Title
Outline Geological Survey of a Portion of Pinnacles National Monument, Central California

Author
Shackley, M. Steven

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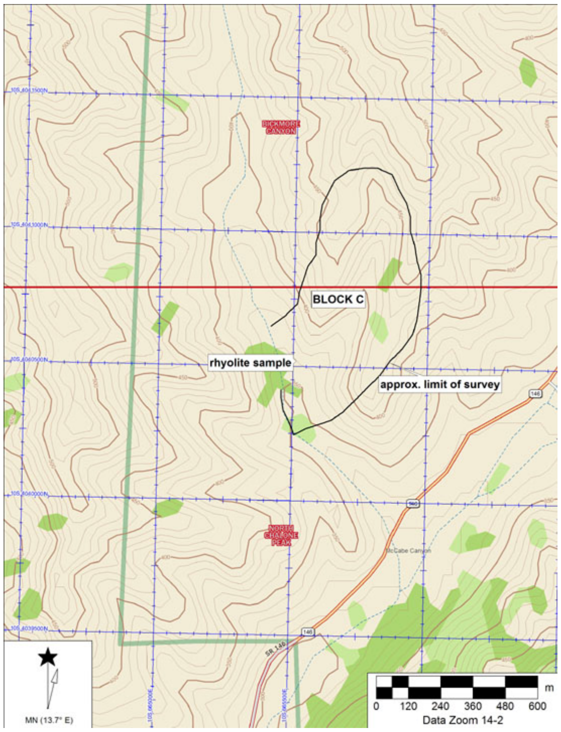
BERKELEY ARCHAEOLOGICAL
XRF LAB

Department of Anthropology
232 Kroeber Hall
University of California
Berkeley, CA 94720-3710

OUTLINE GEOLOGICAL SURVEY OF A PORTION OF PINNACLES NATIONAL MONUMENT, CENTRAL CALIFORNIA



DRAFT

by

M. Steven Shackley, Professor and Director
Geoarchaeological XRF Laboratory
University of California, Berkeley

Report Prepared for

Professor Kent Lightfoot
Department of Anthropology
University of California, Berkeley

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INTRODUCTION

Pinnacles National Monument is dominated by its unique geological history. The phenomena that produced the pinnacles, the Tertiary silicic volcanism and subsequent Quaternary sedimentation has ramifications for the presence and detection of cultural resources. The following is a short outline geological background mainly founded on the 1933 UC, Berkeley Master's thesis study by Philip Andrews of the then smaller monument, my interpretation of that portion of the monument today that is known as McCabe Canyon, the Block C transect I participated in on 2 June 2011, and the chemical analysis of a sample of high-silica rhyolite collected at the base of that transect that is part of the silicic conglomerate so prominent in the monument today.

The Pinnacles National Monument was first set aside as one of the nation's playgrounds by proclamation of President Theodore Roosevelt on January 16, 1908. Additional land grants in the years 1923 and 1924 increased the Park's area to a total of 2980 acres. In 1931, San Benito County purchased additional land from private holders for park use which brought the total area of the Monument to 4609 acres, and this area was practically doubled in July, 1933, by the acquisition of the Chalone Peaks. Since then a number of tracts have been added to the park, one of which is the McCabe Canyon area part of the UCB archaeological field school survey.

The unusual scenic beauty of the Pinnacles was recognized as long ago as 1794, when Captain George Vancouver visited the area. David Starr Jordan visited the area on numerous occasions before it was set aside for public use, and he was instrumental in its selection as a national monument. Tiburcio Vasquez, a local and notorious bandit, is credited with finding refuge among the caves and crags of the Pinnacles in the latter part of the nineteenth century, before he was finally brought to justice.

GEOLOGIC HISTORY

Much of what follows is from Andrews thesis study of the monument in the 1930s. Earth science has changed both theoretically and methodologically since the 1930s, long before tectonic or plume theory and instrumental chemistry, however the basic field geology as described by Andrews is as good as one could expect today, although some details appear to be variant. The terms used for the local formations are the same as used today, and the general chronology is in the correct chronology.

The oldest rocks in the region belong to the Sur series, of which the Gavilan Limestone is a member. These ancient sediments are often called the Santa Lucia series, together with the quartz diorite and granite which intruded and metamorphosed them are both pre-Franciscan. The high silica of the rhyolites (> 75 wt. percent) is likely due to some remelting of the older limestone.

The absence of Cretaceous and early Tertiary sediments in this part of the Gavilan Range indicates that subsequent erosion has removed such deposits. Furthermore, the granite was almost completely unroofed before Miocene time, and today is seen as the remnant granite boulders in the study area. In an epoch considered to be early middle Miocene, rhyolitic magma was forced through fissures in the granitic mass. This appears in the geology of the Block C transect side canyon surveyed here (Figure 1). Later activity developed central vents along a zone trending north and south, and extrusive events from these produced a thick strata of pyroclastics above the earlier lavas (see Andrew’s map copy; Appendix B and attached to print version). The action of erosion on these pyroclastics has given rise to the characteristic "pinnacles." As the Miocene progressed immense deposits of fanglomerate composed of both rhyolitic and granitic detritus, were built up along the flanks of the Gavilan Range. This is essentially the surface geology apparent in the southern portion of McCabe Canyon and particularly the Block C transect of 2 June 2011. Farther from the source, the fanglomerates graded laterally into continental and shallow marine arkosic gravels which were in part interbedded with and overlain by diatomaceous shales of considerable thickness The rather abrupt change from gravel to diatomaceous shale suggests a lowering of the land mass and consequent reduction in the amount of detritus entering the sea. The volcanic rocks of the Pinnacles were probably never submerged.

Pliocene sediments are absent from the area, but during the Pleistocene terrace gravels were deposited about the edges of the central volcanic mass. Subsequent readjustments, with elevation at the end of Pleistocene time, have caused these terraces to be dissected, an action still proceeding. The area lies only 5 miles to the southwest of the San Andreas fault, and it is therefore not surprising that minor and roughly parallel faulting, showing considerable movement since Monterey time, occurs within this region.

SANTA LUCIA SILICIC PLUTONIC ROCKS

In the southern portion of the Gavilan Range the granites and quartz diorites have been more completely denuded than at the northern end, so that only isolated areas of metamorphosed sediments occur in the Pinnacles region. In most places, the schists and quartzites of this southern area occur as intercalations within the Gavilan limestone or in close proximity to these beds and have therefore been mapped together with this formation.

The term "Santa Lucia" is here applied to the granitic rocks of the Gavilan Range, since they are considered to be generally related to the granites of the Santa Lucia Range. The plutonic rocks fall into two main divisions and a number of minor types. There is a considerable area of true granite, and quartz diorite is exposed over a somewhat larger area. No samples were analyzed in this study, so it’s not clear whether higher silica granite or quartz diorite dominates in the study area. My hand sample examination of the plutonic rocks in the transect indicated a high proportion of quartz, so granite proper is probably the dominant rock.

In the area to the east of the Pinnacles volcanic belt, including the study area, true granite is exposed. Locally, this is a medium grained, light gray, sodic type in which albite is the chief feldspar, according to optical petrography in Andrews study. In this soda granite, quartz is abundant, and in many specimens approaches 50 per cent of the rock, with muscovite and biotite as the characterizing accessories. Muscovite is more abundant than biotite but the two account for less than 10 per cent of the rock. Minor accessories include hematite, apatite, and a very small amount of magnetite. This is the mineral mode that I saw in the Block C transect.

More abundant than the gray, sodic granite, is a medium to coarse grained granite with light pink orthoclase, which is usually fresh and glassy. One type contains large phenocrysts of pink microcline up to 4 cm. in diameter, together with smaller grains of anorthoclase, albite, orthoclase, muscovite, biotite, etc.

All the xenoliths of plutonic rock within the central mass of lavas are granite, rather than quartz diorite, as seen in the transect. Granite was also abundantly expelled with the fragmental ejecta. The rhyolite was unable to alter the orthoclase to sanidine, and in no crystal was the observed optic angle less than 70 degrees.

On the west side of the Pinnacles volcanic area, and in sharp contrast to the granite on the east, all the plutonics are quartz diorite. They are typically medium to coarse grained and gray in color although abundant biotite may produce a dark shade. Locally, the quartz diorite contains as much as 50 per cent of shiny black biotite.

Along Miners Gulch (southwest part of Andrews map) and for some distance to the southwest, the plutonic rocks are gneissoid and locally there are mica schists. Faulting may account for part of this structure although the zone of gneissoid granite is rounded, rather than elongated along the adjacent fault. Probably the gneissoid structure indicates a border facies of the batholith. Injection gneisses have been noted locally and pegmatite dikes of considerable size and persistence are prevalent.

Southwest of Miners Gulch and at the east central edge of section 32, a single exposure carrying both well-developed talc-actinolite schist and talc schist was found. While I didn't see this, some of this rock could have been used prehistorically for ornaments or specialized mortars.

Although exact relations between the granite and quartz diorite could not be determined by Andrews, the evidence points toward a rather definite separation of the two and possibly a difference in age, but has not been chronometrically tested (1933). Generally, the quartz diorite is more weathered and in many places is greenish at the surface because of the alteration of biotite to chlorite and saussuritization of feldspars. Whether the granite had intruded the quartz diorite or vice versa was not evident from field observation. A northwest-southeast line through the southern part of section 36, near the mouth of Chalone Creek, marks the southern limit of the granite. The contact of the granite and quartz diorite, to the northwest, is obscured by the rhyolite extrusives.

Even if the granite and the quartz diorite were intruded at different times, it is reasonable to assume that the age difference between the two is not great. For both, the period of intrusion cannot be stated more definitely than that it is pre-Franciscan and younger than the Sur series.

UNMETAMORPHOSED SEDIMENTS

Unmetamorphosed epiclastic sediments of the area mapped include:

1. Gravel of undetermined age, resting upon the granitic complex
2. Fanglomerate and gravel deposits of pre-Monterey age (Temblor)
3. Terrace deposits of probable Pleistocene age
4. Recent sands, gravel, and alluvium (Andrews 1933: 23).

TERRACE DEPOSITS

Terrace deposits most closely describe my investigation at Block C and presumably much of McCabe Canyon. The surface sediment is dominated by a mix of rhyolitic ash conglomerate and the earlier granite with some of the conglomerate boulders up to 2 meters in diameter.

Terrace deposits composed chiefly of fragments derived from volcanic rocks occur at several places about the edges of the central volcanic mass of the Pinnacles National Monument, including McCabe Canyon. These deposits are poorly stratified although there is a general alignment of pebbles, and they vary from a feather edge to 100 or more feet in thickness, according to Andrews survey (1933). Dips average from 3 to 5 degrees away from the central mass and they were apparently deposited on a partly sheetwashed surface. This action, could serve to cover early (i.e. Paleoindian and Archaic) sites and features if present.

Fragments varying from clay particles to blocks and boulders of from 2 to 3 feet in length are chiefly rhyolitic, but granitic material also occurs. Just over the granite surface a layer of residual granitic detritus is usually present. Iron cement binds the terrace deposits and frequently lends a red color to them. This describes much of the geology of the Block C transect canyon, and deviates from Andrews (1933) mapping which he described as a fanglomerate (Tmt) the surface of which grades into “arkosic gravels and diatomaceous shale” (see Appendix B and folded map in print report).

The terrace deposits unconformably overlie both granite and rhyolite surfaces and clearly are derived from the central volcanic mass. Their age is later than the rhyolitic intrusion, and presumably a result of an explosive ash flow tuff eruptive event. These beds are also younger than much of the faulting which has dropped this central mass, as proved by the minor displacement of these deposits where cut by the Pinnacles Fault. Erosion subsequent to their deposition has cut rather deep canyons in both granite and rhyolite so that at least a Pleistocene age is postulated. This describes the McCabe Canyon environment. The surface beds of rhyolitic outwash material to the north are also correlated with these deposits although their nature is less well defined.

Chief interest in the Pinnacles region centers about the volcanic rocks, since it is the erosion of these that has produced the unusual and scenic effects for which the National Monument is famous. They range from rhyolites through andesites to basalts and occur typically as thick beds of fragmental ejecta, although flows as well as dikes and sills are abundant. Rhyolites are much more abundant than the more basic types, probably comprising 80 per cent or more of the total. The chief volcanic mass occupies an area approximately 7 miles long in a north-south direction by 2 miles wide, although numerous dikes and sills are exposed outside this area.

RHYOLITIC INTRUSIVES

Within the principal volcanic area the distinction between intrusives and extrusives cannot usually be seen in the geology according to Andrews (1933), so that, under this heading, the main emphasis will be on the dikes and sills which are intruded into the granitic mass, most appropriate for the study area. It will be noted on Andrews' map that the dikes generally follow the dominant structural trend of the Coast Ranges, that is, northwest to southeast. It seems that the first expression of volcanic activity within the region was the intrusion of dikes and sills, several of them of large size. Continued activity developed central vents from which issued abundant fragmental material and sporadic flows (see Appendix B and map attached).

The material in most of the dikes and sills may be classified as a porphyritic rhyolite although some petrographers might refer to them as quartz porphyry or liparite (Bates and Jackson 1984). The dacite and andesite present in smaller proportions is not discussed here (see

Andrews 1933). The minerals of the rhyolite vary slightly from place to place and the texture differs with the size of the intrusion and proximity to the margins. That the width of an intrusion does not always determine its grain, however, is shown by the fact that a dike in the southern part of the area and at least 1000 feet thick is aphanitic throughout.

Typical examples of the rhyolite porphyry are white to gray in color and contain abundant phenocrysts of glassy quartz and feldspar up to several millimeters in diameter. Black shiny biotite in minute flakes is also abundant. This perfectly describes the sample analyzed in this study (Tables 1 and 2, Figure 3).

Andrews petrographic analysis of one of these rocks describes a porphyritic fabric:

> with light grayish brown micro-spherulites in a glassy matrix, although there is some birefringent material in irregular areas. Phenocrysts of clear, glassy, embayed quartz, ranging in size from 2 to 3 mm., compose from 15 to 20 per cent of the whole, and euhedral prisms of glassy sanidine with included biotite and apatite together with albite and oligoclase comprise most of the remaining phenocrysts. Hexagonal flakes of greenish brown mica are abundant (Andrews 1933: 30-31).

Andrews also notes the presence of a vitrophyric obsidian on the western edge of the rhyolite extrusive central mass, but obviously this is not artifact quality (Andrews 1933:34-35). The central mass rhyolite is from a different event, and is likely the darker rhyolite used to produce that scraping tool found along the creek in the Block A transect on 2 June 2011. The raw material was probably procured from the Pinnacles extrusion.

VOLCANIC BRECCIAS

By far the major part of the "Pinnacles Formation" should be called a breccia. The volcanic breccias are massively bedded and of surprising uniformity in the northern portion of the area, but they have suffered from avalanches and lateral eruptions in the southern part. Dips range from 20 to 50 degrees with 35 degrees as an average figure and are inclined generally west, although dips become northerly toward the north part of the area. Bedding planes are often rather poorly defined and the attitude can best be determined at a considerable distance from the outcrop. Individual beds may range from a few feet to several hundred feet in thickness. Close to the source the breccias are interbedded with many thin flows of rhyolitic glass, tuff, and lapilli-tuff, but become purer breccias as the distance from the source increases, presumably the McCabe Canyon area.

Constituents of the volcanic breccias are generally cognate, and vary in size from volcanic ash to fragments or blocks up to 3 m or more in diameter. Average fragments range from 3-4 cm in diameter with a sufficient amount of finer material to serve as interstitial filling. None of the fragments are water-worn, although the corners of many have been rounded by attrition from moving down steep slopes, or by attrition of the fragments in a dry state at the time of explosion. This explains the character of the large conglomerate boulders in the study area.

The volcanic breccias are essentially composed of light gray to pinkish, fine grained, rhyolitic fragments, both massive and banded, in a matrix of the same composition. Cementation of the fragmental material has been sufficient to form solid rock formations, which stand in vertical cliffs several hundred feet high.

Granite is the only accidental material found among the ejecta and this is not surprising in view of the fact that the granite was almost completely denuded of overlying sediments and metamorphic rocks before volcanic activity took place, and likely blown outward during the Plinian rhyolite event.

RECONNAISSANCE SURVEY IN BLOCK C, MCCABE CANYON

The following is from notes and observations taken on 2 June 2011 during the Block C transect survey in the side canyon off McCabe Canyon (Figure 1). The surface of the canyon bottom appeared to be a Quaternary bed of a mixed conglomerate to tuffs, rhyolite rocks, granite boulders, and a few metamorphics, at least 90% angular clasts. Granite boulders up to 50 cm in diameter occur, but the majority are < 30 cm in diameter. In the upper portion of the canyon granite boulders dominate with some rhyolite, all more waterworn than below, possibly due to higher stream flows in the narrower canyon. The sediment seemed moderately sorted.

Along the canyon sides and upper terraces, the tuff conglomerate similar to that described above from Andrews 1933 thesis dominates. Some boulders up to 2 meters in diameter exhibit rhyolite clasts in the tuff matrix. These boulder appear waterworn, but I agree with Andrews conclusion that rounded character is likely from rolling down the canyon sides of these friable rocks rather than fluvial action.

Most interesting is that the geology in the lower McCabe Canyon is certainly characterized by the “volcanic breccias” as described by Andrews (1933:41-43). His map describes the McCabe Canyon are as part of the Temblor fanglomerate composed of arkosic gravels and diatomaceous shale, rocks that appeared nowhere in the study area (see Appendix B and attached map). However, the fragmentary bowl mortar found in the creek in the Block A transect does look like an arkosic sandstone. I must conclude that the canyon surveyed in June 2011 was not surveyed on foot by Andrews in the 1930s.

GEOCHEMISTRY OF RHYOLITE SAMPLE FROM BLOCK C TRANSECT

The following is from an energy-dispersive x-ray fluorescence (EDXRF) analysis of the major oxides and trace elements of one sample of the pinkish-gray rhyolite collected at UTM 10S 066515/4040522 (±5 m error) in the fanglomerate at the base of the canyon. The instrumental settings and protocol for this analysis are in the Appendix. Refer also to Shackley (2005, 2011a, 2011b) for further analytical protocols for silicic rock analyses.

The analysis indicates a very high silica peraluminous rhyolite (Tables 1 and 2, Figure 3). Rhyolite with SiO_2 this high is relatively rare and often indicates remelting of high silica sediments in the crust, in this case possibly the limestone and/or granite basement present in the region as discussed above. Nevertheless, this high-silica rhyolite is probably, with rapid cooling, responsible for the production of the glass described by Andrews in the west side of the Pinnacles eruptive event (1933).

CONCLUSION

The geology of the Pinnacles National Monument is unique in this part of California, and may have ramifications for the archaeology of the monument. The rhyolite of the Pinnacles was obviously used for the production of some tools, and perhaps the arkosic sandstone as well. Whether the vitrophyric obsidian described by Andrews (1933) was used in any way by the prehistoric occupants may be determined by the results of the survey.

There appears to be significant erosional effect within the survey area, partly due to the friable condition of the ash flow tuffs and conglomerates, and the steep gradients of the side canyons. Whether this is responsible for covering archaeological features would have to be determined by an archaeological geomorphological investigation.

REFERENCES CITED

Andrews, Philip
1933 *Geology of the Pinnacles National Monument*. Master's thesis, Department of Geological Sciences, University of California, Berkeley.

Bates, R.L., and J.A. Jackson
1984 *Dictionary of Geological Terms*. American Geological Institute, New York.

Davis, M.K., T.L. Jackson, M.S. Shackley, T. Teague, and J. Hampel
2011 Factors Affecting the Energy-Dispersive X-Ray Fluorescence (EDXRF) Analysis of Archaeological Obsidian. In *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology,* edited by M.S. Shackley, pp. 45-64. Springer, New York.

Govindaraju, K.
1994 1994 Compilation of Working Values and Sample Description for 383 Geostandards. *Geostandards Newsletter* 18 (special issue).

Hampel, Joachim H.
1984 Technical Considerations in X-ray Fluorescence Analysis of Obsidian. In *Obsidian Studies in the Great Basin*, edited by R.E. Hughes, pp. 21-25. Contributions of the University of California Archaeological Research Facility 45. Berkeley.

Hildreth, W.
1981 Gradients in Silicic Magma Chambers: Implications for Lithospheric Magmatism. *Journal of Geophysical Research* 86:10153-10192.

Hughes, Richard E., and Robert L. Smith
1993 Archaeology, Geology, and Geochemistry in Obsidian Provenance Studies. *In Scale on Archaeological and Geoscientific Perspectives,* edited by J.K. Stein and A.R. Linse, pp. 79-91. Geological Society of America Special Paper 283.

Le Bas, M.J., R.W. Le Maitre, A.L. Streckeisen, and B. Zanettin
1991 A Chemical Classification of Volcanic Rocks Based on the Total Alkali-Silica Diagram. *Journal of Petrology* 27:745-750

Mahood, Gail A., and James A. Stimac
1991 Trace-Element Partitioning in Pantellerites and Trachytes. *Geochemica et Cosmochimica Acta* 54:2257-2276.

McCarthy, J.J., and F.H. Schamber
1981 Least-Squares Fit with Digital Filter: A Status Report. In *Energy Dispersive X-ray Spectrometry,* edited by K.F.J. Heinrich, D.E. Newbury, R.L. Myklebust, and C.E. Fiori, pp. 273-296. National Bureau of Standards Special Publication 604, Washington, D.C.

Schamber, F.H.
1977 A Modification of the Linear Least-Squares Fitting Method which Provides Continuum Suppression. In *X-ray Fluorescence Analysis of Environmental Samples*, edited by T.G. Dzubay, pp. 241-257. Ann Arbor Science Publishers.

Shackley, M. Steven

1988 Sources of Archaeological Obsidian in the Southwest: An Archaeological, Petrological, and Geochemical Study. *American Antiquity* 53(4):752-772.

1989 *Early Hunter-Gatherer Procurement Ranges in the Southwest: Evidence from Obsidian Geochemistry and Lithic Technology*. Ph.D. dissertation, Arizona State University, Tempe.

1995 Sources of Archaeological Obsidian in the Greater American Southwest: An Update and Quantitative Analysis. *American Antiquity* 60(3):531-551.

2005 *Obsidian: Geology and Archaeology in the North American Southwest*. University of Arizona Press, Tucson.

2011a An Introduction to X-Ray Fluorescence (XRF) Analysis in Archaeology. In *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology*, edited by M.S. Shackley, pp. 7-44. Springer, New York.

2011b Sources of Archaeological Dacite in Northern New Mexico. *Journal of Archaeological Science* 38:1001-1007.

Table 1. Major oxide values for the Block C rhyolite sample.

Sample	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	MnO	Na_2O	TiO_2
Block C sample	78.319	10.592	0.531	1.386	6.377	0.33	0.012	2.297	2.297
RGM1-S4	74.506	12.303	1.496	2.296	5.118	<.001	0.054	3.743	0.277

Table 2. Minor and trace element values for the Block C rhyolite sample.

Sample	Ti	Mn	Fe	Zn	Rb	Sr	Y	Zr	Nb	Ba	Pb	Th
Block C sample	829	152	10273	39	319	70	36	105	27	625	26	15
RGM1-S4 (standard)	1602	292	13257	36	148	107	25	221	8	832	21	13

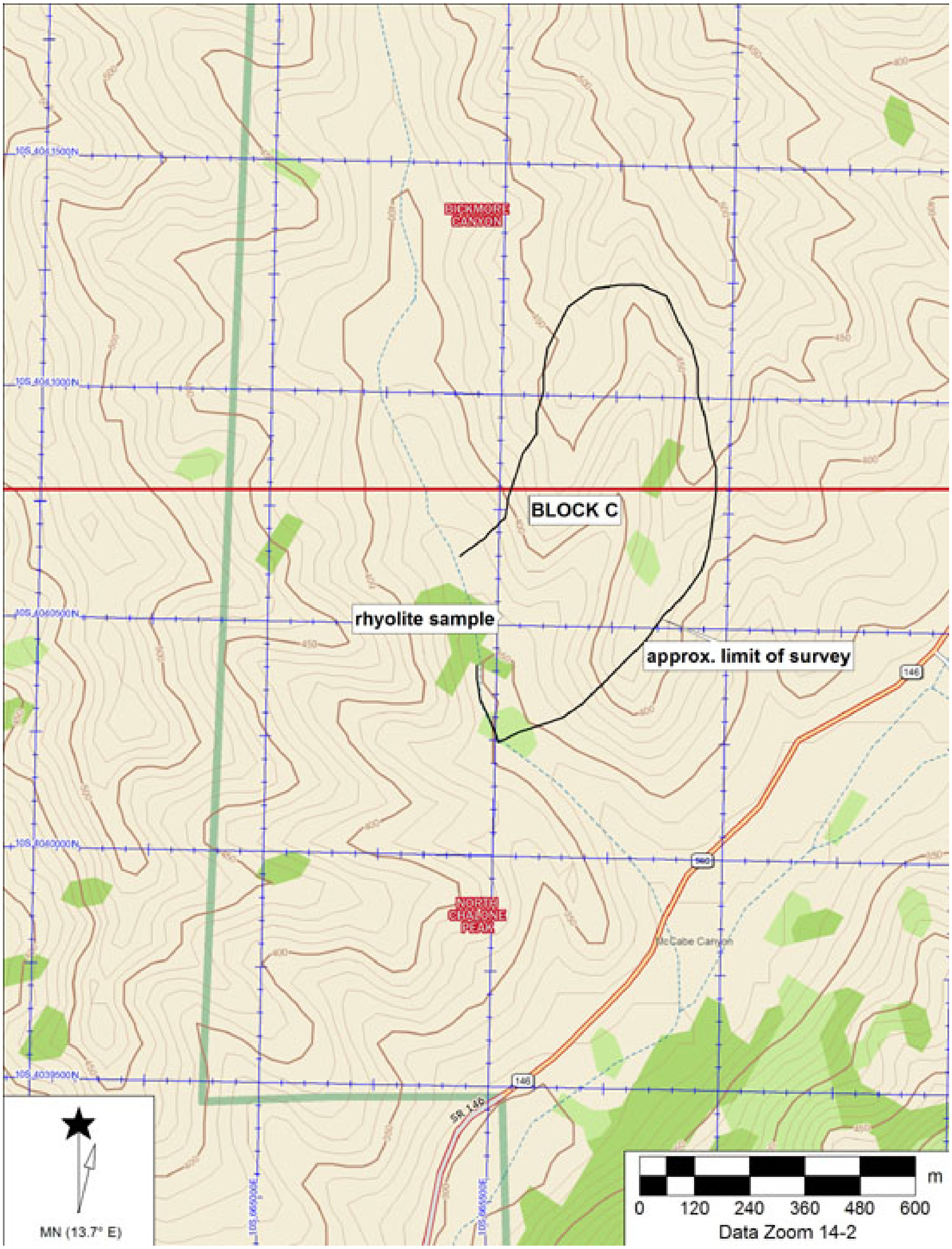

Figure 1. Topographic rendering of approximate location of Block C survey boundaries, rhyolite sample location, and topographic features in McCabe Canyon, Pinnacles National Monument, California.

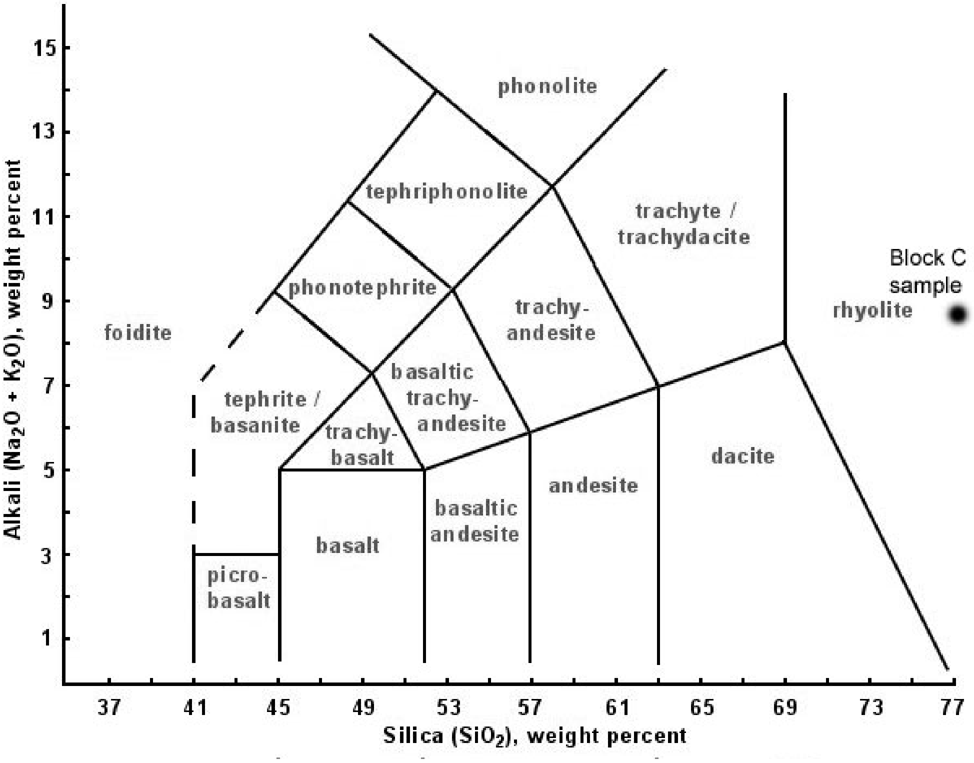

Figure 2. Alkali/Silica plot of the Block C high-silica rhyolite sample.

APPENDIX A

LABORATORY SAMPLING, ANALYSIS AND INSTRUMENTATION

The sample was analyzed whole after splitting the rock to present a fresh surface to the beam. The results presented here are quantitative in that they are derived from "filtered" intensity values ratioed to the appropriate x-ray continuum regions through a least squares fitting formula rather than plotting the proportions of the net intensities in a ternary system (McCarthy and Schamber 1981; Schamber 1977). Or more essentially, these data through the analysis of international rock standards, allow for inter-instrument comparison with a predictable degree of certainty (Hampel 1984).

Trace Element Analysis

The trace element analyses were performed in the NSF Geoarchaeological XRF Laboratory, Department of Anthropology, University of California, Berkeley, using a Thermo Scientific *Quant'X* energy dispersive x-ray fluorescence spectrometer. The spectrometer is equipped with a ultra-high flux peltier air cooled Rh x-ray target with a 125 micron beryllium (Be) window, an x-ray generator that operates from 4-50 kV/0.02-1.0 mA at 0.02 increments, using an IBM PC based microprocessor and WinTrace™ 4.1 reduction software. The spectrometer is equipped with a 2001 min^{-1} Edwards vacuum pump for the analysis of elements below titanium (Ti). Data is acquired through a pulse processor and analog to digital converter. This is a significant improvement in analytical speed and efficiency beyond the former Spectrace 5000 and *QuanX* analog systems (see Davis et al. 2011; Shackley 2005).

For Ti-Nb, Pb, Th elements the mid-Zb condition is used operating the x-ray tube at 30 kV, using a 0.05 mm (medium) Pd primary beam filter in an air path at 200 seconds livetime to generate x-ray intensity $K\alpha_1$-line data for elements titanium (Ti), manganese (Mn), iron (as Fe^T), cobalt (Co), nickel (Ni), copper, (Cu), zinc, (Zn), gallium (Ga), rubidium (Rb), strontium (Sr), yttrium (Y), zirconium (Zr), niobium (Nb), lead (Pb), and thorium (Th). Not all these elements are reported since their values in many volcanic rocks is very low. Trace element intensities were converted to concentration estimates by employing a least-squares calibration line ratioed to the Compton scatter established for each element from the analysis of international rock standards certified by the National Institute of Standards and Technology (NIST), the US. Geological Survey (USGS), Canadian Centre for Mineral and Energy Technology, and the Centre de Recherches Pétrographiques et Géochimiques in France (Govindaraju 1994). Line fitting is linear (XML) for all elements but Fe where a derivative fitting is used to improve the fit for iron and thus for all the other elements. When barium (Ba) is acquired, the Rh tube is operated at 50 kV and 0.5 mA in an air path at 200 seconds livetime to generate x-ray intensity Kα_1-line data, through a 0.630 mm Cu (thick) filter ratioed to the bremsstrahlung region (see Davis et al. 2011). Further details concerning the petrological choice of these elements in North American obsidians is available in Shackley (1988, 1989, 1995, 2005; also Mahood and Stimac 1991; and Hughes and Smith 1993). A suite of 17 specific standards used for the best fit regression calibration for elements Ti- Nb, Pb, and Th, include G-2 (basalt), AGV-2 (andesite), GSP-2 (granodiorite), SY-2 (syenite), BHVO-2 (hawaiite), STM-1 (syenite), QLO-1 (quartz latite), RGM-1 (obsidian), W-2 (diabase), BIR-1 (basalt), SDC-1 (mica schist), BCR-2 (basalt), TLM-1 (tonalite), SCO-1 (shale), all US Geological Survey standards, NBS-278 (obsidian) from the National Institute of Standards and Technology, BR-1 (basalt) from the Centre de Recherches Pétrographiques et Géochimiques in France, and JR-1 and JR-2 (obsidian) from the Geological Survey of Japan (Govindaraju 1994).

Major Oxide Analysis

In order to determine the volcanic rock type, the sample was subjected to a major oxide analysis, and then plotted on an alkali-silica plot (Figure 1). Analysis of the major oxides of Si, Al, Ca, Fe, K, Mg, Mn, Na, and Ti is performed under the multiple conditions elucidated below. This fundamental parameter analysis (theoretical with standards), while not as accurate as destructive analyses (pressed powder and fusion disks) is usually within a few percent of actual, based on the analysis of USGS RGM-1 obsidian standard (see also Shackley 2011a). The fundamental parameters (theoretical) method is run under conditions commensurate with the elements of interest and calibrated with four USGS standards (RGM-1, rhyolite; AGV-2, andesite; BHVO-1, hawaiite; BIR-1, basalt), and one Japanese Geological Survey rhyolite standard (JR-1). Multiple conditions are designed to ameliorate peak overlap identified with digital filter background removal, least squares empirical peak deconvolution, gross peak intensities and net peak intensities above background. Current is set automatically based on the mass absorption coefficient.

Low Za (Na, Mg, Al, Si, P)

Voltage	6 kV	Current	Auto[2]
Livetime	100 seconds	Counts Limit	0
Filter	No Filter	Atmosphere	Vacuum
Maximum Energy	10 keV	Count Rate	Low

Low Zb (S, Cl, K, Ca)

Voltage	8 kV	Current	Auto
Livetime	100 seconds	Counts Limit	0
Filter	Cellulose (0.06 mm)	Atmosphere	Vacuum
Maximum Energy	10 keV	Count Rate	Low

Mid Zb (K, Ca, Ti, V, Cr, Mn, Fe)

Voltage	32 kV	Current	Auto
Livetime	100 seconds	Counts Limit	0
Filter	Pd (0.06 mm)	Atmosphere	Vacuum
Maximum Energy	40 keV	Count Rate	Medium

The data from the WinTrace software were translated directly into Excel for Windows and into SPSS for statistical manipulation. In order to evaluate these quantitative determinations, machine data were compared to measurements of known standards during each run (Tables 1 and 2). RGM-1 is analyzed during each sample run for obsidian artifacts to check machine calibration (Tables 1 and 2). Rock type was determined by plotting on the TAS plot (Figure 3).

APPENDIX B

Andrews (1933) Geological Sheet of Pinnacles National Monument