그리고 TiO_2 함량이 높은 흑운모를 가지고 있는 것이 특징이다. 본암의 기원을 추정하기 위하여 XLFRAC 프로그램을 이용하여 여러 종류의 분화작용을 테스트해 보았다. 그 결과 본암은 shoshonite로부터 분별정출작용에 의하여 형성된 것으로 보인다. 이스트틴틱 화산지대의 shoshonite는 지판의 섭입과 관련되어 형성된 K와 Mg가 풍부한 염기성 마그마로부터 분별정출작용에 의하여 형성된 것으로 추정된다.

핵심어 : Latite Ridge Latite, 이스트틴틱 화산지대, 분별정출작용, shoshonite.