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GEOTHERMAL ENERGY RESOURCE ASSESSMENT

Energy and Environment Division
Lawrence Berkeley Laboratory
University of California

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GEOTHERMAL ENERGY RESOURCE ASSESSMENT

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ABSTRACT

This report covers the objectives and the status of a long-range program to develop techniques for assessing the resource potential of liquid-dominated geothermal systems. Field studies underway in northern Nevada comprise a systematic integrated program of geologic, geophysical, and geochemical measurements, necessary to specify a drilling program encompassing heat flow holes, deep calibration holes, and ultimately, deep test wells.

The status of Nevada field activities is described. The areas under study are in a region characterized by high heat flow where temperatures at depth in some geothermal systems exceed 180°C. Areas presently being examined include Beowawe Hot Springs in Whirlwind Valley, Buffalo Valley Hot Springs, Leach Hot Springs in Grass Valley, and Kyle Hot Springs in Buena Vista Valley.

Geologic studies encompass detailed examinations of structure and lithology to establish the geologic framework of the areas. The geothermal occurrences are characterized by zones of intense fault intersection, which

furnish permeable channelways for the introduction of meteoric water into regions of high temperature at depth.

Geophysical studies emphasize techniques to measure electrical resistivity. Comparison is made of induced and natural field methods, and results indicate that telluric techniques are an excellent reconnaissance tool. These techniques appear to be more economic and efficient than bipole-dipole resistivity surveys, and provide the basis for detailed dipole-dipole surveys. The self-potential method detected strong anomalies, believed to be associated with upwelling thermal water along a prominent fault near Leach Hot Springs. Passive seismic monitoring located a zone of microearthquakes south of Leach Hot Springs, and a zone northwest of Buffalo Valley. The Kyle Hot Springs area appears to have little microearthquake activity.

Geochemical studies have emphasized analyses of trace elements in rocks and waters by neutron-activation, x-ray fluorescence, and radiometric methods. Element abundances in hot and cold springs are used to estimate the amount of mixing of near-surface cold waters with ascending hot geothermal waters. The low abundance of uranium in hot springs, compared to cold springs, together with the relatively high abundance of uranium daughter products in some hot spring waters, suggest that uranium may be concentrating at depth in some geothermal systems.

Computer models of geothermal systems are being developed, wherein reservoir parameters can be varied. These models will incorporate actual field data as subsurface samples are obtained.

The long-range program involves studies in resource types characterized by different geologic settings. Such areas may include the Salton

Trough in southern California, a region characterized by Quaternary silicic volcanic activity, an area of high regional heat flow, and an active tectonic area of relatively normal heat flow. This program would span five years and cost approximately thirty-two million dollars (in 1975 dollars).

INTRODUCTION

An important facet of the Lawrence Berkeley Laboratory's geothermal energy resource program is the development of methods to assess geothermal potential. In Part One of this report, the status of the on-going LBL field research program in resource assessment techniques is described; Part Two formulates an expanded long-range program of field and laboratory activities.

A. Objective

The principal objective of the geothermal resource assessment program is to develop techniques to locate, delimit, and evaluate the energy potential of given goethermal resource sites. Emphasis is on the liquid-dominated hydro-thermal resource, the resource type expected to furnish the bulk of electrical and non-electrical geothermal energy during the next few decades. To best accomplish this objective, a comprehensive, systematic approach is required, incorporating geologic, geophysocal and geochemical techniques to determine locations for a sequence of drill holes. The drilling sequence begins with relatively shallow (~100 m) heat flow holes whose results influence location and depth of intermediate deeper (1/2 to 1-1/2 km) calibration test holes, culminating in the drilling of one or more deep (1-1/2 to 3 km) test wells. Fluids from the test wells can be utilized in a field site, testing heat exchange and energy conversion methods, as well as in a pilot plant site. Concurrently, surface and subsurface techniques to monitor the configuration of geothermal reservoirs will be developed and tested at existing resource sites, along with downhole methods to evaluate the energy potential of a reservoir.

B. The Nature of the Resource

Geothermal waters can be broadly classified according to their temperature and quality (dissolved chemical constituents):

low temperature (80 to 150°C), high quality (<5000 ppm total dissolved solids);

moderate temperature (150 - 210°C), high quality;

and high temperature (>210°C), low quality (>5000 ppm total dissolved solids).

Of these three hydrothermal resource types, the high temperature, low quality type is considered characteristic of one region, the Imperial Valley. The lower temperature, higher quality resource types are characteristic of much of the western U.S., including Alaska. Of these, the low temperature resource lends itself best at this time to non-electrical utilization, while the moderate temperature resource can be utilized for both non-electric and electric power production, either separately or in a combined scheme.

A comprehensive assessment program must include examination of several sites in a variety of geologic terranes. Included among such sites are those associated with Quaternary silicic igneous activity, as occur on the margins of the Great Basin and within or near the Rio Grande Rift zone. Of more widespread occurrence are potential resource areas in regions of generally high heat flow, such as southeastern Oregon and north-central Nevada where Quaternary volcanism, if present at all, is primarily basaltic. Most geothermal manifestations, albeit of relatively low temperature, are in regions of nearly normal heat flow, where deeply penetrating, active fault zones furnish channelways to warm depths. In these regions, low temperature geothermal resources lend themselves best to non-electrical utilization.

Therefore, hydrothermal-resource technique development and assessment studies are to be carried out in at least four sites: (1) Imperial Valley, (2) margin of Great Basin or other area characterized by Quaternary silicic igneous activity, (3) high heat flow area, and (4) an area of active tectonism, characterized by normal heat flow. Guidance in locating sites will continue to be furnished by the U.S. Geological Survey, and programs will be carried out in close cooperation that agency, employing combined ERDA laboratory, USGS, and university equipment and expertise in field exploration techniques.

PART ONE: STUDIES IN NEVADA

To illustrate the nature of the resource assessment program, the status of the Lawrence Berkeley Laboratory's Nevada geothermal program is described in some detail. The Nevada program utilizes a systematic approach, incorporating several geoscience disciplines. Geology, geophysics and geochemistry are presently employed in evaluating the resource potential of selected sites in a region of high heat flow. Hydrogeologic model studies are presently underway, and will furnish the basis for evaluation of reservoir systems as drilling data become available.

A. Location

The area chosen for the studies, north-central Nevada, is characterized by higher than normal regional heat flow (Sass, et al.[1]). Temperatures at depth in some hot spring systems determined by chemical geothermometers (Mariner, et al.[2]) exceed 150-170°C, total dissolved solids are less than 5000 ppm. Thus, many systems are considered to be in the medium-temperature, high-quality category. Figure 1 shows the distribution of heat flow in the western U.S., and the region of high heat flow in northern Nevada. Four sites within this region, Whirlwind Valley east of Battle Mountain, Buffalo Valley southwest of Battle Mountain, Grass Valley south of Winnemucca, and Buena Vista Valley southwest of Winnemucca are under study. These sites, indicated on the location map (Fig. 2), are all essentially on Federal land, and each contains an active hot spring system (Beowawe Hot Springs in Whirlwind Valley, Buffalo Valley Hot Springs, Leach Hot Springs in Grass Valley, and Kyle Hot Springs in Buena Vista Valley).

B. General Geologic Setting

Active hot spring areas and potential geothermal resource sites in

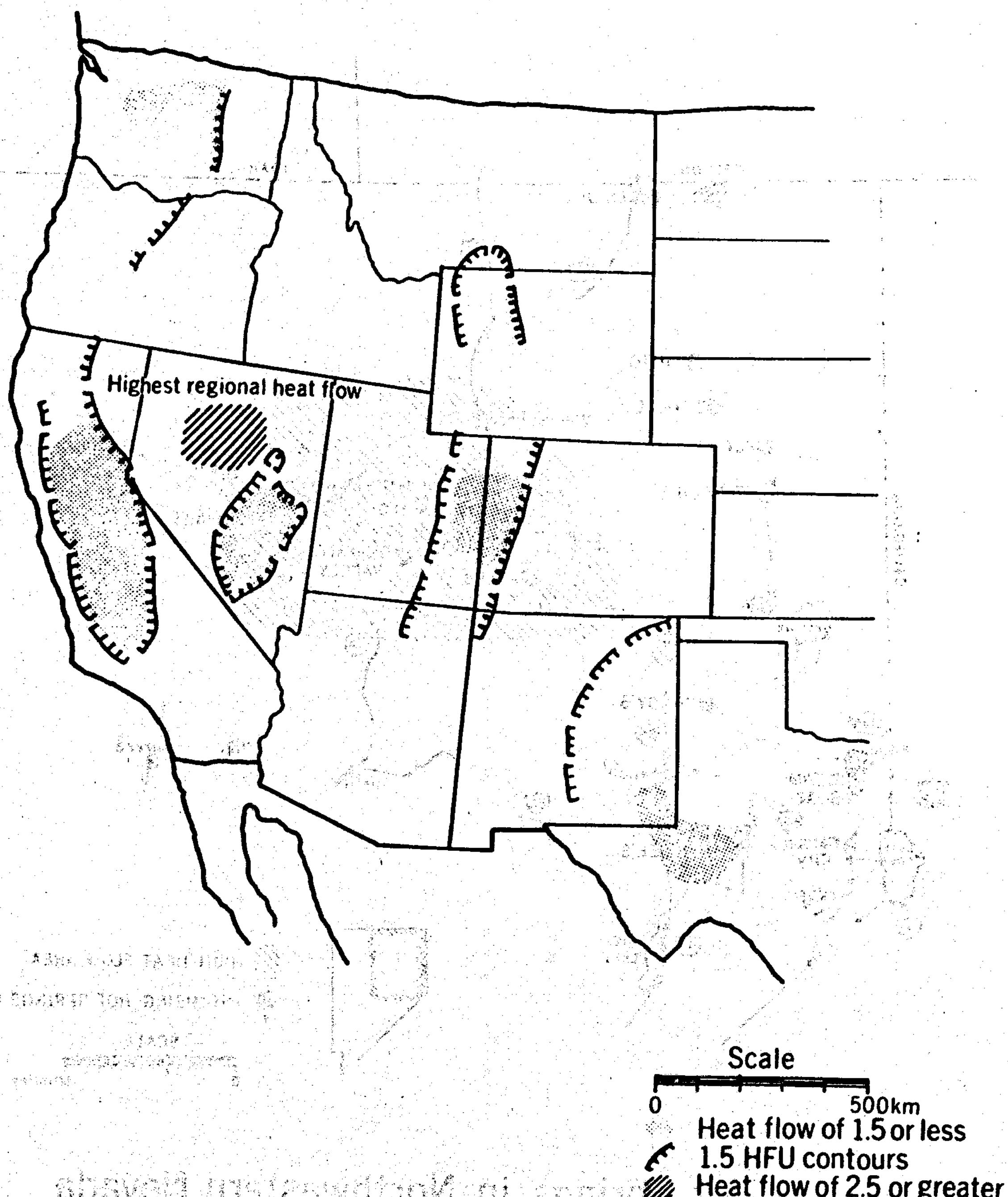

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Fig. 1. Regional heat flow in the western U.S. (after Sass et al., 1971). The stippled areas have heat flows estimated less than 1.5 μ cal cm^{-1} sec^{-1}, (hfu) while in the dashed area, the "Battle Mountain High" heat flow probably exceeds 2.5 hfu. Hachured lines indicate the fairly well defined position of the 1.5 hfu contour.

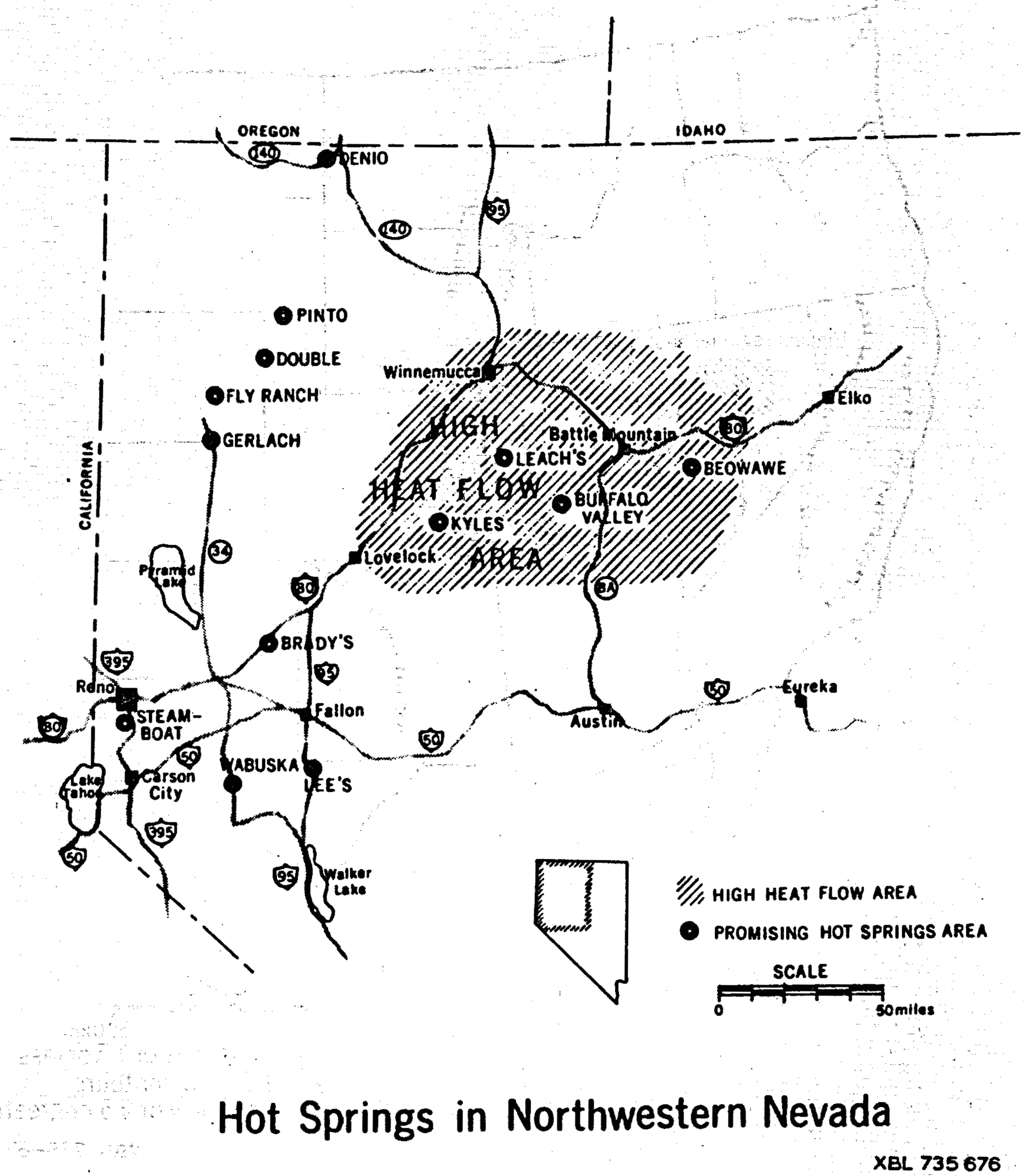

Fig. 2. Location map, northwestern Nevada, showing prominent thermal spring areas within and outside of the Battle Mountain High heat flow region.

the Great Basin are in almost all cases associated with steeply dipping basin-and range faults (Hose and Taylor[3]), often at the intersections of two major orientations of faulting. This is exemplified in Whirlwind Valley (Fig. 3), where the ENE-trending Malpais escarpment is intersected by a nearly north-south trending fault zone just to the east of the active Beowawe Hot Springs and their accompanying blowing geothermal wells. The fault zones furnish permeable pathways for downward percolating, meteoric water to reach sufficient depth (4 to 5 km) in a region of high geothermal gradient (40° to 60° C/km). The water is heated, then rises on the upward-flowing limb of a convection cell (Fig. 4). Thus, fracture permeability, afforded by intersecting faults in sub-alluvial bedrock, is the mechanism by which waters can reach depths great enough for heating, and provides channelways for upward transport of hot waters. Geothermal reservoirs may be in fractured rock of fault zones, or in relatively permeable beds of Tertiary sedimentary deposits and Quaternary valley fill alluvium.

C. Field Activities

Our site evaluation program combines interrelating geologic, geophysical, and geochemical studies. Interpretation of high, middle, and low altitude aerial photography (much of it provided by the National Aeronautical and Space Administration) together with surface geologic mapping, discloses the geologic structure of the areas. This information is used to orient geophysical traverses and to provide an understanding of the general structural setting, necessary for interpretation of geophysical results. Concurrently, sampling of country rock and hot and cold spring waters, and their subsequent analyses by x-ray fluorescence and neutron activation techniques yield major- and trace-element contents. Information from the geological,

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Fig. 3. Vertical aerial photograph of Whirlwind Valley region, Nevada, from 60,000 feet above surface, showing the association of geothermal area (center) near intersection of ENE-trending Malpais escarpment and NNW-trending zone of en-echelon faults. Width of field: approximately 27 km.

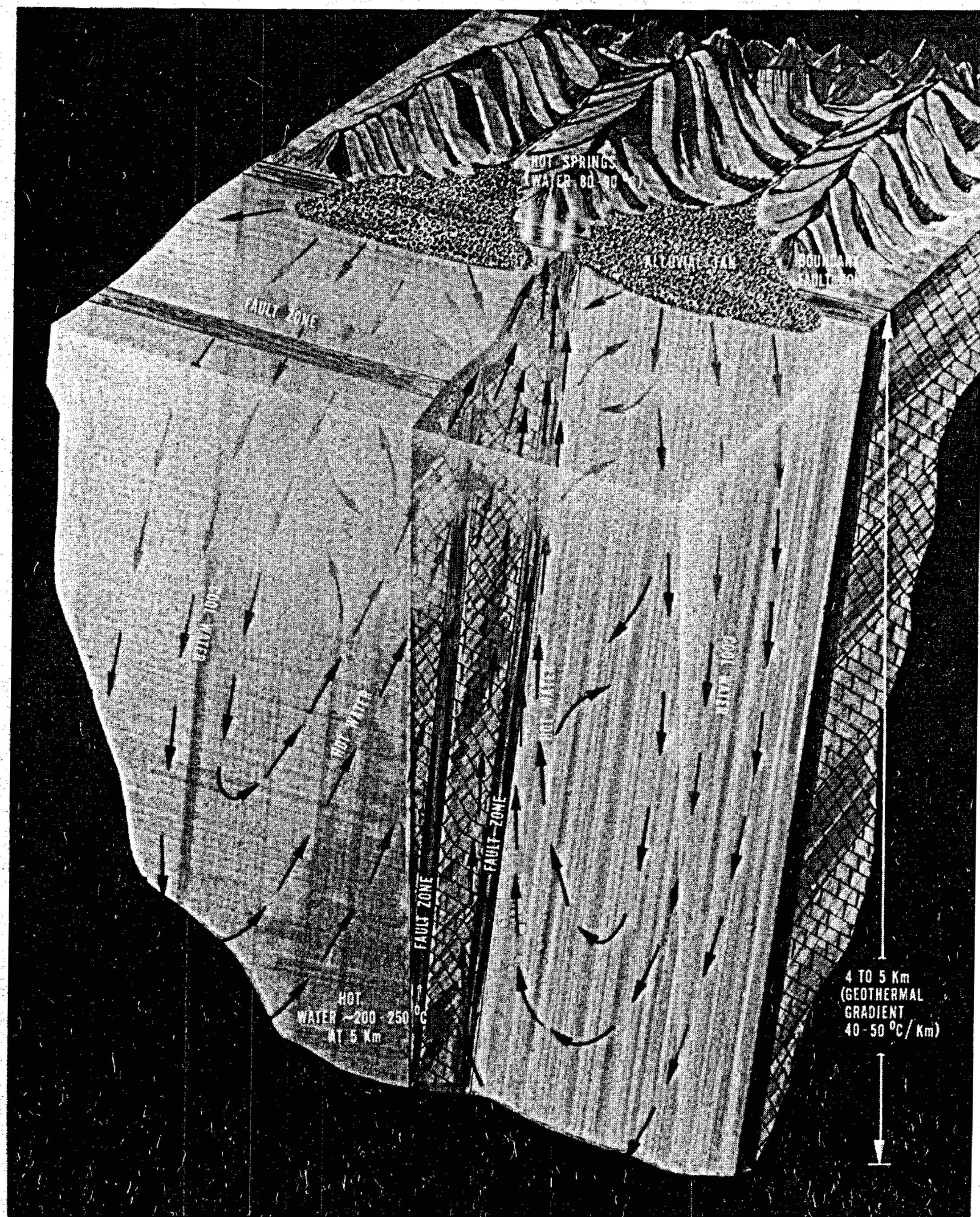

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Fig. 4. Schematic cutaway diagram of a geothermal system within a permeable fault zone. Meteoric water enters the fault zone where it intersects near-surface aquifers. Some of the water percolates downward to regions where temperatures reach 150 to 200°C, is heated and rises on the upward limb of a convection cell. Hot springs occur where the cell intersects the surface.

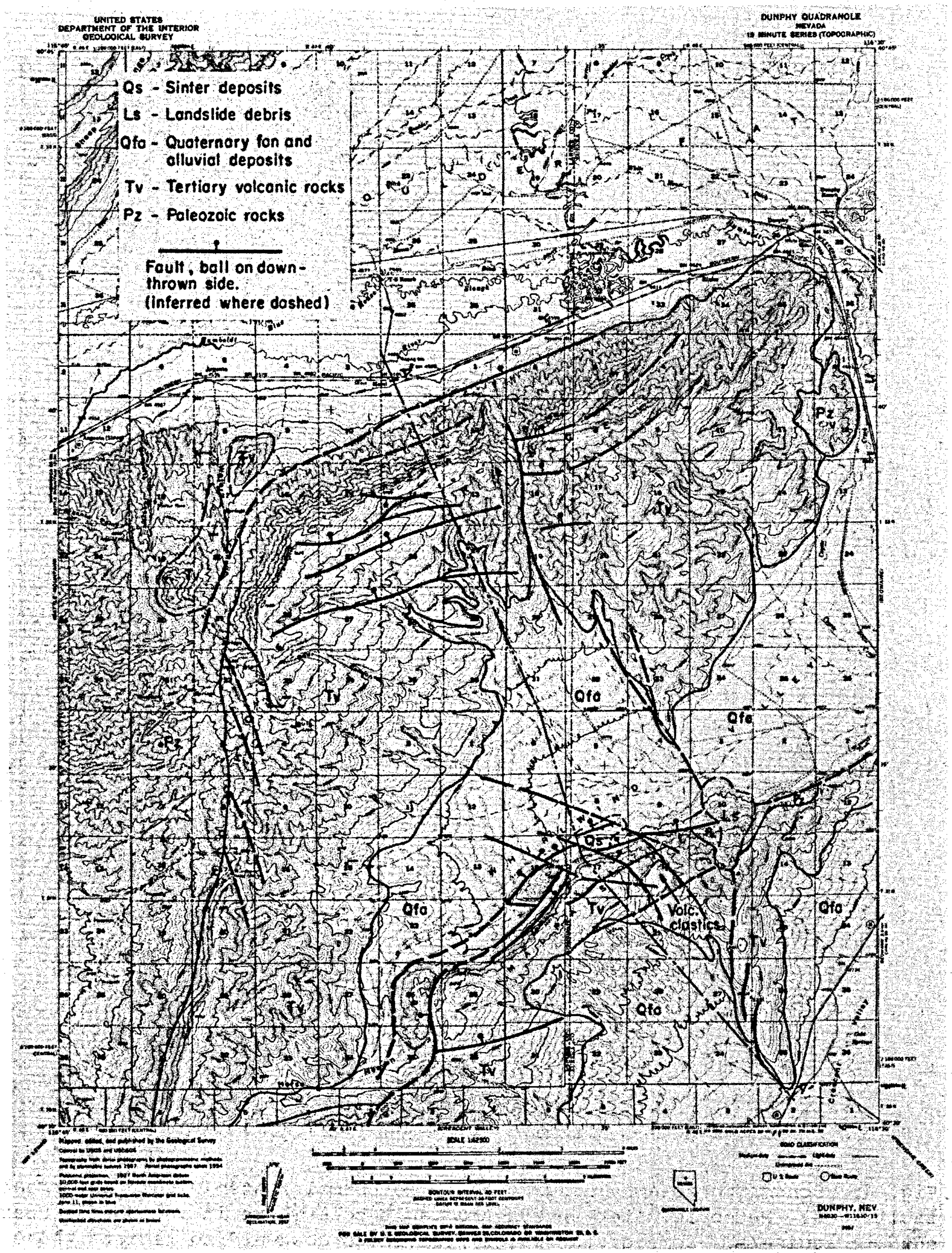

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Fig. 5. Generalized geologic map of Whirlwind Valley area.

geophysical, and geochemical activities is combined to locate several 100 m to 150 m deep heat flow holes in each of the areas under study. Results of the heat flow measurements will, in turn, strongly influence the locations of one or more confirmation test holes (~.5 to 1.5 km) which will be followed by drilling one or more deep test wells (1.5 to 3 km). The deep test wells may furnish the fluid for a preliminary heat-exchanger test facility.

1. Geologic Studies

Because much of the area is in valley fill alluvium, reconnaissance and detailed mapping relies heavily on the aforementioned aerial photography. High altitude (65,000 ft) flights by NASA U-2 aircraft provide regional coverage of high-resolution black and white photographs at low sun angles (Fig. 3 is an example), enhancing fault-related features on the desert floor. Lower altitude (6,000 ft above surface) color photography at higher sun angles shows detail associated with faulting on the immediate site areas. The structural maps of the Buffalo Valley, Leach, and Kyle areas (Figs. 7, 10a, and 12 respectively), resulted primarily from interpretation of such aerial photography, followed up by confirmation on the ground of the presence of the apparent features. Airborne infrared imagery, obtained by NASA in pre-dawn and mid-day hours, indicates well the known hot spring areas. It also discloses a hitherto unknown warm-spring area in the west portion of Buffalo Valley playa, and a possible warm spot near the mouth of Sheep Ranch Canyon, in the vicinity of Leach Hot Springs (Quade and Trexler[4]).

a. Whirlwind Valley

The Beowawe geothermal area, approximately 30 km east of Battle

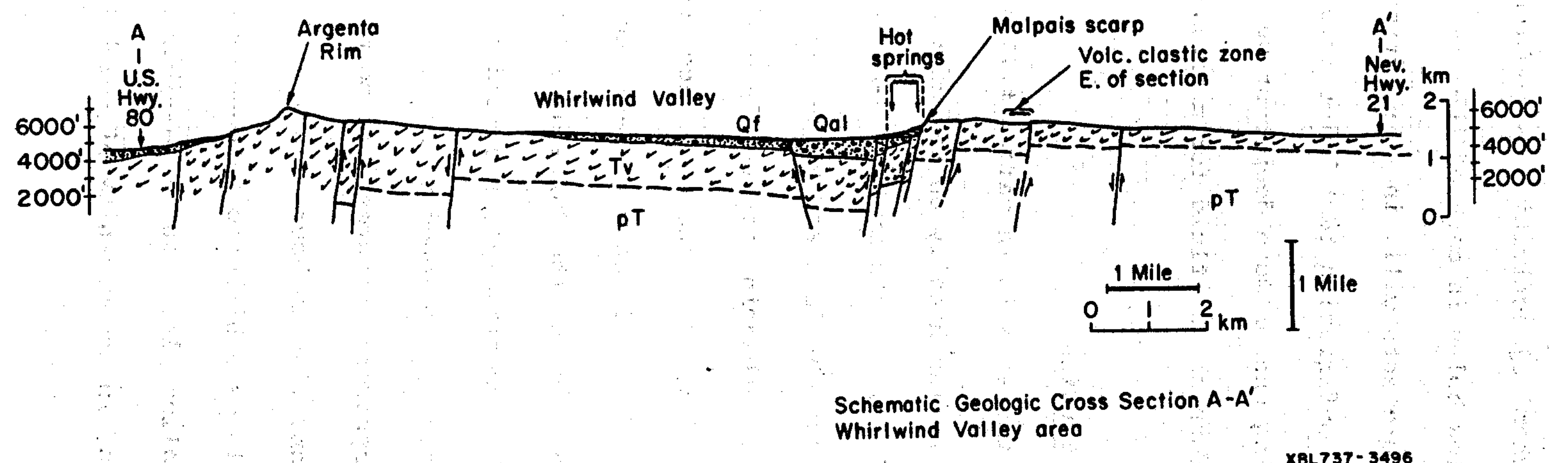

Fig. 6. Idealized geologic cross section, Whirlwind Valley area. Qal: Quaternary alluvium, Qf: Quaternary fan deposits, Tv: Tertiary volcanic rocks, pT: pre-Tertiary rocks.

Mountain, consists of active hot springs and blowing hot-water wells at the south margin of Whirlwind Valley, on the lower slopes of the steep Malpais Escarpment (a generalized geologic map comprises Fig. 5). The geology of the area is described by Oesterling[5]. Tertiary volcanic rocks, predominantly andesitic but capped by basalt, have been tilted and fractured along the Argenta Rim, bordering the Humboldt River Valley, and along the Malpais Escarpment, prominent topographic features trending ENE-WSW. The area of active springs occupies a broad siliceous sinter apron, approximately 2 km west of the intersection of the Malpais and a nearly N-S trending zone of en-echelon faults. The structural setting is illustrated on the high altidude aerial photo, Fig. 3. The fault intersection furnishes fracture permeability in the Tertiary volcanic rocks and the siliceous clastic Paleozoic rocks which underlie the volcanics. An idealized geologic cross section (Fig. 6) shows the configuration of faulted Tertiary volcanic bedrock underlying the northward-thinning wedge of Whirlwind Valley alluvium.

Temperatures by chemical geothermometry of hot spring and well waters exceed 200°C (Mariner et al.[2]); these were substantiated by temperatures measured in test wells by Magma Power Company. Hot fluid production, in wells drilled by Magma Power Company, is predominantly from fractured volcanic and Paleozoic rock on the footwall side of the steeply-dipping faults of the Malpais system (Oesterling[6]). Chevron Oil Company has recently drilled a geothermal test hole to approximately 3 km, approximately 2 km west of the active springs area; results of drilling and well tests have not been disclosed publicly.

b. Buffalo Valley

Buffalo Valley is a well-defined intermontane basin situated 35 to 40 km WSW of Battle Mountain. Its geologic setting is illustrated on the geologic map (Fig. 7) and an idealized cross section (Fig. 8). The geology has been described in detail by Noble.[7] The northern Fish Creek Mountains, bounding the valley on the east, are composed predominantly of Paleozoic clastic and Triassic carbonate rocks, overcapped by a several hundred foot thickness of Tertiary volcanic rocks, principally ash flow tuffs of Miocene age (McKee).[8] Basaltic rocks of Pliocene age, potassium-argon-dated at 2.6 - 3 m.y. by McKee and Archibald (1974, private communication) were extruded from NNE-trending basin- and range-faults which cut the earlier Tertiary and Mesozoic rocks on the east side of the valley. The basalts are exposed in well-preserved cinder cones. A series of prominent normal faults transects the western portion of the valley, cutting alluvial fan deposits near and at the eastern base of the Tobin Range. The Tobin Range is made up primarily of eugeosynclinal siliceous clastic rocks of Paleozoic age.

Structurally, the valley occupies an asymmetrical graben, closed at its southern end. As indicated by gravity data of Grannell,[9] shown in Fig. 9, the maximum thickness of alluvial cover, 1.5 to 2 km, is west of the geographic axis of the valley, indicating that most vertical displacement occurs on the north-south-trending west-side faults. Observed faults and lineaments on the east side of the valley trend NE-SW, as do west-side faults north of latitude 40° 25'. The southern margin of the graben is outlined by a series of east-west trending lineaments most of which are fault-related. South of this zone of lineaments, valley alluvium is

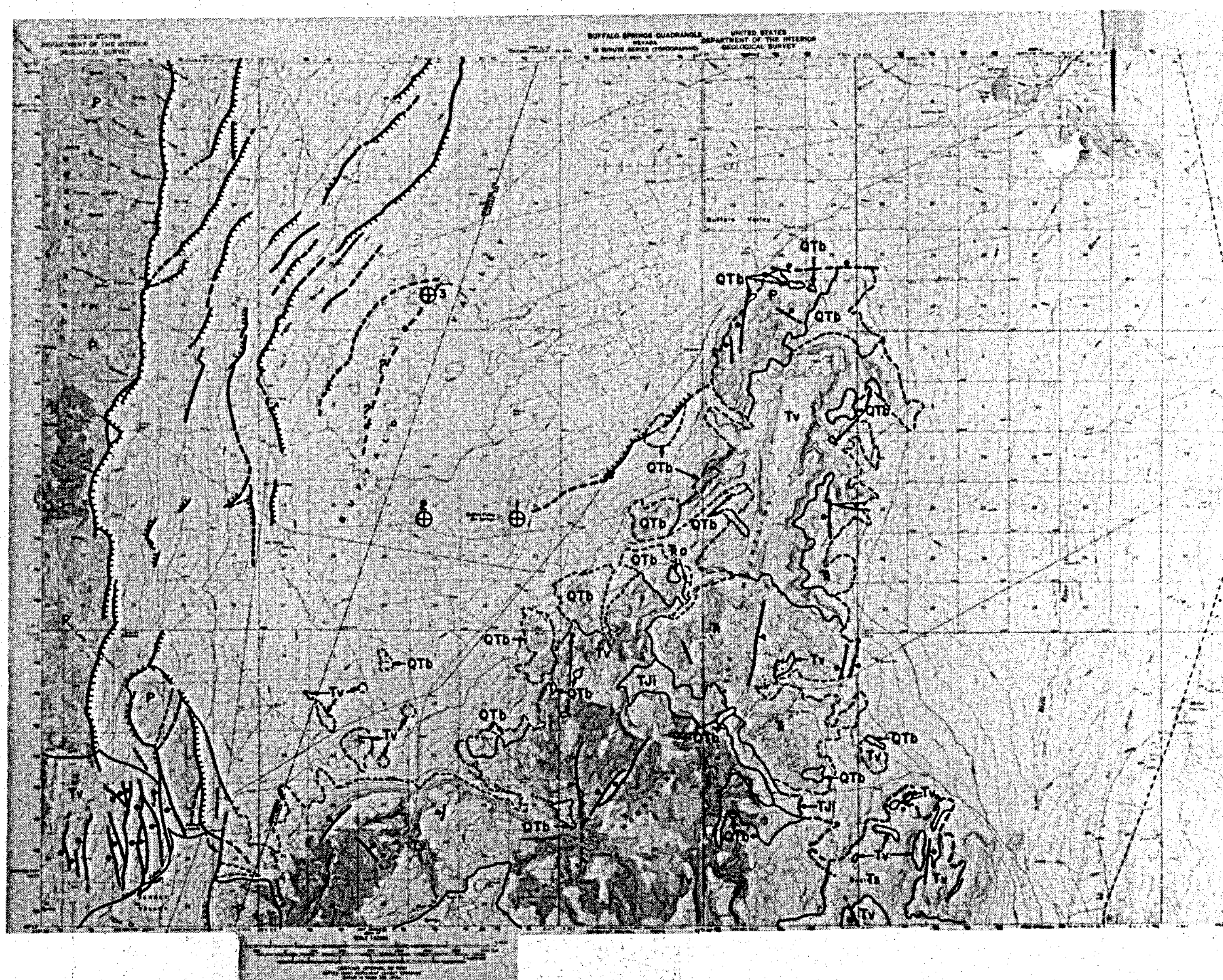

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Fig. 7. Generalized geologic map of Buffalo Valley area. Legend, QTb: Quarternary-Tertiary basalt, Ts: Tertiary sedimentary rocks, Tv: Tertiary rhyolitic ash flow tuffs, TJi: granitic rock of mesozoic or Tertiary age, TR: undifferentiated Triassic sedimentary rocks, predominantly carbonates, P: undifferentiated predominantly eugeosynclinal Paleozoic sedimentary rocks, Heavy lines: faults, balls on downthrown side, Hachured lines: observed fault scarps, Dashed heavy lines: inferred faults, Numbered crossed circles: locations of heat flow holes.

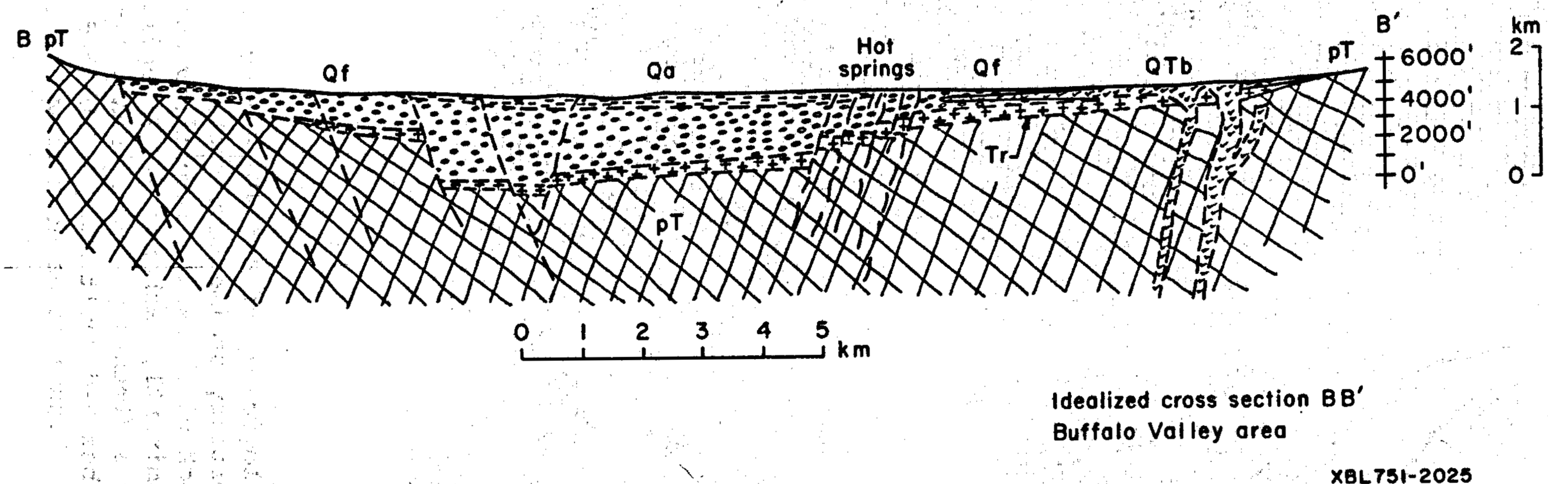

Fig. 8. Idealized geologic cross section along B-B' (fig. 16), Buffalo Valley area. Qa: Quaternary alluvium, Qf: Quaternary fan deposits, QTb: Quaternary-Tertiary basalt, Tr: Tertiary rhyolitic tuffs, pT: pre-Tertiary rocks.

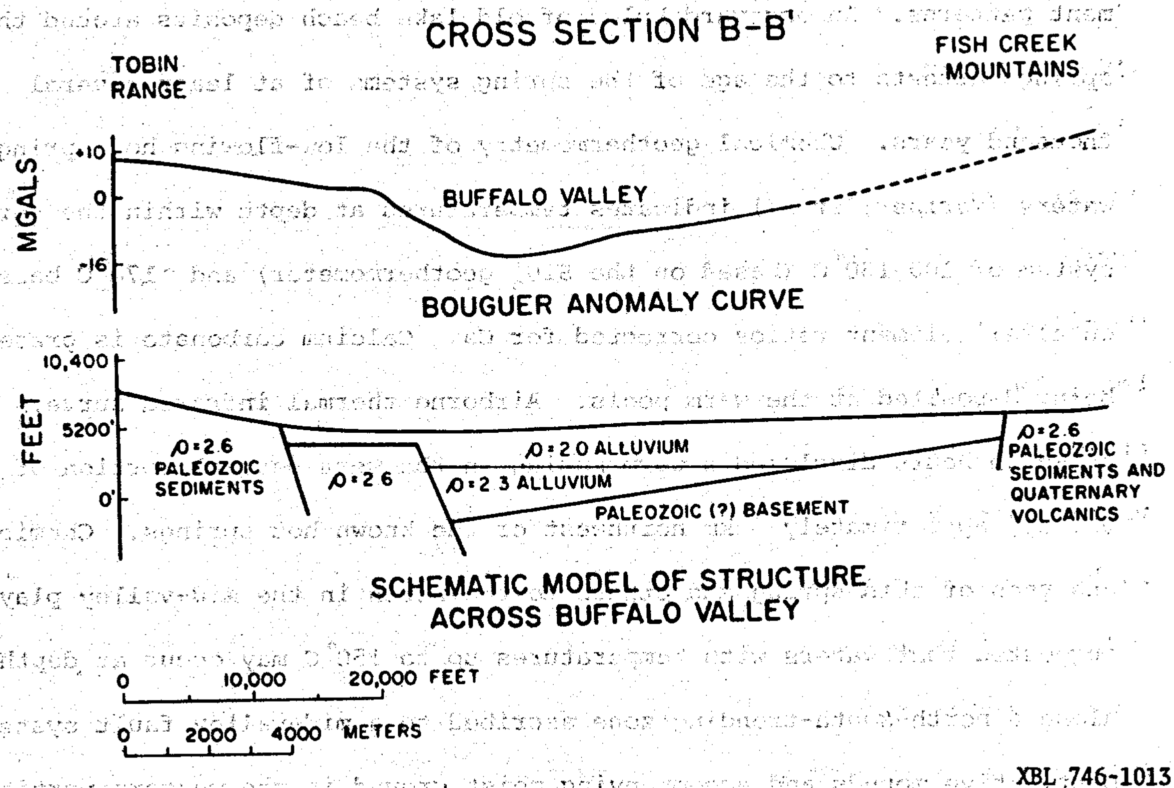

Fig. 9. Bouguer gravity profile across Buffalo Valley, after Grannell (1974).

fairly thin, covering a pediment surface on Tertiary volcanics.

Buffalo Valley Hot Springs are associated with a recognizable fault, extending southwestward from the Fish Creek Mountains, as well as with a zone of intense faulting inferred from air photo observation of lineament patterns. An eastward bulge of old lake beach deposits around the springs attests to the age of the spring systems of at least several thousand years. Chemical geothermometry of the low-flowing hot spring waters (Mariner, et al) indicates temperatures at depth within the spring system of 100-130°C (based on the SiO_2 geothermometer) and ~170°C based on alkali element ratios corrected for Ca. Calcium carbonate is presently being deposited at the warm pools. Airborne thermal infrared surveys in pre-dawn hours disclosed a warm spring in the west central portion of the valley, approximately 5 km northwest of the known hot springs. Chemical analyses of this spring and others to the north in the mid-valley playa, suggested that waters with temperatures up to 150°C may occur at depth along a north-south-trending zone ascribed to a mid-valley fault system. Distinctive mounds and accompanying moist ground in the western portion of the Buffalo Valley playa also reflect the presence of the mid-valley fault system.

c. Grass Valley

A potential geothermal resource area in Grass Valley is located in the vicinity of Leach Hot Springs, approximately 50 km south of Winnemucca. The Sonoma and Tobin Ranges bound the valley on the east, while the valley is constricted south of the hot springs by the Goldbanks Hills, locus of earlier mercury mining. Grass Valley is bounded on the west by the basalt-capped East Range. The distribution of major lithologic units in the

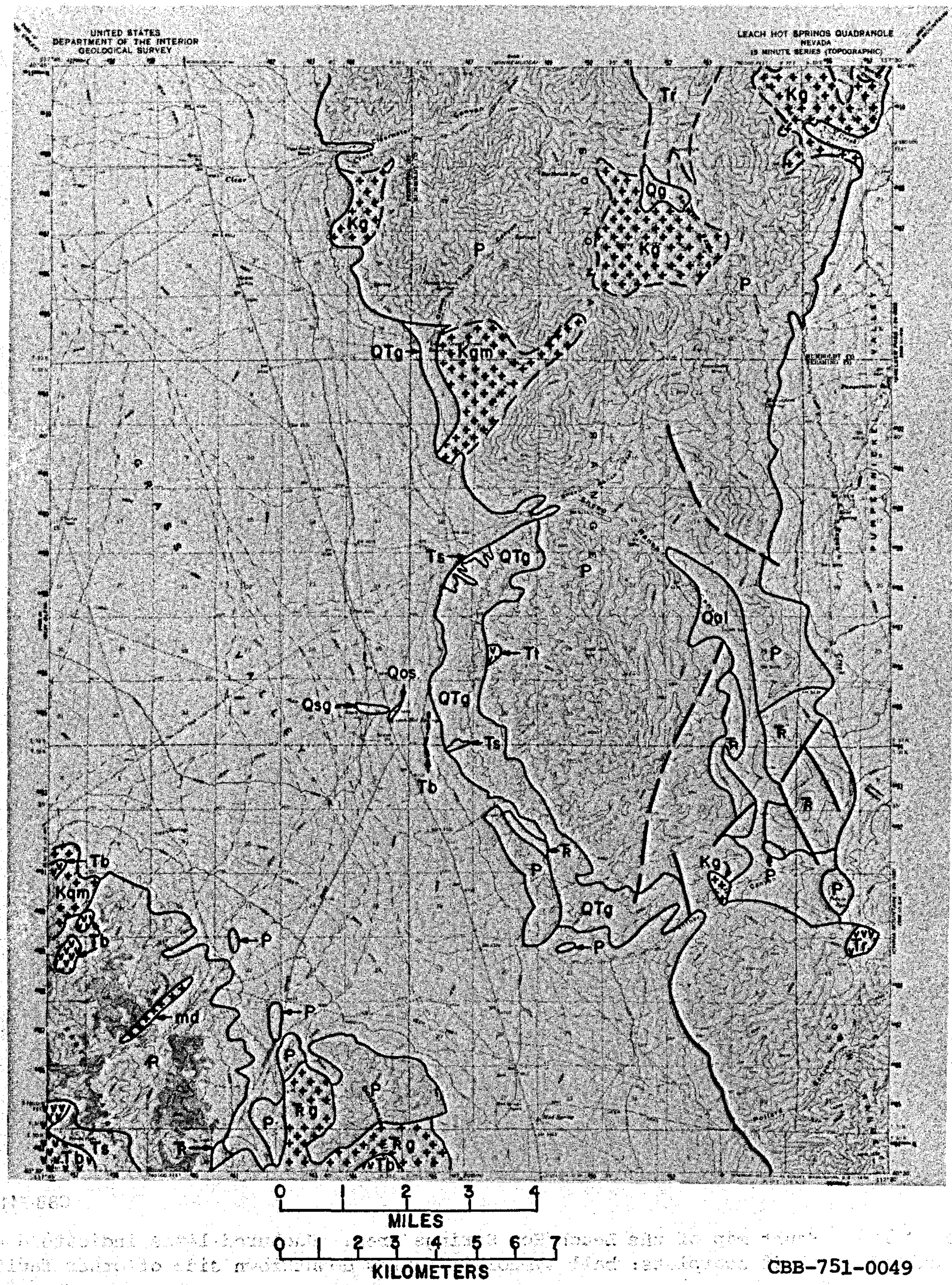

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Fig. 10. Lithologic map, Leach Hot Springs area. Qal: alluvium, Qos: older sinter deposits, Qsg: sinter gravels, QTg: Quaternary-Tertiary gravels and fanglomerates, Tb: Tertiary basalt, Tr: Tertiary rhyolite, Tt: tuff, Ts: Tertiary sedimentary rocks, Kqm: quartz monzonite, Kg: granitic rock, md: mafic dike, TRg: Triassic granitic rocks, TR: undifferentiated Triassic sedimentary rocks, P: undifferentiated Paleozoic sedimentary rocks.

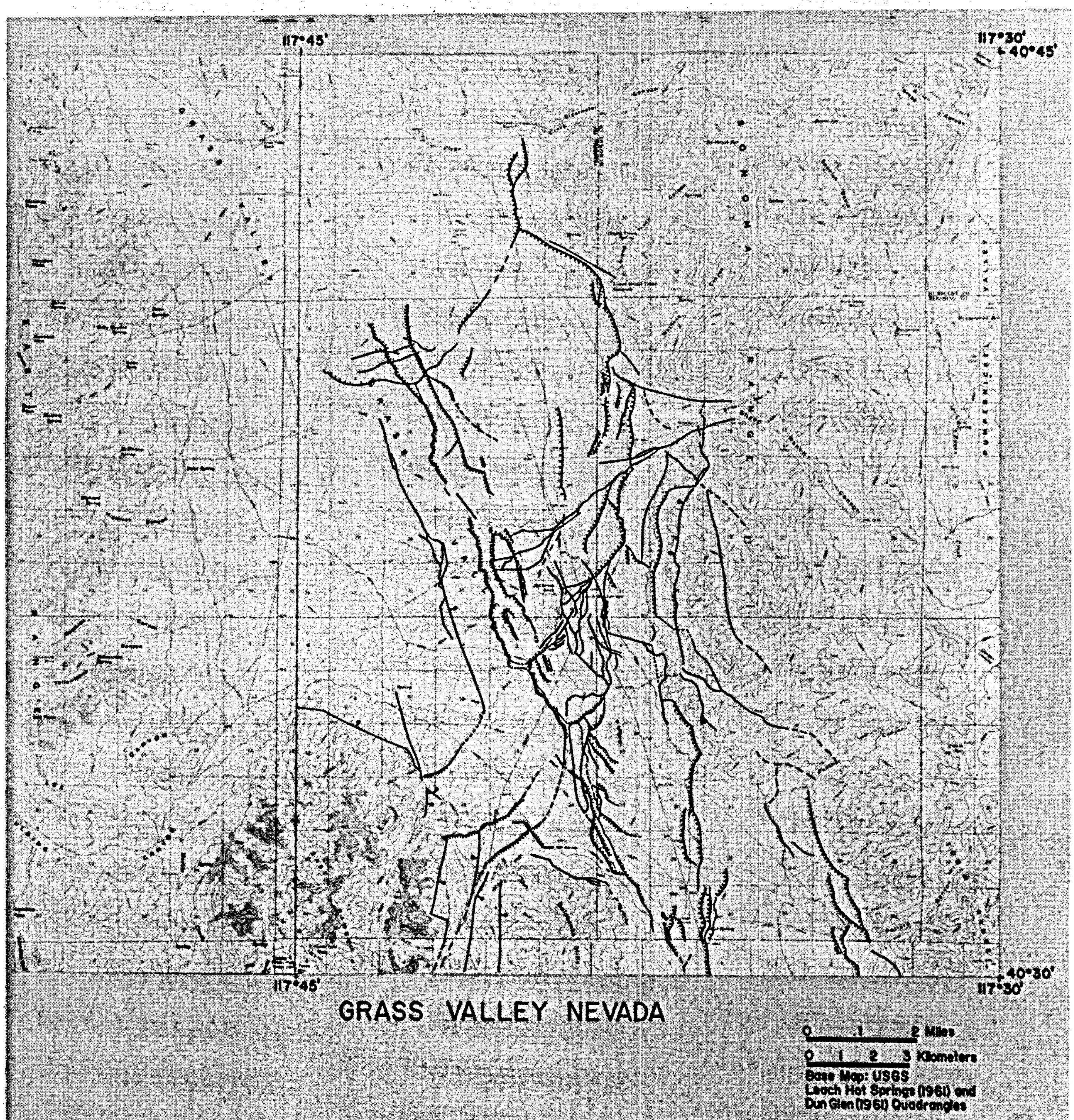

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Fig. 10a. Fault map of the Leach Hot Springs area. Hachured lines indicate down-faulted sides of scarplets; ball symbol indicates downthrown side of other faults.

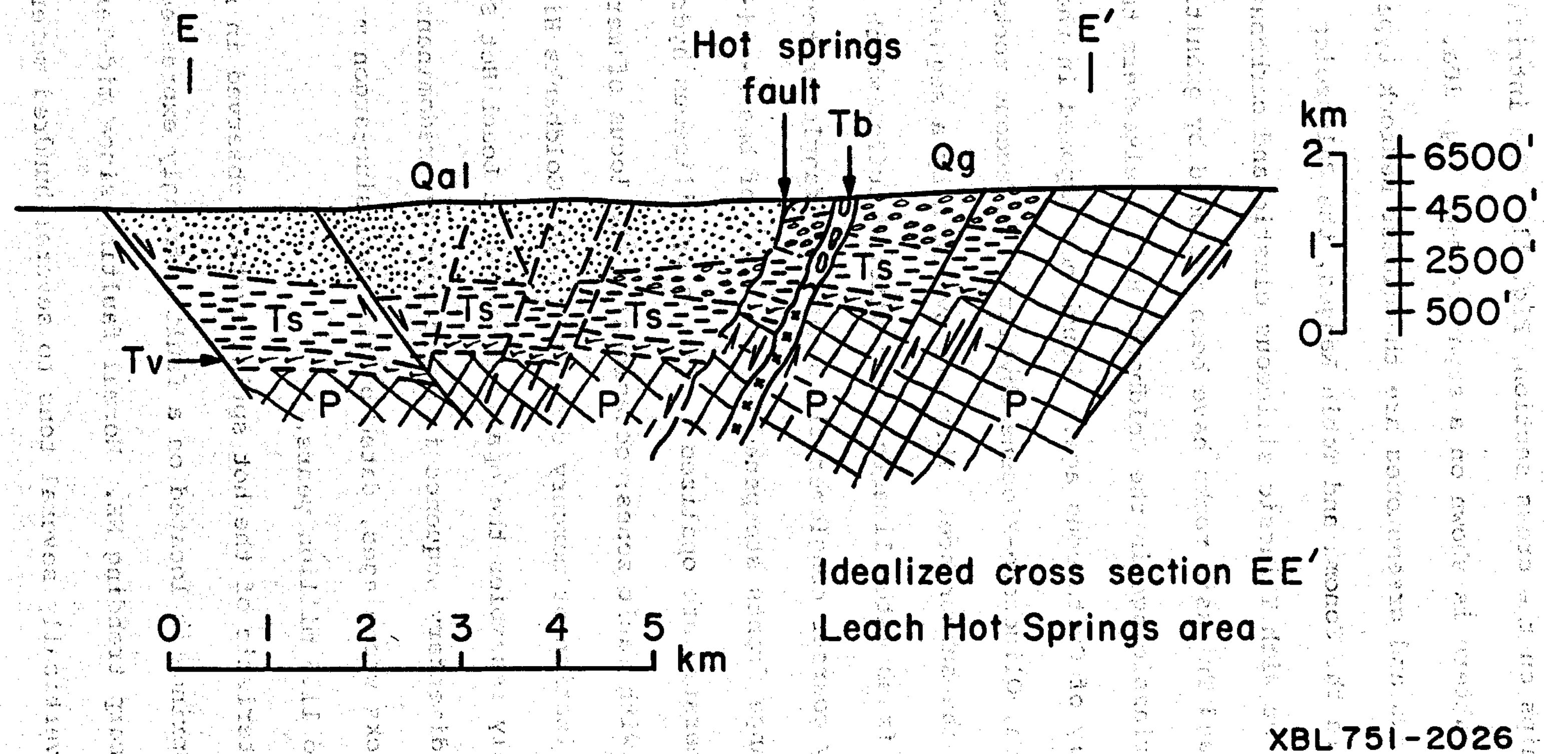

Fig. 11. Idealized geologic cross section along E-E' (fig. 18) Leach Hot Springs area. Qal: alluvium, Qg: gravel and fanglomerates, Tb: basalt, Ts: Tertiary sedimentary rocks, TV: Tertiary tuffaceous rock, P: undifferentiated Paleozoic sedimentary rocks.

region is illustrated on the geologic map (Fig. 10) and their stratigraphic relationships on the cross section, Fig. 11. The intricate fault and lineament pattern is shown on a separate map, Fig. 10a. Paleozoic siliceous clastic rocks and greenstones are the oldest bedrock types in the region. In places in the Sonoma and Tobin Ranges, the Paleozoics are in thrust-fault contact with Triassic siliceous clastic and carbonate rocks. The Paleozoic and Triassic rocks have been intruded by granitic rocks, of probable Triassic age in the Goldbanks Hills; elsewhere the granitics are probably of Cretaceous age. Though not exposed in the Leach Hot Springs area, Oligocene-Miocene rhyolitic tuffaceous rocks are probably present in the subsurface. They are overlain by a sequence of interbedded sandstone, fresh water limestone and altered tuffs, which are in turn overlain by coarser conglomeratic sediments (fanglomerates) derived from mountain range fronts steepened by the onset of basin-and-range faulting. The fanglomerates are opalized in places by siliceous hydrothermal activity associated with fault zones; occasionally the locus of mercury mineralization. Opalization of mercury deposits in the Goldbanks Hills and East Range closely resembles the opalized sinter at Leach Hot Springs. The Tertiary sedimentary sequence is overcapped by predominantly basaltic volcanic rocks whose ages, dated by the potassium-argon method, range from 14.5 to 11.5 million years.

Characteristic of the hot spring systems observed in northern Nevada, Leach Hot Springs is located on a fault, strongly expressed by a 10- to 15-m-high scarp trending NE. Normal faulting since mid-Tertiary has offset rock units vertically several tens to several hundred meters (idealized cross section, Fig. 11). As shown on the fault and lineament map (Fig. 10a), based strongly on air photo interpretation, the present-day hot springs occur at the zone of intersection of the NE trending fault and the NNW-SSE trending lineaments. The zone of intersecting lineaments and scarplets southwest of Leach Hot Springs, between the springs and the Goldbanks Hills, corresponds to an area of appreciable microearthquake activity (Majer and McEvilly[11]), suggesting that active faulting may be associated with hydrothermal activity.

Total surface flow from the Leach Hot Springs system has been measured at 130 ℓ min^{-1} (Olmsted, et al.,[11a]). Surface temperatures of the springs reach 94°C, boiling at their altitude, and water temperatures at depth are estimated to be 155 to 170°C, based on silica and alkali-element geothermometers (Mariner et al.[2]). Material deposited by Leach Hot Springs, presently and in the past, is predominantly SiO_2.

d. Buena Vista Valley

The Kyle Hot Springs area of Buena Vista Valley is situated 35 to 50 km south of Imlay, a crossroads on Interstate 80 approximately 40 km south of Winnemucca. The area occupies a large eastward "embayment" of Buena Vista Valley into the East Range, accentuated by the east-west buttress of Granite Mountain on the south. Pleistocene still-stand shorelines of Lake Lahontan contour the valley a few km west of Kyle Hot Springs.

Pre-Tertiary basement rocks, exposed in the East Range, bordering the site area, are similar in lithology to the Palezoic eugeosynclinal and Mesozoic miogeosynclinal rocks bordering Grass Valley. Felsic igneous rock of Triassic as well as Tertiary age intrudes the pre-Tertiary sedimentary sequence in aptly named Granite Mountain.

Little is known at present about the stratigraphy and lithology of Tertiary strata in the Buena Vista Valley area. If Tertiary strata are

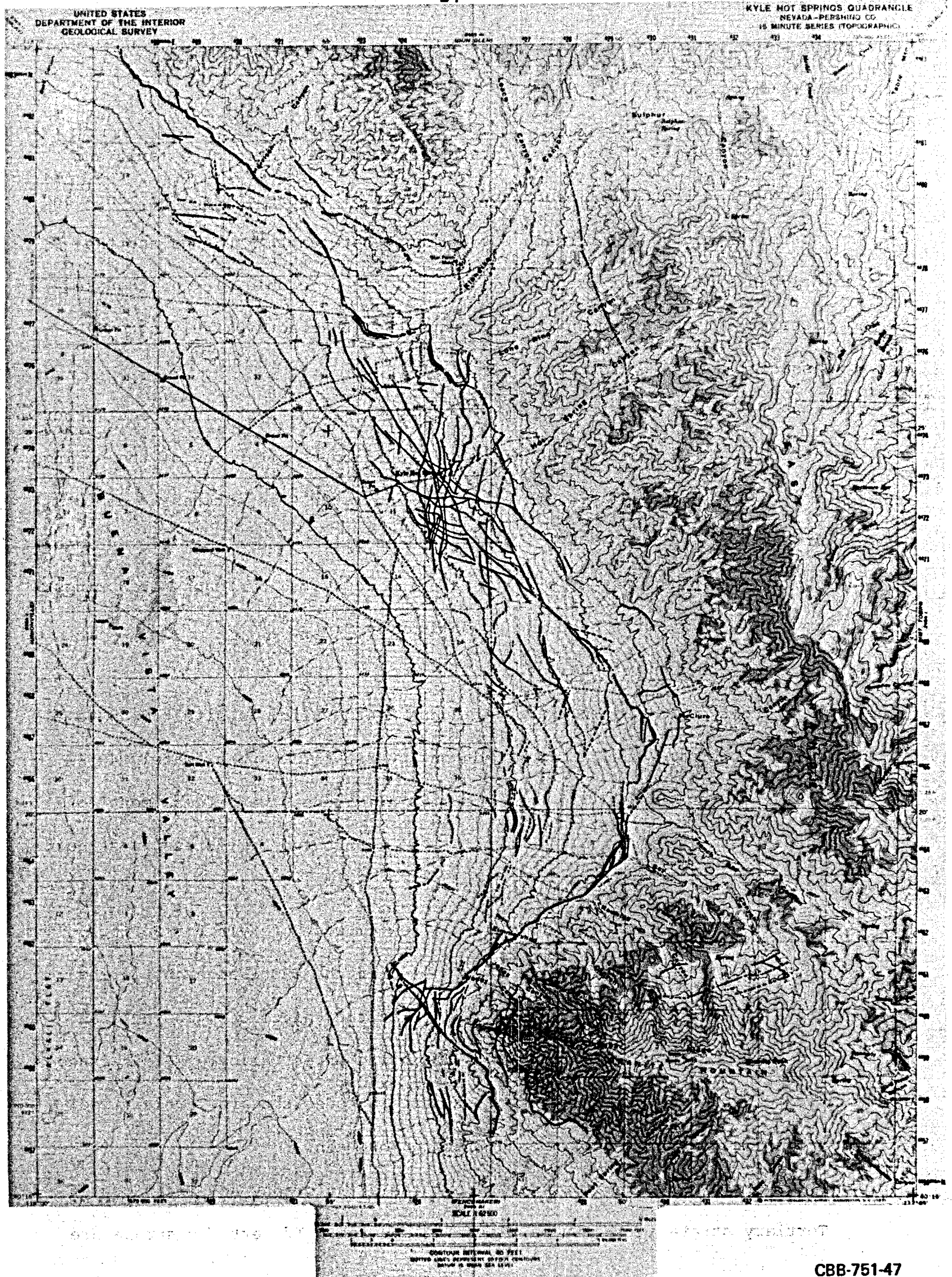

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Fig. 12. Fault and lineament map, Kyle Hot Springs area. Hachured lines indicate down-faulted sides of scarplets. Dashed lines are inferred features.

preserved, the oldest are probably Oligocene and/or Miocene ash flow tuffs and intermediate lavas. These volcanics may be overlain by coarse fanglomerates with interbedded silicic tuffs, similar to those observed on the eastern slopes of the East Range. Basalt, similar to that which now caps the central part of the East Range, may overlie the fanglomerate-silicic tuff sequence. The mid-Tertiary and pre-Tertiary sedimentary rocks are covered by Quaternary and late Tertiary sedimentary material whose thickness increases valleyward from the East Range, reaching 2 to 2-1/2 km in the central part of Buena Vista Valley (Erwin,[12]).

Air photo and on-site observations by Noble[13], indicate that Kyle Hot Springs are localized by intense faulting and fault intersections; these are indicated on the lineament map, Fig. 12. A prominent system of normal-fault scarps follows the western front of the East Range, northward from Granite Mountain, passing east of Kyle Hot Springs. Another prominent fault system trends southward from near the mouth of Klondike Canyon, thence southwestward to pass through the active hot springs. This system continues southwestward through the old, now inactive, spring area. The active and inactive spring areas at Kyle, then, are situated within a belt about 2 km long by 1 km wide which contains an unusually large number of faults and fault intersections. Another intense zone of intersecting faults is apparent in alluvium at the western end and northwestern edge of Granite Mountain. However, fracturing here does not appear as intense as at Kyle Hot Springs; evaluation of geothermal potential must await comparison of geophysical data from the two areas.

The active hot springs at Kyle consist of quiescent pools, developed for bathing and "steaming". Maximum surface water temperature is 77°C;

total outflow is estimated at 20 ℓ/min, and temperatures at depth within the spring system are expected to be between 170 and 190°C, based on chemical geothermometers (Mariner et al., 1974). The active hot springs are presently depositing predominantly $CaCO_3$, though opalized sinter is abundant in older deposits and predominates at the inactive "fossil" hot spring area.

Surface electrical geophysical surveys and a gravity survey are yet to be done in Buena Vista Valley. In contrast to Grass Valley, microearthquake monitoring, by an eight-station detector array in the summer of 1974, did not detect appreciable microseismic activity in the Kyle area.

2. Geophysical Studies

Geophysical efforts to delineate geothermal reservoirs in Nevada have concentrated on techniques to measure the electrical conductivity of an area and to determine its seismicity. The former is important because electrolyte in the pores of a rock increases in conductivity with increase in temperature, and because it has been observed that, in most geothermal occurrences world-wide, the reservoir is of higher conductivity than the surrounding cold rock. The seismic studies are important in determining the location of active faults which are believed to control fluid flow in geothermal areas.

Auxiliary geophysical studies such as self potential and gravity have also been undertaken. These methods have provided valuable data for interpreting the geological structure of the area and some of these may prove to be useful for direct reservoir detection. Studies of the spatial variations in seismic ground noise, in several frequency bands in the 1 to 30 Hz range, are being pursued to test the feasibility of this technique in geothermal resource delineation. In addition, the effect of geothermal zones on propagation of teleseismic body--and surface-waves is being investigated. Summaries of the geophysical techniques used and results obtained for three of the Nevada study areas are presented below.

a. DC Resistivity

Electrical resistivity may be determined either by measuring the fields produced by a controlled current source or by measuring fields produced by distant natural sources. The most common of the former techniques, termed the resistivity method, is to inject commutated dc current into the ground between two electrodes and to measure the voltage difference produced between two distant electrodes. A reconnaissance version of this method, called bipole-dipole, consists of a large current transmitter with electrodes up to 2 km apart (the bipole), and voltages measured with a roving receiver array using electrodes 100 meters apart (the dipole). Reconnaissance techniques have become the most critical part of the delineation program since the typical geothermal site comprises an area of several hundred square kilometers within which targets for detailed studies have to be selected quickly and efficiently.

In 1973 bipole-dipole surveys covering about 100 sq km at Beowawe and over 200 sq km at Buffalo Valley were completed. About 75% of the area selected for investigation at Leach Hot Springs was surveyed in 1974.

At Beowawe surveys were conducted in Whirlwind Valley and the southward-sloping dissected volanic tableland, south of the Malpais Escarpment. Apparent resistivity contours from a survey based on a current transmitter at a location south of the escarpment (Fig. 13) indicate a conductive zone corresponding to the present-day active hot springs and blowing wells. The

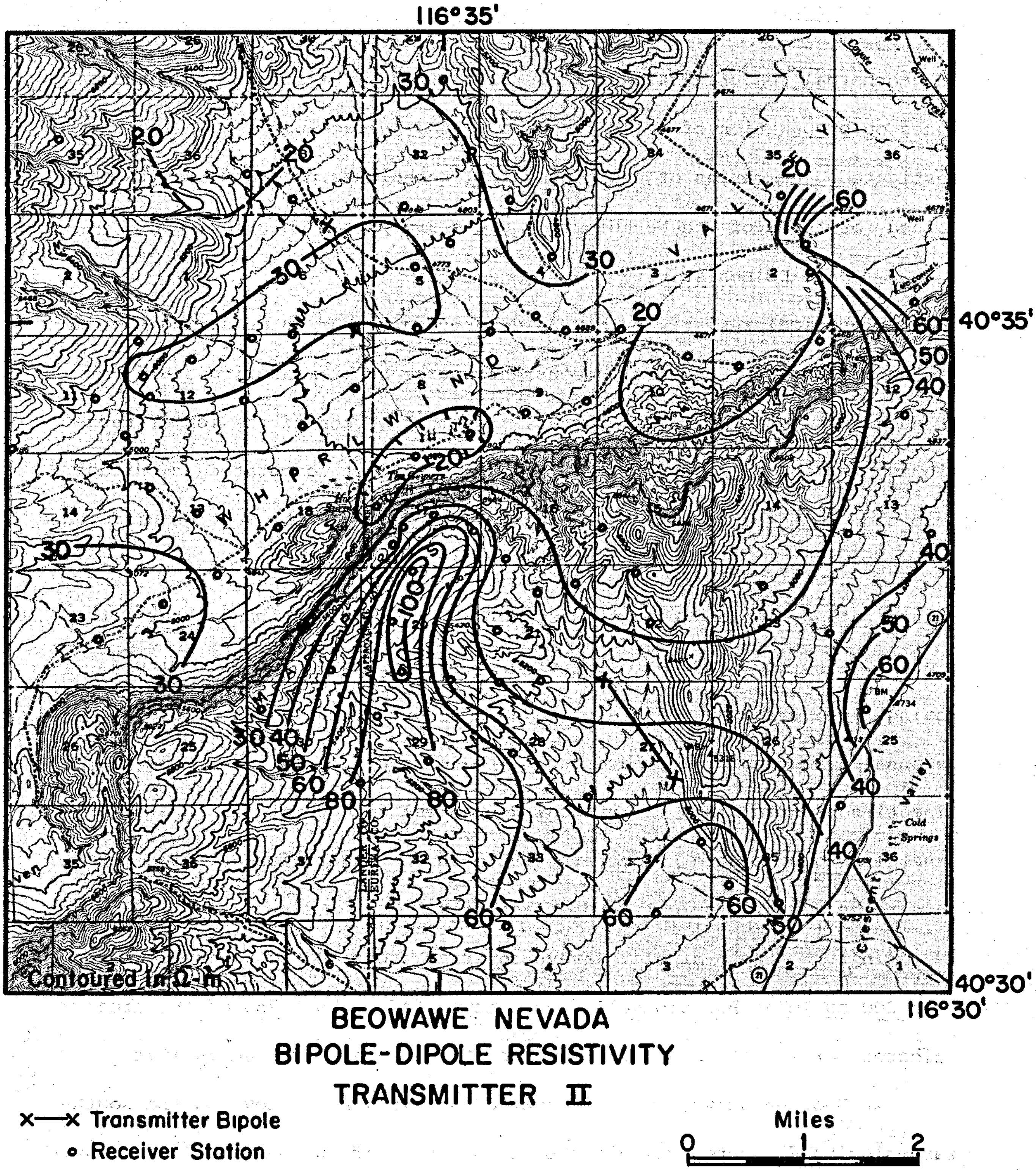

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Fig. 13. Apparent resistivity contours, Whirlwind Valley area; transmitter south of Malpais Escarpment.

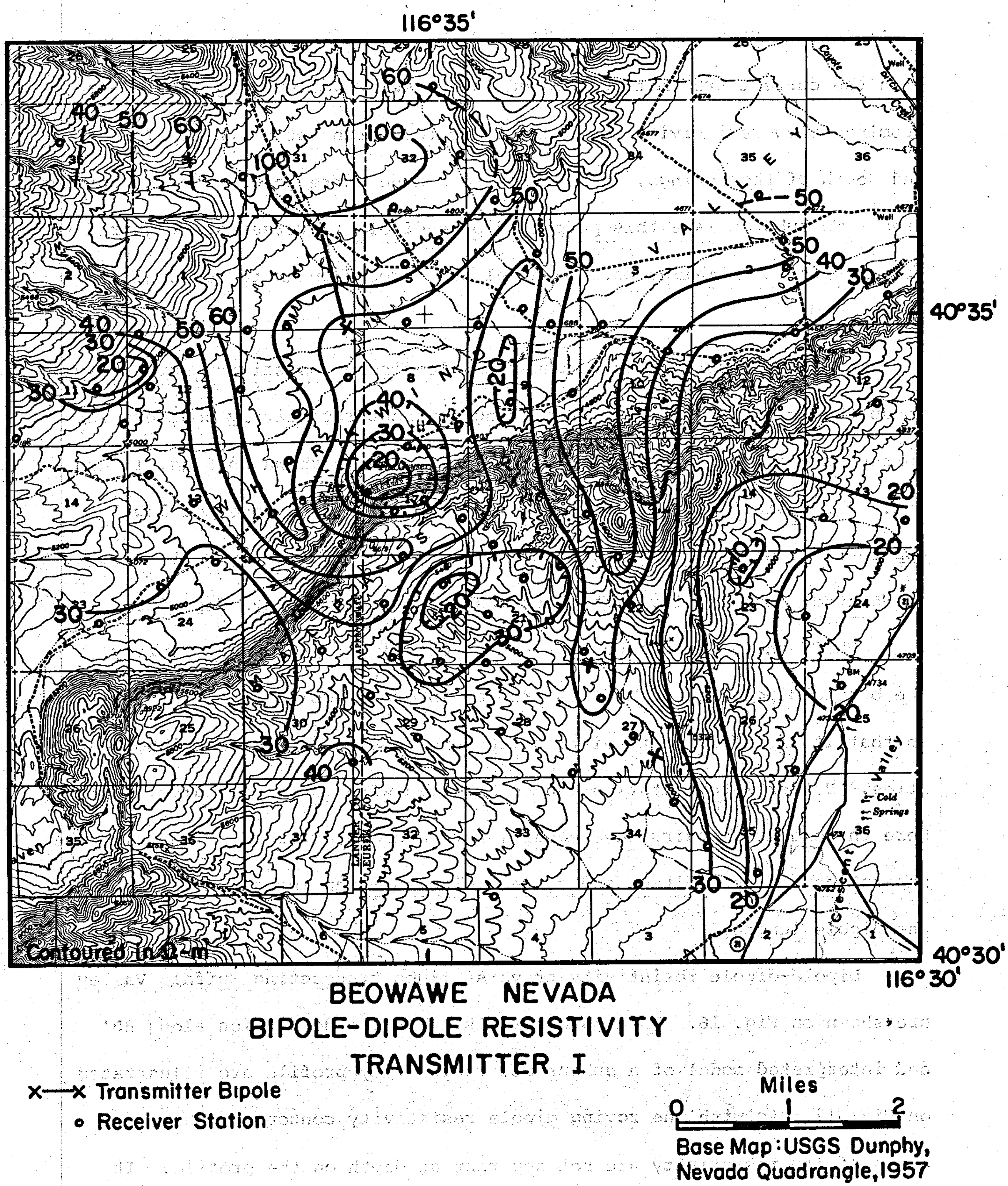

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Fig. 14. Apparent resistivity contours, Whirlwind Valley area; transmitter in Whirlwind Valley.

resistivity pattern is more complicated when contours are based on a survey with the current transmitter located in Whirlwind Valley (Fig. 14). Here, prominent low resistivity zones are indicated northeast of the springs area and south of the springs, in addition to a zone corresponding to the springs area. To substantiate this pattern dipole-dipole traverses are required to transect these anomalies both parallel and perpendicular to regional strike.

Similar to surveys at Beowawe, bipole-dipole resistivity surveys were conducted in Buffalo Valley. Resulting apparent resistivity contours for current-transmitters at two different locations are shown on Figs. 15 and 15a. The resistivity pattern indicates no well-defined zones of low apparent resistivity; instead, rather broad areas of low apparent resistivity associated, most likely, with electrically conductive playa deposits.

While these methods have proven essential for preliminary surveys, the bipole-dipole method suffers from an inherent ambiguity of interpretation in that it is difficult to distinguish between shallow and deep inhomogeneities. Better interpretation can be achieved with the dipole-dipole array. Here the electrode pairs have equal length and are arranged colinearly; the separation between voltage and current dipoles is an integer multiple of the dipole length.

Dipole-dipole resistivity traverse lines transecting Buffalo Valley are shown on Fig. 16. An apparent resistivity pseudo-section along BB' and interpreted model of a subsurface resistivity profile are illustrated on Fig. 17. As with the roving dipole resistivity contours, coherent zones of low resistivity are not apparent at depth on the profile. It may be that the electrically conductive near-surface alluvium inhibits

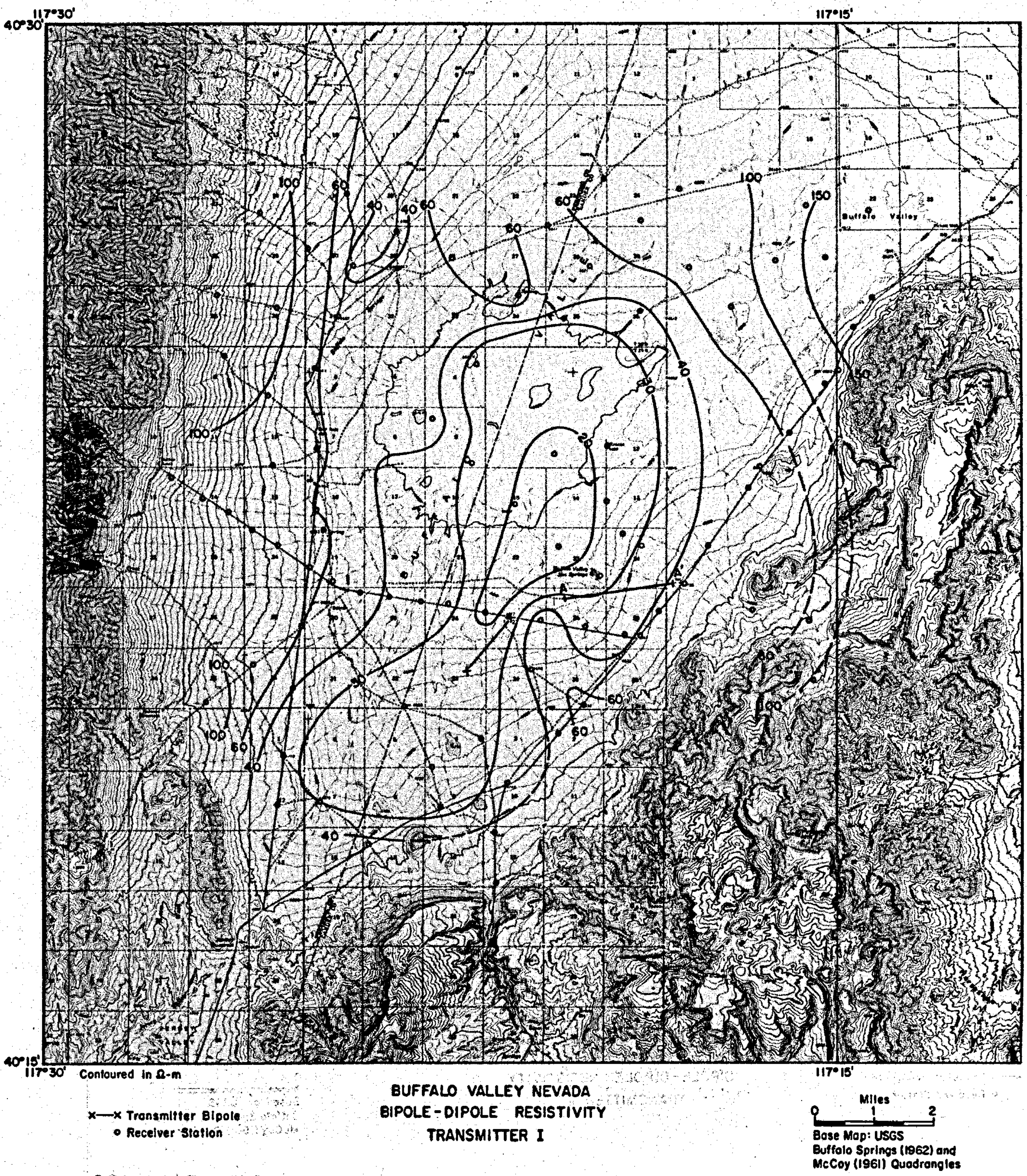

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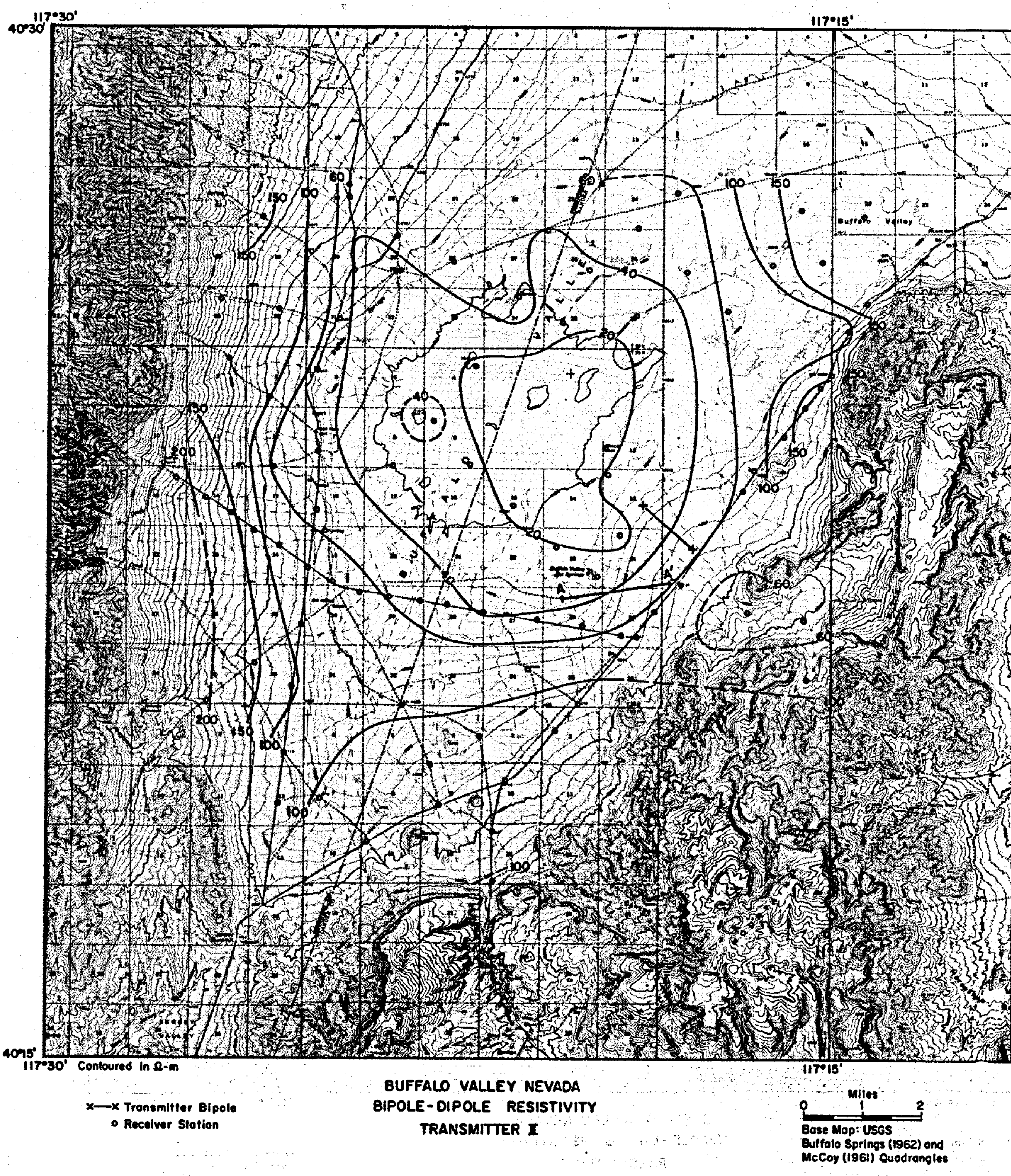
Fig. 15. Apparent resistivity contours, bipole-dipole survey at Buffalo Valley; current transmitter at location I.



XBB 743-1629

Fig. 15a. Apparent resistivity contours, bipole-dipole survey at Buffalo Valley; current transmitter at location II.

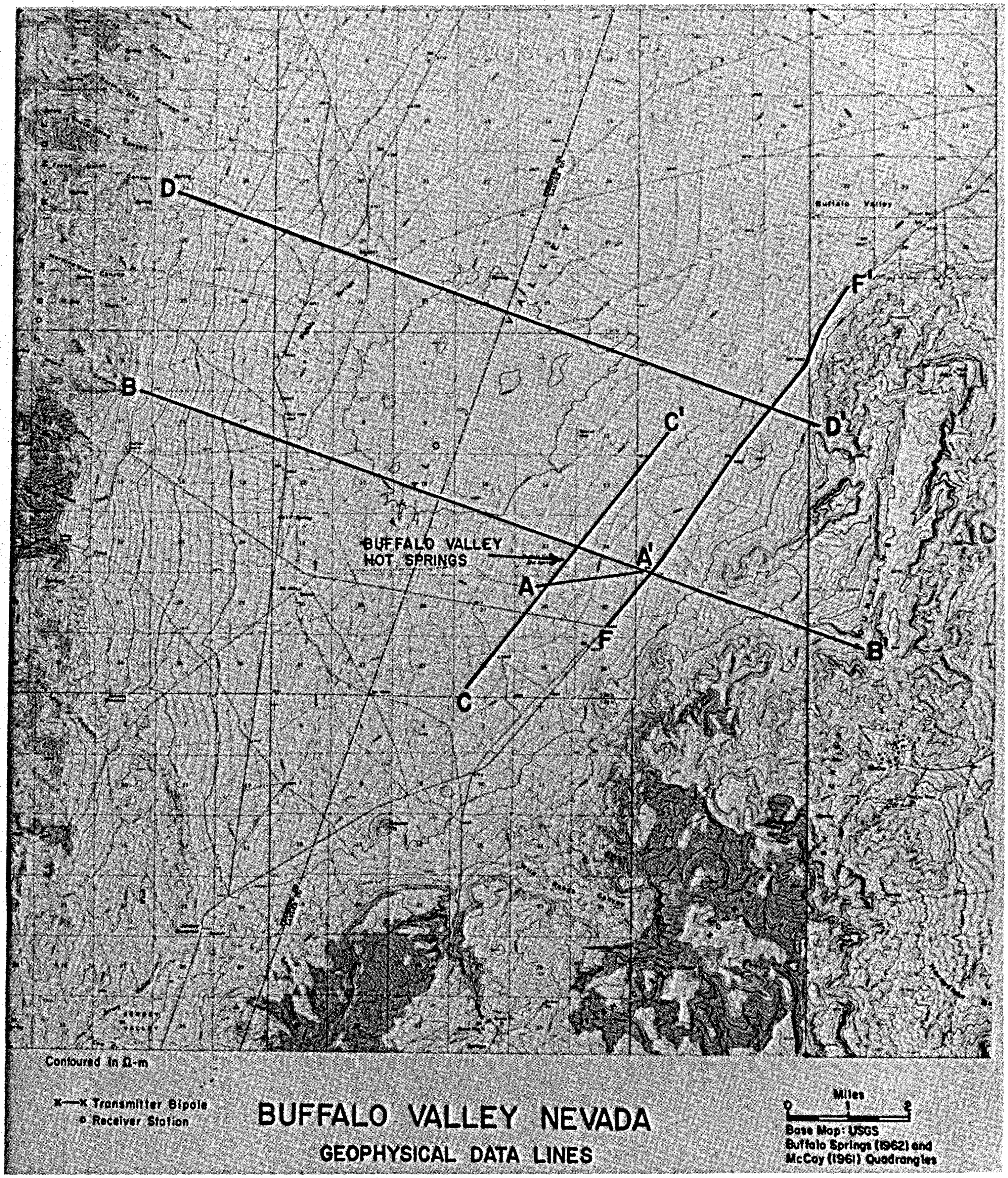


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Fig. 16. Dipole-dipole resistivity profile lines, Buffalo Valley.

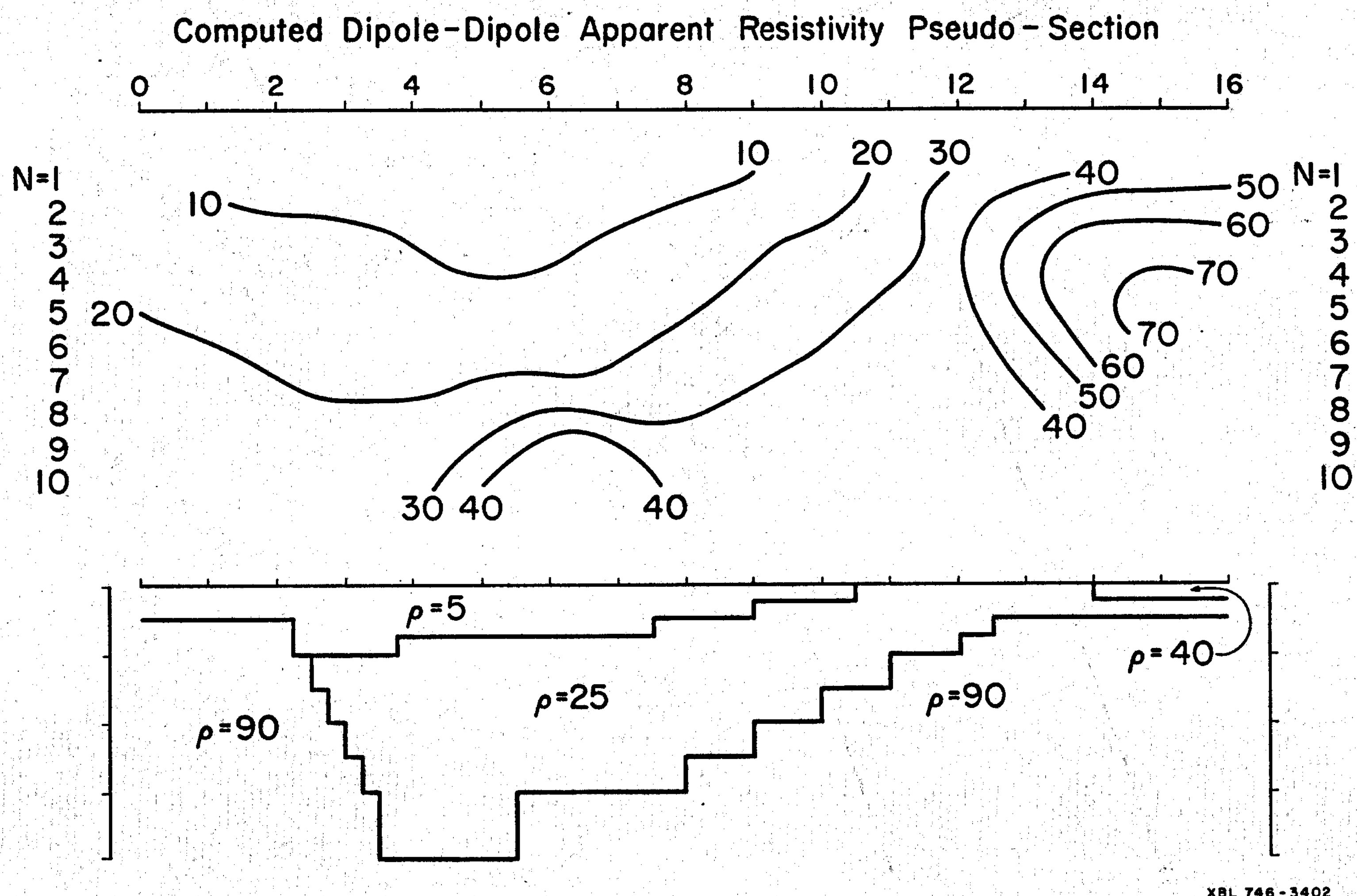

Fig. 17. Computed dipole-dipole pseudo section and interpretation model, profile line BB', Buffalo Valley; values are in ohm-meters.

penetration of electrical current to depths where conductive hot water zones exist. Dipole-dipole resistivity line CC', which passed through Buffalo Valley Hot Springs, indicated a low resistivity zone associated with the springs. Comparison of the resistivity profile BB', the gravity profile (Fig. 9), and the idealized geologic cross section of Buffalo Valley (Fig. 8), shows the configuration of the westward thickening, wedge-shaped prism of alluvium whose thickness is controlled by offsets on normal faults.

The bipole-dipole survey, as well as the telluric current reconnaissance technique described below, showed a complex resistivity distribution along the east side of Grass Valley in the vicinity of Leach Hot Springs. A short dipole-dipole line with dipole lengths of 250 meters and separations up to 3.5 km was run on an east-west profile line, EE', located in Fig. 18, and results, together with the electric field ratio profile, are shown in Fig. 19. This line is the first of many such detail lines which are being run at this location to resolve a rather complex subsurface structure. An example of a satisfactory model for this first line is shown in Fig. 19. Several strong conductivity contrasts associated with intersecting faults are promising candidates for reservoir potential in this area.

Two motor-generators were used for the dc resistivity surveys. In the bipole-dipole mode, a 30 kVA trailer-mounted unit was operated simultaneously with a 60 kVA truck-mounted system. The generator-transmitters are normally located at sites several km apart. Resulting voltages were measured with a clock controlled synchronous detector; the prototype units demonstrated the advantages of electronic signal averaging over manual averaging from chart recorder data.

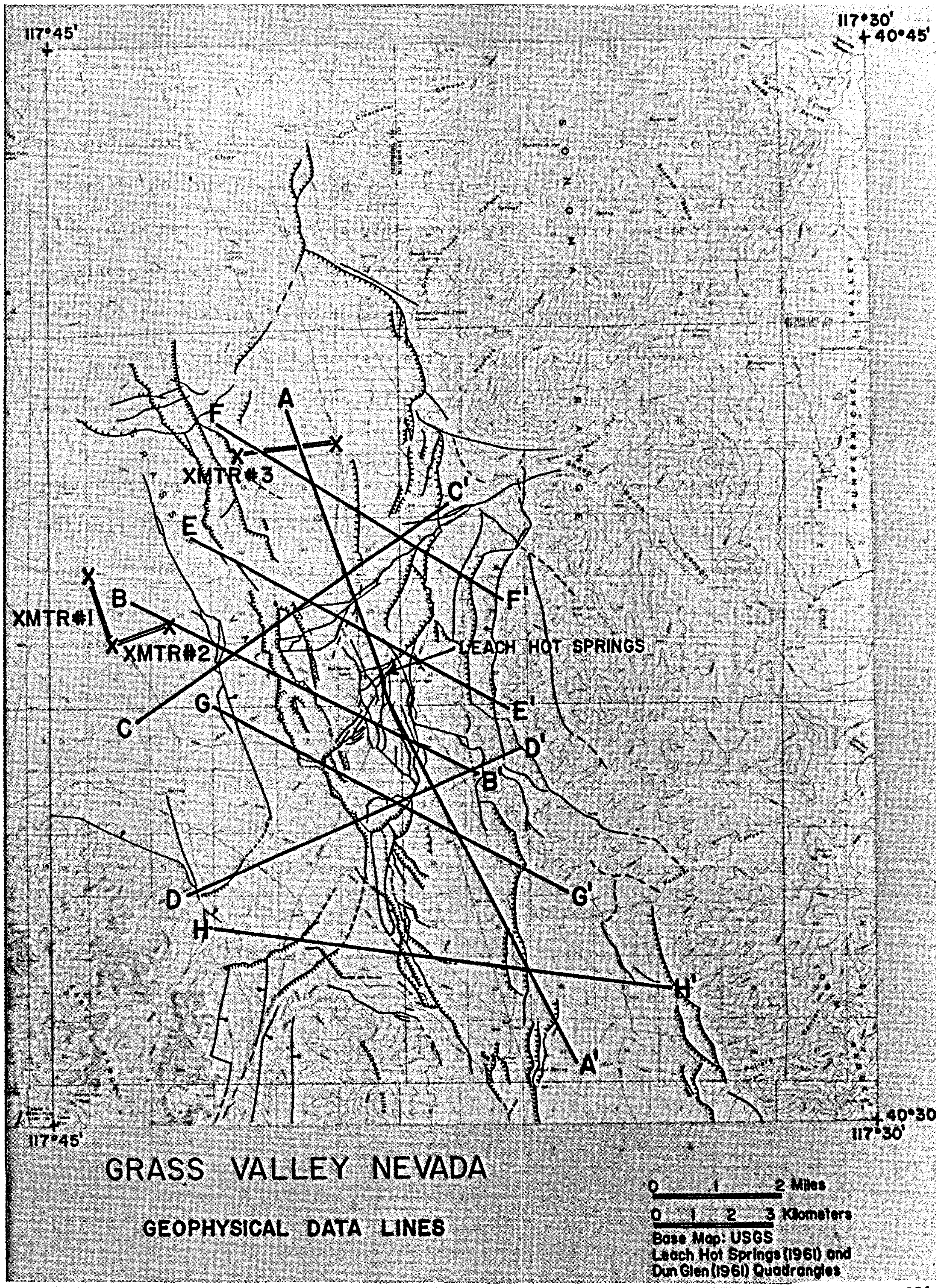

Fig. 18. Electrical geophysical survey lines, Grass Valley. CBB-7410-7621

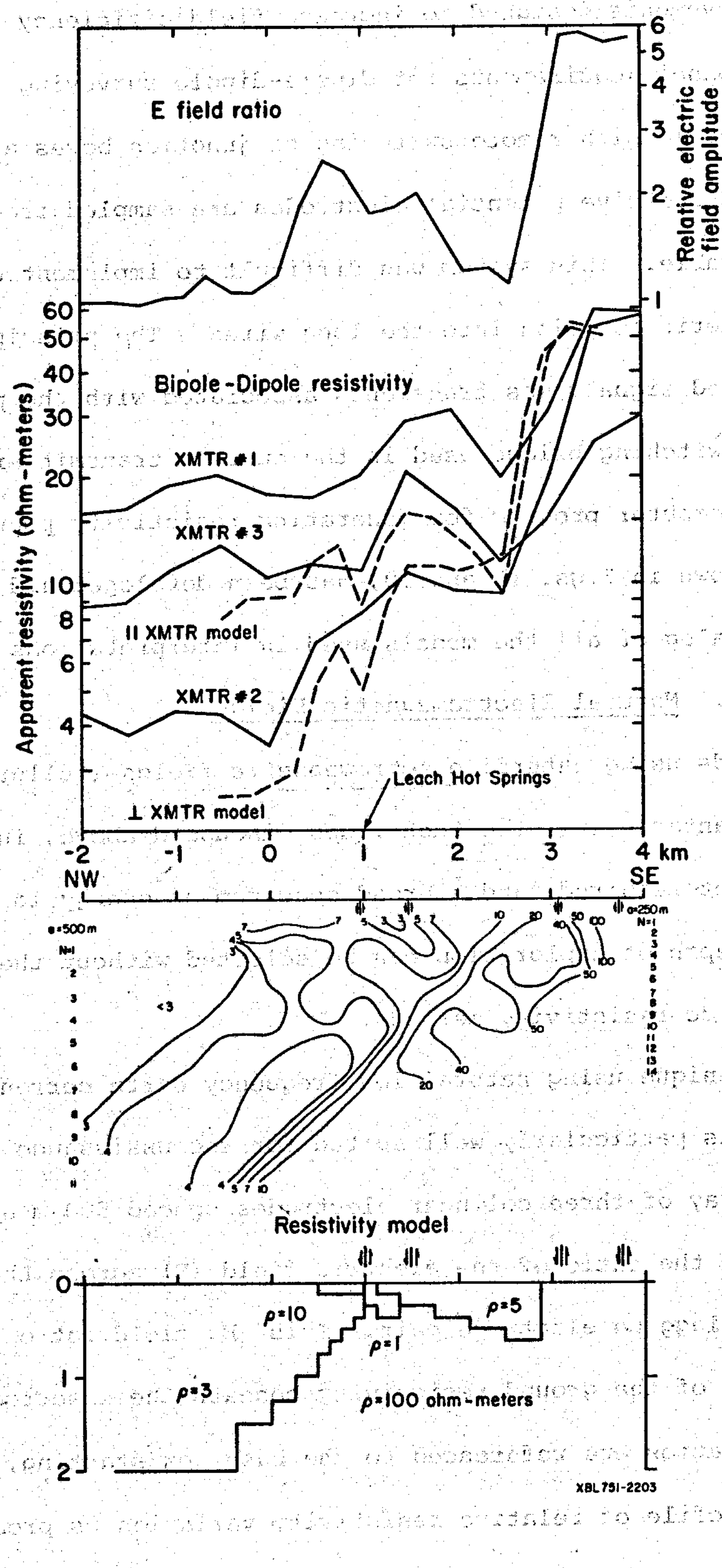

Fig. 19. Electrical field ratios, bipole-dipole profiles, and apparent resistivity model, along line E-E', Grass Valley.

Improvements designed to increase field efficiency and decrease field personnel requirements for dipole-dipole surveying include a multiple-conductor cable with remote switching of junction boxes at electrode locations. Successive potential electrodes are sampled from a single position along the cable. This system was difficult to implement due to excessive electromagnetic coupling into the long wires. The principal source of these coupled signals was transients associated with the particular form of rectifier-switching bridge used in the current transmitter.

Suggested improvement

The computer program for generating resistivity pseudo sections such as those shown in Figs. 17 and 19, has been developed and is in routine use. A catalog of all the models used in interpretations is being compiled.

b. Natural Electromagnetic Fields

Methods using natural electromagnetic fields (telluric methods) have obvious advantages over the techniques discussed above, in that a current source is not required, and a broad spectrum of energy is available. Therefore, the depth of exploration can be selected without the need large arrays required in dc resistivity methods.

A technique using natural low frequency earth currents has been developed which is particularly well suited for reconnaissance surveys. A leap-frogging array of three colinear electrodes spaced 500 m apart is employed to determine the ratio of the electric field (E) across the leading electrode pair to the lagging electrode pair. This E field ratio is proportional to the ratio of the ground resistivity beneath the electrode pairs. Successive ratios are referenced to the base, or starting, electrode pair so that a profile of relative resistivity variation is produced.

The voltages of the leading electrode and the lagging electrode with respect to the center electrode are fed, respectively, to the x and y inputs of a small battery operated x-y recorder. For a monochromatic signal the ratio is easily taken as the slope of the resulting x-y plot.

When the ground becomes highly anisotropic it can be shown theoretically that the E field ratio becomes dependent on the polarization of the magnetic field inducing the earth currents, especially if the direction of the profile is not in the maximum earth current direction. Further, it was found that the ratio is a function of frequency so that if more than one frequency is present the x-y plot becomes a Lissajou-like figure for which a slope cannot easily be estimated.

The field procedure, then, was to take data in profile lines that were approximately parallel to the maximum earth current direction as determined from an initial study using an orthogonal electrode array. Narrow band filtering was used to eliminate the multiple frequency effect. The dominant frequency was determined from a chart recording of the telluric field as a function of time, and an appropriate band pass was selected about this center frequency. This passband would then be used until the data quality deteriorated, at which time the frequency content would again be measured. Several x-y plots were taken for each location so that a mean slope and standard deviation could be calculated. The ratios obtained with these techniques are generally good to plus or minus 5%.

The method is very successful in defining major conductivity variations, especially when compared to the reconnaissance dc resistivity methods. An example of this is shown in Fig. 20, comparing the bipole-dipole, telluric and dipole-dipole data along line BB' at Buffalo Valley. The bipole-dipole resistivity values for two different transmitters are

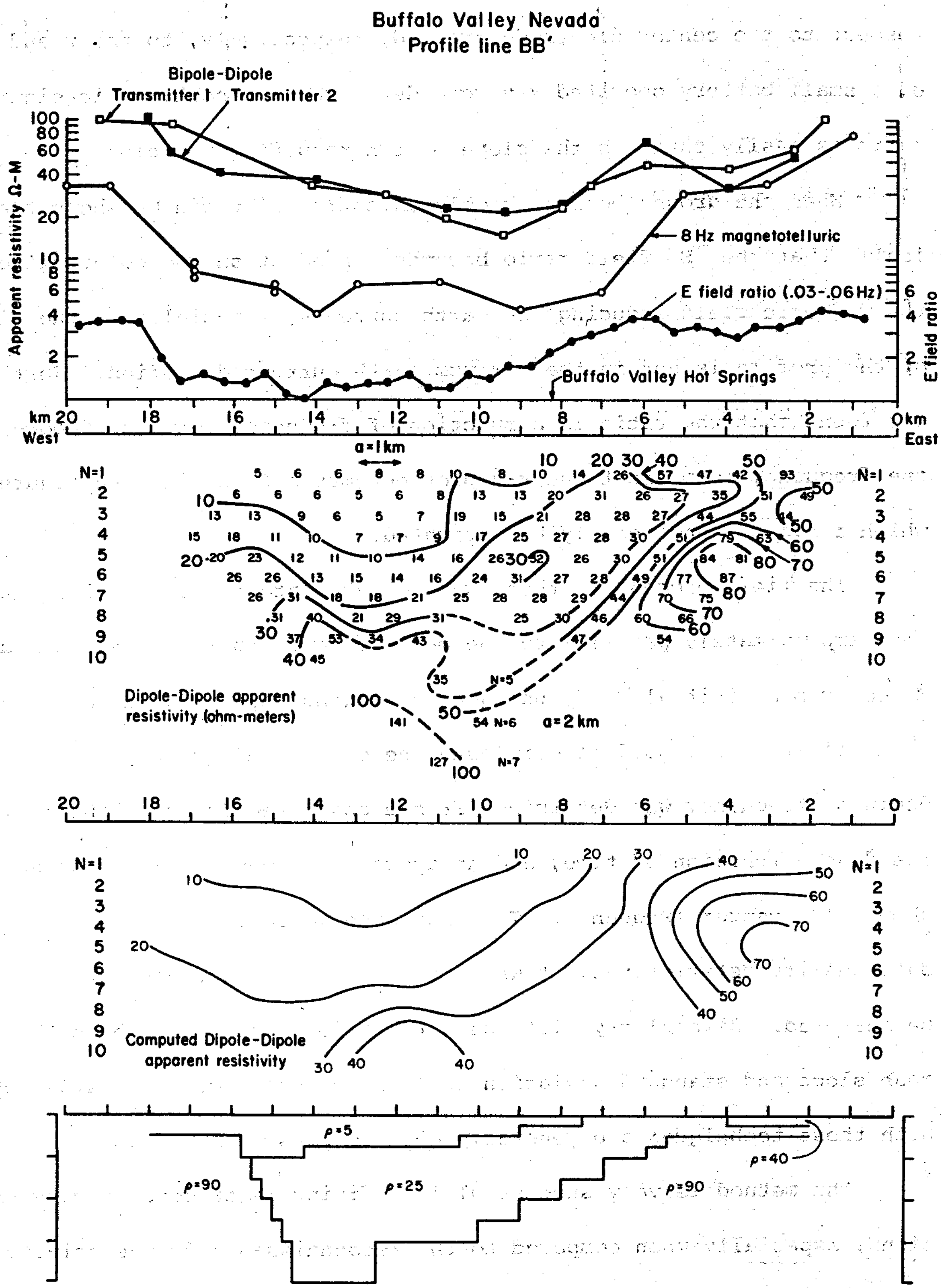

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Fig. 20. Apparent resistivities, electrical field ratios and resistivity models along profile line B-B', Buffalo Valley.

interpolated onto line BB' from the contour maps of bipole-dipole data.

Similar excellent agreement between bipole-dipole data and telluric data has been obtained on 76 line km of telluric surveying at Leach Hot Springs. A comparison of the telluric, bipole-dipole and dipole-dipole data is shown in Fig. 19. The telluric method described here requires very simple portable equipment and is operated by only two men. The conclusion that it can be used to replace bipole-dipole surveys, which require heavy high-power generators, electrode emplacement, and a minimum of four men, is a significant advance in geothermal exploration.

The magnetotelluric method is a more quantitative method using natural electromagnetic fields. In this method an apparent resistivity of the ground is calculated from a measurement of the surface impedance, E/H, of the incident electromagnetic fields. The method is preferable to the telluric method because measurements can be made at a convenient grid of points over the area of interest rather than along a profile, and because absolute values of resistivity are obtained rather than relative variations. Further, the variation of impedance with frequency can reveal, quantitatively, the variation of resistivity with depth in the section.

A new magnetic field sensor, the Josephson effect magnetometer,* was used on an experimental 20 km magnetotelluric profile in Buffalo Valley. This sensor provides sensitivities an order of magnitude better than existing induction coil sensors and is easier to deploy in the field. Using simple narrow band electronics around the natural spectral peak at 8 Hz, and taking only the scalar ratio of the electric field in the profile direction to the orthogonal magnetic field, the values shown in Fig. 20 were

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* The Josephson-junction magnetometer for this survey was loaned to the Engineering Geoscience Group by AMAX Incorporated.

obtained. These apparent resistivities at 8 Hz reflect only the upper half kilometer of the section and agree very well with the short spacing dipole-dipole values.

Magnetotellurics thus promises to provide the best reconnaissance device for geothermal delineation. With improved data acquisition and processing capability it also promises to provide greater detail and conductivity resolution than other reconnaissance tools.

c. Self Potential

Theoretical analysis and some limited field data has suggested that geothermal activity might result in an associated dc field. The sources for these fields are either the motion of conducting fluids in a porous medium or the result of thermoelectric effects. Due to the great variation of the fluid flow properties of rocks, it is difficult to make quantitative estimates of the streaming potentials in given geologic situations. However, self-potential anomalies of several hundred millivolts for known subsurface flow have been observed, and anomalies of 50 to 100 millivolts are often observed in areas of active flow, especially along faults. Thus the flow regime in a geothermal area may have good self-potential expression.

Thermoelectric potentials for a large hot buried sphere, representative of a geothermal reservoir, have been calculated for the site delineation study in Nevada (Corwin[14]). This study showed that values of self potential, negative over the center of the reservoir, as great as 60 mV might be expected; therefore, direct detection of a hot volume at depth might be possible.

Analysis of self-potential surveys in Buffalo and Grass Valleys has been accomplished by Corwin[14]. In general these preliminary surveys have revealed that:

SP is not suitable for hidden Rs

i. Distinct self-potential anomalies are associated with the geothermal activity. Strong anomalies, believed to be associated with upwelling thermal fluids along a prominent fault passing through the hot springs, were discovered.

ii. Electrode response to changes in soil chemistry and moisture content appears to be the major source of irreproducibility and background noise in self-potential surveys.

iii. Long wavelength anomalies associated with deep seated thermoelectric sources would almost certainly be concealed within the noise sources described in ii. and by survey procedure which, in traversing large distances using short electrode spread, accumulates significant error.

d. Gravity

Gravity data were taken on a profile in Buffalo Valley (Grannell[9]) and on the electrical lines in Grass Valley. The required level survey is presently being carried out, so that the field data are not yet reduced to the standard Bouguer anomaly form. A rough reduction based on interpolated elevations taken from topographic maps is in progress. This data will be useful in resolving the complex faulting in the vicinity of Leach Hot Springs.

e. Seismic Studies

Preliminary surveys of September and December 1973 at Buffalo Valley and Whirlwind Valley indicated the existence of microseismicity near Buffalo Valley. Consequently, a project of reconnaissance in the Battle Mountain heat flow high was conducted in 1974 (Majer and McEvilly[11]) using 8 portable smoked-paper MEW-800 seismographs. Recording intervals were as follows:

Buffalo Valley	3-31 July
Grass Valley	1-30 August
Kyle Hot Springs	2-12 September
N. Pleasant Valley	12-15 September

Results of the 1973 surveys indicated that a one-month recording period in each area of interest was required to locate a reasonable number of hypocenters. The field technique was to record initially in a valley with a very wide station coverage, process the data as quickly as possible, then modify the network to concentrate on any clusters of microearthquakes.

Gain levels were generally 108 decibels at good sites (magnification of 1.5 $\times 10^6$ and 6 $\times 10^6$ at 5 and 20 Hz, respectively) with high pass filters set at 30 Hz. In Buffalo Valley, however, 102 dB and 10 Hz filters were required at many sites because of high background noise (due to the larger alluvial filled valley).

At the 108 dB gain level, (4.5 Hz vertical geophones were used), the magnitude threshold (central California M_L equivalent) corresponding to about 2 mm amplitude on the record is approximately -0.5.

Hypocenter location computation was complicated by lack of velocity information in the region and by severe lateral variations in velocity due to the thick valley fill which thins to zero at the valley edge. A series of numerical experiments with P and S wave arrivals was required to determine the best location technique.

The field effort detected two activity clusters, one in Buffalo Valley and one in Grass Valley. Station locations and microearthquake activity zones are shown on Fig. 21. Fifty-three microearthquakes were located out of approximately 100 detected in Buffalo Valley during the recording period. Two methods of estimating the hypocenter locations

Sum

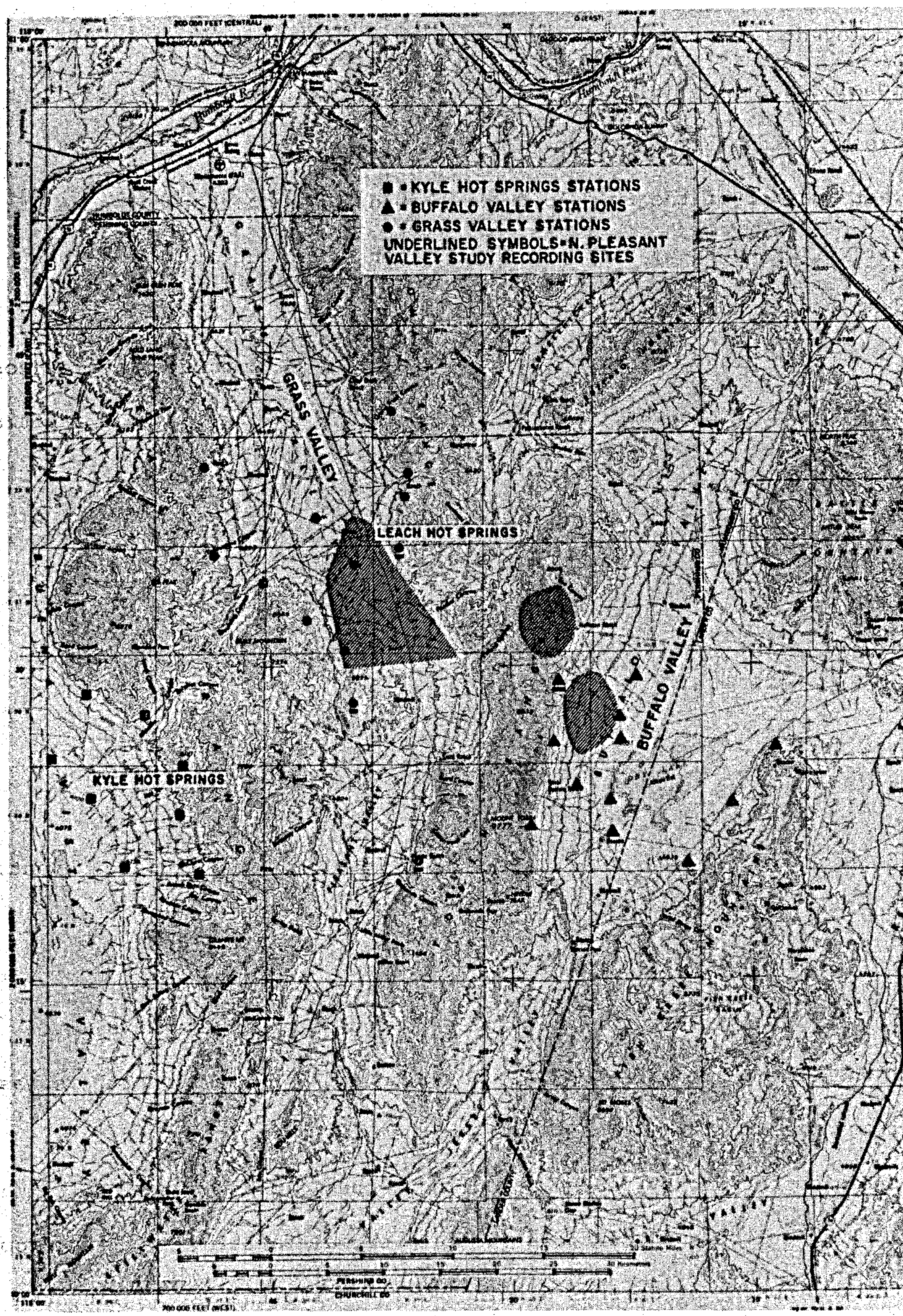

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Fig. 21. Station locations and zones of microearthquake activity (shaded) in north-central Nevada.

were employed: compressional (P) wave arrivals only, and combined compressional and shear (S) wave arrivals. The two different methods did not agree. Using P times only, a cluster of shocks was located in the northwest quarter of the Buffalo Springs quadrangle on the west edge of the valley. Using P and S times, the cluster moved out of the array some 8 km to the northwest into the Tobin Range.

The fault plane solutions using P-locations were indeterminate, consistent with errors in the location of the foci. However, normal faulting along the west boundary of Buffalo Valley is consistent with the data.

Wadati plots (S-P vs P times) indicate normal Poisson's ratio of 0.25 throughout the area. The velocity model adopted for hypocenter locations is:

h(km)	α(km/sec)	β(km/sec)
1	2.8	1.6
3	4.7	2.7
half space	6.0	3.5

Station corrections determined from teleseismic and regional events ranged to 0.25 seconds near mid-valley and were applied to the arrival times.

Thirty-five microearthquakes were located with the Grass Valley array. When the P locations were compared to P and S locations there was general agreement. The microearthquakes seem to be occurring in a triangular region bounded by Leach Hot Springs, the Goldbank Hills and Pollard Canyon. The fault plane solutions indicate normal faulting striking from SW to NE through Leach Hot Springs dipping 45° - 50° to the SE. Again, the velocity structure shows no anomalies; the Poisson ratio is 0.25. The velocity model for Buffalo Valley was used in Grass Valley. Station corrections were not applied in the location computations in Grass Valley.

To check the spatial relationship of the clusters found in the region encompassing Buffalo, Grass, and Buena Vista Valleys, one large-scale array was installed reoccupying several selected stations in Buffalo Valley and Grass Valley, plus an additional station in Pleasant Valley. This configuration permitted simultaneous recording of the larger events in the three valleys.

Five events were recorded and located in a four day period. P and S locations agreed well with P locations and all the epicenters were in the same triangular cluster area found in the Grass Valley study. The same velocity model was used and Wadati diagrams again showed normal Poisson's ratio of 0.25.

In summary, areas of intense microearthquake activity are located in the Battle Mountain high heat flow region. Microearthquake clusters were detected in the Tobin Range west of Buffalo Valley, and in Grass Valley southwest of Leach Hot Springs. There was no appreciable microearthquake activity in the vicinity of Kyle Hot Springs. Hypocenter precision with the reconnaissance network is not sufficient for detailed mapping of fault surface geometry because timing resolution is limited (0.05 sec). Lateral velocity variations are severe in the Basin and Range geologic setting, due to rapidly varying thickness of low-velocity valley fills. Station corrections can be determined from regional and teleseismic P-wave arrivals and some velocity information may be obtained from blasting at local mines.

A 12-station radio linked network has been field tested and is now being used for detailed studies of the seismic activity groundnoise, and variations in velocities and attenuation characteristics in all the above areas. This system will also permit analysis of the ground noise in geothermal areas.

f. Heat Flow Measurements

In the fall of 1974 three holes were drilled in Buffalo Valley, primarily to measure the temperature gradients in and thermal conductivities of soils and rock within the upper 100 meters of valley-fill material. The product of temperature gradient (degrees C per unit distance) and thermal conductivity (cal $^{\circ}C^{-1}cm^{-1}sec^{-1}$) is heat flow (cal $cm^{-2}sec^{-1}$ or heat flow units, hfu).

This is the initial stage of a cooperative heat flow measurement program between the USGS and LBL. At Buffalo Valley LBL contracted the drilling, and USGS completed the holes for permanent access, obtained electrical, radioactivity, and temperature logs, and performed subsequent conductivity measurements.

The hole locations are shown on the geologic map (Fig. 7), and variations of temperature with depth on Fig. 22. Hole #1 was drilled approximately 500 m east of the easternmost pool of Buffalo Valley Hot Springs, in an area of known warmth, disclosed by previous USGS heat flow measurements (F. Olmsted, private communication). The hole bottomed at approximately 62 meters in alluvium after intersecting a ~20-m-thick zone of hard basalt; bottom-hole temperature was 125°C and the thermal gradient observed in the upper 35 m was 149°C km^{-1}. Hole #2 was drilled ~2 km west of the hot springs thermal anomaly, to observe "background" heat flow in valley aluvium away from hot springs. Total depth reached was ~118 m, where the bottom hole temperature was 19°C; observed thermal gradient was

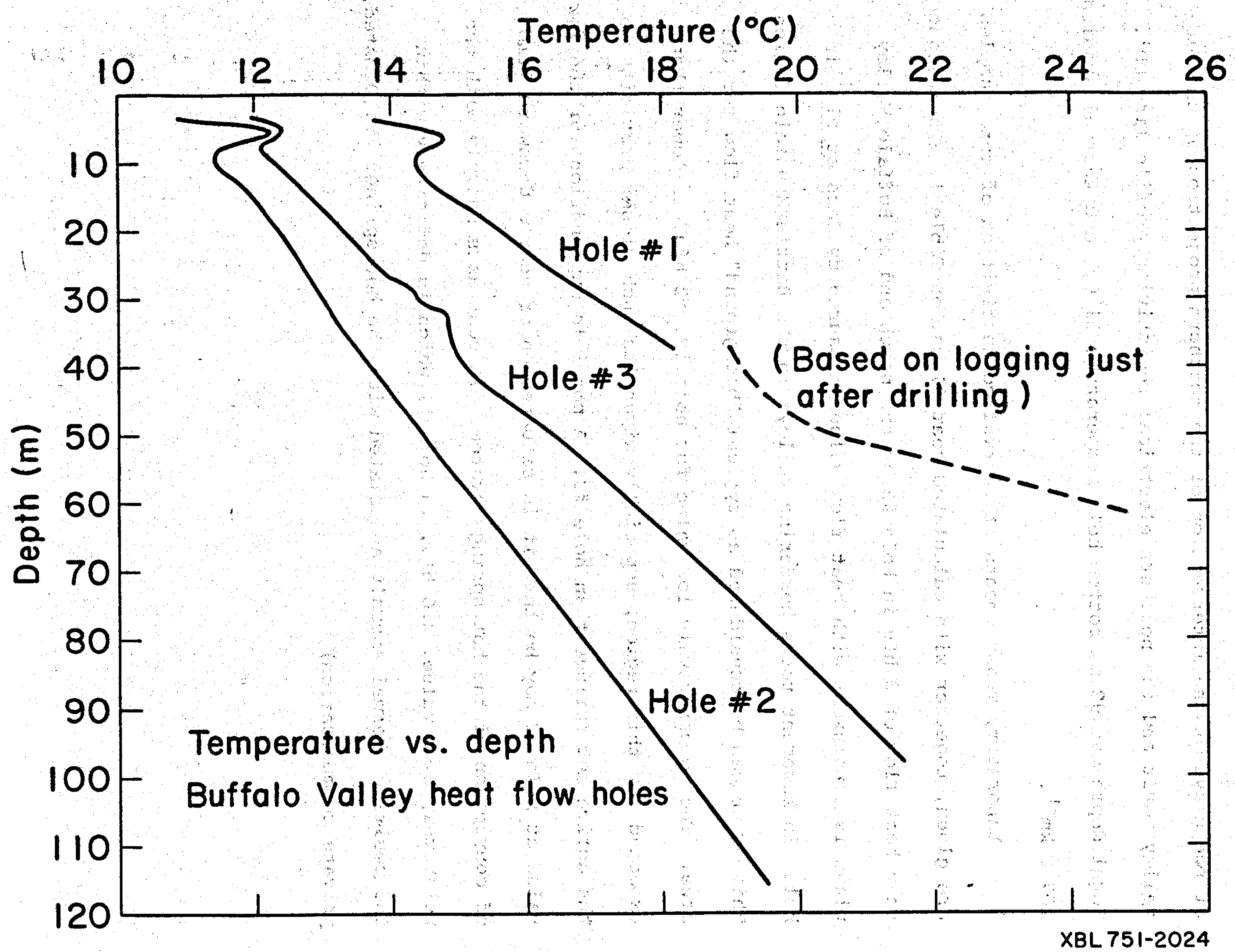

Fig. 22. Downhole temperature logs, Buffalo Valley heat flow holes.

$70^\circ C\ km^{-1}$. Hole #3 was drilled on a low mound in the northwestern portion of the playa at the intersection of the northern projection of the mid-valley fault and the northern electrical resistivity profile line DD'. Total depth was 98 m, bottom hole temperature $21^\circ C$, and thermal gradient $107^\circ C\ km^{-1}$.

Laboratory measurements of thermal conductivities of core samples are given, together with calculated heat flows, on Table 1. The weighted mean heat flow of 3 hfu in hole #3 at the north end of Buffalo Valley playa is consistent with heat flow values measured by Sass _et al._[1] in holes in basement rocks bordering valleys in the Battle Mountain region. This value can be considered as typical "background" heat flow for the area. The comparatively low value for hole #2, ~2 hfu, is lower than expected for this region, especially given its much closer proximity to the active hot springs than hole #3. A possible explanation for the low value at hole #2 may be that it is situated on or near a downward limb of convection of the hot springs system. It contrasts sharply with the relatively high value, 4.6 hfu, in hole #1 which is definitely within the positive thermal anomaly associated with the hot springs (F. Olmsted, private communication).

Table 1. Buffalo Valley Heat Flow

Hole	Lithology	Thermal conductivity (m cal° C^{-1} cm^{-1} sec^{-1})	Calculated heat flow (ucal cm^{-4} sec^{-1})	
1	Basalt, $\rho = 2$	3	4.5	
	Basalt, $\rho = 2.7$	4.5	6.7	4.6 weighted mean
	Silty sand, 62 m	2.65	3.95	
2	Clayey sand	2.5-2.6	1.98-2.05	
3	Silty sand	2.4-2.7	2.6-2.9	3.0 weighted mean
	Silty clay	2.6-3.4	2.8-3.6	

Of added interest is a ~1 to 2 m-wide zone of high gamma radioactivity encountered at about 50 m depth in hole #3, suggesting that radioactive material was deposited in the past by a now inactive hot spring system. An old 215-m-deep test hole, drilled by the Saval Ranch for evaluation of water resources in the west-valley fault zone, will be probed to accessible depth by the USGS in the near future, providing a "background" thermal gradient measurement on the west side of Buffalo Valley.

The absence of anomalously high heat flow in the northern portion of Buffalo Valley, as well as closer to the active hot springs, substantiates the supposition from interpretation of geophysical surveys that a geothermal resource, if present in Buffalo Valley, is relatively diffuse and probably not of high temperature.

In the Spring of 1975, the heat flow program was continued in Grass Valley, in cooperation with the U.S. Geological Survey. Holes exceeding 150m were drilled at seven locations. Initial temperature surveys have been conducted, and results await further temperature measurements and thermal conductivity determinations.

3. Geochemical Studies

Nuclear analytical techniques in use at Lawrence Berkeley Laboratory provide quantitative measurements of elemental abundances in water, rock, and soil samples from geothermal areas. A number of potentially diagnostic elements have been determined which heretofore have not been utilized in geothermal applications.

The major trace, and radioactive element abundances including noncondensible gas contents, of hot and cold spring waters from geothermal resource areas in north-central Nevada are being studied. As well as providing subsurface geothermometry and brine quality data, these studies will serve as a baseline for the evaluation of the environmental impact of geothermal resource development.

a. Analyses of Spring Waters and Associated Rock Units

Water-analysis techniques include neutron activation, soft x-ray (Hebert and Street[15]), and gamma ray spectrometric analysis. These methods are capable of analyzing over 50 elements in a sample if concentrations are great enough. About 15 elements were usually detected in the normally basic hot waters, and substantially more in a single acid pool at Beowawe.

Sampling locations at hot and cold springs in the Battle Mountain high heat flow region are shown on the map, Fig. 23. Preliminary results from initial chemical analyses of hot and cold water systems, and their associated rocks and spring deposits, from four geothermal areas in Nevada suggest that this type of data may lead to indicators of:

(1) The temperatures and rock types within the geothermal system.

(2) The size and depth of the convecting system.

(3) The extent to which hot and cold waters mix.

(4) The amounts of valuable elements and compounds in these waters.

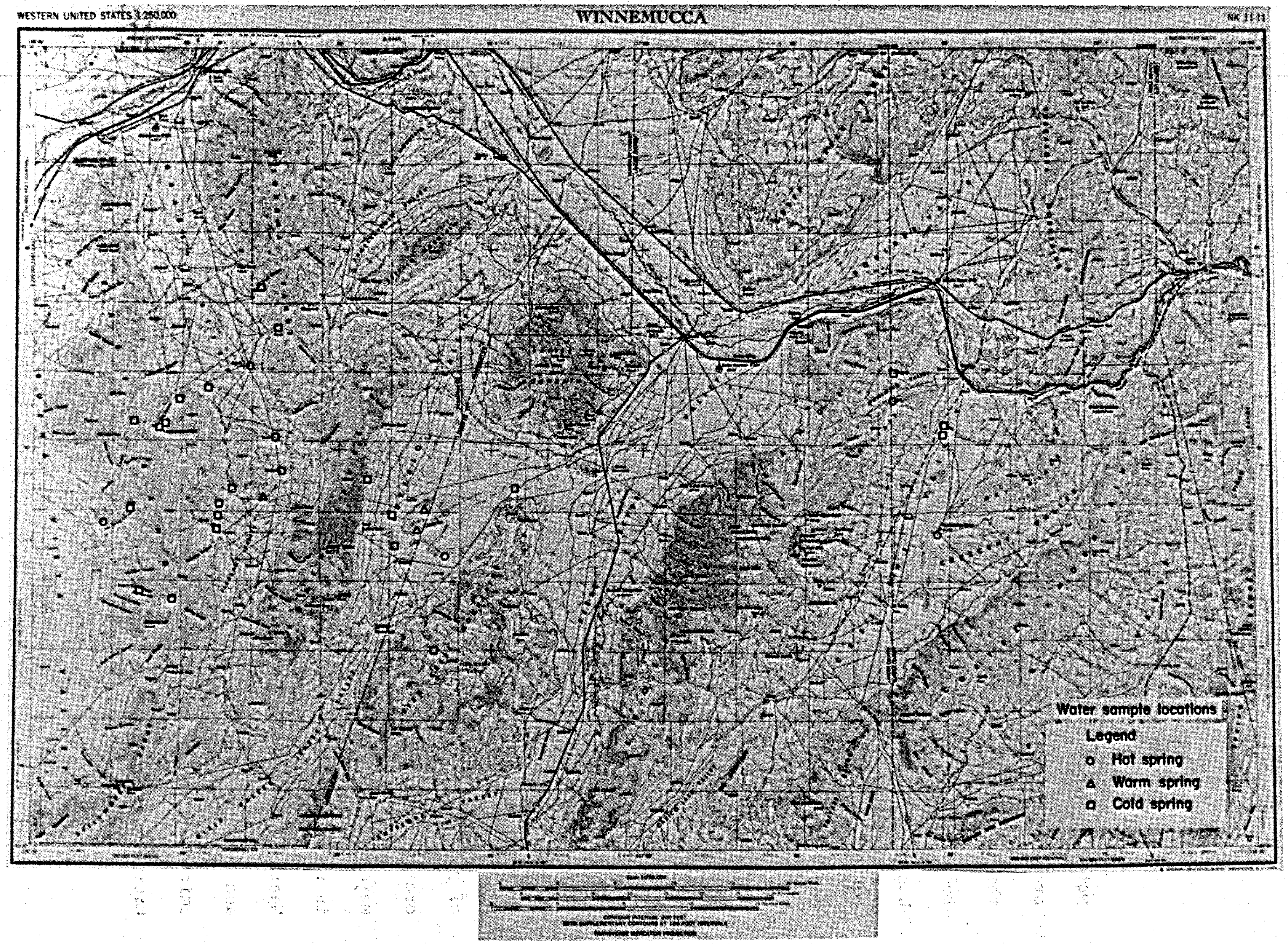

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Fig. 23. Water sample locations, hot and cold springs in north-central Nevada.

(5) The extent to which noxious and hazardous materials are released into the environment.

(i) X-ray Fluorescence Analysis

This technique provides analyses of the major element components of water and rock samples. Drops from filtered or unfiltered water samples are evaporated onto lexan plastic discs, either at the sampling site or in the laboratory. Results of the analyses furnish data for estimation of temperatures at depth in geothermal systems, using the geothermometer based on dissolved silica, as well as that based on alkali element ratios, corrected for calcium content. Silica contents and temperatures of hot and cold springs within a hydrologic region can be entered into mixing models eveloped by Fournier et al.[16], yielding estimates of the degree of mixing of the waters and the temperature at depth of the unmixed hot water. Such an analysis, based on preliminary silica content data for the Grass Valley area, indicates that temperatures of the deeper waters of Leach Hot Springs, prior to mixing with near-surface cold waters, probably exceed 200°C.

(ii) Neutron Activation Analysis

A high-precision neutron activation technique developed for analysis of pottery (Perlman and Asaro[17]), was used in these measurements. Evaporates from water samples and powders from crushed rock and soil samples were made into pellets and irradiated along with a composite standard pellet in the Triga Research Reactor at the University of California, Berkeley. Nearly all elements in the samples have their counterparts in the standard, and the abundances were determined by comparing the activated gamma rays emitted from the unknowns and standards. This method is capable of quantatively analyzing in excess of 50 elements in a sample. In rock samples, more than two dozen elements can be determined with precisions of less than 5%, and a number of these are determined to better than 1% (Bowman, et al.[18]).

Table 2 shows the abundances of some of the elements in hot and cold spring waters measured by neutron activation analysis. Tungsten was unusually high in abundance in the hot waters but not in cold, while conversely, uranium appears to be nearly absent in the hot waters. In two areas, uranium was detected at the level of ∿2 to 5 ppb in cold water and not detected in the hot spring waters. Attempts are being made to correlate the uranium abundances of hot and cold springs with measurements of radon and radium in the springs to determine the minimum age of the hot aquifer and the hot water flow rate.

Figure 24 shows the uranium content of hot and cold springs in the areas surrounding Kyle, Leach, Buffalo Valley, and Beowawe hot springs. The cold springs at Kyle and Leach have appreciable uranium, but uranium was not detected in the hot springs. In a carbonate-dominant hydrothermal system, this might be expected since uranium has a retrograde solubility in the carbonate form. Uranium can also be reduced from the +6 state to the +4 and precipitated in the presence of H_2S.

From these uranium data along with assumptions based on the radium and radon measurements (Wollenberg[19]), one may be able to estimate the hot water subsurface-flow rates or, conversely, the amounts of uranium accumulated at depths.

Buffalo Valley Hot Springs (a)

Figure 25 shows abundances of a number of the more prominent elements found in four separate hot pools at Buffalo Valley hot springs. Sodium

TABLE 2

Elemental abundances and precision of measurement
in hot and cold spring waters as measured by neutron activation.

Location	Sample Identifier	Spring temp (°C)	F/N[1]	U (ppb)	W (ppb)	Mo (ppb)	Sb (ppb)	Ba (ppb)	Na (ppm)	Cl (ppm)
					HOT SPRINGS					
Buffalo Valley	15-1	72°	F	< .16	29±3	< 1	64±4	148±20	264±4	27±2
	15-4	65°	F	< .18	32±4	< 1	40±3	134±20	272±4	25±2
	15-5	68°	F	< .14	34±4	< 1	24±2	127±20	275±4	24±2
	15-6	72°	F	< .08	27±3	4±2	41±3	157±20	263±4	27±2
Kyle	1		F	< .7	80±15	< 2	8±1	550±50	569±13	721±17
Beowawe	10-2	steam	F	< .16	132±14	12±1	10±1	50±17	268±5	64±3
	10-2	steam	[F]	< .6	135±14	12±1	11±1	48±25	265±5	67±3
	10-4	88°	F	< .26	147±15	19±2	13±1	61±24	207±4	56±3
Leach	23AB	75°	F	.10±03	84±10	.8±.7	9.3±.7	186±13	149±2	25±1
	23AB	75°	N	.40±.03	94±11	.9±.6	13±1	286±15	167±2	27±2
	23B	95°	F	< .28	24±3	13±1	134±9	126±20	87±1	12±1
	23B	95°	N	.35±.06	44±5	14±1	156±11	214±22	89±1	13±1
	6-3	94°	F	< .25	75±8	13±1	177±12	182±14	77±2	12±1
	6-1	79°	F	.08±.03	120±2	1.5±.5	10±1	166±11	159±3	26±1
					COLD SPRINGS					
Grass Valley	7[2]		F	1.52±.03	< 1.1	< .7	< .3	121±9	32.9±4	56±2
Buena Vista Valley	#2[3]		F	3.07±.04	< 2	2.3±.8	< .4	87±14	80±2	82±2
	#2[3]		[F]	2.72±.04	< .8	2.7±.7	< .35	47±12	73±1	73±2
Buffalo Valley	#17[4]		F	2.04±.02	3.0±.5	2.0±.3	.5±.1	187±5	17±1	22±1
	#17[4]		[F]	2.03±.03	2.7±.5	1.8±.4	.9±.1	159±7	18±.2	22±1
	18[5]		F	3.4±.5	2±1	2.4±1.0	< 2	69±16	133±2	105±3
	21B[6]		F	.37±.01	.3±.1	< .2	1.0±.4	65±3	5.8±.1	4.1±.3
	22[7]		F	.56±.01	< .7	< .4	< .2	180±5	14.7±2	22.5±.6
	16[8]		F	.14±.02	.9±.6	12±1	< .2	47±10	48±1	47±1
Crescent Valley	12[9]		F	1.44±.06	2.9±.3	3±1	1.0±.4	73±21	192±2	123±4
					COOL - WARM SPRINGS					
Buffalo Valley	19[10]	25°	F	1.1±.02	6.8±.8	14±1	<.6	11±6	76±1	19±1
	20[11]	12°	F	.46±.07	25±3	56±1	<1	58±26	319±4	246±7

Table 2 (cont'd)

Notes

1 F - filtered water sample, N - unfiltered water sample, - indicates duplicate sample.

2 Leach, Mudsprings.

3 Kyle, Kyle cold spring.

4 Buffalo Valley, Buffalo Springs.

5 Buffalo Valley, Buffalo Valley Windmill.

6 Buffalo Valley, Frank and Helen Canyon.

7 Buffalo Valley, near Buffalo Valley Hot Springs.

8 Buffalo Valley, Fish Creek Mountain Spring.

9 Crescent Valley.

10 Buffalo Valley, South Spring, west of Hot Springs.

11 Buffalo Valley, North Spring, west of Hot Springs.

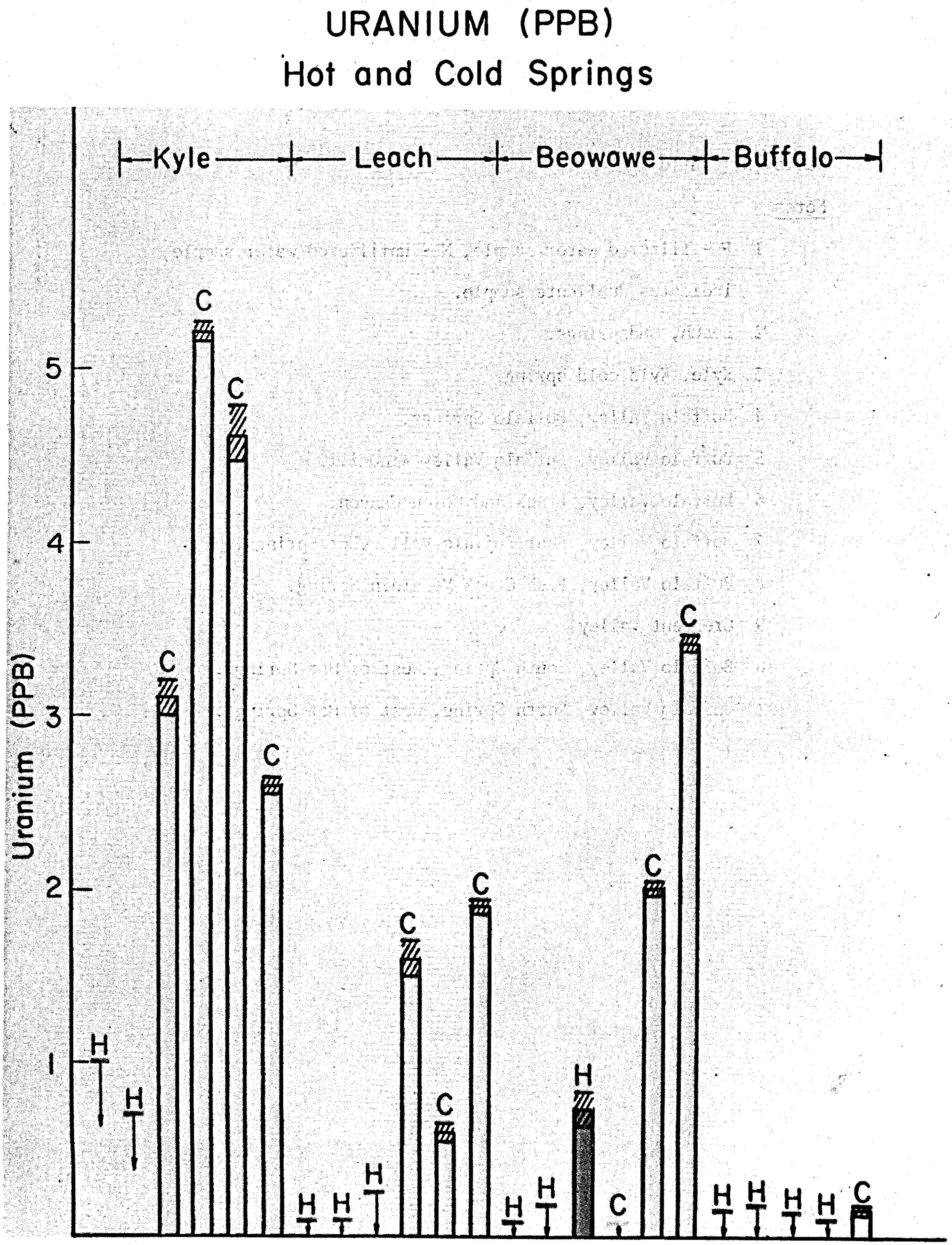

Fig. 24. Uranium abundances (ppb) in hot and cold springs at four geothermal areas in north-central Nevada. C - cold springs, H - hot springs, tails of vertical arrows indicate detection limits.

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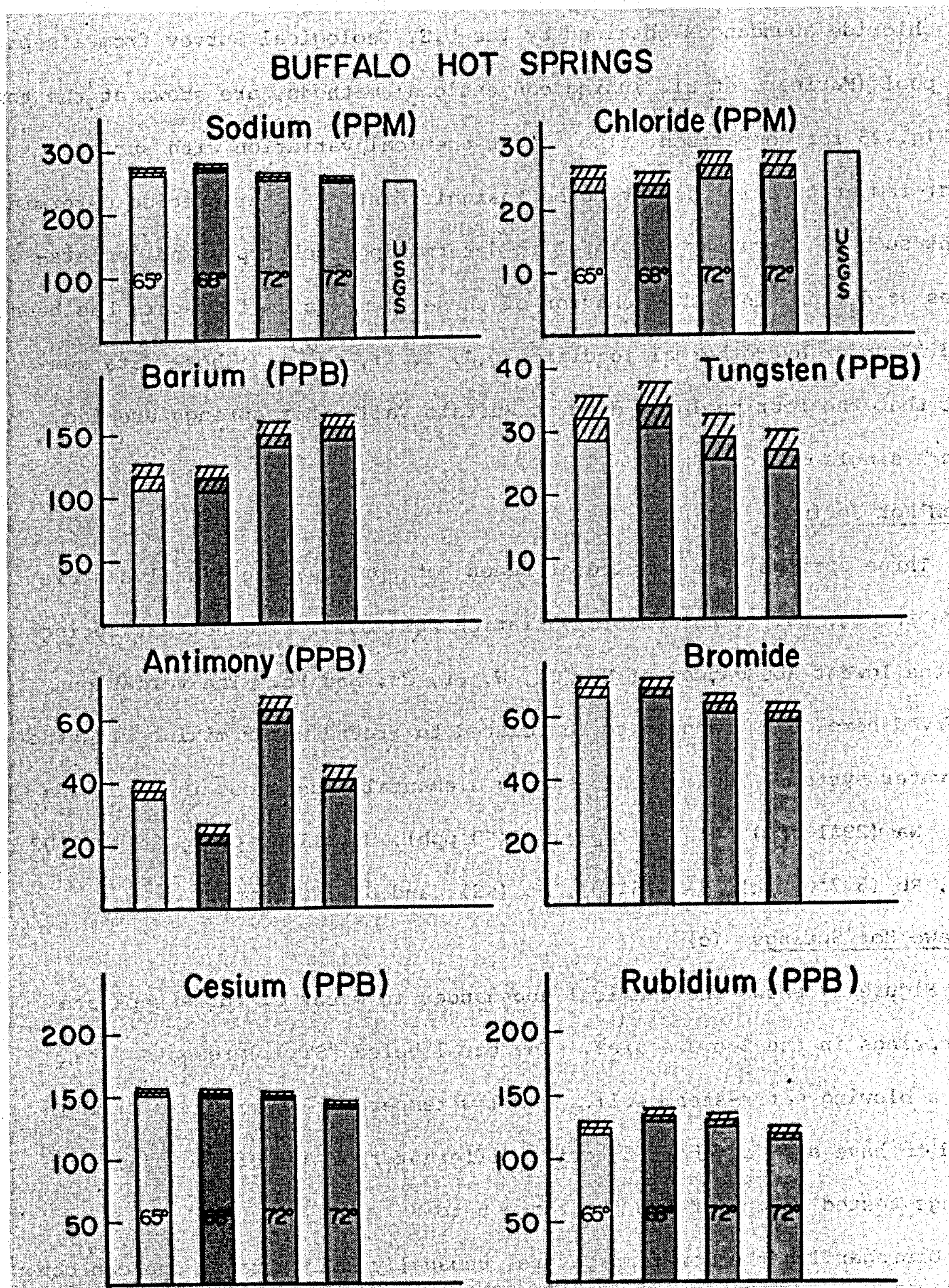

Fig. 25. Abundances of the most prominent elements found in four separate hot water pools at Buffalo Valley Hot Springs. Surface water temperature is shown on each bar graph.

and chloride abundances obtained by the U.S. Geological Survey from a separate pool (Mariner, et al.[2])using conventional methods, are shown at the top of Fig. 25 for comparison. The slight chemical variation with surface water temperature is thought to be insignificant. Rather precise determinations such as these may be useful in determining rock types and temperatures at depths since the behavior of these elements in feldspars has been studied under hydrothermal conditions (J. I. Iiyama[20]). These data suggest that the four pools studied at Buffalo Valley hot springs are fed from a single source.

Leach Hot Springs (b)

Three springs were sampled at Leach hot springs; their analyses are shown in Fig. 26. Considerable variation was found. The hottest spring had the lowest abundances of Na, Cl, W, Br, Cs, and Rb. The variations observed here do not appear to be related to ground water mixing with the hot water system. Typical cold-spring elemental abundances in this area are: Na (29±1 ppm), Cl (56±2ppm), W (<3 ppb), Br (118±2 ppb), Cs (.23±02 ppb), Rb (3.7±6 ppb), Ba (75±10), Mo (<2), and Sb (<0.2 ppb).

Beowawe Hot Springs (c)

Figure 27 shows the chemical abundances in water of three separate hot springs in the Beowawe area. The bar labeled "ST." epresents data from a blowing water-steam well. The low temperature spring (78°C) was found to have a pH of about 3, quite different from all of the other hot springs tested which were in the range 6 to 8.

Disregarding the low temperature, unusually acid spring, one can consider the differences found in the other two sources in terms of groundwater mixing. Elemental abundances for W, Sb, As, and Mo from a nearby

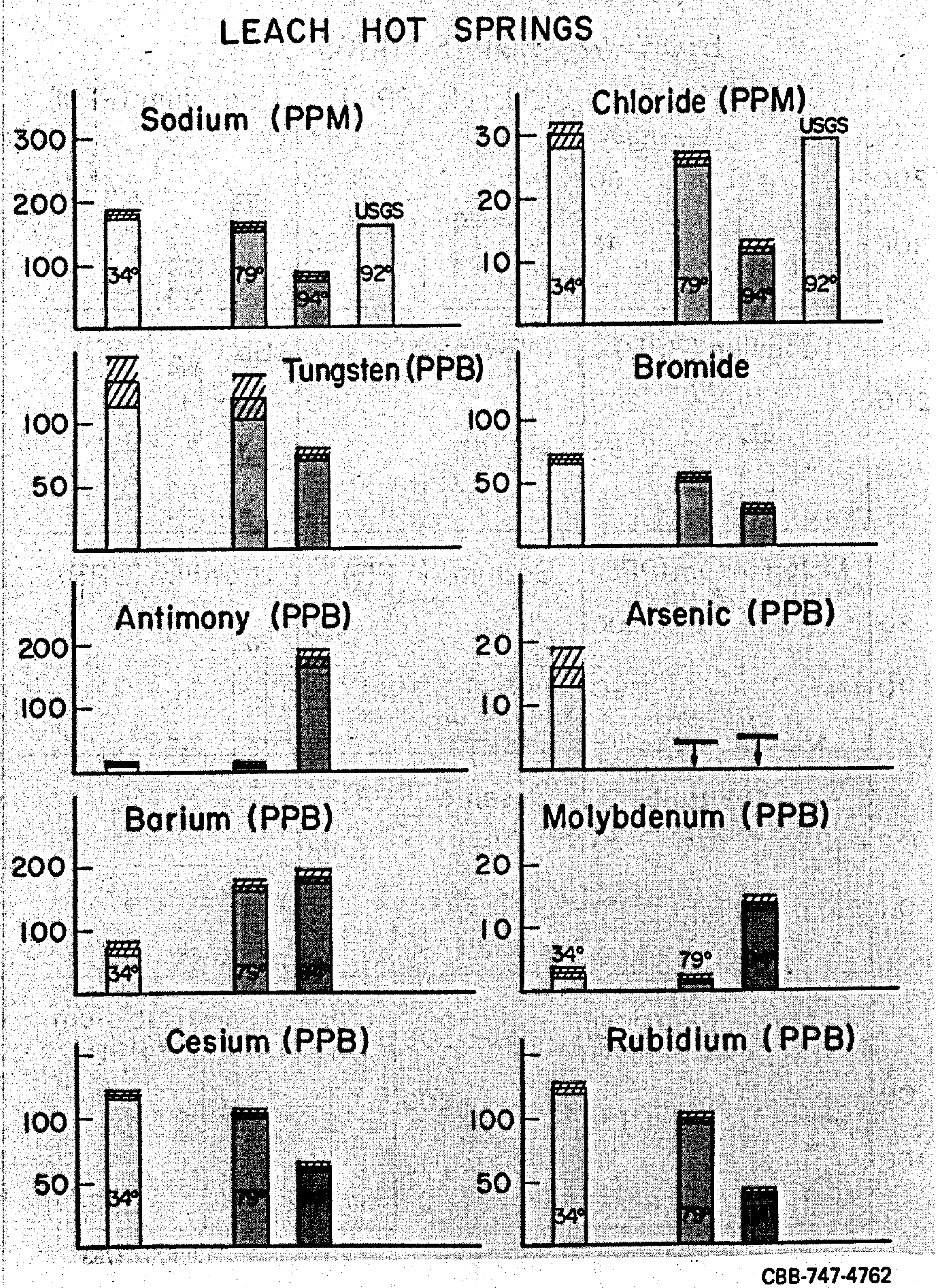

Fig. 26. Abundances of prominent elements in three separate hot pools at Leach Hot Springs.

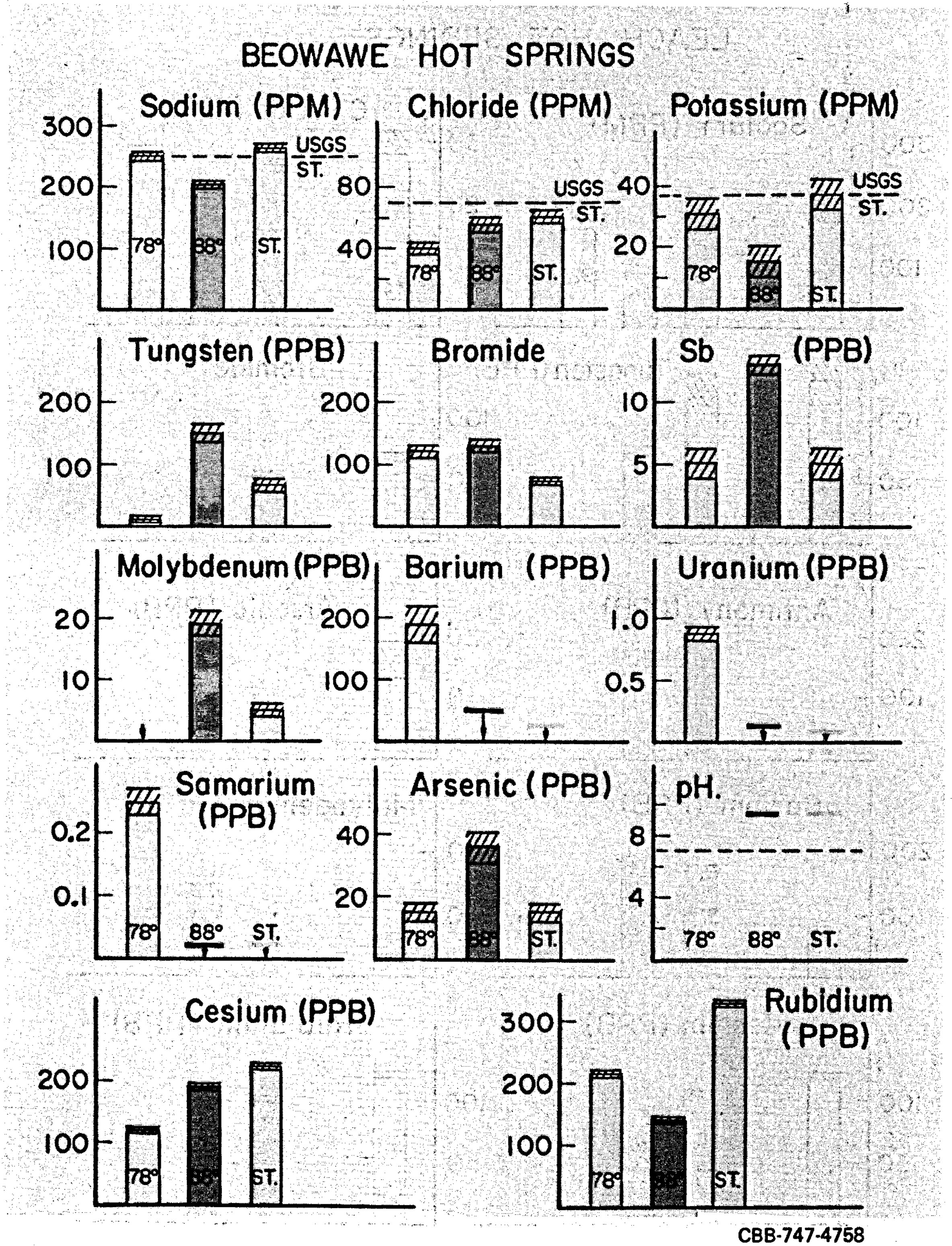

Fig. 27. Element abundances in three separate hot sources at Beowawe. ST - blowing hot-water-steam well.

well were <1, <.3, 4±1 and <2 ppb, respectively. The waters from these pools are probably not responsible for the elemental abundance variations found in the two hotter sources.

Kyle and Brady Hot Springs (d)

Only a single sample was taken from Kyle Hot Springs and a blowing well at Brady. No cold spring samples were taken from the Brady area. The hot water results are shown in Fig. 28. In general, the elemental abundances at Kyle and Brady are much higher than for the other hot springs sampled. Spring deposits at Brady are SiO_2-dominated while the most recent deposits at Kyle are dominated by $CaCO_3$. The greater Ba, Cs, and Rb abundances at Kyle probably reflect the high concentration of $CaCO_3$ in the water.

Rock Analyses (e)

Rock samples from the probable source terranes for the geothermal waters were also collected. The location of sampling sites is shown in Fig. 29. These data are quite extensive. Analyses and interpretation are in progress. Only a brief description of some of the findings is given here.

The very high uranium and thorium abundances in the Fish-Creek-Mountain-tuff near Buffalo Valley reflects its rhyolitic character. Typical uranium values are 20 ppm while thorium is as high as 85 ppm. The high uranium content of this volcanic ash may be principally responsible for the relatively high uranium content of a cold spring in the northeast portion of Buffalo Valley. Many other heavy cations were found to be very abundant in the tuff. Of the rare-earth elements, europium is depleted considerably. This is termed a negative europium anomaly and is

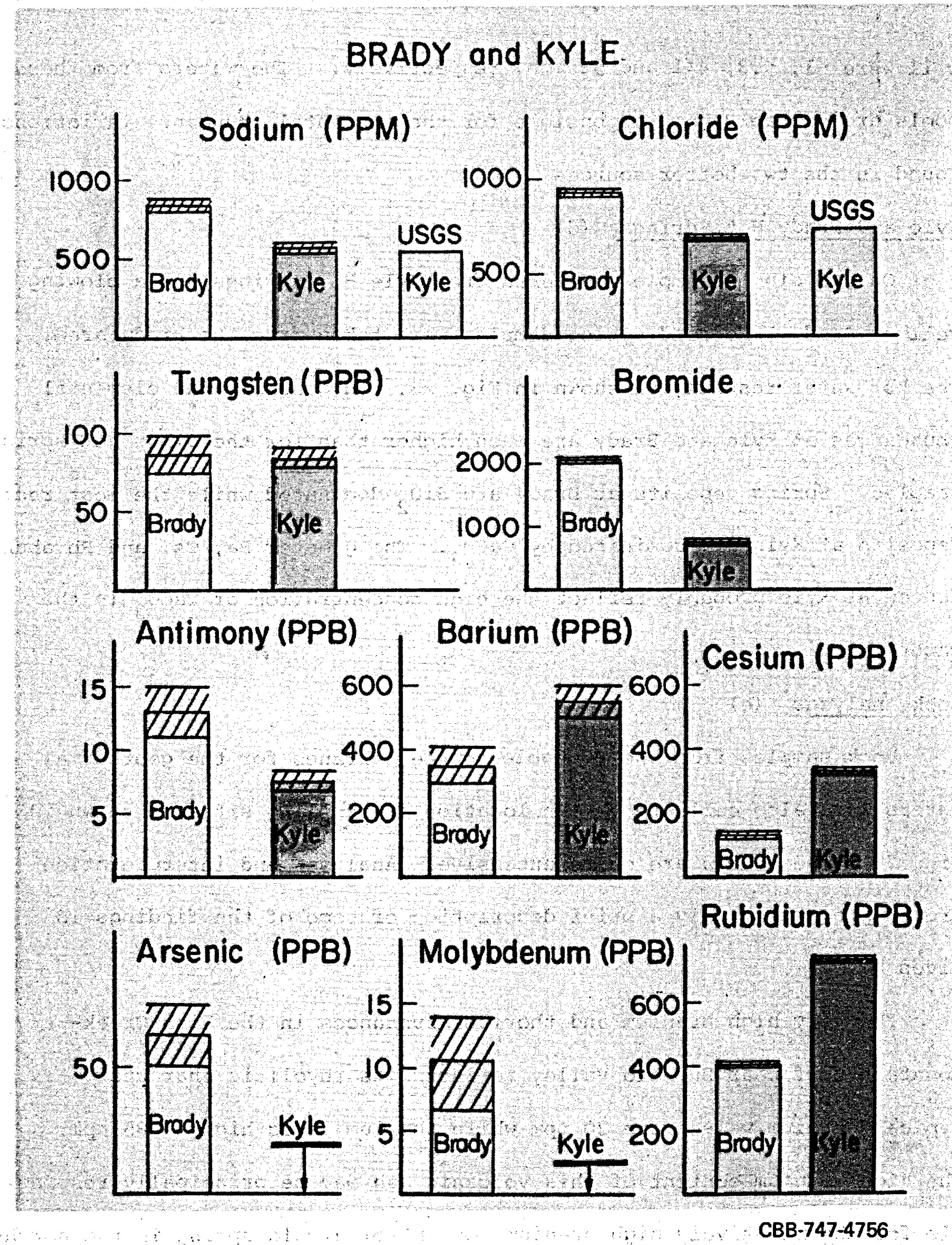

Fig. 28. Element abundances in a hot water pool at Kyle Hot Springs and in water from a blowing well at Brady Hot Springs

quite evident in acidic igneous rocks when their rare-earth contents are normalized to rare earth abundances in chondrites. In general, Eu anomalies in magmas are indicative of extensive differentiation under the low pressure conditions where feldspar is stable (Philpotts, et al.[21]).

b. Geothermal Radioactivity

Early in our geothermal studies hot-spring areas in northern Nevada were visited to evaluate sites for a field program. The radioactivity of the spring systems was studied, with the expectation that knowledge of the distribution and abundance of radioelements may disclose the plumbing systems operating beneath the springs; equally important, an assessment of the environmental impact of a geothermal development project requires an understanding of its radioactive setting. Detailed results were reported by Wollenberg[19].

The hot-spring areas examined to date are shown on the location map (Fig. 30) and are listed by names on Tables 3 and 4. At the sites field gamma radioactivity was measured with a portable 3 in. by 3 in. NaI(Tℓ) scintillation detector coupled to a count-rate meter. Field radioactivities were measured over hot pools, sinter (SiO_2-rich), and tufa ($CaCO_3$-rich) deposits, and also away from the spring areas to obtain background values. Samples of spring-deposit tufa, sinter, spring-wall muck, and water were collected at all sites, and on return to the laboratory, were analyzed for ^{238}U, ^{232}Th, their daughter products, and ^{40}K by gamma-ray spectrometry (field and laboratory instrumentation and procedures have been described by Wollenberg and Smith[22]).

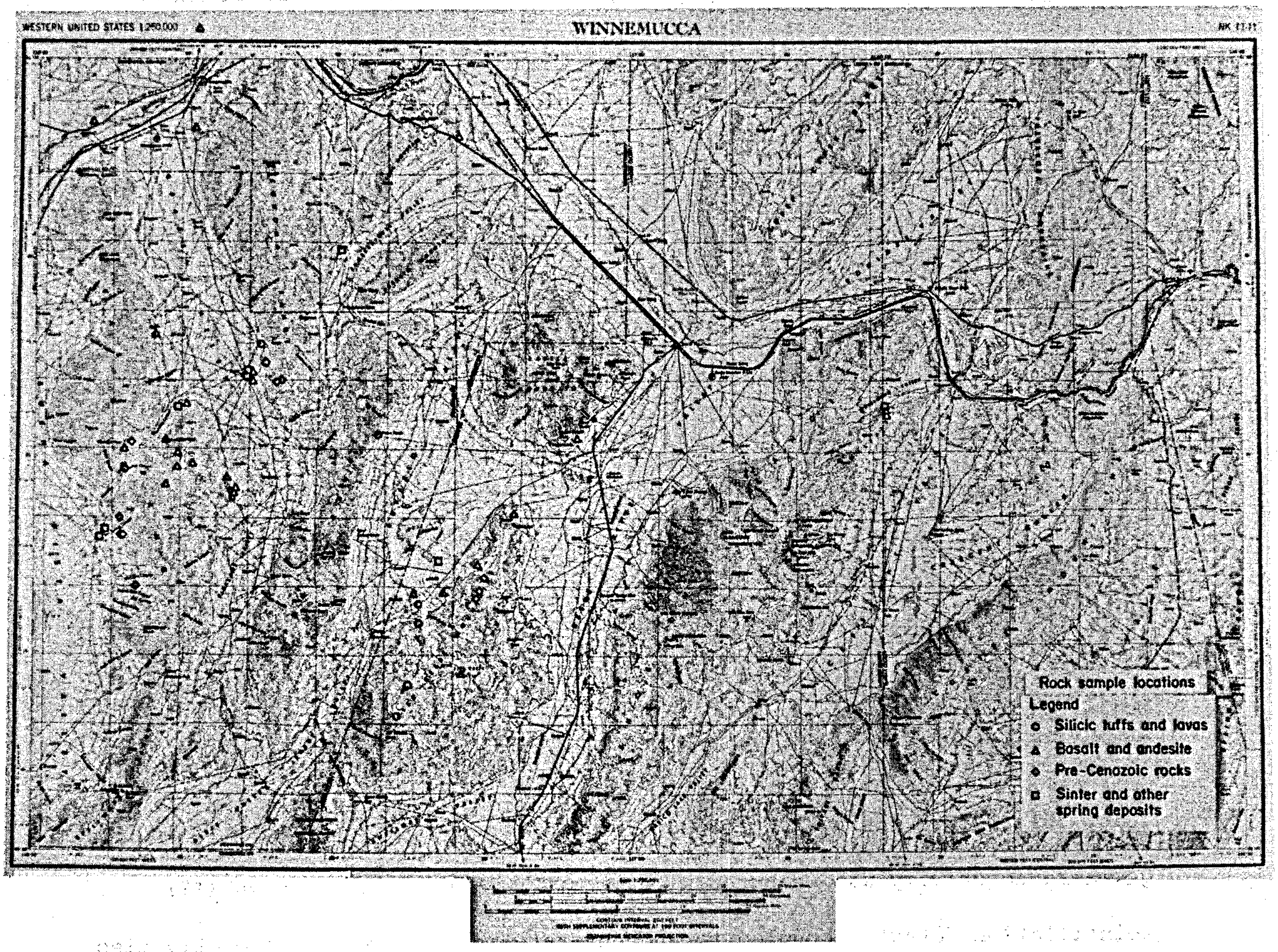

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Fig. 29. Location map, rock sampling sites in north-central Nevada.

(i) Field Measurement Results

Table 3 summarizes the field radiometric data; radioactivities are expressed in microroentgens per hour (μr/hr), based on calibration of the field instrument (counts/sec to μr/hr) with a radium source of known strength. Immediately apparent is the association of high radioactivities, "anomalies," with $CaCO_3$-rich spring deposits. The greatest radioactivities, 250-500 μr/hr, were observed over hot pools (75 -90° C) at Kyle Hot Springs where $CaCO_3$ is being deposited, while the lowest values, two orders of magnitude lower than at Kyle, were measured over hot and boiling pools and siliceous sinter at Beowawe Hot Springs. In no case was there any apparent connection between surface spring temperature and radioactivity. At Buffalo Valley and Kyle Hot Springs, $CaCO_3$-rich sites, sharp field-radiometric anomalies were detected downwind from pools, indicating the emanation of ^{222}Rn from the waters and spring walls.

(ii) Laboratory Measurement Results

(a) Spring Deposits

Table 4 summarizes laboratory gamma-spectrometric analyses of spring-deposit materials. As with the field data, the high radioactivities, attributable primarily to "equivalent U," are associated with the calcareous hot-spring deposits. Siliceous deposits are comparatively low in U and Th, and most have Th/U ratios similar to those of ordinary siliceous rocks.

The uranium values in Table 4 are listed as equivalent because they are based on the gamma-ray peaks of ^{214}Bi, one of the radioactive decay products of ^{226}Ra. Radium-226, in some chemical environments, may be completely separated from its parent ^{238}U, transported in bicarbonate-rich waters, and deposited with $CaCO_3$ on spring walls in the upper portions of a spring system (Tanner,[23]). Therefore, the high apparent U in samples of

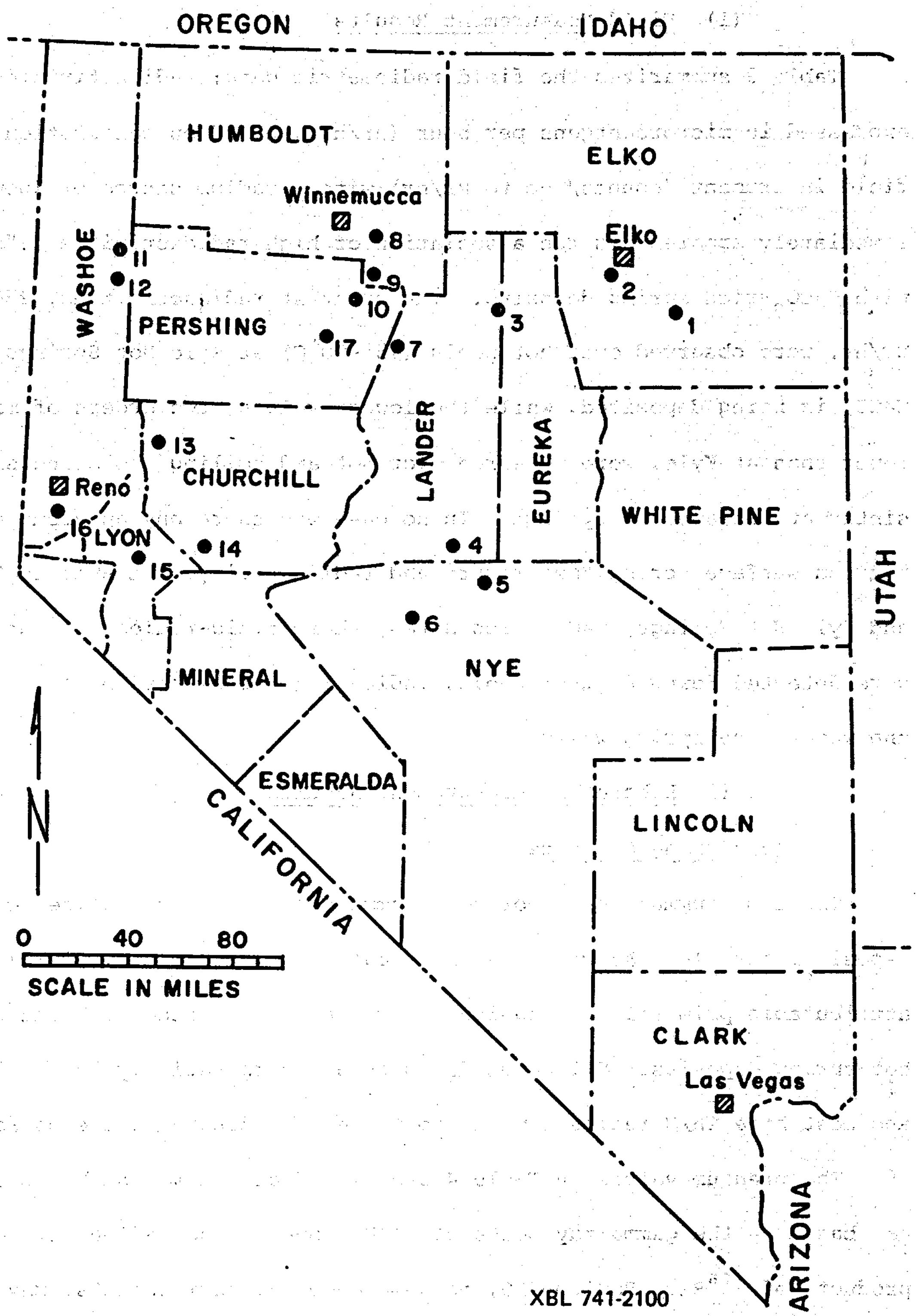

Fig. 30. Hot spring areas examined for radioactivity in northern Nevada. Numbered springs: 1) Big Sulfur, 2) Elko, 3) Beowawe, 4) Spencer, 5) Diana's Punchbowl, 6) Darrough, 7) Buffalo Valley, 8) Golconda, 9) Pumpernickel, 10) Leach, 11) Fly Ranch, 12) Gerlach, 13) Brady, 14) Lee, 15) Wabuska, 16) Steamboat, and 17) Kyle.

Table 3. Field gamma radiometry of spring areas.

Location	Gamma exposure rates (μR/hr) General background	Gamma exposure rates (μR/hr) Anomalously high radioactivity	Remarks
Spring systems where $CaCo_3$ is the predominant deposit			
Gerlach	6.25 - 7.5	60 - 65	Tufa, high rad. zone
Gerlach	--	20 - 25	Mixed sinter and tufa
Fly Ranch	6.25 - 8.75	None apparent	Travertine
Kyle	12.5 - 25	250 - 500	Over radioactive pools
Elko	7.5 - 10	19	Tufa at edge of pool
Buffalo Valley	6.25 - 7.5	30 - 38	Tufa mounds
Spencers	5 - 10	19	Tufa at edge of pool
Diana's Punchbowl	5 - 10	16	Springs at base of tufa mound
Wabuska	3.75 - 6.25	None apparent	Blowing wells
Darroughs	15 - 20	75	Edge of fenced pool
Darroughs	10 - 12.5	None apparent	Moderately blowing well
Golconda	12.5 - 17.5	37.5 - 175	Pools and interconnecting streams
Pumpernickel	7.5 - 10	17.5 - 22.5	Small pool
Pumpernickel	15	17.5	Outflow stream
Spring systems where SiO_2 is the predominant deposit			
Brady's	5 - 7.5	--	Sinter soil
Beowawe	2 - 2.5	--	Sinter apron
Beowawe	13.8 - 17.5	--	Andesite, escarpment above blowing wells
Big Sulfur (Ruby V)	2.5 - 5	--	Sinter
Leach	5 - 7.5	--	Sinter
Lee	5 - 7.5	20 - 25	Tufa and sinter
Lee	--	10	Edge of pool
Steamboat	2.5 - 4	--	Main terrace sinter
Steamboat	6.9	--	Altered granitics, west area, blowing well

Table 4. Laboratory gamma spectrometry of spring deposits.

Location	Description	Th (ppm)	Equivalent U (ppm)	K (%)	^{226}Ra* (pCi/g)	Th/U
	Spring systems where $CaCO_3$ is the predominant deposit					
Gerlach	Tufa, high radioactivity zone	13.41	109.25	1.02	39	0.12
	Predominantly Si sinter, some tufa	2.38	33.3	0.41	12	0.07
Fly Ranch	Travertine	2.14	10.99	0.02	4	0.19
Kyle	Calcareous muck from spring walls	11.62	76.32	0.16	27	0.15
	Travertine away from active springs	0.19	4.06	0.09	1.5	0.05
Elko	Tufa	3.12	7.60	0.07	2.7	0.41
Buffalo Valley	Calcareous muck from a small mound	45.89	25.49	0.21	9.2	1.80
	Predominantly tufa, some Si sinter	6.20	65.67	0.35	23.7	0.09
Spencers	Predominantly calcareous mud	10.92	11.54	1.51	4.1	0.95
Golconda	Spring wall tufa	31.20	469.6	--	169	0.07
Pumpernickel	Calcareous muck from small pool	6.33	8.19	0.46	2.9	0.77
	Spring systems where SiO_2 is the predominant deposit					
Brady	Mud from hot vent	6.32	2.93	0.41		2.15
Beowawe	Andesite, escarpment above blowing wells	15.99	3.28	3.74		4.88
	Sinter soil, vicinity of hot pools	0.91	0.37	0.40		2.43
Big Sulfur (Ruby Valley)	Sinter	0.18	0.11	0.16		1.60
Leach	Sinter	1.08	0.72	0.35		1.50
Lee	Sinter	4.76	2.49	1.11		1.91
	Tufa and sinter	3.71	11.67	0.51		0.31
Steamboat	Sinter, main terrace	0.30	1.42	0.13		0.21
	Sinter and altered granitics, west area	8.10	4.90	1.13		1.65

*Calculated from activities ratio, $^{226}Ra/^{238}U = 2.78 \times 10^6$.

calcareous deposits actually indicates ^{226}Ra anomalies. Uranium-238 or its decay products higher in atomic mass number than ^{226}Ra are missing. This was disclosed by examining high-resolution gamma-ray spectra of the calcareous samples, counted on a Ge(Li) detector system.

(b) Waters

Samples of water, approximately 550 ml, were collected from all of the springs for subsequent laboratory gamma-ray spectrometry. Radon-222 was indicated by the presence of the 1.76-MeV peak of ^{214}Bi in the gamma spectra of seven of the water samples. Several days elapsed between collection and laboratory analyses. Therefore, it is expected that in some of the waters ^{222}Rn activity (a 3.8-day half-life) had decayed below detectability. Repeated gamma counting of samples from some of the springs showed that the ^{214}Bi activity decayed with the Rn half-life, indicating that there was little or no ^{226}Ra in these waters. Otherwise, Ra would have resupplied Rn, eventually achieving radioactive equilibrium between these isotopes. The ^{214}Bi activities of the measurable water samples are listed in Table 5; they should be considered in the relative sense, pending calibration experiments. There is no apparent correlation between the radio-activities of the waters and those of the calcareous hot-spring deposits.

(iii) Radon Alpha-Track Survey

Alpha-track detectors for radon-222, provided by Terradex Corporation and General Electric Company, were placed in the ground near and away from radio-active warm pools in Buffalo Valley, Nevada (Figure 31). This area is a good test site, because of the sharply varying gamma-ray fields measured at the springs. Subsequent etching of the detectors revealed high track densities at locations near the pools and a tenfold decrease

Table 5. Radioactivity of hot-spring waters.

Location	Net radioactivity in 1.76 MeV peak of ^{214}Bi (counts $min^{-1}g^{-1}$)[a]
Gerlach	.0117
Kyle	.0179
Buffalo Valley	.0034
Golconda	.0070
Pumpernickel:	
Small pool	.0362
Outflow	.0162
Lee	.0166

[a]Corrected for 3.8-day half-life decay of ^{222}Rn.

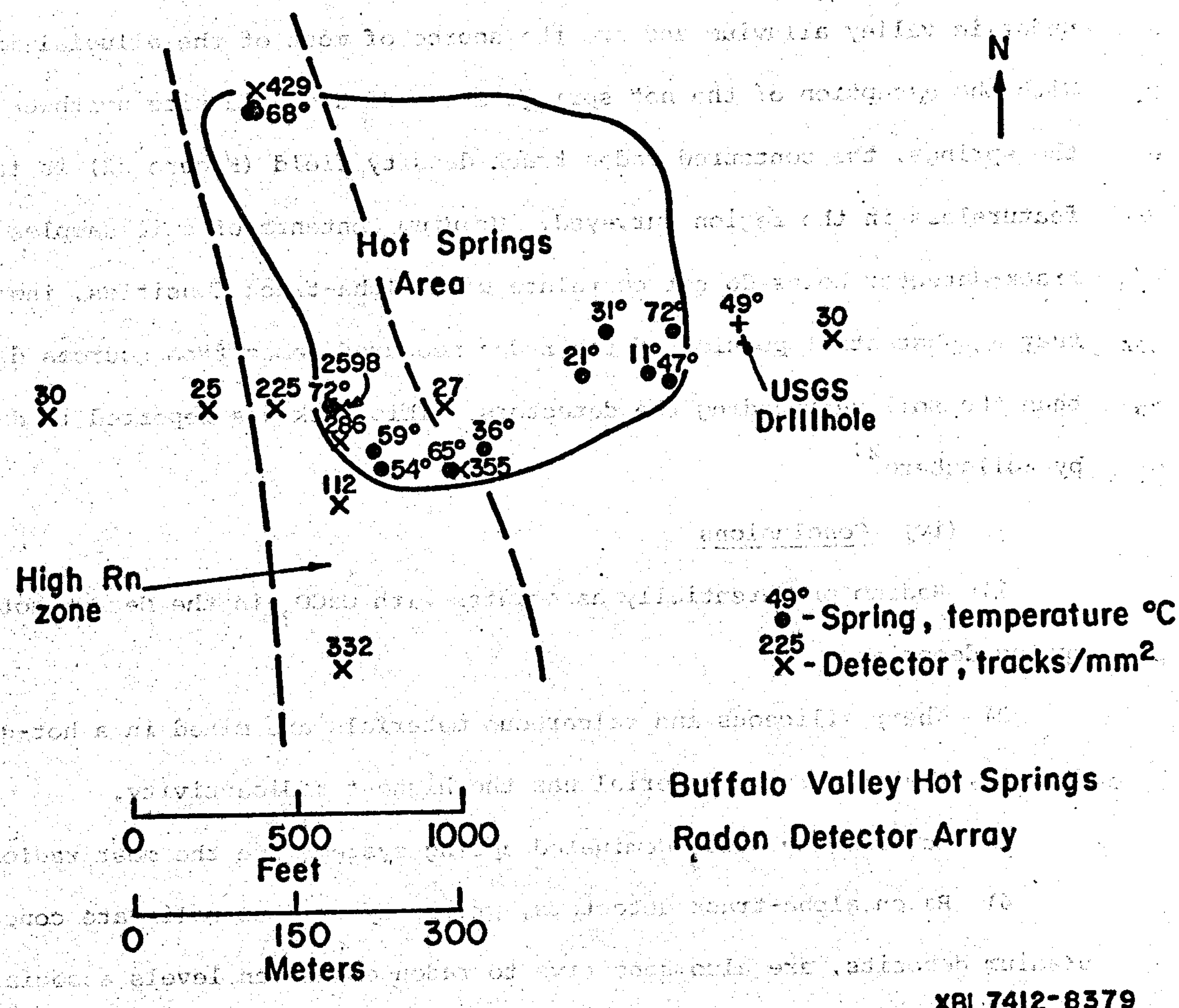

Fig. 31. Sketch map of Buffalo Valley Hot Springs area, showing locations of some of the warm pools, temperatures, and normalized track densities.

in track densities in detectors away from the pools. In the southern part of Buffalo Valley, relatively high track densities reflect the proximity of the detectors to comparatively high-radioactivity rhyolitic tuffs which underlie valley alluvium and are the source of most of the alluvial material. With the exception of the hot springs area and a single site northwest of the springs, the contoured radon track density field (Figure 32) is fairly featureless in the region surveyed. Uranium contents of soil samples from track-detector holes do not correlate with alpha-track densities, indicating that a substantial portion of the radon measured comes from sources deeper than the soil surrounding the detectors. This work was reported in detail by Wollenberg[24].

(iv) Conclusions

1) Radium preferentially associates with $CaCO_3$ in the Nevada hot-spring deposits.

2) Where siliceous and calcareous materials are mixed in a hot-spring deposit, the calcareous material has the highest radioactivity.

3) Low-flowing $CaCO_3$-dominated spring systems are the most radioactive.

4) Radon alpha-track detectors, presently used to delineate concealed uranium deposits, are also sensitive to radon emanation levels associated with radioactive geothermal systems.

Tentatively, it may be concluded that waters in some of the $CaCo_3$-dominated hot-spring systems deposit ^{226}Ra near the surface of low-flowing springs. Most of the ^{222}Rn observed in these waters is probably derived from decay of ^{226}Ra deposited on the spring walls.

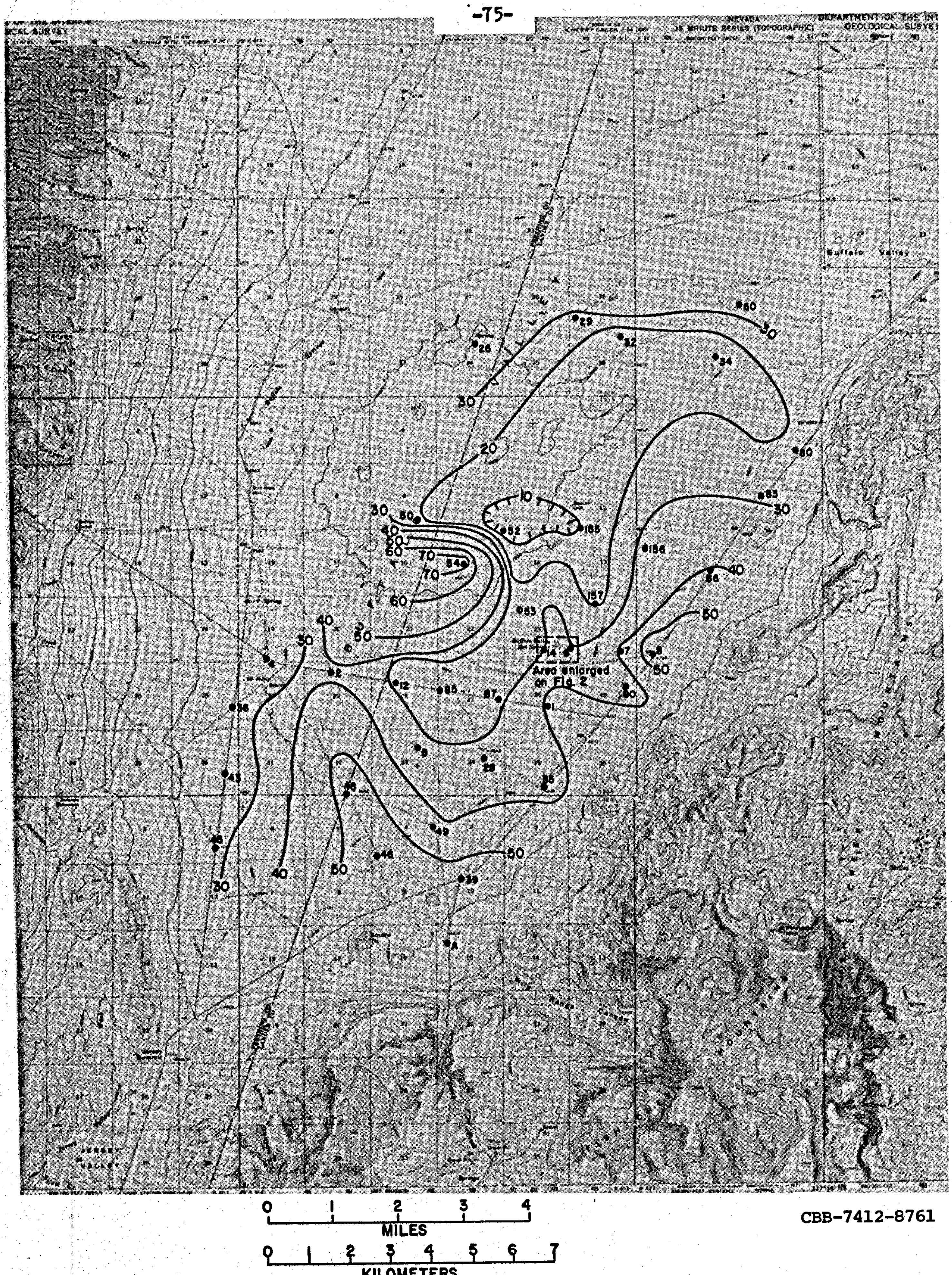

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Fig. 32. Contours of radon alpha-track density (in tracks mm^{-2}, normalized to a 30-day exposure) in Buffalo Valley.

(4). Summary.

In summary, field work to date in northern Nevada has included regional and detailed geologic studies, electrical, seismic, gravity and heat flow measurements, and geochemical and radiometric sampling and analyses. These studies are continuing with more emphasis placed on natural telluric current measurements to disclose zones of low electrical resistivity at depth. More detailed microearthquake surveys will monitor seismic activity in potential geothermal site areas, and regional and localized heat flow patterns will be discerned. Continued geochemical sampling and analysis will emphasize the interrelationships between trace and radioelements, and their applications to geothermometry and delineation of geothermal channelways. Hydrogeologic modeling studies will progress from formative stages into development of useful tools incorporating borehole data.

PART TWO: LONG-RANGE PROGRAM

A. Introduction

A long-range program for geothermal resource assessment, to encompass at least five years, is an expansion of the existing program, described in the preceding sections. It involves, essentially, the development of techniques for assessment of the hydrothermal liquid-dominated resource, in regions of contrasting geologic character. If sufficient funds are available, studies can be conducted concurrently in parallel operations in at least four regions: the Imperial Valley; a region characterized by Quaternary silicic volcanic activity, such as the western margin of the Great Basin; an area of high regional heat flow, such as north-central Nevada, or parts of southeastern Oregon; and an area of active tectonism, but of relatively normal heat flow, typified by many locations in the central Great Basin.

In this section activities will be outlined, their time sequence arranged, and their budget estimated.

B. Activities

Activities encompass almost the full spectrum of geoscience techniques, from high altitude photography to surface geological, geophysical, and geochemical surveys, to shallow, intermediate, and deep drilling. Concurrently throughout the program, laboratory facilities are utilized for chemical and radiometric analyses, as well as for determination of physical properties of samples: computer facilities are employed to develop geophysical and hydrogeologic models, and to subsequently refine them as data is received and digested.

An outline of activities comprises most of this section. Geological, geophysical and geochemical techniques have been described in some detail in the preceding sections on the status of field activities. In this section, along with the outline, amplification will be given regarding aspects of drilling, hydrogeologic techniques, reservoir monitoring, and research and development wherein industry can play a major role. These aspects have not been covered in sufficient detail in preceding sections.

1. OUTLINE OF ACTIVITIES

I. Geologic Techniques

A. Structural Analysis

1. Airphoto coverage

Low sun angle: Regional high altitude
Local low altitude

High sun angle: Regional high altitude
Local low altitude

B. Geologic Mapping

1. Photo interpretation confirmation

2. Lithologic contacts

3. Igneous relationships

C. Age Dating (see geochemical)

II. Geophysical Techniques (includes reservoir monitoring applications)

A. Resistivity

1. Induced currents: bipole-dipole, dipole-dipole

2. Tellurics

3. Magnetotellurics

B. Self Potential

C. Electromagnetics

D. Magnetics

E. Gravity

F. Seismic

1. Microearthquakes

2. Seismic noise

G. Heat flow (see drilling)

H. Airborne Multispectral

1. Infrared

2. Microwave

I. Radiometrics (see geochemical)

Above includes data acquisition, data reduction, modeling, interpretation, and report.

III. Geochemical Techniques (a detailed plan with costs is provided in WASH-1344, "A Recommended Program in Geothermal Chemistry, 1974).

A. Spring and well sampling and analyses

1. Hot springs
2. Cold springs

{ major elements, trace elements, isotope ratios, radioelements }

B. Rock Sampling and Analyses

1. Major elements

2. Trace elements

3. Radioelements

C. Field Atmospheric and Soil Gas Sensing

1. Hg

2. Rn

3. Others

D. Age Dating

1. K/Ar

2. Rb/Sr

3. Fission track

E. Isotope Ratioing

Oxygen

Hydrogen

F. Analyses of heat flow hole samples

G. Analyses of calibration hole samples

H. Analyses of deep test wells

I. Rare-gas sampling and analyses

IV. Drilling

A. Heat Flow Holes

1. Logs
Natural gamma, moisture, resistivity, self potential, temperature, caliper, lithologic

2. Samples
Cuttings, cores, water

3. Repeated temperature measurements

4. Lab analyses
Thermal conductivities
Chemical analyses of cuttings, cores, water (see geochemical)

B. Calibration Test Holes
Same sequence as above, plus physical properties of cores, downhole sonic, sidewall sampling

C. Deep Test Wells

1. High temperature logging

2. Flow tests

V. Hydrogeologic Techniques

A. Modeling Studies; develop models
Variables: temperature, pressure, porosity, permeability, lithology, flow rate

B. Test Hole Data

Input from heat flow holes, calibration holes, and deep test well.

VI. Reservoir Monitoring at an Existing Resource Site

A. Surface Measurements

1. Resistivity grid

2. Microearthquake grid

B. Subsurface Measurements

1. Periodic logging of producing wells

2. Periodic sampling and analyses

VII. Industry R and D Projects

A. Logging in Hostile Environments

1. Survey of state of art

2. R and D projection pertinent parameters

B. Down-hole sampling

1. Survey of state of art

2. R and D project on pertinent parameters

2. Amplifications

a. Drilling

A number of 1 to 1.5 km-deep holes are proposed. The purpose of these holes is to furnish subsurface geological, geophysical and geochemical data, to compare with data presently being collected by surface surveys. Results of heat flow measurements in shallower holes will strongly influence the location of these calibration holes. Of primary interest are electrical properties of subsurface materials and their comparison with deep resistivities estimated by surface bipole-dipole, dipole-dipole and telluric measurements. An understanding of the lithology and physical properties of near surface and deep alluvial material, Tertiary sedimentary and volcanic rocks, and pre-Tertiary bedrock is necessary for proper interpretation and evaluation of surface geophysical techniques. Information from these calibration holes, from shallower heat flow holes, and results of surface geological and geophysical surveys shall be combined to ultimately choose the locations for one or more deep test wells.

Holes will be 500 to 1500 meters deep, depths to depend upon site geologic setting and drilling conditions. Hole diameters will be slim, 5 to 6 inches. Provision will be made for coring at about 30-m intervals; push or pitcher samples in alluvial material, diamond drill cores in sub-alluvial bedrock. Where available, samples of fluids encountered will be obtained for subsequent laboratory geochemical studies. Such studies on cores and fluids will help calibrate proposed geothermometers, especially those based on trace elements. Upon completion of drilling, downhole logging will include active and passive radiometrics, sonic, electrical and temperature measurements. Holes will be completed so that access remains for subsequent logging, either in lined or unlined portions of the holes.

Other activities in connection with the calibration drilling include measurements of rock properties, and interpretation of downhole and laboratory data. Rock properties evaluated will include lithology, thermal conductivity, porosity and permeability. Interpretation will involve a detailed comparison of subsurface physical properties, lithology, and structure with results of surface geophysical and geological surveys.

The decision to drill one or more 2 to 2-1/2-km-deep test wells will depend on data from the calibration holes. Logging operations, similar to those in the calibration holes, will be conducted in the deep test wells. On completion and perforation, well production will be tested, and if the site is determined viable, a second well will be drilled for re-injection of fluids, associated with a field test facility.

b. Hydrogeologic Techniques

Successful assessment of a geothermal resource requires an understanding of its hydrogeologic setting, and the effects of production of fluids on the setting. Computer modeling studies are underway to test the effects of production on several parameters in a confirmed reservoir. Variables include proportions of liquid and vapor phases, temperature, pressure, porosity, permeability, lithology and flow rate. A two-dimensional finite-element matrix is used in the model, and resulting computer plots show locations and magnitudes of effects of production with time on the above parameters. When the confirmed reservoir models are successfully refined, the study will expand to include effects of reinjection, and natural replenishment of fluids in more complicated geologic settings. The models will be satisfactorily refined to accommodate data from calibration holes and deep test wells.

c. Reservoir Monitoring

Surface and subsurface techniques to monitor the configuration, volume, and quality of a geothermal reservoir as production proceeds, can best be developed at one or more sites of existing production. Ideally, techniques should be developed to encompass the various hydrothermal resource types. Presently, production is limited to the Geysers-Clear Lake and Imperial Valley areas. The latter area affords many opportunities to develop monitoring methods at sites of widely varying salinity and temperature.

Surface tehniques include continuous or periodic monitoring of apparent resistivity at depth on a grid pattern, incorporating a fixed bipole-dipole array, and dipole-dipole transects. Changes in the subsurface apparent resistivity configuration, if occurring, will be correlated with well production data. Concurrently, microseismic activity, both microearthquake and noise, as well as teleseimic activity, will be monitored by a fixed telemetered geophone array. To furnish a baseline for evaluation of surface techniques, producing wells will be logged periodically, and sidewall samples of material from the producing zone analyzed to observe changes in formation properties.

d. Industrial R and D Projects

Of pertinent importance to the successful assessment of geothermal resources are problems associated with logging and sampling in high temperature, downhole environments. Sectors of industry should be encouraged to attack these problems, and design and construct equipment and components capable of obtaining meaningful data and samples in regimes where temperatures exceed 150 to 250°C. This program should begin with a survey of the states of the art of downhole logging and sampling, critical areas defined, and projects scoped to develop and test components at existing sites of varying properties.

C. Time Sequence of Activities

The accompanying chart illustrates the sequence of activities for fiscal years 1976-1980 at a site characteristic of a given geothermal resource. The headings are keyed to the outline of activities in the preceding section. The time period encompasses six years, though inspection of the chart indicates that most of the program at a site can be

TIME CHART

Time chart of activities at a site characteristic of a given resource. Fiscal Years are 76 through 80, though at one resource-type area, northern Nevada, a large segment of the program is already into the second year.

	FY76	FY77	FY78	FY79	FY80
I. Geologic Techniques					
A. Literature search	XXXXX				
B. Structural analysis	XXXXXX	XXXXXXX			
C. Geologic mapping	XXXXXXXXXX	XXX			
D. Interpretation		XXXXXXXXX			
E. Report		XXXXXXX			
II. Geophysical Techniques					
A. Data acquisition	XXXXXXXXXX	XXXXXXXXX			
B. Data reduction	XXXXXX	XXXXXXXXXXXXX	XX		
C. Modeling	XXX	XXXXXXXXXXXXX	XXXXXX		
D. Interpretation		XXXXXXX	XXXXXXXXXXXX		
E. Report			XXXXXXXXXX	XXX	
III. Geochemical Techniques					
A. Spring and well sampling and analysis	XXXXXXXXXX				
B. Rock sampling and analysis	XXXXXXXXXX				
C. Field atmospheric sensing	XXXXXX	XXXXXXX			
D. Age dating	XXX	XXXXXXXXXX			
E. Isotope ratioing	XXX	XXXXXXXXXXXX			
F. Interpretation of A thru E		XXXXXXXXXXXX	XXXXXXX		
G. Report			XXXXXXXXX		
H. Heat flow hole analysis		XXXXXXXXXX			
I. Calibration hole analysis		XXX	XXXXXXX		
J. Deep test well analysis			XXX	XXXXXXXX	

TIME CHART

	FY76	FY77	FY78	FY79	FY80
IV. Drilling (including logging, sampling, data analyses)					
A. Heat flow holes	XXX	XXXXXXX			
B. Calibration test holes		XXXXXXXXXX			
C. Deep test wells			XXXXXXXXXX		
Report covering I, II, III A thru H, and IV A and B	In second half of fourth (4th) year.				
V. Hydrogeologic Techniques					
A. Modeling studies	XXXXXXXXXX	XXXXXX			
B. Borehole data		XXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXXXXXXXXX	XXXXXXXX
VI. Reservoir Monitoring (existing resource site)					
A. Surface measurements					
1. Resistivity grid	XXXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXX	
2. Seismic grid	XXXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXX	
B. Subsurface measurements					
1. Continuous logging	XXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXX	
2. Periodic sampling and analyses	XXXXXXXXX	XXXXXXXXXXXXX	XXXXXXXXXXXXX	XXXXXXXX	
VII. Industry R and D Projects					
A. Hostile environment logging					
1. Survey State of Art	XXXXXX				
2. R and D project	XXXXXX	XXXXXXXXXXXXX	XXXXXXX		
B. Down-hole sampling					
1. Survey State of Art	XXXXXX				
2. R and D project	XXXXXX	XXXXXXXXXXXXX	XXXXXXX		

accomplished within five years. It is proposed that this sequence of activities be conducted at at least one site in each of four geothermal resource types. At one resource-type area, northern Nevada, a large segment of the program is already into its second year. At Long Valley, on the western margin of the Great Basin in an area characterized by Tertiary and Quaternary silicic volcanic activity, the USGS is conducting an in-depth multidisciplinary program of assessment of regional geothermal potential. Similar programs, where the resources and expertise of ERDA laboratories may be utilized, are in their early stages in the Coso Hot Springs and Geysers-Clear Lake areas of California.

D. Budget Estimates

The accompanying tables show estimated budgets for the geothermal resource assessment program, based on two modes of operation. Table 6 illustrates expenditures as if concurrent examination of four sites was begun in FY76. In this mode almost all operations would be completed by the end of the fourth year. A stretched-out schedule is illustrated on Table 7. Here operations are carried out in parallel at two of the four sites. The sequence begins with parallel operations at two sites, and within the second half of the second year, parallel operations commence at the other two sites. This may be the more realistic mode of the two, primarily because the same drill rigs and same drilling materials could be employed at more than one site. An obvious disadvantage of the stretched-out mode is the increased length of the overall program, operating in periods of greater cost escalation. It should be noted that cost escalation has not been taken into account on the tables; all figures are in 1975 dollars.

Table 6

BUDGET - RESOURCE ASSESSMENT
NORMAL SCHEDULE
(in thousands of 1975 dollars)
Four Sites - Parallel Operation

		Fiscal Year					
		1976	1977	1978	1979	1980	Subtotal
I.	Geologic Techniques	560	600				1,160
II.	Geophysical Techniques	1,950	2,900	2,950			7,800
III.	Geochemical Techniques	350	450	300	110		1,210
IV.	Drilling	1,700	6,500	7,500			15,700
V.	Hydrogeologic Techniques	425	700	700	700	350	2,875
VI.	Reservoir Monitoring	650	900	900	450		2,900
VII.	Industry R and D projects	130	250	120			500
	TOTAL	5,765	12,300	12,470	1,260	350	$32,145

5-year Total $32.145 M

Table 7

BUDGET - RESOURCE ASSESSMENT
STRETCH-OUT SCHEDULE
(in thousands of 1975 dollars)
Four Sites - Two in Parallel Operation

		Fiscal Year					
		1976	1977	1978	1979	1980	Subtotals
I.	Geologic Techniques	320	580	260			1,160
II.	Geophysical Techniques	1,100	1,700	1,700	1,700	1,600	7,800
III.	Geochemical Techniques	200	260	260	250	240	1,210
IV.	Drilling	1,600	4,000	4,300	3,700	2,100	15,700
V.	Hydrogeologic Techniques	400	630	630	630	630	2,920
VI.	Reservoir Monitoring	500	600	600	600	600	2,900
VII.	Industry R and D Projects	130	220	100	50		500
	TOTAL	4,250	7,990	7,850	6,930	5,170	32,190

5-year Total $32.190 M

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