KANSAS GEOLOGICAL SURVEY
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GUIDEBOOK
CRETACEOUS LAMPROITES OF THE SILVER CITY AND ROSE DOMES, WOODSON AND WILSON COUNTIES, KANSAS

by

Field Trip Leaders

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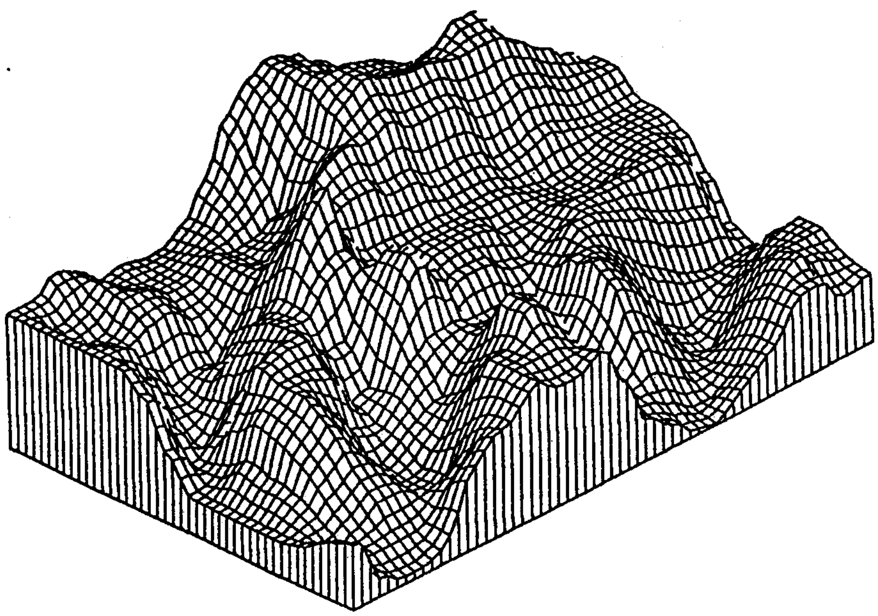
Guidebook

Cretaceous Lamproites of the Silver City and Rose Domes

Woodson and Wilson Counties, Kansas

Pieter Berendsen and Ralph Knapp, leaders



GSA South-Central Section
Field Trip 2

March 13, 1988

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Cretaceous Lamproites of the Silver City and Rose Domes, Woodson and Wilson Counties, Kansas

Pieter Berendsen and Ralph Knapp
Kansas Geological Survey

Cover:
Three dimensional terrain diagram of the area surrounding the Rose and Silver City Domes. Digital terrain data from the Defense Mapping Agency was processed using the Surface II software package developed at the Kansas Geological Survey

Guidebook for Field Trip number 2

March 13, 1988

Cover graphics, design, and layout by Kevin P. Blair

PREFACE

Since the discovery of igneous rocks in Woodson and Wilson counties in the latter part of the 19th century, several scientific communications have been published on the subject. Because of the limited number of exposures some of the earlier interpretations were hampered by lack of information, especially that obtained by drilling. In the following paper the history of discovery and subsequent early studies will be reviewed, followed by the results and interpretations arrived at in more recent unpublished studies and work in progress.

Starting with a publication by Holly C. Wagner (1954) entitled "Geology of the Fredonia Quadrangle" (U.S.G.S., Map GQ 49), a number of excellent papers were published dealing with the petrological, petrographical, geochemical, geochronological and geophysical aspects of the occurrences.

Rather than trying to rewrite and condense this material, some of these papers have been reproduced and are included as part of this guidebook.

Acknowledgments: We thank Mr. Gerald Winterscheidt, Executive Vice-President, Micro-Lite, Inc. of Chanute, for his permission to visit the mine site at Silver City Dome.

We would also like to thank the authors and the publishing companies for giving us permission to reproduce the papers that are included in the guidebook.

THE LAMPROITES OF WOODSON AND WILSON COUNTIES, SE KANSAS

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Introduction

Lamproites occur at two localities in southeast Kansas, about 100 miles (170 km) south of Lawrence and 7 miles (10 km) south of the town of Yates Center in Woodson County. Silver City Dome is situated at the boundary between Woodson County to the north and Wilson County to the south in Townships 26 and 27S, Ranges 14 and 15 E. On the surface it appears as a northeast-elongated, elliptical depression, about 2.5 miles by 1.5 miles in diameter. Rose Dome, located 6 miles (9 km) to the northeast in Wilson County, in Township 26S and Ranges 15 and 16E is similar in size and morphology. Narrow, northeast-trending linear ridges, characterize the area between the two domes. The general altitude of higher parts of the area is about 1000 feet above sea level.

Igneous rocks were first recognized in the area in the latter part of the 19th century, even though the extent and true nature of the rock was not well understood for quite some time. The history of discovery and subsequent studies will be briefly reviewed.

At the surface the lamproite occurs in Upper Pennsylvanian sediments of the Lansing and Douglas Groups (Figure 1). The sediments consist of alternating beds of limestone and shale with minor sandstone. As a result of doming older sedimentary units are exposed in the center of the structure. About 1300 feet of Pennsylvanian limestones, shales and sandstones overlie the Mississippian carbonates. Oil production is from distributary channel sands that occur above the Mississippian carbonates. The granitic basement in the general vicinity of the domes is at approximately 2500 feet.

Stratigraphic column along US 59/169
Lawrence to Buffalo, Kansas

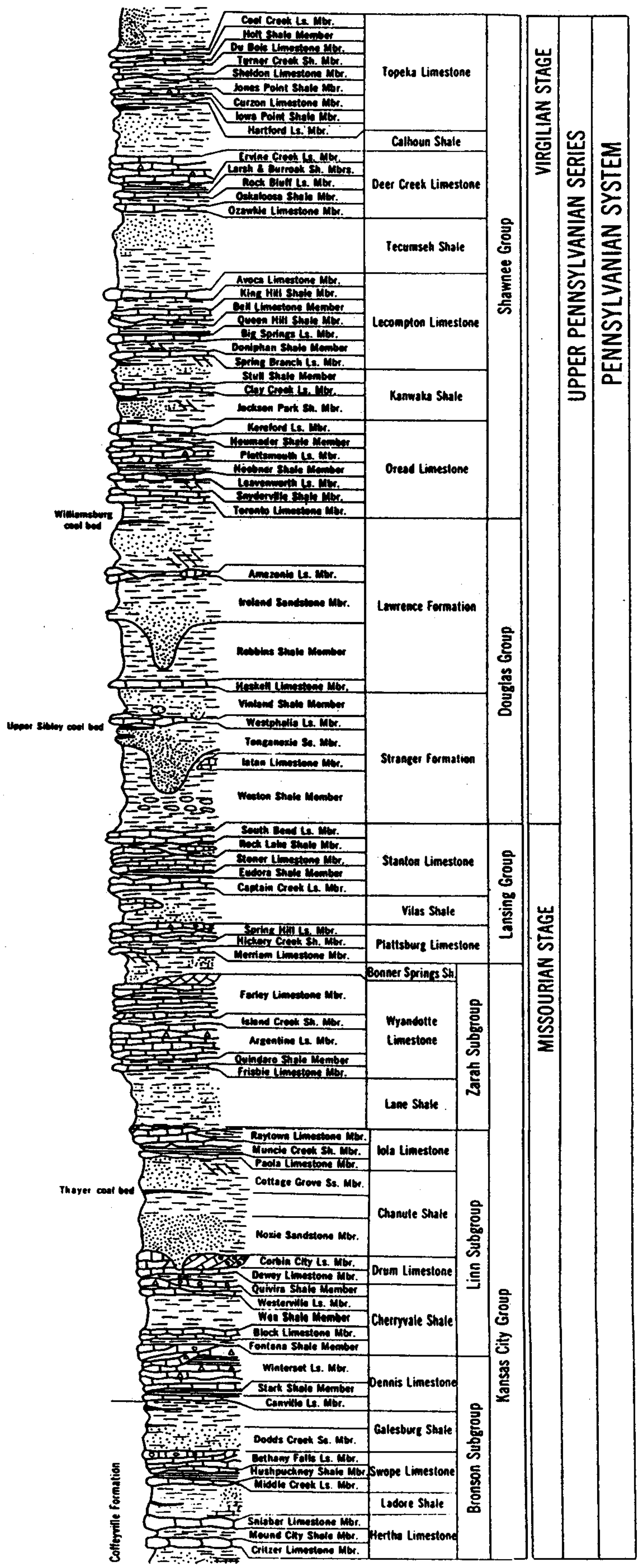

Figure 1

History

Attention to the Silver City Dome area was drawn in the late 1870's by reports that gold and silver was being mined in sections 29 and 32, Township 26S, Range 15E. For a short time a mining camp, named Silver City, existed at the site and several prospect pits, some as deep as 100 feet, were dug into the hillside. In a report to the Kansas Academy of Science, Professor B.F. Mudge (1881) gave an early account of the metamorphic deposit in Woodson County. He recognized the lamproite, but thought it to be a sedimentary rock that was moderately metamorphosed due to the action of warm mineral salacious water, probably under pressure. He described that the clay shales (lamproites?) assumed a more granular appearance and were interspersed with small flakes of mica (phlogopite?). In several places over thirty feet of the material was present. The sandstone in close proximity to the clay shale was altered to a quartzite.

Mudge sampled some of the material and had it analyzed for its precious metal content. No silver or any other metal was found making him believe that the samples, that presumably contained silver, might have been salted, or that the whole story was a fabrication. Professor Mudge was accompanied in his visit to the area in 1879 by Professor Robert Hay who published a subsequent paper on the igneous rocks of Kansas (Hay, 1883). Among other observations made elsewhere in Kansas, he discussed the rocks at Silver City. Hay recognized both metamorphic and igneous rocks. In some of the earlier exploration trenches a dark-blue rock was exposed, which he believed to be of igneous origin and to have been pushed up from below in cracks and fissures. He also recognized the weathered lamproite which he referred to as micaceous dirt, perhaps being altered shale.

Twenhofel (1917) described the elliptical shape of the dome and referred to it as the Silver City anticline. Drillers looking for oil in the anticline complained that they encountered rocks which did not look familiar to them but they did not think they were igneous in character. In his paper, Twenhofel (1917) describes the metamorphic effects on the surrounding sediments. He believed that hydrothermal processes were the cause of the alteration of the sediments especially the development of hornblende, chlorite and epidote. Twenhofel (1917) considered, but rejected, a possible connection between the granite boulders occurring at the surface near Rose, about 6 miles to the northeast and igneous activity in the area. The idea that the granite was evidence of intrusive-extrusive activity was dismissed because three wells drilled near Rose encountered no altered strata or igneous rock.

The igneous nature of the dark-blue rock was confirmed by Weidman (1933) who briefly described the mineralogy of material recovered from near an old silver exploration pit. Shaffner (1938), in a short publication, suggested that both Silver City Dome and Rose Dome were affected by the same or certainly similar magmatic and hydrothermal processes.

Granite was discovered in 1915 at Rose Dome near the town of Rose by Twenhofel (1926). The granite, which is coarse-grained and occurs as rounded boulders up to several feet in diameter lies scattered over the area. Initially, the theory was favored that glaciation transported the rock to he site or that they came from an outcrop in the neighborhood. During drilling for oil in 1923, and in the course of road construction, more and more granite and metamorphic minerals were encountered. From these observations Twenhofel (1926) concluded that the granite had to be intrusive. He also drew a parallel between hydrothermal processes at Silver City Dome and Rose Dome. Small granite xenoliths, up to a few centimeters in diameter, were also found by Berendsen in a core of lamproite taken in 1984 from a depth of 920 feet at the northwestern end of the Silver City Dome.

In the publication on the geology of the Fredonia Quadrangle, Wagner (1954) described the Silver City lamproite in considerable detail. By that time more drill hole information had become available and he was able to correctly interpret the lamproite as occurring in sills within the Pennsylvanian strata (Figure 2). He believed that the lamproite penetrated along a NW-SE-trending fault

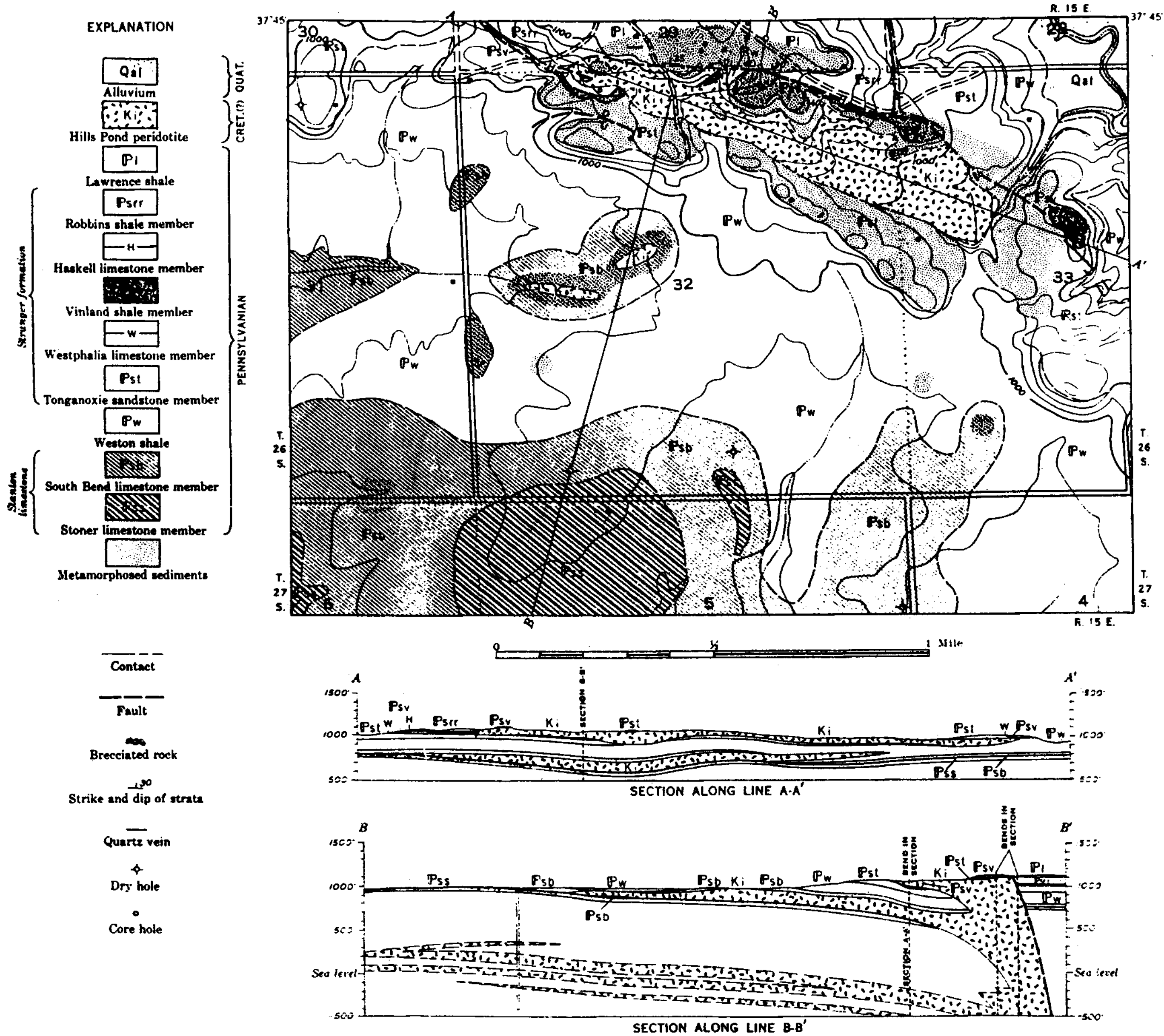

Figure 2

The geology in the northeastern part of the Silver City dome as interpreted by Wagner (1954) is shown. The cross-sections depict the intrusion of lamproite along the NW-trending fault (located immediately north of the Micro-Lite mine pit), and the injection of the rock as sills within the Pennsylvanian sediments. Few drill holes penetrated the lamproite at that time. Wagner noted that the occurrence of it at several horizons and the wide variation in thickness made correlations between individual sills extremely difficult.

at the northern perimeter of the dome and spread laterally in a southerly direction in between the sediments.

It was soon realized that similar igneous rock occurred at Rose Dome and that the granite blocks were brought up as rafts within the mafic rock, which was referred to as mica-peridotite at the time.

Since the publication of Wagner (1954) and a paper by Snyder and Gerdemann (1965), in which they drew attention to the occurrence of similar igneous activity along a 400-mile eastward-trending zone starting at Silver City and Rose Domes, a number of excellent studies dealing with the various geological aspects of these occurrences have been published. Several of these have been reproduced and are included as part of this guidebook. These papers contain additional references of interest.

The petrographic character of the granite xenoliths at Rose Dome was described by Franks and others (1971), and the results of a study of the growth of mg-rich hollow sanidine in the granite by the interaction with the lamproite magma was discussed by Smith and Franks (1986) (both papers included in this guidebook).

Rb–Sr whole rock isotopic analysis by Bickford and others (1971) (included in guidebook) showed the granite to be 1190 ±100 m.y. In a more recent paper addressing the geochronology and distribution of Precambrian basement rocks in Kansas and Missouri, Bickford and others (1981) calculated a more reliable age of 1400 ±21 m.y. by analyzing zircons from the granite. This age falls within the range of ages for basement rocks in southern Kansas. K-Ar ages on three samples of phlogopite from the lamproite yielded an age of 88-91 ±5 m.y. (Zartman and others, 1967). A Rb-Sr age of K-feldspar from granite from Rose Dome was reported by Muehlberger and others (1966) as 1220 ±70 m.y.

The chemistry, petrography, and field relations of the Hills Pond peridotite (Silver City Dome) was described by Merrill and others (1977). Using core material, the geochemistry and petrogenesis of the Rose Dome and Silver City Dome was discussed by Cullers and others (1985) (included in guidebook), who then refer to the rock as a lamproite after terminology used by Mitchell (1985).

ROAD LOG

Cummulative Miles	Stop Distance	Activity
0.0	0.0	Assemble at Lawrence, Holidome at 7:30 am. Turn left (south) on Turnpike Access Road. Head south on US Highway 59.
14.0	14.0	Junction with US Highway 56
24.0	10.0	Overpass (Santa Fe Railway). Entering **Ottawa, Kansas.**
34.7	10.7	Entering **Princeton, Kansas**
36.0	1.3	Quarries in the South Bend and Stoner Limestone Members of the Stanton Limestone (Lansing Group).
41.0	5.0	Entering **Richmond, Kansas**
46.0	5.0	Crossing **Pottawatomie Creek**
47.0	1.0	Abandoned quarry of the Garnet Rock Company. Plattsburg Limestone of the Lansing Group.
48.0	1.0	Entering **Garnet, Kansas**
52.0	4.0	Junction with US Highway 169
56.0	4.0	Junction with US Highway 59. Field trip continues south on US 169.
58.0	2.0	Entering **Welda, Kansas**
67.0	9.0	Entering **Colony, Kansas**
67.5	0.5	Tertiary river gravels exposed on hilltop left (south) of road.
69.0	1.5	Junction with Kansas Highway 57
74.0	5.0	Birthplace of General Frederick Funston.
78.0	4.0	Entering **Iola, Kansas**
79.0	1.0	Turn right (west) on US Highway 54

80.0	1.0	Crossing **Neosho River**
86.0	6.0	Entering **Piqua, Kansas** (pronounced Pick-way)
96.0	10.0	Overpass on Union Pacific Railroad
98.0	2.0	Entering **Yates Center, Kansas.** Turn left (south) on US Highway 75.
103.0	5.0	**View** north rim of **Rose Dome.**
105.2	2.2	**STOP 1...Rose road.** Turn off US 75 to the left (east). Proceed a few hundred feet on county road. **Vista** of the north rim of Rose Dome.
105.8	0.6	Continue on county road to intersection, turn back right (south). Cross **"moat"**, and rise gently to center of dome.
106.3	0.5	**STOP 2...Rose Dome granite outcrops.** Cross US 75...**BE CAREFUL!!** Granite is hidden in small clumps of trees. Near highest point of the central uplift of Rose Dome.
106.8	0.5	Return to US 75, turn right (west). View to southwest is of connecting valley between the Rose and Silver City Domes.
107.8	1.0	Turn left (south)
108.7	0.9	Passing middle linear ridge
109.9	1.2	**STOP 3...**Brief stop as we descend into the connecting valley between the two domes.
110.5	0.6	Turn right (west)
111.4	0.9	Turn left (south). View east rim to the right.
112.4	1.0	Turn right (west). Begin climbing east rim of the Silver City Dome.
113.5	1.1	**STOP 4...Silver City Vista.** Climb hillside above Ecco Ranch extension of the Silver City oil field.
115.6	2.1	Continue on county road along Wilson-

		Woodson County line. Turn left (south) at Little Sandy Cemetery.
115.9	0.3	**STOP 5...LUNCH** at abandoned quarry.
116.6	0.7	Turn left (east)
116.9	0.3	**STOP 6...Silver City** view of dome from south.
118.3	1.4	Turn left (north)
119.6	1.3	Descend into dome. Pass Ecco Ranch headquarters. Turn left (west), continue along county line road.
120.1	0.5	Turn right (north)
120.9	0.8	**STOP 7...Silver City Lamproite** exposed at the Micro-Lite mine site.
121.7	0.8	Return south along mine access road. Turn right (west).
123.2	1.5	Turn right (north)
123.9	0.7	Climb north rim, pass northwest oil wells.
124.3	0.4	Turn left (west)
124.9	0.6	Turn right (north)
125.5	0.6	Turn right (east)
126.2	0.7	Outcrops of massive sandstone north of road.
127.3	1.1	Turn left (north). Pass Silver City oil field.
130.9	3.6	Turn left (north)
132.3	1.4	Turn right (east). Return to US 75.
133.5	1.2	US Highway 75. Turn left (north). Return to Yates Center, Kansas.

END OF ROAD LOG

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STRUCTURES ASSOCIATED WITH THE ROSE AND SILVER CITY DOMES, WILSON AND WOODSON COUNTIES, KANSAS

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Kansas Geological Survey

Introduction

It is difficult, if not impossible, to determine the overall structure of the Rose and Silver City Domes directly from outcrop data. Small mounds of granite boulders comprise the only outcrops at Rose Dome. Although the outcrops at Silver City are laterally extensive, only recently has an active mining program exposed the lamproite body for direct study.

The general structure of the region may be deduced by combining information from direct observation (oil drilling, mining) with data obtained by indirect means (gravity and magnetics, seismic, terrain analysis). The results of the seismic studies are reported elsewhere in this guidebook. This section will deal with data obtained by recent oil drilling, mining, and interpretation aerial photography.

Recent Oil Drilling

Oil exploration in the area dates from the early 1920's. The Shiltz #1 Lauber, SE NW SW NE, section 23, T 26S, R 14E (2-2-26),was the discovery well of the Big Sandy oil field, located northwest of the Silver City Dome. Development of the Silver City oil field occurred following the successful completion of the Bisagno Campbell #1, SE SE SE, section 19, T 26S, R 15E on December 13, 1946. Both of these oil fields produce from Pennsylvanian distributary channel sands known locally as the "Bartlesville".

Production within these oil fields follows NW (Silver City) and NE (Big Sandy) linear trends. These trends are parallel to the dominant structural orientations in Kansas (Berendsen and Blair, 1986). Although these fields are stratigraphic traps, the location of the Pennsylvanian channels may have been influenced by pre-existing structures.

The Silver City oil field formerly terminated near the northeast rim of the dome. However, recent drilling in the early 1980's extended the "Bartlesville" production southeastward along the east flank of the dome.

Geophysical logs were obtained for most of the wells, but individual lamproite sills can not be identified. If a full suite of geophysical logs were evaluated, the sills may indeed be interpretable. Driller's logs obtained from these wells indicate that lamproite sills do occur along the eastern flank of the dome. A condensed version of the geologist's log from the Ecco Ranch well (SE SE SW, section 33, T 26S, R 15E; stop 4) is reproduced in figure 1. This well produces from the "Bartlesville" sand at 1176 feet (-193 MSL). The well encountered at least 6 lamproite sills from 374 feet to 755 feet, which range in thickness from 10 to 30 feet. Recently completed seismic work shows the internal structure of the dome to be complex, and correlation with any of the sills traced from the outcrop area into the subsurface is difficult.

Exploration efforts have also been concentrated along the northwest rim of the dome. Production here may be associated with a northeast) trending channel parallel to the Big Sandy field. In one instance, oil is produced at or near the contact between a lamproite sill and the Pennsylvanian sandstones.

Drilling has revealed that lamproite sills occur to a depth of at least 1300 feet around the perimeter of the Silver City Dome. Seismic studies indicate that an intrusive body of lamproite may exist within the center of the dome, as well (Markezich, Knapp, and Wojcik, this guidebook). All available evidence from drilling indicates that the lamproites are confined to the interior of the Silver City Dome. Dikes and sills have penetrated the sediments in a number of places within the dome.

Terrain and Lineament Analysis

The Rose and Silver City Domes are ellipsoidal depressions surrounded by low, hummocky hills. These hills are bounded on the southeast by Buffalo Creek, and to the southwest by the Verdigris River floodplain. The hummocky terrain extends approximately 10 miles north of the confluence of these two streams. This landscape is quite different from the plains to the east, north, and south of the domes, and is readily apparent to the traveller approaching the area on US Highway 75. Higher hills and woodlands adjoin the domes to the west. This hummocky terrain may be the result of a broad, regional doming of the area surrounding the intrusions.

Both domal depressions display almost crater-like morphologies with each central area surrounded by a "moat" having almost complete internal drainage. We believe the location of these "moats" are structurally controlled by the ring fractures circling the central uplifts. In the southeastern part of the Silver City Dome a discreet circular feature, approximately 0.5 mile in diameter, is apparent on topographic maps and on aerial photography. One may speculate, whether this feature represents a distinct and separate pulse of lamproite intrusive activity. Both domes

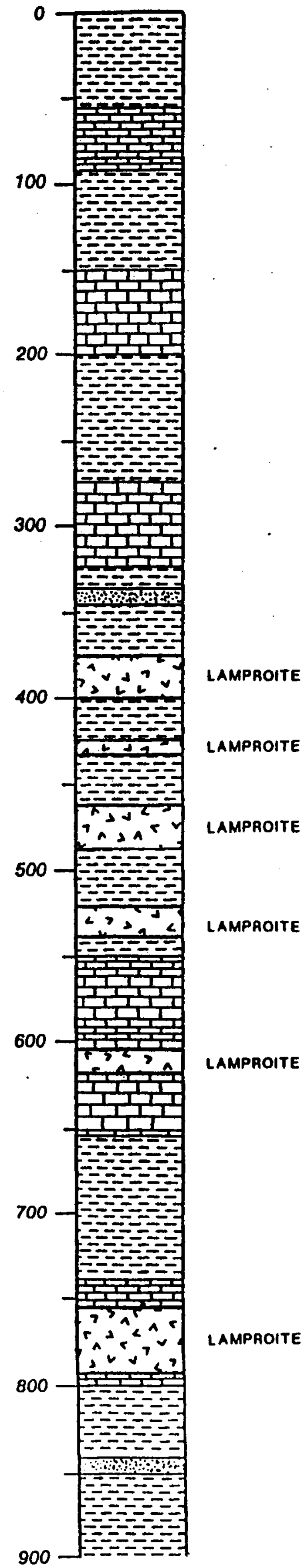
STRIP LOG

1 ECCO RANCH

SE SE SW

SECTION 33/ T26S-R15E

WOODSON COUNTY, KANSAS



NO SILLS BETWEEN 900 FEET AND TD

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are breached by major streams. The Silver City Dome is breached on the southwest flank by Little Sandy Creek. The location of the creek is probably controlled structurally. Rose Dome is breached on the southwest flank by an unnamed tributary of West Buffalo Creek.

Many lineaments are discernable from infrared and black and white aerial photography. Some of the more prominent linear trends are shown in figure 2. These lineaments may either be joints, or the surface manifestations of faults associated with the domes. Except for the faulting recognized by Wagner (1954), no other faults have been mapped.

Radial lineaments are prominent around the perimeters of the central uplifts at Rose Dome. No such pattern is seen within the Silver City Dome.

From a cursory examination of the aerial photography, it is tempting to suggest that the two domes are structurally interconnected. A connecting valley continues southwest from Rose Dome, and is flanked on the north by three separate, linear ridges. The southern boundary of this valley is less discrete. The linear ridges may be fault-bounded horsts. The valley is probably also fault-bounded on the southern side.

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GRAVITY AND MAGNETIC OBSERVATIONS AT SILVER CITY AND ROSE DOMES

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Extensive gravity and aeromagnetic data have been gathered over all of Kansas. In Woodson and Wilson counties the gravity data are sampled at each road intersection that has elevation control, ostensibly at one-mile centers. The aeromagnetic data has been flown on east-west flight lines spaced at one-half mile. Sampling within the flightlines is twelve to fourteen points per mile. Flight elevation is 1500 feet, and ground elevation is about 1000 feet, average.

Maps of the data were perused to see the effects of the domes. Various filters were applied to attempt to isolate the sedimentary section, the upper crust, and the lower crust. These attempts failed. There is no obvious affect of the crustal section that correlates with the domes. That is, the crust and upper mantle beneath the domes are not unusual material compared to the rest of the crust and mantle.

It is not until the data are examined on a broader scope that features become apparent. Looking at the gravity data of the southeastern corner of Kansas, high passed filtered at a five mile wavelength to emphasize the upper crust, a ring feature centered on Neosho County becomes apparent (Figure 1). Silver City and Rose domes are in the northwestern edge of this feature and, thus, appear to be small components of a larger system. Note that the northwest-southeast grain, evident in Crawford County, truncates at this feature. The Falls River lineament forms the western edge of the feature, and the trend from Silver City to Rose forms the northwestern edge.

Magnetic data (Figure 2) show the same feature, although not to the same detail. On the magnetic map it is the southwest-northeast grain that most evidently truncates at the feature.

There is little known of the feature, and, therefore, little to say beyond speculation. Its boundaries are related to the location of the Silver City and Rose domes and, to some extent, known lineaments, suggesting that these boundaries are regions of crustal weakness.

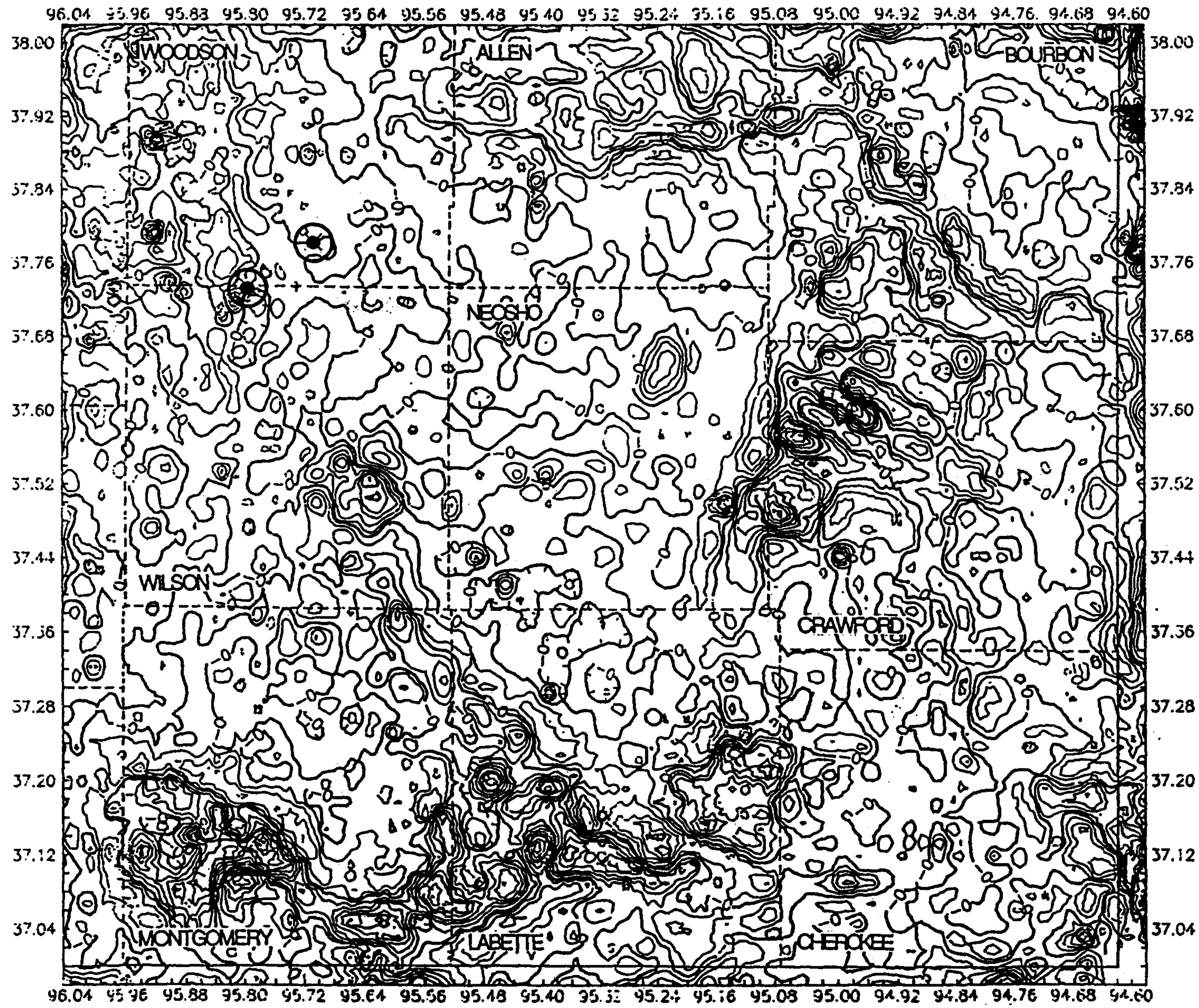

Figure 1 Gravity map of southeastern Kansas. Residual of the average from 5 mile by 5 mile area. The map focuses on features of the upper crust. Silver City (southwestern most circle) and Rose (northwestern most circle) domes are positioned in the northwest corner of the map.

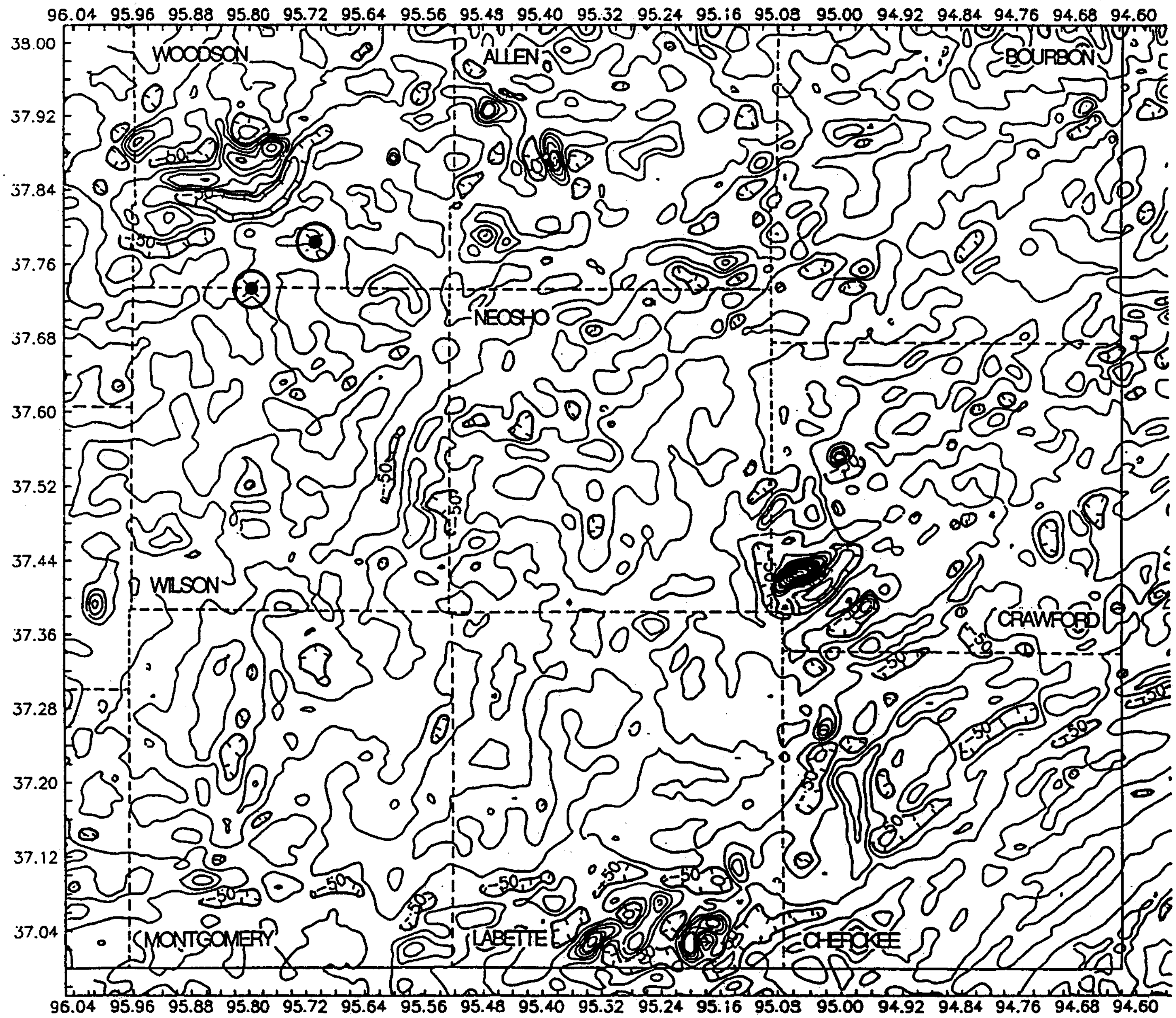

Figure 2 Aeromagnetic map of southeastern Kansas. Residual of the average from 6 mile by 6 mile area. The map focuses on features of the upper crust. Silver City (southwestern most circle) and Rose (northwestern most circle) domes are positioned in the northwest corner of the map.

THE USE OF SEISMIC REFLECTION DATA IN LOCATING LAMPROITE SILLS AT SILVER CITY DOME

Mary Anne Markezich, Ralph W. Knapp and Krzysztof M. Wojcik
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GEOLOGICAL BACKGROUND

Silver City Dome, located in southeastern Kansas, is believed to have formed by the intrusion of the Hills Pond Lamproite into Pennsylvanian sedimentary rocks. Lamproites are mafic to ultramafic alkaline igneous rocks which have higher K/Na and K/Al ratios than other igneous rock types. Petrographically, they are very diverse, but they can be characterized by the major and accessory mineral content, alteration products, mineral chemistry, and mineral paragenesis. Lamproites have been noted in 20 localities on 6 continents (Figure 1). Prior to the late 1970's, kimberlites were the only igneous rocks to be associated with diamonds. Since that time, some lamproites have been found to contain diamonds. A kimberlite in Arkansas has been reclassified as a lamproite, and other diamond-bearing lamproites have been found in western Australia. These discoveries have increased the importance of lamproites in terms of economics and petrogenesis (Bergman, 1984).

The Hills Pond Lamproite is believed to have been emplaced non-violently as a primarily liquid intrusion. One piece of evidence for this type of intrusion is its presence as thin sills. Crystallization of the magma formed a porphyritic mica peridotite with a groundmass consisting of phlogopite and serpentine. Phenocrysts include serpentinized olivine, augite, richterite, and phlogopite. Accessory minerals include apatite, perovskite, and chrome spinel. The age of the body was dated by K-Ar dating to be 90 my old which is Late Cretaceous (Merrill, et al., 1977).

Rose Dome is a structure which is located about 9 km to the northeast of Silver City Dome and was also formed about 90 my ago by the intrusion of lamproite magma into Pennsylvanian rocks. The uprising magma contained xenoliths of Precambrian granite which were dated to have been formed 1400 million years ago (Bickford, et al., 1981). Some partial melting of the granite occurred. The intrusions at Rose and Silver City Domes appear to be genetically related. Petrographic evidence indicates a liquid emplacement of the magma in both cases. In addition, both intrusions have the same mineral content (Franks, et al., 1971).

Snyder and Gerdemann (1965) believe that Rose and Silver City Domes are the westward extension of a 400-mile-long-east-west lineament called the 38th parallel lineament of Heyl (Figure 2). The lineament consists of a large number of alkalic bodies which penetrate the stable platform as stocks, plugs, sills, dikes, and diatremes. They range in composition from nepheline syenite to alkalic peridotite and range in age from Late Ordovician to Late Cretaceous. These structural features extend across Missouri into Illinois and are shown here on the map (Figure 2). The Decaturville Disturbance has since been named an impact structure. It is circular in shape with an intensely brecciated core and a central zone consisting of many shatter cones.

Silver City Dome is elliptical in shape and covers an area of approximately 21 square kilometers. Figure 3 shows a generalized version of Holly Wagner's geologic map of the northeastern corner of Silver City Dome . The Pennsylvanian age Stanton Formation, Weston Shale, and Stranger Formation outcrop in this area. Lamproite is also exposed. The fault at the north edge of the lamproite is described by Wagner as being steeply dipping to the north. Magma is thought to have risen along this fault with the peridotite sills injected to the south into the Pennsylvanian sequence (Wagner, 1954). This is shown by the cross-section (Figure 4). A 9-meter-thick sill at approximately 230 meters depth has been reported from a drill hole which is located along the line of the cross-section (Franks, 1959).

A 300-meter-wide contact metamorphic aureole is noted around the outcrop of the lamproite on the north flank of the dome as shown by the lined pattern on the map (Figure 3). The Tonganoxie Sandstone Member of the Stranger Formation and the Ireland Sandstone Member of the Lawrence Formation are metamorphosed into quartzites (Franks, 1966).

GEOPHYSICAL DATA

In 1985, seismic reflection data were collected at the dome in the areas shown by Figure 5. The numbers are the common midpoints (CMPs). The purpose of that study was to use reflection seismology to determine the structure of the dome and to attempt to detect the sills. MiniSOSIE earth compactors were used as the source, and the final section is shown in Figure 6. There is interpreted to be two scales of doming. The first is a broad gentle dome over the whole structure. The second is a smaller-scale dome which is superimposed on the broad dome. Associated with the small-scale dome is a depression. The northern and southern edges of the dome are bounded by grabens. Intrusion of a deep-seated magma body caused the gentle doming and subsequent faulting of the marginal grabens. Later, magma was removed from beneath the area showing the depression and formed the smaller-scale dome. A collapsed zone was interpreted to be a potential feeder for magma emplacement. If this is true, then the feeder is farther south than originally described by Wagner (1954). On Figure 5, the northern graben is located between CMP's 300 and 340 while the southern graben is located between CMP's 675 and 760. The collapsed zone is located between CMP's 400 and 480. The elliptical shape of the dome is outlined by the faults which are shown by the dashed lines. Rose and Silver City Domes appear to be aligned along a series of faults which trend in a northeast-southwest direction (Wojcik, et al., 1986).

This study introduced new ideas on the dome's formation. In addition, it helped to improve the understanding of the structure. It was also concluded that higher resolution data were needed to find the location of the sills.

In 1986 and 1987, additional seismic data were collected at the dome between CMP's 365 and 489. The purpose of the study was to try to resolve the events within the collapsed zone. Dynamite was used as the source. Dynamite imparts higher energy and gives higher frequency signals than the miniSOSIE earth compactors, and thus better resolution was achieved. The dynamite was placed in holes which were 3-4 feet deep and were roughly spaced 55 feet apart. The geometry of the line was end-on with a linear array of 30-Hz geophone groups spaced 55 feet apart. There were 10 equally-spaced geophones per group. The data were recorded by the Kansas Geological Survey on an I/O DHR 2400 24-channel recording system.

Magnetic data were also collected in the northeastern portion of the dome. A proton-precession magnetometer was used to collect the data. There were six north-south trending lines, one of which was located along the seismic line. Data were also collected along three east-west trending lines which intersected three of the the north-south lines. The data were collected at sample intervals of 7.5 and 15 meters. These data were drift-corrected and then were plotted as profiles.

PROCESSING

Data were processed on the Kansas Geological Survey's Data General MV 20 000 computer. Standard processing was applied to all data; however, the dynamite data had several special steps applied to it. First, refraction static corrections were applied. The purpose of static corrections is to make the data look as though it were recorded on a flat surface without the presence of weathering or low velocity near-surface materials. Refraction statics is a type of correction procedure which is based on the arrival times of refraction events, rather than the arrival of the reflectors themselves. An advantage of refraction statics is that first-arrival refraction signal is not contaminated by seismic noise. The disadvantage is that the correction is not directly tied to the reflection information. However, the refraction data contain information about the near surface layers so that accurate surface-consistent corrections can be calculated. For these data, refraction statics were successful and other methods were not because of seismic noise contamination.

The next step in the processing was the application of a velocity filter using the slant stack method. The velocity filter removed low velocity noise from the data, including ground roll and the air-coupled wave. Seismic noise from the nearby quarry was also attenuated.

The final section was analyzed using complex trace analysis, a processing technique which separates the seismic data into its components of instantaneous amplitude, frequency and phase. Used in conjunction with color plot displays, complex trace analysis enhances certain aspects of the results, including amplitude anomalies, continuity of reflectors, discontinuity of reflectors, and modulation due to changes in reflector thickness.

RESULTS

MiniSOSIE Data (1985)

Both the northern and southern ends of the seismic section (CMP's 230-300 and 610-680) represent a normal stratigraphic sequence of southeastern Kansas Paleozoic rocks. Correlation with the borehole data enabled the identification of several reflections which correspond to major stratigraphic horizons (Figure 6). Thickness of the normal stratigraphic section increases locally within the area of the dome due to the injection of lamproite magma. The dome itself displays a pronounced asymmetry. The maximum closure is located in the northern part of the structure (CMP's 330-400), where the doming affected mainly the Pennsylvanian sequence. The southern part has smaller closure that is not associated with any stratigraphic division (CMP's 470-500, 830-750). The northern and southern portions of the dome are separated by a distorted and collapsed zone that is bounded by several normal faults (CMP's 420-470). This relationship suggests that the feeder along which magma intruded was located at the center rather than at the northern margin of Silver City Dome as described previously (Wagner, 1954). The margins of the structure are dissected by normal faults that form graben-like ring fractures.

The lamproite sills themselves are difficult to recognize on the seismic sections. However, several high-amplitude low-frequency reflectors which trend obliquely to the stratigraphic horizons may correspond to lamproite bodies in the subsurface (Figure 6). Those reflectors are located in the northern part of the structure. This fact and the general asymmetry of the dome suggests a two-phase evolution of the Silver City Dome. Deep-seated magmatic processes caused gentle doming and instantaneous formation of the marginal ring-grabens. Subsequently, a centrally-located feeder was formed and liquid lamproite magma penetrated the Paleozoic sedimentary sequence. The injection of magma into the sedimentary section took place mostly to the north of the feeder, and consequently a steeper dome, superimposed on the pre-existing gentle structure, was formed. The fault that bounds the northern ring-graben from the south provided a conduit for the magma that formed the Hills Pond Lamproite.

Dynamite Data (1986 and 1987)

The final section for the dynamite data is shown as Figure 7. Figure 8 is an interpreted line drawing. The horizontal distance across the line is about one kilometer. There are three distinct areas on the section: the sill zone (shaded), the zone with continuous reflectors, and the chaotic zone (clear). The shaded zone is interpreted to be a zone of sills interlayered with the sedimentary rocks. This interpretation is based on its difference in character with respect to the zone of continuous reflectors. The zone of sills is bounded on the north by a system of fractures. The reflection events within the sill zone are stronger and of lower frequency than the reflectors to the north of the fractures (undisturbed section). The reflectors are also more discontinuous than in the undisturbed section. The zone containing sills penetrates to a greater depth than was described in earlier works; however, a driller's log from a well (ECCO Ranch, Inc. #2, drilled by White Pine Petro. Co.) located less than one mile away on the eastern edge of the dome notes lamproite in Mississippian rock at 360 meters depth and thus confirms the seismic data.

A massive zone is located beneath the disturbed zone containing sills. It is called massive by its seismic expression. It does not have any continuous reflectors within it compared to the events on either side of it. This zone is interpreted to contain shattered country rock

(Precambrian) mixed with igneous rock that came up from deep within the earth. This zone is the local source for the overlying sills.

The interpretation presented above is illustrated most clearly using complex trace analysis. The instantaneous amplitude plot (Figure 9) clearly shows the sills. Taner, et al. (1979) state that boundaries across which major lithologic changes occur often have high reflection strength. Such boundaries could be those existing between sedimentary rock and lamproite sills. Because the adjacent normal section does not show the amplitude anomalies, this interpretation is reasonable.

The instantaneous phase plot (Figure 10) emphasizes the continuity (or discontinuity) of reflection events. The reason is that all amplitude information is removed and thus strong and weak reflectors show up equally. The sills are not as distinguishable as they are on the instantaneous amplitude plot (Figure 9) because they are an amplitude phenomenon. Instead, the fractures within the zone of the sills are the obvious features as edges of areas of continuity. The chaotic (massive) zone is also evident as a region lacking continuity. With the use of complex trace analysis, boundaries of regions recognized on the standard seismic section were more clearly delineated.

Magnetic Data

The magnetic data profiles (Figure 11) were useful as support for the seismic data. On the magnetic profile line 4, which was located along the path of the seismic line, an anomalous zone is present in the region of the collapsed zone seen on the seismic data. The collapsed zone is located from CMP 380 to CMP 480. The rest of the magnetic profile is quiet by comparison to this zone. On the other profiles, the anomalous zone is present on six profiles and has a slight southwest-northeast trend.

The anomaly patterns could be due to a combination of two factors. The broadest anomalies occur to the north over the chaotic zone and the bounding fracture, suggesting that the presence of the anomalies is related to the amount of lamproite in the rocks. In addition, because the faulting is more complex in this region, the short wavelength anomalies show where lamproite has been faulted. The southern portion of the magnetic profiles levels off beyond the boundary of the chaotic zone where less faulting has occurred, and the lamproite is present only as sills.

CONCLUSIONS

Complex trace attributes clearly revealed details which were only hinted at on the standard seismic section and thus were useful in the interpretation. Their most useful application was in showing the boundaries of the massive zone and showing the fractures. Prior to the application of complex trace analysis, the application of data processing techniques such as refraction statics and slant stack successfully brought out the signal relative to the noise. The final result was a seismic section whose interpretation, along with the 1985 data, revises some of the previous ideas on the formation of Silver City Dome.

Wagner's interpretation of the formation of the Dome was that magma intruded up the stratigraphic section along a fault described only as dipping steeply to the north. It then penetrated laterally as sills into the Upper Pennsylvanian sedimentary rocks. The seismic data yield a different interpretation. Upward intrusion of a deep-seated magma body is believed to have caused gentle doming in the area and subsequent formation of the marginal grabens. A smaller-scale frequency of doming is located in the northern part of the dome as was shown on the 1985 data.

From the 1986 data, a massive zone was interpreted to be the feeder through which magma penetrated the overlying rock units. The massive zone is believed to consist of igneous rock and shattered country rock. This source is farther toward the center of the dome than the source proposed by Wagner (1954). The zone believed to contain sills is heavily fractured and is bounded on the north by a fracture zone which extends down to the massive zone.

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LAMPROITE LOCALITIES

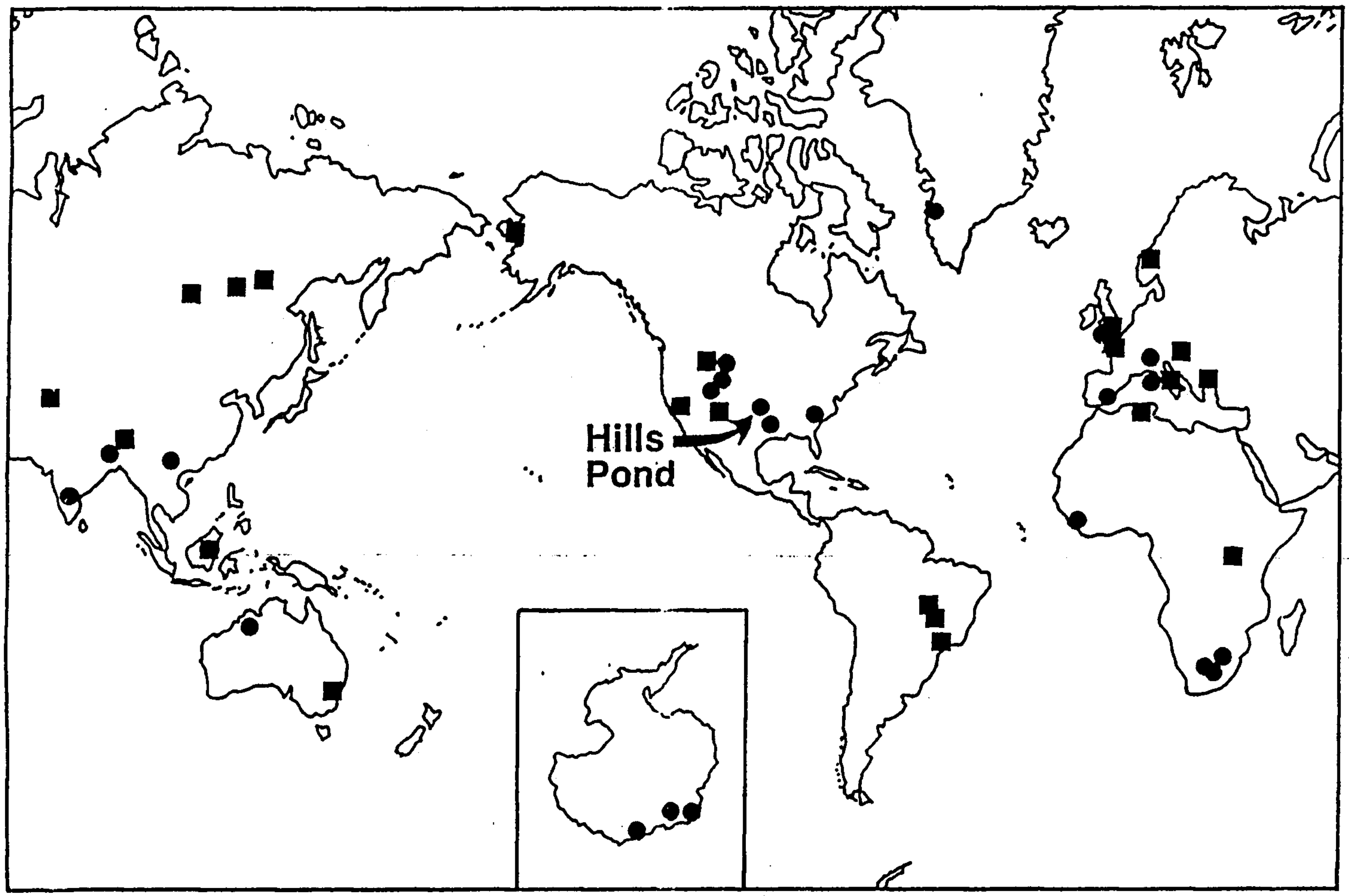


Fig.1. Lamproites have been found in 22 localities across the world. Circles represent lamproite localities while the squares represent locations of other potassic and ultra-potassic rocks. Diamond-bearing lamproites are found in Prairie Creek, Arkansas and at two locations in Western Australia.

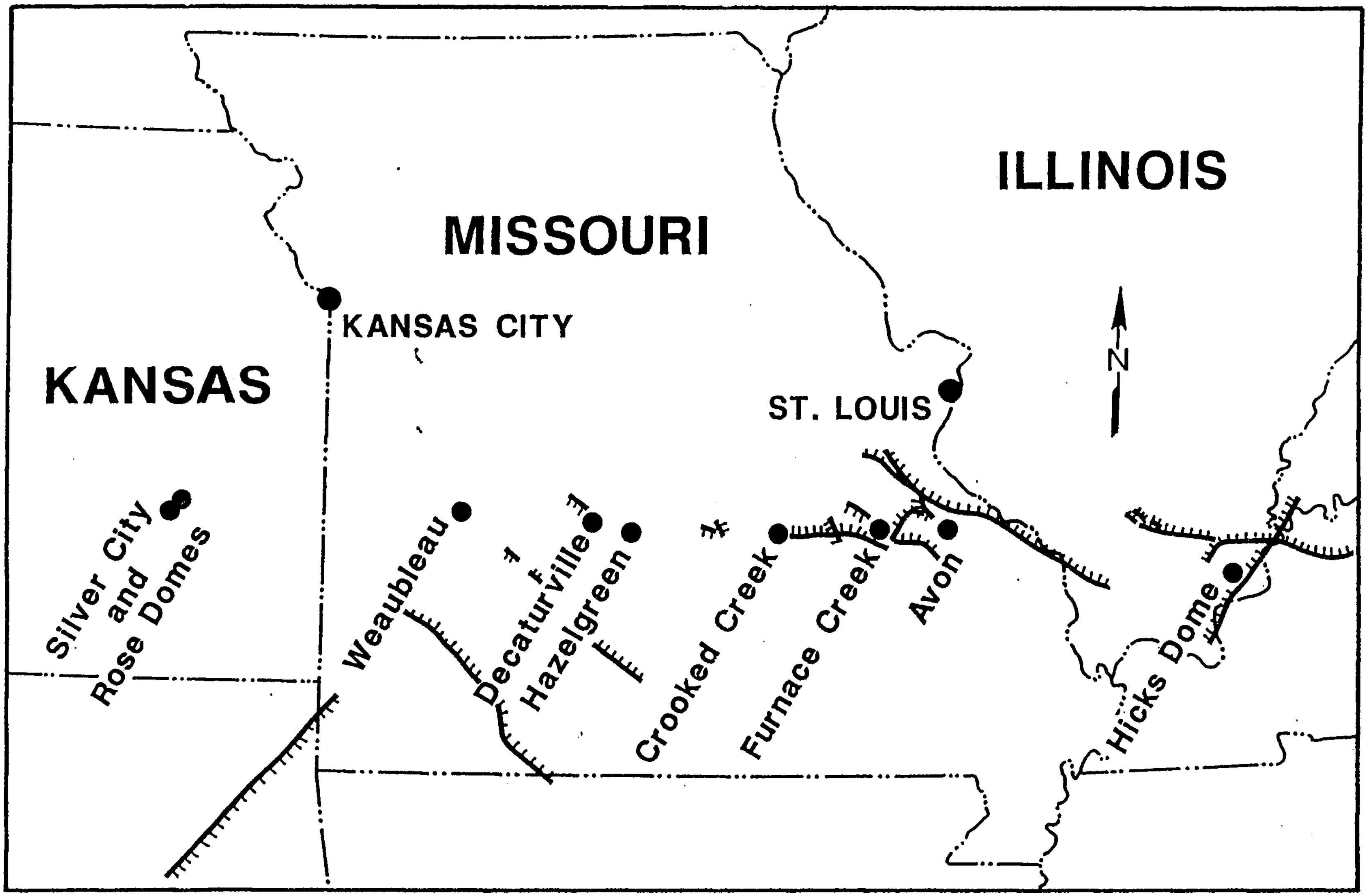


Fig.2. Circles show the nine structural features which form the 38th -parallel lineament of Heyl.

GEOLOGY OF NORTHERN SILVER CITY DOME

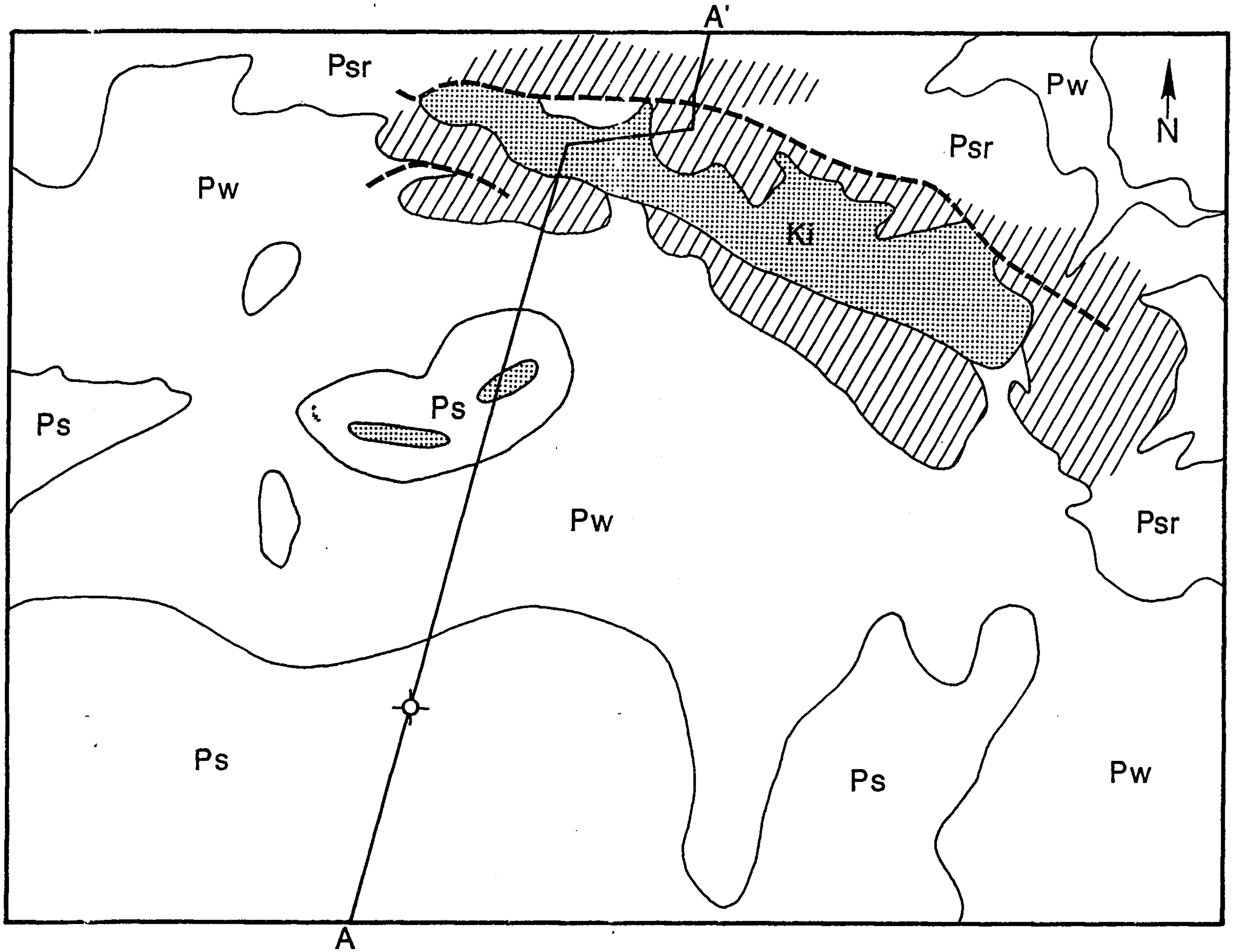


Fig.3. Generalized version of the geology of the northeastern corner of Silver City Dome (after Wagner, 1954). The stippled pattern shows the outcrop of the lamproite. The lined pattern shows the metamorphic aureole surrounding the intrusion. The heavy, dashed line is the steeply-dipping fault described by Wagner to be the pathway for the magma. Franks (1959) reports a nine-meter-thick sill at an approximate depth of 230 meters at the well located along the line of the cross-

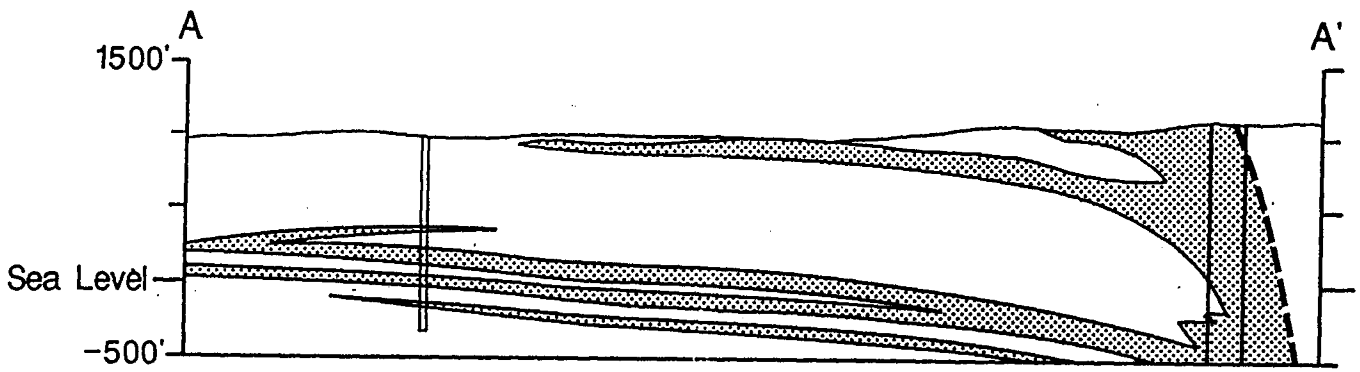


Fig.4. Generalized cross-section showing Wagner's interpretation of the formation of Silver City Dome. The heavy, dashed line is the steeply-dipping fault interpreted to be the conduit for the rising magma. The drill hole near the southern end of the section records sills at a depth of approximately 230 meters (765 feet). The two, solid, vertical lines at the north end are bends in the line of section.

SILVER CITY DOME

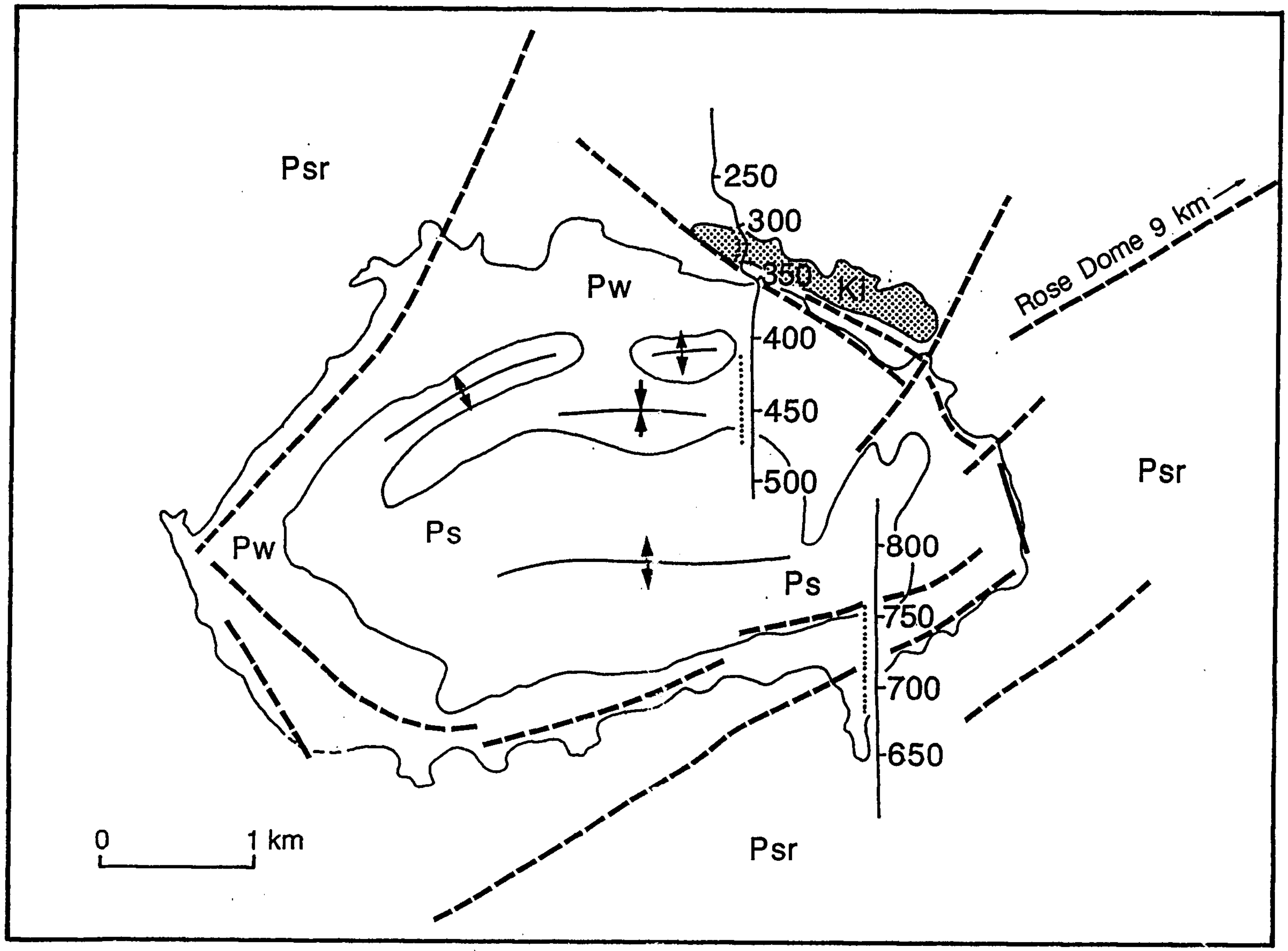


Fig.5. Generalized geological sketch of the Silver City Dome (after Wagner, 1954). Bold lines are seismic sections; parallel to them dotted lines are important structural elements of the dome recognized on the seismic section. Dashed lines are lineaments interpreted from the aerial infrared image.

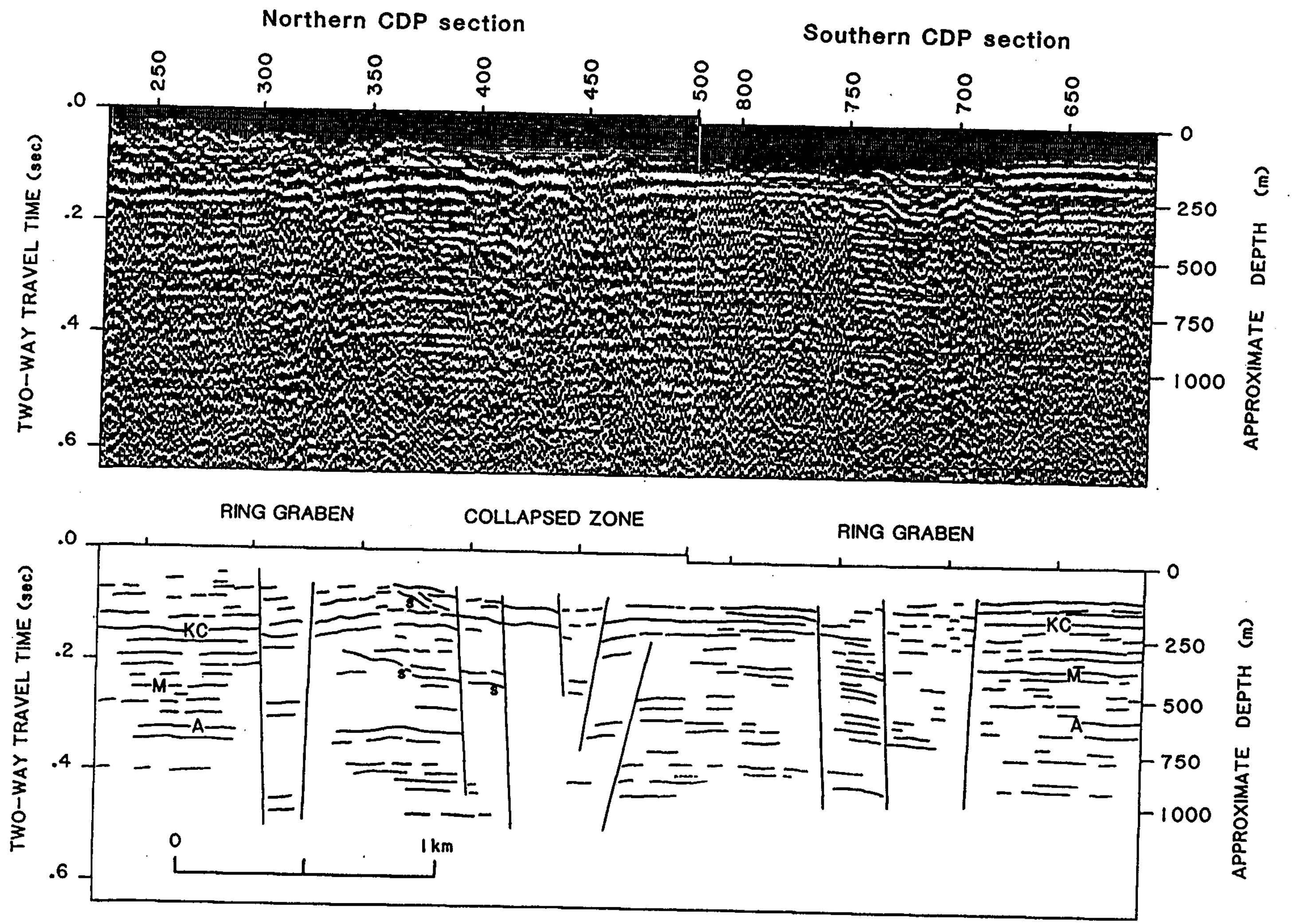


Fig.6. Seismic reflection profiles and interpretative line drawings. **A** -- top of the Arbuckle Group, **M** -- top of the Mississippian limestones, **KC** -- base of the Kansas City Group, **s**-- possible location of lamproite sills.

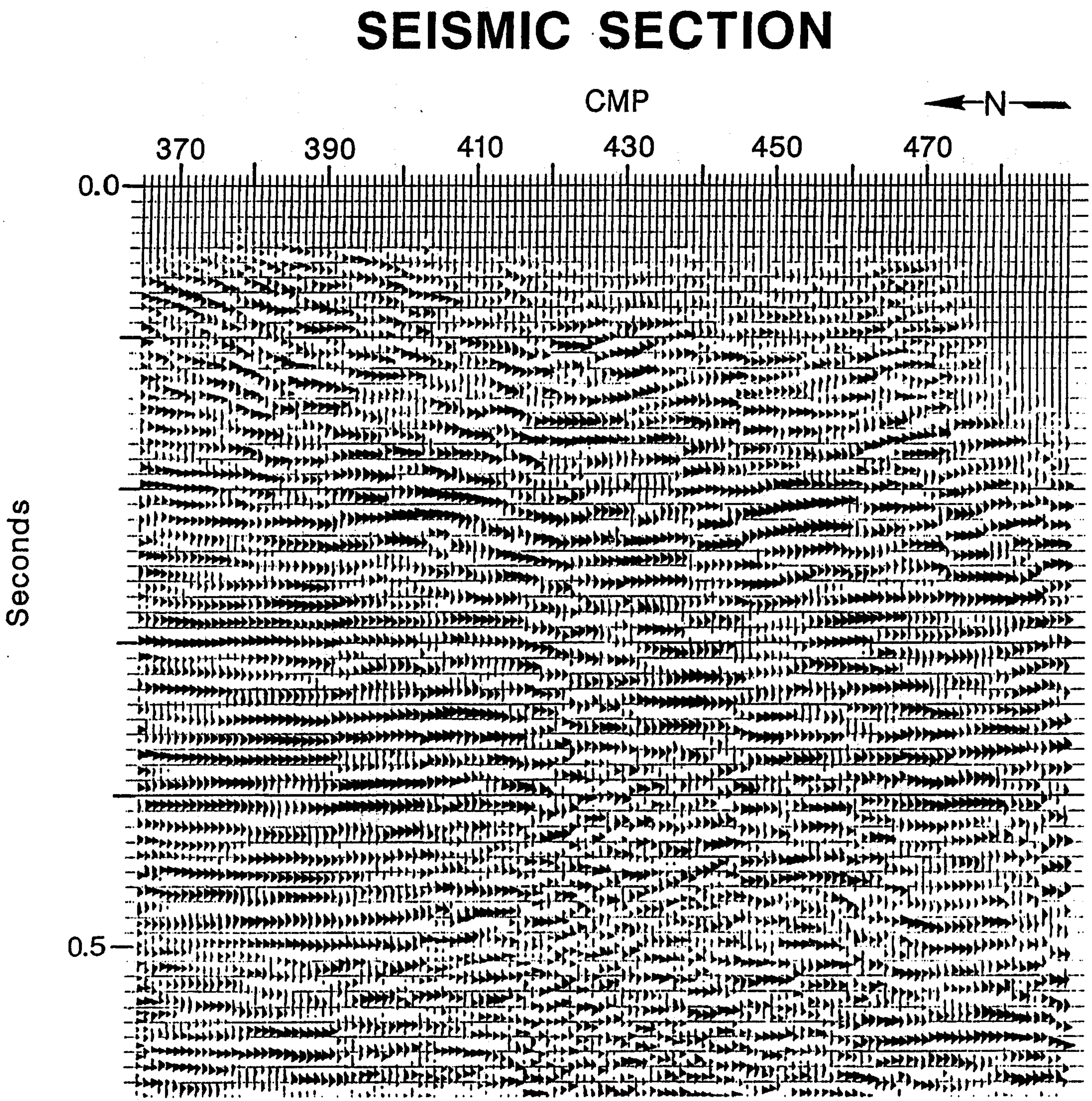


Fig.7. Seismic reflection profile for the dynamite data. Horizontal distance across the line is approximately one kilometer.

INTERPRETED SECTION

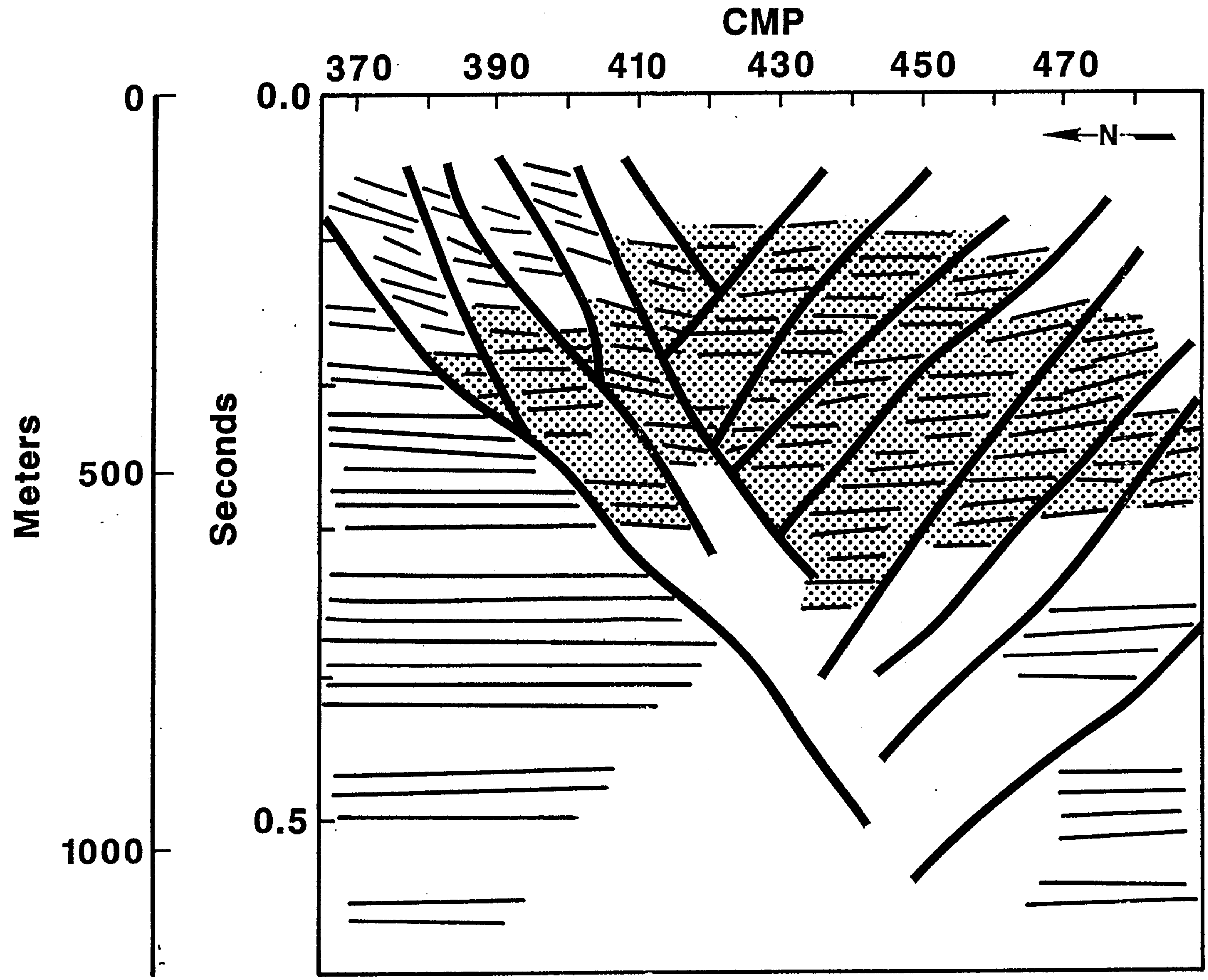


Fig.8. Interpretative line drawing for the seismic profile shown in Fig.7. The shaded region is the zone of sills. Continuous lines indicate the region of continuous reflectors. The clear region is the massive zone. The top of the Mississippian is at approximately 220 ms. The top of the Arbuckle is at approximately 300 ms. The basement is located at approximately 380 ms.

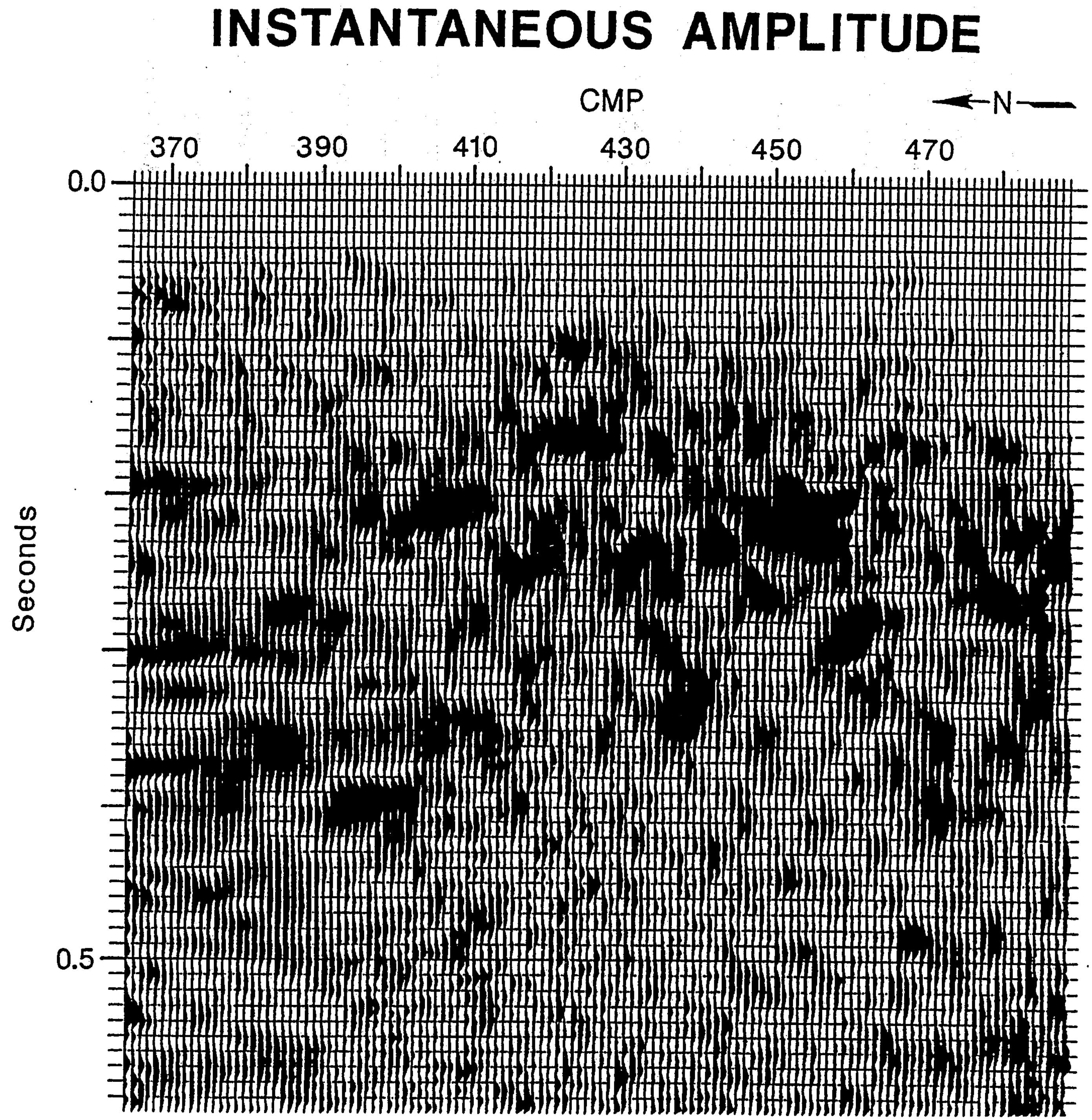
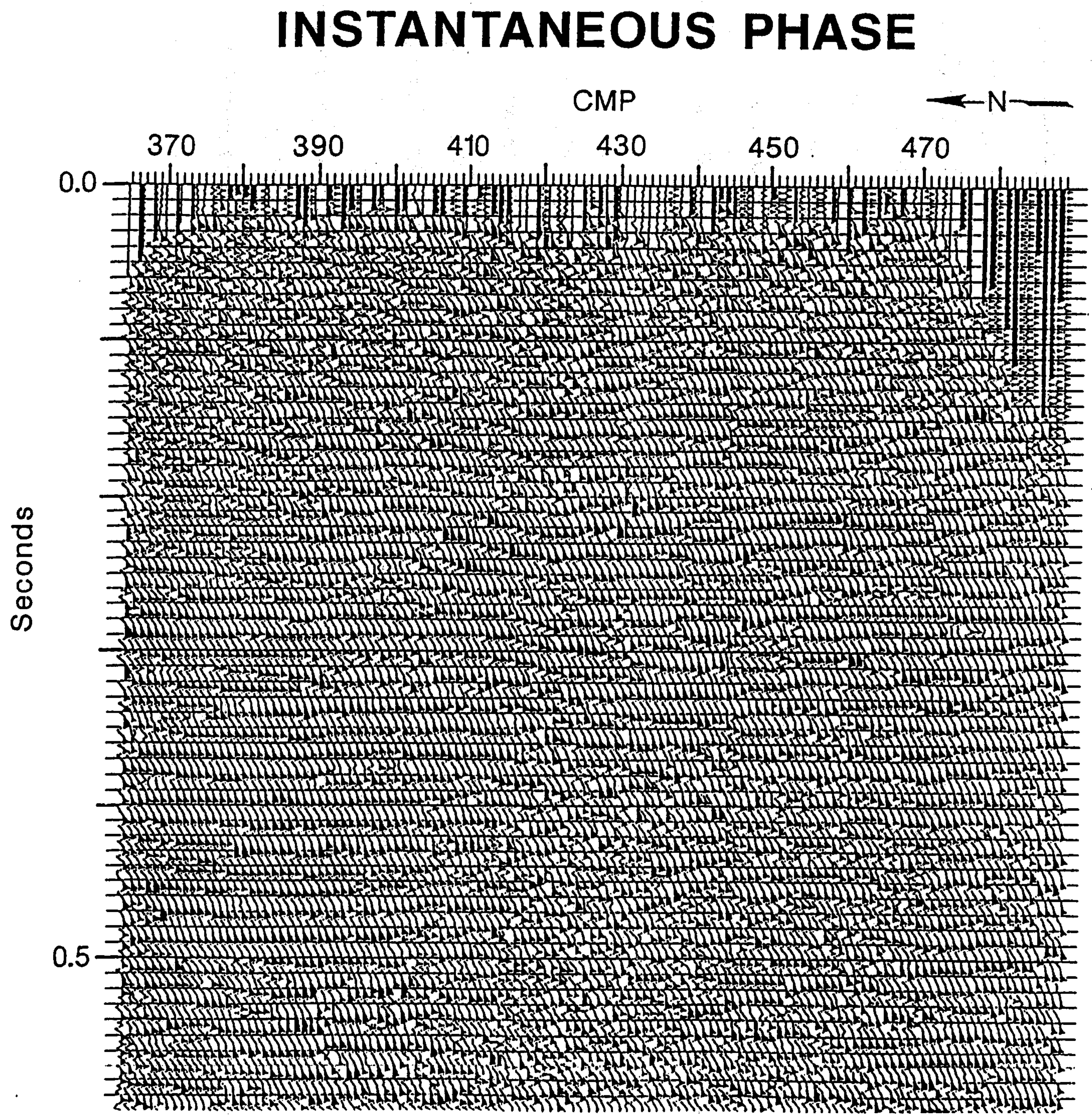
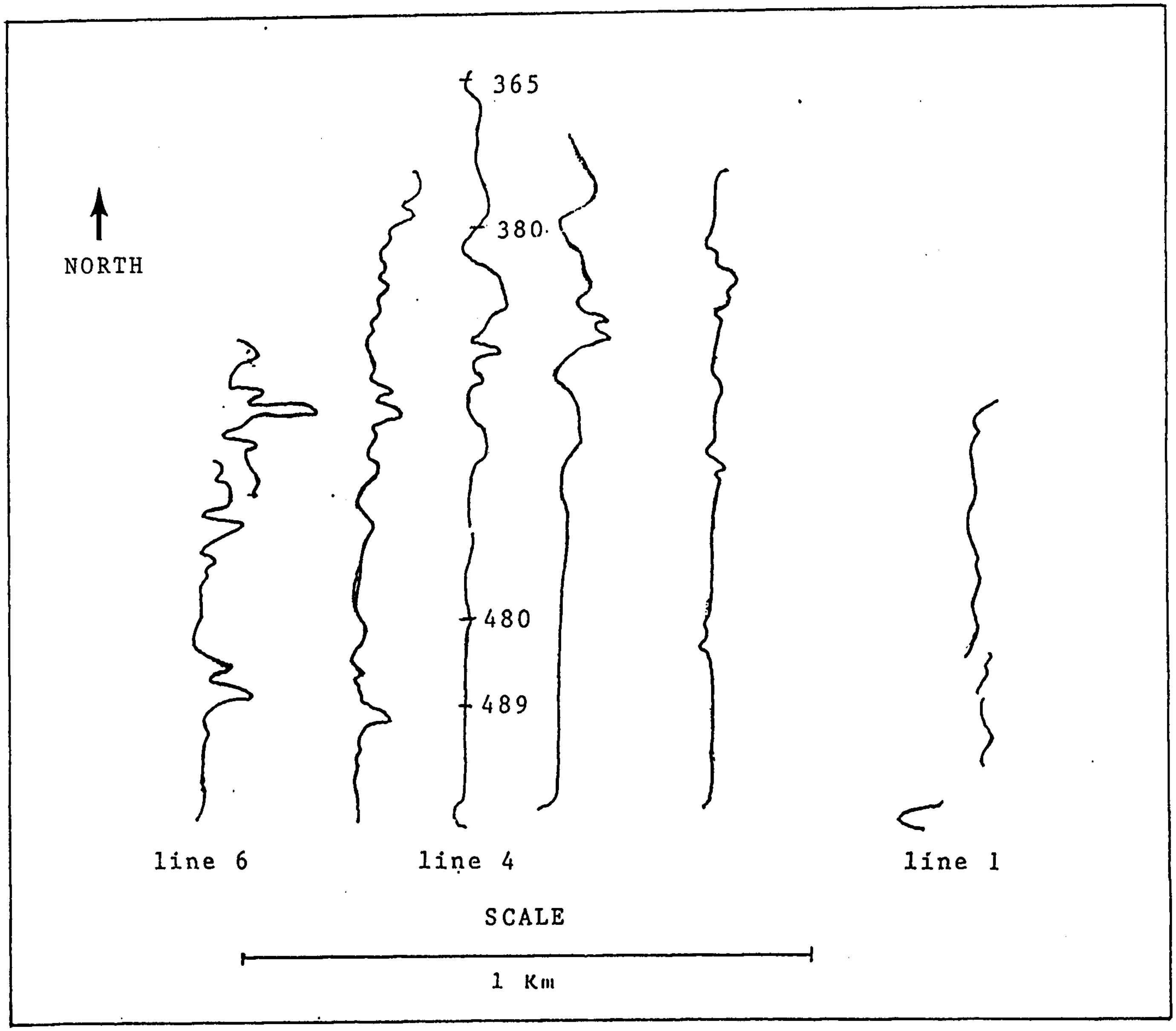


Fig.9. Instantaneous amplitude plot for the dynamite data. Areas of highest amplitude are shown by the heavy black patches. The zone of sills is characterized by having the highest amplitudes on the



.Fig.10 Instantaneous phase plot for the dynamite data. This plot emphasizes the discontinuity of reflection events within the zone of sills and within the massive zone. Fractures are evident as edges



.Fig.11. Profiles for north-south-trending magnetic lines 1-6. Line 4 was located along the path of the seismic line. The numbers along this line show corresponding CMP locations. All of the magnetic anomalies on this line are located within the region of the collapsed zone found on the seismic data between CMPs 380 and 480. A zone of anomalies present on six of the magnetic profiles has a slight southwest-northeast trend as shown.

DISCUSSION

Introduction

MERRILL *et al.* (1977) concluded that the Woodson County lamproites formed by melting a garnet-rich mantle source or by crystal fractionation, but they did not specify in their extended abstract how this conclusion was reached. As discussed below, we agree that the lamproites are most likely the result of magma formation by incipient melting of upper mantle garnet peridotite since the incompatible elements, Cr, Co and the La/Lu ratios are high. The high Co and Cr content, however, precludes crystallization and removal of the phases that concentrate these elements and occur as phenocrysts in these rocks (olivine, phlogopite, diopside, and amphibole) since fractional crystallization of these phases would drastically reduce the Co and Cr concentrations from their measured values.

Melting models

A small percent partial melting of garnet-rich mantle sources has often been used to explain the chemical and isotopic characteristics of alkaline magmatism as well as being consistent with the results of experimental petrology (*e.g.*, GAST, 1968; KAY and GAST, 1973; SUN and HANSON, 1975; CULLERS and MEDARIS, 1977; FREY *et al.*, 1978; CULLERS *et al.*, 1982; summary in CULLERS and GRAF, 1984). A major problem is that predicted concentrations of incompatible elements during melting are too low compared to measured concentrations from average or "undepleted" upper mantle even if the lowest D.C.'s and very small degrees of melting are assumed in order to maximize the predicted incompatible element concentrations in the melt. For example, CULLERS *et al.* (1982) assumed that an average, upper mantle peridotite consisting of 56 percent olivine, 33 percent orthopyroxene, 5 percent clinopyroxene, and 6 percent garnet (mineralogically and chemically the same as that given by WEDEPOHL and MURAMATSU, 1979) underwent 0.5 percent equilibrium and modal melting (after SHAW, 1970; HASKIN, 1984) to produce the Riley County, Kansas, kimberlites. Although most predictions matched the observed range of kimberlites, some predictions tended to be too low (especially LREE and Th). In addition, it is difficult to visualize how such tiny degrees of melt may be separated from the bulk of the residual solid. If the same model is compared to the Woodson County lamproites (Fig. 10), the predicted LREE, Th, and Hf concentrations are much lower than observed although predicted and measured contents of other elements are approximately correct considering the many assumptions.

To overcome the above difficulties, an H_2O- or CO_2-rich, metasomatized upper mantle, variably enriched in incompatible elements, has been proposed as the source for alkaline magmatic rocks (FREY and GREEN, 1974; PAUL *et al.*, 1975; BACHINSKI and SCOTT, 1979; KURAT *et al.*, 1980; LUHR and CARMICHAEL, 1981; PAUL and POTTS, 1981; RODEN, 1981; JAQUES *et al.*, 1984; RODEN *et al.*, 1984). For example, lamproites at West Kimberley, Australia, have low CO_2, but high F and H_2O (JAQUES *et al.*, 1984). Based on experiments in the peridotite-H_2O-CO_2 systems (BOETTCHER *et al.*, 1975; EGGLER, 1978; EGGLER and WENDLANDT, 1979; WYLLIE, 1979; BARTON and HAMILTON, 1982), JAQUES *et al.* (1984) conclude that the West Kimberley saturated lamproites (olivine-hypersthene normative) formed by melting of phlogopite-rich peridotite that was metasomatized and variably enriched in incompatible elements at high pressure of H_2O and F. Minettes saturated or slightly undersaturated in silica have also been attributed to have formed by melting of garnet peridotite with high H_2O/CO_2 ratios (ROGERS *et al.*, 1982). In contrast, the undersaturated kimberlite and carbonatite magmas (larnite in the norm) would form under high CO_2 pressure and low H_2O pressure (*e.g.*, JAQUES *et al.*, 1984; ROGERS *et al.*, 1982). The Silver City lamproite like the West Kimberley lamproites, is saturated and is also probably low in CO_2 since there are no carbonate minerals so the high LOI is surely due to H_2O-loss from the abundant serpentine (neither F or CO_2 were analyzed). The Silver City lamproite, therefore, could also have formed by melting of a metasomatized, phlogopite-rich peridotite variably enriched in the incompatible elements. We suspect that the abundant carbonate minerals in the Rose Dome lamproite are secondary so this lamproite could have formed in a similar fashion as the other lamproites. The initial $^{87}Sr/^{86}Sr$ ratios for the Silver City lamproite and the Rose Dome lamproite are lower than those of the West Kimberley lamproites (JAQUES *et al.*, 1984) so the metasomatized mantle that melted to form the Woodson County lamproites may not have been as enriched in Rb relative to Sr or perhaps enriched on a shorter time scale. The higher Rb/Sr ratios in the West Kimberley lamproites (Mean = 0.41; JAQUES *et al.*, 1984) compared to the Woodson County lamproites (0.14 and 0.20 for two measurements) tend to support the former although it would still of course be possible for the time of metasomatism to be different in the two areas.

VAN KOOTEN (1980) demonstrated that ultrapotassic basalts in the central Sierra Nevadas had to form by 1.0 to 2.5 percent melting of a phlogopite-garnet peridotite. About 49–53 percent phlogopite of a composition similar to those in kimberlites or in xenoliths of kimberlites along with 28–38 percent orthopyroxene and 13–19 percent clinopyroxene typical of mantle composition could melt and produce major element compositions similar to the ultrapotassic basalts. The residuum left after melting would increase in olivine and garnet. As a K-rich, Na-poor source was required, it was concluded that phlogopite was present in the source rock and was involved in the melting; the presence of amphibole was precluded by its high Na/K ratio.

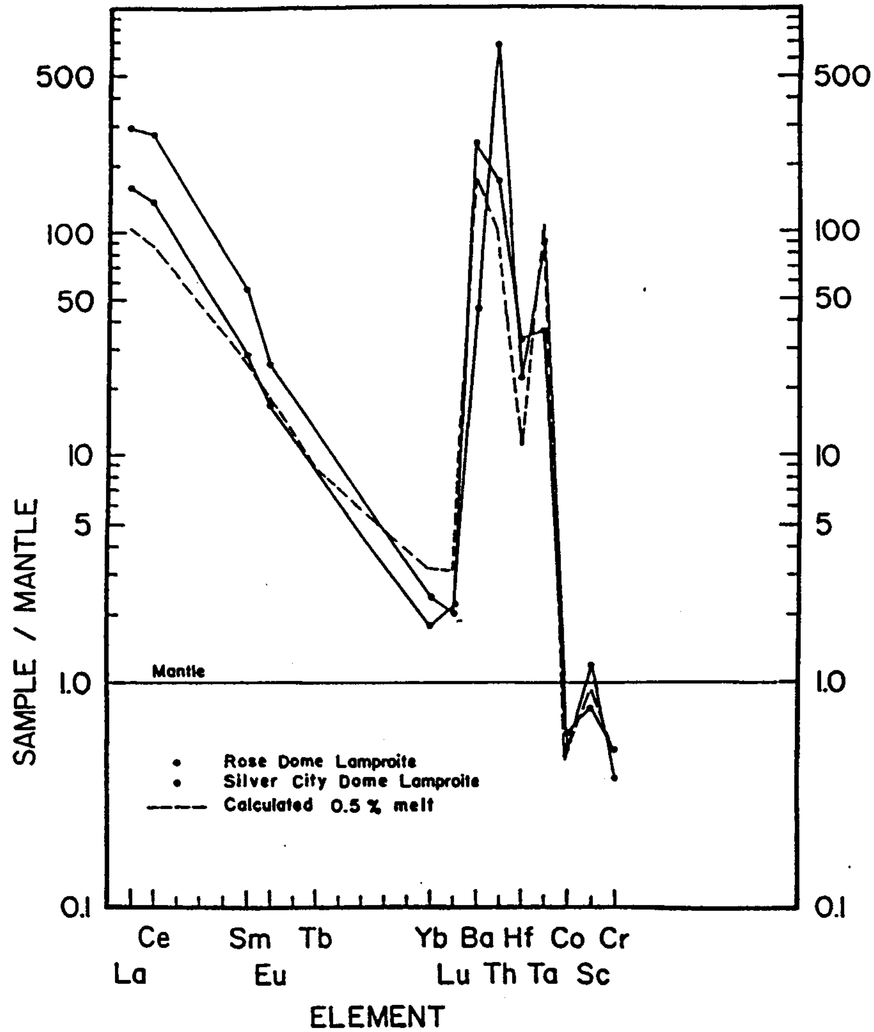


FIG. 10. The predicted element content of a melt (dashed line) formed by 0.5 percent modal, equilibrium melting of a peridotite source from the mantle containing 56 percent olivine, 33 percent orthopyroxene, 5 percent clinopyroxene, and 6 percent garnet is compared to the least altered and least differentiated portions of the Rose Dome lamproite (solid lines and solid circle) and Silver City lamproite (solid line and open circle).

If similar compositions of minerals as Van Kooten used are assumed to melt and produce the Woodson County lamproites, there is no melting ratio of these minerals that will produce the major element composition of the lamproites. The best fit gives predicted melts that are too high in Al and Mg and too low in Ti and Fe. If the composition of the melting phlogopite is assumed to be similar to the center of phlogopite grains in the Silver City lamproite, then the predicted melt is much closer to the measured magma composition using melting ratios similar to those of van Kooten. The best fit of predicted melts to the range of magma composition assumes that phlogopite/clinopyroxene/orthopyroxene melting ratios are 60/20/20 (Table 9). Considering the assumptions involved, we feel this is a good fit between predicted melt and the observed range of magma composition. Certainly no other melting ratios or composition of reasonable melting minerals from the upper mantle even comes close to approximating the unusual composition of lamproites. As K and Na may have been lost by alkali metasomatism at low pressure, the original magma formed in the mantle could have been even more K- and Na-rich than observed so our estimates of K and Na in the magma could be low. On the other hand, Na and K metasomatism at mantle pressure could possibly enrich the magma more in Na and K than our simple-minded model above would predict. We have no way of evaluating that possibility.

If lamproites are produced by a small percent melting of upper mantle variably enriched in incompatible trace elements, lamproite magmas in different areas would be expected to have the extreme and variable enrichment observed (Table 8), depending on the concentration of the elements in the source and the percent melting. Thus, we believe detailed comparisons of predictions to observations of magma

TABLE 9. The composition of minerals (weight percent) assumed to melt to form the Silver City lamproite.

	Phlogopite[1]	Clino-pyroxene[2]	Ortho-pyroxene[2]	Predicted Melt assuming a 60/20/20 ratio of phlog/cpx/opx	Range of Silver City lamproite
SiO_2	41.2	53.5	55.4	46.5	41.6–49.8
TiO_2	5.0	0.2	0.1	3.0	1.9–3.0
Al_2O_3	5.7	2.9	2.6	4.5	3.9–4.5
FeO	8.8	5.6	9.3	8.3	7.0–8.2
MgO	22.9	16.1	30.4	23.0	16.7–22.5
CaO	——	20.8	1.3	4.0	1.6–3.9
Na_2O	0.1–0.2	1.0	0.5	0.21–0.42	0.3–0.99
K_2O	10.1	——	——	6.5	6.2–9.5

[1]from Merrill et al., 1977
[2]from Van Kooten, 1980

compositions of lamproites melting from assumed mantle sources would only match if xenoliths of mantle representative of unmelted, enriched upper mantle were found in the lamproite being studied. No such mantle xenoliths have been found in these lamproites. The best candidates that might be most similar to the mantle that melted to produce the Woodson County lamproites (especially at Silver City) would be the metasomatic phlogopite-peridotites ± garnet described in NIXON *et al.*, 1981 (samples PHN 2713 and 2771). These two metasomatized nodules are considerably enriched in the incompatible elements, LREE, Ba, Rb, and Sr by factors of 4.2–5.8, 2.4–8.6, 14.2–73, 2.3–11, respectively, over average ultramafic mantle of WEDEPOHL and MURAMATSU (1979). The HREE like Lu are depleted in the metasomatized nodules by a factor of 0.17–0.23 compared to average ultramafic rock, and the compatible elements are similar in the two. We had to assume residual garnet and phlogopite were present in the source to be able to match predictions with observations for the HREE and Rb. Degrees of melting much less than 2 percent tended to give predictions of the LREE, Ba, Sr, and Rb that were too high and larger degrees of melting tended to give predictions that were too low compared to observed magmas.

The best match between predictions and observations (Fig. 11) using the low D.C.s summarized in CULLERS *et al.*, (1982) assumed a non-modal and aggregate melting model (after SHAW, 1970) in which a residual peridotite with olivine/opx/cpx/garnet/phlog = 0.60/0.315/0.06/0.01/0.015 melted in the ratio of opx/cpx/phlog = 0.2/0.2/0.6 (this melting ratio was used since it best explained the major elements). The compatible elements, Co and Cr, still give good matches between predictions and observations since these concentrations are similar in enriched and average mantle rocks. We believe this model is a good match to element concentrations in observed lamproites considering that the actual metasomatized mantle that melted to produce the Woodson County lamproites could have had a different ratio of incompatible elements or mineralogy than we had available for our model. In fact, we would be surprised if metasomatized mantle was not found to be variable in mineralogy and trace elements on a very fine scale (centimeters to meters). Finally, two percent melting, as used in this model, should be sufficient to permit the melt to aggregate and move from the site of formation to where it was injected at shallow depth. Even more melting could be allowed if the metasomatized mantle that melted to produce the Woodson County lamproites was even more enriched in incompatible elements than that used in our model.

Fractionation within the sills

Vertical chemical variation within the sills could be due to some combination of crystal fractionation,

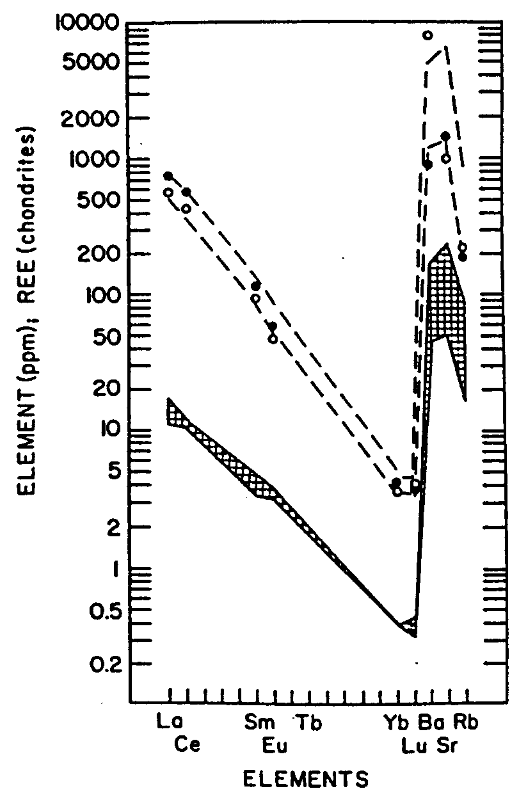


FIG. 11. The predicted trace element content of a melt (dashed line) formed by 2 percent non-modal, aggregate melting of a metasomatized peridotite (cross-hatched; after NIXON *et al.*, 1981) containing 60 percent olivine, 31.5 percent orthopyroxene, 6 percent clinopyroxene, 1 percent garnet, and 1.5 percent phlogopite and melting in a ratio of ol/opx/cpx/phlog = 0.2/0.2/0.6 is compared to Rose Dome (solid circle) and Silver City (open circle) lamproites.

multiple injection, flow differentiation, and metasomatism. The Rose Dome lamproite increases in carbonate closer to the lower limestone resulting in obliteration of most of the original minerals, suggesting contamination took place. This chemical alteration makes it difficult to interpret any vertical chemical changes within the Rose Dome lamproite, limiting the discussion of vertical variation to the Silver City lamproite.

As discussed previously, Ba and, to a lesser extent, K and Rb appear to have increased in contact metamorphic zones relative to unaltered country rocks above both sills and to a lesser extent below the sills. Those alkali and alkaline earth elements that occur in significant amounts in the serpentinized groundmass or olivine and are soluble in H_2O might be most susceptible to removal by the H_2O-rich fluids escaping to the country rock. A large proportion of the K and Rb is concentrated in the abundant phlogopite, but there is still a significant mass of these elements and Ba present in the serpentine. In addition, the concentrations of Ba and, to a lesser extent, K (but not Rb) also decrease upward in the Silver City lamproite. A partial explanation could be gradual loss of these soluble elements primarily upward into the overlying contact metamorphic zone. The problem is that other elements (REE, Th, Hf; possibly Ta and Sc) also decrease upward in the Silver City lamproite while others increase upward. Thus, there is at least one other reason for this element fractionation. While considering possible multiple injection, fractional crystallization, or flow differentiation, however, one should bear in mind the possibility of reequilibration of elements between altered phenocrysts and groundmass as well as element transport in H_2O-rich fluids circulating through the magma.

Vertical discontinuities in mineralogy, grain size, or composition in the Silver City lamproite might be expected if multiple injections of different magma occurred. We visually examined the core and noticed only a gradual increase in phenocryst/groundmass ratio up the core consistent with what MERRILL *et al.* (1977) found in a different core in this area. Thus, we only sampled at wide intervals to find what we expected to be gradual changes in mineralogy and composition due to flow differentiation or fractional crystallization. A more detailed sampling campaign would let us see if any discontinuities in mineralogy or composition are present, but the gradual change in percent phenocrysts vertically coupled with the gradual compositional changes over the wide sampling interval, lead us to believe multiple injection was not important.

Fractional crystallization within the sill was also tested assuming the phenocryst-poor lower portion of the sill might be a fine-grained chill zone representing the initial magma composition and that it cooled and crystallized inward by crystal formation and settling. Using reasonable D.C. for observed phenocrysts and groundmass (using either the D.C. of CULLERS *et al.*, 1982 or D.C. estimated in this study) and crystal fractionation models (*e.g.*, HASKIN, 1984), there was no combination of evolving melt composition and phenocryst ratios that would explain vertical chemical trends of the least volatile elements in the sill. Thus, either fractional crystallization did not occur or metasomatism may have changed ratios of elements among phases within the sill so that fractional crystallization effects may have been obliterated.

A flow differentiation model gives us the best match between predicted and observed concentrations of elements so we suspect this is the second process causing vertical fractionation within the sill. In flow differentiation, dense olivine phenocrysts concentrate toward the center of dikes as they flow upward along conduits (*e.g.*, GIBB, 1968; KOMAR, 1972). As magma in the dike is injected as a sill, the vertical flow differentiation may be preserved as sparse phenocrysts (especially olivine) at the top and bottom of the sill that increase inward toward the center as is observed in this sill.

Additionally, assuming the minerals and groundmass have the same composition throughout the sill as summarized in Tables 4 and 7 (element compositions of the groundmass were estimated from the sample at 57 feet in the core by subtracting off phenocryst compositions from the phenocrysts plus groundmass), it is possible to match predicted with observed element concentrations within ±20 percent for all elements but Ba, Na, and in several samples, Ca (Fig. 12). Ba has already been shown to be the most mobile element of those removed from the magma and transported into the country rock and is largely tied up in the groundmass. Estimates of Ba concentrations up the core are systematically higher than observed, tending to support significant Ba loss up the core into the overlying country rock as is also observed. Estimates of Na also are higher up the core than measured, suggesting Na may be lost into the overlying country rock. Na concentrations in the country rock are variable and overlap with the low concentrations of Na in the intrusion although there is a hint Na is more enriched in the hornfels relative to the nearest unmetamorphosed shales (Table 2). K and Rb have also been suggested to have been lost to the country rock, but apparently not enough has been lost from the serpentinized portions to cause differences between observations and predictions in our flow differentiation model. Perhaps K and Rb cannot be easily removed from the abundant phlogopite phenocrysts so that loss of these elements from the less concentrated serpentinized portions cannot be detected within the uncertainties of our model.

Finally, the bulk of some elements may have been concentrated in minerals of low abundance, especially Ca in diopside and Cr in spinel. If the modes of the low abundance minerals enriched in certain elements did not quite match the actual amount of minerals

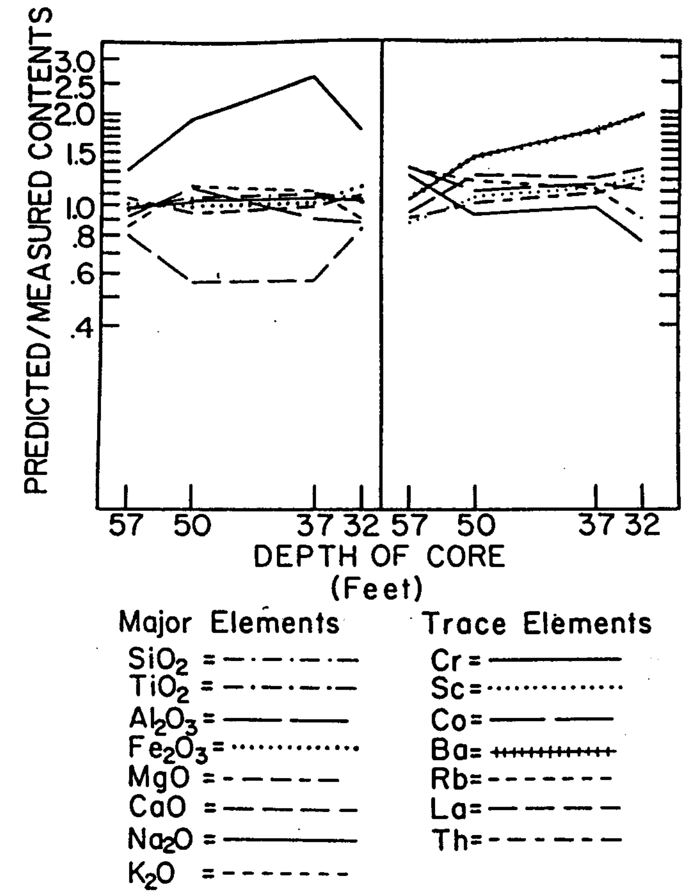


FIG. 12. The ratio of elements predicted in the flow differentiation model are compared to the measured contents of elements.

in the analyzed samples, then estimates of element concentrations would not agree very well with observed values. If we make small, arbitrary adjustments in modes of clinopyroxene, we can get much better agreement between observations and predictions than obtained at 50 feet and 37 feet in Fig. 12. The relatively good agreement of Cr in Fig. 12 was obtained by making these small, arbitrary adjustments in spinel modes from those observed.

Thus, flow differentiation and, for some elements, metasomatism probably combined to produce fractionation within the sill. Fractional crystallization or multiple injection cannot be completely precluded, however, due to undetected metasomatic effects that could cause local movement of elements among phases or to other parts of the sill that might completely obscure element changes due to crystal fractionation or multiple injection.

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APPENDIX

Description of thin sections

Silver City Dome

HP-1.5′ *Quartzite.* Quartz grains are anhedral and interlocking. Average grain size 0.25 mm. Minor amounts of mica present. Some foliation accentuated by the concentration of mica in thin layers up to a few mm wide. Some secondary fracturing of quartz grains within one thin layer.

HP-1.11′ *Shale.* Abundant organic debris and clay minerals making identification of individual minerals difficult. Small anhedral quartz grains make up about 17% of the rock.

HP-1.28′ *Sandstone.* More argillaceous material than HP-1.5′. Quartz grains are angular. Patches of clays and organic material distributed throughout, but bedding is evident.

HP-1.46′ *Quartz sandstone.* Angular interlocking quartz grains. Some overgrowth of quartz along grain boundaries as well as some alteration. Contains minor zircon as an accessory mineral plus some other opaques.

HP-1.54′ *Shale.* The bulk of the rock consists of clay. Rock also contains magnetite, patches of dark organic material, and about 5% small quartz grains.

WC-1 *Hornfels.* Slightly foliated. Very fine-grained mixture of clay minerals, mica and quartz. Minor small anhedral quartz grains scattered throughout. Accessory magnetite.

WC-2 *Lamproite.* Olivine pseudomorphs are rounded and up to 2 mm in diameter. Phlogopite crystals are up to 2 mm long. Rock similar to HP-21.37′. Euhedral perovskite crystals scattered throughout. Other accessory minerals include apatite, spinel and magnetite.

HP-21.32′ *Lamproite.* Olivine pseudomorphs up to 3 mm in diameter consist of serpentine minerals. The nature of most of the anhedral crystal aggregates indicate it to be antigorite and/or lizardite. Veinlets of serpentine exhibiting crossfibers cut through the pseudomorphs and are believed to be chrysotile. The crystal boundaries are less well defined than in the fresher material deeper down. Euhedral phlogopite crystals are generally less than 1 mm long and altered mainly along their edges as well as inside the crystals to serpentine. Subhedral, moderately pleochroic diopside; subhedral, light reddish-brown richterite showing good cleavage and subhedral dark red-brown spinel are the other major minerals. Diopside is readily altered shown by lower interference colors starting along their edges. The crystals are often clustered and intergrown with phlogopite.

HP-21.37′ *Lamproite.* Similar to HP-21.32′. Alteration of groundmass to serpentine is slightly less advanced.

HP-21.52′ *Lamproite.* The olivine pseudomorphs are slightly less altered and crystal boundaries better defined. The serpentine replacing the olivine has a larger grain size than in the previous samples. Large spinels up to 1 mm are common. Phlogopite crystals are also less altered.

HP-21.57′ *Lamproite.* Sample is quite fresh looking with rounded olivine pseudomorphs up to 3 mm in diameter. Olivine grains are partially surrounded by phlogopite which is generally better crystallized. Phlogopite crystals are subhedral to euhedral, up to 2 mm long, slightly pleochroic, and some are bent and deformed. Inclusions of apatite in phlogopite are common. Richterite occurs as lamellar, bladed or sometimes fan-shaped, strongly pleochroic crystals up to 1 mm long, and is partially altered to serpentine. Spinel and diopside are major phases. Magnetite and perovskite are common accessory minerals.

HP-21.64′P *Lamproite.* Rounded olivine phenocrysts up to 3.5 mm in diameter are altered to serpentine, which typically consists of veinlets of chrysotile surrounding more coherent patches of antigorite and lizardite. Rims of fine-grained phlogopite surround all olivine pseudomorphs. Small phlogopite crystals, partially altered to serpentine occur throughout the matrix. Richterite is also quite altered. Magnetite is the main accessory mineral.

HP-21.64′ *Hornfels.* Very fine-grained rock consisting mostly of serpentine and quartz, partially replaced and overgrown by sericite and chlorite. Rock is stained by iron oxides and irregular patches of dark brown material that may be altered organic matter. Minor zircon, trace of feldspar. One narrow fracture contains very fine-grained carbonates impossible to estimate percentages of minerals present.

HP-21.66′ *Mixed serpentinized hornfels and altered lamproite.* Very fine-grained groundmass consisting of serpentine, sericite, chlorite and quartz. Sample must be very close to or at the contact of a lamproite vein, because totally altered olivine pseudomorphs can be recognized in part of the rock. Small amounts of limonite and carbonate. Magnetite is distributed throughout. In one part of the section small phlogopite crystals. A fracture filled with carbonate minerals, believed to be calcite (staining), and quartz traverses the section. Modal analysis based on 500 counts:

Groundmass 64.4%
Olivine pseudomorphs 14.0%
Quartz 11.2%
Phlogopite 3.4%
Carbonate 7.0% (mainly associated with a veinlet).

HP-19.14′ *Hornfels.* Rock is very fine-grained and consists of a mixture of clay minerals with chlorite and sericite. Anhedral quartz grains constitute about 10% of the rock (based on 100 counts), and have a cloudy appearance due to overgrowth or replacement by chlorite-sericite as well as iron staining. Some magnetite.

HP-19.22′ *Quartzite.* Interlocking and sutured anhedral quartz grains make up the bulk. Small amounts of mica, clay minerals, and iron oxides concentrated along grain boundaries. Average quartz grain size about 0.1 mm. Accessory zircon.

HP-15.6′ *Quartz wacke.* About 55% quartz grains and 45% matrix (clay minerals, finely dispersed quartz and mica). Quartz grain size is less than 0.1 mm. Accessory zircon and rutile. For the most part sand grains are not in contact with each other.

HP-15.21′ *Quartz wacke.* Much like HP-15.6′ About 45% quartz. Clay minerals, mica, and organic matter make up the matrix.

Rose Dome

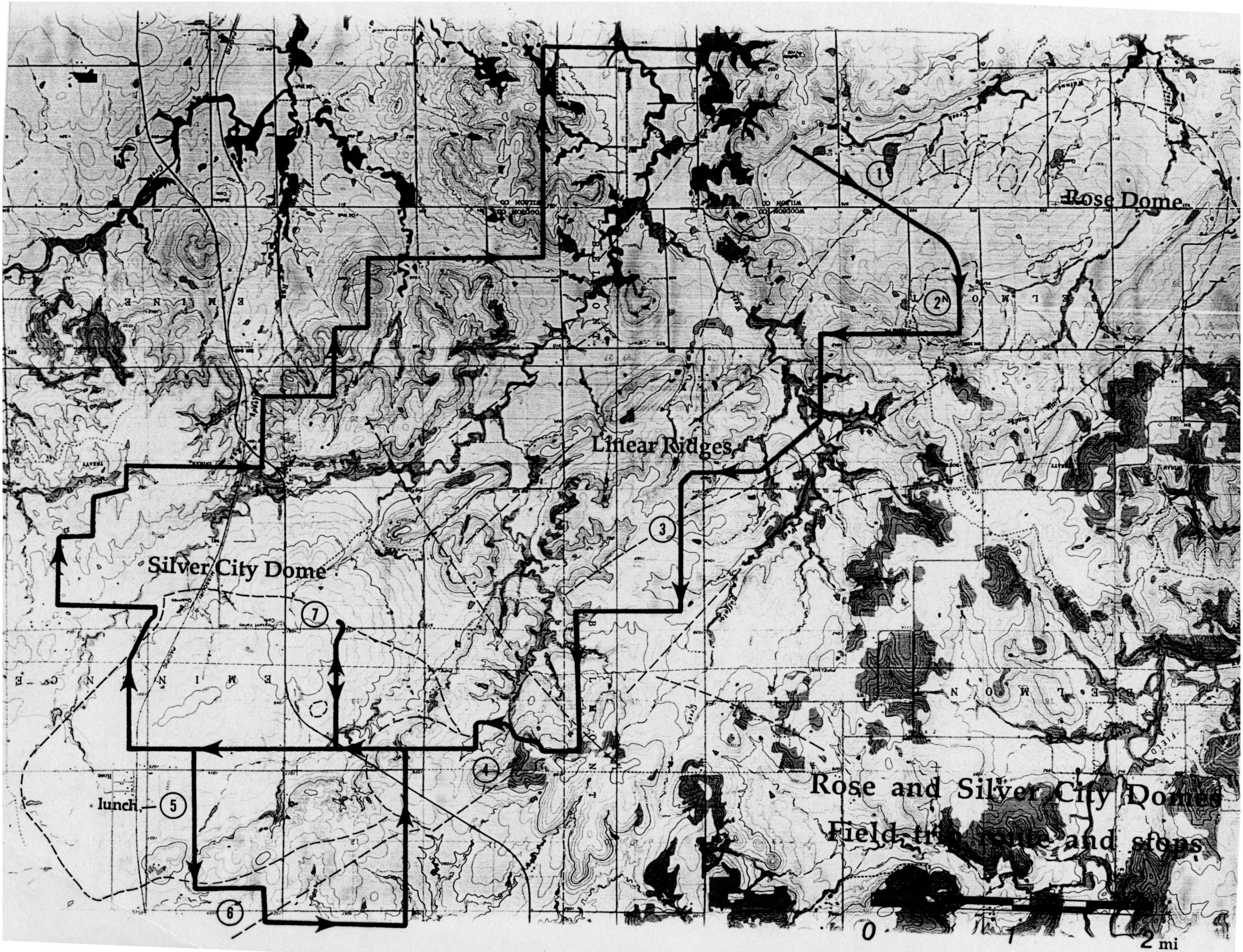
DDH-2.39.1′ *"Spotted" Hornfels.* A very fine-grained mass of clay minerals and a minor amount of quartz. Limonite and/or organic materials impart a brown color to the rock. As a result of thermal metamorphism redistribution of organic material and iron oxides has occurred.

DDH-2.39.3′ *Altered Lamproite and Hornfels.* The rock consists of two distinct portions, one of which is coarser-grained and can be recognized as a totally altered lamproite; the other may be an altered hornfels close to the contact. Although there is a well-defined contact between the two in most places, inclusions and one veinlet of altered lamproite occur in the altered hornfels. The altered lamproite consists of olivine pseudomorphs completely replaced by fine- to medium-grained carbonate and smaller amounts of quartz. Staining of the rock and X-ray diffraction pattern show that the bulk of the carbonate is dolomite. No calcite or other carbonate minerals are detected. Remnants of phlogopite can easily be recognized. The groundmass consists also of carbonate (dolomite) and quartz. The hornfelsic portion of the rock consists of a very fine-grained mass of orthoclase (XRD-identification) and lesser amounts of calcite and quartz. Apatite and magnetite are common accessory minerals.

DDH-2.43.4′ *Altered Lamproite.* About 17% of the rock consists of serpentine pseudomorphs after olivine which altered to dolomite and lesser amounts of quartz; in some grains remnants of serpentine are still present. About 30% of the rock consists of very fine-grained phlogopite in various stages of alteration to carbonate, which is probably also dolomite (no calcite detected by X-ray diffraction). Some of the phlogopite is difficult to recognize except for its color. The rest of the groundmass consists mainly of very fine-grained carbonate (dolomite). Several percent of opaques, including magnetite which is a common accessory mineral, are present (probably iron oxides).

DDH-2.45′ *Limestone.* Consists of very fine-grained calcite, some quartz and minor opaques. Quartz is only found filling in pores and/or vugs and the calcite around the vugs is generally fine- to medium-grained.

DDH-2.47′ *Biosparite.* Totally recrystallized limestone.


Rose Dome
Linear Ridges
Silver City Dome
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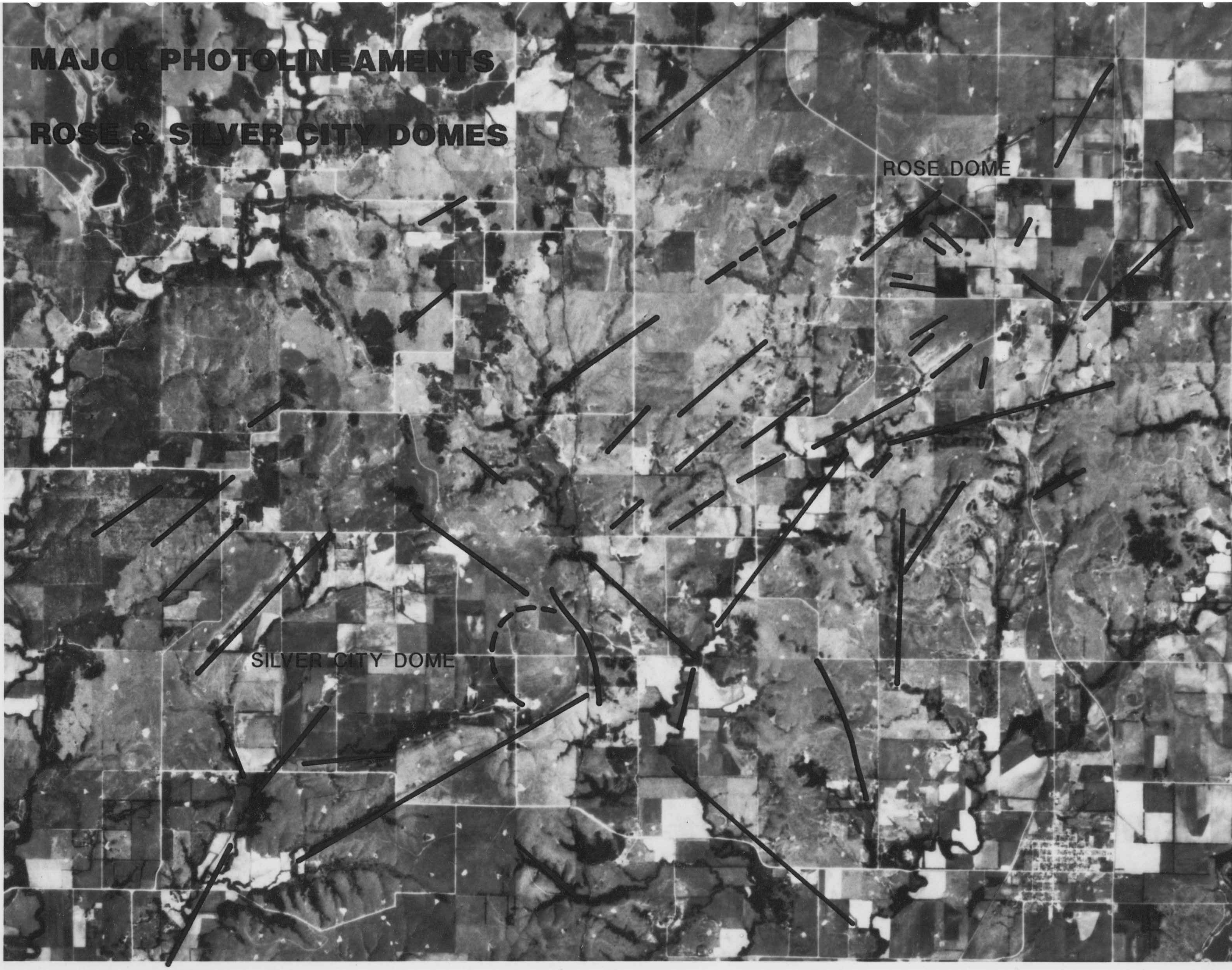
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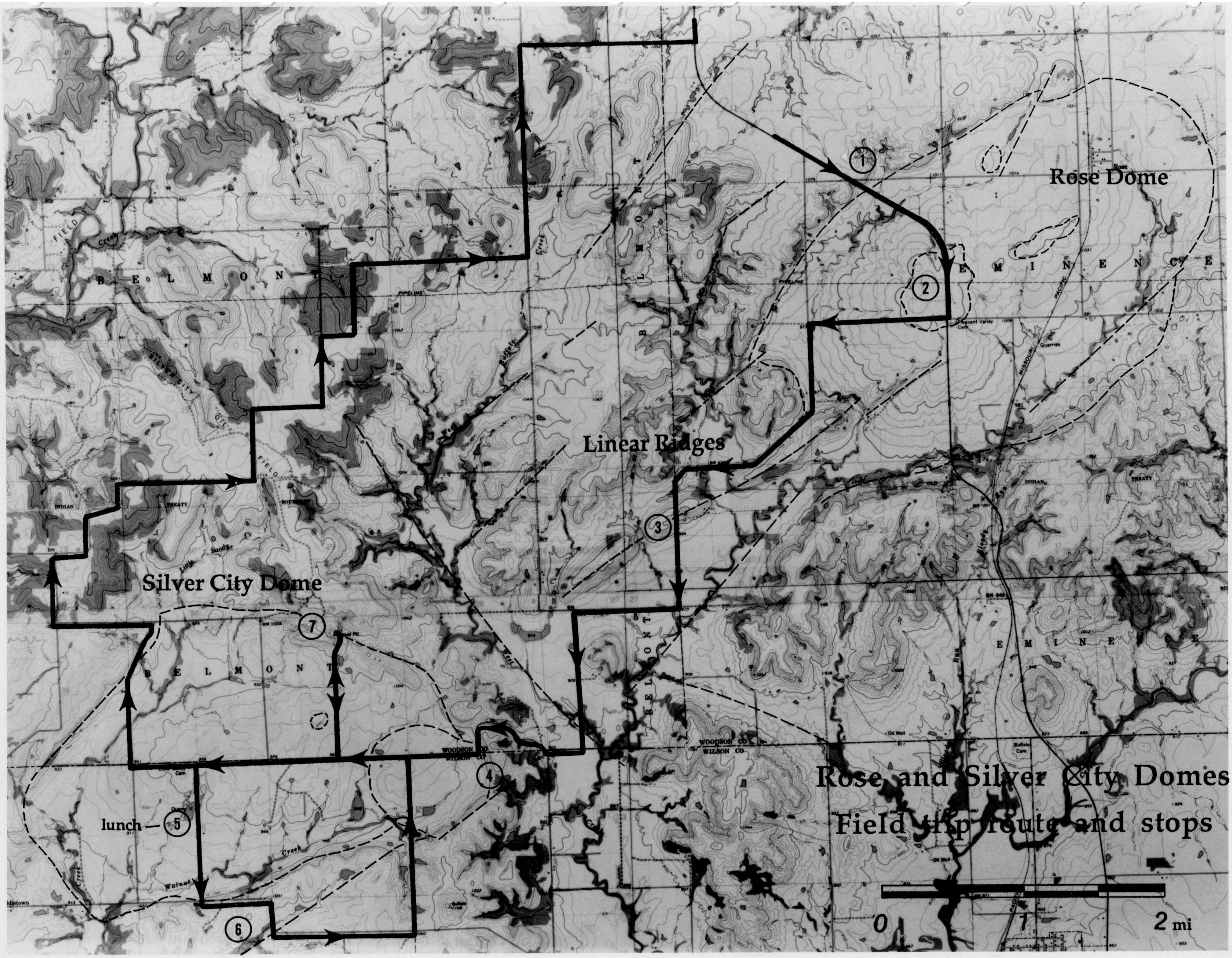

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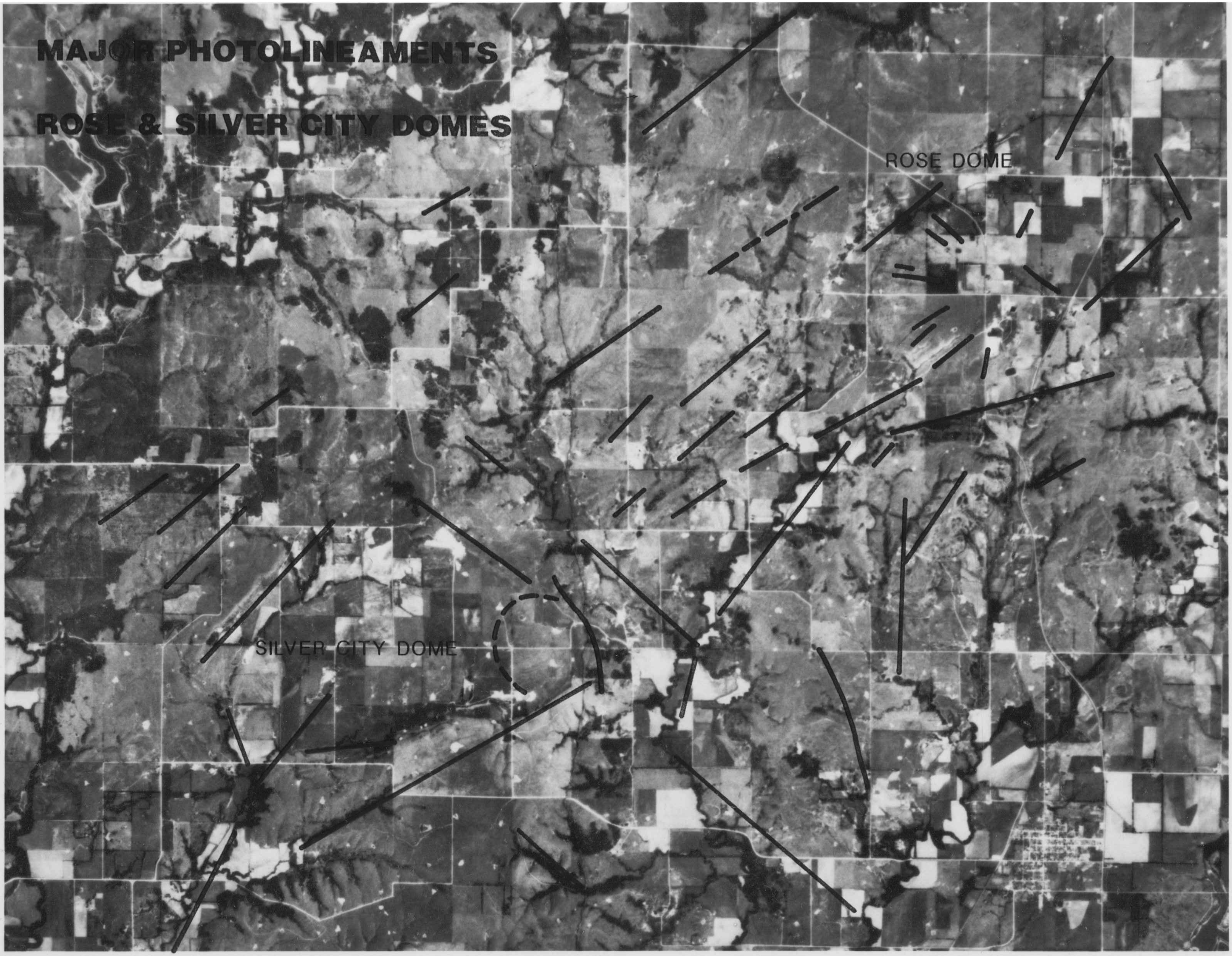
MAJOR PHOTOLINEAMENTS
ROSE & SILVER CITY DOMES
ROSE DOME
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