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Cover photograph: View northward across Grasshopper Creek hay meadow from center of SE¼, section 27. Light-colored tuffs in foreground are zeolitic strata; tuffs on the far side of the valley are non-zeolitic. Bold outcrops on the skyline are Tertiary basalt. Courtesy of Bruce E. Cox.

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Abstract

The largest recognized zeolite deposit in Montana is exposed along Grasshopper Creek 10 miles (16 kilometers) southwest of Dillon, where Cretaceous tuffaceous beds have altered to clinoptilolite accompanied by minor mordenite. The cation exchange capacity, as determined by the NH_4 method for 12 samples from this deposit, ranges from 0.68 to 1.29 milliequivalents/gram. Detailed mapping, surface sampling, and three drill holes demonstrate that this is a mineable deposit. Fourteen of 37 localities throughout Montana, mainly of Tertiary sedimentary rocks, are zeolitic. Approximately 60 percent of the 192 samples analyzed by X-ray diffraction contain a zeolite, usually clinoptilolite. Other commonly identified constituents are quartz, opal-CT, feldspar, biotite, and glass. Cation exchange capacity values determined for 80 samples range from 0.08 to 1.86 milliequivalents/gram with most values between 0.8 and 1.2 milliequivalents/gram. The 23 localities from which zeolites were not identified are described in appendix I. Podiform and discontinuous bedded zeolitic alteration at Muddy Creek, 38 miles (60 kilometers) southwest of Dillon, may prove to have greater continuity when mapped in more detail. Zeolitization of these Tertiary sedimentary rocks in southwestern Montana is thought to have been caused by interaction of ground water with permeable tuffaceous beds.

Introduction

Zeolites

The name, zeolite, is derived from the Greek word for *boiling stones* because when heated, zeolites form a frothy mass as if they were boiling. Zeolites are a unique group of minerals with more than 60 distinct natural species that because of their unusual properties have a large variety of uses (Mandarino, 1999). In addition to natural zeolites, more than 100 zeolite structures have been synthesized. Initial interest in zeolites centered around those that formed in cavities in igneous rocks and were of interest to mineral collectors because of their delicate crystals. More recently, mineable bedded zeolite deposits have gained commercial importance.

Zeolites are silicate minerals that contain aluminum, silicon, oxygen, and water in addition to sodium, calcium, and potassium ions that are loosely held in the crystal structure. Na, Ca, and K occur in channels in the zeolite lattice along with water molecules. The size of these channels in natural zeolites ranges from 2.6 Å for the relatively common zeolite analcime to 4.6 X 6.3 Å for laumontite. Exchangeable ions such as Na, Ca, and K balance the negative charge on the crystal structure, which is caused by the substitution of Al^{+3} for Si^{+4}. If a cation, such as Ca^{+2}, is displaced from one of the channels, it must be replaced by cations with an equal charge, *e.g.,* two Na^{+1} ions. The ability to exchange one cation for another can be measured and is reported as the cation exchange capacity (CEC) of the mineral. The smectite group of clays, including the common clay montmorillonite found in bentonite, and vermiculite also have high CECs. (See Mumpton [1977] for an excellent general discussion of the mineralogy and history of zeolite studies.)

Uses

Natural zeolites have numerous uses that primarily utilize their ability to selectively absorb specific cations or gaseous molecules. In spite of these many uses, markets have not developed in North America to the extent that many producers had anticipated. United States production of natural zeolites in 1998 was 42,400 short tons (38,500 metric tons) (Virta, 1999). Several companies developed zeolite deposits in the United States and began marketing their product only to find that the markets were insufficient to support their operations. Major deposits are found in Oregon, Idaho, Wyoming, Utah, Nevada, Arizona, California, New Mexico, and Texas (Holmes, 1994). All of these deposits have formed by the alteration of volcanic ash beds. Clinoptilolite is the dominant zeolite in these deposits, but mordenite, chabazite, erionite, phillipsite, and ferrierite also commonly occur.

The following description of some of the uses of natural zeolites is abstracted from Holmes (1994), who provides an excellent source of information on the occurrence and uses of natural zeolites.

Agriculture–Soil conditioners and carriers for insecticides and herbicides.

Feed supplements–Addition of a zeolite to animal feed improves weight gain of the livestock by promoting more efficient feed digestion.

Aquaculture–The ability of a zeolite to absorb ammonia helps to purify the water in fish farms. This is an important market for clinoptilolite in Japan.

Nitrogen removal from air–Several zeolites have been successfully used to remove nitrogen from air to produce an oxygen-enriched gas suitable for applications ranging from industrial to medical.

Pet litter–This is the largest market for natural zeolites in the United States. This application makes use of the ability of zeolites to absorb moisture and odor.

Removal of radioactive isotopes–Clinoptilolite has been used to remove the radioactive isotopes Sr^{90} and Cs^{137} from wastewater at nuclear facilities. Chabazite is especially effective in absorbing Cs^{137}.

Removal of heavy metals–Much research has been conducted in determining the suitability of zeolites for the removal of heavy metals such as Pb, Zn, and Cd from contaminated water and soils (see Duaime and others, 1997).

In addition to natural zeolites, there are more than 100 varieties of synthetic zeolites. Synthetic zeolites are preferred over natural zeolites in those applications where uniform quality is required or where a zeolite must be tailored to satisfy specific requirements. One example of widespread use is in detergents where, for environmental reasons, phosphates have been replaced by synthetic zeolites. These synthetic zeolites improve the efficiency of the detergent by acting as a water softener by absorbing Ca ions in hard water.

Previous Work

Prior to this study, there have been no published reports that systematically described zeolite occurrences in Montana. The only published information on a zeolite occurrence of sufficient size for possible mining is the report by Pearson (1989) on the occurrence of clinoptilolite in Cretaceous volcanic rocks along Grasshopper Creek and mordenite in similar volcanic rocks at Badger Pass—both areas south and west of Dillon, respectively. Sheppard (1976) tabulated 17 localities in Montana where zeolites had been identified. These occurrences, although of mineralogic interest, are generally too small to be of economic interest. For instance, some clinoptilolite occurs in low concentrations in the sand-size fraction of Cretaceous bentonites.

The following are some localities not listed by Sheppard (1976) and not examined in this study. Hare (1959) described small spherical masses of analcime in clay layers in the Tongue River Formation exposed in the Medicine Rocks area near Ekalaka in southeastern Montana. Lyons (1942) described zeolite veinlets, amygdule fillings, and the replacement of rock-forming minerals in igneous rocks in the Big Belt Mountains of central Montana. He found analcime, mesolite, thomsonite, stilbite, heulandite, and apophyllite in these igneous rocks. A similar occurrence of zeolites is reported from the Adel Mountain Volcanics, also in central Montana (Whiting, 1977). Analcime also occurs in veinlets and in irregular masses up to several inches across in mafic phonolite exposed in the Highwood Mountains of central Montana (Vuke and others, 1995). A variety of zeolites occur at the Stillwater mine near Nye, Montana. Calcitic veinlets within the palladium and platinum-bearing Banded series contain lenticular vugs lined with zeolites. Mineral species tentatively identified to date include chabazite, stilbite, natrolite, and laumontite (personal communication Ennis Geraghty, Stillwater Mining Company, 2001).

Present Work

In 1991, Montana Bureau of Mines and Geology (MBMG) and Resource Development Bureau of the Montana Department of Natural Resources and Conservation researchers began investigating the use of natural zeolites in reducing the heavy-metal concentrations in water. This cooperative project was directed toward providing an economic means of water purification associated with small abandoned mines. (See Duaime and others [1997] for the results of extensive laboratory testing of natural zeolites, largely from Montana localities.) The results of the search for bedded zeolite deposits in central and western Montana are described in this report, which supersedes MBMG Open-File Report 267 (Berg and Lonn, 1993).

Tertiary and Cretaceous formations were examined for zeolitic beds. This reconnaissance concentrated on Tertiary volcaniclastic rocks of western Montana, largely in the intermontane basins in the southwestern part of the state. Those localities where zeolites were identified by x-ray diffraction analysis were further examined and sampled. Although zeolites occur in extrusive igneous rocks, such as basalts, these occurrences were not investigated because they are limited to amygdule fillings or veinlets and are of insufficient size to be economically important. The localities where zeolites were found are shown in figure 1.

Recognition and Characterization of Zeolites

Field Recognition of Zeolitized Beds

Some characteristics of zeolitized beds, such as weathering and color, are recognizable from a distance and are helpful in field reconnaissance. Most important, these characteristics enable one to eliminate most non-zeolitized beds from further consideration and to concentrate on examining and sampling the beds that appear zeolitized. These observations were made during field work in western Montana and may not apply to areas of different climatic conditions.

Weathering Characteristics

Zeolitized beds are more resistant to erosion than other beds typically associated with them and in many instances form ledges, ridges, or mesas. However, bentonitic mud-

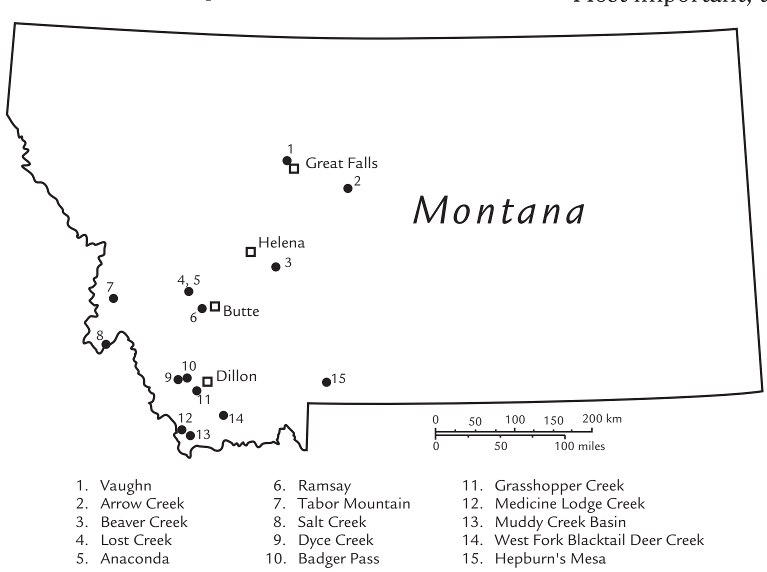

Figure 1. Map showing localities where zeolites were identified.

stone beds, which are frequently associated with zeolitic beds, form cliffs that typically erode to form slightly rounded outcrops or badlands topography. In contrast, zeolitized beds generally weather to form more angular outcrops and blocky fragments. Small rills generally form on slopes of bentonitic mudstone but are absent on zeolitized beds. Non-zeolitized beds of volcanic ash can be resistant to erosion and can be confused with zeolitized beds. However, in exposures where there are prominent ash beds, there is a reasonable possibility of the occurrence of zeolitized beds, and they should be examined thoroughly. Glassy volcanic ash can often be recognized with a hand lens in bright sunlight. Unaltered volcanic ash and bentonite commonly occur with zeolitic beds, but many bentonite and volcanic ash beds show no evidence of zeolitization.

Color

Most zeolitized beds identified in Montana appear white from a distance but in some instances show scattered pale green areas. Light color is the most easily recognizable initial clue to the possibility of zeolitic alteration. Tan beds common in the Tertiary sedimentary sequence of southwestern Montana were not zeolitized. Color designations of samples reported here are based on the rock color chart prepared by Goddard and others (1963).

Field Tests

No simple field test was found that could easily be used for the identification of zeolitic beds. During the study, approximately 50 percent of the samples of possible zeolitized tuff collected in the field were found to contain a zeolite in significant concentration when analyzed by x-ray diffraction. Many non-zeolitic samples consisted mainly of glass with pyrogenic quartz and feldspar.

Because of its high porosity, zeolitic material is lightweight and sounds “punky” when hit with a hammer. Most zeolitic samples weather to form small, blocky fragments and when broken with the hammer, break into blocky chunks. Stinson (1988) stated that when small fragments of a zeolitized rock are shaken together they have a dull hollow rattle. Zeolitized specimens will stick to the tongue as will other porous rocks. A test that has met with success in identifying natural zeolites uses a tetraalkylammonium bromide solution after treatment with silver nitrate (Helfferich, 1964). Although this is probably a simple laboratory procedure, it is not a test that can be conveniently accomplished under most field conditions and was not tried in this study.

Because zeolites form a frothy mass when heated, it was thought that this property could be used to advantage in a simple field test. Therefore, a small chip of the suspected zeolite (about 3 millimeters across) was heated for 5 seconds in the hottest part of the flame of a miniature gas torch. The torch uses a mixture of nitrous oxide and butane to produce a flame with a reported temperature of 2760°C. Most specimens showed some vesiculation or frothing when heated. The samples were divided into four categories based on the degree of vesiculation as judged by examination with a binocular microscope (figure 2). A comparison of these categories with the presence of a zeolite as determined by x-ray diffraction analysis shows a tendency for those samples that contain a zeolite to vesiculate more than those lacking a zeolite; however, this test is far from consistent.

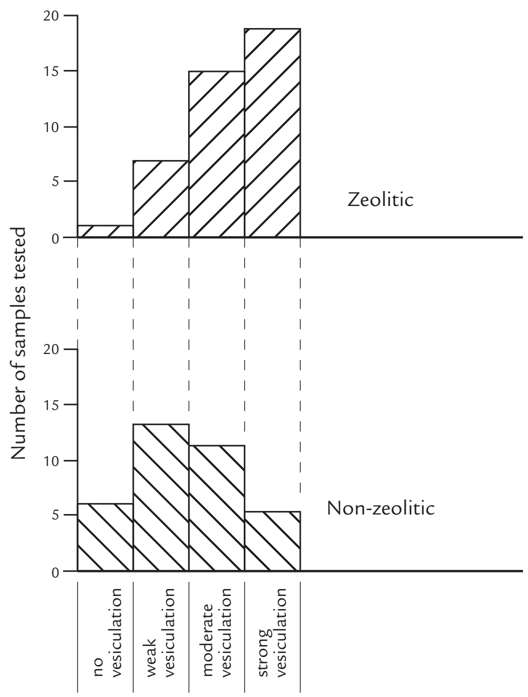

Figure 2. Effects of heating 88 zeolitic and non-zeolitic samples with nitrous oxide–butane torch. Identification of zeolitic specimens by x-ray diffraction analysis.

The moisture content of the samples probably is varied and influences the amount of vesiculation and, therefore, possibly explains the inconsistent results. Because the attempt was to develop a simple field test, drying the samples to uniform moisture content was not tried.

Mineralogy

Mineralogy of samples of altered tuffaceous beds was determined using a Norelco x-ray diffractometer equipped with a diffracted-beam monochrometer yielding a CuKα diffracted beam. Samples were prepared by packing pulverized material into metal sample holders and routinely scanned at 2° 2θ/minute from 2° to 32°, except for a few samples that were scanned to higher values of 2θ. A range of 1 K and time constant of 2 were used; samples were scanned using 1° soller and scatter slits. Routine identification of commonly encountered minerals was determined by comparing the x-ray diffraction trace obtained from the sample to traces of specific minerals. Pulverized samples of some specimens were examined in immersion oil using the petrographic microscope. Because of the small grain size of zeolites in these samples, optical examination was not very useful. Some samples were examined using scanning electron microscopy, which was particularly useful in showing textural relationships between mineral phases.

The most common zeolite in the 190 samples analyzed by x-ray diffraction analysis was clinoptilolite (table 1, back pocket). Ninety-five samples contained clinoptilolite in concentrations that ranged from a trace to more than 90 percent. Crude estimates of clinoptilolite concentrations were based on the height of the 044 peak as compared to peak intensities for other phases such as opal-CT, quartz, and feldspar. The 044 peak was chosen because other minerals commonly present in these samples do not interfere with it. The typically intense 020 peak was not used because it is strongly influenced by preferred orientation of clinoptilolite caused by its perfect 010 cleavage. The semi-quantitative relationship between peak intensity and clinoptilolite content is exemplified by sample Z-93 from the Ramsay area (locality 6) and sample Z-466 from Tabor Mountain (locality 7). Both samples consisted essentially of clinoptilolite on the basis of scanning electron microscopy, and each had a relatively high cation exchange capacity. However, comparison of the x-ray diffraction traces shows a large variation in peak intensities (figure 3).

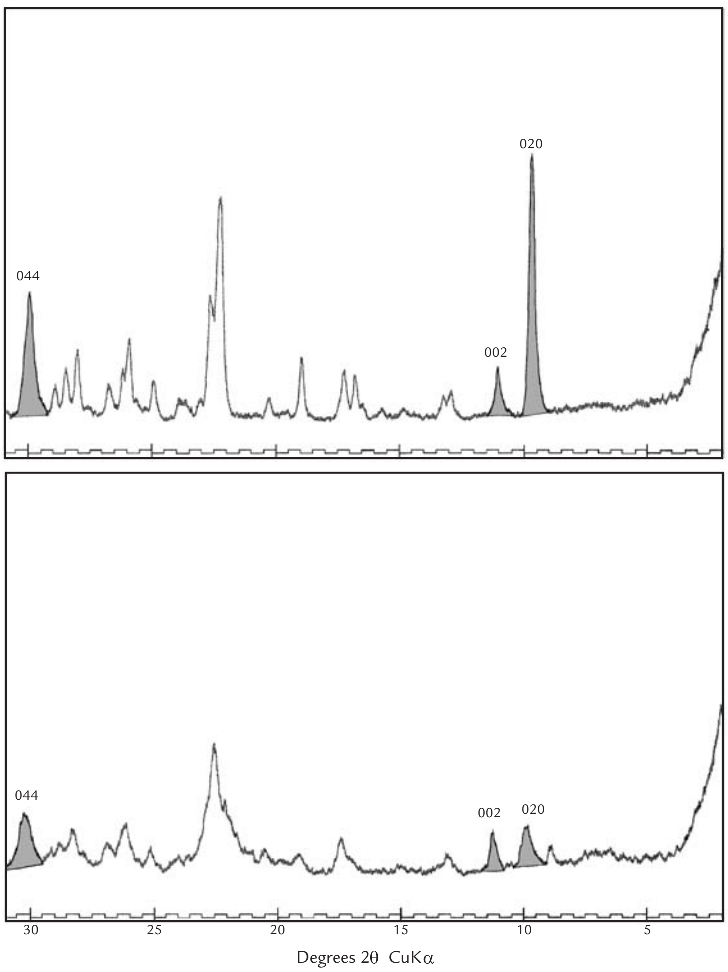

Figure 3. X-ray diffraction traces of samples that consist essentially of clinoptilolite. Both samples were prepared in the same manner and packed into metal sample holders. Instrument settings were the same for both samples, which were scanned using CuKα radiation. Major clinoptilolite peaks used for identification or to estimate abundance are shaded. A–Sample Z-93 clinoptilolite from the Ramsay locality with CEC of 0.94 (see figure 17 for scanning electron micrograph of this specimen); B–Sample Z-466 clinoptilolite from the Tabor Mountain locality with CEC of 1.86 (see figure 20 for scanning electron micrograph of this specimen).

To verify the identification of clinoptilolite, five samples (Z-93, Z-127, Z-134, CH, and XY) were heated at 450°C overnight. Zeolites CH and XY are commercially available clinoptilolite provided by Teague Mineral Products of Adrian, Oregon. The lower thermal stability of heulandite will cause it to become x-ray amorphous under these conditions, whereas clinoptilolite will be unaffected (Mumpton, 1960). Although similar in crystal structure, clinoptilolite contains more silica in the structure than heulandite. X-ray diffraction traces from scans made after heating these samples showed no change from the unheated samples, thus identifying clinoptilolite.

Analcime is a major constituent of samples Z-72 and Z-73 from the Blackleaf Formation in the Vaughn area (locality 1) and a minor constituent of one sample (Z-324) from Medicine Lodge basin (locality 12). An x-ray diffraction trace of a sample consisting mainly of analcime is shown in figure 4. Mordenite is a major constituent of only one sample (Z-71 from Badger Pass) and a minor constituent of several other clinoptilolite-bearing samples (table 1).

Numerous samples thought to be zeolitized tuff when collected were found to consist mainly of glass when analyzed by x-ray diffraction techniques. Glass was recognized by a "hump" in the background of the x-ray diffraction trace in the range between approximately 19 and 24° 2θ.

Smectite in low concentrations is a common constituent of many of these samples. The presence of a mineral of the smectite group was generally recognized by a broad peak that indicates a mineral with a d spacing between 12 and 15 Å.

The opaline silica phase, opal-CT, is a common constituent of altered tuffaceous rocks and occurs in low concentrations in many of the zeolitic samples. Identification was based on the broad x-ray diffraction peak from 4.07 to 4.09 Å (Elzea and others, 1994). This peak was recognized only as a shoulder on the low-angle side of the clinoptilolite 004 peak in some samples. For those samples scanned past 36° 2θ, the small opal-CT peak that indicates a d spacing of 2.5 Å could be recognized (figure 5). As would be expected, alpha quartz is present in most samples. The quartz 100 peak (3.34 Å) is a useful internal standard for the determination of other d spacings.

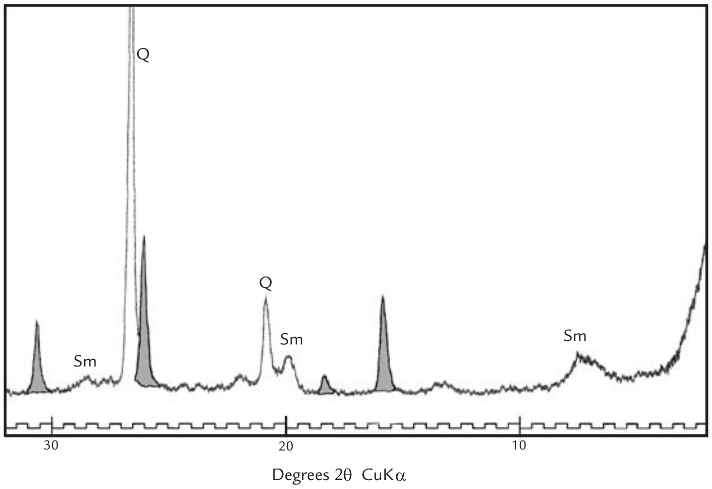

Figure 4. X-ray diffraction trace of sample Z-72 of analcime from the Vaughn Member of the Bootlegger Formation exposed near Vaughn, Montana. Pulverized sample packed into metal sample holder and scanned with CuKα radiation. Analcime peaks are shaded, Sm indicates smectite peaks, and Q indicates quartz peaks.

Small, shiny black flakes of biotite are recognizable with a hand lens in some samples and produce a sharp 10 Å peak that is enhanced by the preferred orientation of these flakes. Feldspar is a common constituent of many samples as indicated by the 3.2 Å peak. Calcite is a common constituent that occurs in many samples in low concentrations, and gypsum was also detected in several samples.

Cation Exchange Capacities

Cation exchange capacities (CEC) of selected samples were determined by Steven Boese, Department of Geology/Geophysics, University of Wyoming (table 2). The ammonium ion exchange capacity was determined by saturating the zeolite with Na by using a solution of 1M Na_2SO_4, washing the sample with distilled water, drying, displacing the Na using a solution of 0.1M $(NH_4)_2SO_4$, and determining the Na concentration in the displacing solution by atomic absorption. Exchangeable cations were determined by displacing the cations with a solution of 1M $NH_4C_2H_3O_2$ at pH 7.0 and determining the cation concentration in the displacing solution by flame atomic absorption.

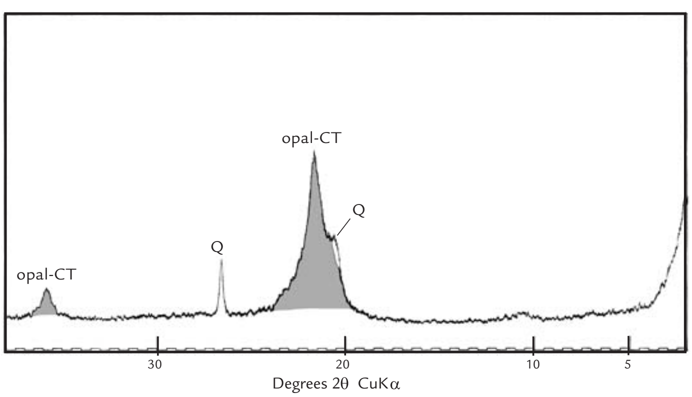

Figure 5. X-ray diffraction trace of sample Z-213 from Beaver Creek that consists of opal-CT and minor quartz. Pulverized sample packed into metal sample holder and scanned with CuKα radiation. Opal-CT peaks shaded. Q indicates quartz peak.

Table 2. Exchangeable cations, CEC, and ratio of 020/002 xrd peak heights for selected samples. A=analcime, M=mordenite, C=clinoptilolite. Sample number followed by "d" indicates blind split of same sample submitted for analysis. Exchangeable cation and CEC analyses by Steven Boese.

Sample number	Dominant zeolite	NA	K	Ca	Mg	Sr	Sum of exchangeable cations meq/gm	NH_4 CEC meq/gm	Ratio of 020/002 xrd peak heights
VAUGHN									
Z73	A							0.23	
Z76	A							0.26	
ARROW CREEK									
Z85	C							1.21	1.60
Z86	C							1.12	1.10
BEAVER CREEK									
Z36	C							1.19	2.30
Z37	C							0.86	3.20
Z39	C							1.40	1.10
Z49	C							0.86	1.40
Z50	C							1.02	1.90
Z60	C							1.08	1.60
Z60d	C							1.06	
Z206	C							1.00	1.90
Z207	C							0.99	1.90
Z209	C							1.19	1.50
Z211	C							0.50	2.50
Z402	C							1.34	
Z405	C	0.19	0.41	0.17	0		0.77	0.80	2.20
Z406	C	0.45	0.74	0.29	0.01		1.49	1.41	1.70
Z408	C	0.30	0.59	0.29	0.01		1.19	1.10	1.50
LOST CREEK									
Z288	C							0.65	6.0
RAMSAY									
Z93	C	0.24	0.45	0.12	0.01	0.004	1.08	0.94	
Z93d	C	0.13	0.36	0.14	0.01	0.87	0.64	0.87	
Z313	C							0.52	3.50
TABOR MOUNTAIN									
Z346	C							1.44	1.40
Z349	C							1.54	1.20
Z351	C	0.36	0.39	0.73	0.01		1.49	1.50	1.50
Z353	C							1.24	3.60
Z354	C	0.74	0.56	0.62	0		1.92	1.80	1.40
Z466	C	0.73	0.58	0.53	0	1.86	1.84	1.86	
Z467	C	0.46	0.35	0.65	0	1.6	1.46	1.60	
Z468	C	0.35	0.42	0.57	0.01	1.33	1.35	1.33	
Z469	C	0.37	0.3	0.43	0	1.11	1.1	1.11	
Z471	C	0.66	0.58	0.56	0	1.9	1.8	1.90	
SALT CREEK									
Z340	C							0.79	1.80
Z341	C							0.08	13.0
Z342	C							0.58	2.40
Z342d	C							0.56	
Z343	C							0.76	3.0
Z344	C	0.49	0.32	0.25	0		1.06	1.04	1.80
Z344d	C							1.00	

Table 2 continued.

Sample number	Dominant zeolite	NA	K	Ca	Mg	Sr	Sum of exchangeable cations meq/gm	NH_4 CEC meq/gm	Ratio of 020/002 xrd peak heights
				SALT CREEK CONTINUED					
Z324	C							0.17	
Z328	C							0.18	
Z329	C							0.37	2.80
				DYCE CREEK					
Z274	C							1.38	1.50
Z276	C							0.65	2.80
Z277	C							1.21	1.40
Z319	C							0.52	2.50
Z319d	C							0.50	
Z320	C							0.86	1.60
				BADGER PASS					
Z71-1	M							1.04	
Z71-2	M							0.89	
Z193	M							0.36	
Z196	M							1.27	
				GRASSHOPPER CREEK					
Z126	C							0.96	1.80
Z127	C	0.19	0.28	0.59	0.016	0.004	1.08	0.93	
Z127d	C							0.91	
Z131	C							0.76	3.0
Z133	C+M							1.29	2.20
Z134	C	0.17	0.35	0.42	0.039	0.007	0.98	1.17	
Z134d	C							0.93	
Z136	C							1.17	2.80
Z137	C							1.10	3.40
Z138	C							0.68	5.10
Z140	C	0.15	0.62	0.56	0.02		1.35	1.23	3.10
Z364	C							0.94	6.60
Z365	C							1.15	3.0
Z366	C							0.89	8.70
Z444	C	0.49	0.24	0.68	0.03		1.44	1.22	2.70
Z445	C	0.57	0.21	0.37	0.02		1.17	1.22	2.80
				MEDICINE LODGE CREEK					
Z324	C							0.17	
Z328	C							0.18	
Z329	C							0.37	2.8
				MUDDY CREEK					
Z246	C	0.01	0.57	0.34	0.01		0.93	0.87	2.30
Z247	C	0.01	0.55	0.46	0.02		1.04	0.98	2.20
Z248	C	0.02	0.58	0.6	0.02		1.22	1.19	1.50
Z249	C	0.01	0.45	0.42	0.01		0.89	0.89	2.0
Z416	C							0.77	1.60
Z417	C							0.29	3.60
Z421	C							0.96	2.30
Z428	C							0.51	2.80
Z429	C							0.49	2.20
Z433	C							0.50	2.10
				WEST FORK BLACKTAIL DEER CREEK					
Z222	C	0.30	0.7	0.41	0.03		1.44	1.31	1.50

Comparison of X-ray Diffraction Data and CEC Values

A plot of the NH_4 CEC, and the ratio of the 020/002 peak heights shows an interesting relationship (figure 6 and table 2). Those samples from Tertiary beds with a higher ratio of 020/002 peak heights tend to have lower CEC values. However, samples from the Grasshopper Creek deposit in Cretaceous beds do not show this relationship. There may be several factors that contribute to this trend for samples from Tertiary beds. Coarser grained clinoptilolite, when pulverized and packed in the metal sample holder, has a greater degree of preferred orientation caused by the perfect 010 cleavage as compared to finer grained clinoptilolite. This preferred orientation causes an increase in the 020 peak intensity as compared to the 002 peak intensity. Coarser grained clinoptilolite has less external surface area than finer grained clinoptilolite. Greater external surface area should, at least to some extent, increase CEC. Although not directly evaluated, crystal imperfections may play a role in determining CEC. Less nearly perfect crystals would tend to give broader x-ray diffraction peaks with lower peak heights than those peaks produced from crystals with fewer imperfections. It is likely that those crystals with more imperfections would have greater CECs. Variation in the exchangeable cation populations (not total CEC) also may have an effect on peak intensities.

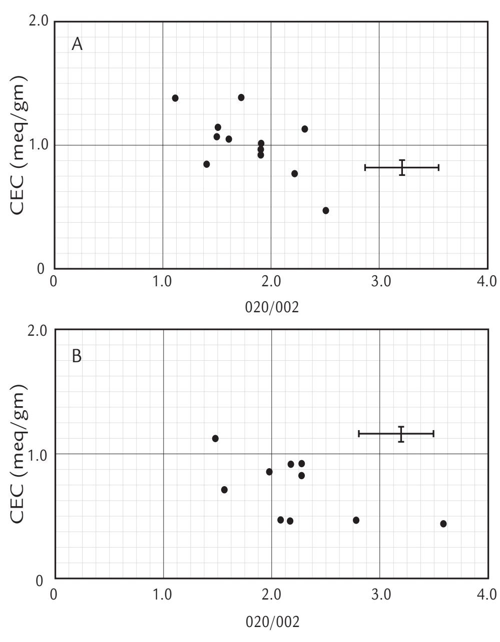

Figure 6. Plot of CEC values vs ratio of 020/002 clinoptilolite x-ray diffraction peak heights for samples from Beaver Creek (A) and Muddy Creek (B). Reproducibility of analyses shown by bars.

Montana Occurrences

The occurrences of zeolites in Cretaceous and Tertiary sedimentary rocks in southwestern Montana are not limited to one geographic area or to beds of one age. Zeolites, mainly clinoptilolite, occur in beds ranging from lower Cretaceous (*e.g.,* the Vaughn occurrence) to Miocene (the Hepburn's Mesa occurrence) (table 3). However, most of the described occurrences are in Tertiary beds because these beds more commonly contain high concentrations of volcanic ash and perhaps because these beds were more thoroughly examined than the Cretaceous beds of central and eastern Montana.

Zeolitic beds were found in only four of the major Tertiary basins of southwestern Montana (figure 7). The greatest abundance of zeolite occurrences recognized are in two basins south of Dillon. Because Tertiary sedimentary rocks are not shown on geologic maps for the Madison Valley, this area was not examined for possible occurrences. Although other basins were searched for zeolitized beds, evidence of zeolitization was not found. Localities that were examined but did not contain zeolites are listed in appendix 1. The following are descriptions of specific occurrences.

Figure 7. Tertiary basins of southwestern Montana modified and simplified from Geologic Map of Montana (Ross and others, 1955). Stippled basins are those in which at least one occurrence of a zeolitic rock was identified.

Vaughn

Location: S½ section 2, T. 21 N., R. 2 E. and S½ section 35, T. 22 N., R. 2 E., Manchester 7 ½-minute quadrangle, Cascade County. Approximately 6 miles (10 kilometers) northeast of Vaughn.

Table 3. Zeolite species listed in order of decreasing abundance for distribution of zeolite occurrences by geologic age of zeolitic beds for a specific locality. Numbers refer to localities shown on figure 1; clino=clinoptilolite, mord=mordenite.

	Age	Host Rock or Formation	Locality	Zeolite
Tertiary				
	Miocene	Hepburn's Mesa Formation	Hepburn's Mesa (15)	clino
	Oligocene	Renova Formation	Muddy Creek (13)	clino
		Not designated	Beaver Creek (3)	clino
	Eocene	Challis Volcanics	Salt Creek (8)	clino
			Tabor Mountain (7)	clino
		Lowland Creek Volcanics	Lost Creek (4)	clino
Tertiary undivided				
			Anaconda (5)	clino
			Ramsay (6)	clino
			Dyce Creek (9)	clino
			Medicine Lodge Creek (12) West Fork	clino
			Blacktail Deer Creek (14)	clino
Cretaceous				
		Tuff of Grasshopper Creek	Grasshopper Creek (11)	clino, mord
		Tuff of Grasshopper Creek	Badger Pass (10)	mord, clino
		Mowry Formation (Arrow Creek Bed)	Arrow Creek (2)	clino
		Blackleaf Formation (Taft Hill Member)	Vaughn (1)	analcime

Ownership: Unknown

The Taft Hill, Vaughn, and Bootlegger members of the Lower Cretaceous Blackleaf Formation are exposed in a 320-foot (98-meter) section north of the Sun River Valley (Lemke, 1977). The Taft Hill Member, the lowest of these members, consists of bentonitic shale with some sandstone and siltstone beds (Cobban and others, 1976, p. 15–25). The zeolitic layer occurs within a bentonite bed that forms a small mesa visible from the county road (locality 72, figure 8). The zeolitized bed appears white from a distance, but on closer examination is very pale orange (10 YR 8/2). This 8-inch- (20-centimeter-) thick bed is massive, except for the upper 1 inch (3 centimeters), which is finely laminated. Quartz is the most abundant constituent, analcime the next most abundant, and smectite is present in low concentrations. This bed is traceable for 38 feet (12 meters) and pinches out in both directions along strike. No other zeolitized beds were recognized in the Taft Hill Member. However the >44 µm fraction of bentonite from this exposure contains some bright orange–red grains that appear similar to the orange-red grains of clinoptilolite in the Vaughn Member of the Blackleaf Formation.

The other zeolite occurrence in these exposures is within a 10-foot- (3.0-meter-) thick bentonite bed in the Bootlegger Member of the Blackleaf Formation (locality 76, figure 8). Hard, light grey (N 8) fragments apparently derived from concretions 1.6 feet (<0.5 meters) long are scattered over exposures of the bentonite bed. These fragments consist mainly of quartz with lesser analcime and smectite with minor feldspar.

Arrow Creek Bed

Location: The Arrow Creek Bed of the Bootlegger Member of the Blackleaf Formation was sampled at the following three localities (figure 9).

(1) Exposure along the road to the top of Belt Butte in the SW¼ NE¼ section 30, T. 19 N., R. 7 E., Belt 7½-minute quadrangle, Cascade County, approximately 3 miles (4 kilometers) east of the town of Belt (figure 9A).

(2) In a cut on a ranch trail on the north side of Arrow Creek in the SW¼ NW¼ section 24, T. 18 N., R. 10 E., Geyser 7½-minute quadrangle, Judith Basin County, approximately 6 miles (9 kilometers) northeast of Geyser (figure 9B).

(3) Southeast portal of the Dover railroad tunnel in the SW¼ SW¼ section 13, T. 17 N., R. 11 E., Merino 7½-minute quadrangle, Judith Basin County, approximately 6 miles (9 kilometers) northwest of Stanford (figure 9C).

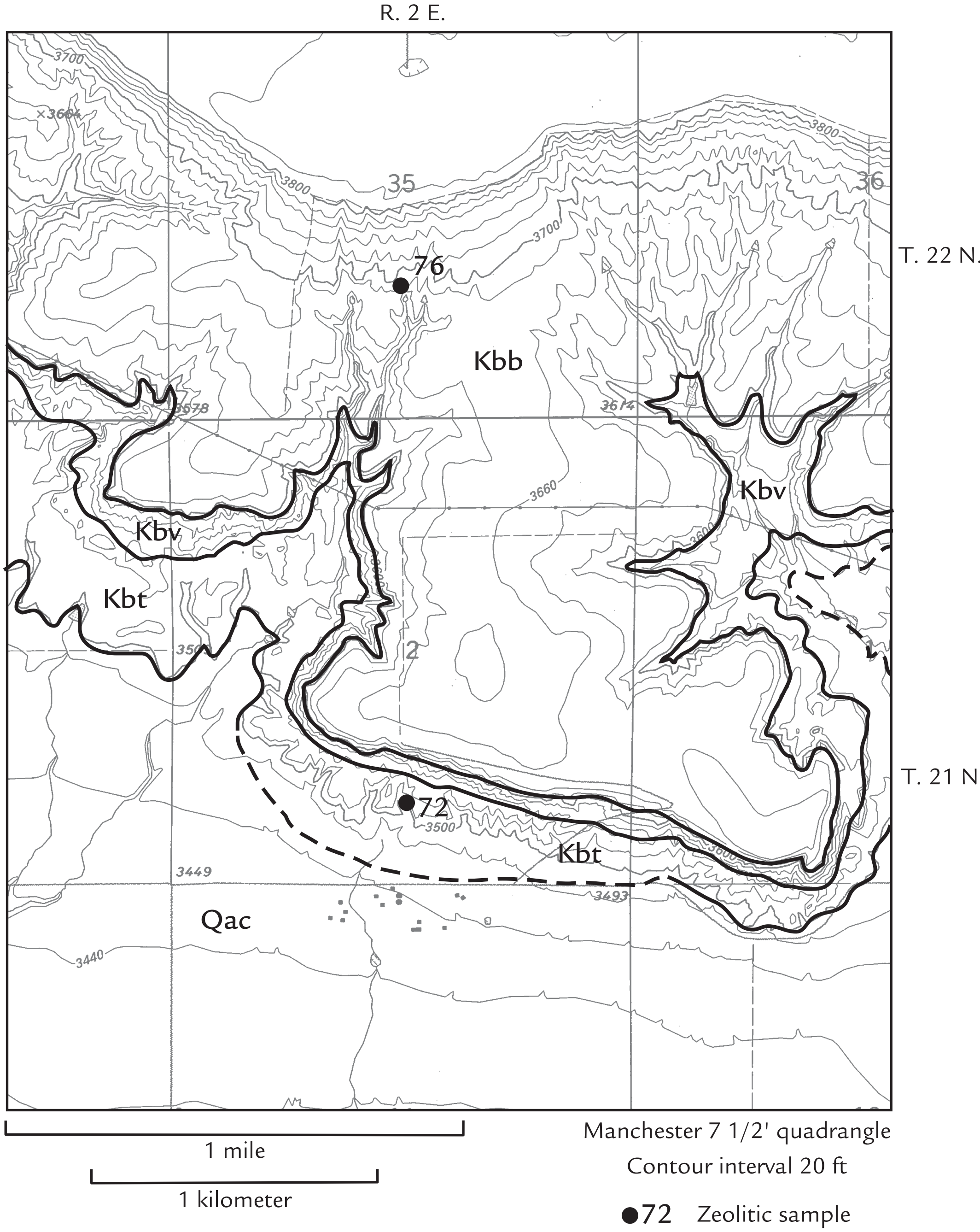

Figure 8. Vaughn analcime occurrence. Geology from Lemke, 1977. Kbb=Bootlegger Member, Kbv=Vaughn Member, Kbt=Taft Hill Member, all of the Blackleaf Formation. Qac=alluvium and colluvium.

Ownership: Private land

The Arrow Creek Bed is intermittently exposed southeast of Great Falls from Belt Butte for at least 37 miles (59 kilometers) southeast to the Stanford area (Vuke and others, 1995). This prominent bed, which ranges from 5 inches (13 centimeters) to 65 feet (20 meters) thick, is in the Bootlegger Member of the Upper Cretaceous Blackleaf Formation. Near the southeastern extent of these exposures, a change in stratigraphic nomenclature places the Arrow Creek Bed at the base of the Mowry Formation. Because of the light grey exposures of the Arrow Creek Bed and abundance of sparsely vegetated bentonite, this bed is easily recognized north of Geyser.

At Belt Butte, the Arrow Creek Bed is 33 feet (10 meters) thick and is 213 feet (65 meters) above the top of the sandstone at the base of the Bootlegger Formation, which forms the belt on this butte (Berg, 1991). Four samples of the Arrow Creek Bed collected along the road to the top of Belt Butte and on the south side of Belt Butte consist mainly of quartz and albite.

Farther southeast, the Arrow Creek Bed is well exposed along Arrow Creek and consists of concretionary masses of zeolitized tuff (light grey,

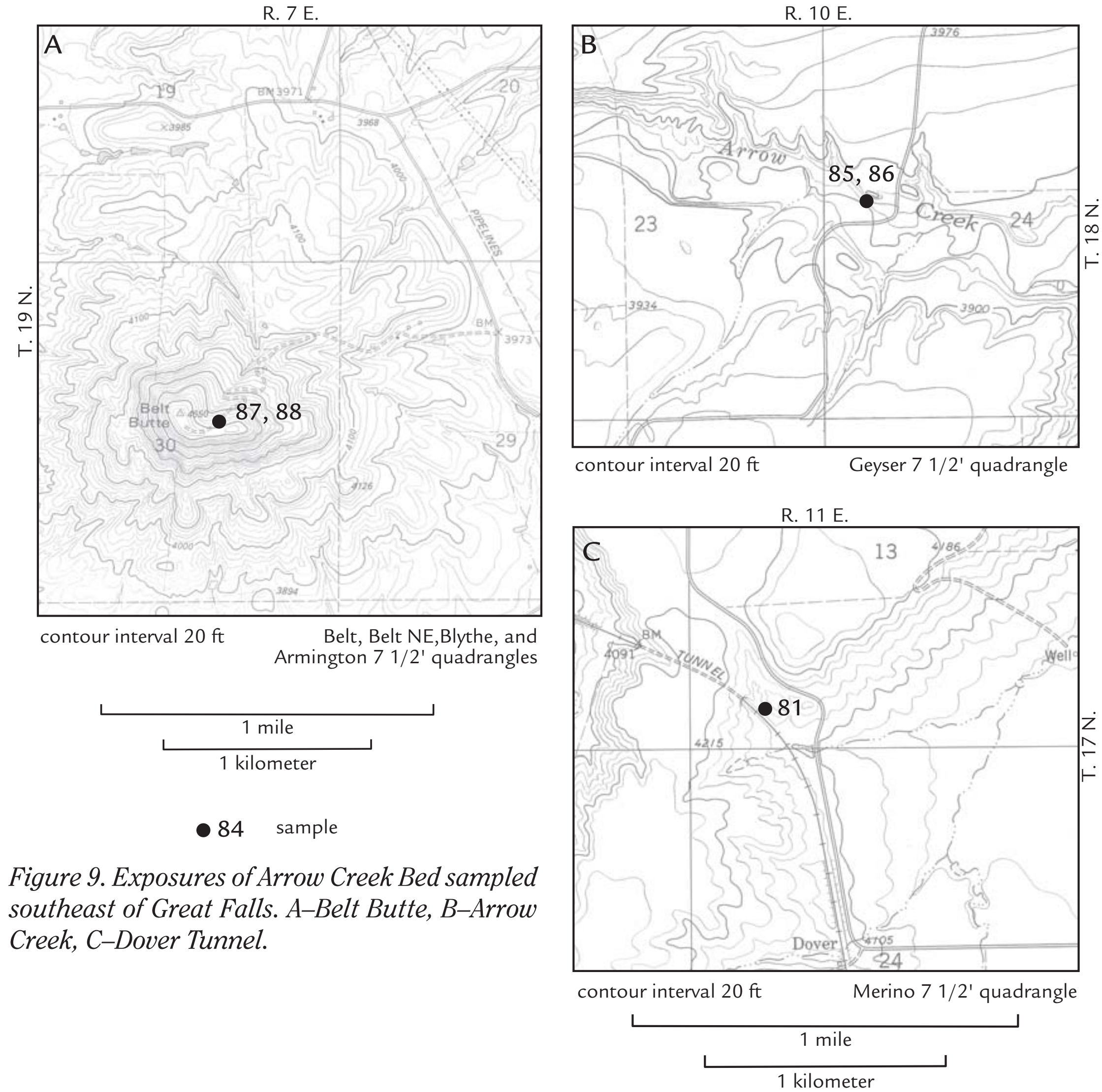

Figure 9. Exposures of Arrow Creek Bed sampled southeast of Great Falls. A–Belt Butte, B–Arrow Creek, C–Dover Tunnel.

N 7) in bentonite (figure 10). Two specimens of these concretionary masses contain major concentrations of quartz, clinoptilolite and lesser opal-CT. A chemical analysis of a sample from this bed shows it contains 10.65 percent Al_2O_3, which if entirely attributed to clinoptilolite, indicates that clinoptilolite is the major constituent (table 4). A sample of a concretionary bed within the Arrow Creek Bed collected at the portal of the Dover railroad tunnel also consists mainly of quartz and clinoptilolite with lesser calcite and smectite. Light tan laminae, <1 millimeter to several millimeters thick, in these concretions show small folds and faults with displacements of a few millimeters. Relict glass shards are recognizable in thin section.

Between Belt Butte and the Geyser area, the Arrow Creek Bed is poorly exposed but can be traced from float of flinty porcellanite concretions. Although zeolites may be scattered over a large area, there is no indication of an economic deposit.

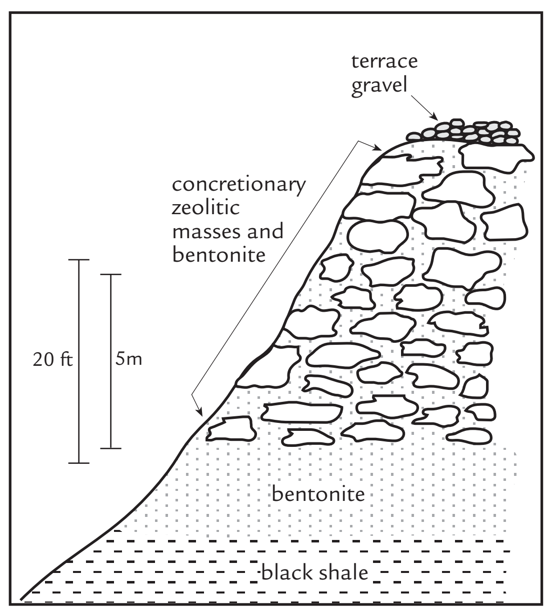

Figure 10. Sketch of exposure of the Arrow Creek Bed along Arrow Creek.

Table 4. Chemical analysis of sample from zeolitic concretionary bed exposed along the north side of Arrow Creek about 6 miles (9 kilometers) northeast of Geyser (figure 10). Analysis by the analytical laboratory of the Montana Bureau of Mines and Geology. Total Fe is calculated as Fe_2O_3.

	wt. %
SiO_2	73.38
Al_2O_3	10.65
Fe_2O_3	0.35
MgO	0.74
CaO	2.61
K_2O	1.50
Na_2O	1.78
TiO_2	0.10
P_2O_5	0.13
MnO	0.0072
CO_2	0.48
H_2O+	7.63
Total	99.36

Beaver Creek

Location: West side of Canyon Ferry Lake in sections 17, 18, 19, 20, 21, 22, 27, 28, 29, 33, 34, T. 9 N., R. 1 E., Canyon Ferry SW, Canyon Ferry SE, Winston, and Townsend NE 7½-minute quadrangles, Broadwater County. Exposures north and south of Beaver Creek are approximately 3 miles (5 kilometers) east of Winston. The best access to the northern exposures is from a private road, not shown on the topographic map, that joins the county road at the SW corner of section 24, T. 9 N., R. 1 E. A dry-weather jeep trail branches off to the east from this private road in the SW¼ NW¼ section 24, T. 9 N., R. 1 E., and continues into the area of exposed beds.

Ownership: Private, Bureau of Land Management–administered land and Bureau of Reclamation–administered land along the shore of Canyon Ferry Lake.

The Townsend Valley, situated in the fold and thrust belt of west-central Montana, is a north south–trending valley that curves westerly and joins the Helena Valley to the north. It is surrounded by metasedimentary rocks of the Proterozoic-age Belt Supergroup and by Paleozoic sedimentary rocks that have been intruded by Tertiary or Cretaceous granitic plutons. Tertiary sedimentary rocks that contain a large component of volcanic material are exposed in the Townsend Valley. Although exposures of these sedimentary rocks were examined near Helena, along the east shore of Canyon Ferry Lake and south of Townsend, the only recognized zeolitic alteration is east of Winston along Beaver Creek where clinoptilolite was identified. The White Earth Campground, named for exposures of white tuffaceous beds, is on the shore of Canyon Ferry Lake north of Beaver Creek.

These white Oligocene volcaniclastic beds dip from 10° to 50° northeasterly. Limestone of the Madison Group (Mississippian) and a small remnant of the overlying Quadrant Formation (Pennsylvanian) are exposed in the low hills west of the exposures of Oligocene beds (Mertie and others, 1951). A granitic pluton (Tertiary or Cretaceous) has intruded the Madison Group. Mertie and others (1951) divided the Oligocene beds along Beaver Creek into two units; the older unit 1 is exposed just east of the Paleozoic outcrops and is overlain by unit 2 to the east. Unit 1 is mainly conglomerate that contains clasts eroded from exposures to the west and a few shale beds, whereas unit 2 consists mainly of volcanic material. Zeolitic beds are confined to unit 2. Unit 2 consists mainly of tuff, lapilli tuff, bentonite, and a few thin beds of carbonaceous shale. Erosion-resistant beds of well-indurated tuff form small mesas where dip is shallow and where steeply dipping these beds form small flatirons. Because of their resistance to erosion, these beds resemble zeolitized tuff, but many samples from these beds were found devoid of zeolites when analyzed by x-ray diffraction. Becraft (1958) suggested that uranium was leached from tuffaceous sediment and deposited in carbonaceous shale to produce numerous radioactivity anomalies. No correlation between radioactivity anomalies as shown by Becraft and zeolitic alteration was recognized.

Exposures of tuffaceous sediment that have been altered to clinoptilolite are scattered throughout this area (figure 11). In spite of the excellent exposures in this area, zeolitic beds could not be traced laterally. Zeolitic alteration was "patchy" rather than following individual beds traceable for any significant distance. For this reason, none of these occurrences can be considered a mineable deposit of clinoptilolite. The thickest zeolitized bed is slightly over 3 feet (1 meter) thick and is discontinuous (table 5).

The discontinuous nature of zeolitization is well shown by exposures on the east side of a small coulee situated near the center of the SE¼ SE¼ section 18, T. 9 N., R. 1 E. The beds exposed here are tuff, lapilli tuff, sandstone, bentonite, and clinoptilolite-bearing beds (figures 12 and 13A). Zeolitization of these beds extends for only 95 feet (29 meters) along this coulee. The same beds exposed 150 feet (50 meters) away on the west side of the coulee show no evidence of zeolitization. Although some silification was recognized next to a high-angle fault along the next major coulee to the west, no zeolitization was seen. Faults were

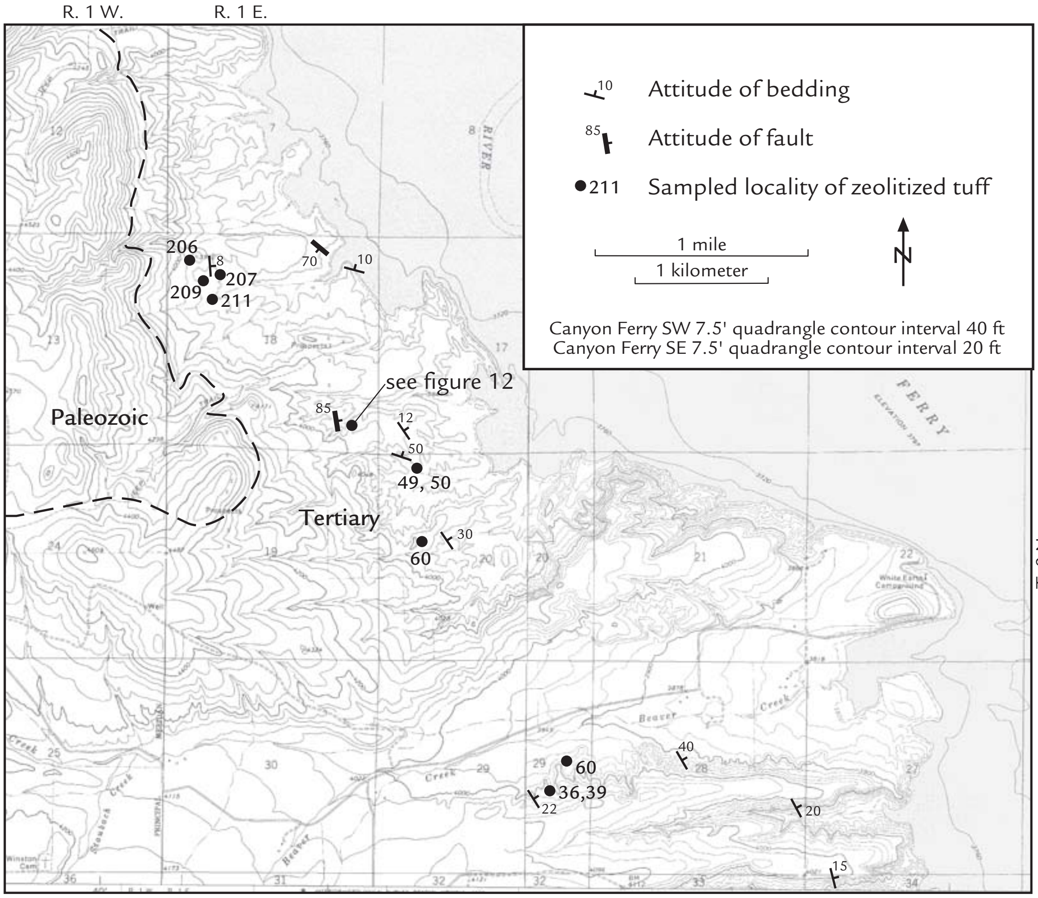

Figure 11. Sampled localities of zeolitized tuff in the Beaver Creek area. Base map from Canyon Ferry SW and Canyon Ferry SE 7½-minute quadrangles.

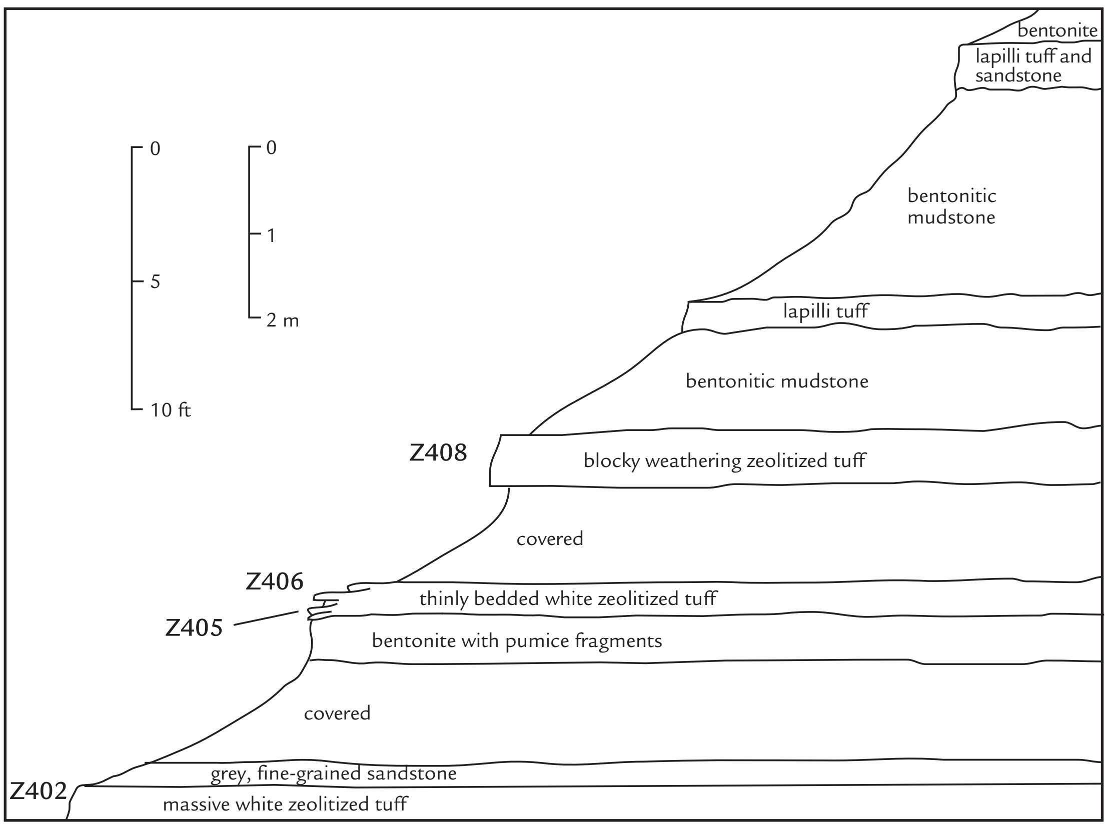

Figure 12. Exposure of zeolitized tuff beds in C, SE¼ SE¼ section 18, T. 19 N., R. 1 E., Beaver Creek area.

Table 5. Analyzed samples of zeolitized tuff from the Beaver Creek area.

Sample Number	Location	Thickness	Description	Clinoptilolite	Mordenite	Quartz	Opal-CT	Feldspar	Smectite	Other	CEC meq/gm
Z-30	SE1/4SE1/4NE1/4 sec. 29, T. 9 N., R. 1 E.	5 in. (12 cm)	massive bed	M		T		M		T biotite	
Z-36	SE1/4NE1/4SE1/4 sec. 29, T. 9 N., R. 1 E.	3 ft (1 m)	massive bed w/lithic clasts in upper 6 in. (15 cm)	M		m		M	T	T kaolinite	
Z-37	same location	20 in. (50 cm)	massive, ledge-forming bed	M		m		M		T biotite	
Z-38	same location	12 in. (30 cm)	massive, ledge-forming bed	M		m	M	m	T	m opal A	
Z-39	same location	5 in. (12 cm)	ledge-forming bed	M	T?	M					
Z-49	NE1/4NW1/4NW1/4 sec. 20, T. 9 N., R. 1 E.	upper 3 in. (8 cm)	pavement-like surface developed on top of this bed	M		M	M	m			
Z-50	NE1/4NW1/4NW1/4 sec. 20, T. 9 N., R. 1 E.	lower 7 in. (17 cm)	lower part of same bed, but less erosion resistant	M		T	M	T			
Z-60	SE1/4SE1/4NW1/4 sec. 20, T. 9 N., R. 1 E.	28 in. (70 cm)	bed forms small, flat iron	M		T	m	M	T		
Z-206	C, NW1/4NW1/4 sec. 18, T. 9 N., R. 1 E.	4 ft (1.2 m)	prominent white bed on top of ridge	M		T	m		m		
Z-207	SE1/4NW1/4NW1/4 sec. 18, T. 9 N., R. 1 E.	0.4 in. (1 cm)	forms prominent ledge	M	T		m	M	m		
Z-209	SE1/4NW1/4NW1/4 sec. 18, T. 9 N., R. 1 E.	3 ft (1 m)	slight greenish cast to blocky bed	M		M		M	T		
Z-211	NE1/4SW1/4NW1/4 sec. 18, T. 9 N., R. 1 E.	3 x 6 ft (1 x 2 m)	greenish, weathers into chips	M		T	M	T			
Z-402	C, SE1/4SE1/4 sec. 18, T. 9 N., R. 1 E.	14 in. (46 cm)	see figure 12	M		T	m				1.34
Z-405	same location	3 in. (7 cm)	see figure 12	M		T	M		T		0.80
Z-406	same location	9 in. (24 cm)	see figure 12	M		m			T		1.41
Z-408	same location	2.2 ft (0.7 m)	see figure 12	M		m	M		T		1.10

Figure 13A. Exposure of zeolitized tuff beds in C, SE¼SE¼ section 18, T. 9 N., R. 1 E., Beaver Creek area.

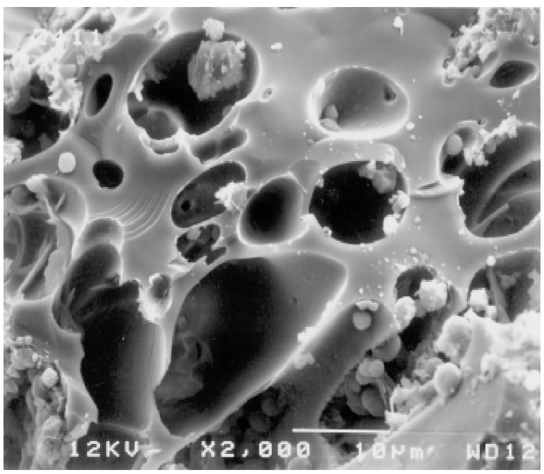

Figure 13B. Scanning electron micrograph of unaltered pumice fragment from exposure shown in figure 13.

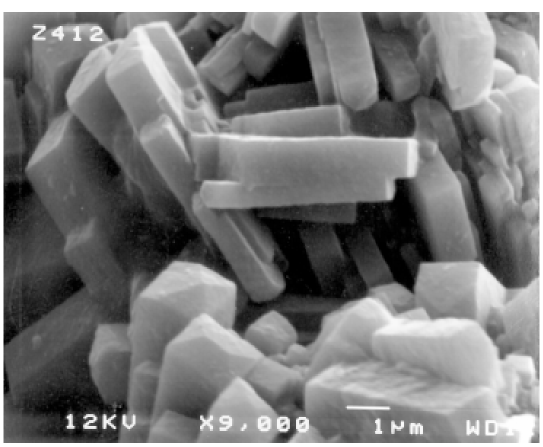

Figure 13C. Scanning electron micrograph of clinoptilolite in zeolitized portion of same bed as that from which unaltered pumice fragment was collected. Scanning electron micrographs by Nancy Equall, ICAL, Montana State University.

not recognized on the east side of the coulee where beds are locally zeolitized. A comparison of two samples collected from the northern limit of zeolitization of the most prominent bed shown in figure 13A illustrates the abrupt transition from unaltered tuff to zeolitized tuff. Scanning electron photomicrographs of two specimens collected 6 feet (2 meters) apart at this locality show the difference between an unaltered pumice fragment and tuff that is essentially completely zeolitized (figures 13B, 13C). Clearly zeolitization of tuffaceous sediment in the Beaver Creek area was not a pervasive process. A comparison of the trace-element chemistry of the unaltered tuff and zeolitized tuff show some differences, particularly for the lanthanides (La, Ce, Nd, Sm, Eu, Yb, and Lu)—all of which are in lower concentrations in the zeolitized rock as compared to the unaltered tuff (table 6). Uranium and thorium are also in lower concentrations in the zeolitized tuff as compared to the unaltered tuff.

Lost Creek

Location: E½ NE¼ NW¼ and NE¼ SE¼NW¼ section 30, T. 5 N., R. 10 W., Anaconda, North 7½-minute quadrangle, Deer Lodge County. Twenty-two miles (35 kilometers) northwest of Butte.

Ownership: Cliff Galle Ranch

The ash-flow tuff unit of the Eocene Lowland Creek Volcanics extends north from just south of Lost Creek for several miles along the low foothills of the Flint Creek Range (Wanek and Barclay, 1966). This unit was examined for evidence of zeolitization near the mouth of Lost Creek where it is well exposed (figure 14). Clinoptilolite was identified in 7 of 8 samples that were analyzed and is in the greatest concentration in sample Z-

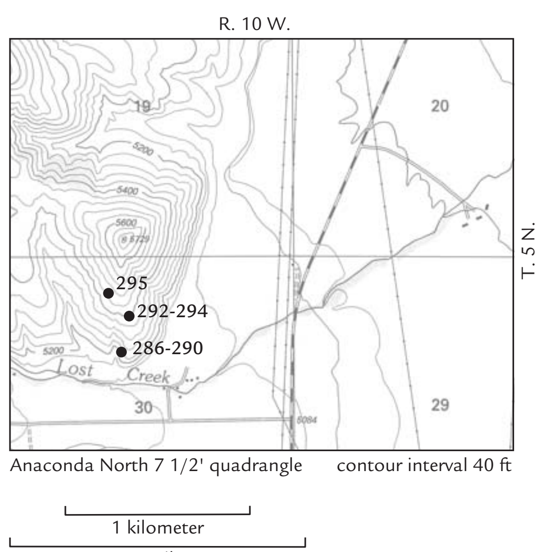

Figure 14. Zeolite occurrence north of Lost Creek.

Table 6. Trace element analyses of unaltered tuff (Z-411) and zeolitized specimen from same bed (Z-412), Beaver Creek occurrence. See figure 13 for scanning electron micrographs of these two specimens. Neutron activation analyses by XRAL Activation Services Inc., Ann Arbor, Michigan.

Element	Units	Z-411	Z-412
Ag	ppm	<5	<5
As	ppm	4	3
Au	ppb	14	6
Ba	ppm	300	600
Br	ppm	6	5
Ca	%	<0.5	<0.5
Co	ppm	3	1
Cr	ppm	11	<2
Cs	ppm	22	10
Fe	%	0.79	0.37
Hf	ppm	5.3	4.0
Mo	ppm	<5	<5
Na	ppm	12000	7200
Ni	ppm	<200	<200
Rb	ppm	520	170
Sb	ppm	0.7	0.8
Sc	ppm	2.1	1.3
Se	ppm	<3	<3
Sr	ppm	<500	<500
Ta	ppm	6	6
Th	ppm	45	29
U	ppm	23.1	13.2
W	ppm	15	<3
Zn	ppm	50	50
La	ppm	18.1	8.0
Ce	ppm	43	19
Nd	ppm	27	12
Sm	ppm	8.5	3.7
Eu	ppm	0.4	0.2
Tb	ppm	2.0	0.5
Yb	ppm	7.0	1.9
Lu	ppm	1.03	0.29
Ir	ppb	<20	<20

288, which was collected from unusually light-colored tuff in a small prospect pit. In addition to clinoptilolite, this sample contains mordenite, feldspar, quartz, opal-CT, and smectite. The two other samples (Z-294, Z-295) with the highest concentration of clinoptilolite are from small areas (<1 meter in maximum dimension) of bleached rhyolite. Other zeolitic samples are from similarly small areas of partially zeolitized tuff. There is no evidence of a continuous zeolitized bed here.

Anaconda

Location: SE¼ SE¼ SE¼ section 34, T. 5 N., R. 11 W., Anaconda North 7½-minute quadrangle, Deer Lodge County. Twenty-three miles (37 kilometers) northwest of Butte.

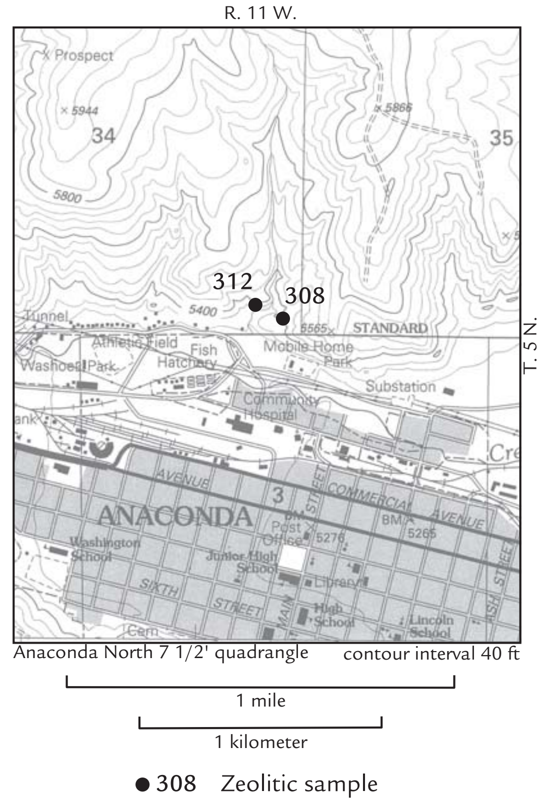

Figure 15. Zeolite occurrence north of Anaconda at the Placer Fire Clay pit.

Ownership: Harold P. Snow

Clay has been mined from bentonitic beds in the volcanic breccia and red bed member of the Eocene Lowland Creek Volcanics as mapped by Wanek and Barclay (1966). Two samples, Z-308 and Z-302, were analyzed from the Placer Fire Clay pit (figure 15). Sample Z-308 is from a bed that contains concretions estimated to be about 1.5 feet (0.5 meters) across. This bed is poorly exposed above the bentonite bed in the east pit, and the specimen consists mainly of glass and smectite. Sample Z-302 is from the upper and harder part of a bentonite bed, which is between 3 and 6 feet (1 and 2 meters) thick. Clinoptilolite is only a minor constituent of this sample, which consists mainly of quartz and smectite with lower concentrations of biotite and feldspar (table 1). Although minor zeolitization was identified at this clay pit, clinoptilolite was not recognized in significant concentration.

Ramsay

Location: Zeolitic rock was found at two localities southwest of Ramsay, in the NW¼ NE¼ section 21, T. 3 N., R. 9 W., Ramsay 7½-minute quadrangle and in the NE¼ NE¼ section 27, T. 3 N., R. 9 W., Buxton 7½-minute quadrangle. Both localities are in Silver Bow County and approximately 10 miles (16 kilometers) southwest of Butte.

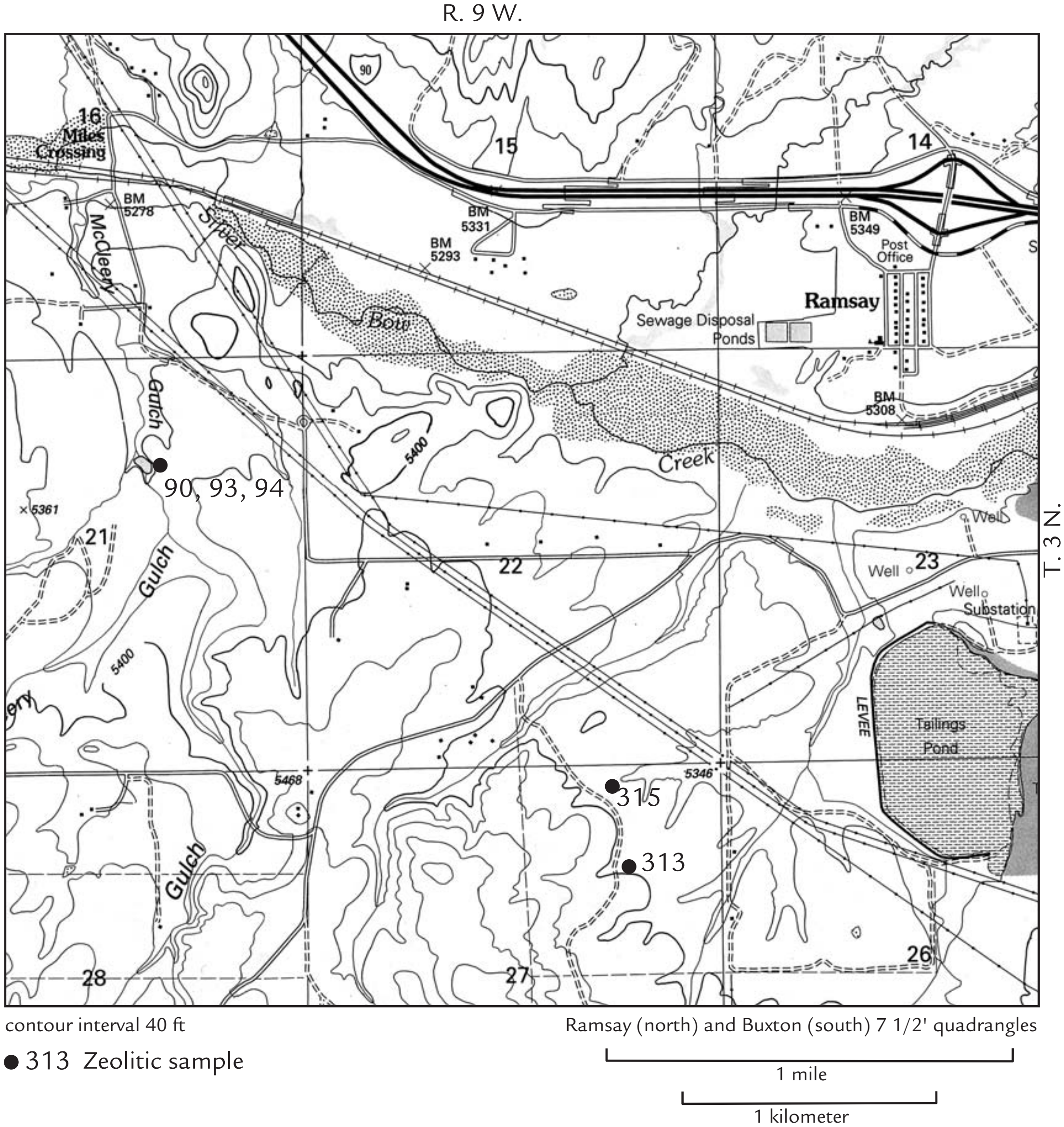

Figure 16. Zeolite occurrences southwest of Ramsay.

Ownership: Private land

Tertiary beds, poorly exposed southwest of Ramsay, are locally zeolitic. These beds are inferred to belong to the Melrose basin sequence as described by Derkey and Bartholomew (1988) in the Ramsay 7½-minute quadrangle just to the north. Porcellanite and zeolitic concretions occur in bentonitic beds that are exposed on the east side of McCleery Gulch along a small reservoir (figure 16). A sample of one of the siliceous concretions (Z-90, table 1) consists of quartz and opal-CT. Sample Z-93 of zeolitic float collected at this locality is one of the purest clinoptilolite samples analyzed during this investigation, as shown by SEM and x-ray diffraction analysis (figures 3 and 17).

In addition to clinoptilolite, this sample contains quartz in trace concentration and probably mordenite. A zeolitic bed 2.4 inches (6 centimeters) thick also is poorly exposed here. Samples Z-313 and Z-315 collected from poorly exposed beds, also presumably of the Melrose basin sequence, contain clinoptilolite in major concentration (figure 16). Sample Z-313, of float judged to be zeolitic, was collected for about 40 feet (12 meters) along a small gully 5 feet (1.5 meters) deep. Sample Z-315 is from a zeolitic concretion. In addition to clinoptilolite, these samples contain quartz and opal-CT (table 2).

Tabor Mountain

Location: West slope of Tabor Mountain along the Bitterroot River in the SE¼ section 23, and NE¼ section 26, T. 4 N., R. 21 W., Darby 7½-minute quadrangle, Ravalli County. Four miles (6.4 kilometers) north of Darby.

Ownership: Mainly private with small area of the Bitterroot National Forest.

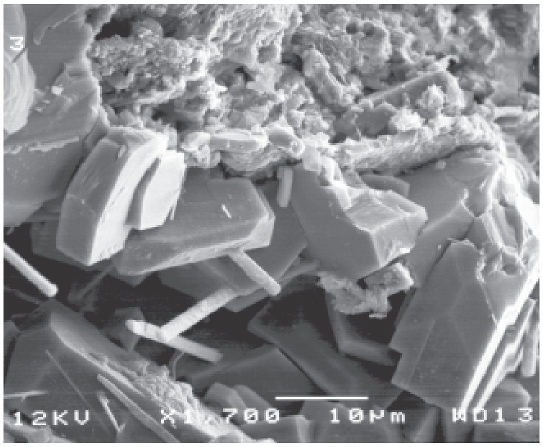

Figure 17. Scanning electron micrograph of sample Z-93 from the Ramsay locality. Tabular crystals are clinoptilolite and the small prismatic crystals are probably mordenite. Scanning electron micrograph by Nancy Equall, ICAL, Montana State University.

Tertiary volcaniclastic beds are exposed on the west side of Tabor Mountain, which is on the east side of the Bitterroot River (figure 18). These white cliffs of tuffaceous beds, easily recognizable from the highway, are overlain by a pale reddish brown (10 R 5/4) aphanitic lava flow. The tuffaceous beds range from white (N 9) to yellowish grey (5 Y 8/1) to greyish yellow green (5 GY 7/2). All 11 samples thought to be zeolitic when examined in the field were found by x-ray diffraction analysis to contain clinoptilolite either as a major or minor constituent. Individual lithologic units exposed at this locality vary substantially in thickness and in some instances pinch out entirely. Bedding is variable; dips are southeasterly at 25° to 50°. A fault just south of the exposure sketched in figure 19 strikes approximately N 90° E with the north side displaced downward about 90 feet (30 meters). Zeolitization does not appear to be more intense near the fault. On the basis of field observation and the analyzed samples, zeolitization is

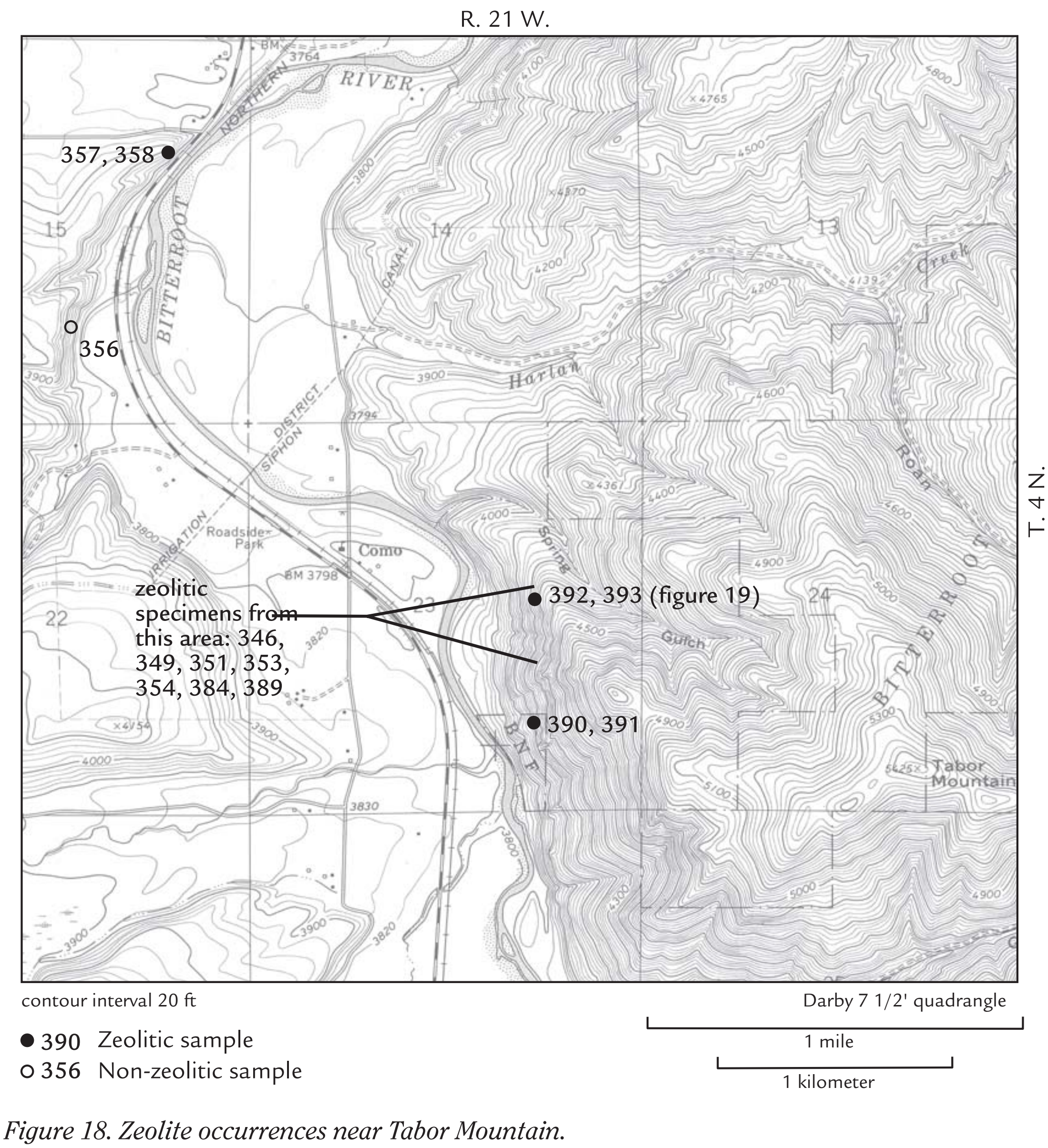

Figure 18. Zeolite occurrences near Tabor Mountain.

irregularly distributed within individual exposures; some zeolitized areas are only a few feet across. For instance near the southern end of this exposure, a partially zeolitized mass 3 by 6 feet (1 by 2 meters) contains a mixture of clinoptilolite, quartz, feldspar, opal-CT, and biotite (sample Z-390, table 1). A prominent, cliff-forming bed at this locality is 1.5 feet (0.5 meters) thick and consists of lithic tuff that contains gneiss and volcanic rock clasts in a zeolitized matrix. Clasts range between 2 and 4 inches (5 and 10 centimeters) in maximum dimension. Flow-banded vitrophyre overlies this bed. Sample Z-391 consists mainly of clinoptilolite with lesser opal-CT, feldspar, and quartz with smectite in a trace concentration. The dip of this bed is 25° SE. At an outcrop of this same bed near the northern limit of these exposures, this cliff-forming sequence of beds is at least 69 feet (21 meters) thick. Here the lower contact of this sequence is covered. The main constituents of the sampled intervals shown in figure 19 are clinoptilolite, quartz, and feldspar. Sample Z-

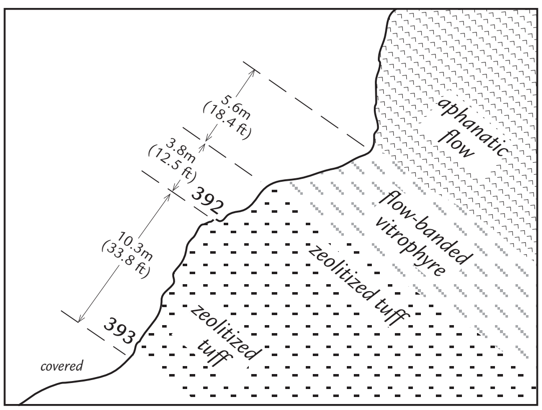

Figure 19. Sampled exposure of zeolitized tuff on the west side of Tabor Mountain.

393 from the lower interval also contains biotite. Seven additional grab samples collected from these beds during the initial reconnaissance contain clinoptilolite as a major constituent. Beds exposed on the west side of Tabor Mountain are not exposed to the northeast along Spring Gulch.

In these same exposures, a glassy, light grey rock with poorly developed perlitic texture and prominent biotite phenocrysts is altered along a small fracture. The zone of bleaching along the fracture is only 4 inches (10 centimeters) wide. A sample from the center of the bleached zone along this fracture consists mainly of clinoptilolite with lesser quartz and unaltered biotite. A specimen (Z-471) from this veinlet has a CEC of 1.90 milliequivalents/gram, the highest of any sample analyzed during this investigation (table 2 and figure 20). A comparison of the trace-element chemistry of the unaltered volcanic rock and the zeolitic sample shows significantly higher values

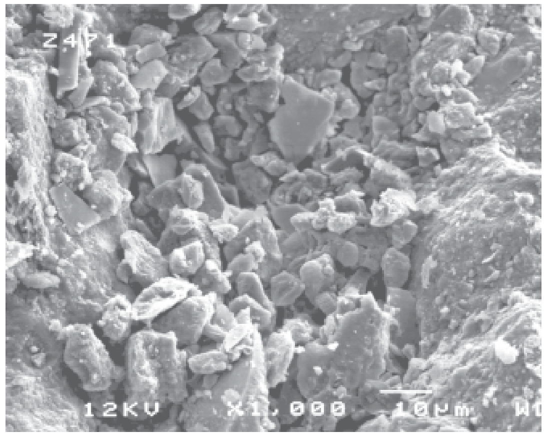

Figure 20. Scanning electron micrograph of sample Z-471 from Tabor Mountain. Scanning electron micrograph by Nancy Equall, ICAL, Montana State University.

for the lathanides (La, Ce, Nd, Sm, Eu, Yb, and Lu) in the zeolitized rock (table 7). Zinc also shows an increase from <40 parts per million in the unaltered rock to 120 parts per million in the clinoptilolite. An exposure of similar tuffaceous beds along the west side of Lick Creek in the SW¼ SE¼ section 15, T. 4 N., R. 21 W. (locality 356, figure 18) was examined, but zeolitized rock was not recognized. A roadcut along U.S. Highway 93 less than a mile to the north in the NW¼ NE¼ section 15, T. 4 N., R. 21 W. also was examined. Sample Z-358 collected from the most likely looking zeolitized tuff exposed in this roadcut consists mainly of opal-CT with minor clinoptilolite, quartz, and smectite in trace concentrations. Much of the tuff exposed in this roadcut has been altered to bentonite.

Tuffaceous beds exposed on the west side of Tabor Mountain show widespread zeolitization, particularly the massive cliff-forming beds. However, within these beds unaltered lithic fragments and pyrogenic quartz and feldspar are abundant, which would make this material undesirable as a source of commercial zeolite.

Salt Creek

Location: SE¼ SE¼ and SE¼ SW¼ section 22, NW¼ NW¼ and SW¼ NW¼ section 23, and NW¼ SE¼ and NE¼ SE¼ section 27, T. 3 S., R. 22 W., Alta 7½-minute quadrangle, Ravalli County. Approximately 34 miles (54 kilometers) south of Darby.

Ownership: Bitterroot National Forest

Bedded tuff, felsite, and rhyolite have filled the paleovalley of the West Fork of the Bitterroot River from Hughes Creek on the north to Johnson Creek on the south (Berg, 1977). Proterozoic quartzite is exposed between these volcanic rocks and the present valley of the West Fork of the Bit-

Table 7. Trace element analyses of unaltered perlitic rock (Z-470) and adjacent zeolitized rock (Z-471) from the Tabor Mountain locality. Neutron activation analyses by XRAL Activation Services Inc., Ann Arbor, Michigan. See figure 20 for scanning electron micrograph of Z-471.

Element	Units	Z-470	Z-471
Ag	ppm	<5	<5
As	ppm	<2	<2
Au	ppb	<5	<5
Ba	ppm	700	1000
Br	ppm	5	2
Ca	%	<0.5	1.7
Co	ppm	3	3
Cr	ppm	8	5
Cs	ppm	16	12
Fe	%	0.79	0.83
Hf	ppm	4.9	5.6
Mo	ppm	<5	<5
Na	ppm	21000	18000
Ni	ppm	<200	<200
Rb	ppm	260	150
Sb	ppm	0.3	0.3
Sc	ppm	1.8	2.0
Se	ppm	<3	<3
Sr	ppm	<500	<500
Ta	ppm	1	<1
Th	ppm	20	23
U	ppm	7.0	2.7
W	ppm	<3	<3
Zn	ppm	<40	120
La	ppm	33.6	85.3
Ce	ppm	60	159
Nd	ppm	21	60
Sm	ppm	4.1	10.9
Eu	ppm	0.5	1.2
Tb	ppm	<0.5	1.0
Yb	ppm	1.4	2.9
Lu	ppm	0.20	0.42
Ir	ppb	<20	<20

terroot River. The age of these volcanic rocks has not been determined; however, they probably are related to the extensive Eocene Challis Volcanics exposed to the south in Idaho.

Exposures of the volcanic rocks along logging roads were examined for zeolitization. Partially zeolitized rocks were found in the vicinity and north of Salt Creek (figure 21). North of this area of partial zeolitization, alteration of volcanic rocks to smectite has produced hummocky terrain with numerous landslides and poor exposures. The best exposures are along the north side of Salt Creek in the SE¼ SE¼ section 22, T. 3 S., R. 22 W. Most of the exposed tuffaceous beds show no indication of having been zeolitized to any significant extent. A white (N 9) bed 2 inches (5 centimeters) thick exposed near the top of the outcrop on the north side of Salt Creek consists mainly of clinoptilolite and cristobalite with minor quartz, feldspar, and smectite (sample Z-380, table 1). A pinkish grey (5 YR 8/1) porcellaneous bed with a conchoidal fracture overlying the zeolitized bed consists mainly of opal-CT with lesser clinoptilolite (sample Z-381). A grab sample collected from the most massive part of the white cliffs, about one third of the way to the top of the exposure on the north side of Salt Creek, contains opal-CT and clinoptilolite in the groundmass and megascopic quartz and biotite phenocrysts (sample Z-344). Two samples (Z-382 and Z-383) of what appeared to be zeolitized tuff exposed along the road on the south side of Salt Creek were found to lack zeolites when analyzed by x-ray diffraction.

Four samples (Z-340–343) collected north of Salt Creek show some zeolitization. Sample Z-342 (yellowish grey 5 Y 8/1) collected from float found scattered along a logging road for about 240 feet (80 meters) consists mainly of opal-CT and lesser amounts of clinoptilolite, quartz, and feldspar, accompanied by smectite in low concentrations. Sample Z-340, a very light grey (N 8) sample of float collected from an open grassy slope consists mainly of feldspar with lesser clinoptilolite and quartz. Sample Z-343 (very light grey, N 8) of altered tuff exposed in a road cut contains opal-CT, quartz, and clinoptilolite with lesser amounts of biotite. Samples Z-340 and 341 (very light grey, N 8) also of float contain feldspar, clinoptilolite, and quartz. Sample Z-341 is of similar mineralogy. Limited sampling in this area of best exposures suggests that partial zeolitization is widespread. However, no individual highly zeolitized beds of mineable thickness were recognized.

Dyce Creek

Location: NE¼ NE¼ section 15, T. 7 S., R. 12 W., Mill Point 7½-minute quadrangle, Beaverhead County. Twenty miles (32 kilometers) west of Dillon.

Ownership: Private

Bentonitic mudstone and thin beds of zeolitized tuff, presumably of Tertiary age, are well exposed in the area just north of the county road (figure 22). Bentonite was mined from a small clay pit west of the area in which the zeolitized beds are exposed. Bentonite is interbedded with mudstone and sandstone, but no zeolitic beds were found at the clay pit. Erosion-resistant beds were sampled at the localities shown in figure 22. Sample Z-274 is from a white bed 31 inches (80 centimeters) thick that forms a dip slope. Clinoptilolite is the major constituent with lesser amounts of quartz, opal-CT, and

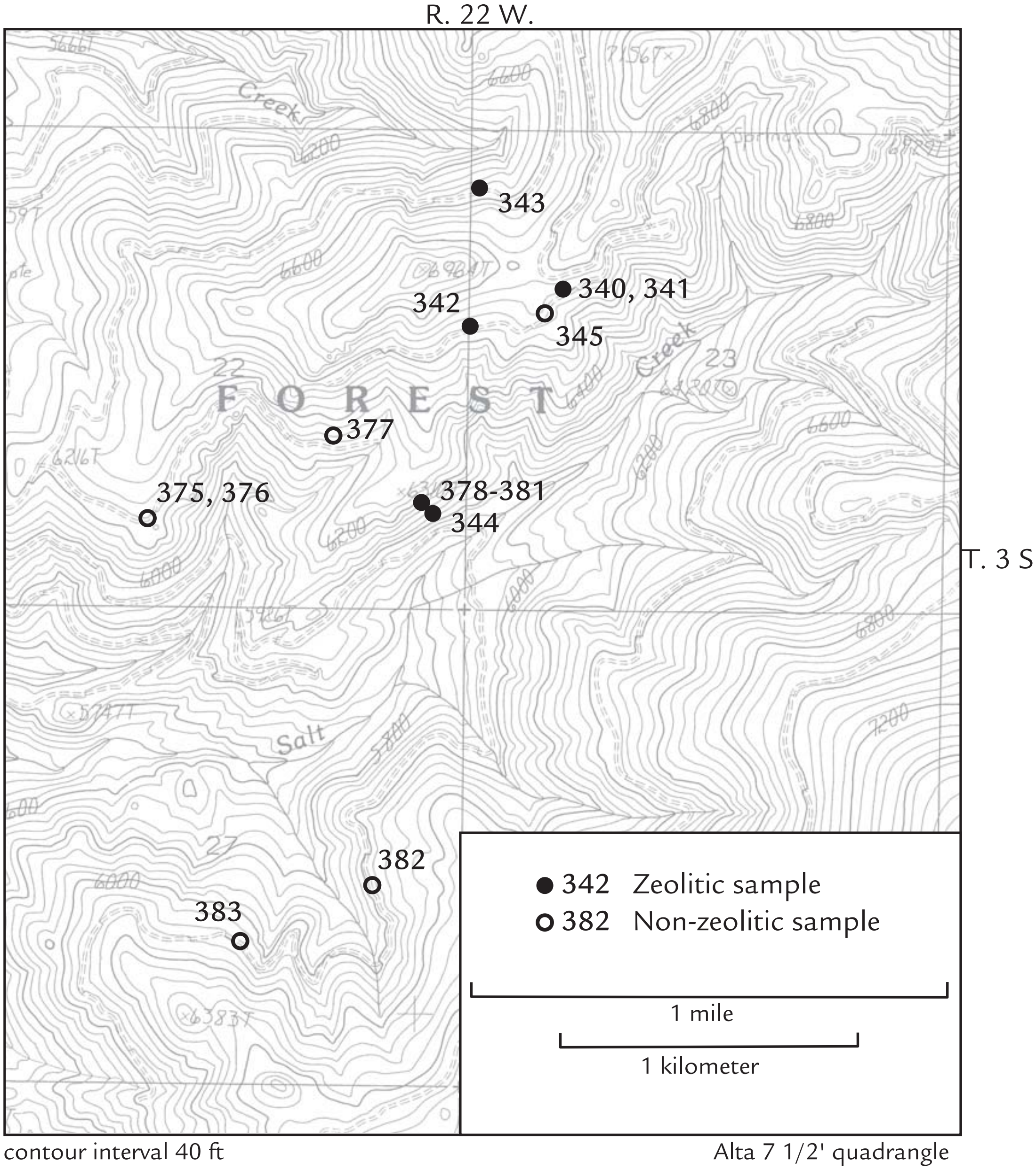

Figure 21. Zeolite occurrences near Salt Creek.

smectite (table 1). Twenty-seven inches (70 centimeters) below the base of this bed, an erosion-resistant bed 1–3 inches (3–7 centimeters) thick consists mainly of opal-CT and glass (sample Z-275). A distinctive white bed only 0.2 inches (5 millimeters) thick in bentonitic mudstone consists mainly of clinoptilolite and opal-CT with lesser amounts of smectite (sample Z-276). Four beds of zeolitized tuff that are interbedded with bentonitic mudstone are exposed in the ditch alongside the county road (figure 23). These beds (samples Z-277–280, table 1) consist of clinoptilolite, opal-CT, quartz, feldspar, and smectite in varying proportions.

Badger Pass

Location: Exposures north and south of Highway 278 just east of Badger Pass and exposures in a road metal pit just south of the highway in parts of sections 1, 2, 11, 14, 22, and 23, T. 7 S., R. 11 W. and sections 6 and 7, T. 7 S., R. 10 W., Beaverhead County 14 miles (21 kilometers) northwest of Dillon. This area is covered by the Bannack, Ermont, Burns Mountain, and Argenta 7½-minute quadrangles.

Ownership: Mainly BLM–administered land with private ownership of most of section 12, T. 7 S., R. 11 W.

Tuff of Grasshopper Creek of Cretaceous age as described by Pearson (1989) is exposed just east of Badger Pass north and south of Highway 287 (figure 24). Best exposures of this locally zeolitized and locally silicified tuff are in the road metal pit just south of the highway, to the east of this pit,

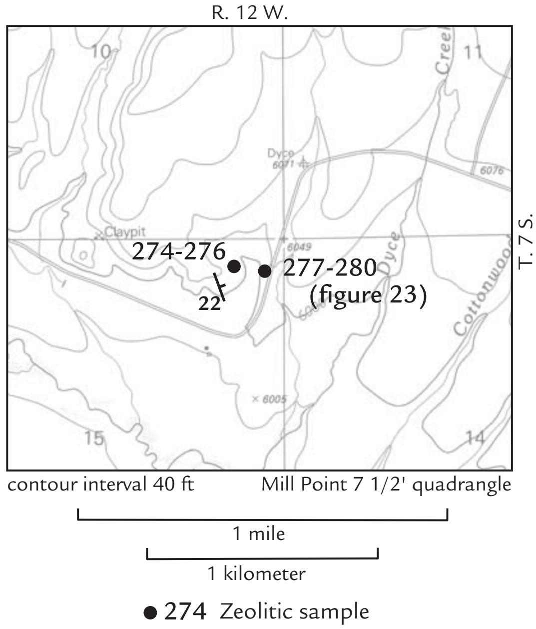

Figure 22. Zeolite occurrences west of Dyce Creek.

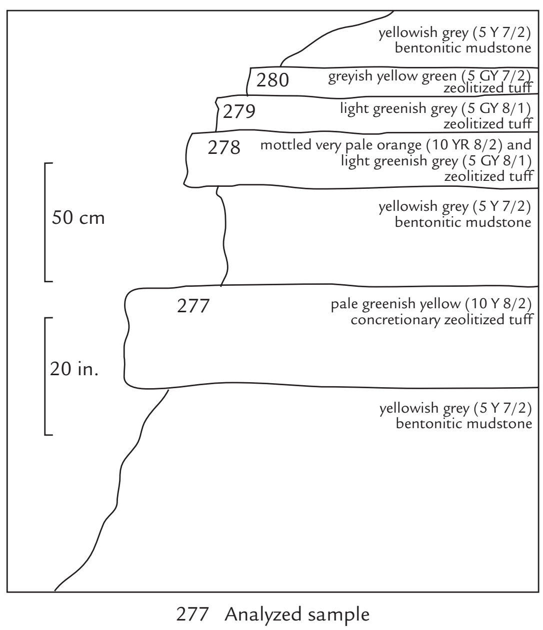

Figure 23. Exposure of zeolitized beds in ditch on the west side of the road (figure 22). Color designations from color chart prepared by Goddard and others, 1963.

in road cuts along the highway, and along cliffs about 1,000 feet (300 meters) north of the highway. Mission Canyon Limestone of the Madison Group (Mississippian) exposed just west of the tuff of Grasshopper Creek has been thrust over this unit. Tuff of Grasshopper Creek is overlain to the east by Cretaceous or Tertiary andesite flows and breccias, rhyolite flows and tuffs, and volcanic agglomerate (Thomas, 1981). Conglomerate of the Beaverhead Group (Cretaceous and Tertiary), intrusive andesite (Cretaceous), and rhyolite (Tertiary) also are exposed in the area of the tuff of Grasshopper Creek. A small, Cretaceous granodiorite stock intruded the tuff.

Pearson (1989) divided the Cretaceous volcanic rocks of this area southwest of Dillon and north of Bannack into two distinctive units. The lower unit that was designated tuff of Grasshopper Creek, for exposures along Grasshopper Creek, is well indurated and locally zeolitized and at some localities appears silicified. The zeolite deposit along the lower part of Grasshopper Creek is in this unit. Pearson (1989) estimated that the tuff of Grasshopper Creek may be over 1,000 feet (300 meters) thick, although making accurate thickness estimates are difficult because of structural complexities in this area. Major exposures of the tuff of Grasshopper Creek are limited to three general areas: (1) Exposures extend south from Ermont Gulch across Highway 278, (2) about 7 miles (10 kilometers) south of Badger Pass north and south of Grasshopper Creek, and (3) along the lower part of Grasshopper Creek where this unit is extensively zeolitized (Pearson, 1989; figure 1). See the description of the Grasshopper Creek deposit for detailed information on this latter area.

The tuff of Grasshopper Creek is overlain by a volcanic unit designated by Pearson (1989) as volcanics of Cold Spring Creek that are also Cretaceous. This unit consists mainly of volcanic breccia of intermediate composition, lava flows, and shallow intrusive bodies; it is exposed from the Ermont Gulch area south across Grasshopper Creek. The tuff of Grasshopper Creek and volcanics of Cold Spring Creek were initially thought to be Tertiary (Lowell, 1965), but $^{40}Ar/^{39}Ar$ dates indicate that these volcanic rocks and associated intrusive igneous rocks are in the range of 75–80 Ma (radiometric dates by L.W. Snee reported in Ivy, 1989). The tuff of Grasshopper Creek is the only Cretaceous volcanic unit in southwestern Montana that was recognized as being zeolitized.

The tuff of Grasshopper Creek near Badger Pass forms erosion-resistant beds or sequences of beds from 6 to 30 feet (2 to 10 meters) thick that are laterally traceable. Bedding dips southeast 30° to 40°. Some of the tuff is massive with barely recognizable bedding, whereas in other exposures, the tuff is thinly bedded with beds only a couple of centimeters thick. Beds up to 4 inches (10 centimeters) thick with dendritic growths of a manganese mineral were quarried on a small scale for decorative use. Some beds contain up to 30 percent pumice fragments that are up to 4 inches (10 centimeters) across. Fragments of other types of volcanic rock also occur in some beds but usually in lower concentration than pumice

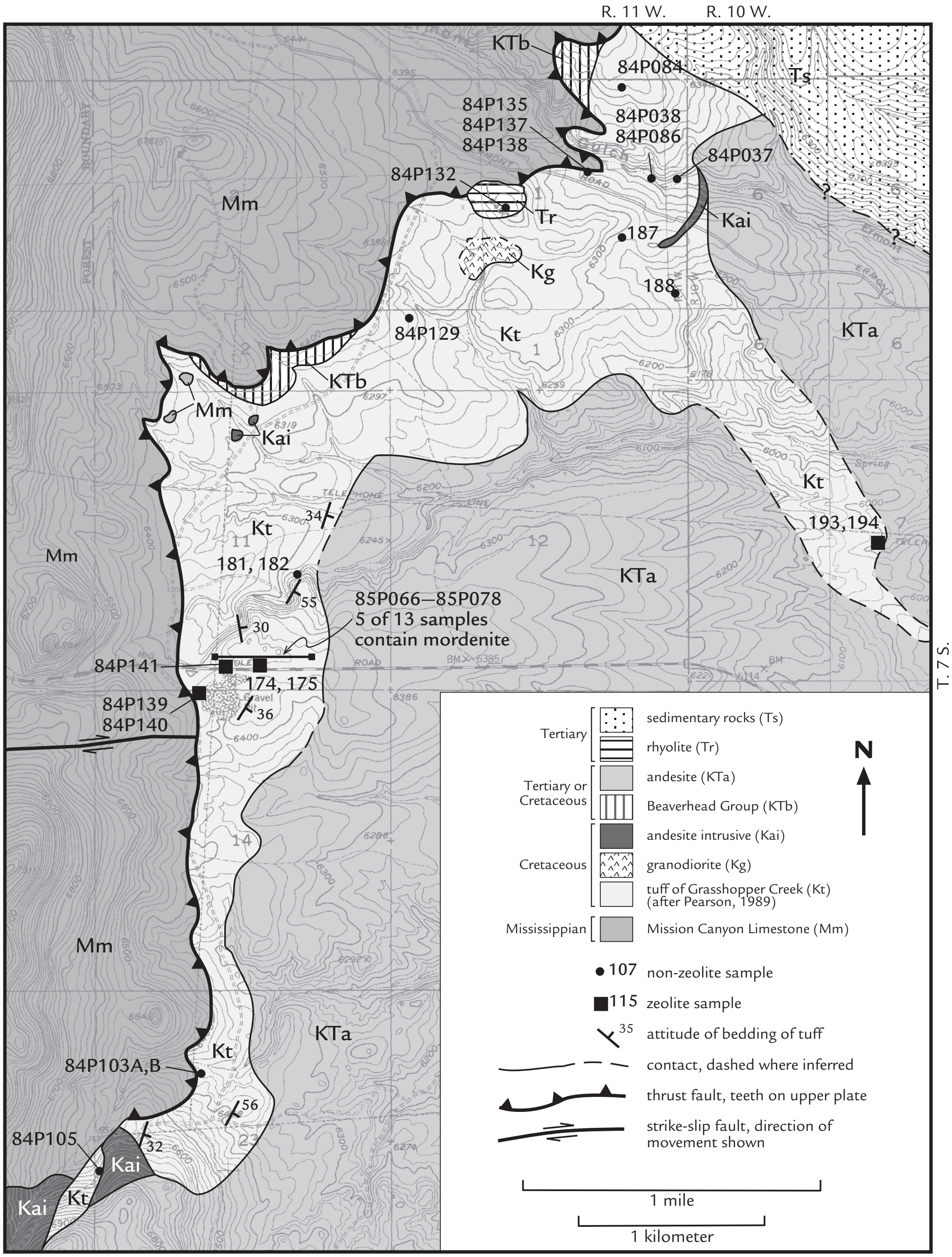

Figure 24. Map of the Badger Pass area showing the extent of the tuff of Grasshopper Creek from Thomas (1981), except for the southeastern extent of tuff, which is modified slightly from Lowell (1965). Base map from Bannack, Ermont, Burns Mountain, and Argenta 7½-minute quadrangles all with 20-foot contour interval. Mineralogy of samples with prefixes 84P or 85P given in table 8 are from Pearson (1989). Mineralogy of other samples given in table 1.

fragments. The abundance and size of pumice fragments are highly variable with some beds entirely devoid of lithic fragments of any type. The abundance of the pyrogenic minerals—quartz, K-feldspar, and plagioclase—is also highly variable. Grains of these minerals are several millimeters across. Two colors of tuff predominate in this area: moderate orange pink (10 R 7/4) and more commonly white (N 9) with intermediate shades generally absent. Typically, variation in color follows bedding: some individual beds are orange, and some are white. In a few instances, orange

Table 8. Mineralogy of samples from the Badger Pass area as described by Pearson (1989, table 1). M=major constituent, m=minor constituent, T=trace constituent, and ?=identity uncertain. See figure 24 for sample sites.

Sample Number	Mordenite	Clinoptilolite	Analcime	Feldspar	Quartz	Opal-CT	Mica	Smectite	Chlorite	Calcite
84P037				m	M		m		T	m
84P038				m	M		T	T	T	M
84P084				m	M		m	T	T	M
84P086				M	M		T			m
84P103A	T?			m	M	M	m			
84P103B	T?			m	m	M		m		
84P105		T		M	M			T		
84P129				M	M		m	T		
84P132				m	M		m			
84P135					M		m		m	
84P137	T			m	M		T		T	
84P138	T?	T?		M	M					
84P139	M	T		m	m			T		
84P141	M	m		m	m					
85P066	M			m	M		T?			
85P067	M			m	M		T?			
85P068	M			m	M		T?			
85P069		m		m	M					
85P070		M		m	M				T	
85P071	M			m	M			T	T	
85P072	M			m	M					
85P073	m			m	M			T	T	
85P074	m			m	M				T	
85P075	m			m	M					
85P076				M	M					
85P077	m			m	M					
85P078	M			M	M					

blotches up to several meters across occur within the white tuff. Limonite coats fractures of some of the tuff, and in several instances, there are brown spots of limonite a few millimeters across.

Unlike most other occurrences of zeolitic tuffs examined in western Montana, the dominant zeolite in the tuff of Grasshopper Creek exposed at Badger Pass is mordenite. Sixteen samples were collected from what were initially thought to be zeolitic outcrops. Analysis by x-ray diffraction showed that mordenite occurred in minor concentrations in nine of these samples (table 1). Clinoptilolite occurs in addition to mordenite in one sample and is the only zeolite present in one sample. Pearson (1989, tables 1 and 8) analyzed 27 samples from the Badger Pass area and found that 12 contained mordenite in minor to major concentrations and that three samples contained clinoptilolite in minor to major concentrations. Mainly based on Pearson's analyses, the greatest concentration of zeolitic tuff is close to or in the road-metal pit at Badger Pass (figure 25). Two samples (Z-193 and Z-196) collected near the eastern limit of exposures of the tuff of Grasshopper Creek also contained mordenite. The limited sampling reported herein indicates there is not a bed or area of continuous zeolitic alteration, only scattered areas of zeolitization. Because of the difficulty of distinguishing in the field between unaltered beds and zeolitic rock, it was impractical to map areas of zeolitic alteration.

Medicine Lodge Creek

Location: NE¼ NE¼ SE¼ section 11, T. 13 S., R. 12 W., Tepee Mountain 7½-minute quadrangle, Beaverhead County. Thirty-eight miles (61 kilometers) southwest of Dillon.

Ownership: Hildreth Ranch

Tuffaceous beds of Tertiary age are exposed along the road from the Medicine Lodge Creek road to the Hildreth ranch house (figure 26). The apparent dip of beds exposed in this roadcut is 15° south. Sample Z-329 collected from a pale yellowish green (10 GY 7/2) bed about 3 feet (1 meter) thick consists mainly of clinoptilolite, quartz, opal-CT, and feldspar with lesser smectite (table 1); sample Z-330, also collected from this roadcut, consists mainly of quartz and feldspar.

Muddy Creek Basin

Location: Exposures on the west side of Muddy Creek in sections 1, 12, 13, 24, 25, 36, T. 13 S., R. 11 W.; sections 7, 18, 19, 30, 31, T. 13 S., R. 10 W.; sections 5, 6, 8, 9, T. 14 S., R. 10 W. Graphite Mountain and Dixon Mountain 7½-minute quadrangles, Beaverhead County, approximately 13 miles (21 kilometers) northwest of Lima. Access to the area is provided by the road along Muddy Creek, that because of bentonitic beds is passable only in dry weather.

Ownership: Mainly BLM–administered land with some private land.

The Muddy Creek Basin is flanked on the west by the leading edge of the Medicine Lodge thrust fault, and the Tendoy thrust fault (both of Laramide age) lies just east of the basin (Scholten and others, 1955). White-weathering, poorly vegetated, tuffaceous beds form discontinuous exposures in the low hills on the west side of Muddy Creek basin (figures 27 and 28). Dunlap

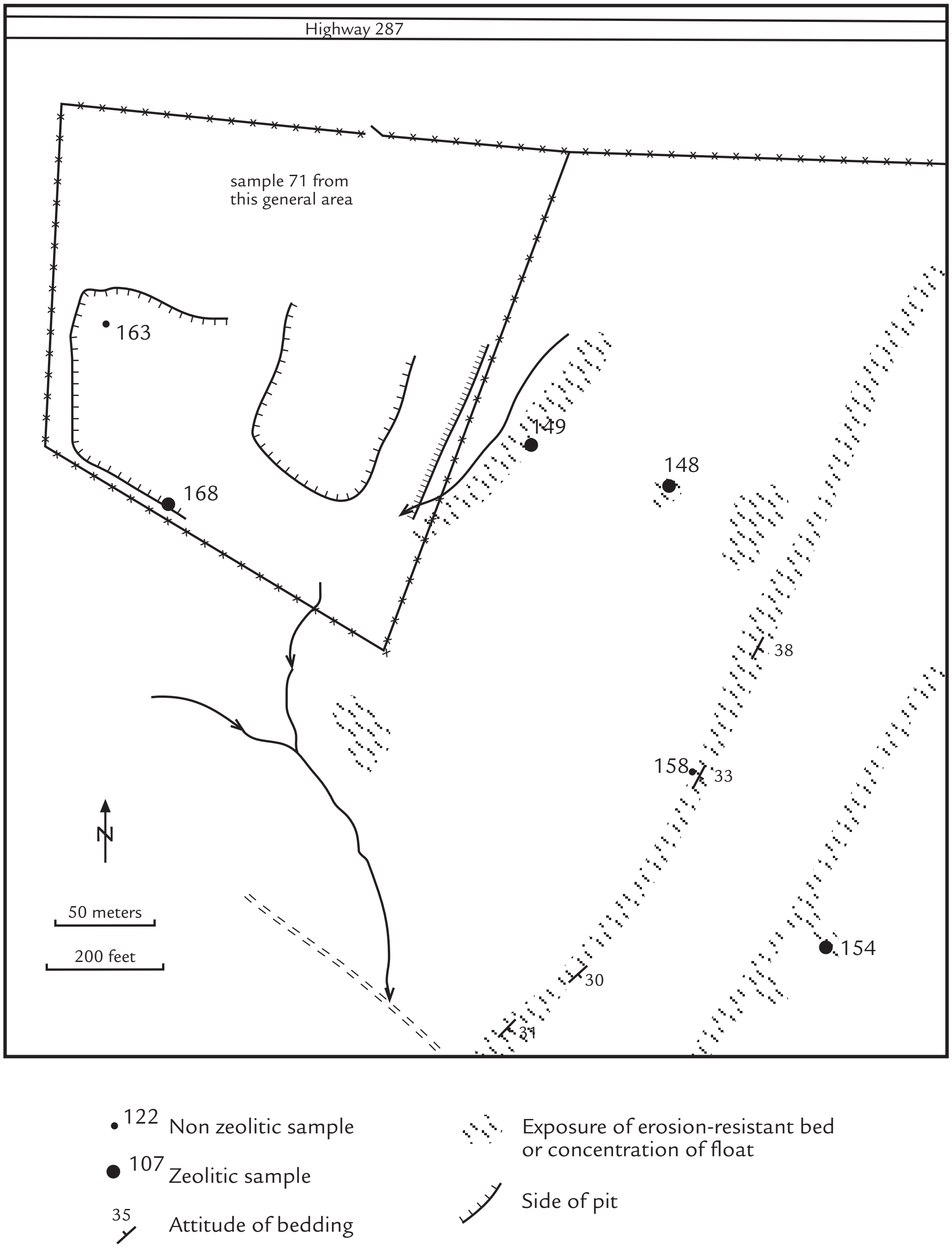

Figure 25. Area surrounding the road metal pit at Badger Pass (shown as gravel pit on topographic map).

(1982) interpreted these fine-grained, tuffaceous beds to be lacustrine deposits belonging to the Renova Formation, which here is Oligocene or slightly older. Total stratigraphic thickness of these beds that dip 20°–35° east is 3,300 feet (1,000 meters). Recognized zeolite occurrences are confined to these tuffaceous beds.

Eighteen samples, thought to be zeolitic when examined in the field, were all found to contain clinoptilolite in major concentrations when analyzed by x-ray diffraction (table 1). No other species of zeolite was identified in these samples. In addition to clinoptilolite, opal-CT was a major constituent of most of these samples; quartz and feldspar were either minor or major constituents of most samples.

Although when viewed from a distance, white tuffaceous beds appear well exposed on the low hills west of Muddy Creek, individual beds are not traceable because of gentle dip in the same direction as the slope of the hills. Most zeolitized beds are traceable for only a few tens of meters. Beds that weathered to form cohesive fragments, typically with crude conchoidal fractures and ranging from light greenish grey (5 G 8/1) to white (N 9), were sampled, and thickness or width was measured (table 9). Zeolitization of these beds appears to be discontinuous because no ridge-forming

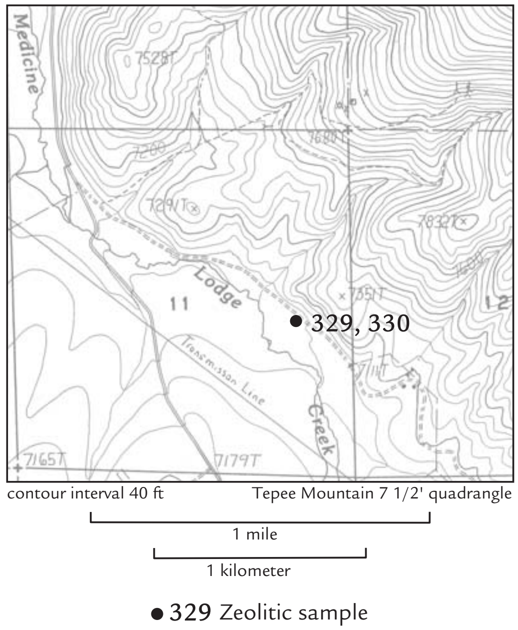

Figure 26. Zeolite occurrence along Medicine Lodge Creek.

beds or prominent ledge-forming beds were recognized. A few concretionary masses that appeared to be zeolitized are exposed, but these were not sampled. On the basis of the 18 samples analyzed and field reconnaissance, the greatest concentration of partially zeolitized tuff is in the E½ section 12, T. 13 S., R. 11 W. Eight samples analyzed from exposures in this section were zeolitic (figure 27 and table 9). One sample from a granular-weathering bed estimated to be 32 feet (10 meters) thick contains clinoptilolite and feldspar in major concentration with lesser quartz and opal-CT (Z-249, table 1 and locality 249, figure 27). Because of the abundance of relatively thick zeolitic beds, this area warrants further investigation. Detailed mapping might demonstrate more continuity to zeolite beds than was recognized during this reconnaissance.

West Fork Blacktail Deer Creek

Location: NE¼, SW¼, and NW¼ SE¼ section 8, T. 11 S., R. 6 W., Price Creek NE 7½-minute quadrangle, Beaverhead County, 26 miles (42 kilometers) southeast of Dillon.

Ownership: BLM–administered land

Excellent exposures of light-colored bentonitic beds of Tertiary age are visible from the road along the West Fork of Blacktail Deer Creek. Two erosion-resistant beds suspected of being zeolitic were sampled (figure 29). The upper bed ranges from 1 to 4 inches (3 to 10 centimeters) thick, is overlain and underlain by tan bentonitic beds, and is white (N 9). Clinoptilolite is the major constituent of this sample with minor opal-CT and smectite (sample Z-222, table 1). The lowest of the sampled beds, also white (N 9) and erosion resistant, is 6.8 feet (2.1 meters) thick and grades into the overlying bentonitic bed but has a sharp contact with the underlying bentonitic bed. Opal-CT and glass are major constituents of this sample with lesser concentrations of clinoptilolite and smectite (sample Z-223, table 1).

Hepburn's Mesa

Location: East side of the Yellowstone River in the NE¼SE¼ section 23, T. 6 S., R. 7 E., Dailey Lake 7½-minute quadrangle, Park County. Approximately 29 miles (46 kilometers) southwest of Livingston.

Ownership: Private

The Middle Miocene Hepburn's Mesa Formation is exposed in cliffs along the northwestern side of Hepburn's Mesa next to the Yellowstone River (figure 30). Tuffaceous claystones, siltstones, and sandstones of this formation were deposited in and adjacent to a saline lake (Barnosky and Labar, 1989). These authors interpreted textures to indicate that air-fall ash has been altered to clinoptilolite at Hepburn's Mesa. Seven samples analyzed by x-ray diffraction by Barnosky and Labar (1989) are reported to contain between 30 and 59 percent clinoptilolite. Other constituents reported from these samples are clay and lesser amounts of calcite, quartz, halite, gypsum, K-spar, albite, and cristobalite.

The "CC-North" section described by Barnosky and Labar was examined and samples of the most massive and erosion-resistant beds were collected. A sample of their bed 14, the uppermost bed exposed just below terrace gravel at the north end of this exposure, was analyzed and found to consist mainly of clinoptilolite with quartz and opal-CT in low concentrations. This bed where sampled is 20 inches (50 centimeters) thick and pale olive (10 Y 6/2). This sample (Z-436) is a chip sample across the entire bed.

A light greenish grey (5 GY 8/1) pod with conchoidal fractures is exposed within tan-weathering mudstone in the same exposure. This concretionary mass of zeolitic rock is 28 inches (70 centimeters) by 14 inches (35 centimeters) and is elongate parallel to bedding. Clinoptilolite is the major constituent of a sample from this mass (Z-438) and is accompanied by quartz, opal-CT, and feldspar in much lower concentrations.

Partial zeolitization of most of the tuffaceous beds exposed here is indicated by the mineralogical analyses of samples from these beds presented by Barnosky and Labar (1989) and by field examination by the author. The bed with the highest concentration of zeolites as judged by weather-

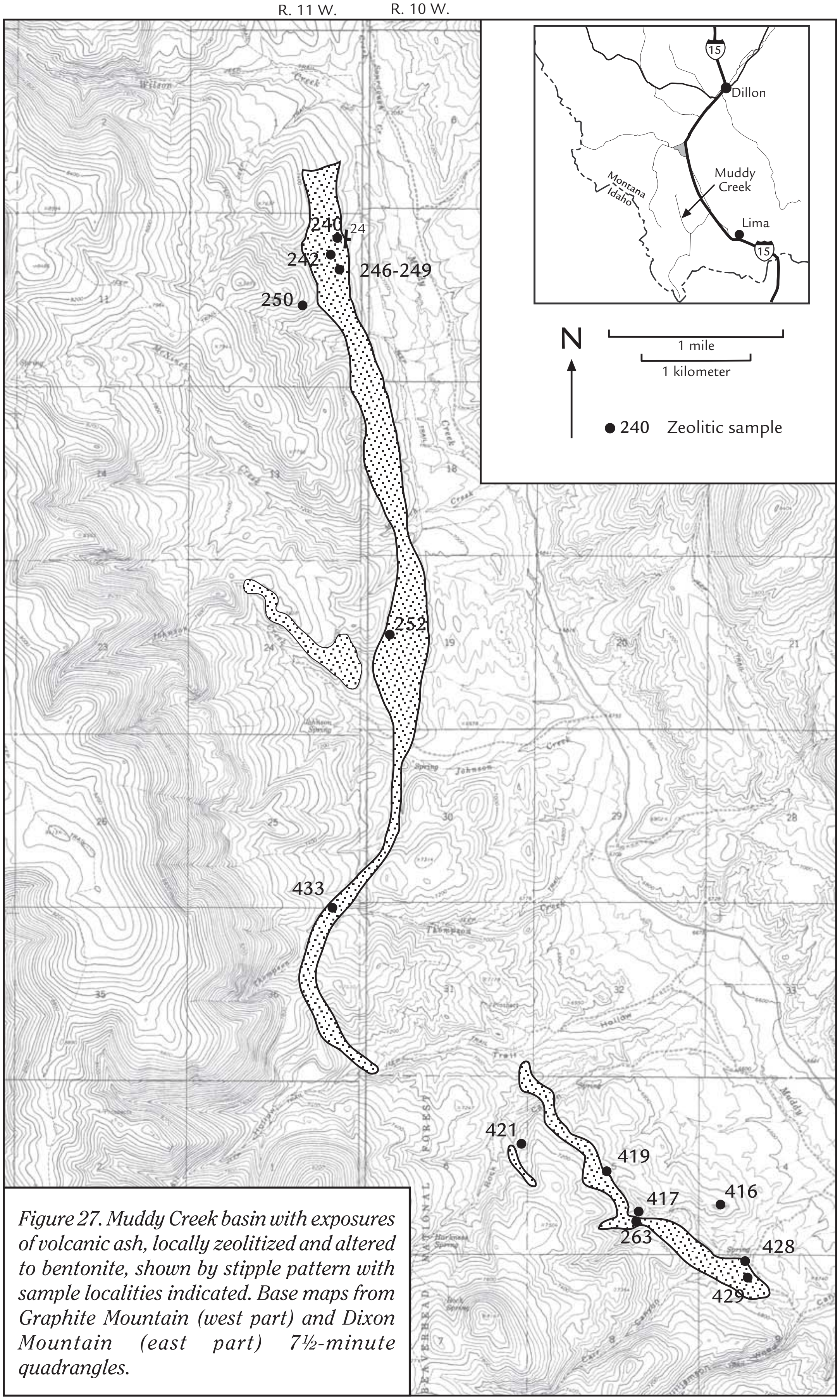

Figure 27. Muddy Creek basin with exposures of volcanic ash, locally zeolitized and altered to bentonite, shown by stipple pattern with sample localities indicated. Base maps from Graphite Mountain (west part) and Dixon Mountain (east part) 7½-minute quadrangles.

Figure 28. Exposures of tuffaceous beds in Muddy Creek basin.

ing characteristics is only 20 inches (50 centimeters) thick where sampled and does not represent a resource. The erodibility of the other beds suggests a fairly high clay content. Seven zeolitic samples analyzed by Barnosky and Labar contain 34–53 percent clay.

ment are located in sections 27 and 28, T. 8 S., R. 10 W., 10 miles (16 kilometers) southwest of Dillon and 2 miles (3.2 kilometers) west of Interstate 15 (see figure 1).

Land status along Grasshopper Creek is a complicated pattern of fee simple, federal minerals, private surface and split mineral/surface estates. Mineral rights of the principal deposits are controlled by B.E. Cox in the Zealot #1 and 13–19 unpatented mining claims. Road access is controlled by the Shaffner, Kuntz, and Chaffin families, whose ranches lie along Grasshopper Creek.

Exploration and Development

D.B. Hawkins of the U.S. Geological Survey was the first to record the occurrence of clinoptilolite and mordenite in the volcanic rocks of the Dillon area (cited by Sheppard, 1976, as written communication from Hawkins, 1974).

Table 9. Analyzed specimens of zeolitized tuff from Muddy Creek Basin. Sample localities shown on figure 27 and mineralogy given in table 1. Clinoptilolite was estimated to be a major constituent of all samples except sample 252, where it is a minor constituent.

Sample	Description
240	bed 9 feet (3 meters) thick exposed in small watercourse between two sandstone beds
242	bed about 1 foot (0.3 meters) thick
246	exposed width of massive bed about 3 feet (1 meter)
247	chippy weathering bed with exposed width of 18 feet (5.5 meters)
248	slabby bed with exposed width of 3 feet (1 meter)
249	granular-weathering bed about 32 feet (10 meters) thick
250	bed about 3 feet (1 meter) thick
251	bed about 3 feet (1 meter) thick
252	sample of float of poorly exposed bed probably about 3 feet (1 meter) thick in purplish silty clay
257	sample from concentration of float at top of ridge
263	interbedded bentonite and zeolitized tuff—about 20 percent bentonite only tuff beds sampled over 6 feet (1.8 meters) stratigraphic interval
416	bed 6 inches (15 centimeters) thick
417	sample of float from poorly exposed bed at top of ridge
419	float from bed probably between 3 and 6 feet (1 and 2 meters) thick
421	bed 5 feet (1.5 meters) thick
428	poorly exposed bed probably less than 3 feet (1 meter) thick
429	float from poorly exposed bed on top of ridge
433	bed about 8 inches (20 centimeters) thick

Grasshopper Creek Deposits

Location and Ownership

Zeolitic strata exposed along Grasshopper Creek contain the largest known coherent deposits of bulk-mineable zeolitic rock in Montana. Deposits in the early stages of economic develop-

Subsequent geologic mapping and analytical work by Sheppard (1976) and by Pearson (1989) identified several locations at which zeolitic alteration occurs in mappable sequences.

In 1989, Earthworks, Inc., and Elizabeth Brenner-Younggren recorded the first mining claims on Grasshopper Creek specifically for zeo-

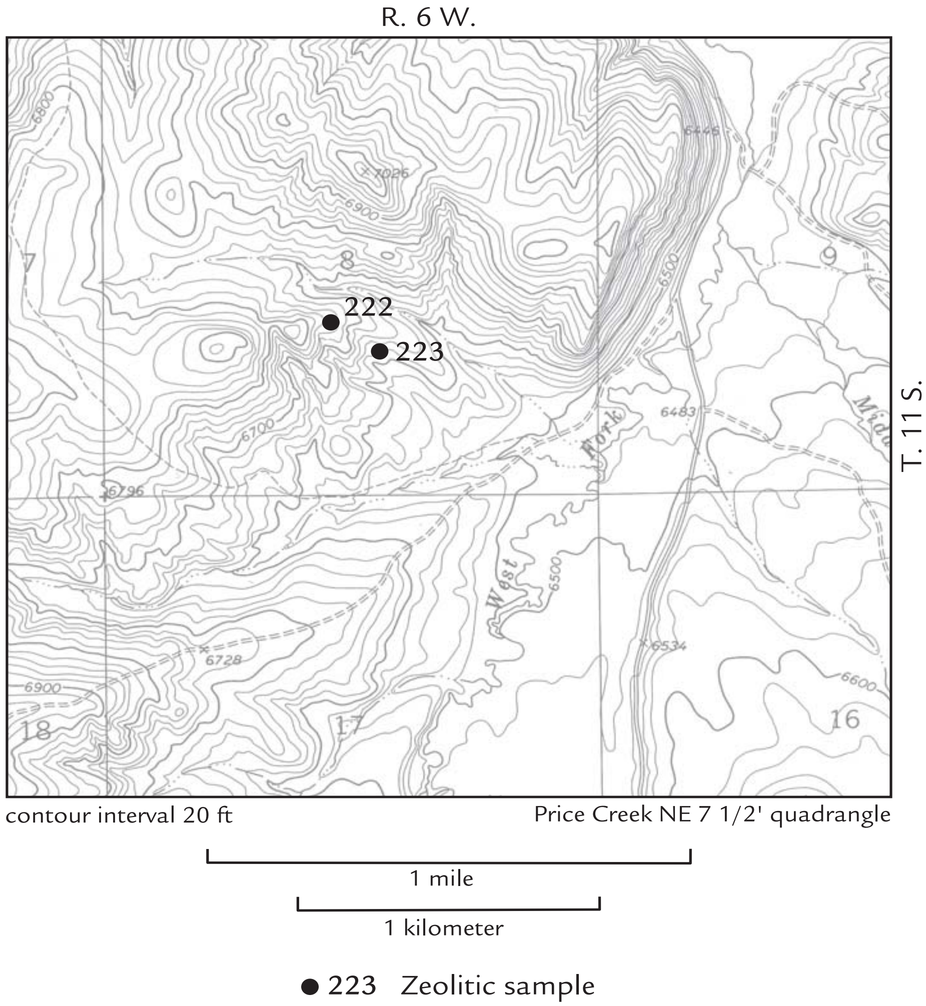

Figure 29. Zeolite occurrence along the West Fork of Blacktail Deer Creek.

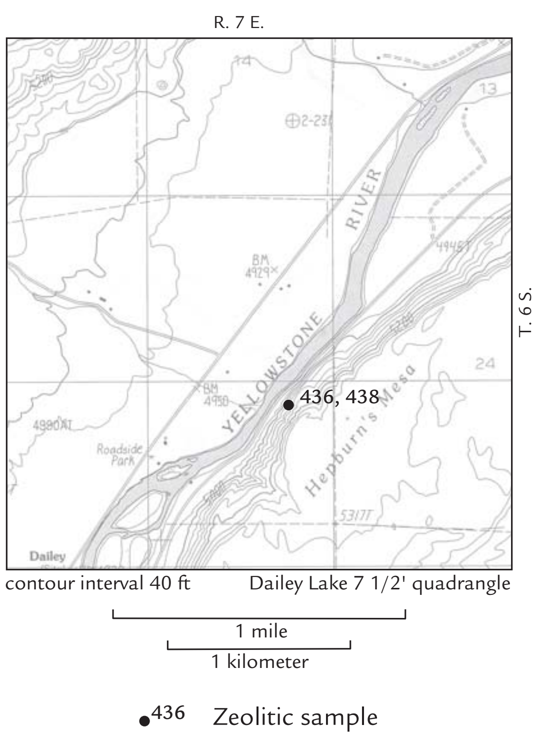

Figure 30. The Hepburn's Mesa clinoptilolite occurrence.

lite minerals. From 1989 to 1992, this joint venture performed reconnaissance-level and site-specific geologic mapping and sampling to better define the grade, tonnage, and mining engineering characteristics of the zeolitized strata. Since 1992, development and marketing for the deposits have been managed by Montana Clino-Z, lc. An access road has been constructed into the principal zeolite deposit and 100 short tons (90 metric tons) of mineralized material have been mined from a small open pit. Three AX-core holes have been drilled in the principal deposit (see appendix II).

Regional Geology

Cretaceous volcanic rocks discontinuously crop out over a 77-square-mile (200-square-kilometer) area, 6–16 miles (10–25 kilometers) southwest of Dillon. Zeolitic alteration appears confined to a basal sequence of graded pyroclastic flows, ash fall materials and possible vent breccias that together compose the "tuff of Grasshopper Creek" (Kg of Pearson, 1989). This tuff lies in angular unconformity on Mesozoic arkosic sandstone and medium-bedded limestone. It is overlain by andesitic lavas and lahars and by locally hematitic conglomerates (Beaverhead Conglomerate?), both of which are probably Cretaceous near Grasshopper Creek. These zeolite deposits lie below or in the immediate hanging wall of the Grasshopper thrust plate as described by Johnson and Sears (1988) and are locally cut by northeast-trending, high-angle faults, probably Tertiary. The high-angle faults may have served as conduits for movement of Tertiary basaltic magmas.

Geology of the Deposits

Field Relationships

The distribution of the tuff of Grasshopper Creek is shown in figure 31 (back pocket). In outcrop, the tuff of Grasshopper Creek is white, light grey, or cream; bedding ranges from flaggy to massive. Macroscopic texture ranges from uniformly fine-grained pumiceous tuff to conglomeratic tuff containing 0.5–3.0-centimeter-diameter lithic clasts of pumice, siltstone, and andesitic volcanics. Local stratigraphic successions of zeolitic tuff to opaline tuff to dominantly smectitic tuff suggest vertical zoning of authigenic minerals. The vertical succession of tuff strata exposed south of Grasshopper Creek is represented in figure 32.

The tuff of Grasshopper Creek unconformably overlies Cretaceous sandstone and limestone. The basal tuff is a white-to-tan, massive conglomeratic tuff in which the size and abundance of lithic fragments decrease upward. In contrast, zeolitization increases upward and is strongest below and into the base of the overlying vitric tuff.

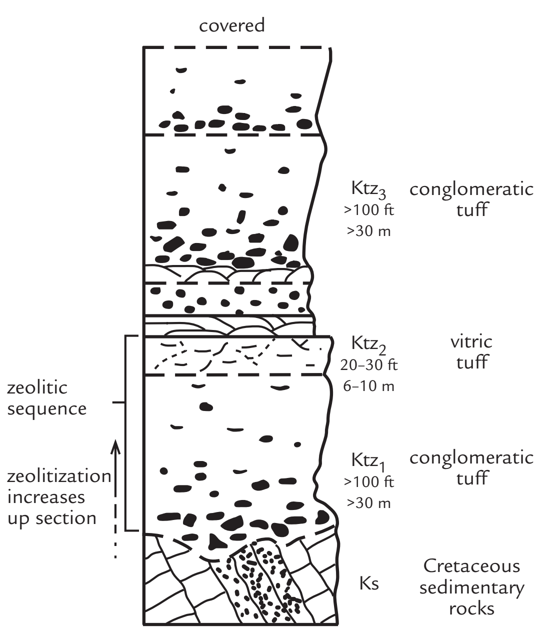

Figure 32. Generalized stratigraphy of zeolitic tuffs of Grasshopper Creek.

Vitric tuff overlying the basal conglomeratic tuff is 23–33 feet (7–10 meters) thick and grades up section from an indistinct basal contact with compact granular texture to vitreous texture along a sharp upper contact. Zeolitization increases upward and is accompanied by increasing pink, tan, and green mottling. Locally, zeolitization is pervasive through the matrix and pumiceous clasts. This “vitric” tuff sequence is interpreted to be a stratigraphic datum that may have exerted a permeability control on zeolitization.

The lower strata of the upper conglomeratic tuff include two 10-foot (3-meter) sequences of white, lithic-poor flaggy tuff separated by 33 feet (10 meters) of ungraded conglomeratic tuff. The upper strata include at least two sequences of conglomeratic tuff that display normal grading of lithic fragments. Conglomeratic tuff commonly contains up to 30 percent pink pumiceous (?) clasts that have been altered to smectite. Most samples from this conglomeratic unit contain only traces of clinoptilolite.

Tuff on the north side of Grasshopper Creek is poorly exposed and partially covered over large areas by the Beaverhead Conglomerate and andesitic volcanics; these factors limit evaluation of tuff stratigraphy. However, geologic cross sections (figure 31) suggest that the 134 and 366 zeolite deposits represent approximately the same stratigraphic sequence as exposed on the south side of Grasshopper Creek.

Field Mineralogy

Initial exploration indicated that clinoptilolite and mordenite occur in various tuffaceous lithologies but not in discrete zeolitic beds. This observation and the suspected complexity of post-Cretaceous faulting prompted the search for a method for rapid field identification and mapping of ore-grade zeolitic rock (*i.e.,* >50 percent clinoptilolite + mordenite).

Empirical review of field sample descriptions and x-ray diffraction analyses indicates that the following macroscopic features have moderate-to-strong correlation with a zeolite content >50 percent (table 10).

(1) HCl effervescence, disseminated fine grains or clots of amber-colored calcite crystals.

(2) Manganese oxides as disseminations, dendrites, and fracture fillings.

(3) Pumiceous lithic fragments that have altered to clays, especially to waxy smectitic clays.

(4) Conchoidal breaking, which is gradational between a friable (unaltered) texture and an opaline texture (silicified or feldspathized) with conchoidal fracture.

Table 10. Macroscopic characteristics of zeolitic and non-zeolitic tuff of Grasshopper Creek (Cox and Brenner-Younggren, 1993).

Sample	Zeolite Content	HCl Effervescence	Mn Oxide Content	Clast Alteration	Conchoidal Breaking	Vugs
ZC9205	>90% C	none	none	N/A	strong	none
ZP8909	>90% C	none	1-2%	strong	strong	2-3%
ZC9203	>90% C	1-2% in vugs	2-3%	T 1%	moderate-to-strong	3-5%
ZC9204	~70% C ~15% M	T	1-2%	moderate-to-strong	moderate	locally 1-2%
ZP8906	~55% C ~20% M	2% in vugs	T	strong	strong	2-3%
ZP8907	~25% C	none	T	weak	weak-to-moderate	none
ZP8910	~15% C	none	T	weak	none	none
ZC8906	~10% C	T 1% in vugs	none	weak	weak	T
ZY8904	0%	none	none	none	none	none
ZC8908	0%	none	none	moderate	none	none

Zeolite content was determined by x-ray diffraction analysis (see table 13); C=clinoptilolite, M=mordenite. Percent given for effervescence is an estimate of the percent of grains that effervesced with diluted HCl.

(5) Presence of open vugs as net-like textures and as spherules commonly with 1–3-millimeter alteration rims of manganese oxides and in some instances also clay.

The features listed above are interpreted to be the macroscopic expression of the zeolitic alteration of tuff, which may have application for identifying zeolitization in other volcanic terranes. Features 1–3 represent the mineralogical change from a nearly monomineralic tuffaceous material to an authigenic mineralogy. Features 4 and 5 represent the textural changes of greater crystallinity and probable decreased volume, respectively. There is no recognized macroscopic feature to distinguish mordenite-bearing tuff from clinoptilolite-bearing tuff.

Mineralogy and Geochemistry

Analytical methods that have been used to characterize the mineralogy and chemical composition of the tuffs include x-ray diffraction, DC plasma emission and multi-element ICP. X-ray diffraction analyses by MBMG and two independent laboratories have determined that clinoptilolite and mordenite are the only zeolite species in the tuffs and that the ratio of clinoptilolite to mordenite in the principal deposits is approximately 7:1. A scanning electron micrograph shows the occurrence of clinoptilolite, mordenite, and smectite in one specimen from the 134 deposit (figure 33).

Mineralogical and chemical analyses indicate that the 134 and 127 deposits contain approximately 70 percent combined zeolites (tables 11, 12, and 13). Accessory minerals and other diluents in approximate decreasing order of concentration are smectite, lithic fragments, quartz, glass, K feldspar, and calcite. Plots of selected elements versus zeolite content show that the concentration of Ca, Na, K, and Mg (probably occurring as exchangeable cations) is an order of magnitude greater in strongly zeolitized samples (figure 34).

Geophysics

A very low frequency–resistivity (VLF–R) reconnaissance survey was performed across the 134 deposit under the direction of W.I. Van der Poel. Data were collected at 50-foot (15-meter) intervals along two east-west lines spaced 400 feet (122 meters) apart. Figure 35 (back pocket) shows the survey data and one resistivity pseudosection. Data indicate that zeolitized tuff produces a 30–100

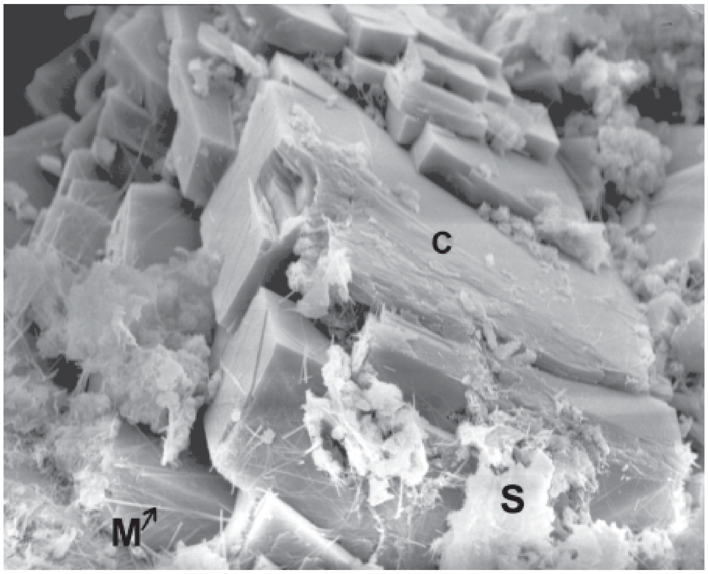

Figure 33. Scanning electron micrographs of clinoptilolite (C), mordenite (M), and smectite (S) in zeolitic tuff from the Grasshopper Creek deposit. Scanning electron micrograph by William Huestis, Montana Tech of The University of Montana.

ohm/meter response, which is in sharp contrast to the 15–30 ohm/meter response over the andesitic volcanic rocks (lahar and dike). Clay-rich fault zones display distinct resistivity lows on the order of 5–20 ohm/meters.

Zeolitization Models

Field relationships indicate that two modes of zeolitic alteration produced these deposits. The 127 deposit (figure 31) is probably most representative of zeolitization produced by the influx of alkaline ground water into a restricted topographic basin. The deposit is nearly flat lying, and zeolitization is concentrated at or below the vitric tuff sequence. Presumed lower permeability of the vitric tuff may have constrained the flow of ground water that derived its alkalinity by flowing through underlying Mesozoic carbonate strata. The 134 deposit (figure 31) probably occurs within the same tuff sequence as the 127 deposit, but several factors indicate a slightly different origin for mineralization. Discontinuous exposures of vitric tuff along the east flank of the deposit suggest that initial zeolitization may have occurred in a restricted basin setting. However, the presence of high-angle, clay-rich faults and locally pervasive manganese oxide alteration suggests that hydrothermal processes also may have contributed to the primary zeolitization or a secondary zeolitic overprint. The lower permeability of the vitric tuff may have served to restrict the movement of hydrothermal fluids.

There is some evidence that the 134 deposit is part of a vent breccia complex. The majority of lithic fragments are distinctly angular, and there is no evidence of particle sorting or bedding. The northwest and southeast margins of the deposit are defined by steeply dipping tabular sequences (faults and/or vent margins?) of tan and pink smectitic clay. The highest grade clinoptilolite tuff from Grasshopper Creek occurs within a small exposure of accretionary lapilli tuff at the northeast margin of the deposit.

Operating Conditions

The 134 deposit probably offers the best combination of conditions favorable to bulk mining zeolitic rock at Grasshopper Creek. Similar x-ray diffraction and whole rock analyses were obtained from several 40–50 pound (18–23 kilogram) samples representing the deposit surface and from AX core samples from three drill holes (see appendix II). These samples and surface mapping indicate that the deposit contains a minimum of 100,000 short tons (90,000 metric tons) of tuff grading approximately 60–70 percent combined zeolites. This drill-indicated resource has little or no overburden and considerable potential for expansion to the west and northeast. The deposit may be floored by a gently west-dipping fault. This deposit is located on a dry, south-facing nose with little vegetation. A spur road has been constructed into the center of the deposit where a bulk sample was collected (figures 36 and 37). Some of the surface materials are rippable, but massive portions of the deposit may require drilling and blasting or use of a hydraulic hammer to aid extraction. Figures 38 and 39 show the topography typical of these deposits on Grasshopper Creek.

An intra-company cash flow/break-even analysis by Montana Clino-Z, lc and an economic evaluation by John Brower, Mineral Economist, Montana Tech of The University of Montana (Duaime and others, 1997) indicate that the Grasshopper Creek deposits could be mined at a profit if sufficient reserves can be defined to yield a 15–20-year mine life and if average product value is greater than $60/ton (F.O.B. Dillon).

Research and Marketing

Grasshopper Creek zeolites have been included in various research projects that deal with cation exchange and adsorption. Because transportation costs are critical to marketability, efforts have focused on regional markets, especially agricultural and industrial uses. The 134 and 127

Table 11. Whole-rock analyses of zeolitized tuff from the Grasshopper Creek deposits. Samples 127, 134, and 366 are bulk samples. XRAL indicates XRAL Activitation Services, Inc. Results given in percent unless otherwise noted, and all Fe reported as Fe_2O_3.

Sample Number	Laboratory	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	Ba	MnO	P_2O_5	TiO_2	Cr	L.O.I.	Total	ppm Nb	Rb	Sr	Y	Zr
ZC8904	Bondar-Clegg	67.3	12.5	0.94	3.4	1.36	3.27	0.98	0.01	0.05	<0.01	0.08	<0.01	11.03	101.13					
ZP8906	Bondar-Clegg	67.6	11.8	0.75	3.0	0.65	4.52	0.72	0.02	<0.01	0.09	0.09	<0.01	10.66	99.80					
ZP8909	Bondar-Clegg	66.7	11.5	1.22	3.2	0.54	3.42	0.84	0.02	0.29	<0.01	0.24	<0.01	12.54	100.50					
									ppm											
ZC9203	XRAL	64.5	11.4	0.76	4.7	0.73	4.07	0.67	1100	0.08	0.08	0.17	0.02	11.70	99.10	20	120	630	20	150
ZC9204	XRAL	66.0	12.8	0.79	3.1	1.44	3.27	0.86	1700	0.04	0.06	0.10	0.02	11.80	100.30	20	90	880	<10	30
									BaO (%)											
PMZ-01	Bondar-Clegg	68.5	10.8	0.68	2.7	0.66	3.23	0.57	0.14	0.01	0.12	0.07	<0.01	11.68	99.20					
PMZ-02	Bondar-Clegg	67.5	12.4	0.60	2.8	1.24	3.35	0.73	0.16	0.05	0.17	0.07	<0.01	10.34	99.30					
PMZ-03	Bondar-Clegg	66.5	12.1	0.80	3.2	2.22	3.62	0.35	0.15	0.03	0.16	0.08	<0.01	11.45	100.70					
PMZ-04	Bondar-Clegg	72.8	12.0	1.04	1.4	1.64	3.87	1.00	0.12	0.07	0.10	0.10	0.01	5.38	99.40					
127	XRAL	64.5	11.4		4.7	0.73	4.07	0.67						11.80	97.80					
134	XRAL	66.0	12.8		3.1	1.44	3.27	0.86						11.80	99.30					
366	Bondar-Clegg	66.5	12.0		3.2	2.22	3.62	0.35						11.40	99.30					

Table 12. Analyses of samples of zeolitized tuff from the Grasshopper Creek deposits. Analyses using ICP by Bondar-Clegg. (*)Arsenic by neutron activation with 1 ppm detection limit.

	Percent						ppm								
Sample Number	Fe	Ca	Na	K	Mg	Al	Cu	Pb	Zn	As	Sb	Mo	Mn	Sr	Ba
ZC9204	0.59	2.07	0.91	1.02	0.45	6.15	2	20	46	<5	8	2	233	592	1345
ZC9205	0.60	1.28	1.48	1.20	0.26	4.92	1	12	32	22	<5	<1	79	546	>2000
MEZ1-95	0.51	1.62	0.78	1.17	0.50	3.88	6	16	46	*4.2	<5	1	651	444	1083
MEZ2-95	0.57	1.71	0.68	0.99	0.58	3.64	3	25	49	*2.7	<5	<1	864	417	1021
MEZ3-95	0.44	1.09	0.87	1.08	0.41	3.30	<1	34	43	*2.0	<5	3	4815	414	1803
Z-127S	0.34	1.52	0.51	1.27	0.28	2.74	<1	19	33	*1.6	<5	1	197	394	838
Z94 600-650	0.31	1.66	0.83	0.96	0.54	3.60	<1	19	28	*1.1	<5	2	770	981	1665
Z94 650-700	0.35	1.75	0.92	0.94	0.56	3.74	<1	20	30	*2.4	<5	2	551	991	1703
Z94 700-750	0.34	1.82	0.66	0.98	0.66	3.99	<1	23	37	*1.6	<5	3	5340	882	1610
ZC8904	0.35	1.81	0.45	1.09	0.56	3.76	<1	96	36	*9.4	<5	8	221	691	1148
ZC8905	0.44	1.12	1.34	0.91	0.27	2.99	2	97	43	*52.9	<5	5	94	495	>2000
ZC8908	0.26	0.46	0.14	0.21	0.46	0.74	<1	7	16	*<1	<5	<1	115	47	87
ZC9206	0.21	1.46	0.74	0.90	0.23	2.85	<1	15	22	*3.3	<5	2	195	470	1965
ZC9208	0.09	0.50	0.17	0.24	0.09	0.86	<1	<2	7	*1.1	18	<1	17	156	412
ZC9210	0.35	3.06	1.12	0.69	0.14	2.38	<1	15	35	*2.6	<5	2	497	443	949
ZC9211	0.29	2.91	0.04	0.86	0.49	3.22	<1	20	30	*<1	<5	2	302	417	1117
ZP8906	0.29	1.70	0.32	1.37	0.38	3.30	2	149	47	*25.8	<5	3	45	719	1953
ZP8909	0.50	1.99	0.27	2.35	0.46	4.61	<1	130	31	*14.4	<5	4	1442	630	1692

zeolites have shown a moderate-to-strong cation exchange affinity for copper, lead, zinc, iron, and thallium from mine effluents (Duaime and others, 1997) and for ammonia from animal wastes. Other markets being investigated are filter media for municipal water-treatment facilities, animal feed supplements, soil conditioners, and innovative building materials.

Origin of Montana Occurrences

Zeolites are generally considered to have formed in one of the following geologic environments (Hay, 1977):

1. Saline-alkaline lakes
2. Soils and surface deposits
3. Deep sea deposits
4. Igneous rocks
5. Burial-diagenetic environment
6. Hydrothermal system
7. Open hydrologic system

The origin of many of the zeolite occurrences in Montana is not evident, nonetheless some generalizations can be made. Some of the purest zeolite deposits in the world were formed in saline-alkaline lakes. Pleistocene Lake Tecopa east of Death Valley in California is an excellent example of this geologic environment of zeolite formation (Sheppard and Gude, 1968). At this former lake, the alteration sequence is from fresh glass near the margin of the lake through a zone of zeolitic alteration to potassium feldspar in the central part of the lake basin. With the exception of the Hepburn's Mesa clinoptilolite occurrence south of Livingston, no evidence was observed for zeolitic alteration in a shallow saline-alkaline lake. The Hepburn's Mesa Formation of middle Miocene age contains smectite, calcite, halite, and gypsum in addition to clinoptilolite (Barnosky and Labar, 1989). Tuffaceous sediment of this formation was deposited in and adjacent to a perennial saline lake.

Zeolite deposits formed in the surface environment by weathering are relatively rare, and there is no evidence that any of the examined zeo-

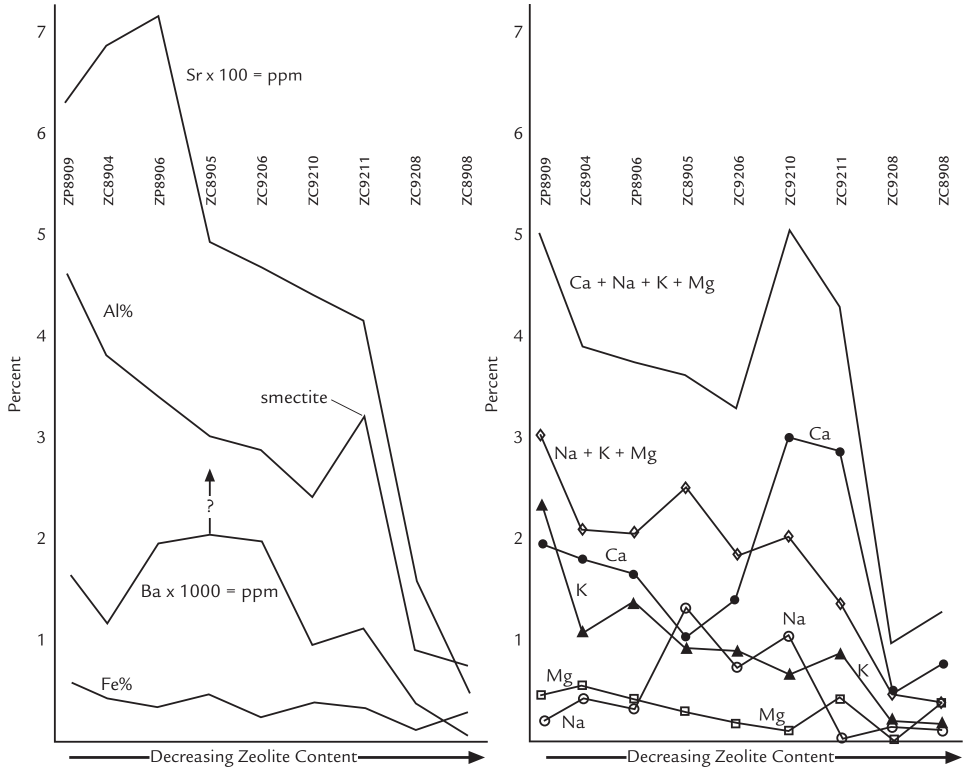

Figure 34. Plot of concentration of selected elements versus zeolite content for samples from Grasshopper Creek. All elemental values are in weight percent, except barium and strontium, which are in parts per million. See tables 11 and 12 for chemical analyses. The principal minerals in each sample and relative clinoptilolite content were determined by x-ray diffraction analysis (table 13).

Figure 37. Excavation of bulk sample from the 134 deposit, Grasshopper Creek.

Figure 39. Photo of 134 deposit at Grasshopper Creek, view east.

Figure 38. Photo of 127 deposit at Grasshopper Creek, view south.

lite occurrences in Montana formed in this manner. If the zeolite occurrences in Tertiary sedimentary rocks in southwestern Montana were related to weathering, then zeolitized beds should be associated with paleosols described by Hanneman and Wideman (1991) in southwestern Montana. However, zeolitic beds were not recognized in association with these paleosols.

Zeolites have been identified in the cores recovered by the Deep Sea Drilling Project (Hay, 1977). Clearly zeolite occurrences in Tertiary sedimentary beds in the intermontane basins of southwestern Montana did not form in a deep sea

Table 13. X-ray diffraction analyses of selected samples from the Grasshopper Creek deposits. See table 1 for additional analyses of samples from Grasshopper Creek. M =major, m = minor, T = trace, mgns = magnesite, hbld = hornblende.

Sample Number	Analyst	Clinoptilolite	Mordenite	Quartz	Glass	Feldspar	Biotite	Smectite	Calcite	Dolomite	Other
ZC8902	Brenner-Younggren			T	M			M			
ZC8903	"			M	M			M			
ZC8904	"	M	m	T							
ZC8905	"	M		m							
ZC8906	"	T		M		M	T				
ZC8907	"	m		M				m			
ZC8908	"			M	M			M			
ZP8901	"			M		M	M	M			M hbld
ZP8902	"	M	T				T	T			
ZP8905	"			M	M			T	M		M hbld
ZP8906	"	M	m					T			
ZP8907	"			M		M		M			
ZP8909	"	M						T			
ZP8910	"	M		M		M			M		
ZY 8901	"							M		M	
ZY8902	"							M			M mgns
ZY8904	"							M		M	
91P007	Pearson	M	m	T				T			
91P008	"	M	m	T							
ZC9206 Z364	Berg	M	m	M					T		
ZC9208 Z365	"	M		T		M		m			
ZC9210 Z366	"	M	m	m		m			m		
ZC9211 Z367	"	M	m	m					m		
ZC9212 Z368	"					M		M			

environment because these beds were deposited in lacustrine and fluvial environments. The thin bed of analcime in the Taft Hill Member of the lower Cretaceous Blackleaf Formation (figure 8) near Vaughn may have formed in a marine environment because the Taft Hill Member is of marine origin. Also, the Arrow Creek Bed of the Bootlegger Member of the Cretaceous Blackleaf Formation is marine (figure 9).

Zeolites have long been collected from amygdules and veinlets in igneous rocks, mainly extrusive flows and dikes. There are numerous zeolite occurrences of this origin in the Cretaceous and Tertiary volcanic rocks of Montana. However, these occurrences were not examined during this study because, although of mineralogical interest, they do not constitute deposits that are of sufficient size to be of commercial interest.

Zeolitic deposits of a burial-diagenetic origin tend to occur over large areas and in some instances show mineralogical zoning caused by increasing temperature with increasing depth. As explained by Hay (1977), burial-diagenetic deposits grade into zeolite deposits formed in open hydrologic systems but where increasing temperatures were encountered at increasing depths. Hay suggested that in open hydrologic systems zeolitic alteration is short lived and may be penecontemporaneous with deposition.

Obviously, most geologic environments in which zeolites are observed to form can be eliminated from consideration in the formation of bedded zeolite occurrences in Montana simply because there is no evidence for the existence of such environments during zeolitization. Most of the zeolite occurrences described from Montana probably formed in either open hydrologic systems or hydrothermal systems. The two geologic environments grade into one another with water temperature the only factor separating them. In an open hydrologic system, presumably the water is near or at surface temperature, whereas in a hydrothermal system the water is at an elevated temperature. The amount of the hydrothermal component in the zeolite occurrences in southwestern Montana cannot be estimated on the basis of field relationships. No occurrences spatially associated with past or present hot spring activity were recognized.

It is suggested that most of the zeolite occurrences in southwestern Montana formed in open hydrologic systems. In those systems, movement of ground water through volcanic ash resulted in alteration to a zeolite, in some instances with the associated formation of smectite. The discontinuous nature of most Montana zeolite occurrences, some of which consist of large concretionary masses, is suggestive of zeolitization caused by movement of ground water, probably at a low temperature. Perhaps even while volcanic ash was being deposited in these basins, ground water flowing through sediment began the zeolitization process. In two areas, Beaver Creek southeast of Helena and Muddy Creek southwest of Dillon (figures 11 and 27, respectively), adjacent limestone of the Madison Group may have played a part in the zeolitization of volcanic ash. These limestone beds are an important aquifer and may have been the source of an abundant flow of ground water into the Tertiary volcanic sediment.

Acknowledgements

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Without exception, landowners granted permission to look for zeolite occurrences on their land. Many of these sites could not have been examined without their cooperation. Partial support was provided by the Montana Department of Natural Resources and Conservation–Resource Development Bureau. Ted Duaime, James Madison, and others involved in the testing of zeolites provided helpful suggestions and enjoyable discussions. Reviews by Phyllis Hargrave, Ron Geitgey, and Bob Virta improved the report and are appreciated.

References

Barnosky, A.D., and Labar, W.J., 1989, Mid-Miocene (Barstovian) environmental and tectonic setting near Yellowstone Park, Wyoming and Montana: Geological Society of America Bulletin, v. 101, no. 11, p. 1448–1456.

Bartlett, M.W., Enders, M.S., Volberding, J.E., and Wilkinson, W.H., 1996, The geology of the McDonald gold deposit, Lewis and Clark County, Montana, in Coyner, A.R., and Fahey, P.L., eds., Geology and ore deposits of the American Cordillera, Symposium Proceedings: Reno, Geological Society of Nevada, p. 981–1000.

Becraft, G.E., 1958, Uranium in carbonaceous rocks in the Townsend and Helena Valleys Montana: U.S. Geological Survey Bulletin 1046-G, p. 149–164.

Berg, R.B., 1977, Reconnaissance geology of southernmost Ravalli County, Montana: Montana Bureau of Mines and Geology Memoir 44, 39 p.

Berg, R.B., 1991, Field guide, Belt Butte and Tiger Butte, in Baker, D.W., and Berg, R.B., eds., Guidebook of the Central Montana Alkalic Province: Montana Bureau of Mines and Geology Special Publication 100, p. 163–174.

Berg, R.B., and Lonn, J.D., 1993, Reconnaissance survey of bedded zeolite occurrences in Montana: Montana Bureau of Mines and Geology Open-File Report MBMG 267, 20 p.

Bierwagen, E.E., 1964, Geology of the Black Mountain area, Lewis and Clark and Powell Counties, Montana: Princeton, N.J., Princeton University, Ph.D. dissertation, 160 p.

Birkholz, D.O., 1967, Geology of the Camas Creek area, Meagher County, Montana: Butte, Montana College of Mineral Science and Technology, M.S. thesis, 68 p.

Blumer, J.W., 1971, Geology of the Deadman Canyon–Copperopolis area, Meagher County, Montana: Butte, Montana College of Mineral Science and Technology, M.S. thesis, 68 p.

Brenner-Tourtelot, E.F., Meier, A.L., and Curtis, C.A., 1978, Lithium in rocks from the Lincoln, Helena and Townsend areas, Montana: U.S. Geological Survey Open-File Report 78–430, 29 p.

Cobban, W.A., Erdman, C.E., Lemke, R.W., and Maughan, E.K., 1976, Type sections and stratigraphy of the members of the Blackleaf and Marias River Formations (Cretaceous) of the Sweetgrass Arch, Montana: U.S. Geological Survey Professional Paper 974, 65 p.

Cox, B.E., and Brenner-Younggren, Elizabeth, 1993, Exploration of a late Cretaceous zeolitic tuff, Beaverhead County, Montana, in Program and Abstracts for 4th International Conference on the occurrence, properties, and utilization of natural zeolites: Boise, Idaho, p. 74–76.

Dahl, G.G., Jr., 1971, General geology of the area drained by the North Fork of the Smith River, Meagher County, Montana: Butte, Montana College of Mineral Science and Technology, M.S. thesis, 58 p.

Derkey, P.D., and Bartholomew, M.J., 1988, Geologic map of the Ramsay quadrangle, Montana: Montana Bureau of Mines and Geology Geologic Map 47, scale 1: 24,000.

Duaime, T.E., Berg, R.B., Madison, James, Feldmann, J.C., III, and Bowler, T.P., 1997, The use of natural zeolites in reducing heavy-metal concentration at mining operations and impacted lands: Montana Bureau of Mines and Geology Open-File Report MBMG 353, 97 p.

Dunlap, D.G., 1982, Tertiary geology of the Muddy Creek basin: Missoula, The University of Montana, M.S. thesis, 134 p.

Elzea, J.M., Odom, I.E., and Miles, W.J., 1994, Distinguishing well ordered opal-CT and opal-C from high temperature cristobalite by x-ray diffraction: Analytica Chimica, v. 286, no. 1, p. 107–116.

Goddard, E.N., Trask, P.D., DeFord, R.K., Rove, O.N., Singewald, J.T., Jr., and Overbeck. R.M., 1963, Rock-color chart, New York, New York, Geological Society of America, 6 p.

Hanneman, D.L., and Wideman, C.J., 1991, Sequence stratigraphy of Cenozoic continental rocks, southwestern Montana: Geological Society of America Bulletin, v. 103, no. 10, p. 1335–1345.

Hare, E.G., 1959, Geology of the Medicine Rocks and adjoining areas in southeastern Montana: Princeton, N.J., Princeton University, B.A. thesis, 62 p.

Hay, R.L., 1977, Geology of zeolites in sedimentary rocks, in Mumpton, F.A., ed., Mineralogy and geology of natural zeolites: Mineralogical Society of America Short Course Notes, v. 4, p. 53–64.

Helfferich, F., 1964, A simple identification reaction for zeolites, (molecular sieves): American Mineralogist, v. 49, nos. 11 and 12, p. 1752–1754.

Holmes, D.A., 1994, Zeolites, in Carr, D.D., ed., Industrial minerals and rocks, 6th edition: Littleton, Colorado, Society for Mining, Metallurgy and Exploration, Inc., p. 1129–1158.

Hruska, D.C., 1967, Geology of the Dry Range area, Meagher County, Montana: Butte, Montana College of Mineral Science and Technology, M.S. thesis, 89 p.

Ivy, S.D., 1989, Source, evolution, and eruptive history of the Cold Spring Creek volcanics, Beaverhead County, Montana: Corvallis, Oregon State University, M.S. thesis, 132 p.

Johnson, L.M., and Sears, J.W., 1988, Cordilleran thrust belt–Rocky Mountain foreland interaction near Bannack, Montana, in Schmidt, C.J., and Perry, W.J., Jr., eds. Interaction of the Rocky Mountain Foreland and Cordilleran thrust belt: Geological Society of America Memoir 171, p. 229–236.

Kauffman, M.E., 1963, Geology of the Garnet-Bearmouth area, western Montana: Montana Bureau of Mines and Geology Memoir 39, 40 p.

Lange, I.M. and Zehner, R.E., 1992, Geologic map of the Hog Heaven volcanic field, northwestern Montana: Montana Bureau of Mines and Geology Geologic Map 53, scale 1:50,000.

Lemke, R.W., 1977, Geologic map of the Great Falls quadrangle, Montana: U.S. Geological Survey Map GQ-1414, scale 1:62,500.

Lowell, W.R., 1965, Geologic map of the Bannack-Grayling area, Beaverhead County, Montana: U.S. Geological Survey Map I-433, scale 1:31,360.

Lyons, J.B., 1942, Geology of the northern Big Belt Range, Montana: Boston, Massachusetts, Harvard University, Ph.D. dissertation, 144 p.

Mandarino, J.A., 1999, The zeolite group: The Mineralogical Record, v. 30, p. 5–6.

McClernan, H.G., 1969, Geology of the Sheep Creek area, Meagher County, Butte, Montana College of Mineral Science and Technology, M.S. thesis, 122 p.

Mertie, J.B., Fischer, R.P., and Hobbs, S.W., 1951, Geology of the Canyon Ferry quadrangle, Montana: U.S. Geological Survey Bulletin 972, 97 p.

Mumpton, F.A., 1960, Clinoptilolite redefined: American Mineralogist, v. 45, p. 351–369.

Mumpton, F.A., 1977, Natural zeolites, in Mumpton, F.A., ed. Mineralogy and geology of natural zeolites: Mineralogical Society of America Short Course Notes, v. 4, p. 1–17.

Pearson, R.C., 1989, Zeolite-bearing Cretaceous tuff in Beaverhead County, southwestern Montana: U.S. Geological Survey Open-File Report 89-0297, 10 p.

Phelps, G.B., 1969, Geology of the Newlan Creek area, Meagher County, Montana: Butte, Montana College of Mineral Science and Technology, M.S. thesis, 56 p.

Robinson, G.D., 1967, Geologic map of the Toston quadrangle, southwestern Montana: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-486, scale 1:24,000.

Ross, C.P., Andrews, D.A., Witkind, I.J., 1955, Geologic map of Montana: U.S. Geological Survey, scale 1:500,000.

Ruppel, E.T., O'Neill, J.M., and Lopez, D.A., 1993, Geologic map of the Dillon 1° x 2° quadrangle, Idaho and Montana: U.S. Geological Survey Map I-1803-H, scale 1:250,000.

Scholten, R., Keenmon, K.A., and Kupsch, W.O., 1955, Geology of the Lima region, southwestern Montana and adjacent Idaho: Geological Society of America Bulletin, v. 66, p. 345–404.

Sheppard, R.A., 1976, Zeolites in sedimentary deposits of the northwestern United States—Potential industrial minerals, in Eleventh Industrial Minerals Forum: Montana Bureau of Mines and Geology Special Publication 74, p. 69–84.

Sheppard, R.A., and Gude, A.J., 3rd, 1968, Distribution and genesis of authigenic silicate minerals in tuffs of Pleistocene Lake Tecopa, Inyo County, California: U.S. Geological Survey Professional Paper 597, 38 p.

Stinson, M.C., 1988, Zeolites in California: California Division of Mines and Geology Bulletin 208, 74 p.

Thomas, G.M., 1981, Structural geology of the Badger Pass area, southwest Montana: Missoula, The University of Montana, M.S. thesis, 58 p.

Virta, R.L., 1999, Zeolites: U.S. Geological Survey Mineral Industry Survey, 1998 Annual Review, 3 p.

Vuke, S.M., Berg, R.B., Colton, R.B., O'Brien, H.E., 1995, Geologic map of the Belt 30 X 60-minute quadrangle, central Montana: Montana Bureau of Mines and Geology Map 54, scale 1:100,000.

Vuke-Foster, S.M., Berg, R.B., and Colton, R.B., 1989, Reconnaissance geologic maps of the northeastern part of the Belt 30 x 60-minute quadrangle, west-central Montana: Montana Bureau of Mines and Geology Open-File Report 212, scale 1:24,000.

Wanek, A.A., and Barclay, C.S.V., 1966, Geology of the northwest quarter of the Anaconda quadrangle, Deer Lodge County, Montana: U.S. Geological Survey Bulletin 1222-B, p. B1–B28.

Whiting, C.K., 1977, Small laccoliths and feeder dikes of the northern Adel Mountain volcanics: Missoula, The University of Montana, M.S. thesis, 74 p.

Appendix I

Localities Examined without Finding Zeolites

In addition to the described localities where zeolites were found, numerous exposures of Tertiary tuffaceous beds were examined and in some instances sampled and analyzed without finding zeolites. The following are basins and specific exposures examined where zeolitic beds were not recognized. Letters refer to localities shown on figure 40.

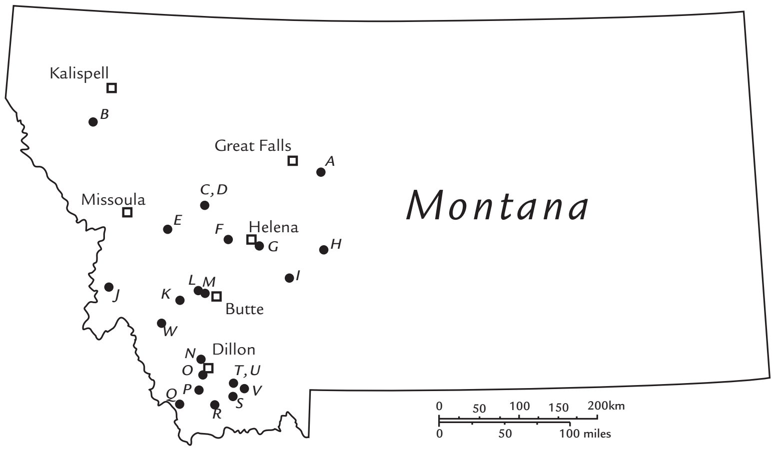

Figure 40. Map showing areas examined without finding zeolites. Letters refer to localities described in the text.

A–Belt Butte

Location: Twenty miles (32 kilometers) southeast of Great Falls in the NW¼ SE¼ section 30, T. 19 N., R. 7 E., Cascade County, Belt 7½-minute quadrangle.

The Arrow Creek Bed in the Bootlegger Member of the lower Cretaceous Blackleaf Formation (Vuke-Foster and others, 1989) is exposed on Belt Butte 213 feet (65 meters) above the prominent sandstone bed at the base of the Bootlegger Member of the Blackleaf Formation. The Arrow Creek Bed is 32 feet (10 meters) thick where sampled on the south side of Belt Butte. Four specimens analyzed by x-ray diffraction show the following minerals: quartz (major), albite (major), and smectite (trace).

B–Hog Heaven Volcanic Field

Location: Thirty miles (48 kilometers) southwest of Kalispell in Sanders and Flathead Counties.

No zeolitized beds were recognized in road reconnaissance of the ash-flow tuff unit in the Hog Heaven Volcanic field as mapped by Lange and Zehner (1992). Reconnaissance was from the southern extent of this unit in the NW¼ section 24, T. 24 N., R. 24 W., past Sullivan Hill in the NE¼ section 14, T. 24 N., R. 24 W. and along the road north from Little Meadow Creek to the northern extent of this unit in the NE¼ section 14, T. 24 N., R. 24 W.

C–Lincoln Vicinity

Location: Fifty-eight miles (93 kilometers) northeast of Missoula in the NE¼ NE¼ SE¼ section 25, T. 15 N., R. 10 W., Lewis and Clark County, Arrastra Mountain 7½-minute quadrangle.

No zeolitized beds were recognized in Oligocene sedimentary rocks as described by Brenner-Tourtelot and others (1978). Exposures are confined to road cuts.

D–Landers Fork

Location: Sixty miles (99 kilometers) northeast of Missoula in the W½NW¼ section 30, T. 15 N., R. 7 W., Lewis and Clark County, Silver King 7½-minute quadrangle.

Tertiary volcaniclastic beds are exposed in cliffs east of Landers Fork (Bartlett and others, 1996). No evidence of zeolitization was recognized.

E–Bearmouth

Location: Thirty-two miles (51 kilometers) southeast of Missoula in the NE¼ NE¼ section 21, T. 11 N., R. 14 W., and the NW¼NW¼ section 22, T. 11 N., R. 14 W., Granite County, Bearmouth 7½-minute quadrangle.

Tertiary tuffaceous beds are exposed in an inactive pit (Kauffman, 1963). No evidence of zeolitization was found.

F–Blossburg Clay Pit (Inactive)

Location: Sixteen miles (25 kilometers) northwest of Helena in the SW¼ NW¼ section 3, T. 10 N., R. 6 W., Powell County, Greenhorn Mountain 7½-minute quadrangle.

Bierwagen (1964) described partial alteration to clinoptilolite of the glass matrix in Tertiary flows near the Blossburg clay pit. A specimen of altered rhyolite collected from the inactive clay pit consists mainly of quartz and feldspar with minor dolomite and kaolinite.

G–East Helena

Location: Four miles (6 kilometers) southeast of Helena in the SE¼SE¼ section 26, T. 10 N., R. 3 W., Lewis and Clark County, East Helena 7½-minute quadrangle.

A 10-foot (3-meter) thickness of tuffaceous sediment is exposed in a road cut. No evidence of zeolitization was recognized.

H–White Sulphur Springs Area

Location: This reconnaissance covered an area from 17 miles (27 kilometers) east of White Sulphur Springs to 23 miles (37 kilometers) west of White Sulphur Springs and from 2 miles (3.2 kilometers) south to 16 miles (26 kilometers) north of White Sulphur Springs.

Exposures of tuffaceous Tertiary sedimentary rocks were examined by road reconnaissance in the White Sulphur Springs area. Localities of exposures of these beds are from Birkholz, 1967; Blumer, 1971; Dahl, 1971; Hruska, 1967; McClernan, 1969; and Phelps, 1969. Zeolitized beds were not recognized during this survey.

I–Vicinity of Toston

Location: Forty miles (64 kilometers) southeast of Helena in the SW¼ SE¼ section 31, T. 6 N., R. 3 E., Broadwater County, Toston 7½-minute quadrangle.

A white vitric tuff of the Oligocene Dunbar Creek Formation forms prominent exposures on the north side of Dry Hollow (Robinson, 1967). Zeolitized beds were not recognized in these exposures.

J–Lick Creek

Location: Fifty-four miles (86 kilometers) south of Missoula in the NW¼ SW¼ SE¼ section 15, T. 4 N., R. 21 W., Ravalli County, Darby 7½-minute quadrangle.

Slightly altered tuff, presumably of Tertiary age, is exposed on the west side of Lick Creek. An analyzed sample consists of quartz (major), feldspar (major), and biotite (minor).

K–French Creek

Location: Twenty-six miles (42 kilometers) southwest of Butte in the SE¼ SW¼ SE¼ section 3, T. 2 N., R. 12 W., Deer Lodge County, Lincoln Gulch 7½-minute quadrangle.

Two samples from Tertiary volcaniclastic beds exposed on the northwest side of French Creek consist mainly of glass, quartz, feldspar, and smectite.

L–Clay Pit near Opportunity

Location: Twelve miles (19 kilometers) northwest of Butte in the NE¼ SW¼ section 32, T. 4 N., R. 9 W., Silver Bow County, Ramsay and Opportunity 7½-minute quadrangles.

A pit has been excavated in clayey sediment of the Tertiary Melrose Basin sequence (Derkey and Bartholomew, 1988). No zeolitized beds were recognized; although, a bed of unusually white tuff <2 feet (<0.5 meters) thick is exposed in the bottom of the pit.

M–Ramsay

Location: Eight miles (13 kilometers) west of Butte in the SE¼NE¼NW¼ section 15, T. 3 N., R. 9 W., Silver Bow County, Ramsay 7½-minute quadrangle.

Rhyodacite tuff unit within the Eocene Lowland Volcanics is exposed in this area (Derkey and Bartholomew, 1988). Green areas up to several tens of meters across within the rhyodacite tuff were sampled, but zeolites were undetected by x-ray diffraction analysis.

N–Frying Pan Basin

Location: Six miles (10 kilometers) northwest of Dillon in the SW¼ NE¼ NW¼ and S½ SE¼ NW¼, section 28, T. 6 S., R. 9 W., Beaverhead County, Bond 7½-minute quadrangle.

Beds of the Tertiary Bozeman Group (Ruppel and others, 1993) were sampled on the east side of Frying Pan Basin where rhyolite, tuff, and bentonite are exposed. Six samples collected from light tan to white erosion-resistant beds thought to be zeolitized on the basis of field characteristics were analyzed by x-ray diffraction. None of these six analyzed samples contains a zeolite. Cristobalite is a major constituent of four samples, and opal-CT is a major constituent of one sample and a minor constituent of another. Other constituents present in some samples are feldspar, glass, biotite, and smectite.

O–Barretts

Location: Six miles (10 kilometers) southwest of Dillon in the W½NW¼NE¼, section 19, T. 8 S., R. 9 W., Beaverhead County, Dillon West 7½-minute quadrangle.

Tuffaceous sediment consists of fresh glass with no evidence of zeolitization.

P–Clark Canyon

Location: Sixteen miles (26 kilometers) southwest of Dillon along Clark Canyon in sections 34 and 35, T. 9 S., R. 10 W., Beaverhead County, Dalys 7½-minute quadrangle.

Exposures of white tuffaceous beds of Tertiary age along the road on the north side of Clark Canyon were examined. No evidence of zeolitization was recognized.

Q–Schwartz Creek

Location: Thirty-three miles (53 kilometers) southwest of Dillon in the SW¼, section 28 and SE¼, section 29, T. 11 S., R. 12 W., Beaverhead County, Medicine Lodge 7½-minute quadrangle.

Three samples of possible zeolitized rock were collected from exposures of tuffaceous Tertiary beds along a newly constructed road. X-ray diffraction analysis of these samples failed to identify zeolites.

R–Sage Creek

Location: Twenty-five miles (40 kilometers) southeast of Dillon in sections 24, 25, and 26, T. 11 S., R. 8 W., Beaverhead County, Rock Island Ranch and Beech Creek 7½-minute quadrangles.

Exposures of Tertiary bentonitic beds and tuffaceous beds were examined in the Sage Creek drainage including exposures in the sections listed above in the White Hills area. No zeolitized beds were recognized.

S–East Fork Blacktail Deer Creek

Location: Twenty-seven miles (43 kilometers) southeast of Dillon in section 6, T. 11 S., R. 5 W., Beaverhead County, Price Creek NE 7½-minute quadrangle.

White cliffs and hoodoos of cross-bedded Tertiary volcaniclastic beds on the north side of the East Fork of Blacktail Deer Creek were examined. None showed evidence of zeolitization.

T–Sweetwater Road

Location: Twenty-two miles (35 kilometers) southeast of Dillon in the SE¼ SW¼ NW¼ and NW¼ NE¼ SW¼, section 4, T. 9 S., R. 5 W., Madison County, Belmont Park 7½-minute quadrangle.

Altered Tertiary tuff in an area devoid of vegetation 16 by 40 feet (5 by 12 meters) below slightly silicified siltstone was sampled and also an 8-inch- (20-centimeter-) thick bed that appeared zeolitized. X-ray diffraction analysis showed that both samples consist mainly of quartz with minor feldspar and kaolinite.

U–Belmont Park Ranch

Location: Twenty-one miles (34 kilometers) southeast of Dillon in the SW¼ NE¼ SE¼, section 21, T. 9 S., R. 5 W., Madison County, Belmont Park Ranch 7½-minute quadrangle.

Four samples were collected from tuffaceous beds of the Tertiary Bozeman Group (Ruppel and others, 1993) exposed in cliffs. They consisted mainly of glass with lesser quartz, smectite, and calcite.

V–Upper Ruby Basin

Location: Large area 30 miles (50 kilometers) southeast of Dillon in Madison County.

Tertiary sedimentary rocks of the Bozeman Group (Ruppel and others, 1993) underlie a large area in the Upper Ruby drainage bounded by the Ruby Range on the west, the Greenhorn Range on the east and the Snowcrest Range on the south. A reconnaissance of this area failed to show any zeolitized beds.

W–Big Hole Basin

Location: Large basin 50 miles (80 kilometers) southwest of Butte. Except for the northernmost part of this basin, which is in Deer Lodge County, this basin is in Beaverhead County.

Tertiary sedimentary rocks of the Bozeman Group occupy this basin (Ruppel and others, 1993). The sedimentary rocks are generally overlain by alluvium and are only exposed at a few localities, mainly around the edge of the basin. Examination of these exposures failed to show any evidence of zeolitization.

Appendix II

Mineralogy from the Grasshopper Creek Deposits (Table 14)

Table 14. Mineralogy of samples of cores from holes GC 98-1, GC 98-2, and GC 98-3, Grasshopper Creek deposit. Mineral abundances estimated by x-ray diffraction analyses performed by the Mineral Lab, Inc., Lakewood, Colorado, and shown in weight percent.

Drill Hole	GC 98-1					GC 98-2			GC 98-3			
Interval (ft)	4-8	11-16.3	16.3-21.5	21.5-24	24-36	4-14	14-19	19-29	3.3-10	10-20	20-30	30-34
Clinoptilolite	45	30	45	25	15	15	45	<10	50	65	65	50
K feldspar	5	8	7	8	6	5	5	-	5	10	10	10
Plagioclase feldspar	6	17	10	16	16	16	8	16	7	7	7	7
Quartz	6	5	<5	<5	<5	<5	<5	<5	<5	10	10	8
Smectite	<5?	10	<10	10	33	40	<10	55	<5?	-	-	-
Mica/illite	-	-	-	-	-	-	-	<5	-	-	-	-
Magnetite	-	-	-	-	-	-	-	<3?	<3?	-	-	-
Cristobalite*	-	-	-	-	-	5?	-	10	-	-	-	-
"Amorphous"	25-35	20-30	20-30	30-40	20-30	<20	25-35	-	20-30	<10	<10	20-30
"Unidentified"	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5

(*) Note: These XRD data fit the standard data for cristobalite, but opaline silica may give similar diffraction data. Field determinations or other methods of analysis may differentiate cristobalite from an opaline phase.