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Volcanoes of the McCullough Range, southern Nevada

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ABSTRACT

The McCullough Range preserves a unique record of Miocene volcanism in the western Lake Mead area of Nevada. The basal part of the volcanic section is composed of interbedded basalt and dacite of the McClanahan Spring, Cactus Hill, and McCullough Wash volcanoes (Eldorado Valley volcanic section), and the Colony volcano, which is age-equivalent to, but does not crop out within, the Eldorado Valley volcanic section (18.5–15.2 Ma). These units lie on Precambrian basement and locally on the Peach Springs Tuff (18.5 Ma). Over 400 m of andesite lava, agglomerate, and breccia of the Farmer Canyon volcanic section forms the McCullough stratovolcano. Eruptions occurring after 15.2 Ma were lower in volume and are mainly present on the flanks of the McCullough stratovolcano. These include the eruption of (1) the McCullough Pass caldera and outflow tuff (14.1 Ma), (2) Hidden Valley andesite, including 300 m of andesite lavas erupted from local centers (mainly cinder cones), (3) four Sloan volcanoes on the west flank of the McCullough stratovolcano (Mount Ian, Mount Sutor, Center Mountain, and Mount Hanna) (13.1 Ma), and (4) the Henderson dome complex on the northern flank of the McCullough stratovolcano.

The volcanic rocks in the McCullough Range are calc-alkaline and vary in composition from rhyolite to basalt. Intermediate compositions (andesite and dacite) prevail, while basalt and rhyolite are rare. The trace-element signature (low Nb, Ti, Zr, and P compared to primitive mantle) is an indication of either a magma source in the continental lithosphere or lithospheric contamination. Rhyolite and dacite probably formed by partial melting of crust, while mafic magmas (basalt and andesite) either originated by melting of lithospheric mantle or reflect asthenospheric magmas contaminated in the lithosphere.

INTRODUCTION

The McCullough Range provides a unique view of pre-extensional volcanism in the northern part of the Colorado River extensional corridor. Nearby volcanic terranes in the Eldorado and River Mountains and the Highland Range were tilted and dismembered during mid-Miocene extension (Anderson, 1971; Smith et al., 1990; Darvall, 1991; Olsen, 1996; Olsen et al., 1999; Faulds et al., 2002a), but the McCullough Range was not extensively faulted, and volcanoes remained relatively intact. The McCullough Range lies in the southern Basin and Range Province near the western border of the Colorado River extensional corridor (Fig. 1). The range extends 100 km from the city of Henderson in Las Vegas Valley in the north to the New York

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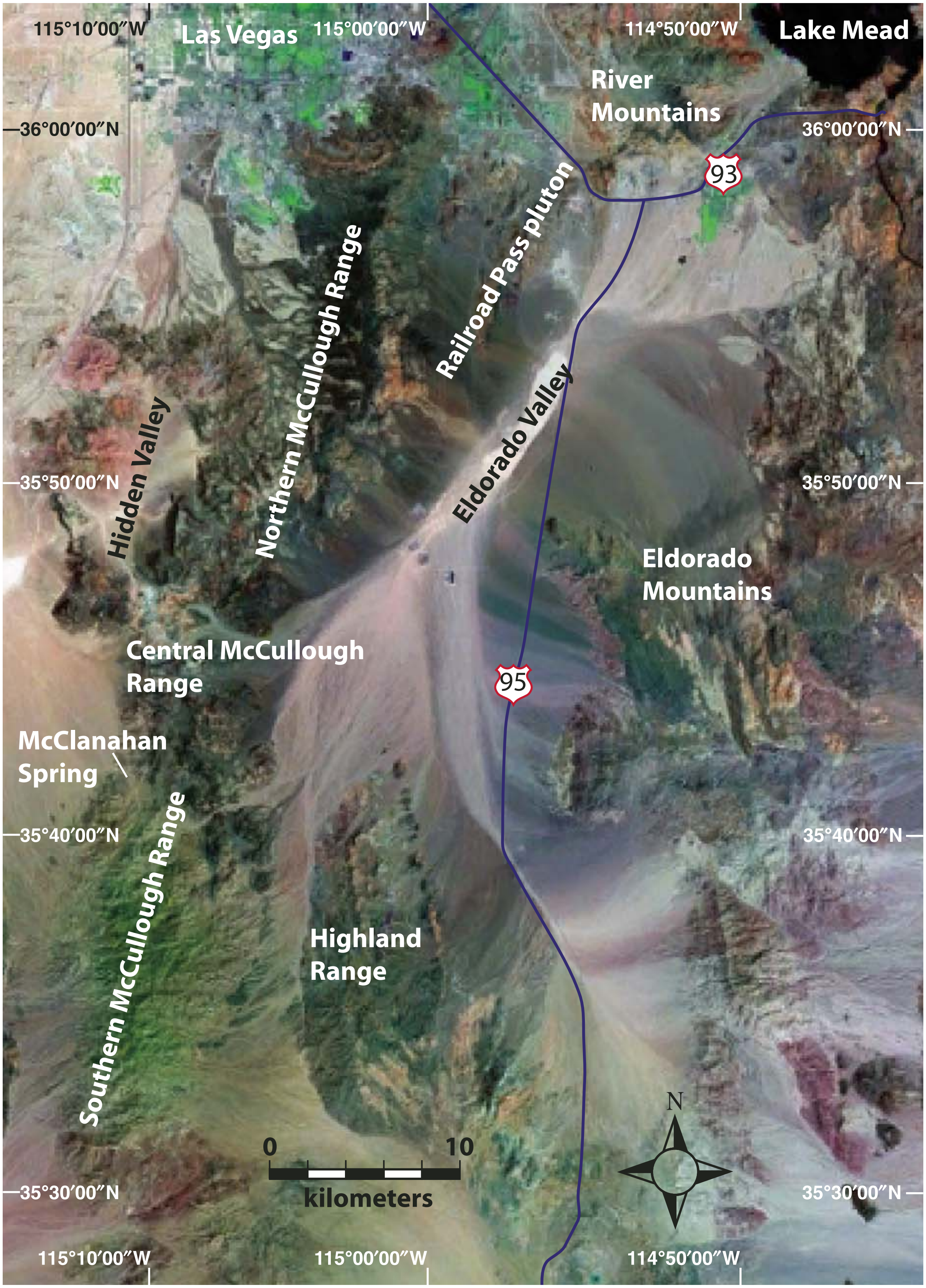


Figure 1. Index map showing the location of the McCullough Range in the Lake Mead area.

Mountains of California to the south. The McCullough Range was not studied in detail until the mid-1980s due to the lack of mineral wealth and perceived minor role in terms of regional tectonic significance. Early studies in the McCullough Range by Hewett (1956), Longwell et al. (1965), and Bingler and Bonham (1973) provided the first descriptions of the volcanic rocks. Carnotite (uranium oxide) occurrences in caliche on the west side of the McCullough Range prompted Kohl (1978) to study parts of the Hidden Valley area. His mapping identified the source of the carnotite as the Erie Tuff (now the tuff of Bridge Spring) and located dikes, volcanic domes, and lava flows. Studies by geologists at the University of Nevada, Las Vegas (UNLV), began in 1984 as part of a joint study with Lawford Anderson of the University of Southern California to characterize the geology of the southern McCullough Wilderness area (Anderson et al., 1985). Since this initial study, work by UNLV geologists has established the volcanic stratigraphy and identified fifteen volcanoes. The recent establishment by the U.S. Bureau of Land Management (BLM) of the Sloan Canyon National Conservation Area in the northern and central parts of the McCullough Range has prompted more detailed geological and volcanological studies of many of the volcanoes (Honn and Smith, 2005; Honn et al., 2007; Johnsen and Smith, 2008).

Our goal in this paper is to describe the geology of the well-preserved and relatively unfaulted volcanoes in the McCullough Range. This study provides key information that can be used to provide a geologic and stratigraphic framework for unraveling the deformational history of similar but highly extended volcanic fields.

GEOLOGIC SUMMARY

The McCullough Range forms the west side of the Eldorado Valley, an alluvial basin ringed by mountains consisting of mainly Tertiary volcanic, plutonic, and sedimentary rocks (Fig. 1). For discussion in this paper, the McCullough Range is divided into three parts: (1) the southern McCullough Range, composed mainly of Precambrian basement rock, (2) the central McCullough Range, centered in the area about McCullough Pass, and (3) the northern McCullough Range, extending from McCullough Pass to Henderson (Fig. 1). The McCullough Range lies within the northern Colorado River extensional corridor, a 50–100-km-wide structural zone that formed during Miocene crustal deformation (e.g., Howard and John, 1987; Faulds et al., 1990). Both magmatism and crustal extension migrated to the north during Miocene time (Smith and Faulds, 1994; Faulds et al., 1999). Within the corridor, magmatism generally occurred 1–4 m.y. before crustal extension. Surprisingly, little magmatic activity occurred during the period of peak extension (e.g., Smith and Faulds, 1994; Gans and Bohrson, 1998; Faulds et al., 1999). Crustal extension in ranges near the southern part of the Eldorado Valley began ca. 16 Ma and ceased ca. 11 Ma. In mountain ranges bounding the northern part of the Eldorado Valley, extension began at ca. 14 Ma and terminated between 8 and 10 Ma (Anderson, 1971; Gans et al., 1994; Faulds, 1995; Faulds et al., 1994, 1999). While magmatism spread to the north in the Colorado River extensional corridor during Miocene time, volcanic activity in individual fields lasted for considerable periods of time. In the McCullough Range, for example, there is a 4 m.y. record of volcanism.

During the period of active volcanism in the McCullough Range (16–12 Ma) volcanism also occurred in neighboring areas. Volcanic rocks for the most part erupted from local volcanoes and did not extend from range to range (Fig. 2). Exceptions are the tuff of Mount Davis (15.00 ± 0.03 Ma), the tuff of Bridge Spring (15.23 ± 0.14 Ma), and the Peach Springs Tuff (18.46 ± 0.05 Ma; Faulds et al., 1995). All are regional units that are excellent stratigraphic markers (Fig. 2).

Precambrian basement rocks (1.7 Ga) composed mainly of granite paragneiss, granite, and monzogranite form a buttress on the west side of the central McCullough Range and locally crop out at low elevation along the east side of the northern McCullough Range (Boland, 1996). Most of the volcanic section lies on Precambrian basement. Paleozoic and Mesozoic strata common in the Spring Mountains to the west and on the Colorado Plateau to the east are missing in the McCullough Range. The absence of these units may be explained by the fact that the McCullough Range lies on the west flank of the Kingman Arch, a structural uplift that extends from central Arizona to the Las Vegas area (Lucchitta, 1967; Young and Brennan, 1974; Bohannon, 1984; Herrington, 2000). According to Herrington (2000), nearly 5.5 km of Mesozoic and Paleozoic strata were removed from the Kingman Arch between the onset of Sevier thrust faulting (146 Ma) and the deposition of the Peach Springs Tuff (18.5 Ma). Based on fission-track thermochronology, much of the uplift occurred at ca. 70 Ma coincident with the Laramide orogeny. The Kingman Arch, therefore, may represent the westernmost Laramide uplift in the western United States (Herrington, 2000). Locally, a thin (1–5 m) conglomerate containing well-rounded clasts of quartzite and carbonate (up to 5 cm in size) crops out between Precambrian crystalline rocks and the volcanic section. Herrington (2000) suggested that the conglomerate was shed from the rising Kingman Arch during Late Cretaceous–Early Tertiary time and represents the stripping of the Paleozoic and Mesozoic cover during the formation of the arch. Near McClanahan Spring (Fig. 1), an ash-flow tuff crops out above the basal breccia but below the McClanahan Spring basalt. This exposure was identified as Peach Springs Tuff (Wells and Hillhouse, 1989) by its distinctive paleomagnetic pole.

The basal volcanic rocks in the McCullough Range are correlated with the "Patsy Mine volcanics" (Anderson, 1971) (18.5–15.2 Ma) and were named the Eldorado Valley volcanic section by Schmidt (1987) (Figs. 3 and 4). This unit contains dacite domes, debris aprons, and block-and-ash deposits as well as basalt to andesite cinder cones and broad shield volcanoes (Johnsen and Smith, 2007).

The Eldorado Valley volcanic section is overlain by the tuff of Bridge Spring, a regional unit dated at 15.23 ± 0.14 Ma

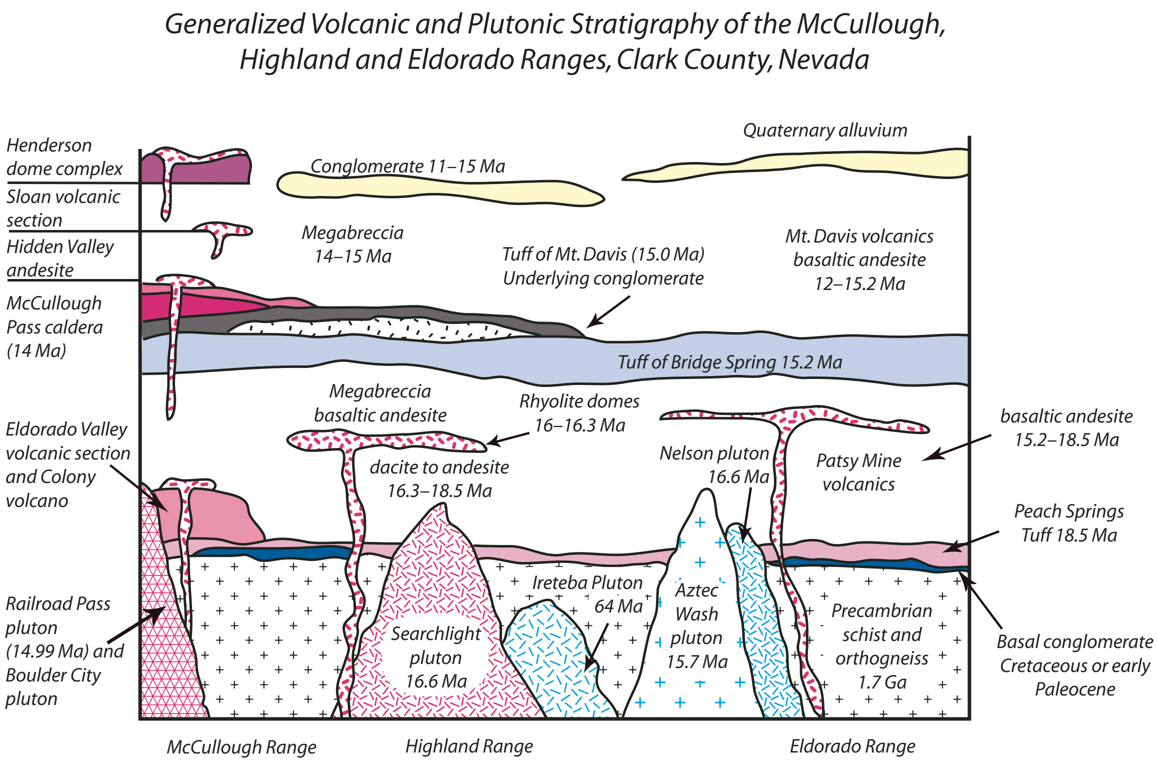


Figure 2. Regional correlation of stratigraphic units to the south of Lake Mead. Note that the tuffs of Bridge Spring and Mount Davis, and the Peach Springs Tuff are the only units that extend from range to range.

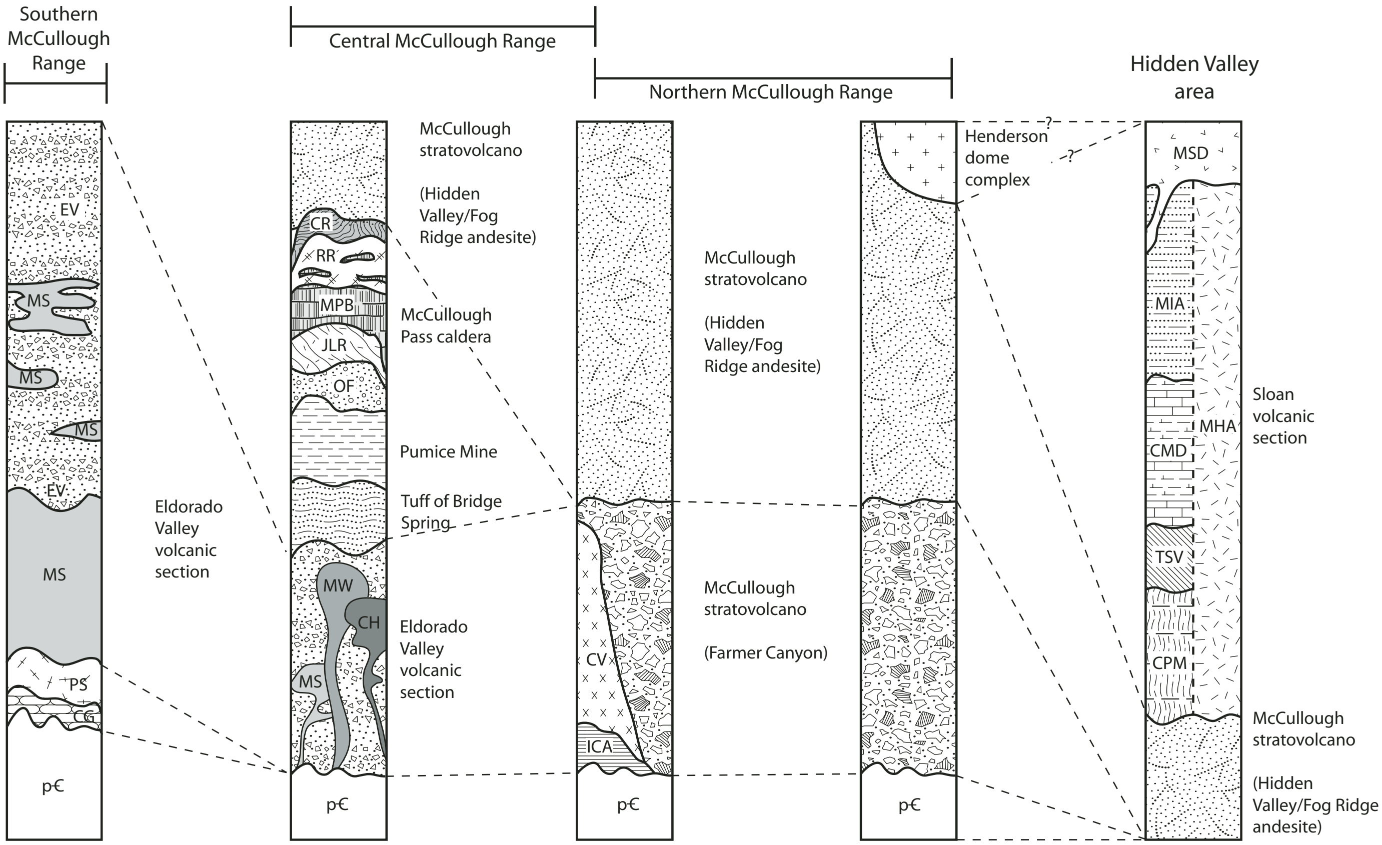
(Bridwell, 1991). The tuff of Bridge Spring is a moderately welded dacite ash-flow tuff originally described by Anderson (1971) and studied in detail by Smith et al. (1993) and Morikawa (1994). The tuff is densely welded and vitric at the base and grades upward to a moderately welded tuff. The base of the tuff is commonly oxidized and has a distinctive orange color. The source of the tuff of Bridge Spring may be in the Eldorado Range (Fig. 1) (Gans et al., 1994; Druschke et al., 2004).

Faulds et al. (2001, 2002a) identified the tuff of Mount Davis in the Highland Range based on a 15.00 ± 0.03 Ma date, a distinctive paleomagnetic pole, and characteristic mineralogy. In the Highland Range, it is separated from the tuff of Bridge Spring by a sedimentary unit, but in areas where this unit is missing (i.e., the McCullough Range), the tuff of Mount Davis lies directly on the tuff of Bridge Spring (Fig. 2). In these areas, it is difficult to separate the units, so it is unclear whether the tuff of Mount Davis crops out in the McCullough Range. Bridwell (1991) dated the tuff of Bridge Spring at 15.2 Ma; however, an $^{40}Ar/^{39}Ar$ date of 14.97 ± 0.08 Ma (Spell et al., 2001) suggests a correlation to the tuff of Mount Davis. Because of this uncertainty and the historical use of the term, tuff of Bridge Spring is used in this paper to encompass both the tuff of Bridge Spring and tuff of Mount Davis.

Basalt flows and scoria of the Pumice Mine basalt overlie the tuff of Bridge Spring and are in turn overlain by the McCullough Pass tuff (14.11 ± 0.06 Ma; Sanford, 2000; Spell et al., 2001), which erupted from the McCullough Pass caldera (Schmidt, 1987). The Hidden Valley volcanic section lies on the McCullough Pass tuff and consists of high-silica andesite flows and domes and an overlying section of basaltic-andesite flows. The northern McCullough Range lacks exposures of the tuff of Bridge Spring; therefore, in this area, the Hidden Valley volcanic section lies directly on the Farmer Canyon volcanic section (Figs. 3 and 4). Work by Boland (1996) determined basalt stratigraphy in the northern McCullough Range and provided a geochemical database.

The Sloan volcanic section (13.07 ± 0.02 Ma; P. Gans, 1997, personal commun.) consists of four volcanoes arranged about Hidden Valley: Mount Hanna, Mount Ian, Center Dome, and Mount Sutor (Figs. 1, 3, and 4) (Bridwell, 1991). Few faults cut this volcanic section, so it likely formed after the major phase of extension.

The youngest volcanic feature is the Henderson dacite dome complex at the northern tip of the McCullough Range (Figs. 3 and 4). Originally interpreted as a caldera (Smith et al., 1993), new mapping (Honn et al., 2007) indicates that it is a complex of domes aligned along an arc concave to the north. Domes are associated with flows, pyroclastic flow, and mesobreccia. The 10-km-diameter dome complex cuts the tilted and faulted Farmer Canyon and Hidden Valley sections and clearly formed subsequent to extension.



CG - Basal conglomerate
CH - Cactus Hill volcano
CR - Capstone rhyolite
CMD - Center Mountain dome complex
CPM - Cinder Prospect member
CV - Colony volcano
EV - Eldorado Valley breccia
ICA - Ivan Canyon andesite
JLR - Jean Lake rhyolite
MS - McClanahan Spring basalt
MPB - McCullough Pass basalt
MW - McCullough Wash dome complex
MHA - Mt. Hanna andesite
MIA - Mt. Ian andesite
MSD - Mt. Sutor dacite
OF - McCullough Pass caldera outflow tuff
PS - Peach Springs Tuff
RR - Ramhead rhyolite
TSV - Tuff of Sloan volcanics

Figure 3. Stratigraphic summary of the McCullough Range.

Eldorado Valley Volcanoes

Based on the work of Johnsen and Smith (2007, 2008), volcanic rocks of the McClanahan Spring, McCullough Wash, and Cactus Hill volcanoes constitute the Eldorado Valley volcanic section. The stratigraphy of the volcanic section is summarized in Figure 5.

McClanahan Spring Volcano

The McClanahan Spring volcano, located ~5 km south of McCullough Pass at McClanahan Spring (Fig. 1), is composed of phlogopite-bearing basalt flows and hornblende andesite flows (Table 1). At McCullough Pass, McClanahan Spring andesite flows are interbedded with Eldorado Valley breccia. The McClanahan Spring basalt lies directly on the 18.5 Ma Peach Springs Tuff just south of McClanahan Spring and contains phenocrysts of phlogopite and minor amounts of plagioclase, clinopyroxene, and olivine altered to iddingsite. McClanahan Spring andesite flows contain phenocrysts of hornblende (1–1.5 cm; 65%) and plagioclase (30%) with less than 5% clinopyroxene. The McClanahan Spring section is characterized by high aluminum values (>18%), which distinguish it from the rest of the Eldorado Valley section.

McCullough Wash Volcano

One of the largest volcanic centers of Eldorado Valley section is the McCullough Wash dome complex (Fig. 4), which is composed of more than 10 coalescing dacite domes, associated flows, and block-and-ash flow deposits. The McCullough Wash dome complex formed in three stages. The first stage produced voluminous block-and-ash flow deposits up to 300 m thick that cover an area of 19 km^2. Blocks and bombs range from 0.5 m to 4 m in diameter and are composed of phenocryst-rich (35%–40%) dacite (63%–65% SiO_2; Table 1). The blocks contain abundant hornblende phenocrysts, plagioclase, and up to 10% clinopyroxene phenocrysts and xenocrysts. The block-and-ash deposit

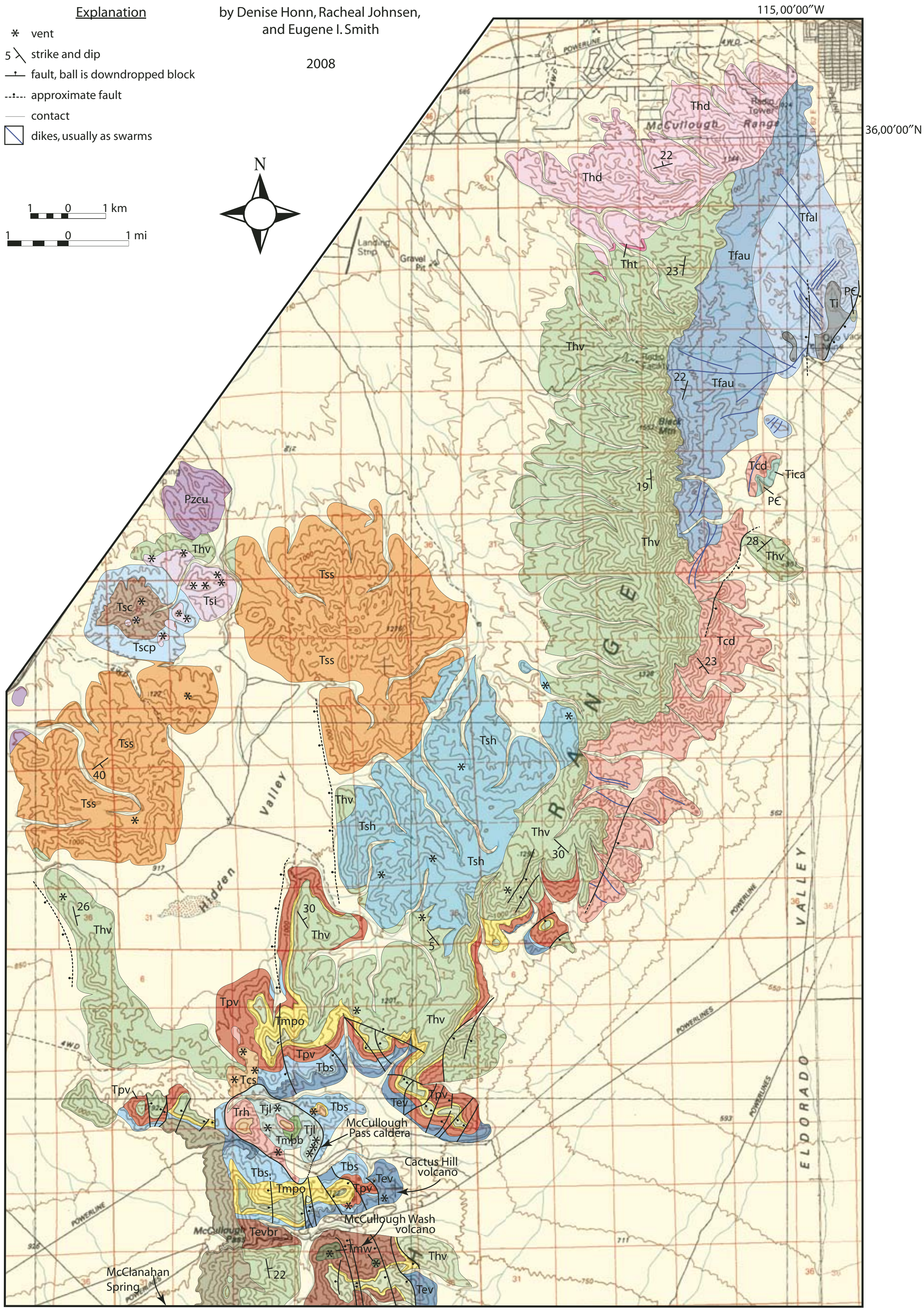


Figure 4 (*on this amd following page*). Geologic map of the northern and southern McCullough Range.

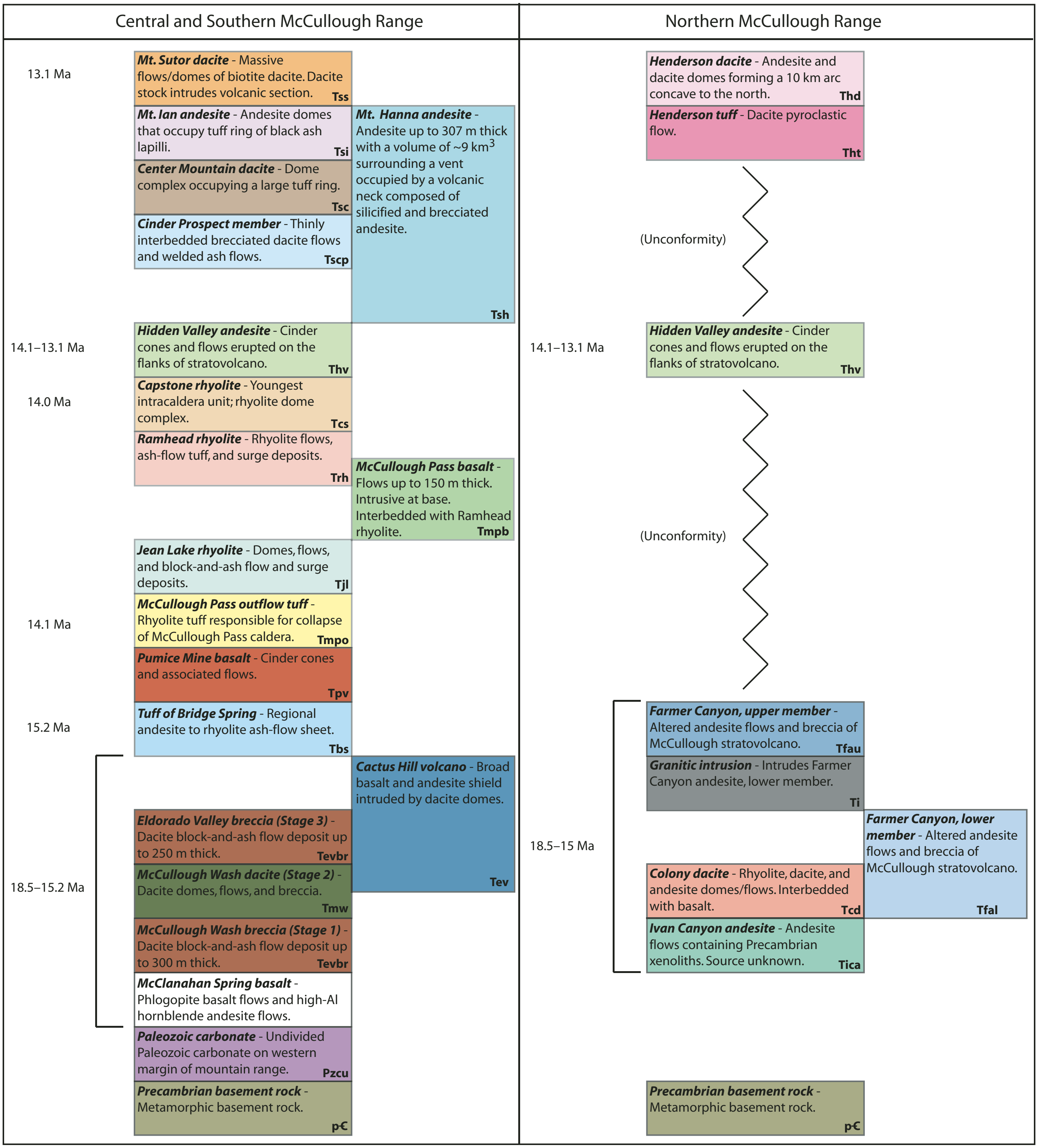


Figure 4 (*continued*).

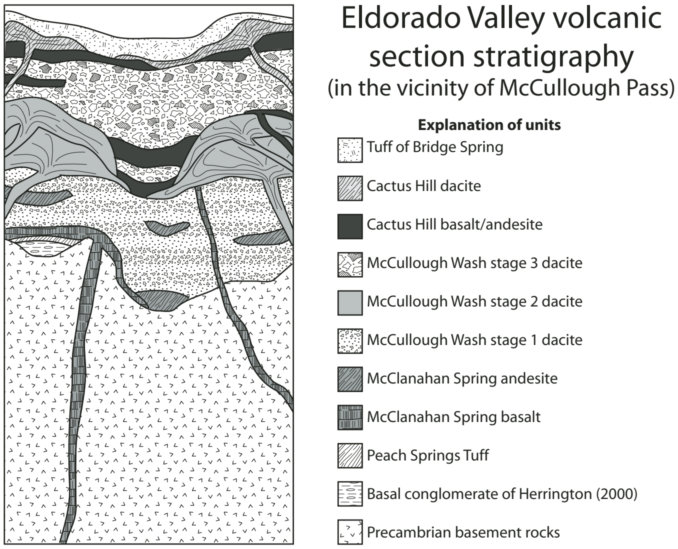


Figure 5. Stratigraphic summary of the Eldorado Valley volcanic section. Figure not to scale.

is hydrothermally altered and is cut by basalt dikes that do not penetrate the middle and upper parts of the Eldorado Valley section. The domes that produced the block-and-ash deposit have not been located and were likely obliterated or buried by subsequent eruptions.

The second stage of McCullough Wash eruptions produced the main volcanic construct consisting of more than 10 coalescing dacite (Table 1) domes spread over an area of ~2.5 km^2. The domes intrude stage-one block-and-ash deposits and are commonly flow-banded with up to 40% phenocrysts of plagioclase and phenocrysts and xenocrysts of clinopyroxene in a glassy matrix. Each dome is surrounded by a glassy carapace of the same composition as the dome interior dacite but with a lower percentage of phenocrysts (20%). Flows are short, typically extending no more than 30 m from a dome margin. Basalt flows from the Cactus Hill volcano are found near the top of the section, and one basalt dike intrudes a dacite dome from this stage (Fig. 5).

The third stage produced the 250-m-thick Eldorado Valley breccia, a block-and-ash deposit containing over 60 4-m-thick flows. Remnants of the domes that collapsed to produce this deposit are rarely found in outcrop. The deposit contains both dacite blocks and bombs (hot blocks). Blocks are 1 cm to 3 m in diameter, while bombs are 10 cm to over 6 m in size. Bombs (Fig. 6) commonly exhibit radial fractures and have bread-crust surfaces. Chemically, blocks, bombs, and dome material are identical to McCullough Wash dacite (66% SiO_2) of stage two, although dacite of stage three is largely aphanitic (95% matrix). Planar and cross-bedded ash beds that are interbedded with the Eldorado Valley breccia are up to 2 m thick. Deposits of the Eldorado Valley breccia pinch out against dacite of stage two and are interbedded with basalt flows of the Cactus Hill volcano.

Cactus Hill Volcano

The Cactus Hill volcano (Fig. 4) is a compound cone composed predominantly of basaltic agglomerate and dikes, along with basalt and hornblende andesite flows (Table 1). Basalt contains olivine altered to iddingsite, clinopyroxene, and plagioclase in a vitric matrix, while hornblende andesite contains iddingsite, clinopyroxene, plagioclase, and up to 2-cm-long hornblende phenocrysts. The volcano itself is ~2 km in diameter; however, flows associated with the volcano maintain thicknesses of greater than 20 m for an additional 3.5 km around the main center, and some flows extend 10 km to the north. Six dacite domes and associated flows intrude basalt agglomerate on the flanks of the Cactus Hill volcano.

Colony Volcano

The Colony volcano (Fig. 4) was first described in the northern McCullough Range by Boland (1996). Recent mapping by Johnsen and Smith (2008) demonstrated that the outcrop area is larger than envisioned by Boland and extends from the pinch out of the McCullough Pass tuff and the tuff of Bridge Spring just north of McCullough Pass to nearly 13.5 km to the north along the east side of the northern McCullough Range. Boland (1996) described Colony as rhyolite and dacite domes, flows, and debris-flow breccia along with high-silica andesite flows. Further mapping by Johnsen and Smith (2008) showed that in addition to these previously mentioned rock types, the unit also contains interbedded dacite, andesite, and basalt flows (Table 1). Colony rhyolite contains sanidine, plagioclase, biotite, Fe-Ti oxides, and clinopyroxene. Colony dacite and andesite contain large plagioclase, biotite, and rare clinopyroxene phenocrysts, while basalt flows contain larger amounts of clinopyroxene with lesser amounts of plagioclase and olivine (iddingsite). The presence of large biotite phenocrysts and ubiquitous 1 cm to 1.5 m fine-grained diorite enclaves in rhyolite and dacite distinguish the rocks of the Colony volcano from the Eldorado Valley volcanoes. Although they are considered age-equivalent and are present in the same general area (Fig. 4), no contact has been found between the Colony volcano and any portion of the Eldorado Valley volcanic section. Because of the lack of contact relationships, the Colony Volcano is not included as part of the Eldorado Valley section.

McCullough Pass Caldera

The McCullough Pass caldera is the most extensively studied of the volcanic centers in the McCullough Range and is the source of the McCullough Pass tuff. The caldera is 2.4 km by 1.5 km in diameter and elongate east-west, with embayments to the northwest and southeast. The total duration of activity was short. The caldera formed by the eruption of the McCullough Pass tuff at 14.11 ± 0.06 Ma, and the last activity (the intracaldera Capstone rhyolite) occurred at 13.98 ± 0.10 Ma (Spell et al.,

TABLE 1. SUMMARY OF GEOCHEMISTRY FOR VOLCANIC ROCKS OF THE MCCULLOUGH RANGE

Sample	Tch-a[1]	Tch-d[2]	Tms-b[3]	Tms-a[4]	Tmw-d[5]	Tmw-b[6]	Tev-d[7]	Tev-b[8]	Tfr-a[9]	Tfc-a[10]
SiO_2	56.20	62.44	55.23	59.78	65.61	63.73	65.38	65.91	54.64	55.64
Al_2O_3	15.97	15.80	18.44	18.37	15.89	16.17	15.68	15.63	16.25	16.40
TiO_2	1.14	0.84	1.04	1.01	0.60	0.69	0.59	0.58	1.23	1.03
Fe_2O_3	6.85	4.75	6.46	5.18	3.91	4.46	3.92	3.83	7.17	6.18
MgO	4.45	2.34	3.03	1.95	1.59	2.04	2.34	1.88	4.40	3.37
Na_2O	3.77	3.92	3.92	4.30	4.00	3.94	3.69	3.76	3.25	3.23
K_2O	3.45	3.99	4.80	4.01	4.16	4.05	3.71	4.03	3.33	3.65
MnO	0.10	0.06	0.11	0.09	0.06	0.08	0.06	0.06	0.11	0.10
CaO	6.55	4.33	5.00	4.86	3.67	3.98	4.17	3.37	6.80	5.65
P_2O_5	0.57	0.38	1.09	0.44	0.27	0.34	0.25	0.24	0.65	0.55
LOI	2.45	1.92		1.61	1.71	1.70		2.21		
Total	99.04	98.86	99.12	99.98	99.76	99.48	99.79	99.29	97.83	95.80
Sc	15	11	10	11	8	9	10	8		
V	162	109	164	106	70	81	73	64		
Ni	71	34	21	10	17	19	32	26	58	21
Cu	39	30	113	15	18	20	20	20		
Ga	20	20	20	21	19	20	19	19		
Rb	73	91	65	81	103	113	90	105	78	87
Sr	1201	957	2828	1067	840	958	802	771	974	939
Y	24	23	28	29	25	29	23	22	24	17
Zr	374	350	762	415	317	343	280	284	347	351
Nb	17	15	41	23	14	16	12	13	17	17
Ba	1599	1523	2121	1578	1464	1509	1625	1488	1344	1507
La	77	64	187	68	63	69	52	61	80	84
Hf	10	10	20	11	9	10	7	8	8	8
Pb	13	15	33	13	18	16	16	20		
Th	21	20	69	20	19	21	16	15	14	14
U	2	2	0	0	3	2	0	4		
No. analyses	13	12	3	3	9	9	4	21		

Note: Major elements are in wt%, and trace elements are in ppm. LOI—loss on ignition.
[1]Average value of Cactus Hill basalt and andesite. Major and trace elements were done by X-ray fluorescence (XRF).
[2]Average value of Cactus Hill domes. Major and trace elements were done by XRF.
[3]Average value of McClanahan Spring basalt. Major and trace elements were done by XRF.
[4]Average value of McClanahan Spring andesite. Major and trace elements were done by XRF.
[5]Average value of McCullough Wash domes. Major and trace elements were done by XRF.
[6]Average value of McCullough Wash bombs. Major and trace elements were done by XRF.
[7]Average value of Eldorado Valley domes. Major and trace elements were done by XRF.
[8]Average value of Eldorado Valley bombs. Major and trace elements were done by XRF.
[9]Average value of Fog Ridge andesite from Boland (1996). Major elements by XRF; trace elements by INAA (instrumental neutron activation analysis) and ICP-MS (inductively coupled plasma mass spectrometry).
[10]Average value of Farmer Canyon andesite from Boland (1996). Major elements by XRF; trace elements by INAA and ICP-MS.

(*continued*)

2001). Considering uncertainties in the dates, the total eruption time was ~100,000 yr (Spell et al., 2001). Kohl (1978) noted rhyolite dikes and domes in the caldera area but did not recognize the caldera. Schmidt (1987) and Smith et al. (1988) provided the first description of the McCullough Pass caldera. This early work was followed by a more detailed study of the caldera by Sanford (2000) and Spell et al. (2001).

Intracaldera units include rhyolite and basalt flows, high-silica rhyolite ash-flow tuff, surge deposits, rhyolite domes, rhyolite and basalt dikes, and sedimentary units. Rhyolite domes lie in an arcuate pattern in the eastern half of the caldera, where five domes form a prominent ridge just inside the eastern caldera wall. Domes also cluster in the northwestern embayment. Dikes generally trend north-south and occur only in the central and western portions of the caldera. The caldera wall is composed dominantly of the tuff of Bridge Spring and Eldorado Valley basalt. Megabreccia blocks (4–6 m in size) of the tuff of Bridge Spring occur in intracaldera units just inside the southwestern wall. Sanford (2000) divided intracaldera rocks into four units: the Jean Lake rhyolite, McCullough Pass basalt, Ramhead rhyolite, and Capstone rhyolite.

The Jean Lake rhyolite forms the base of the intracaldera section (Fig. 4) and consists of rhyolite flows and domes, breccias, and ash-flow deposits, mainly in the eastern part of the caldera. The most prominent features are five rhyolite domes and associated block-and-ash and pyroclastic surge deposits that form an arc just inside the caldera. Rhyolite contains phenocrysts of sanidine, plagioclase, quartz, and biotite in a glassy matrix.

Outcrops of McCullough Pass basalt in the western part of the caldera consist of three to five flows that are each less than 5 m thick. In the eastern part of the caldera, McCullough Pass basalt crops out as a 150 m section of homogeneous rock lacking flow boundaries or agglomerate. The western contact between the homogeneous basalt and intracaldera rhyolite is nearly vertical, but it is not a fault contact. When inspected in detail, the contact is irregular and dikes of basalt cut into neighboring

TABLE 1. SUMMARY OF GEOCHEMISTRY FOR VOLCANIC ROCKS OF THE MCCULLOUGH RANGE (*continued*)

Sample	Tic-a[11]	Tcd-b[12]	Tcd-a[13]	Tcd-d[14]	Thv-a[15]	Tpm[16]	Tmpb[17]	Tmpa[18]	Tmrh[19]
SiO_2	54.15	54.45	59.68	65.01	57.84	49.59	50.06	59.67	73.64
Al_2O_3	15.06	16.28	16.27	16.12	16.84	16.01	16.34	17.11	13.04
TiO_2	1.28	1.45	1.04	0.74	0.74	1.28	1.24	0.85	0.24
Fe_2O_3	6.26	7.87	5.60	4.03	6.60	9.53	8.86	6.10	1.29
MgO	3.40	4.72	3.47	1.82	3.41	7.15	7.68	3.06	0.37
Na_2O	3.45	3.63	3.65	3.91	3.78	3.31	2.83	3.41	3.27
K_2O	4.12	3.18	4.09	4.88	3.91	1.36	1.39	3.49	4.72
MnO	0.20	0.12	0.10	0.06	0.10	0.14	0.14	0.13	0.07
CaO	7.58	7.15	5.31	3.23	5.34	9.48	9.53	4.72	1.92
P_2O_5	0.57	0.69	0.51	0.31	0.43	0.55	0.45	0.56	0.04
LOI					2.28	1.94	2.10	1.71	4.22
Total	96.07	99.53	99.73	100.12	101.27	100.34	98.51	99.11	98.60
Sc		19	12	9			32	14	3
V		210	151	87					
Ni	80	44	37	17			135	108	
Cu		41	33	19					
Ga		20	19	18					
Rb	107	67	92	129	84	28	26	75	159
Sr	836	1133	1187	708	1113	1038	918	989	185
Y	23	29	30	32			33	43	20
Zr	406	434	448	418	400	617	221	305	196
Nb	23	20	22	24			7	10	26
Ba	1066	1713	1755	1481	1578	610	824	1169	570
La	98	93	88	86	78	48	45	69	58
Hf	10	11	12	11	7	6	4	7	5
Pb		12	21	20			10	18	30
Th	24	25	29	27	13	5	6	14	22
U		1	0	2			2	2	4
No. analyses	1	6	9	18		2	5		

[11]Average value of Ivan Canyon andesite from Boland (1996). Major elements by XRF; trace elements by INAA and ICP-MS.
[12]Average value of Colony basalt. Major and trace elements done by XRF.
[13]Average value of Colony andesite. Major and trace elements done by XRF.
[14]Average value of Colony dacite. Major elements by XRF; trace elements by XRF, INAA, and ICP-MS.
[15]Average value Hidden Valley andesite from Schmidt (1987). Major elements by ICP; trace elements by INAA.
[16]Average value of Pumice Mine basalt from Schmidt (1987). Major elements by ICP; trace elements by INAA (instrumental neutron activation analysis).
[17]Average value of McCullough Pass basalt from Sanford (2000). Major elements by XRF; trace elements by ICP-MS (inductively coupled plasma mass spectrometry).
[18]Average value of McCullough Pass andesite from Sanford (2000). Major elements by XRF; trace elements by ICP-MS.
[19]Value of McCullough Pass, Ramhead rhyolite from Sanford (2000). Major elements by XRF; trace elements by ICP-MS.

(*continued*)

rhyolite. Toward the top of the section, basalt becomes oxidized and vesicular and is associated with small volcanic bombs. We interpret the thick section of homogeneous basalt as a subjacent pluton with vertical intrusive contacts. The pluton grades upward into a volcanic section.

The Ramhead rhyolite is composed of flow, ash-flow tuff, and surge deposits interbedded with volcaniclastic deposits and McCullough Pass basalt. Ramhead rhyolite consists of several meters of thinly bedded sedimentary units overlain by a 1–2-m-thick pyroclastic surge, and four 2–3-m-thick pyroclastic flows. The ash-flow tuffs contain phenocrysts of sanidine, plagioclase, and biotite, sparse pumice clasts, and andesite xenoliths in a fine-grained matrix.

The Capstone rhyolite is the youngest intracaldera unit (13.98 ± 0.10 Ma; Spell et al., 2001), and it forms a dome complex in the northwestern caldera embayment and a cluster in the south-central part of the caldera. A Capstone rhyolite flow, up to 50 m thick, caps the highest peaks within the caldera. Capstone flows are massive and contain large blocks of devitrified pumice, up to 0.5 m in size, in a glassy matrix. Both the matrix and pumice blocks contain sanidine and plagioclase phenocrysts.

The McCullough Pass tuff is a composite unit that includes ash-flow tuff, breccias, and conglomerate and extends ~12 km to the northeast, but only 2 km to the south of the caldera (Fig. 4). The ash-flow tuff, responsible for caldera collapse, crops out near the bottom of the outflow sequence. The tuff is generally poorly welded and contains pumice up to 6 cm in size and rhyolite clasts in a matrix of glass shards and small pumice fragments. Common phenocrysts are sanidine, plagioclase, biotite, and quartz. Sphene and hornblende are also present but in minor amounts. Abrupt changes in thickness reflect preflow topography on a surface composed of tuff of Bridge Spring and Pumice Mine basalt.

McCullough Stratovolcano

Weber and Smith (1987) and Boland (1996) identified a stratovolcano in the northern McCullough Range composed of basalt and andesite flows interlayered with volcaniclastic units

TABLE 1. SUMMARY OF GEOCHEMISTRY FOR VOLCANIC ROCKS OF THE MCCULLOUGH RANGE (*continued*)

Sample	Tmcs[20]	Tmjl[21]	Ttbs[22]	Tmha[23]	Tcmd[24]	Tmia[25]	Tmsd[26]	Thdc-t[27]	Thdc-f[28]
SiO_2	75.52	74.54	64.89	59.91	68.06	58.61	63.22	64.46	61.20
Al_2O_3	12.92	13.88	15.74	17.00	15.65	17.07	16.24	16.26	15.83
TiO_2	0.17	0.22	0.52	0.60	0.14	0.64	0.44	0.61	0.98
Fe_2O_3	0.82	1.06	2.73	6.68	3.46	7.36	5.30	3.68	4.79
MgO	0.25	0.27	1.01	1.74	0.49	1.89	1.12	1.51	1.98
Na_2O	3.45	3.55	4.16	3.70	3.71	3.72	3.59	3.97	4.05
K_2O	4.80	4.96	5.43	4.35	5.56	4.25	5.41	3.94	4.21
MnO	0.06	0.04	0.07	0.16	0.16	0.16	0.17	0.077	0.07
CaO	0.82	0.85	2.31	3.98	1.73	4.25	2.70	4.26	4.80
P_2O_5	0.02	0.02	0.07	0.84	0.25	0.85	0.34	0.231	0.40
LOI	1.69	0.85	1.76	0.57	1.01	0.64	0.98		1.50
Total	98.83	99.39	97.51	99.54	100.21	99.43	99.49	99.45	99.83
Sc	3	3		6	5	6	7	9	10
V				78	16	85	26	50	110
Ni	135		18					9	14
Cu								11	47
Ga								17	18
Rb	26	176	138	90	118	84	119	111	117
Sr	918	155	421	1834	707	1850	1474	654	722
Y	33	30	26		12			32	38
Zr	221	178	448	579	488	626	710	321	362
Nb	7	18	31					21	24
Ba	824	611	1042	1899	1755	1979	1869	1455	1368
La	45	56		91	116	86	115	56	63
Hf	4	5		8	9	7	11	9	10
Pb	10	31						18	18
Th	6	23	27	14	21	13	19	17	22
U	2	4		3	5	3	4		
No. analyses			6					1	2

[20]Average value of McCullough Pass, Capstone rhyolite from Sanford (2000). Major elements by XRF; trace elements by ICP-MS.
[21]Average value of McCullough Pass, Jean Lake rhyolite from Sanford (2000). Major elements by XRF; trace elements by ICP-MS.
[22]Average value of tuff of Bridge Spring from Morikawa (1994). Major and trace elements by XRF.
[23]Average value of Mount Hanna andesite from Bridwell (1991). Major and trace elements by XRF.
[24]Average value of Center Mountain dacite from Bridwell (1991). Major and trace elements by XRF.
[25]Average value of Mount Ian andesite from Bridwell (1991). Major and trace elements by XRF.
[26]Average value of Mount Sutor dacite from Bridwell (1991). Major and trace elements by XRF.
[27]Value of Henderson dome complex tuff. Major and trace elements by XRF.
[28]Average value of Henderson dome complex flows. Major and trace elements by XRF.

(Figs. 4 and 7). Boland (1996) divided the stratovolcano stratigraphy into two units and informally named the upper unit the Fog Ridge andesite and the lower unit the Farmer Canyon andesite. Despite the lack of radiometric dates for these units, we suspect, based on field studies, that Fog Ridge andesite is correlative with the Hidden Valley section. Farmer Canyon andesite, however, is separated from Eldorado Valley outcrops by the Colony volcano and cannot be correlated with Eldorado Valley andesite with any degree of certainty. Accordingly, in this paper, we use the term Farmer Canyon for the lower part of the section and Hidden Valley andesite for the upper part of the section in the northern McCullough Range.

The Farmer Canyon section (450 m thick) forms the interior of the McCullough stratovolcano (Fig. 3) and is composed of altered andesite flows, agglomerates, and numerous dikes. The lower part of the Farmer Canyon section contains massive, porphyritic andesite flows with phenocrysts of plagioclase, Fe-Ti minerals, and clinopyroxene, and small (<1.5 mm) phenocrysts of biotite and oxyhornblende. Numerous andesite dikes that are finer grained and more resistant to erosion than the host rocks intrude the section and occur just south of Railroad Pass (Fig. 4). The flows of the upper part of the Farmer Canyon section are porphyritic and fine grained with phenocrysts of plagioclase, clinopyroxene, olivine, and Fe-Ti minerals. In contrast to the lower part of the section, agglomerate is the dominate rock type, and andesite flows are rare.

The Hidden Valley andesite (Fig. 3) unconformably overlies the Farmer Canyon section and consists of thin basaltic-andesite and andesite flows interbedded with agglomerate and breccia. Flows are porphyritic and contain phenocrysts of plagioclase, olivine, and clinopyroxene. Accumulations of red welded scoria and volcanic bombs occur in the vent areas for Hidden Valley andesite. In the central McCullough Range, Hidden Valley andesite overlies McCullough Pass caldera outflow tuff (14.1 Ma).

The vent area for the McCullough stratovolcano has not been located. We suggest, however, that the conduit was in the area of Railroad Pass, but evidence for the vent or conduit was erased by the intrusion of the Railroad Pass pluton (14.99 ± 0.08; P. Gans, 1997, personal commun.) (Figs. 1 and 7). This quartz monzonite pluton intruded a highly altered Farmer Canyon sequence cut by hundreds of dikes. Dike abundance and the degree

Figure 6. Photo of a large bomb (hot block) in the Eldorado Valley breccia. The bomb is 5 m wide and 3 m high. Note the radial fractures and columnar jointing at the margin of the bomb.

of alteration decreases to the west away from the pluton, and dike swarms tend to converge on the area around the pluton. A transect from the pluton to the summit of the McCullough Range may represent a section across the volcano from conduit to flank flows (Fig. 7).

Sloan Volcanic Section

The Sloan volcanic section sits stratigraphically above Hidden Valley andesite (Fig. 4) and consists of the Mount Sutor, Mount Ian, Center Mountain, and Mount Hanna volcanoes.

Mount Hanna is the oldest of the volcanoes and was erupted from a single vent. A section of andesite up to 307 m thick with a volume of ~9 km^3 surrounds a vent occupied by a volcanic neck composed of silicified and brecciated andesite. Andesite is fin grained and commonly trachytic. Phenocrysts are rare (<1%) and consist of highly embayed and pitted plagioclase and biotite. Bridwell (1991) suggested that the Mount Hanna andesite erupted at high temperature (1000 °C) with water content of less than 2% by a lava-fountaining mechanism. The eruption resulted in lava flows composed of agglutinated spatter.

Center Mountain is a dome complex occupying a large tuff ring formed by a pyroclastic unit with a matrix of blocky nonvesicular glass shards. Armored mud balls and discontinuous stringers of dacite suggest hydromagmatic activity and lava fountaining. The Center Mountain dacite erupted within the tuff ring and produced thick, viscous dacite with a volume of 0.44 km^3. Dacite contains plagioclase and biotite phenocrysts in a matrix of aligned plagioclase microlites.

The Mount Ian volcano consists of numerous domes that occupy tuff rings of black ash and lapilli. Domes are characterized by andesite with foliation defined by platy slabs commonly dipping inward toward the conduit but becoming horizontal over the vent. Single domes are usually less than 0.5 km in diameter. The fine-grained andesite contains phenocrysts of plagioclase, oxidized biotite, orthopyroxene, and iddingsitized olivine. The groundmass consists of microlites of plagioclase.

Mount Sutor dacite covers a large area to the north and west of Hidden Valley and is composed of massive flows and domes of biotite dacite. Eruptive centers are domes intruding tuff rings. In the north, Mount Sutor dacite forms a broad dome intruded

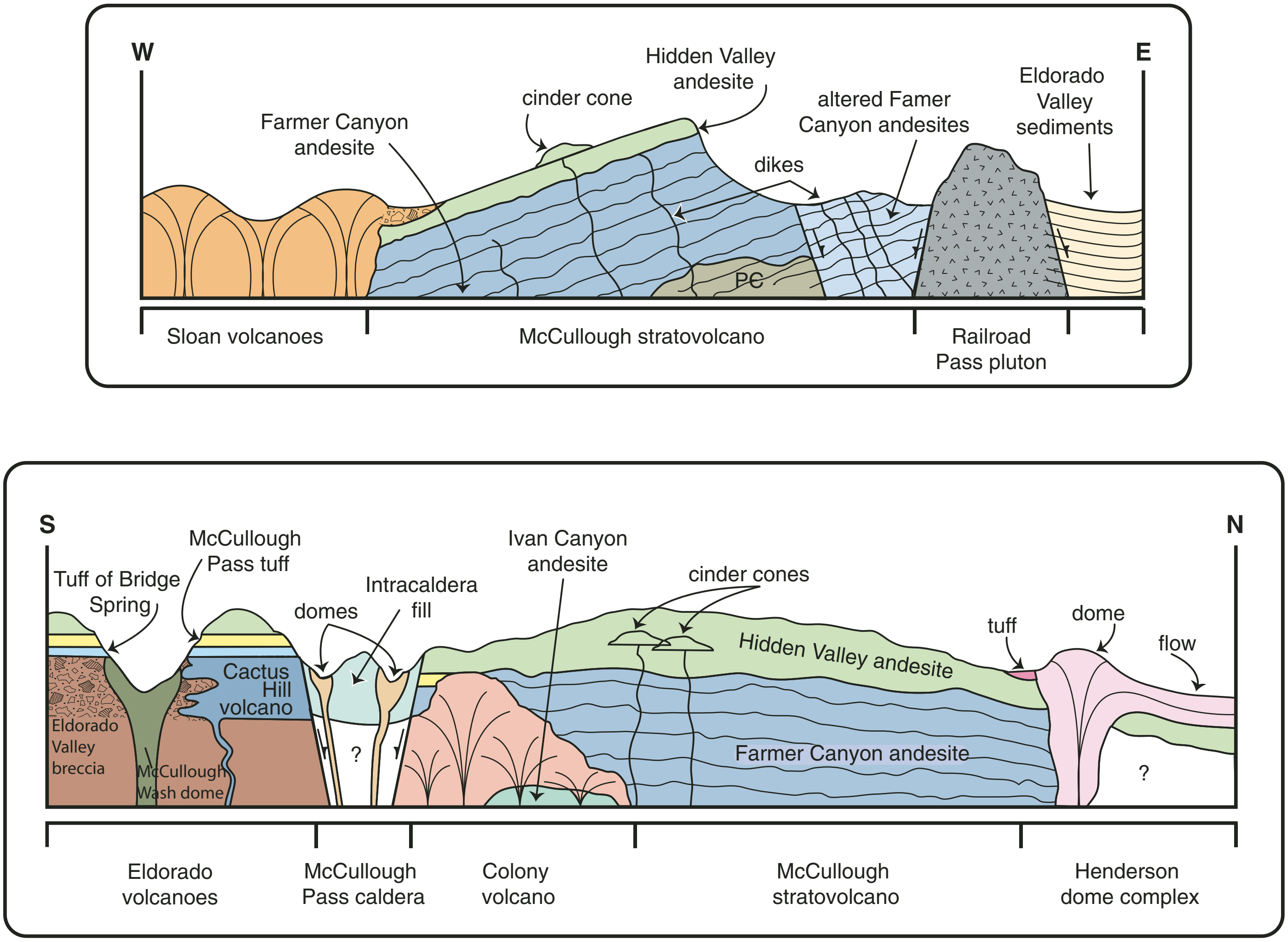


Figure 7. Diagrammatic cross sections from west to east and north to south across the northern McCullough Range.

by a hypabyssal dacite stock. Dacite contains phenocrysts and glomerocrysts of plagioclase, biotite, and clinopyroxene. Dacite of the stock is coarser grained but has the same mineralogy as Mount Sutor dacite flows.

Henderson Dome Complex

The Henderson dome complex is a series of dacite domes and flows located just south of Henderson, Nevada, at the northern tip of the McCullough Range (Fig. 4). The geometry of the complex is simple and is characterized by an arc of dacite domes to the south, which are the sources of dacite coulees that flowed 1–2 km to the north. A dacite flow in the northeastern part of the complex filled a paleovalley on the flank of the McCullough stratovolcano. This flow forms the summit of Black Mountain, a prominent peak that forms the backdrop to the City of Henderson. The earliest eruptions produced a dacite tuff that lies unconformably on Hidden Valley andesite flows of the McCullough stratovolcano. The tuff is ~20 m thick and grades from a pumice-poor, lithic-rich base to a pumice-rich, lithic-poor top. Lithic fragments are mainly andesite of the McCullough stratovolcano.

GEOCHEMISTRY

The volcanic rocks in the McCullough Range are calc-alkaline and vary in composition from rhyolite to basalt (Table 1). Intermediate compositions (andesite and dacite) prevail, while basalt and rhyolite are rare (Figs. 8 and 9; Table 1). Mafic rocks associated with the McCullough stratovolcano, Colony volcano, and the Cactus Hill volcano are andesites (52–60 wt% SiO_2). Intermediate rocks of the Eldorado Valley and Sloan volcanic sections are andesite and dacite. While average values provide important information, individual volcanoes sometimes display considerable variation. An example is the McCullough stratovolcano. Boland (1996) collected 52 samples from major flow units from the base of the Farmer Canyon to the top of the Hidden Valley section (nearly 800 m of section) and demonstrated

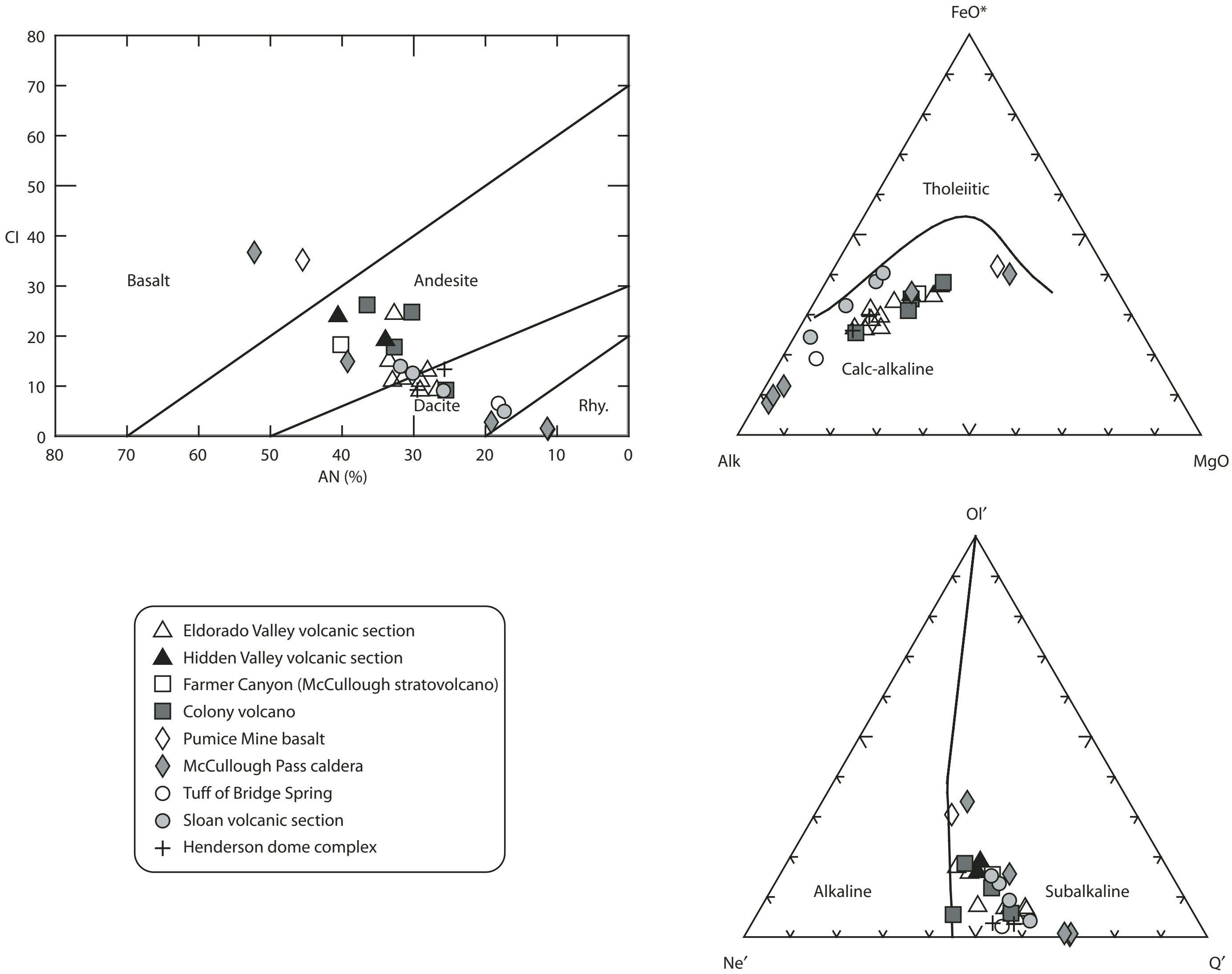


Figure 8. Chemical classification of volcanic rocks in the McCullough Range using the scheme of Irvine and Baragar (1971). Volcanic rocks are subalkaline (based on a normative nepheline, olivine, quartz plot), calc-alkaline (Na_2O+K_2O, MgO, FeO—AMF diagram), and vary in composition from rhyolite to basalt (CI—color index; An—normative anorthite content).

variation in stratovolcano andesite from 50 to 60 wt% SiO_2, without any consistent trend either up or down section.

A common trace-element pattern prevalent throughout the stratigraphic section is low Nb, P, Ti, and Zr when normalized to primitive mantle (Fig. 9). McCullough Pass rhyolite, however, displays greater depletions of these elements when compared to Eldorado Valley and Hidden Valley andesite and dacite. An especially diagnostic element is Zr. Sloan andesite and dacite are characterized by high (>500 ppm) Zr, while Hidden Valley and Eldorado Valley have between 300 and 400 ppm Zr. McCullough Pass rhyolite, andesite, and basalt typically have low Zr values (200–300 ppm). The Pumice Mine basalt is high in Zr (617 ppm), while the McCullough Pass basalt has much lower values (221 ppm Zr).

The trace-element chemical signature displayed by volcanic rocks of the McCullough Range is an indication of either a magma source in the continental lithosphere or lithospheric contamination. Rhyolite and dacite almost certainly formed by partial melting of crust. Mafic magmas (basalt and andesite) either originated by melting of lithospheric mantle, or they reflect asthenospheric magmas contaminated in the lithosphere (Wilson, 1989).

The chemistry in Table 1 is summarized from several studies completed over a period of over 20 yr. Furthermore, analyses were done by a variety of techniques in several analytical laboratories. As a result, differences in chemistry between rock types in some cases may reflect analytical quality and technique; therefore, comparisons between data sets must be viewed cautiously.

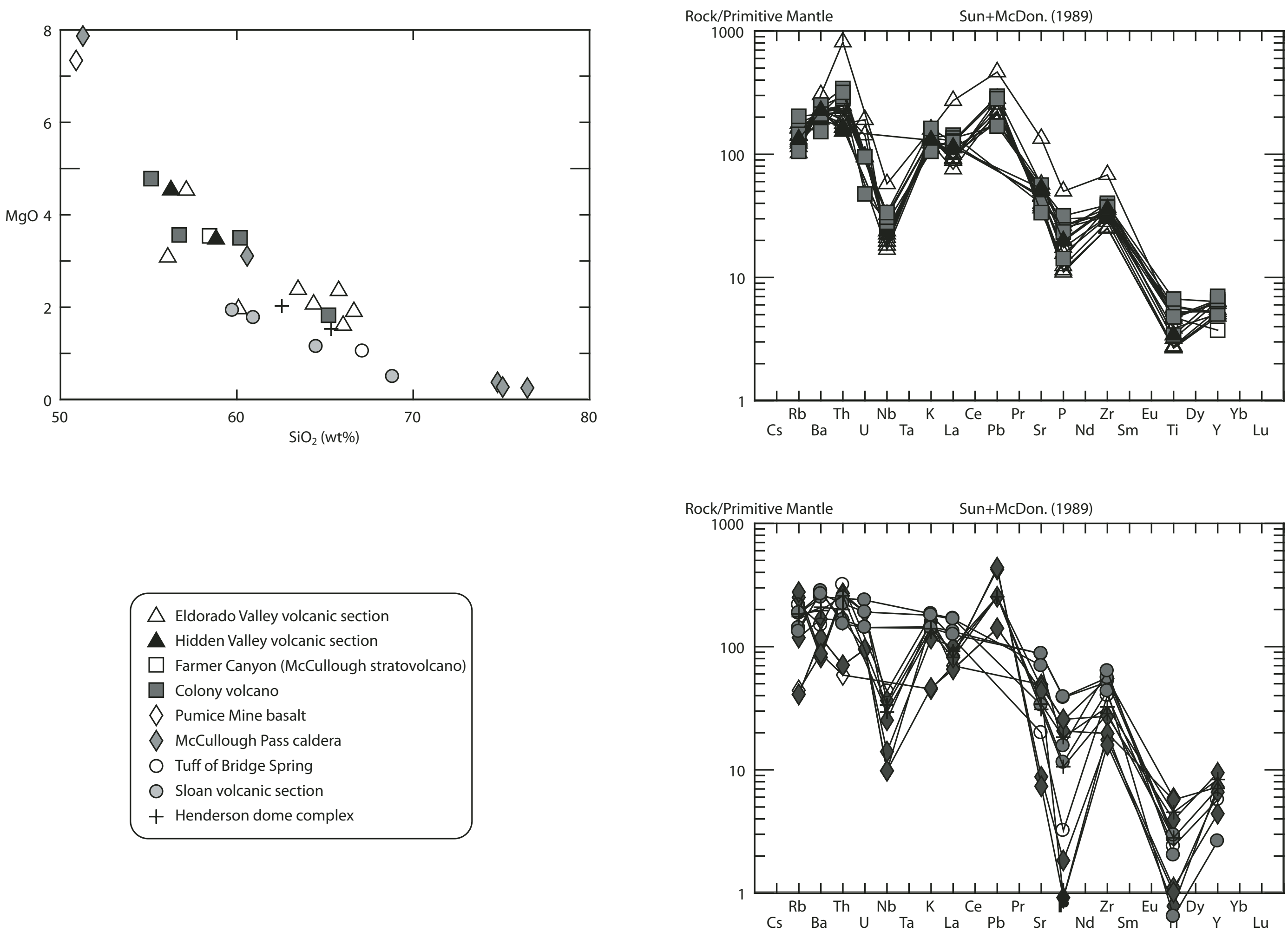


Figure 9. Chemical variation for major and trace elements for volcanic rocks of the McCullough Range.

DISCUSSION

We propose the following geologic sequence for volcanism in the McCullough Range (Figs. 4 and 7).

(1) Volcanism occurred on the west flank of the Kingman Arch, which was uplifted in Late Cretaceous time. Because Paleozoic and Mesozoic sections were stripped during the Early Tertiary, the volcanic section was mainly erupted on an irregular surface composed of Precambrian basement rock. Peach Springs Tuff (18.5 Ma) covered parts of the southern part of the range from a source outside of the McCullough Range, and it forms the base of the volcanic section.

(2) Dacite domes and basalt erupted from the Cactus Hill, McClanahan Spring, McCullough Wash, and Colony volcanoes in the central and southern McCullough Range (18.5–15.2 Ma). Dome formation and collapse events produced the voluminous block-and-ash deposits of the Eldorado Valley breccia.

(3) The McCullough stratovolcano accumulated over 400 m of andesite lava, agglomerate, and breccia of the Farmer Canyon volcanic section in the northern McCullough Range. Although the Colony volcano was partially covered by products of the McCullough stratovolcano, it served as a topographic barrier preventing Farmer Canyon lavas from flowing farther to the south.

(4) The tuff of Bridge Spring swept through the southern and central parts of the range (15.2 Ma). Tuff of Bridge Spring lies on the Eldorado Valley volcanic section in the McCullough Pass area but does not crop out to the north. Presumably, the Colony and McCullough volcanoes were topographic highs during the eruption of the tuff of Bridge Spring, causing the tuff to flow to the south around the southern flanks of these volcanoes.

(5) Cinder cones of the Pumice Mine basalt erupted basalt flows in the McCullough Pass area.

(6) The McCullough Pass caldera erupted explosively and produced the McCullough Pass tuff (14.1 Ma). Intracaldera activity resulted in numerous rhyolite domes, dikes, and related pyroclastic activity. A basalt plug and flows also contributed to intracaldera fill. The Colony volcano acted as a barrier to the

northward flow of the McCullough Pass tuff because it appears to pinch out to the north against exposures of Colony dacite.

(7) Activity continued at the McCullough stratovolcano, producing over 300 m of andesite lavas erupted from local centers (mainly cinder cones) distributed on the older Farmer Canyon andesite. This activity occurred after the eruption of the tuff of Bridge Spring (15.2 Ma), but the upper age is presently not well constrained.

(8) Eruptions formed the Sloan volcanic section and produced four volcanoes on the west flank of the McCullough stratovolcano (Mount Ian, Mount Sutor, Center Mountain, and Mount Hanna) (13.1 Ma).

(9) The Henderson dome complex formed on the northern flank of the McCullough stratovolcano and produced dacite domes, flows, and a thin pyroclastic flow deposit. The age of this event is not known precisely, but the dome complex cuts tilted and eroded lavas of the McCullough stratovolcano.

We regard the Eldorado Valley volcanic section and McCullough stratovolcano as the dominant volcanic constructs. Other younger events represent eruptions on the flanks of the stratovolcano.

The volcanic section in the McCullough Range is coeval with faulting related to regional extension. Although displacement and stratal rotation are minor compared to that in adjacent ranges (e.g., Anderson, 1971), numerous faults cut the Eldorado Valley section and the tuff of Bridge Spring and die out upward in the McCullough Pass caldera outflow tuff. Hidden Valley andesite is locally faulted but younger volcanic sections (Sloan, Henderson dome complex) are largely unaffected by faulting. Boland (1996) noticed that the central and northern McCullough Range is a broad synform with its axis passing through McCullough Pass and Hidden Valley. Many of the volcanoes in the McCullough Range are located on or near the axis of this dip reversal.

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