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Preliminary Geologic Map of the Sleeping Butte Volcanic Centers

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PRELIMINARY GEOLOGIC MAP OF THE SLEEPING BUTTE VOLCANIC CENTERS

by

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ABSTRACT

The Sleeping Butte volcanic centers comprise two, spatially separate, small-volume (< 0.1 km^3) basaltic centers. The centers were formed by mildly explosive Strombolian eruptions. The Little Black Peak cone consists of a main scoria cone, two small satellitic scoria mounds, and associated lobate lava flows that vented from sites at the base of the scoria cone. The Hidden Cone center consists of a main scoria cone that developed on the north-facing slope of Sleeping Butte. The center formed during two episodes. The first included the formation of the main scoria cone, and venting of aa lava flows from radial dikes at the northeast base of the cone. The second included eruption of scoria-fall deposits from the summit crater. The ages of the Little Black Peak and the Hidden Cone are estimated to be between 200 to 400 ka based on the whole-rock K-Ar age determinations with large analytical uncertainty. This age assignment is consistent with qualitative observations of the degree of soil development and geomorphic degradation of volcanic landforms. The younger episode of the Hidden Cone is inferred to be significantly younger and probably of Late Pleistocene or Holocene age. This is based on the absence of cone slope rilling, the absence of cone-slope apron deposits, and erosional unconformity between the two episodes, the poor horizon-development of soils, and the presence of fall deposits on modern alluvial surfaces. Paleomagnetic data show that the centers record similar but not identical directions of remanent magnetization. Paleomagnetic data have not been obtained for the youngest deposits of the Hidden Cone center. Further geochronology, soils, geomorphic, and petrology studies are planned of the Sleeping Butte volcanic centers.

INTRODUCTION

The Sleeping Butte volcanic centers are located about 20 km north of Beatty, Nevada, north of Oasis Valley and within the Nellis Air Force Range (Fig. 1). Each of the two centers consists of a main scoria cone, with minor satellitic scoria cone(s) and multiple lobes of blocky aa lava flows. These small-volume basaltic volcanoes are representative landforms of mildly explosive Strombolian volcanic activity. The southwestern center, the Little Black Peak basaltic center, was erupted through fanglomerate deposits of the alluvial valley flanking the southwest margin of Pahute Mesa and Black Mountain (Fig. 1). The northeast center, the Hidden Cone volcanic center, is located 2.6 km from the Little Black Peak center (distance measured from crater center to crater center). It erupted through and draped the north-northeast facing slope of Sleeping Butte, a prominent mount located about 1 km inward of the range front of the Pahute Mesa-Black Mountain highland.

The two Sleeping Butte volcanic centers are aligned in a north-northeast direction. This is interpreted as a structural alignment for several reasons. First, a north-northeast alignment of basaltic centers is common in volcanic rocks of Pliocene age and younger in the southern Great Basin (Crowe et al., 1983; 1986). Second, the alignment of cones is perpendicular to the least principal stress direction (N 65 degrees west, Stock et al., 1986).

The purpose of this report is to present and describe preliminary geologic maps of the Sleeping Butte volcanic centers. The Sleeping Butte volcanic centers are two of a total of seven Quaternary volcanic centers that are present within the Yucca Mountain region (Crowe and Carr, 1980; Crowe et al., 1983; Crowe and Perry, 1989; Crowe, 1990). These maps are part of site characterization activities for the Yucca Mountain Project. The geologic mapping is the first phase of studies of the Sleeping Butte centers. The justification and applications of this work are described in Study Plan 8.3.1.8.5.1, *Characterization of Volcanic Features*.

The preliminary geologic maps of the Sleeping Butte volcanic centers were completed using a combination of stereo photographic analysis and field mapping on color aerial photographs. These photographs were obtained from EG&G through contract with the Yucca Mountain Project. They were flown and photographed at scale of 1:4975 on September 24, 1989. The photographs are EG&G Series 6615, numbers 01 to 71.[1]

The compiled geologic maps are regarded as preliminary for several reasons. First, the geochronology studies at the volcanic centers are incomplete. Trenching is required for soils and geomorphic studies. This work cannot be completed until permits are obtained by the Department of Energy (DOE) from the State of Nevada. Only preliminary K-Ar age determinations have been obtained (Crowe et al., 1982; US Department of Energy, 1986). Recently completed K-Ar age determinations and paleomagnetic studies have not been conducted under a qualified quality assurance program (Nunes, 1990). Second, because of the very large scale of the aerial photographs used for the mapping, there can be scale distortion at the edge of photographs. To reduce these effects, we compiled the mapping on a limited set of the aerial photographs. The Little Black Peak center was compiled entirely on aerial photograph EG&G 6615, number 043. The Hidden Peak center was compiled on aerial photographs EG&G 6615, numbers 026 and 037. The contacts shown on the geologic maps may not transfer directly to other photographs.

GEOLOGY OF THE LITTLE BLACK PEAK VOLCANIC CENTER

The Little Black Peak volcanic center consists of a main scoria cone, two satellitic scoria mounds directly south of the main cone, and two lava flow lobes. One lava-flow lobe vented from the northwest flank of the main cone, and the second lava-flow lobe is inferred to have vented from the east flank of the main cone (Fig. 2).

The oldest unit of the Little Black Peak volcanic center includes two scoria mounds (Qs_2) located at the south margin of the main cone (Fig. 2). These are irregular mound-shaped accumulations of basalt scoria and volcanic bombs. There is no recognizable vent or crater associated with either scoria mound. However, the abundance of large bombs (> 1 m in diameter) in surface outcrops suggests the mounds were the vents for pyroclastic eruptions. Lenticular dikes of varying strike and dip are exposed at several localities in the scoria mounds (Fig. 2). Small lava-flow lobes are exposed at two sites on the west margin of the eastern scoria mound (Ql_2). The southern lobe is eroded so that only basal rubble of the lava and possible feeder dikes are preserved. The northern lobe includes outcrops of blocky aa lava with vesicular lava flow tops. Small outcrops of basalt lava surrounded by alluvium are exposed south of the scoria mounds (Ql_2?). The lava outcrops may be flows that vented from the scoria mounds, or they may be remnants of regionally extensive Miocene basalt associated with the Black Mountain volcanic episode (Noble and Christiansen, 1968; Luedke and Smith, 1981; Crowe, 1990). The scoria mounds and minor lava flows of the Little Black Peak center are similar in morphology to scoria mounds and small lobate lava flows described at the Lathrop Wells volcanic center (Crowe et al., 1988).

[1]Copies of the aerial photographs with geologic mapping are on file in the Los Alamos Yucca Mountain Site Characterization Project Office, 101 Convention Center Drive, Suite 860, Las Vegas, Nevada.

The main scoria cone (Qs_1) of the Little Black Peak volcanic center has a basal diameter of about 500 meters and a height of about 70 meters. The cone is symmetrical with a summit crater that is slightly elongated in a north-south direction. The upper east side of the scoria cone collapsed, forming a bowl-shaped landslide scarp extending from the summit crater, halfway down the eastern flank. The slide debris from this collapse extends down and beyond the cone margin to the east (Fig. 1). The collapse of the cone is inferred to be a young event because the slide deposits overlie the cone-slope apron deposits, and there are limited cone-slope deposits on the upper surface of the slide deposits. Red (oxidized) zones of the scoria cone (area outlined by dots on the cone summit) are centered on the summit crater. They are inferred to be produced by alteration of the scoria by volcanic gases emitted from the conduit or feeder dikes. The oxidized zone is slightly elongated in a north-northwest direction, which may reflect the strike of the underlying feeder dike for the volcanic center. The upper surface of the scoria cone is extensively rilled, and the cone is surrounded by a well-developed cone-slope apron (Qs_{1a}) except at two locations. These are at the southwest margin of the cone, where erosion has cut through the apron and exposed the underlying fanglomerate (Fig. 2), and at the east side of the center where the apron deposits are overlapped by the slide deposits.

Aa lava flows were extruded from two sites on the flanks of the scoria cone. The larger flow (length 1.1 km, maximum width .3 km) was extruded at the northwest base of the main scoria cone. The vent is marked by a small indentation in the cone profile (Fig. 2) although it is largely covered by the deposits of the cone-slope apron. Confirmation of the vent site is provided by two features: first, the flow is thickest adjacent to the vent (15 m near vent, 10 m distal flow edge), and second, the area of scoria cone oxidation on the northwest side (Fig. 2) is offset and extended toward the vent. This offset oxidation zone is consistent with the lava flow being fed by a dike that extends radially from the main conduit. The oxidation was likely produced by alteration of the cone scoria by gases emitted from the radial dike. The original irregular topography of the aa lava surface has been infilled by eolian material to produce a smoothed, pavement surface. Remnants of the primary flow topography occur only as local areas of irregularities in the pavement surface. Margins of the lava flow are not original flow margins; they have been backcut by erosion. The degree of backcutting and burial of the lava flow surface is in agreement with the assigned age of the center using the geomorphic criteria described in Dohrenwend et al., (1986). Cross-sectional exposures of the lava show that they were erupted as aa flows.

Two lava-flow lobes were identified tentatively in the western flow lobe in the area extending from the south margin of the main scoria cone to the main vent. However, because of the degree of geomorphic modification of the upper flow, these units could not be mapped continuously. They are not separated on Fig. 2. A small section of the western flow lobe lapped onto the western scoria mound. Erosion cut subsequently through the flow and exposed the underlying fanglomerate. This isolated a single small outcrop of lava from the main flow lobe of the western flow (Fig. 2).

The eastern flow lobe is concealed largely by slide deposits (Fig. 2). It is much smaller than the western flow lobe and extends only 400 m from the inferred vent. Cross-sectional exposures of the flow show that it is an aa flow. It exhibits the same degree of geomorphic modification as the western flow lobe (pavement surface, eroded flow margins).

Age of the Little Black Peak Volcanic Center: Preliminary chronology data are available for the Little Black Peak volcanic center. Three K-Ar ages, all with large analytical uncertainty, were reported of from 240 to 320 ka (Crowe et al., 1982; Department of Energy, 1986). Potassium-Ar ages of 208 ± 134 ka (arithmetic mean) and 223 ± 100 ka have been obtained for the Little Black Peak lavas (Turrin, 1989). Preliminary paleomagnetic data for the lava units, the main cone, and the scoria mounds (seven sites) suggest that they all record a single remanent direction (Champion, 1989; 1990). These data are in general agreement with the degree of geomorphic modification and the horizon development of soil on volcanic units of the soil. The preliminary paleomagnetic data suggest the Little Black Peak center is a monogenetic basaltic volcano.

HIDDEN CONE BASALT CENTER

The Hidden Cone volcanic center consists of a main scoria cone that was formed on the north-facing slope of Sleeping Butte. The center consists of two sequences: (1) the main scoria cone and associated lavas and scoria that vented at the northeast flank of the cone and (2) a thin sequence of scoria that erupted from the summit of the main scoria cone and mantled the eroded slopes of the main scoria cone. The second event may be significantly younger, based on age-calibrated dating methods, than the first event. This inference has not been verified or tested by radiometric or isotopic dating methods.

The first, or oldest, event at the Hidden Cone center was the formation of most of the volume of the main scoria cone (Fig. 3). The scoria deposits draped the north slope of Sleeping Butte, a prominent topographic mount. As a result, the cone is widest on the north (downslope) side and is narrowest on the south (upslope side). The basal diameter of the cone is about .62 km. The cone height is about 110 m measured from the north base of the cone; it is about 25 m in height measured from the south base of the cone. The scoria cone is surmounted by an elliptical crater, and the long axis of the crater trends north. The crater and crater rim are surrounded by a zone of red oxidization of scoria (area outlined by dots at cone summit) that is largely centered on the crater but is skewed slightly to the west. This suggests that the feeder dike system for the cone may dip to the west. Scoria deposits of the main scoria cone are mantled by younger scoria deposits for most of the cone exposure. The older scoria deposits (Qs_4) are exposed only in three locations: the summit crater and eastern slide scarp (Qs_4), adjacent to the lava exposures in the northeast cone wall (Qs_4), and locally at the base of the cone on the north and west sides of the cone (Qs_{4a}). The first two sites expose scoria deposits emplaced during fire-fountaining (cone-building) eruptions. The latter site exposes cone-slope apron deposits that were formed by downslope erosion of the cone mass. These deposits contain soils with well-developed soil horizons.

Lava vented from radial dikes at two localities and from a satellitic scoria cone, all on the northeast flank of the main scoria cone (Fig. 3). The major lava feeder vent for the longest lobe of lava is at the northeast edge of the main scoria cone, several tens of meters above the cone base. Here a radial feeder dike passes upward into a lava flow (Fig. 3). The exact contacts of the dike are difficult to map for two reasons. First, the radial strike of the dike is parallel to the strike of the lava flow contacts. Second, the margins of the lava flow are locally steep where the lava sagged internally into the unconsolidated scoria deposits. The steeply dipping lava flow base cannot always be distinguished from the dike. The radial dike was the source of the only extensive lava lobe of the Hidden Cone center (Ql_4). This lava can be traced almost continuously from the dike source laterally for a distance of 1.3 km. It is overlain locally by slide deposits near the cone base (Qls). The Ql_4 lava overlies a much older lava and scoria unit (Mb) that crops out north of the Hidden Cone center. This basalt unit is not part of Hidden Cone center. It can be traced to the north where it is associated with other basalt centers. These centers erupted lavas that locally interfinger with ash-flow deposits of the Thirsty Canyon Tuff (Noble and Christiansen, 1968; Vogel et al., 1989). The older basalt is shown on the map of the Hidden Cone center only where it could be confused with the Quaternary lava units of the Hidden Cone center.

Two other feeder dike systems are exposed in the northeast wall of the main scoria cone (Fig. 3). A dike feeder system is exposed in the northeast cone wall directly south of the Ql_4 dike (Fig. 3). Here, two radial dike systems can be traced from the scoria deposits directly into the Ql_2 lava flow (Fig. 3). This Ql_2 lava flow extends from the dikes to the base of the main scoria cone, where it overlies older scoria deposits (Qs_3). The third feeder dike is exposed in the eroded roots of a satellitic cone (Qs_3) that occurs below the base of the northeast segment of the main cone. This cone is similar in morphology to the scoria mounds of the Lathrop Wells and Little Black Peak centers. It has been eroded to expose lenticular dikes in the south outcrop area of Qs_3. In an east section of exposures of scoria deposits of Qs_3, a feeder dike can be traced into a lava flow. This lava unit extends for about 300 m east of the feeder dike, and overlies the Ql_4 lava flow.

The east wall of the main scoria cone of the Hidden Cone center collapsed and fed a slide mass that extends northeast down the cone slopes (Ql_s). The scalloped depression created by this collapse extends into the summit crater on the north side of the main scoria cone (Fig. 3). The slide deposits cover the Ql_4 lava flow and the Qs_3 scoria mound deposits.

Locally beneath the slide deposits, there are pockets of scoria deposits (Qs_4), and apron deposits the older phase of cone growth (Qs_{4a}). The elevated position of the slide deposits and the lava flow units (Ql_4 and Ql_2), and the local pockets of scoria from the main cone, suggest there is an increased thickness of cone scoria along the northeast cone segment. These deposits extend farther east from the main cone and disrupt the symmetry of the cone shape. A thickened section of cone-scoria deposits probably was formed in association with repeated outbreaks of lava on the northeast segment of the main scoria cone. These inferred deposits are largely covered by the lava flow and slide deposits (Fig. 3).

The lava-flow units of the Hidden Cone center show similar degrees of erosional degradation as the lava units of the Little Black Peak center. Most of the original aa topography has been smoothed and the flow tops are pavement surfaces. Margins of the lava flows are erosional and are not original flow margins. Cross-sectional exposures of the lavas show they were emplaced as aa lava flows.

The youngest unit of the Hidden Cone center (Qs_1) includes deposits of a younger scoria eruption that mantles scoria of the older cone (Qs_4). These deposits draped the slopes of the cone (Qs_1), except for the basal perimeter of the north side of the cone where older cone slope apron deposits (Qs_{4a}) are exposed. The existence and young age of this eruptive event and associated deposits are suggested by the following:

1. The outer slopes of the main cone show only minor erosional rilling. The degree of rilling is inconsistent with the assigned age of the main cone and associated lava-flow units. The only known way for an older cone surface, which experienced a long period of erosion, to have a uniformly smooth surface would be to have been mantled by a younger scoria fall deposit.
2. There are no recognizable apron deposits flanking the upper scoria deposits where they are not underlain by deposits of Qs_{4a}. This suggests that there has been insufficient time since the eruption and deposition of Qs_1 for significant downslope erosion to have formed apron deposits.
3. There is an erosional unconformity between the Qs_4 and Qs_1 deposits. This unconformity is only exposed in the northeast section of the main cone. Here the feeder dikes that produced the lava flows are exposed within scoria deposits of the Qs_4 unit. Examination of the outcrops of the feeder dike of the Ql_4 lava shows that several meters of erosion of the Qs_4 scoria are required to expose the radial dike. Because the dike and Ql_4 lava are partly covered by Qs_1 scoria, this erosion had to occur in the interval between deposition of the two units.
4. There is significant horizon development in the soil on the Qs_4 deposits. There is limited horizon development in the soil on the Qs_1 scoria deposits.
5. Fine-grained scoria-fall deposits are preserved on the **modern alluvial surface** about 0.5 km northeast of the main scoria cone. These deposits could be present only if the final scoria eruptions of the center are significantly younger than the main cone and associated lava-flow units.

Age of the Hidden Cone Center: Samples of basalt lava from the Hidden Cone center were included in the K-Ar ages reported by Crowe et al., (1982) and the Department of Energy (1986). A K-Ar age of 316 ± 200 ka has been obtained for the center (Turrin, 1989). The degree of erosional dissection of the lavas and the horizon development of soil on the lavas and Qs_{4a} apron deposits are consistent with an age of several hundred thousand years using the geomorphic criteria of Dohrenwend et al., (1986). Preliminary paleomagnetic data from six sites in the lavas of the Hidden Cone center appear to record a single remanent direction (Champion, 1989). Moreover, the remanent directions appear to match the directions recorded at the Little Black Peak center suggesting the eruptive units at both centers represent a single event, or events closely spaced in time (Champion, 1990). However, the geomorphic preservation of the Qs_1 unit is not consistent with an age of several hundred thousand years. The degree of development of riling, the steep cone slope angles, and the lack of horizon development in soil on the Qs_1 unit are consistent with an inferred age assignment of possibly late Pleistocene or Holocene.

DISCUSSION

The conventional interpretation of small-volume Strombolian basalt centers like the Sleeping Butte centers is that they form in a single, short-duration event (they are monogenetic). Field and preliminary paleomagnetic studies of the Little Black Peak center and preliminary paleomagnetic studies of the Hidden Cone center are consistent with this interpretation. However, evidence summarized above for the Qs_1 event at the Hidden Cone center are inconsistent with a monogenetic classification. The geomorphic and pedologic characteristics of the Qs_1 deposits are analogous to relations described at the Lathrop Wells center and the Black Tank center in the Cima volcanic field (Crowe et al., 1989; Wells et al., 1990).

We must evaluate carefully any evidence of late Pleistocene or Holocene activity in the Yucca Mountain region and incorporate that information in assessments of volcanic risk. Thus, while the age assignment of the Qs_1 event is conditional, it is important to continue to evaluate potential evidence that suggests a late Pleistocene or Holocene age. We cannot err in the direction of assigning an old age (> 200 ka) to a volcanic event that is potentially young. Such an assignment could result in a non-conservative assessment of volcanic risk. Moreover, a more acceptable error from the perspective of risk assessment would be to assign a young age to an event that is old (> 200 ka). We thus now assume that the Qs_1 event at the Hidden Cone could be significantly younger than the other volcanic events. This assumption creates an important potential discrepancy.

A long time gap (> 100 ka) is required between eruptive events if the Qs_1 unit was formed by a young volcanic event and if the preliminary chronology data are correct for the age of the lava and older scoria deposits of the Hidden Cone center (> 200 ka). It is not generally expected that a young eruptive event, following a long period of no activity, would occur at the identical vent of past eruptions. However, this pattern of repeated volcanic activity after long intervals has occurred at some centers in the Cima volcanic field (Wells et al., 1990). The same eruptive pattern is suspected at the Lathrop Wells volcanic center, although the length of time between eruptions was probably a few tens of thousands of years (Crowe et al., 1989; Crowe, 1990). We will continue to investigate the evidence for a young age of the last activity at the Hidden Cone center because of the current uncertainty of the chronology of eruptive events at the Hidden Cone center and the importance of establishing correct age assignments of volcanic events for risk assessment.

FUTURE WORK

Future work at the Sleeping Butte centers is described in Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features. Geochronology studies will attempt to obtain convergence of age information on the centers using the following methods:

1. Additional age determinations will be obtained using the conventional K-Ar method. We will attempt to determine why K-Ar age determinations have such large analytical uncertainty for samples from both centers. We may also attempt to establish the age of the centers using the $^{39}Ar/^{39}Ar$ method.

2. Samples of lavas from both centers will be submitted for ^{238}U–^{232}Th disequilibrium measurements using solid source mass spectrometry. This work is being conducted by M. Murrell, Los Alamos National Laboratory. Studies at the Lathrop Wells center have shown that the utility of this technique may be affected by the mineralogy of the basalt samples. The lavas of the Sleeping Butte center are aphyric, and thus, it may be difficult to obtain good mineral and phase separations for isotopic analysis.
3. Exposure age dating using *in situ*-produced cosmogenic ^3He will be used to test the validity of assigning a young age to the Qs_1 event at the Hidden Cone center. This work is being conducted by J. Poths, Los Alamos National Laboratory.
4. Trenching and soil pits will be constructed at the Hidden Cone center to expose the soils of the Qs_1 and Qs_4 units for soils studies. This work is being conducted by L. MacFadden, University of New Mexico. If suitable materials are found in the trenches and soil pits, samples will be collected for thermo-luminescence dating. The thermoluminescence dating is being conducted by S. Forman, University of Colorado.
5. Petrology studies of the lavas and scoria units at the centers will be conducted to evaluate magmatic processes. This work is being conducted by F. Perry, University of New Mexico.
6. Rock varnish stratigraphy will be evaluated at the Hidden Cone center to determine if young tephra events near the cone affected varnish accumulation. This work is being conducted by C. Harrington, Los Alamos National Laboratory.

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REFERENCES

Champion, D., US Geological Survey, Written communication to Bruce Crowe, December 18, 1989, TWS-EES-13-LV-09-90-07 (1989).

Champion, D., US Geological Survey, Written communication to Bruce Crowe, January 31, 1990, TWS-EES-13-LV-09-90-07 (1990).

Crowe, B. M., Chapter 16: "Volcanic hazard assessment for disposal of high-level radioactive waste," in *Recent Tectonics: Impact on Society*, National Academy Press, Washington, D.C., 247–260 (1986).

Crowe, B. M., "Basaltic volcanic episodes of the Yucca Mountain region," in *High Level Radioactive Waste Management*, Volume 1, American Nuclear Society, La Grange Park, Illinois, 65–73 (1990).

Crowe, B. M., and W. J. Carr, "Preliminary assessment of the risk of volcanism at a proposed nuclear waste repository in the southern Great Basin," US Geological Survey open file report 80-375 (1980).

Crowe, B. M., M. E. Johnson, and R. J. Beckman, "Calculation of the probability of volcanic disruption of a high-level radioactive waste repository within southern Nevada, USA," *Radioactive Waste Management* 3, 167–190 (1982).

Crowe, B. M., D. T. Vaniman, and W. J. Carr, "Status of volcanic hazard studies for the Nevada Nuclear Waste Storage Investigations," Los Alamos National Laboratory report LA-9325-MS (1983).

Crowe, B. M., K. H. Wohletz, D. T. Vaniman, E. Gladney, and N. Bower, "Status of volcanic hazard studies for the Nevada Nuclear Waste Storage Investigations," Los Alamos National Laboratory report LA-9325-MS, Vol II (1986).

Crowe, B., C. Harrington, L. McFadden, F. Perry, S. Wells, B. Turrin, and D. Champion, "Preliminary geologic map of the Lathrop Wells volcanic center," Los Alamos National Laboratory document LA-UR-88-4155 (1988).

Crowe, B. M. and F. V. Perry, "Volcanic probability calculations for the Yucca Mountain site: Estimation of volcanic rates," *Proceedings Nuclear Waste Isolation in the Unsaturated Zone, Focus '89*, American Nuclear Soc., 326–334 (1989).

Crowe, B. M., B. Turrin, S. Wells, F. Perry, L. McFadden, C. Renault, D. Champion, and C. Harrington, "Volcanic hazard studies for the Yucca Mountain project," in *Waste Management '89, Volume 1–High Level Waste and General Interest*, 485–492 (1989).

Dohrenwend, J. C., S. G. Wells, and B. D. Turrin, "Degradation of Quaternary cinder cones in the Cima volcanic field, Mojave Desert, California," *Geol. Soc. America Bull.* **97**, 421–427 (1986).

Luedke, R. G., and R. L. Smith, "Map showing distribution, composition, and age of late Cenozoic volcanic centers in California and Nevada," US Geol. Surv. Misc. Geol. Invest. Map, I-1091-C (1981).

Noble, D. C. and R. L. Christiansen, "Geologic map of the southwest quarter of the Black Mountain Quadrangle," US Geol. Surv. Misc. Geol. Invest. Map, I-562 (1968).

Nunes, H., Los Alamos National Laboratory, written communication to Bruce Crowe, August 15, 1990, TWS-ESS-13-08-90-02 (1990).

Stock, J. M., J. H. Healy, J. Svitek, and L. Mastin, "Report on televiewer log and stress measurements in holes USW-G3 and UE-25p1, Yucca Mountain, Nye County, Nevada," US Geol. Surv. Open-File Rept. 86-369 (1986).

Vogel, T. A., D. C. Nobel, and L. W. Younger, "Evolution of a chemically zoned magma body: Black Mountain volcanic center, southwestern Nevada," *Journal of Geophy. Res.* **94**, 6041–6058 (1989).

Wells, S. G., L. D. McFadden, C. E. Renault, and B. M. Crowe, "Geomorphic assessment of late Quaternary volcanism in the Yucca Mountain area, southern Nevada: Implications for the proposed high-level radioactive waste repository," *Geology*, **18**, 549–553 (1990).

Turrin, B., US Geological Survey, Written communication to Bruce Crowe, October 16, 1989, TWS-EES-13-LV-09-90-07 (1989).

US Department of Energy, "Environmental Assessment: Yucca Mountain Site, Nevada Research and Development Area, Nevada," DOE/RW-0073 (1986).

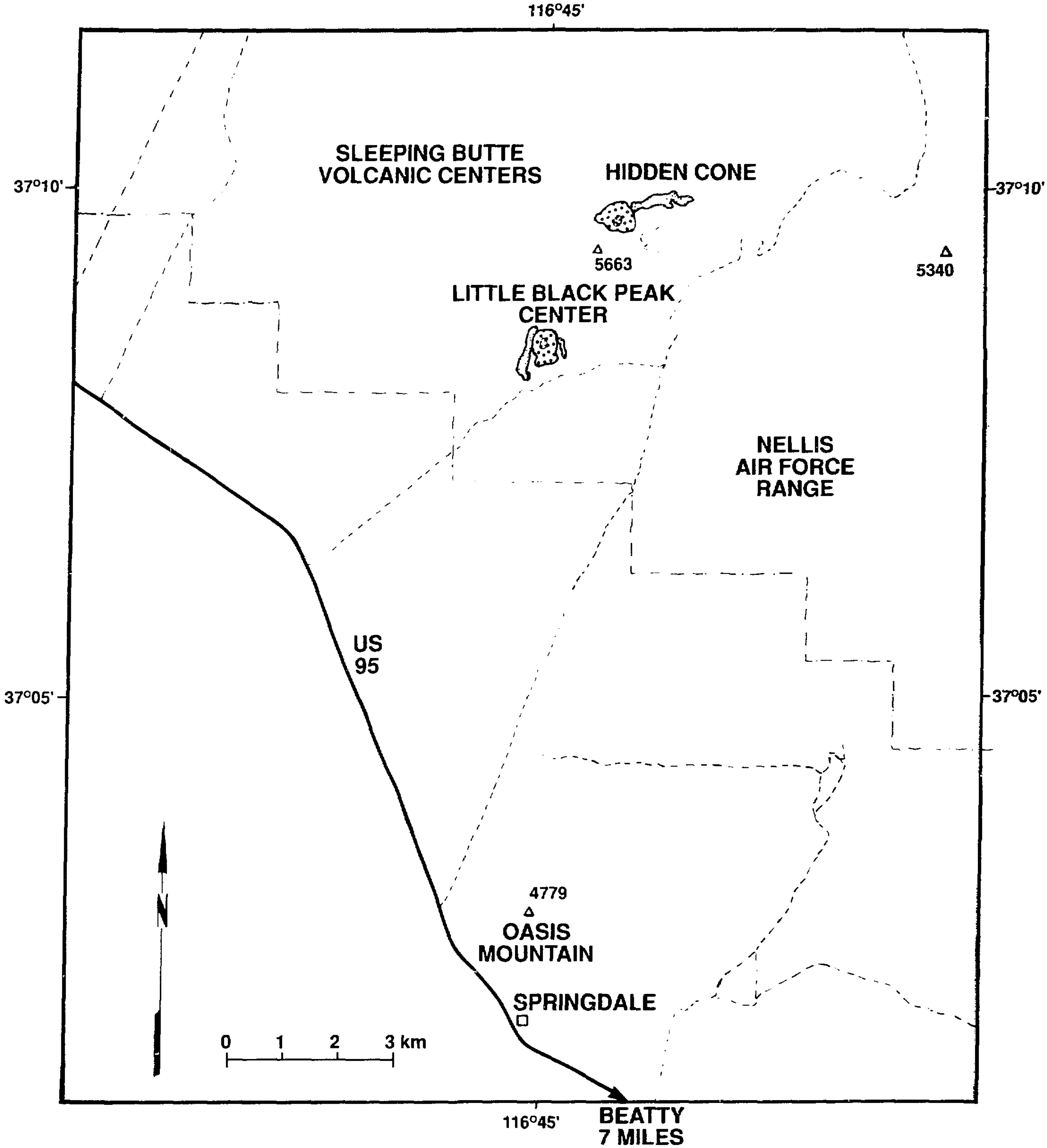


Fig. 1. Location map of the Sleeping Butte volcanic centers.

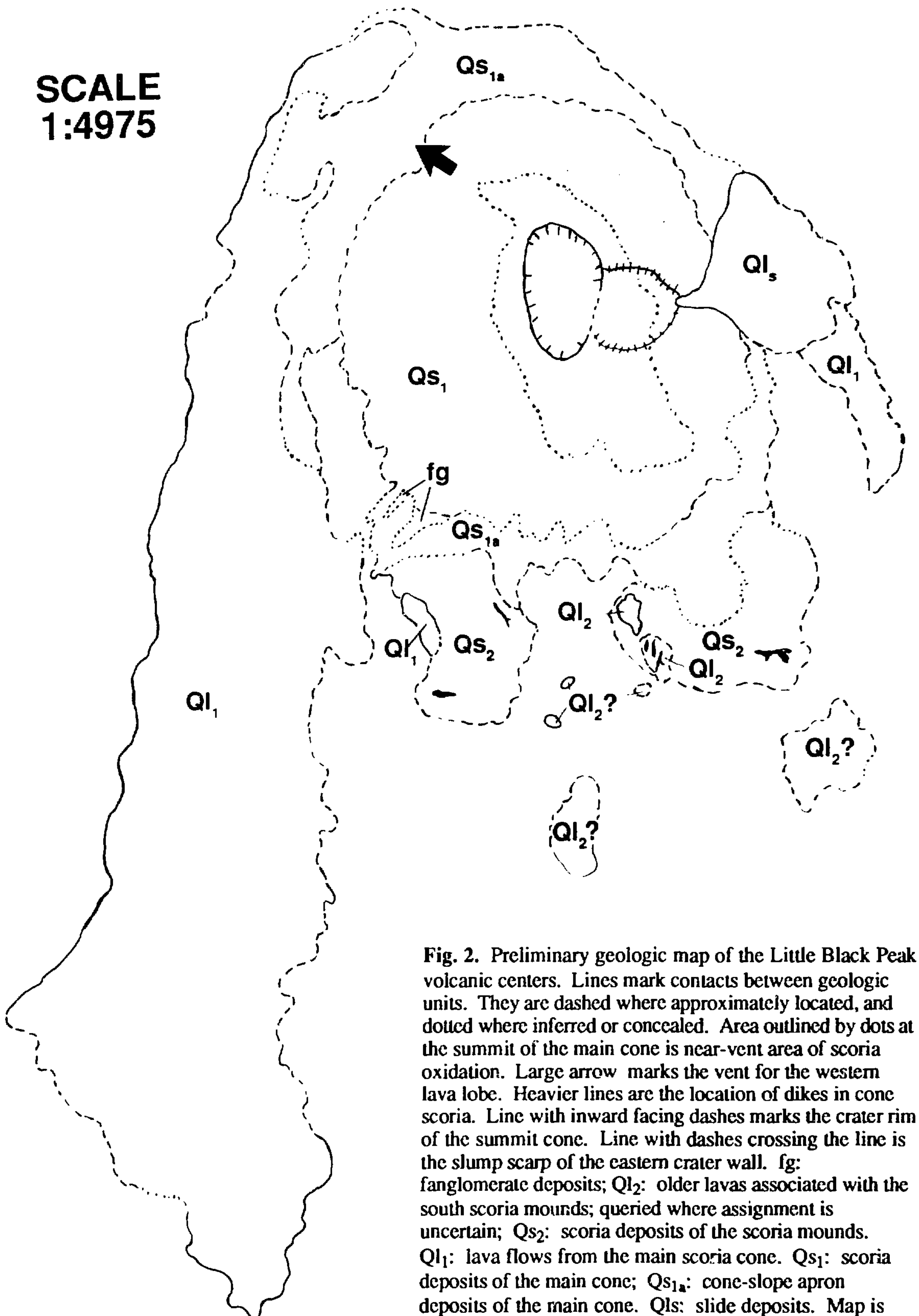
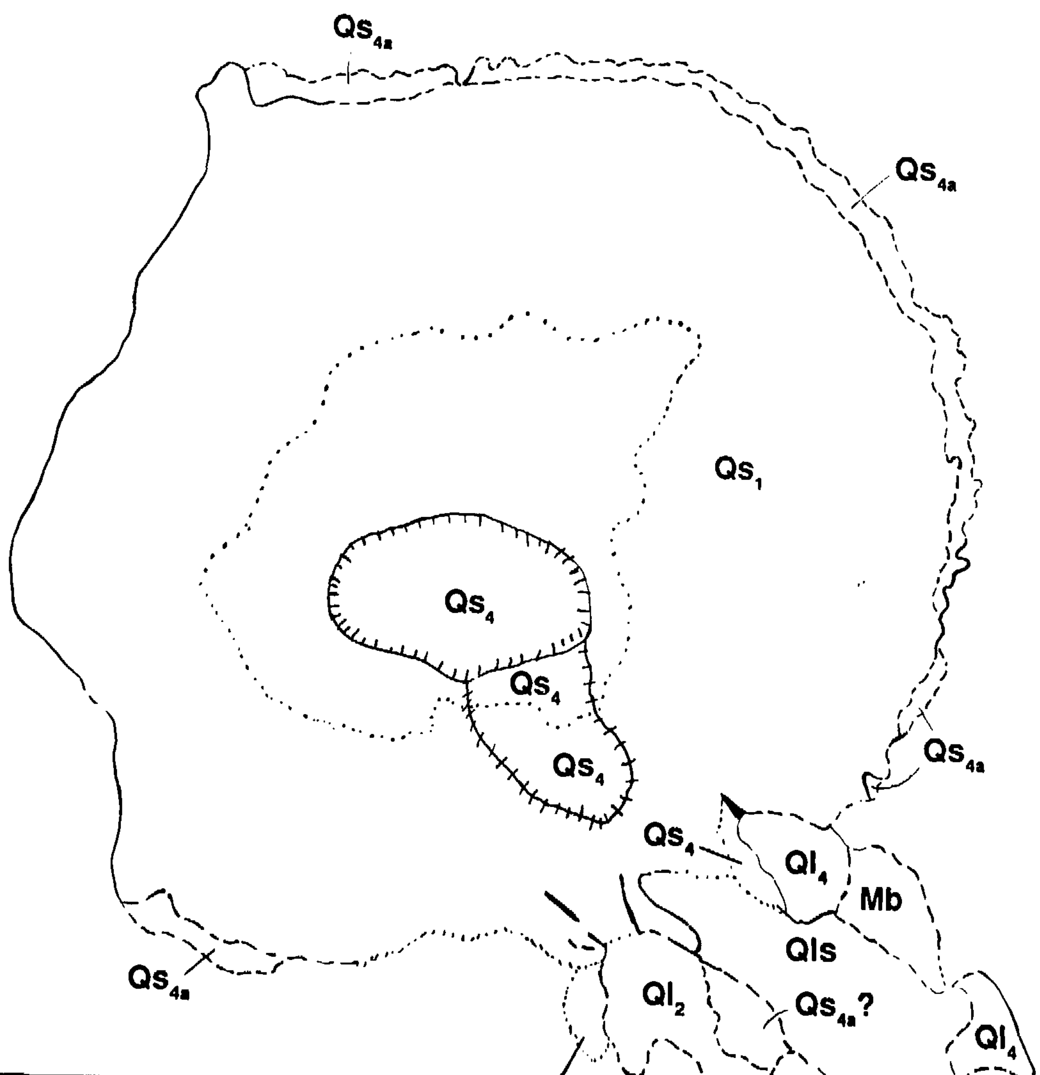


Fig. 2. Preliminary geologic map of the Little Black Peak volcanic centers. Lines mark contacts between geologic units. They are dashed where approximately located, and dotted where inferred or concealed. Area outlined by dots at the summit of the main cone is near-vent area of scoria oxidation. Large arrow marks the vent for the western lava lobe. Heavier lines are the location of dikes in cone scoria. Line with inward facing dashes marks the crater rim of the summit cone. Line with dashes crossing the line is the slump scarp of the eastern crater wall. fg: fanglomerate deposits; Ql_2: older lavas associated with the south scoria mounds; queried where assignment is uncertain; Qs_2: scoria deposits of the scoria mounds. Ql_1: lava flows from the main scoria cone. Qs_1: scoria deposits of the main cone; Qs_{1a}: cone-slope apron deposits of the main cone. Qls: slide deposits. Map is compiled on aerial photograph. To orient map for north direction, refer to Figure 1.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Ql4

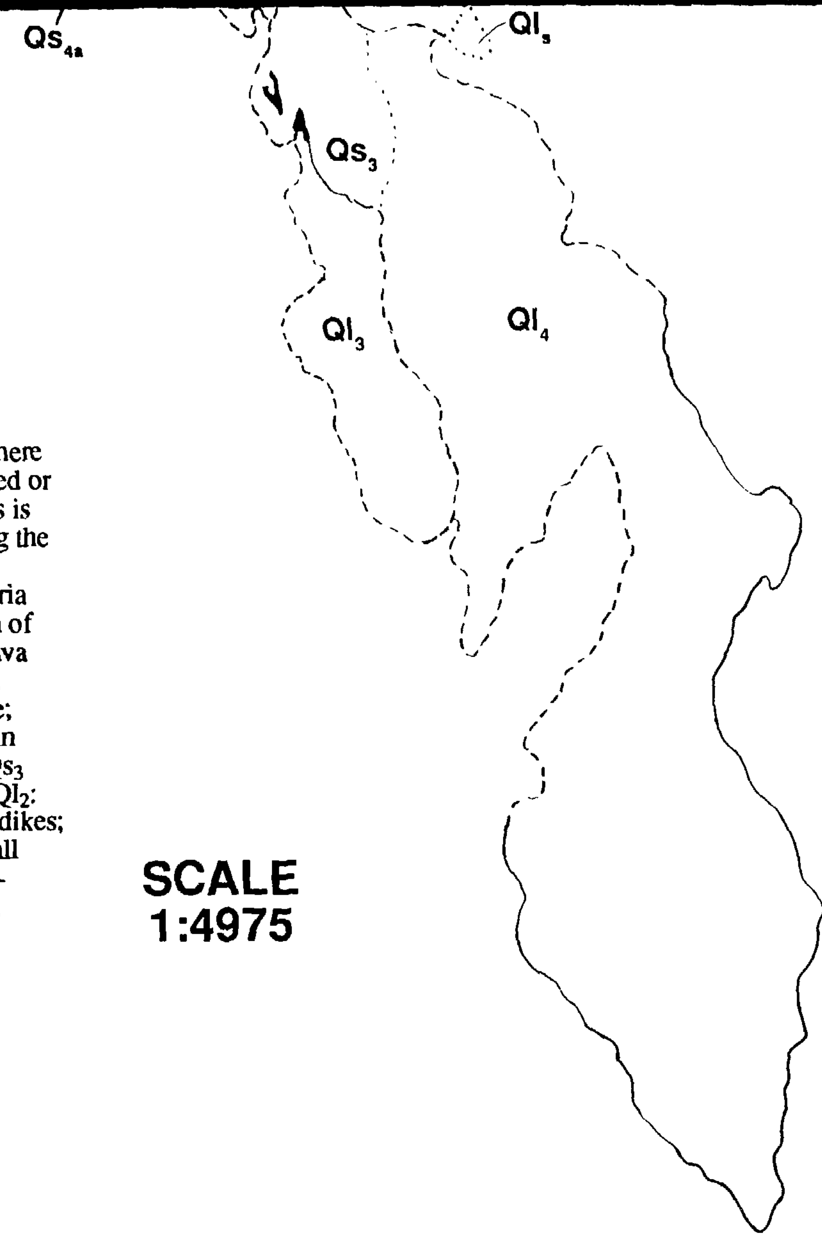

Fig. 3. Preliminary geologic map of the Hidden Cone volcanic center. Lines are contacts between geologic units, dashed where approximately located, dotted where inferred or concealed. Line with inward facing dashes is the summit crater; line with dashes crossing the line outlines the slump scarp of the eastern crater wall; dotted line encloses area of scoria oxidization. Heavy lines mark the location of feeder dikes; Mb: Miocene basalt; Ql_4: lava flow associated with the radial feeder dike. Qs_4: older scoria deposits of the main cone; Qs_{4a}: cone-slope apron deposits of the main cone; Ql_3: lava flow associated with the Qs_3 scoria mound; Qs_3: flank scoria mound; Ql_2: lava flow associated with the radial feeder dikes; Qs_1: late Pleistocene of Holocene scoria-fall deposits. Map is compiled on aerial photographs. To orient map for north direction, refer to Figure 1.

SCALE
1:4975