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GEOLOGIC AND GEOPHYSICAL INVESTIGATIONS OF CLIMAX STOCK INTRUSIVE, NEVADA

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GEOLOGIC AND GEOPHYSICAL INVESTIGATIONS OF CLIMAX STOCK INTRUSIVE, NEVADA

by

U. S. Geological Survey

Chapter A--Geologic Investigations
by Paul P. Orkild[1], D. R. Townsend[2], and M. J. Baldwin[2]

Chapter B--Gravity Investigations
by D. L. Healey[1]

Chapter C--Magnetic Investigations
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FOREWORD

Successful detection of underground nuclear detonations requires investigation of the effects of seismic discontinuities near large geologic features. As part of the Defense Nuclear Agency seismic testing program, the U.S. Geological Survey was requested to define the extent of buried intrusive rock at the Climax stock in the northeastern part of the Nevada Test Site, and to define the nature of geologic contacts with adjoining rock units.

Geologic data were used to define the surface structure in the area of proposed emplacement holes for the nuclear seismic test, code named Midnight Blue. Geologic and geophysical data define the geometry of the stock and other geologic features pertinent to containment of the nuclear test.

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GEOLOGIC INVESTIGATIONS

By
P. P. Orkild, M. J. Baldwin, and D. R. Townsend

ABSTRACT

The Climax stock is a composite granitic intrusive of Cretaceous age, composed of quartz monzonite and granodiorite, which intrudes rocks of Paleozoic and Precambrian age. Tertiary volcanic rocks, consisting of ash-flow and ash-fall tuffs, and tuffaceous sedimentary rocks overlie the sedimentary rocks and the stock. Erosion has removed much of the Tertiary volcanic rocks.

Hydrothermal alteration of quartz monzonite and granodiorite is found mainly along joints and faults and varies from location to location. The Paleozoic carbonate rocks have been thermally and metasomatically altered to marble and tactite as much as 457 m (1,500 ft) from the contact with the stock, although minor discontinuous metasomatic effects are noted in all rocks out to 914 m (3,000 ft).

Three major faults which define the Climax area structurally are the Tippinip, Boundary and Yucca faults. North of the junction of the Boundary and Yucca faults, the faults are collectively referred to as the Butte fault. The dominant joint sets and their average attitudes are N. 32° W., 22° NE; N. 60° W., vertical and N. 35° E., vertical. Joints in outcrop are weathered and generally open, but in subsurface, the joints are commonly filled and healed with secondary minerals.

The location of the water table and the degree of saturation of the granitic rocks are presently unknown. Measurement from drill holes indicated that depth to perched water levels ranges from 30 to 244 m (100-800 ft).

Recent field investigations have shown the contact between the Pogonip marble and the granodiorite is a contact rather than a fault as previously mapped. The thickness of the weathered granodiorite is estimated to be 8 to 46 m (25 to 150 ft).

INTRODUCTION

The Nevada Test Site is approximately 96 km (60 mi) northwest of Las Vegas in Nye County, Nevada. The Climax stock is located in Area 15 at the extreme northeast end of the test site (fig. 1A). The topography of the stock rises northward from an elevation of about 1,490 m (4,900 ft) on the south to over 1,829 m (6,000 ft) at the northern boundary.

Recent field studies have updated previous geologic studies and aided in definition of the geometry of the stock. Trenching was used to increase understanding of the fault model for the stock.

GEOLOGY

The Climax stock is a composite granitic intrusive. Surface exposure is about 2.4 km^2 (0.93 mi^2) in area (Houser and Poole, 1960). The stock is composed of an older medium-grained equigranular granodiorite and a younger

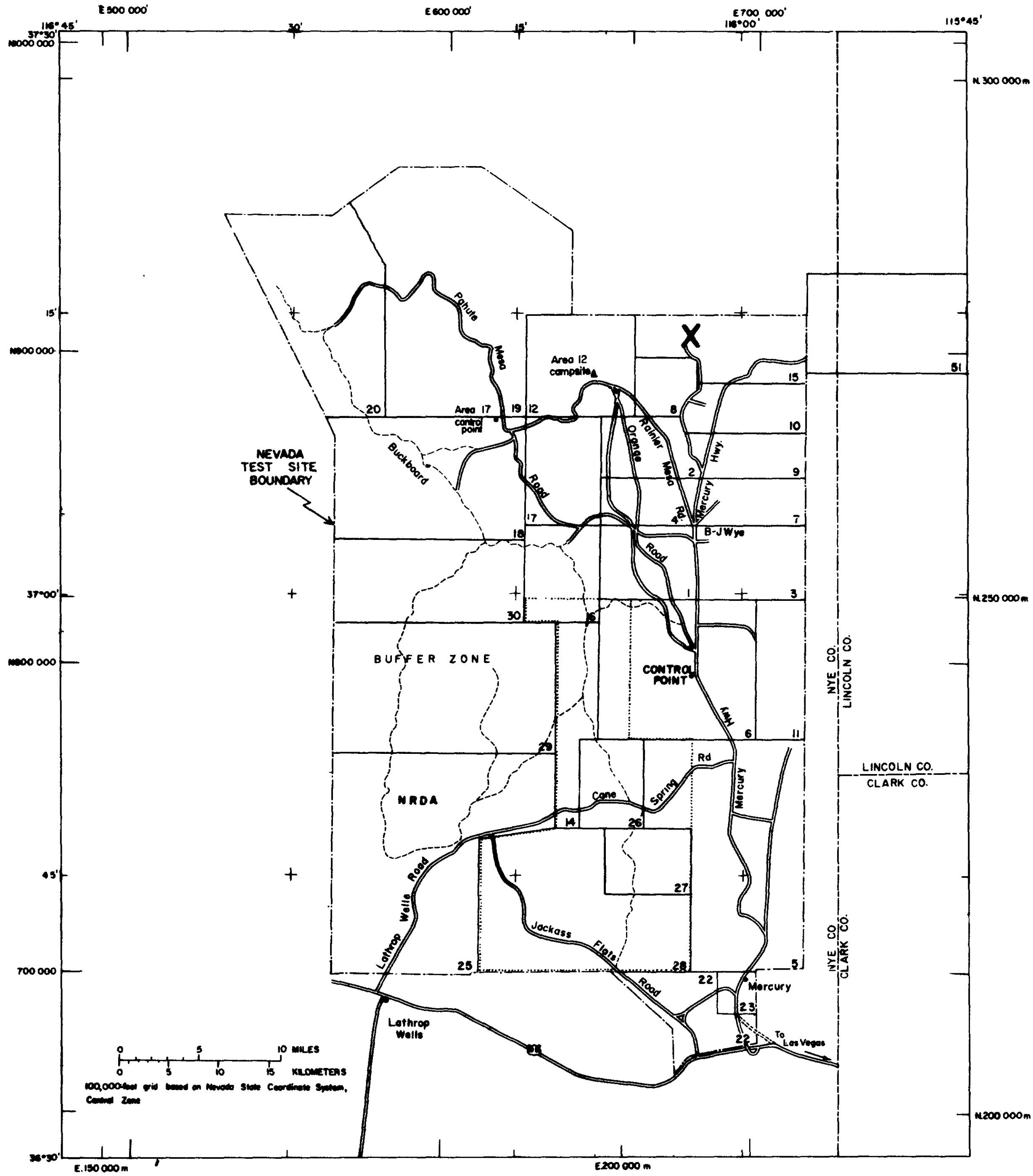

Figure 1A.--Index map showing location of Climax Stock (X) in Area 15, Nevada Test Site.

fine- to medium-grained coarsely porphyritic quartz monzonite, both of Cretaceous age. Fission-track ages for five samples indicate an age of 101 m.y. for the Climax stock (Naeser and Maldonado, 1981). Marvin and others (1970) reported six biotite K-Ar ages from the Climax stock that range from 89 to 97 m.y. These ages were recalculated by Naeser and Maldonado (1981) using the International Union of Geological Sciences constants. The recalculation produced ages of 91 to 100 m.y. which is very close to the average fission-track age for the stock.

The Climax stock intruded complexly folded and faulted sedimentary rock of the Pogonip Group (Ordovician) composed mainly of limestone, dolomite, and shale. In fault contact with the Pogonip group are sedimentary rocks of Precambrian to Mississippian age. Tertiary volcanic rocks, consisting of ash-flow and ash-fall tuffs, and tuffaceous sedimentary rocks overlie the north-east corner of the stock. Tertiary and possibly Paleozoic formations butt against the southeast edge of the stock along a 70-75° angle fault (Boundary). Erosion has removed much of the Tertiary volcanic rocks (pl. 1A). The carbonate rocks have been thermally and metasomatically altered to marble and tactite for as much as 457 m (1,500 ft) from the contact with the stock, although minor discontinuous metasomatic effects are noted in all rocks out to 914 m (3,000 ft). Hydrothermal alteration of granodiorite and quartz monzonite is found mainly along joints and faults; the degree of alteration varies from location to location (Houser and Poole, 1961).

The granodiorite is a light-gray to medium-greenish-gray, equigranular, slightly porphyritic rock consisting of 28 percent quartz, 16 percent potassium feldspar, 45 percent plagioclase, and 9 percent biotite. The average grain size is about 2 mm, but can range from 0.5 to 4 mm. Accessory minerals, mainly apatite, sphene, opaque iron oxides, and zircon, constitute 1-2 percent of the rock (Houser and Poole, 1961). In the central part of the stock, the granodiorite is locally fine grained. In places, fine-grained inclusions ranging from quartz diorite to granodiorite are common.

The quartz monzonite is light- to medium-gray, fine- to medium-grained, porphyritic rock consisting of 28 percent quartz, 25 percent potassium feldspar, 40 percent plagioclase, and 6 percent biotite. The most conspicuous minerals in hand specimen are potassium feldspar phenocrysts as much as 15 cm across and averaging about 5 cm in length. The border zones are fine-grained and range in composition from quartz diorite to granodiorite.

The contact between the granodiorite and quartz monzonite is generally vertical or very steep. It is highly irregular and shows mutually penetrating fingers of each rock type. These fingers are measurable in inches or feet in width and length. No glassy, chilled zone has been noted in either rock (Houser and Poole, 1961, p. B-176). The border zones are fine-grained and range in composition from quartz diorite to granodiorite.

Dikes and Sills

Dikes and sills as much as 152 m (500 ft) long and 15 m (50 ft) thick cut the stock and the surrounding calcareous rocks of the Pogonip Group. They have no predominant trend except in the central part of the granodiorite, where they strike northwest.

Hydrothermal effects of the Climax stock produced widespread, moderate, argillic alteration of plagioclase feldspar and chloritic alteration of biotite as well as deposition of veinlets or joint fillings of quartz and secondary minerals. Quartz veins are widespread through the stock and in the surrounding Paleozoic rocks but are most numerous in the northeastern part of the quartz monzonite. The secondary minerals in the veinlets are clay minerals, chlorite, feldspar, sericite, quartz, and calcite. Sparse amounts of sulfide minerals also occur in some of the joints. Pyrite and chalcopyrite occur disseminated in the granodiorite (W. L. Emerick, written commun. 1966). Pyrite also occurs as fracture filling with limonite, manganese, and secondary feldspars.

The limestones and dolomites within a few hundred meters of the stock have been metamorphosed. The thick-bedded relatively pure carbonate rocks, such as the Goodwin Limestone and the Antelope Valley Limestone, have been marbleized, whereas, the thin-bedded silty limestones of the Ninemile Formation have been changed to tactite. The thin limestone beds intercalated in the argillite of the Eleana Formation have not been metamorphosed, although they are closer to the stock than the marbleized dolomite of the Nevada Formation. Tactite mineralogy consists of garnet, quartz, epidote, chlorite, limonite, calcite, and idocrase. Small amounts of scheelite and powellite have been found in the tactite, especially northeast of the stock.

Faults and Joints

Three major faults define the area structurally: (1) the Tippinip fault, trending north-northeast, forms the contact between the Pogonip Group and the Eleana Formation west of the stock; and intersects the Boundary fault southwest of the stock; (2) the Boundary fault, trending northeast, forms the contact between the stock and the alluvium and pyroclastic rocks to the southeast; (3) the Yucca fault trending approximately north-south through the middle of Yucca Flat, is projected to join the Boundary fault east of the stock. North of the junction of the Boundary and Yucca faults, the faults are collectively referred to as the Butte fault (pl. 1A).

Other minor faults found in the sedimentary rocks overlying the stock are high angle, with strikes of north, northwest, and east-west. Houser and Poole (1961) interpreted these faults as later than the igneous intrusion and before the deposition of the pyroclastic rocks. Minor postvolcanic faults are present, but none appear to disrupt the integrity of the stock.

The dominant joint sets and their average attitudes are N. 32° W., 22° NE; N. 64° W., vertical; and N. 35° E., vertical (Houser and Poole, 1961). Joints in outcrop are weathered and generally open, but in subsurface the joints are commonly filled and healed with secondary minerals. The drainage has a general northwest-northeast pattern and probably reflects in part the dominant joint orientation.

Pertinent previous work in the Climax stock area has been reported by Houser and Poole (1959, 1960), Izett (1960), Sargent and Orkild (1973), and Maldonado (1977).

Ground Water

Ground water is thought to exist only locally where the rock is most fractured and to occur in limited quantity (Walker, 1962). There is apparently no extensive zone of saturation in the stock. The water supply is replenished by precipitation in the immediate area. Two shafts were excavated in the Climax stock for nuclear tests, the Tiny Tot and Pile Driver shafts. Extensive horizontal tunnel complexes are associated with the Pile Driver shaft. At the 250 m (820 ft) depth level, there are drifts from the Hard Hat event; and at the 420 m (1,378 ft) depth level, drifts from the Pile Driver event. The working level at 420 m (1,378 ft) below the ground surface is accepted to be above the regional water table and is almost devoid of groundwater with the exception of a few isolated seeps.

Borehole investigations were conducted to estimate the quantity of groundwater in the Climax stock (Walker, 1962). The location of these exploratory holes in the granite and the adjacent quartzite and limestone west of the stock are shown in figure 2A. Table 1A summarizes total depth and water level in each hole. None of the holes penetrated to the level of the regional water table, the locally occurring water is perched. Measurement from drill holes indicates that depth to perched water levels ranges from 25 to 237 m (82 to 942 ft).

Table 1A.--Boreholes in the Climax stock and vicinity[1/]

Borehole	Ground Surface elevation[2/] m (ft)	Hole depth m (ft)	Water level[2/] m (ft)	Comments
ME#1	1588 (5210)	115 (377)	1486 (4875)	perched water
ME#2	1599 (5246)	60 (197)	1549 (5082)	perched water
ME#3	1621 (5318)	298 (978)	1475 (4839)	perched water
ME#4	1674 (5492	362 (1188)	1387 (4551)	perched water
15a#31	1559 (5115)	366 (1201)	1502 (4928)	perched water
15a#32	1548 (5079)	277 (909)	1418 (4052)	perched water
15a#33	1570 (5151)	301 (988)	----	dry
15a#34	1571 (5154)	301 (988)	1363 (4472)	perched water
15a#35	1519 (4984)	251 (823)	1494 (4902)	perched water
15a#37	1543 (5062)	508 (1667)	----	dry
15a#38-2	1536 (5039)	610 (2001)	----	may be dry
U15bEx#1	1590 (5217)	549 (1801)	----	unknown
U15bEx#2	1550 (5085)	549 (1801)	----	unknown

1/ From Walker (1962) and Thordarson, et al. (1966).

2/ Referenced to MSL.

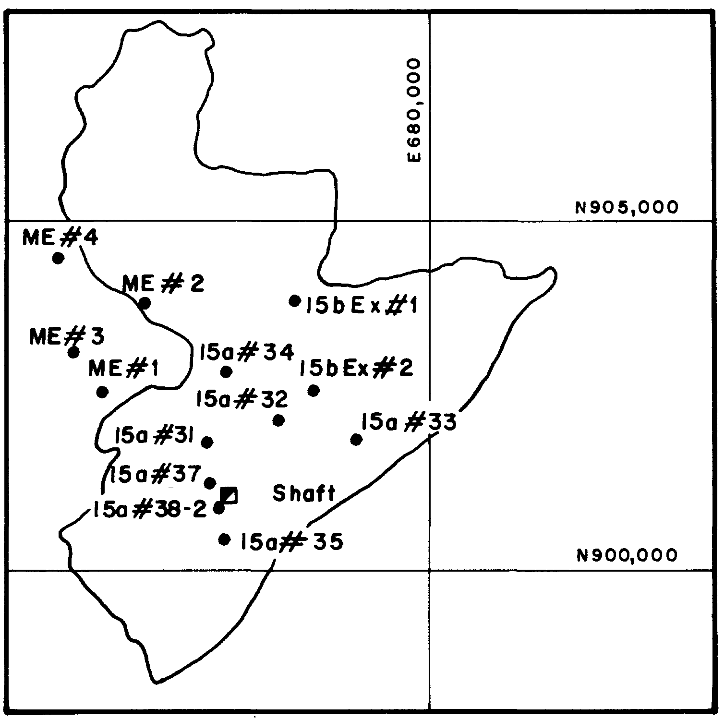

Figure 2A.--Borehole locations in the Climax stock.

Drill Holes

Drill holes UE15d, U15gz#24, and U15gz#25 (pl. 1A) were reexamined. Lithologic logs indicate 88 m (290 ft) of alluvium and 453 m (1,485 ft) of tuff in UE15d and 1,288 m (4,225 ft) of Precambrian metasedimentary rocks. The tuff interval extends from 88 m (290 ft) geophysical logs indicate a depth of 84 m (275 ft) to 541 m (1,775 ft); geophysical logs indicate a depth of 544 m (1,784 ft). No granitic rocks were penetrated by the drill hole, although metamorphic minerals were seen in the dolomite at the bottom of the hole.

No cuttings or lithologic logs are available for drill holes U15gz#24 and #25; however, limited geophysical logs are available. The mudpits were examined for both holes and granitic cuttings were found in both pits. Approximately half the cuttings in U15gz#24 were composed of granitic rocks. The U15gz#25 mudpit has been destroyed by erosion and only large chips of altered granitic rocks could be found. Drill holes U15gz#24 and #25 can be projected into line 901,000, figure 5B, in the "Gravity Investigations" section of this report. This projection combined with the geophysical logs indicates that U15gz#24 probably penetrated granitic rock at approximately 229 m (750 ft). A distinct lithologic change is reflected by the geophysical logs at 457 m (1500 ft) in U15gz#25. At this depth there is an abrupt increase in velocity coupled with a marked increase in resistivity, either of which could indicate granitic or Paleozoic rocks. In this drill hole, identification of granitic rock on the basis of log data can only be expressed in the most tentative terms.

RECENT INVESTIGATIONS

Trench Mapping

In order to define the stock boundaries and examine the geologic features pertinent to nuclear weapons containment, the following features (fig. 3A) were investigated: (1) Structural features including two major bounding faults, the Tippinip on the west and the Boundary on the east and southeast; and two small features on the west side of the stock, originally called faults; (2) tuff section overlying pre-Tertiary rock and granite; (3) nature of the surface structure in the area proposed for emplacement holes.

Initial geologic mapping was done by Houser and Poole (1960); minor differences were observed during field mapping which needed to be addressed to determine the adequacy of the site for emplacing an experiment to enhance our knowledge of the geologic modal of the stock, and to document certain geologic features required for the CEP.

These areas of concern are: (1) the attitude of Yucca fault near its juncture with the Boundary fault, (2) attitude of the Boundary fault; (3) attitude and displacement of the Tippinip fault; (4) the characteristics of the West-central fault (a fault mapped by Houser and Poole, 1960, and Barnes and others, 1963, which extends due west of U15-33 hole); and (5) the nature and dip of the Dome fault extending northwest near ME-2 (Barnes and others, 1963).

Five bulldozer trenches were excavated at sites across features of interest in the area being examined at the stock. Trenches 1 and 2 are located

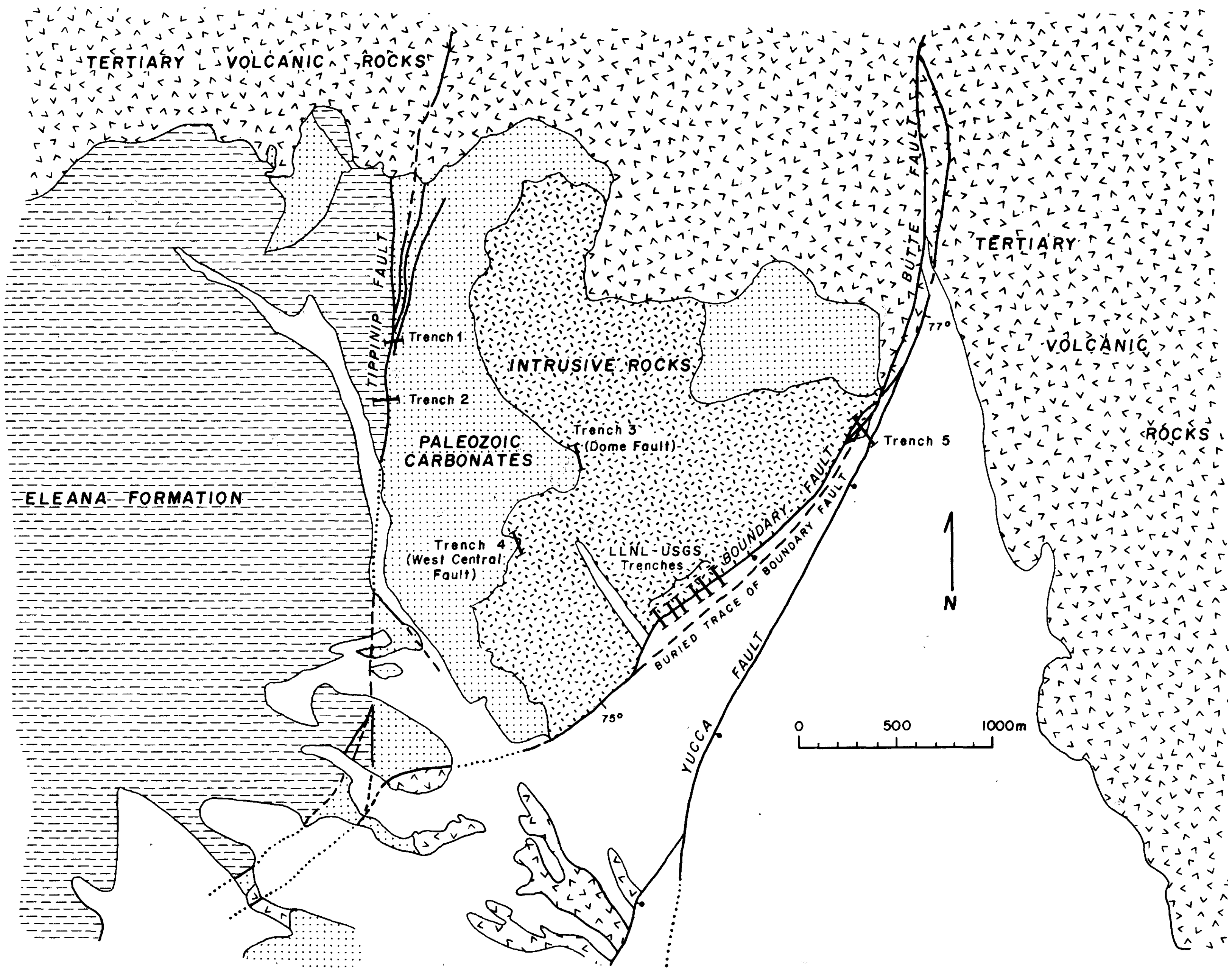

Figure 3A.--Geologic map of Climax stock area showing Eleana Formation, intrusive rocks of the stock, Tertiary volcanic rocks, trench locations, and main faults. (Blank area represents alluvial deposits.)

on the Tippinip fault, trenches 3 and 4, along the features referred to as the west-central fault and the Dome fault, and trench 5, near the point of intersection of the Boundary and Yucca faults (fig. 3A). The trenches exposed enough of each feature to determine the nature of the contact and its strike and dip. Six trenches, excavated previously by USGS (U.S. Geological Survey) and LLNL (Lawrence Livermore National Laboratory), across the Boundary fault, were re-examined during this investigation.

Trench 1

Trench 1 cuts the northern part of the Tippinip fault (fig. 4A). The fault, as seen in this trench, strikes N. 2° W. and dips 84° toward the west. This attitude agrees with that originally mapped from surface exposures of the fault by Houser and Poole (1960). The fault has a nearly vertical, clay-rich (possibly kaolin) gouge zone 0.3 to 0.5 m wide. Rocks of the Late Paleozoic Eleana Formation lie adjacent to rocks of the Ordovician Pogonip Group.

The Eleana Formation, as exposed in the trench west of the fault, consists of several beds of calcareous argillites and siltstones. All the beds are highly fractured, and many show iron staining. The bedding dip in Eleana units, where measureable, is approximately 75° toward the west. At least five small faults within the Eleana were exposed in trench 1. These faults strike due north to N. 10° W., and dip 70-78° west (fig. 4A).

East of the Tippinip fault, limestones and marbles of the Pogonip Group are exposed. The carbonates at this location are massive, sugary-textured, light-to-medium gray, and highly fractured, dipping approximately 50° to 55° toward the west.

Trench 2

Trench 2 cut the Tippinip fault approximately 290 m (951 ft) south of trench 1 (fig. 3A). The fault in this exposure has nearly the same attitude as seen in trench 1: strike N. 2° W., dip 85° west (fig. 5A). Altered rocks surround the fault. A narrow zone (0.3 m wide) west of the fault is made up of brittle yellow-green clay and altered argillite. East of the fault a wider zone (0.8 m) is made up of yellow, red, and orange clay and contains inclusions of partially altered limestone.

Rocks of the Eleana Formation exposed on the west side of the fault, are similar to those seen in trench 1. They consist of thin-bedded, highly fractured, iron-stained, calcareous argillites and siltstones. Near the fault the argillites and siltstones bear numerous calcite stringers. A surface feature, approximately 30 m (98 ft) west of the Tippinip fault, was also exposed in the trench. A distinct color change is visible at the surface, but in the trench this feature is a lithologic contact, possibly a bedding plane, and not a fault. Bedding planes in the Eleana units at this location dip approximately 55° W. There are three main joint sets, striking N. 65° W., N. 60°, and east-west.

Rocks of the Pogonip Group, exposed east of the Tippinip fault, consist of partially altered limestone and marble dipping 50° to 60° toward the west.

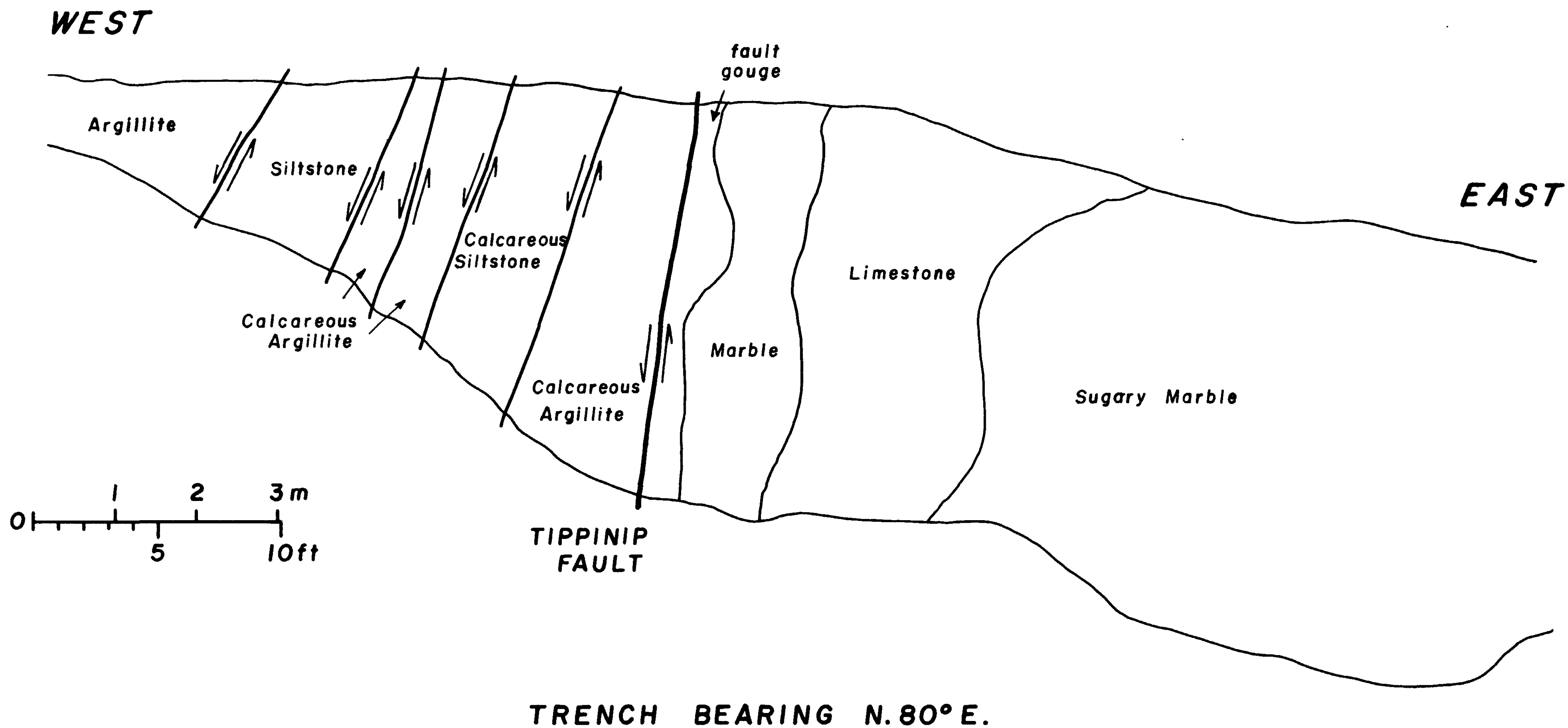

Figure 4A.--Geology of trench 1, north face.

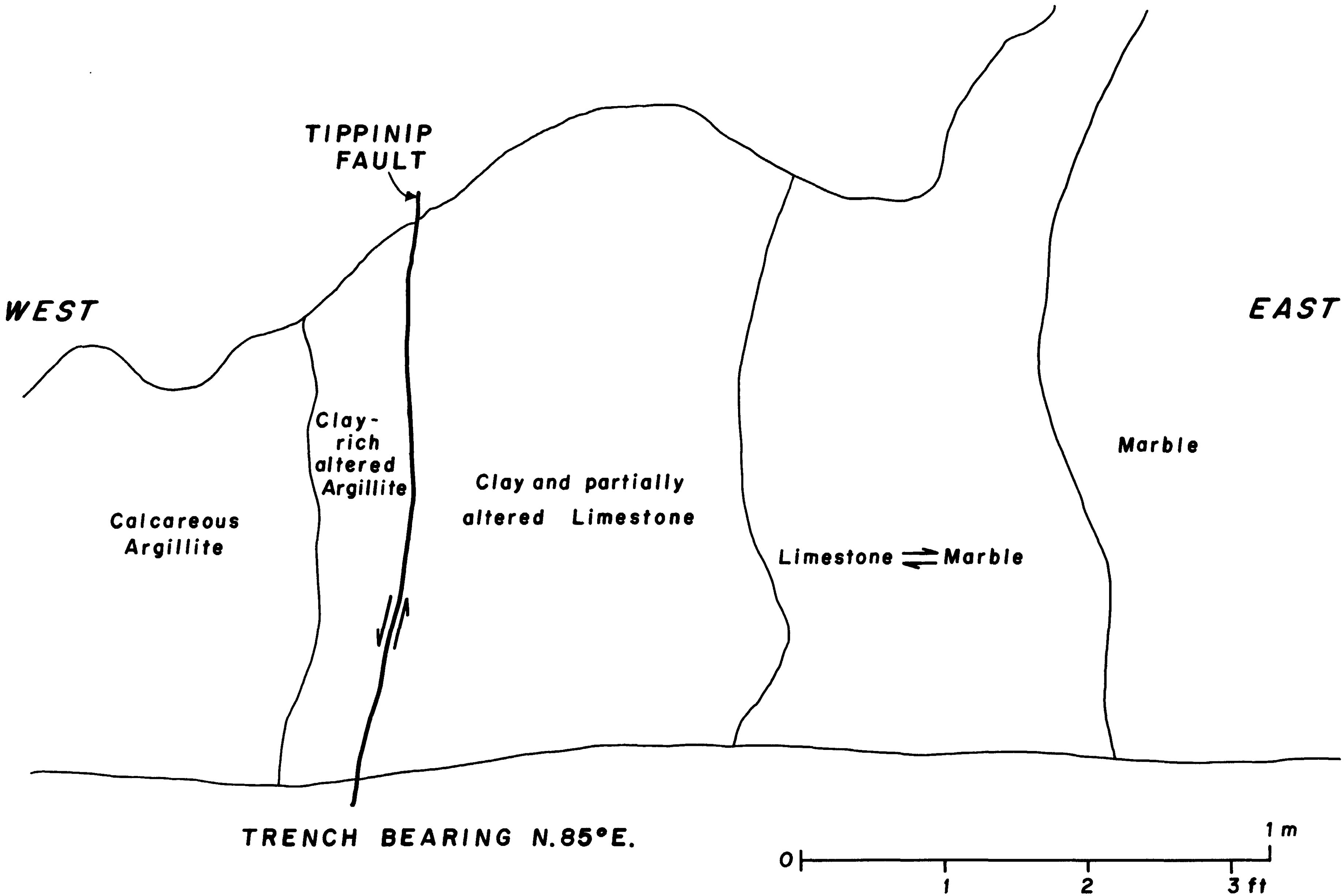

Figure 5A.--Geology of trench 2, north face.

Trench 3

Trench 3 was excavated on the contact between the granodiorite of the Climax stock and carbonate rocks of the Goodwin Limestone (fig. 3A). The plane between the two rock types appears to be a normal lithologic contact, formed as the granodiorite was emplaced beneath the limestone. The contact, shown in figure 6A is irregular and contains a layer of red clay 3-18 cm thick. Slickensides are present on the clay, indicating some slippage as the granodorite was emplaced or shortly after emplacement.

The Mesozoic granodorite of the Climax stock seen in this trench, is light gray in color, fine to medium grained, equigranular to slightly porphyritic, and somewhat weathered and iron-stained. The older (Early Ordovician) Goodwin Limestone is a thick-bedded limestone, locally recrystallized to marble. In this exposure the limestone is highly fractured and intensely altered. The central block of Goodwin Limestone, as shown in figure 6A, is now marble. The northern block of limestone is sugary-textured and partially altered to marble. The southern block of limestone is more massive and shows less alteration. Although highly fractured and altered, the limestone and marble beds have an easterly dip ranging from 10° to 30° and striking N. 40° W. The underlying granodiorite shows some weathering and alteration, but is fairly competent.

Trench 4

Trench 4 exposed the contact between a carbonate of the Goodwin Limestone and the quartz monzonite of the Climax stock (fig. 3A). Most of the trench was excavated in granitic rock, but a large block of highly brecciated carbonate rock, possibly a roof pendant, is present in the quartz monzonite (fig. 7A). No fault is present at the contact of quartz monzonite and carbonate. As seen in trench 3, the plane is a normal lithologic contact. A thin clay layer is present on the contact, and slickensides are visible on the clay, indicating slippage as the stock was emplaced.

The quartz monzonite seen in trench 4 is light to medium gray and medium grained to porphyritic. The carbonate at this locality is very similar to that observed in trench 3. The block is a limestone, highly fractured, iron-stained, and partially altered to marble. South of the block, the quartz monzonite becomes progressively less altered (fig. 7A). A bedded alluvial deposit is present, north of the block, that cuts the limestone and the granitic rock. A normal fault of unknown displacement was mapped, within the quartz monzonite, approximately 4 m (13 ft) north of the carbonate block. The fault dips approximately 60° south, and strikes N 70° W. The fault cannot be traced on the surface into the carbonate rocks to the west; however, the strike is subparallel to faults previously mapped within the carbonate rocks.

Trench 5

Trench 5 was excavated near the junction of the Boundary and Yucca faults on the eastern part of the Climax stock area (fig. 3A). Several structural features and rock types are exposed here (fig. 8A). At the extreme northern end of the trench, Tertiary volcanic rock has been faulted against Mesozoic quartz monzonite. This fault, mapped as the Boundary fault, strikes N. 35° E. and dips 43° southeast. The quartz monzonite at this location is highly

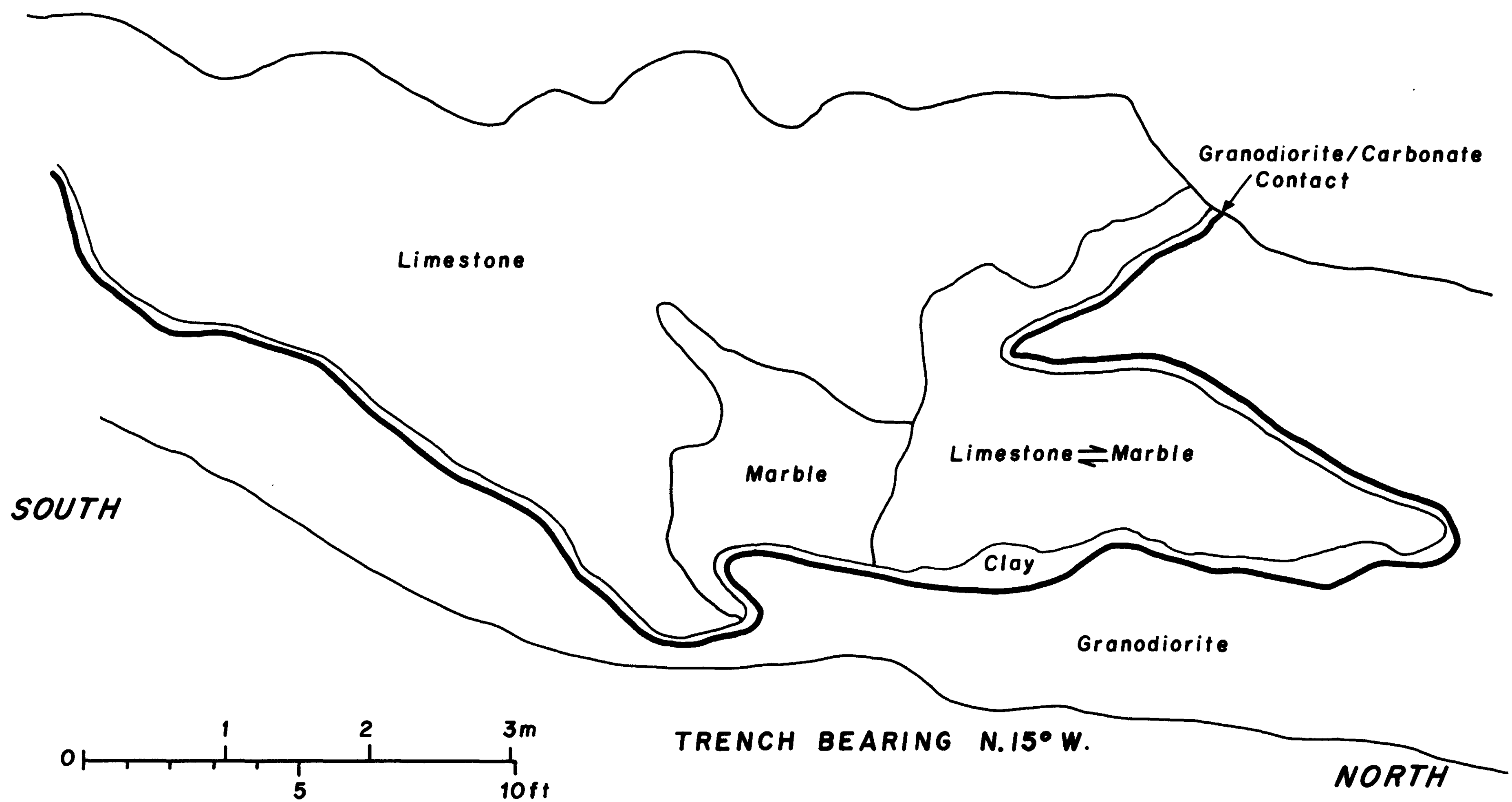

Figure 6A.--Geology of trench 3, west face.

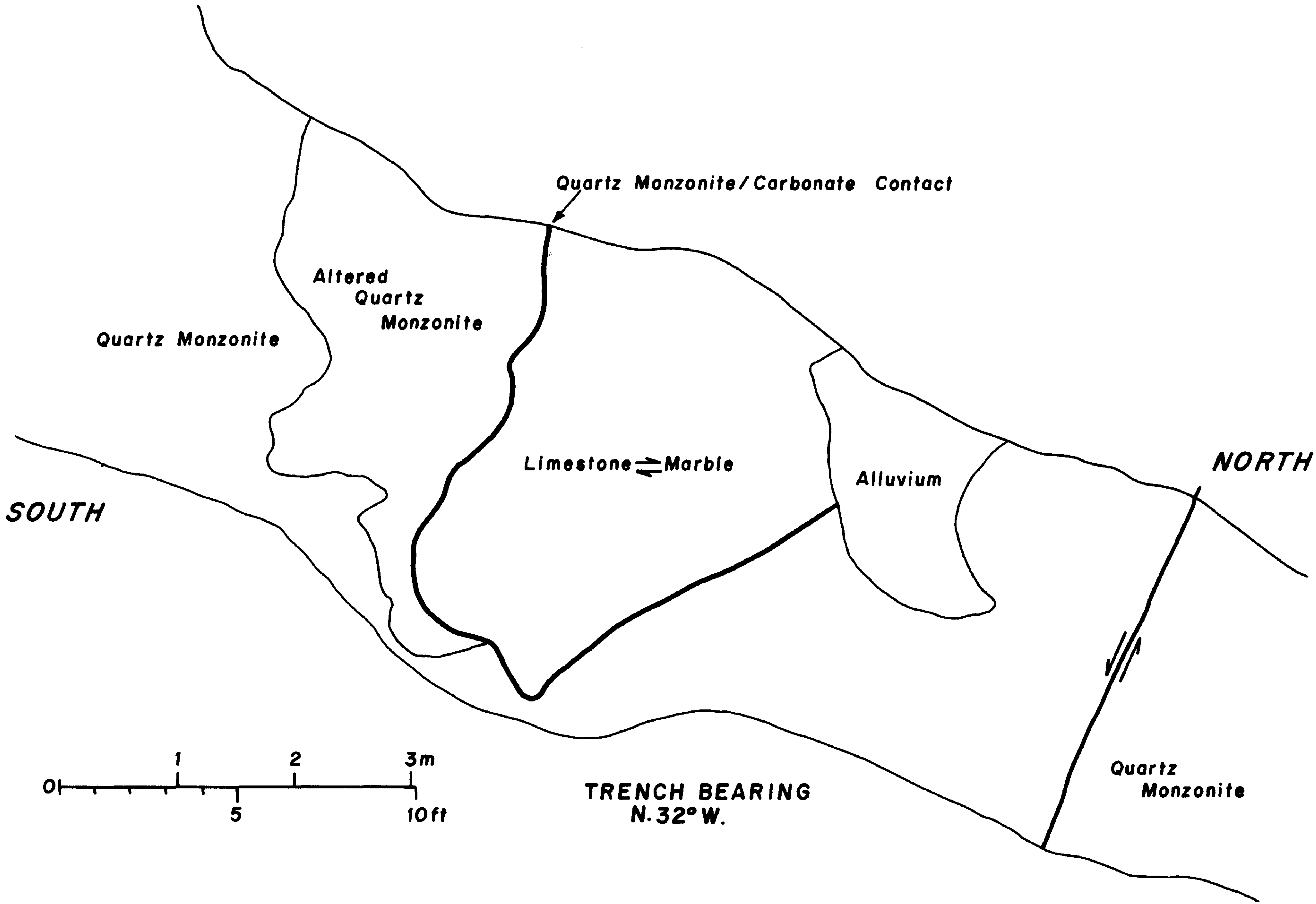

Figure 7A.--Geology of trench 4, west face.

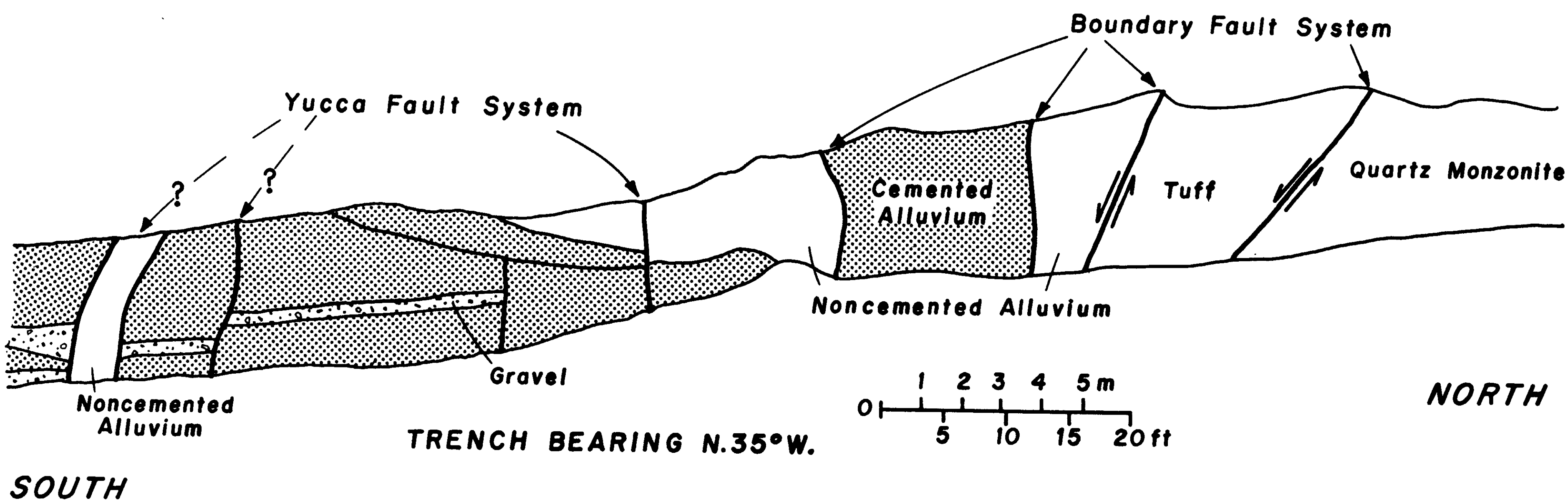

Figure 8A.--Geology of trench 5, west face.

fractured and intensely altered. The rock contains considerable clay, and is fairly incompetent. The volcanic unit is a nonbedded, gray-brown, fine-grained, calcalkaline nonwelded tuff. It contains small, white, zeolitized pumice, few lithic fragments, and sparse biotite. This tuff unit occurs stratigraphically beneath the peralkaline ash-fall tuffs of the Tub Spring Member of the Belted Range Tuff.

A fault striking N. 45^{o} E. and dipping 67^{o} southeast, which is believed to be part of the Boundary fault system, bounds the contact between the tuff unit and a noncemented alluvial unit. This unit is made up of sand-to-boulder-sized fragments of limestone, tactite, granitic rock, and tuff.

A fault, dipping 80^{o} to the east, has dropped the noncemented alluvium next to an older, well cemented alluvial unit. This unit contains sand-to-boulder-sized fragments of granitic rock, tactite, limestone, and tuff. The unit also contains calcite stringers 2-3 cm in width, and beds of gravel cemented with calcium carbonate.

The older alluvial unit has been faulted against another alluvial unit. This fault strikes N. 65^{o} E. and dips 85^{o} southeast. The lower part of this unit is an older, cemented alluvium bearing calcite stringers 2-3 cm wide. The upper part is a younger, noncemented alluvium. The lower section may be the same alluvium as that on the east side of the fault.

In the southern part of the trench, a series of alluvial units are found. A bed of firmly cemented material extends across the trench, dipping northwest about 20^{o}, and resembles a channel deposit. Beneath this bed is a flat-lying gravel layer approximately 0.3 m thick. This unit is cut by a near-vertical fault, displacing the gravel down 1 m to the southeast. Further south, a pair of near-vertical faults has allowed the deposition of young unconsolidated material. South of this unit another older alluvial unit is present, bearing a cemented gravel bed.

All the fault planes, from that placing alluvium against tuff, south through the various units of alluvium, may represent the northern extension of the Yucca fault. All of these faults are nearly vertical and show normal displacement down to the southeast.

A pure white calcrete in the fault next to granite in trench 5 was sampled and dated by the uranium-thorium method. The isochron-plot age is 219,000±30,000 years B.P. (J. N. Rosholt, written commun., 1981). The carbonate sample appears undisturbed by faulting; thus, it yields a minimum age for the last displacement of the fault. Estimated age for this sample from its geologic setting is more than 8,000 years B.P. The isochron-plot constructed from the analytical data of both the carbonate and detrital fractions appears reliable. The reason for the discrepancy is not understood at present.

A laminar soil caliche sample was taken from an LLNL trench south of trench 5, dug across the Boundary fault. The caliche is displaced by the fault, and gave an age of >8,000 years (Szabo and others, 1981), whereas the calcrete from the fault zone itself gave an age of about 24,000 years. The calcrete in the fault appeared to be crusted and jostled by subsequent movements. The age of the offset caliche appears to be somewhat younger than the age of the fault as estimated from other evidence. The faulting occurred after deposition of most of the laminar soil caliche. Rough ages based on scarp-slope technique of estimating ages of recent fault scarps determined by Wallace (1977, p. 1275) for north-central Nevada and by scarp-slope studies by Orkild for central and southern Nevada suggest that the Boundary fault scarp formed about 10,000 years ago, which is in fairly good agreement with the age of >8,000 years, determined on the offset caliche.

LLNL/USGS Trenches

The first two exploratory trenches across the Boundary fault were excavated by the USGS in 1973, and four additional trenches were dug by the LLNL early in 1980. These six previously excavated trenches expose approximately 400 m (1,312 ft) of the Boundary fault as shown on figure 3A.

The geology mapped in each of the six trenches is relatively uniform. The Boundary fault dips between 43^{o} and 59^{o} SE. The fault is characterized by a strongly altered, highly fractured zone 1 to 2 m (3 to 6 ft) in width (fig. 9A). Slickensides are visible and show only a vertical component of movement. The quartz monzonite is highly fractured, decomposed, and iron stained. The alluvium is not cemented and is only slightly altered along the fault contact.

In summary, data collected from trenches 1 and 2 documented the steeply dipping nature of the Tippinip fault, which agrees with that originally mapped from surface exposures by Houser and Poole (1960). The geologic nature of the granodiorite west of the Tippinip fault is still uncertain; however, detailed geophysical surveys indicate there is no evidence of displaced granitic rock at the fault. Examination of trenches 3 and 4 indicated that the previously mapped Dome(?) and West-Central(?) faults were not faults, but were contacts between granite and marble. Trench 5 uncovered the contact between the Yucca and Boundary faults. The fault exposed in trench 5 resulted in a revision of the existing map of the confluence of the Boundary and Yucca faults (pl. 1 and fig. 3A). The Yucca fault, traced in the Smokey Hills region and in the alluvium, consists of numerous close-spaced en echelon breaks that consistently step to the left as it approaches the Boundary fault. This is consistent with a component of right-lateral slip. Examination of the tuff units northeast of trench 5 indicates that maximum displacement of Yucca fault occurs in the tuff units rather than between the alluvium and tuff.

Field Studies North and Northeast of Climax Stock

The tuffs in the east corner of the area and west of the Butte fault indicate structure which is inferred to reflect the expression of the contact of the granite and pre-Tertiary rocks beneath these overlying tuffs. The structure and stratigraphy of these tuffs, as well as the tuff structure in the vicinity of Oak Canyon north of Oak Spring Butte, have been examined.

For a complete understanding of the regional Tertiary geologic history in the vicinity of Oak Spring Butte, it is necessary to decipher the local structure. Anticlines and synclines that were formed by deposition on the hilly pre-Tertiary erosional surface underlying the older bedded and ash-flow tuffs and Belted Range Tuff, must be distinguished from similar structures of tectonic origin.

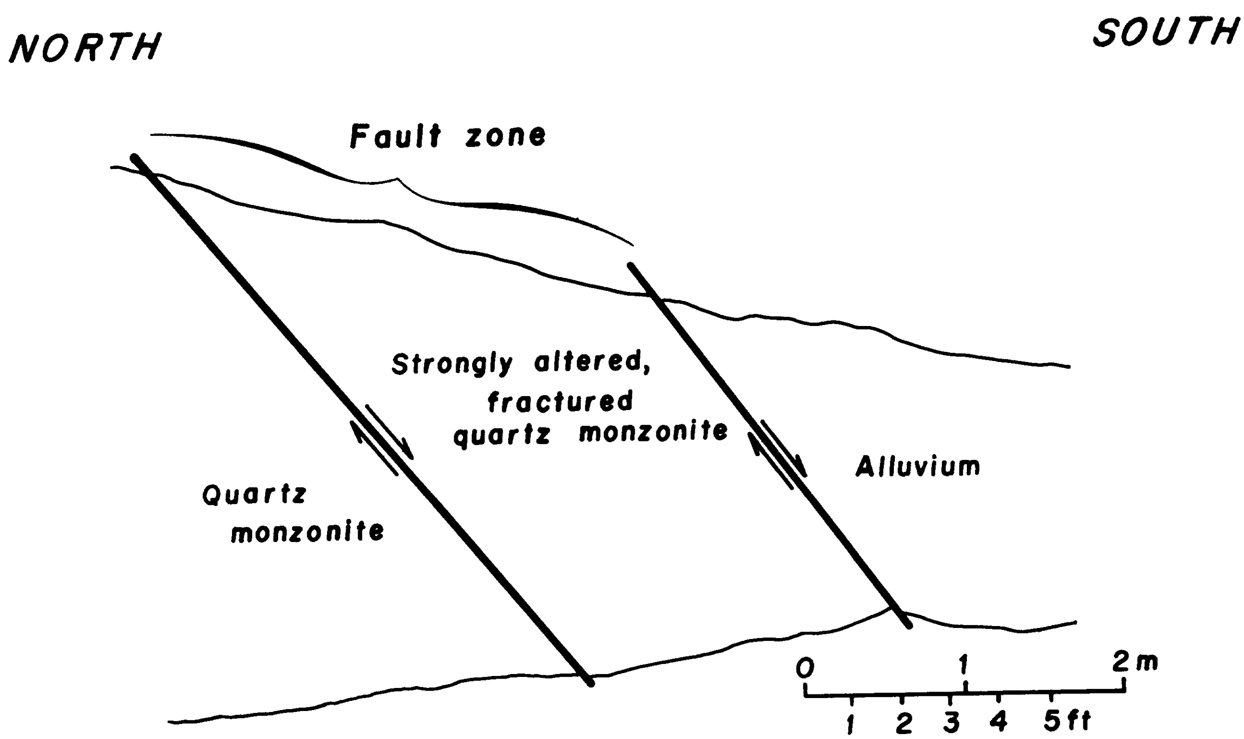

Figure 9A.--Geology of LLNL 5 trench, east face. Typical of geology in trenches across Boundary fault.

The depositional anticlines and synclines are moulded on preexisting ridges and valleys, and delimit the areas of relatively thin and thick tuff. The initial dips imposed on the beds have been modified to an unknown extent by differential compaction.

North of Oak Spring Butte, the Tertiary volcanic rocks are as much as 671 m (2,200 ft) thick, and consist of welded and nonwelded ash-flow tuff and thick-bedded to laminated reworked fluvial and possibly eolian tuffaceous deposits. The tuffs were initially deposited as ash fall and ash flows on an irregular surface of considerable relief. One ash flow was confined to a valley bottom and subsequently reworked in large part by water and wind to form tuffaceous sedimentary rocks.

Field observations by the author indicate that the local relief on the erosional surface under older bedded and ash-flow tuffs and the Belted Range Tuff north and northeast of Oak Spring Butte is of the same order of magnitude as the relief on the present exposed topography of nearby surfaces carved from Paleozoic rocks (fig. 10A). The maximum local relief on the old eroded surface ranges from 122 to 610 m (400 to 2,000 ft) in horizontal distances of 366 to 4877 m (1,200 to 16,000 ft). The rocks on which this surface is cut are structurally complex Paleozoic argillites, quartzites, carbonates, and granitic rocks of the Climax stock. In some localities, the present stream valleys and ridges developed in these rocks are in part alined with those on the surface underlying the older bedded and ash-flow tuffs and the Belted Range Tuff.

The variations in the thickness and structure of the older units in the Climax area reflect the underlying topography. Because these units were deposited on a very irregular surface, the older units range in thickness as much as 366 m (1,200 ft). The thicker parts generally overlie the old low areas, though they never completely fill them. Pyroclastic rocks only partly filled the valleys and draped themselves over buried ridges. The bedding in the basal part of the units is generally subparallel to the underlying surface. Dips of 25° are common but locally dip of as much as 40° can be observed. As the unit accumulated, the dips became progressively lower because the topographic relief was gradually subdued by continued deposition, erosion, and redistribution of volcanic material. Figure 10A shows the relationship of primary anticlines and synclines to the configuration of the underlying surface. These relationships are best observed in Oak Canyon and in the vicinity of the Climax stock.

The ash-fall and reworked bedded tuffs were deposited in valleys and are generally in horizontal or very gently dipping beds, depending on the slope of the underlying surface.

In the welded ash-flow tuff the layering is horizontal or gently dipping except where flows encountered steep cliffs or rugged paleotopography. The initial dips of Belted Range welded tuff are 3° to 7°. The welded tuffs beneath the older bedded tuffs and the Belted Range have the characteristics of ash flows restricted to old valleys. The Fraction Tuff and Tuff of Whiterock Spring both thicken in the lower parts of the valleys and have slightly concave upper surfaces.

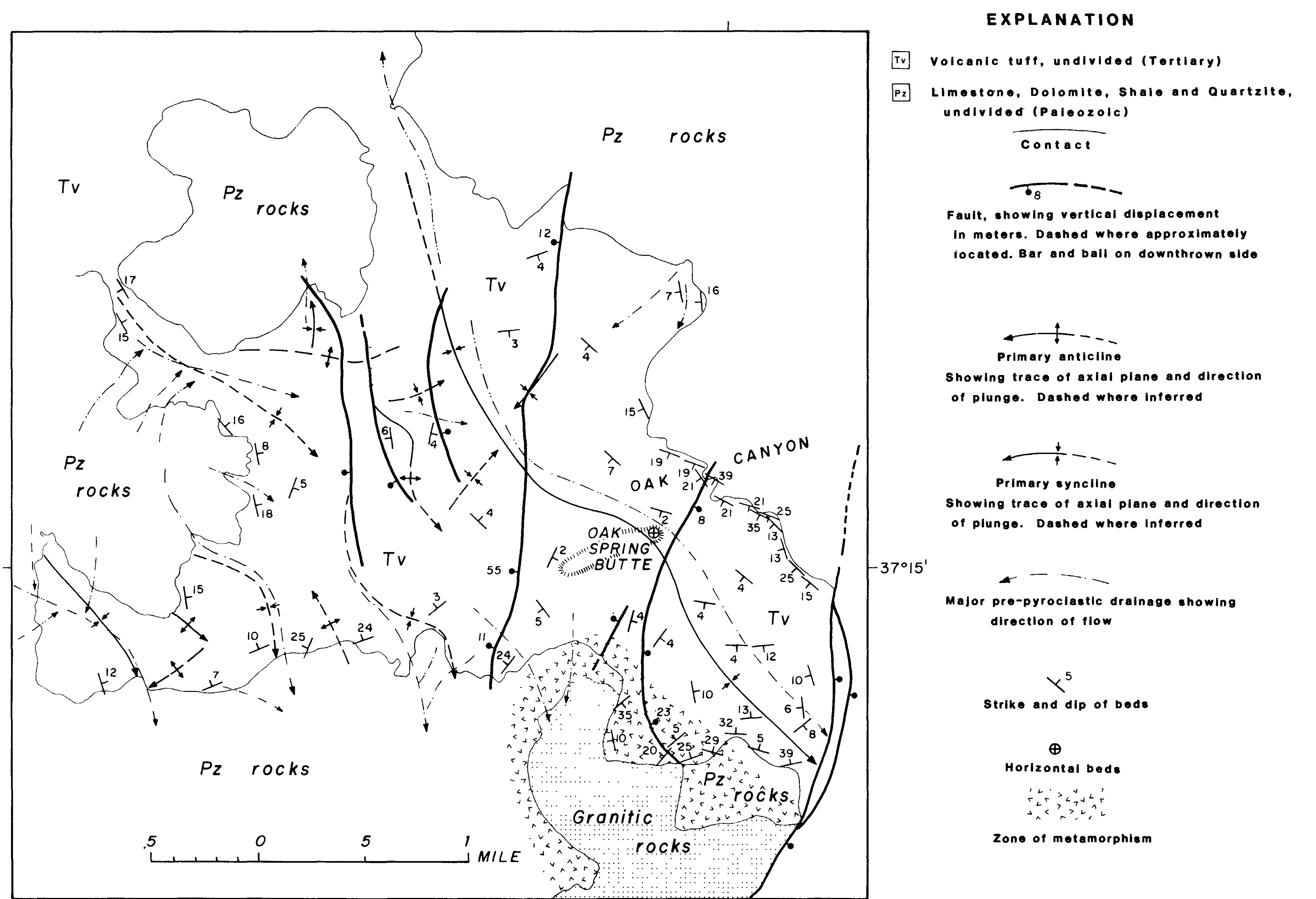

Figure 10A.--Map of the Climax-Oak Spring Butte area showing the relations between the general structure of welded tuff marker units to the former drainages of the underlying surface. (Modified from Sargent and Orkild, 1973.)

The ash falls are blanketlike and conform to the old topography. On the north and south side of Oak Spring Butte, where ash fall and thin ash flows were deposited against a steep preexisting Paleozoic hill, the primary dips at the contact were 25° to 30°, whereas 46-61 m (150-200 ft) above the old erosion surface, dips are 8° to 10°.

The paleotopography indicates that a deeply eroded canyon, as much as 305-610 m (1,000 to 2,000 ft) deep, and draining to the southeast, existed north of Climax stock. The syncline trending southeast through Oak Spring Butte on figure 10A represents the surface expression of the filled canyon. No metamorphosed limestones, dolomites, or tactitic rocks were found in the basal parts of the ash-flow tuffs or in the Tertiary gravels between the flows which were deposited in the valley bottom. This is a good indication that the zone of metamorphism which generally extends out a few hundreds of meters surrounding the stock had not been breached by the drainage and occurs 450 to 600 m (1,500-2,000 ft) to the south and southwest of the paleodrainage.

The approximate near surface shape of the stock can be inferred on geologic evidence. The carbonate rock for as much as few hundred meters from the granite have been metamorphosed to dolomitic marble and locally to complex silicate rock known as tactite (fig. 10A). The degree of metamorphism generally decreases away from the intrusive. This alteration zone gives a suggestion as to the configuration of the granitic body below the Paleozoic rocks.

Original bedding in the marble west of the granite is difficult to determine, but it strikes north essentially parallel with the western boundary of the granitic rocks and dips generally very steeply to the west. The contact of the granite with the marble dips steeply to the west.

Along the northeast contact of the intrusive, near the Climax mine, the altered carbonate rocks strike N. 40° to 75° W., and dip 15° to 50° NE. The granite contact with metamorphic rocks dips gently northeastward in this area as suggested by the northeast dipping sill of granite exposed in the mine workings.

The relation of the intrusive to the Paleozoic rocks on the north indicate that the granite contacts dip between 20° to 75° to the north. The proximity of the steeply dipping and tightly folded Paleozoic rocks which are exposed about 1.5 km to the north of the stock suggests that the intrusive maybe discordant of its northern extremity.

The Tertiary rocks overlap the granite with erosional unconformity at the northern boundary of the intrusive. The pre-Tertiary relief in this area was over 80 m (260 ft). The attitude of beds in the lower part of the Tertiary section just northwest of Climax mine conforms to the irregular pre-Tertiary erosional surface indicating that the tuff beds were draped over a granite hill.

GEOLOGIC APPRAISAL OF AREA PROPOSED FOR EMPLACEMENT HOLES

The surface structure in the area proposed for emplacement holes was examined and mapped (pl. 2A and fig. 11A). Initial geologic mapping was done

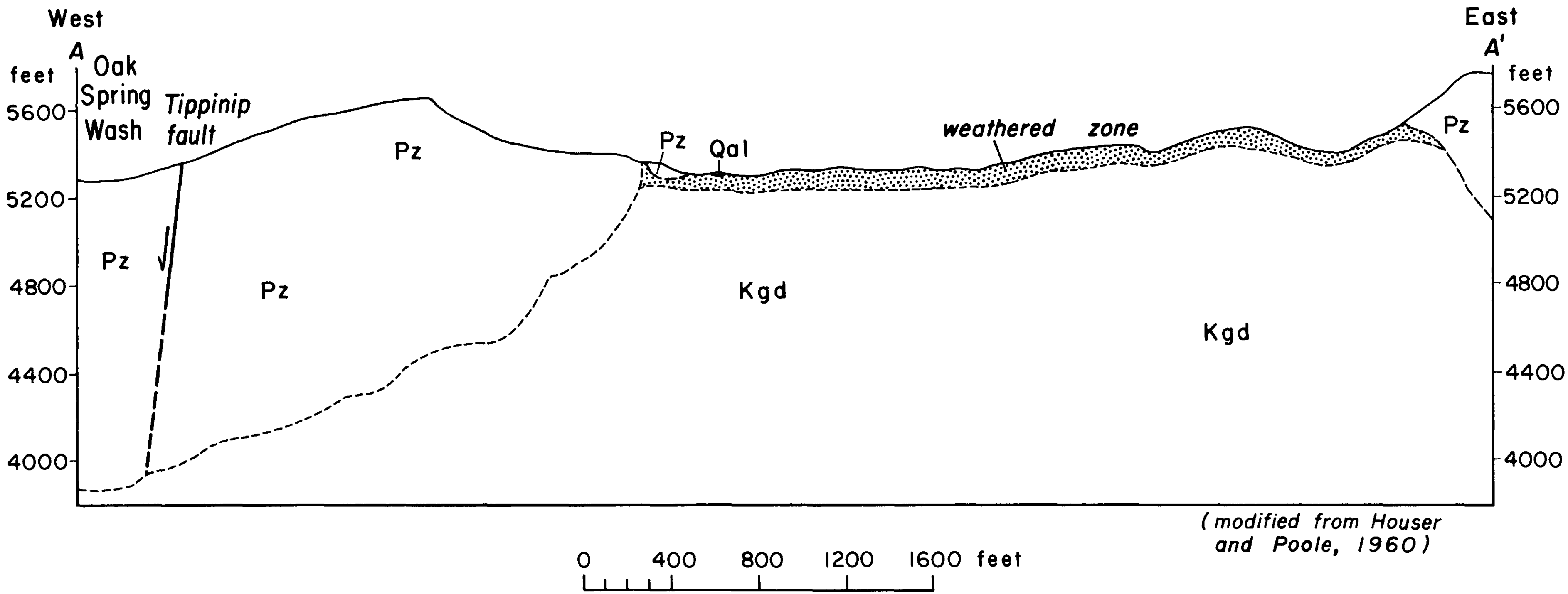

Figure 11A.--Generalized east-west section through the Climax stock.

by Houser and Poole, 1960; only minor differences were observed during field mapping. These differences include: (1) the contact between Pogonip marble and the granodiorite is a contact instead of a fault; mapping of trench 3 confirmed this hypotheses; (2) only minor joints, trends, and attitudes could be added to the original geologic map. Examination of the site indicates that the depth for trenching to uncover solid rock would be exorbitant and, therefore, no trenches in drainage features were located in the area. It is estimated that the thickness of weathered granodiorite could be on the order of 8 to 46 m (25 to 150 ft).

The proposed site area lies in the granodiorite phase of the Climax stock. The rock is jointed and probably contains numerous shear and fault zones at depth.

Three dominant joint trends have been mapped in the area. These trends are as follows: (1) generally N. 32° W. and low angle; (2) N. 32° W. and high angle; and (3) N. 20° to 40° E. vertical or dipping at high angle to the southeast.

In the area proposed for emplacement holes, the drainages do not appear to be controlled completely by structures in the granodiorite. The exposures are poor in the area and what is shown on Map I-238 (Houser and Poole, 1960) as granodiorite is a combination of colluvium and highly weathered granodiorite with only the more resistant granite dikes and sills exposed with an occasional outcrop of granodiorite in stream bottoms. Where the granodiorite occurs, its strucutre appears to have no bearing on the drainage development or orientation. Headward erosion of the drainages on the Climax stock was accelerated when the Boundary and Yucca faults were reactivated some 8,000 to 10,000 years ago.

If the total drainage pattern which traverses the Climax stock area is considered, most of the stream channels are subparallel to the Paleozoic/granite outcrop pattern in the west side of the stock. They trend approximately N. 40° E. at the lower extremities and change to a north to northeast trend at head of the washes. Where the drainage channels are incised in granite rock, they very probably are influenced by the N. 38° W. joint system.

The frequency of faults, fractures, and shear zones in the vicinity of U15a, 853 m (2,800 ft) to the south of the proposed site, is 4.5, 1.3, and 0.2 per 30 m for the northwest, east-west, and northeast-trending structures, respectively (Houser and Poole, 1961). The frequencies of these structures as noted above probably are representative in the area for the proposed drill holes. Additional fractures probably do exist and locally the number of fractures per 30 m may be greater. However, this cannot be predicted unless core drilling is undertaken.

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GRAVITY INVESTIGATIONS
by
D. L. HEALEY

ABSTRACT

A large density contrast exists between the Paleozoic rocks (including the rocks of Climax stock) and less dense, Tertiary volcanic rocks and alluvium. This density contrast ranges widely, and herein for interpretive purposes, is assumed to average 0.85 Mg/m^3 (megagrams per cubic meter). The large density contrast makes the gravity method a useful tool with which to study the interface between these rock types. However, little or no density contrast is discernible between the sedimentary Paleozoic rocks that surround the Climax stock and the intrusive rocks of the stock itself. Therefore the gravity method can not be used to define the configuration of the stock.

Gravity highs coincide with outcrops of the dense Paleozoic rocks, and gravity lows overlie less-dense Tertiary volcanic rocks and Quaternary alluvium. The positions of three major faults (Boundary, Yucca, and Butte faults) are defined by steep gravity gradients. West of the Climax stock, the Tippinip fault has juxtaposed Paleozoic rocks of similar density, and consequently, has no expression in the gravity data in that area. The gravity station spacing, across Oak Spring Butte, is not sufficient to adequately define any gravity expression of the Tippinip fault.

Two-dimensional (2-D) and three-dimensional (3-D) analysis of the gravity low anomalies have been made. The gravity data were interpreted to define the vertical displacements on the major faults; the configuration of the buried upper surface of the Paleozoic rocks, and the combined thickness of the Tertiary volcanic rocks and alluvium beneath Oak Spring Butte and Rhyolite Hills.

INTRODUCTION

The Climax stock gravity survey (pl. 2B) is a small part of a much larger gravity survey that covers all of the Nevada Test Site (NTS) and much of the surrounding region. A complete Bouguer gravity map that includes the Climax stock area was published by Healey, Wahl, and Currey (1980).

Previous studies of the stock include an interpretation of the high-level aeromagnetic data (Allingham and Zietz, 1962) which included a 2-D interpretation of gravity data showing the general configuration of the Paleozoic rocks southeast of the stock, and an investigation across the Boundary fault along the southeast side of the stock (C. H. Miller and D. R. Miller, written commun., 1973).

The gravity coverage in the Climax stock area was accumulated from 1958 until 1980 under the sponsorship of the U.S. Atomic Energy Commission, the Energy Research and Development Administration, and the U.S. Department of Energy. The corrections that were applied to and the estimated accuracy of the gravity data herein reported is summarized in Healey and others (1978, 1981). Data reduction to complete Bouguer values was by standard procedures (Nettleton, 1976) using the computer program of Plouff (1977) and the 1971 International Gravity Standardization Network (Morelli, 1974). The reduction density was 2.67 Mg/m^3. Terrain corrections from each station outward to a radial distance of either 2.615 km (1.62 mi) (Zone H) or 14.74 km (9.16 mi) (Zone L) (Hammer, 1939) were calculated by hand or estimated (in low-lying areas) from adjacent stations. The remaining correction for the variation in terrain, to a radial distance of 166.7 km (103.6 mi), were computer generated using the USGS version of the DMA (Defense Mapping Agency) digital terrain data.

About 80 to 90 of the gravity stations are located in mountainous areas where the terrain correction is most subject to error. The accuracies of some of these stations may be ±0.4 mGals or more. The effect of these uncertainties on the model calculations will be discussed later.

Numerous faults are shown on Plate 1A. However, in this report emphasis will be placed on the Boundary, Yucca, and Butte faults. These three faults are major features that have influenced much of the present structure adjacent to the stock. The Tippinip fault is also a major fault that has influenced geologic structure along the west side of the stock. However, west of Climax stock, the Tippinip fault has juxtaposed rocks of similar density and therefore has no gravity expression. The Tippinip fault is traced northward across Plate 1A to the northern limit of the outcropping Paleozoic (Pz) rocks. Beneath Oak Spring Butte the gravity coverage is inadequate to define any gravity anomaly associated with Tippinip fault.

Examination of Plate 1A indicates that Climax stock is located in the southeast part of a large block of Paleozoic rocks. The southeast side of the stock is truncated by the Boundary fault. A thick sequence of Tertiary volcanic rocks, exposed in a northwest trending outcrop, overlies these Paleozoic rocks north of the stock at Oak Spring Butte. Additional outcrops of Paleozoic rocks occur in the southeast corner of the map, and also east of Butte fault in the area north of lat 37°15' N. In the Rhyolite Hills, which lie between these two areas, and east of the Yucca-Butte fault zone, is a large area of Tertiary volcanic rocks. The thickness of the Tertiary volcanic rocks and configuration of the Paleozoic surface in these areas has been interpreted from the gravity data. The terrain-imposed relatively sparse gravity coverage in the hills around the Climax stock (pl. 2B) imposes some restrictions on the interpretation; small changes in the gravity anomaly are not adequately defined. This is especially true near the contact between the Paleozoic rocks and the overlying Tertiary volcanic rocks north of the stock.

Acknowledgments

Appreciation is expressed to F. E. Currey who made many of the gravity observations, assisted with the data reduction and terrain corrections; to R. R. Wahl who assisted the program intermittently over the years and provided specialized gridding and contouring routines; to R. Saltus for processing the "perspective" data; and to colleagues for discussions concerning the findings of other geologic and geophysical studies of this most interesting area.

DENSITY DATA

The gravity meter measures minute changes in the Earth's gravity field which are called "anomalies". Gravity anomalies are caused by lateral variation in rock density. The magnitude and form of the anomaly is dependent on the densities involved, anomaly magnitude, topographic relief, depth, and horizontal extent of causative rocks (Nettleton, 1971, p. 4).

The undivided Paleozoic rocks (labelled Pz on pl. 1A) consist of quartzite, argillite, limestone, dolomite, shale, marble, tactite, and conglomerate and range in density from 2.49 to 2.85 Mg/m^3 (Healey, 1968). At the NTS, this sedimentary section totals about 11,300 m (37,000 ft) in thickness (Harley Barnes, written commun., 1962) with a weighted average density of 2.67 Mg/m^3.

Climax stock is composed of quartz monzonite (Kqm on pl. 1A) and granodiorite (Kgd on pl. 1A). Izett (1960) reported dry bulk densities that range from 2.65-2.69 and average 2.68 Mg/m^3 for these rocks. F. N. Houser (written commun., 1962) reported values that range from 2.5-2.7 and averaged 2.64 Mg/m^3 for both rock types.

The undivided Tertiary volcanic rocks (Tv on pl. 1A) vary widely in bulk density. Densities range from 1.49-2.34 and average 1.93 Mg/m^3 for nonwelded tuff, and from 1.85-2.50 and average 2.36 Mg/m^3 for partly welded to welded tuff (Healey, 1968, p. 151). The density of Quaternary alluvium also varies considerably. In Yucca Flat, the mean density of 2,225 m (7,300 ft) of alluvium, measured in several drill holes by density logs and borehole gravity meter, is 2.01 ±0.01 Mg/m^3 (Healey, 1970, p. B61).

The small contrast in average density (0.03Mg/m^3) between the Climax stock and the surrounding Paleozoic rocks precludes the use of the gravity method in defining the configuration of the stock. However, the large density between the Paleozoic rocks (combined stock and Paleozoic rocks) and the Quaternary alluvium and Tertiary volcanic rocks makes the gravity method useful in defining the thickness of these two latter units.

Density data is not available for the Tertiary volcanic rocks that comprise the Rhyolite Hills and Oak Spring Butte. However, the value of -0.85 Mg/m^3 has been found to yield valid predictions in parts of northern Yucca Flat where drill holes verify the depths calculated from gravity data. Therefore, a contrast of -0.85 Mg was assumed in these two areas for modeling purposes.

INTERPRETATION

Early investigations

A preliminary 2-D geologic cross section (located along line A-A', pl. 1A) prepared by the author and published in Allingham and Zietz (1962, p. 607), was based on scattered gravity data and an assumed density contrast of 0.80 Mg/m^3. Based on a residual anomaly of 12.5 mGals, the interpreted depths east of Boundary and Yucca faults were 300 m (1,000 ft) and 600 m (2,000 ft), respectively. In response to a DNA request for a detailed study of Boundary fault, a grid of five northwest trending lines (labelled Line A through Line E, fig. 1B) were established in 1973. Gravity stations were located at 152 m (500 ft) intervals along these lines.

The two-dimensional interpretations of the residual gravity anomaly along

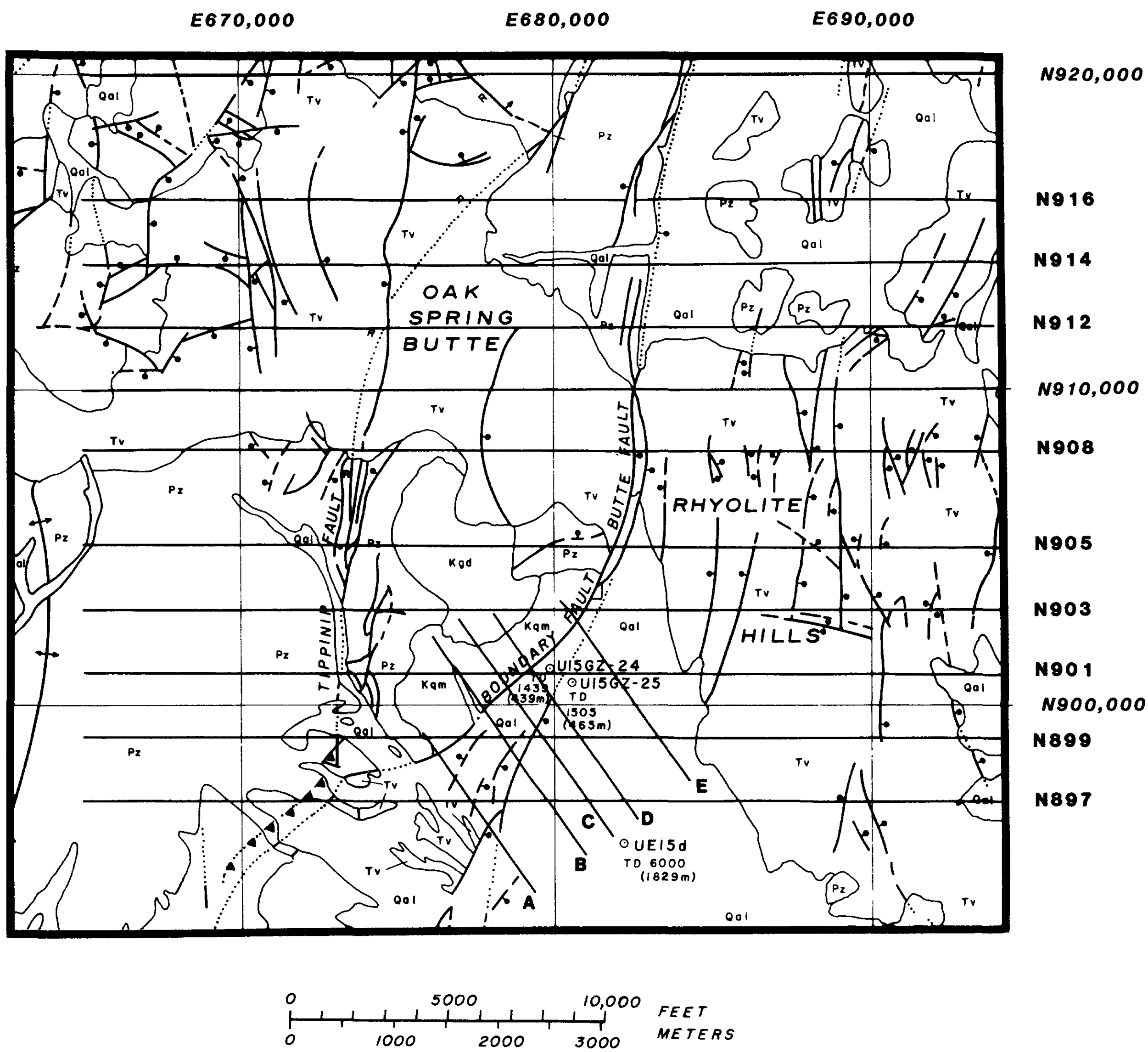

Figure 1B.--Locations of 2-D and 3-D gravity lines. (See plate 1A for explanation of geologic symbols.)

each of these five lines, are shown on figure 2B. The computed displacements along Boundary fault range from 120 m (400 ft) to 350 m (1,150 ft). East of Yucca fault the interpreted thickness of the combined alluvium and volcanic rocks ranges from 300 m (1,000 ft) to 480 m (1,600 ft). These earlier interpretations agree well with recent 3-D dimensional interpretations that will be discussed later.

Recent investigations

The Bouguer gravity anomaly map (pl. 1B) includes all available gravity data. The map is dominated by a broad gravity high that trends northeastward from the southwest corner to near the northeast corner of the map. This gravity high is caused by the large block of Paleozoic rocks that crop out in this area. Other gravity highs coincide with the Paleozoic rocks that crop out in the southeast corner of the map and in the Smoky Hills.

Major gravity lows occur on the northwest side of the gravity high (West of Burn Mountain), at the north end of Yucca Flat, over Rhyolite Hills and Oak Spring Butte, and in the northeast corner of the map. These lows are associated with Tertiary volcanic rocks and alluvium.

The steep gravity gradients associated with the Boundary and Yucca faults indicate areas where low-density rocks have been juxtaposed against more dense rocks by the offset on these faults.

The steep gravity gradient in the northwest corner of the map indicates that the section of Tertiary volcanic rocks thickens rapidly away from the Paleozoic outcrops. A postulated fault with displacement down to the northwest, but of unknown magnitude, is shown on plate 1A. This postulated fault coincides with the steepest part of the gravity gradient.

At the north end of Yucca Flat (on either side of Smoky Hills) the low anomalies reflect the southward deepening section of Tertiary volcanic rocks and alluvium. Further north, the low anomalies over Rhyolite Hills and Oak Spring Butte were both investigated as part of this study. Little is known about the small low in the extreme northeast corner. The 3-D interpretation was terminated south of this low and it has not been investigated.

The majority of the gravity coverage is concentrated in Yucca Flat, in and around Climax stock, and along Butte fault. In these areas, the anomalies are well defined. The gravity coverage in the elevated, more difficult terrain is sparse. For this reason, major anomalies in the elevated area are well defined but minor anomalies having small flexures are not. The lack of detailed gravity data along the transition zone between the Climax stock and Oak Spring Butte did not permit a complete interpretation along line N908,000 (fig. 1B). The line numbers, i.e., N897,000, for the southernmost line, is the Nevada State coordinate along which the cross section is drawn.

The Climax stock modeling is based on two 3-D models. As part of the continuing study of Yucca Flat, a 3-D model that covered as far north as N905,000 (fig. 1B) was recently completed. However to study the area from N905,000 to N920,000 a second 3-D model was constructed. Both models are based on the 3-D program "Polygrav" written by Donald Plouff (1975). Polygrav

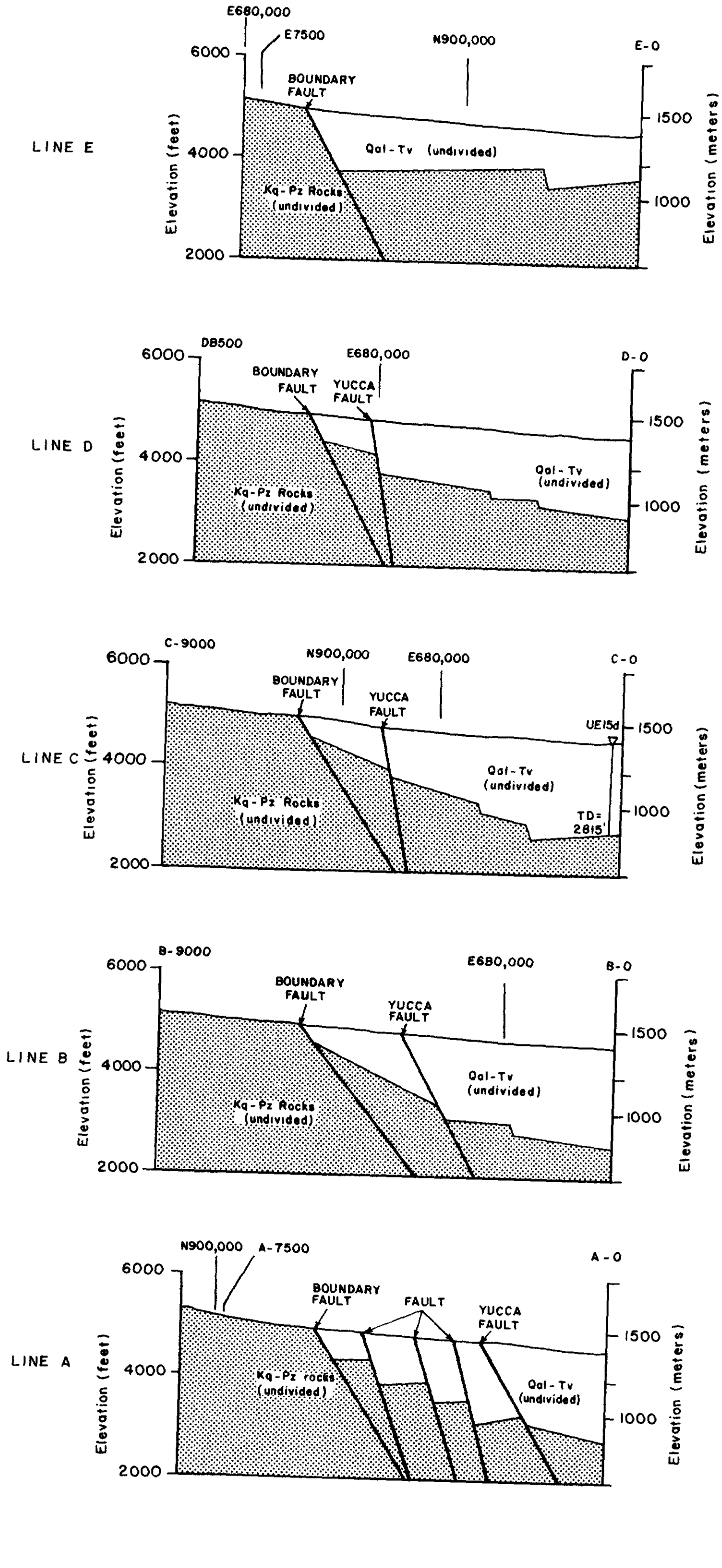

Figure 2B.--Interpreted Geologic cross sections along lines A-E as determined by 2D analysis of gravity data. (See plate 1A for explanation of geologic symbols.)

is a forward program that computes the gravity effect of "bodies" described by polygons. The bodies may be irregularly shaped but each corner must be defined. The entire model must be completely covered by the defined bodies. Experience has shown that body edges should be placed to coincide with flexures in the gravity anomaly, at known, or suspected faults, or at geologic contacts. Density contrasts and elevations are assigned to each body of the model. Density data and drill holes are used to choose the density contrast and elevation assigned to certain bodies. In the absence of density data and drilling, assumptions are made for these two parameters.

As stated earlier, a density contrast of 0.85 Mg/m^3 was assumed in this modeling. This value has been found applicable in northern Yucca Flat. If this assumed density contrast is less than the actual contrast, the resulting interpretation is too deep. Conversely, if this assumed contrast is larger than the actual contrast, the interpretation is too shallow. In the area of Oak Spring Butte and Rhyolite Hills, where the medium residual anomalies are about 10 and 14 mGals, a change in the density contrast of ±0.05 Mg/m^3 will change the interpretation by about ±30 m (100 ft).

The calculated gravity effect is compared to the residual (Bouguer gravity minus the regional gradient) gravity value along selected cross sections through the model. The body elevations and (or) positions are adjusted until a satisfactory agreement between the residual and calculated value is achieved.

Due to the ambiguity inherent in the gravity method, an infinite number of interpretative solutions is possible (Nettleton, 1971, p.47). In addition, the gravity coverage in the mountainous areas is sparse and these stations may have relative Bouguer gravity errors that may distort the gravity anomaly. The effect of any error in the Bouguer gravity of these stations is believed minimal when compared to the possible error introduced by an incorrect density contrast. In an extreme case, the interpretation may be in error by ±60 m (200 ft) due to all the above conditions.

The five cross sections interpreted from the Yucca Flat 3-D model are shown on fig. 3B. The six cross sections interpreted from the new Climax stock 3-D model are shown on fig. 4B.

The cross sections shown on figs. 3B and 4B illustrate: 1) the interpreted thickness of the combined Tertiary volcanic rocks and Quaternary alluvium along the downthrown sides of Boundary, Yucca, and Butte faults, and 2) the interpreted thickness of the Tertiary volcanic rocks beneath Oak Spring Butte and Rhyolite Hills. For convenience in describing these features, I will proceed from south to north.

On line N897,000 the Boundary fault has juxtaposed rocks of equivalent density, consequently, there is no gravity anomaly associated with the fault. The relatively small offset gravity-inferred faults at E674,300 and E675,500 do not have mapped surface expressions. The fault at E677,500 appears to have a greater displacement than does the Yucca fault. The combined displacement on both is about 244 m (800 ft) resulting in a total thickness of Quaternary alluvium and Tertiary volcanic rocks of 457 m (1,500 ft) east of Yucca fault. The Quaternary alluvium and Tertiary volcanic rocks beneath Rhyolite Hills along this line are about 244 m (800 ft) thick.

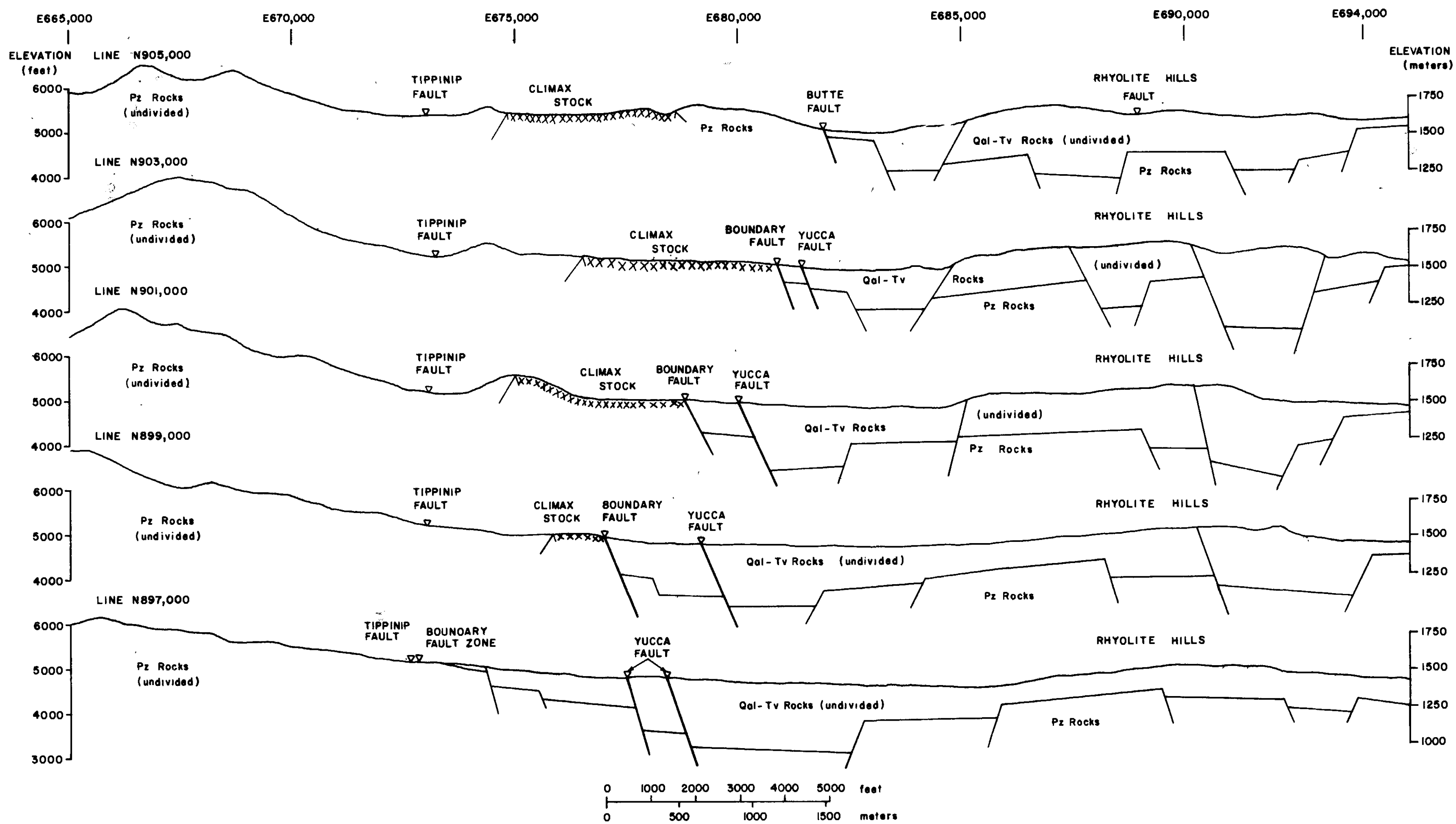

Figure 3B.--Nested generalized geologic E-W cross sections as determined by 3-D analysis of gravity data in the vicinity of Climax stock. Lines of sections are shown on fig. 1B. (See plate 1A for explanation of geologic symbols.)

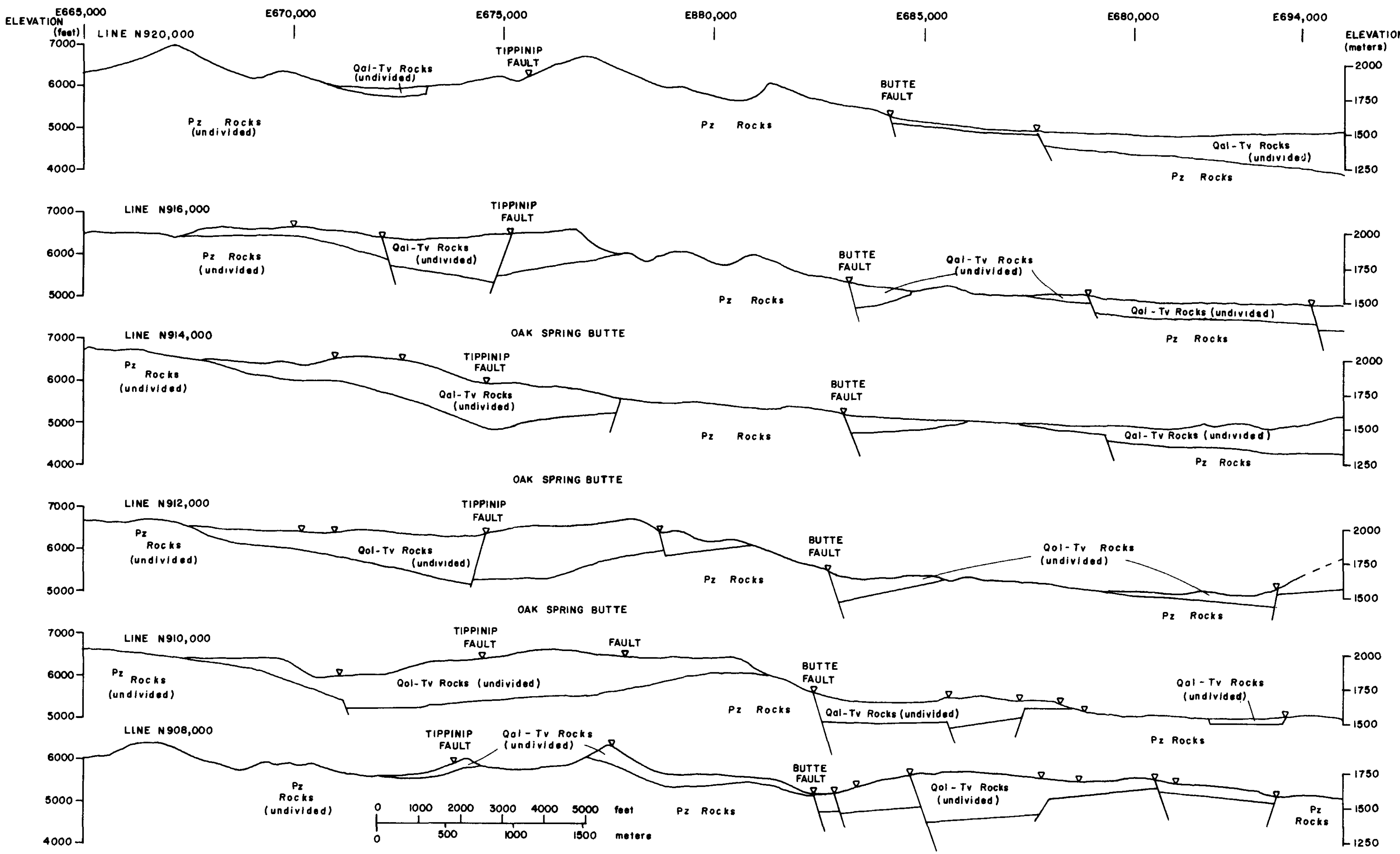

Figure 4B.--Nested generalized geologic E-W cross sections as determined by 3-D analysis of gravity data in the area north of Climax stock. Lines of section are shown on fig. 1B. (See plate 1A for explanation of geologic symbols.)

On line N899,000 the Boundary fault has about 244 m (800 ft) of displacement. The gravity inferred fault at E678,000 has no surface expression. Yucca fault apparently has little offset and the interpreted Quaternary alluvium and Tertiary volcanic rocks are about 427 m (1,400 ft) thick. Beneath Rhyolite Hills the Quaternary alluvium and Tertiary volcanic rocks are now 396 m (1,300 ft) thick (maximum). On line N901,000, both Boundary and Yucca faults indicate an offset of 244 m (800 ft). The Quaternary alluvium and Tertiary volcanic rocks, at Yucca fault, are interpreted to be 457 m (1,500 ft) thick. Beneath Rhyolite Hills the Quaternary alluvium and Tertiary volcanic rocks show a maximum thickness of 518 m (1,700 ft) in an apparent graben located at E692,000.

On Line N903,000, Boundary and Yucca faults have almost converged. Interpreted offsets have reduced to 122 m (400 ft) and 30 m (100 ft). The gravity inferred fault at E682,500 appears to have about the same offset as Boundary and Yucca faults combined. Beneath Rhyolite Hills, the interpreted maximum thickness of the Quaternary alluvium and Tertiary volcanic rocks is 549 m (1,800 ft) and also occurs in an apparent graben at E692,000. A second, smaller graben appears at E688,500.

Boundary and Yucca faults have merged and the continuing fault is called Butte fault on line N905,000. The gravity interpretation indicates little displacement on Butte fault. However, the gravity inferred fault at N903,000 seems to have about 198 m (650 ft) of displacement. The Quaternary alluvium and Tertiary volcanic rocks are beginning to shallow beneath Rhyolite Hills and two distinct grabens are now apparent. The rocks filling the graben at E687,500 are interpreted to be about 457 m (1,500 ft) thick.

On line N908,000 (fig. 4B) the displacement on Butte fault is indicated as 122 m (400 ft). The Tertiary volcanic rocks of Rhyolite Hills continue to shallow and are now 335 m (1,100 ft) thick in the graben centered at E686,500. As mentioned earlier, the sparse gravity coverage in the transition zone from the Climax stock to Oak Spring Butte does not adequately define the gravity anomaly along line N908,000. The magnitude of the anomalies associated with the small areas of outcropping Tertiary volcanic rocks are not known and, consequently, the configuration shown is very speculative.

Line N910,000 exhibits about 183 m (600 ft) of displacement on Butte fault and the Tertiary volcanic rocks of Rhyolite Hills have shallowed to a maximum thickness of 213 m (700 ft) in the minor graben at E685,500. Beneath Oak Spring Butte (at E676,000) the Tertiary volcanic rocks are interpreted to be 335 m (1,100 ft) thick. The gravity inferred fault at E671,200 may be an artifact of the machine contouring of sparse gravity data. The interpreted thickness of the Tertiary volcanic rocks at this fault is 244 m (800 ft), which may be too deep by 30-60 m (100-200 ft).

Line N912,000 indicates a maximum of 198 m (650 ft) of Quaternary alluvium and Tertiary volcanic rocks east of Butte fault. This line falls completely north of Rhyolite Hills and passes close to the highest part of Oak Spring Butte. The maximum thickness of Tertiary volcanic rocks beneath Oak Spring Butte is 396 m (1,300 ft) and occurs at E676,000.

Line N914,000 indicates a maximum of 122 m (400 ft) of Quaternary alluvium and Tertiary volcanic rocks east of Butte fault. East of E690,000 the Quaternary alluvium and Tertiary volcanic rocks are beginning to thicken. Beneath Oak Spring Butte the Tertiary volcanic rocks are beginning to shallow northward. The maximum interpreted thickness is 335 m (1,100 ft) at E675,000.

On line N916,000, a maximum thickness of 183 m (600 ft) of Quaternary alluvium and Tertiary volcanic rocks occur at Butte fault. Beneath Oak Spring Butte the maximum thickness of the Tertiary volcanic rocks is 335 m (1,100 ft).

On line N920,000 the Butte fault has little expression in the gravity anomaly and the interpretation indicates little displacement. East of E688,000, the Quaternary alluvium and Tertiary volcanic rocks continue to increase in thickness. Line N920,000 lies north of Oak Spring Butte where only a small outcrop of Tertiary volcanic rocks occur. Here again, the sparse gravity data do not define the anomaly associated with these rocks and the interpreted thickness of 61 m (200 ft) is speculative.

The upper surface of the Paleozoic rocks of the Climax stock area, whether exposed or interpreted, is shown on figure 5B. The elevations on this surface were picked at 305 m (1,000 ft) intervals on a grid. The area shown is that covered by the cross sections on figures 3B and 4B with interpolated elevations between cross sections. The gridded data were processed through computer program Perspective to produce the configuration shown. The view is from the southeast at a view angle of 30°. The approximate surface traces of Boundary, Yucca, and Butte faults are shown.

CONCLUSIONS

The absence of a density contrast between the intrusive rocks of Climax stock and the adjacent Paleozoic rocks precludes the use of the gravity method to delineate the granite configuration. The Tippinip fault displacement was not delineated for the same reason. However, the large density contrast (0.85 Mg/m^3 assumed) between the Paleozoic rocks and the combined Quaternary alluvium and Tertiary volcanic rocks makes the gravity method a useful tool to study this interface.

The gravity low anomalies associated with the Quaternary alluvium and Tertiary volcanic rocks that comprise northern Yucca flat, Rhyolite Hills, and Oak Spring Butte were investigated by 3-D analysis. The traces of Boundary, Yucca, and Butte faults are well defined in the gravity analysis.

The interpreted structure in northern Yucca flat and beneath Rhyolite Hills is a series of horsts and grabens, modified by faulting. The thicker Quaternary alluvium and Tertiary volcanic rocks occur east of Yucca fault and in the eastern graben (centered at about E692,000).

The Quaternary alluvium and Tertiary volcanic rocks of Oak Spring Butte are interpreted to be a synclinal structure, slightly modified by faulting. The interpreted maximum thickness of these rocks is 396 m (1,300 ft) based on the assumed density contrast of 0.85 Mg/m^3. If the actual density contrast is larger than 0.85 Mg/m^3, the interpreted thickness is too great. Conversely, if the actual density contrast is less than 0.85, the interpreted thickness is too shallow.

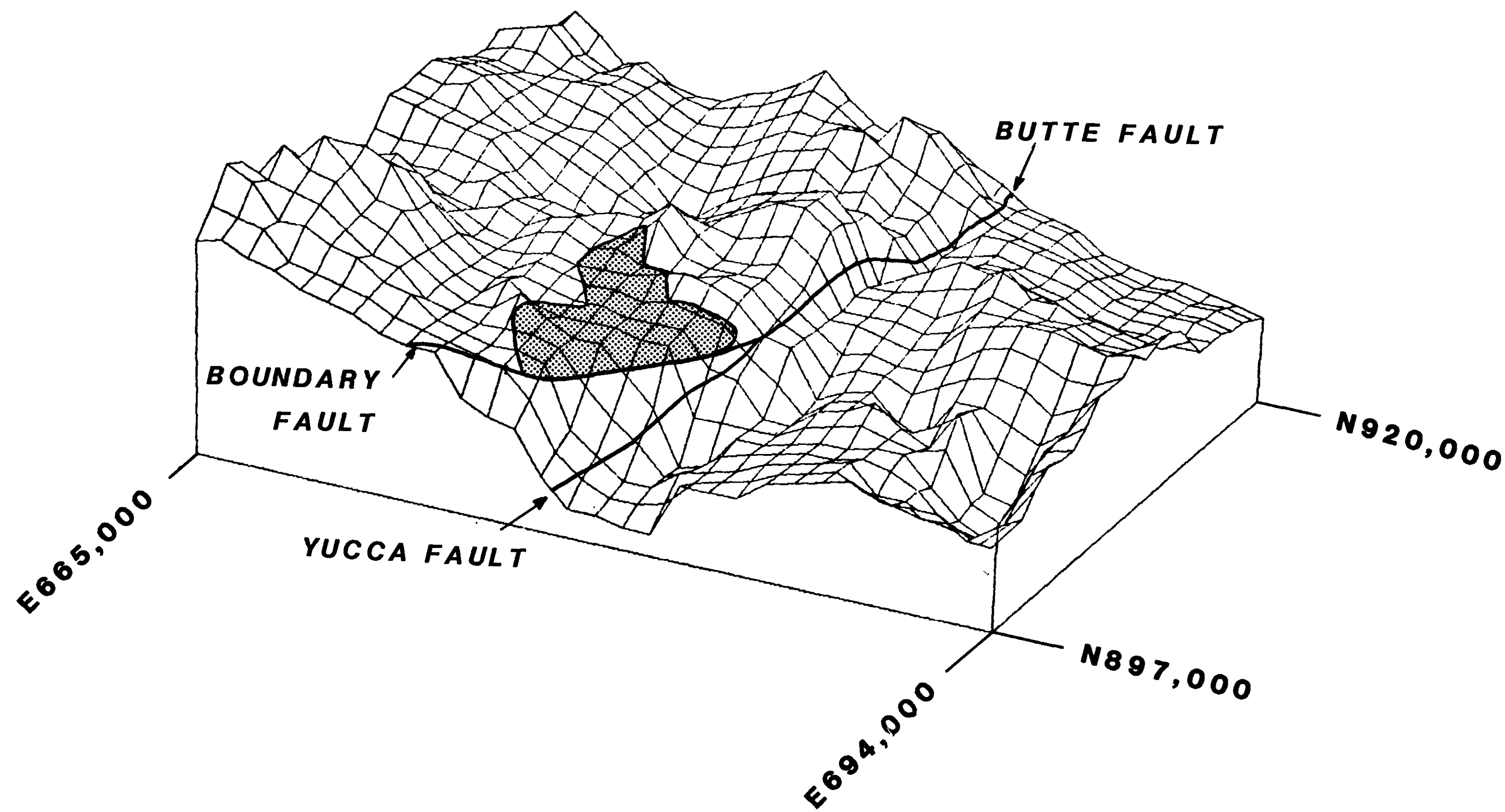

Figure 5B.--Perspective view of Climax stock (stippled) and adjacent area showing the outcropping and interpreted upper surface of the Paleozoic rocks. View is from the southeast (horizontal angle of 135°) at a vertical angle of 30°. Approximate traces of Boundary, Yucca, and Butte faults are shown. Grid size is 24x30 at a 305 m (1,000 ft) spacing.

It is thought that the interpretation presented for the Climax area depicts the general structural configuration of the Paleozoic/Quaternary alluvium and Tertiary volcanic rock interface. Additional study is not warranted unless a major effort is made to obtain additional gravity stations in the elevated and rugged terrain of Oak Spring Butte and vicinity.

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MAGNETIC INVESTIGATIONS

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ABSTRACT

Air and ground magnetic anomalies in the Climax stock area of the NTS help define the gross configuration of the stock and detailed configuration of magnetized rocks at the Boundary and Tippinip faults that border the stock. Magnetizations of geologic units were evaluated by measurements of magnetic properties of drill core, minimum estimates of magnetizations from ground magnetic anomalies for near surface rocks, and comparisons of measured anomalies with anomalies computed by a three-dimensional forward program. Alluvial deposits and most sedimentary rocks are nonmagnetic, but drill core measurements reveal large and irregular changes in magnetization for some quartzites and marbles. The magnetizations of quartz monzonite and granodiorite near the stock surface are weak, about 0.15 A/m, and increase at a rate of 0.00196 A/m/m to 1.55 A/m, at depths greater than 700 m (2,300 ft). The volcanic rocks of the area are weakly magnetized. Aeromagnetic anomalies 850 m (2,800 ft) above the stock are explained by a model consisting of five vertical prisms. Prisms 1, 2, and 3 represent the near surface outline of the stock, prism 4 is one of the models developed by Whitehill (1973), and prism 5 is modified from the model developed by Allingham and Zietz (1962). Most of the anomaly comes from unsampled and strongly-magnetized deep sources that could be either granite or metamorphosed sedimentary rocks. A combination of horizontal and vertical prisms was used to relate details of structure at faults to ground magnetic anomalies 1.5 m (5 ft) above the surface. The stock is defined at its southeastern edge by the Boundary fault which has dips of 70 to 80^{o} to the southeast and a displacement of 2,000 m (6,500 ft). The western edge of the stock dips at an angle of 30^{o}, and there is no evidence of displaced granitic rock at the Tippinip fault. A small anomaly west of the fault arises from magnetized sedimentary rocks, and not from displaced granitic rocks. New data from a recent aeromagnetic survey show that the trend of positive magnetic anomalies over the Gold Meadows, Climax, and Twinridge stocks extends to the southeast for more than 65 km (40 miles).

INTRODUCTION

This study is similar to several the USGS has undertaken at the NTS and nearby areas to locate large bodies of buried granitic rock, estimate their depths and shapes, and thus define prospects for further investigations as possible sites for storage of radioactive waste. Measurements of magnetic properties indicate that the total magnetization of a granitic mass usually has a normal polarity in the approximate direction of the Earth's magnetic field, and prominent positive anomalies are often found over large exposures of granitic rock. Examples of normally-magnetized quartz monzonite and granodiorite bodies that produce broad positive anomalies include the Climax stock (Allingham and Zietz, 1962), and satellitic stocks or certain plutons within the Sierra Nevada batholith 250 km (155 mi) to the west (Currie and others, 1963; Gromme and Merrill, 1965; and Oliver, 1977). In the test site region metamorphosed sedimentary rocks, volcanic ash, and rhyolitic lava flows may also be magnetized along the Earth's field. They can occur in large volumes and may cause prominent positive anomalies. Identification of a buried source is thus often difficult.

Within the NTS and nearby areas, a number of positive anomalies are positioned over the relatively few intrusive rocks that have been identified during surface mapping and drill-hole logging. The residual aeromagnetic map of figure 1C shows nine magnetic highs that are associated with areas of known intrusive rock, as indicated by letters A through I. Five of the nine areas of intrusive rock are alined across the northern part of the NTS: (A) Twinridge (Barnes and others, 1965); (B) Climax stock (Houser and Poole, 1960, and Barnes and others, 1963): (C) Gold Meadows stock (Gibbons and others, 1963; (D) northwest Pahute Mesa (Orkild and Jenkins, written commun., 1978); and (E) Black Mountain (Noble and Christiansen, 1968). The remaining four areas are (F) Wahmonie (Ekren and Sargent, 1965); (G) Calico Hills (McKay and Williams, 1964); (H) Timber Mountain (Carr and Quinlivan, 1966); and (I) Quartzite Mountain (Rodgers and others, 1967).

Residual maps were prepared by subtracting the regional field from observed anomalies, a process designed to give a residual datum of about zero over large areas underlain by thick deposits of nonmagnetic alluvium and bedrock. To prepare figure 1C, a least-square procedure was applied to data at 3-km grid intervals to define a planar regional field for an area of 10,000 Km^2 (3,860 mi^2) covered by 14 published aeromagnetic maps that includes the NTS and most of the Nellis Air Force Bombing and Gunnery Range: Boynton and Vargo, 1963a,b; Boynton and others, 1963a,b; and Philbin and White, 1965a-j. A graphical method was then used to remove regional from observed contours.

Most anomalies in the stock region appear to be related to outcrops of granitic or volcanic rocks as indicated by comparing positions of the more detailed aeromagnetic anomalies of figure 2C and the generalized geology of plate 1A. The western third of figure 2C was compiled from the survey data of figure 1C, and the eastern two thirds of figure 2C were taken from the survey data of figure 3C. The aeromagnetic survey and compilation of figure 3C were made in 1980 by the U.S. Naval Oceanographic Office for an area of about 3,800km^2 (1,450 mi^2) in eastern Nye and western Lincoln counties, Nevada. This coverage was not available during the compilation of aeromagnetic maps of Nevada by Zietz and others (1977), and Sweeney and others (1978).

Some of the significant aeromagnetic anomalies of figure 2C have been investigated in recent years and their sources can be stated with confidence, but others have not and their sources must be inferred. From east to west in figure 2C, the positive anomalies arise from the following sources: an inferred stock that is covered by older sedimentary rocks at A in the Papoose Range; a quartz monzonite stock that is mostly covered by alluvium, volcanic rock, and older sedimentary rock at B near Twinridge hill; a body of quartz monzonite and granodiorite C at Climax stock; an inferred stock that is covered by volcanic rock at D northwest of Climax stock; and a body of quartz monzonite E at Gold Meadows stock.

The strongly-magnetized volcanic rocks in the Climax region have reversed magnetic polarities and produce negative anomalies. From east to west in figure 2C, negative anomalies arise from the following sources: the Rainier Mesa Member ash flow (Sargent and Orkild, 1973) at Aqueduct Mesa F and at Rainier Mesa G; and from pre-Ammonia Tanks rhyolite lavas (Byers and others, 1976) buried by alluvium and volcanic flows at H, I, and J in the Timber Mountain caldera, and exposed and penetrated by drilling at K on Pahute Mesa.

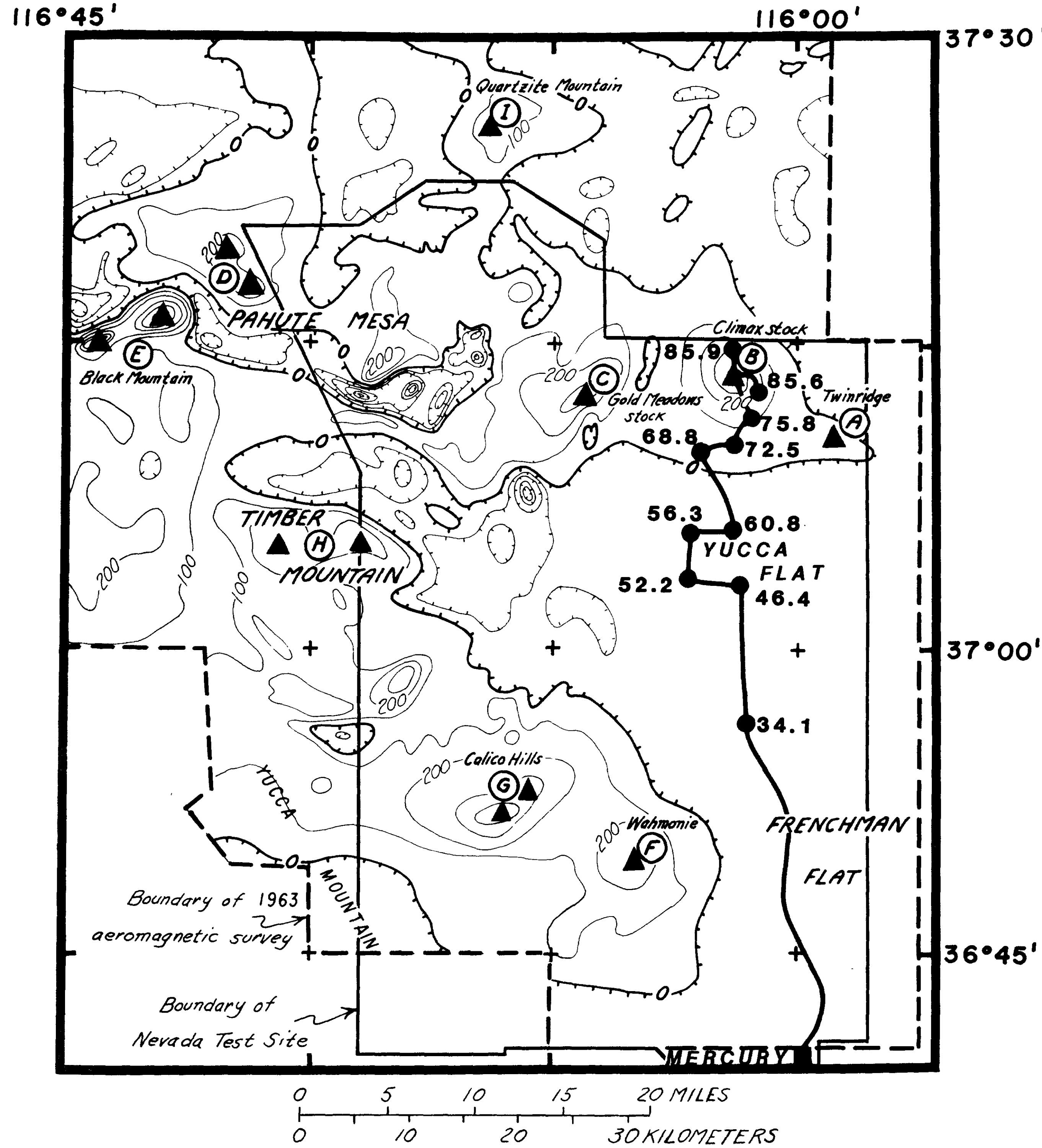


Figure 1C--Residual aeromagnetic map of Nevada Test Site and nearby regions showing nine prominent positive anomalies (lettered A through I), over exposed granitic rock, or over areas where granitic rock is inferred at depth. Measurements were at about 2,450 m (8,000 ft) above sea level, contour interval is 100 nanoteslas, and zero and negative contours are hachured. The bold hashured line represents the zero contour that separates positive from negative residual anomalies. Solid triangles give locations of anomaly maxima, and solid line indicates traverse along which ground magnetic anomalies were measured by a truck-mounted magnetometer from Mercury to Climax stock. Traverse distances are in kilometers.

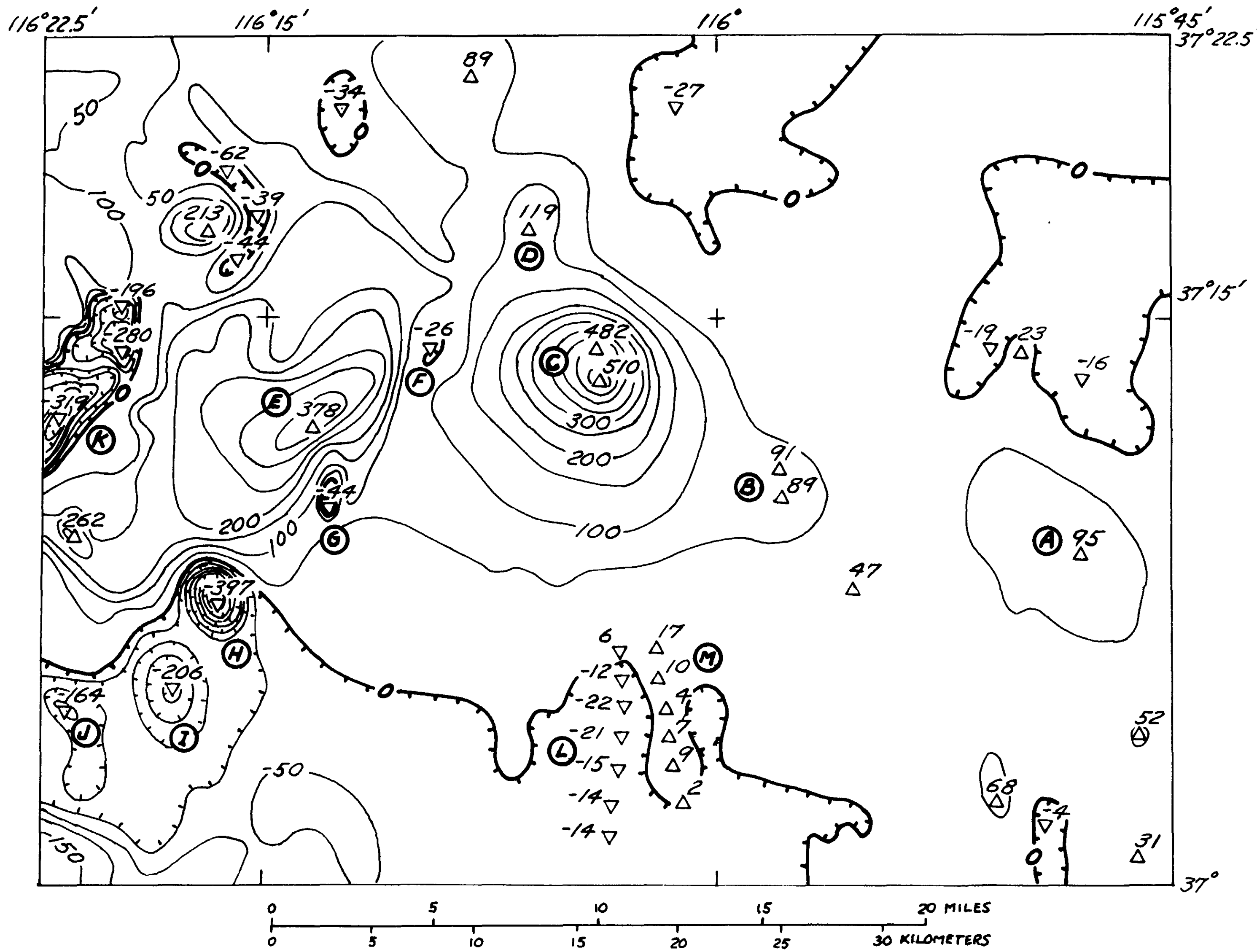


Figure 2C.--Residual aeromagnetic map of Climax stock region showing broad positive anomalies (lettered A through E), over known or inferred granitic rock; narrow negative anomalies (lettered F through K), over known or inferred volcanic rock; and anomaly minima (near L) and maxima (near M), over volcanic rock along the Yucca fault. Measurements were at about 2,480 m (8,000 ft) above sea level for western third of map, and at about 2,130 m (7,000 ft) for eastern two thirds of map. Contour interval is 50 nT, and zero and negative contours are hachured. Triangles give locations of anomaly maxima, and inverted triangles give locations of anomaly minima.

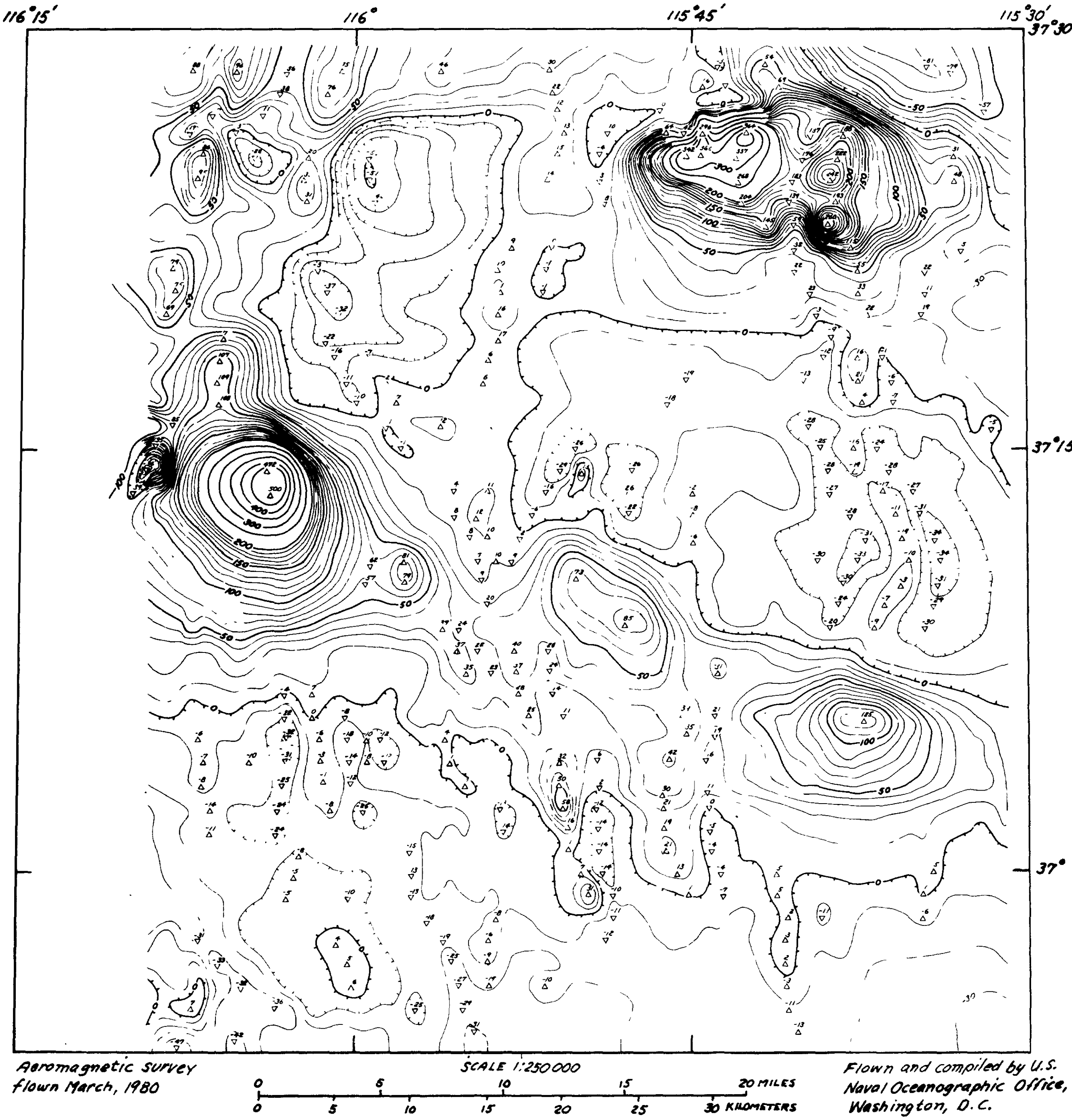


Figure 3C.--Aeromagnetic map of parts of eastern Nye and western Lincoln Counties, Nevada, showing residual anomalies in total magnetic intensity relative to 1980 International Geomagnetic Reference Field. Datum was increased 280 nT to give values near zero over large areas of nonmagnetic rock. Contour intervals are 10 and 50 nT, and zero and negative contours are hachured. Triangles give locations of anomaly maxima, and inverted triangles give locations of anomaly minima. Measurements were at about 2,285 m (7,500 ft) barometric elevation for southern half and about 2,560 m (8,400 ft) for northern half of map.

Also, the Rainier Mesa Member ash flow, which underlies alluvium and a volcanic flow along the Yucca fault, produces a line of negative anomalies L on the high-standing side of the fault, and a positive anomalies M on the low-standing side of the fault.

MAGNETIC PROPERTIES

The average total magnetization of a uniformly magnetized rock mass, denoted as the vector $\vec{J}_t$, is defined as the vector sum of the induced magnetization, $\vec{J}_i$, and remanent magnetization, $\vec{J}_r$:

$$\vec{J}_t = \vec{J}_i + \vec{J}_r.$$

The direction and intensity of induced magnetization is a function of the magnetic susceptibility, k, and field, $\vec{B}_0$:

$$\vec{J}_i = \frac{kB_0}{\mu_0},$$

where $\mu_0 = 4\pi x 10^{-7}$ henrys/m.

Remanent magnetization, on the other hand, is independent of the external field. The Koenigsberger ratio (1938), $Q = J_r/J_i$, is often used to indicate the relative contribution of the two components to J_t.

Air and ground magnetic surveys will usually detect a geologic unit when its total magnetization is equal to or greater than 0.05 A/m (ampere per meter). Therefore, rocks having average intensities less than 0.05 A/m are designated nonmagnetic; and those having greater intensities are here arbitrarily designated as either weakly, moderately, or strongly magnetized, as defined by the following limits:

nonmagnetic < 0.05 A/m
0.05 A/m < weakly magnetized < 0.50 A/m
0.50 A/m < moderately magnetized < 1.50 A/m
1.50 A/m < strongly magnetized

The magnetic properties of older sedimentary rocks, granitic rocks, volcanic rocks, and alluvial deposits in the Climax region were estimated by collecting and measuring surface and drill core samples, and by relating maximum slopes of ground magnetic anomalies to minimum estimates of magnetization for geologic features close to the surface. Also, general information is available on the magnetic properties of NTS rocks of nearby areas (Bath, 1968, 1976).

Estimate of Magnetization

A minimum estimate of total magnetization, J_t, is given by Smith (1961, equation 2.7) which requires information only on anomaly amplitude and depth to the magnetized body. No assumptions are necessary for body shape or direction of magnetization except that the direction must be uniform throughout the body. The anomaly amplitude, t, is measured between two points separated by a distance, c. The relation is given by

$$J_t \geq \hat{J}_t = \frac{|t|}{F\left(\frac{h}{c}\right)} \quad (1)$$

where h is the depth to anomaly source, and $F\left(\frac{h}{c}\right)$ is a function tabulated by Smith.

In our studies, the anomaly amplitude is measured over the slope distance, c, as defined by Vacquier and others, 1951. The distance is designated the maximum slope parameter by Nettleton (1976 p. 395-403), and it is commonly assumed equal to the approximate depths of anomaly-producing bodies. Under this assumption, c = h, and equation 1 reduces to a simple expression,

$$\hat{J}_t = \frac{|t|}{289} \quad (2)$$

when J_t is expressed in A/m, and t in nanoteslas.

The amplitudes of ground magnetic anomalies can now be employed to designate magnetizations of near surface rocks as follows:

nonmagnetic < 15 nT
15 nT < weakly magnetized < 150 nT
150 nT < moderately magnetized < 450 nT
450 nT < strongly magnetized

Ground magnetic surveys have been used as a convenient and prompt method over large areas of the Test Site and have provided estimates of magnetization for geologic features at or near the surface that compare favorably with magnetic properties determined from surface and drill-core samples in the laboratory. For example, the anomaly profile of traverse B66-B66', located on the west side of the stock (fig. 4C), indicates dolomite and marble are nonmagnetic, and that masses of quartz monzonite within 10 m (32.8 ft) of the surface are only weakly magnetized (fig. 5C). Slope distances and their respective t and c components are shown along the traverse for the three strongest anomalies on the traverse which occur over the quartz monzonite. The amplitudes average 75 nT and yield a minimum estimate for J_t of 0.26 A/m. Elsewhere on the traverse the amplitudes are considerably less, but remain mostly within the weakly-magnetized range.

Older Sedimentary Rocks

Sedimentary rocks of Paleozoic and Precambrian age at the NTS consist mainly of argillite, dolomite, limestone, and quartzite that are usually found to be nonmagnetic. Thick deposits are often present within large areas characterized by a relatively uniform aeromagnetic field. This is illustrated by the thick section of quartzite and marble of the Eleana Formation in the Eleana Range west of Yucca Flat on plate 1A, and the lack of a significant magnetic anomaly over the Eleana Range in the aeromagnetic map of figure 2C. There are, however, notable exceptions to this generalization, as observed in

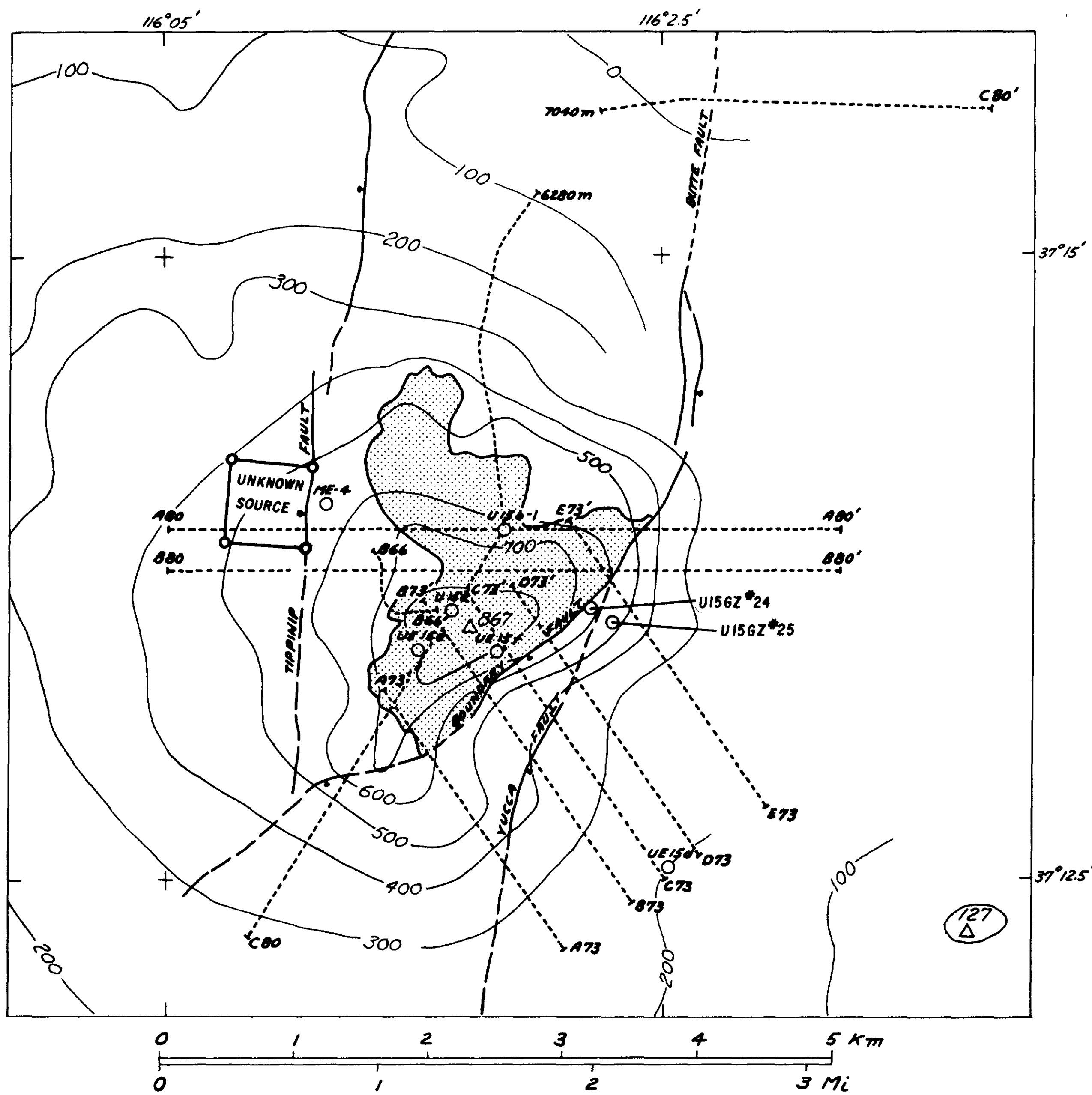


Figure 4C.--Residual aeromagnetic map showing broad positive anomaly over Climax stock (shaded outline of exposed part of stock); major faults bordering the stock; drill holes ME-4, U15b-1, U15a, UE15e, UE15f, U15gz#24, U15gz#25, and UE15d; ground traverses A80-A80', B80-B80', C80-C80', A73-A73', B73-B73', C73-C73', D73-D73', E73-E73', and B66-B66'. Square outline of unknown source was used on figure 20 to model Tippinip fault. Measurements were at about 120 m (394 ft) above the ground surface; contour interval is 100 nT, and triangles give locations of anomaly maxima. Readings were not taken along interval 6,280 to 7,040 m (20,604-23,097 ft) over steep topography of ground traverse C80-C80'.

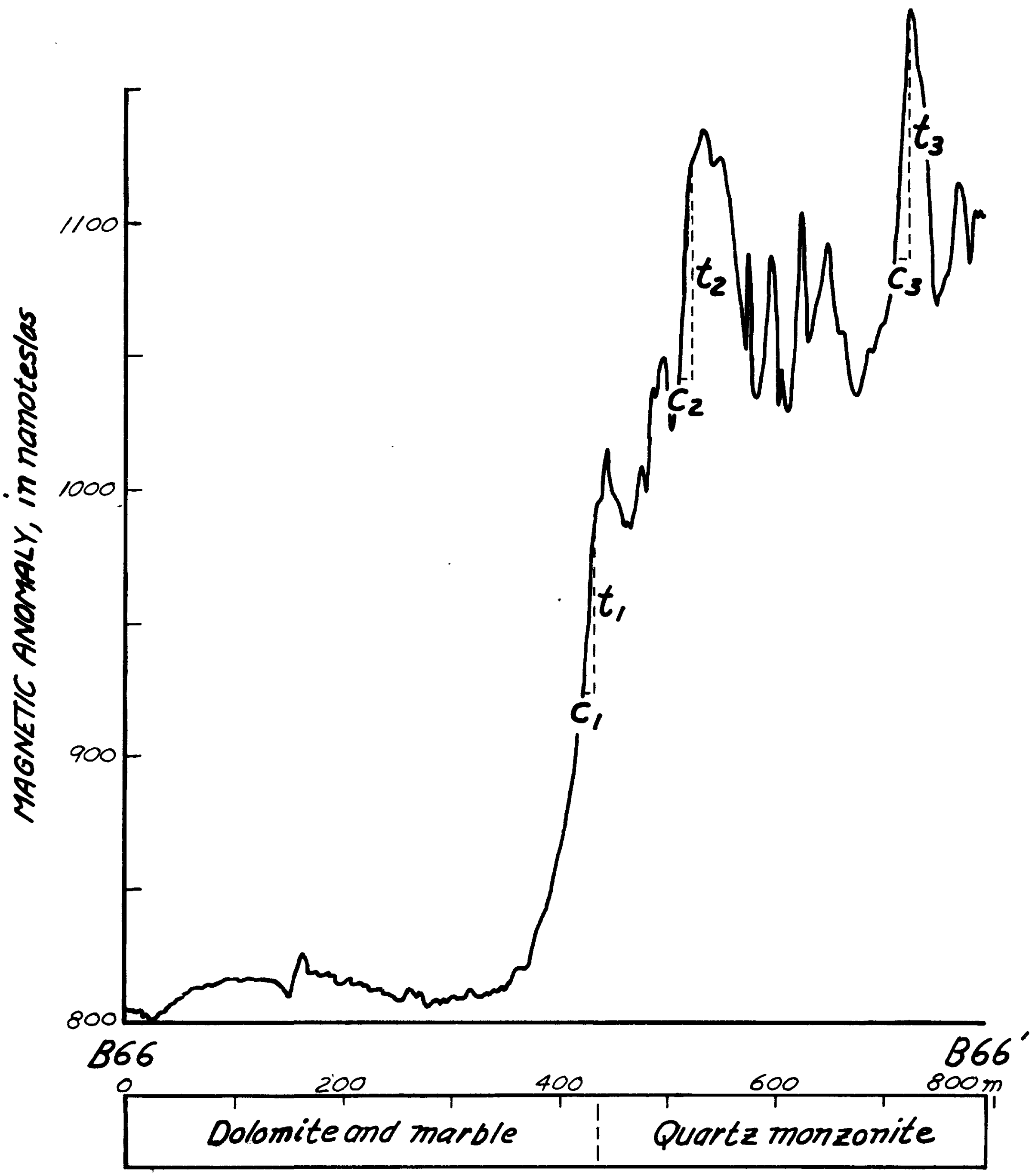


Figure 5C.--Profile of residual ground magnetic anomalies along traverse B66-B66' over dolomite and marble, and quartz monzonite showing distances, c and amplitudes, t, that are used to compute minimum estimates of magnetization. Profile is plotted from 516 rubidium magnetometer measurements 1.5 m (5 ft) above ground surface.

the magnetic properties of surface exposures and drill core from the Calico Hills (Baldwin and Jahren, 1982), and in the core from two holes drilled near the Climax stock. At Calico Hills in the southwestern part of the NTS, the strongly-magnetized argillite of the Eleana Formation appears to be the principal cause of the prominent aeromagnetic anomaly, G of figure 1C. In that region, nonmagnetic argillite has been altered to strongly-magnetized rock, apparently by the conversion of pyrite to magnetite. At the Climax stock, similar high values of magnetic susceptibility were reported by P. H. Cole and W. P. Williams (written commun., 1962) for a 200 m (656 ft) interval of quartzite and siltstone in drill hole UE15d.

Measurements of susceptibility and remanent intensity of core samples from drill holes UE15d and ME-4 fig. 4C supplement the magnetic property data mentioned above. UE15d penetrated 88 m (289 ft) of alluvium, 452 m (1,483 ft) of gently dipping volcanic rocks, and 1,288 m (4,226 ft) of steeply dipping Precambrian metasedimentary rocks (Harley Barnes, written commun., 1962). ME-4 penetrated 350 m (1,148 ft) of marble and 5 m (16 ft) of granite.

Magnetic susceptibilities of core samples were measured by means of a digital susceptibility meter which is available commercially; and induced magnetizations were computed from susceptibilities using the formula

$$J_i = (k_{SI}/4\pi)\ B_{nT} \times 10^{-2}, \text{ where } B_{nT} = 51900 \text{ nT},$$

the strength of the Earth's field in the stock area. Susceptibilities and remanent magnetizations of representative samples were then determined by the method of Jahren and Bath (1967). Koenigsberger ratios were computed from these measurements and average values were assigned to the various rock types. Total magnetizations were computed for all samples by assuming a normal polarity of remanence, and by using the relation

$$J_t = (Q + 1)\ J_i.$$

Averages of total magnetization vary from nonmagnetic to moderately magnetic for older sedimentary rocks available from the two drill holes, as shown in tables 1C and 2C. Values of Q were based on only 42 samples. The Q values used in the tables, their standard deviations, and the number of samples are 0.5±1.0 for 10 samples of quartzite, 2.0±1.9 for 12 samples of marble, 0.3±0.3 for 5 samples of granite, and 0.9±1.7 for 15 samples of volcanic rock.

A reliable estimate of the magnitude of magnetization for the sedimentary sequence penetrated by drilling could not be determined because of large, apparently unsystematic changes in total magnetization from nonmagnetic to 9.59 A/m in UE15d and 5.81 A/m in ME-4, and insufficient available core. No consistent pattern of magnetization could be determined. The values do not increase with depth, or with relation to known granitic rock at ME-4, or to inferred granitic rock at UE15d. Samples from two zones, 1168-1354 m (3,832-4,442 ft) in UE15d and 335-338 m (1,099-1009 ft) in ME-4 have average total magnetizations of 0.7 A/m and 1.4 A/m respectively (tables 1C and 2C). This result indicates that both the quartzite and the marble may show moderate magnetizations comparable to that of granite. If present in sufficient thicknesses, these magnetized sediments will contribute to the aeromagnetic anomaly, and their effects may be indistinguishable from those of the intrusive.

Table 1C.--Average induced magnetization, J_i, and total magnetization, J_t, of core of irregular shape from drill hole UE15d.

Rock type	Interval sampled: Depth (m)	Thickness (m)	Core available (m)	Number of samples	J_i (A/m)	Assigned Q	J_t (A/m)
Volcanic tuff	228-541	313	295	15	0.16	0.9	0.3
Quartzite	541-1,140	599	285	(1/)	<.05	.5	<.1
Quartzite	1,140-1,168	28	7	25	.08	.5	.1
Quartzite	1,168-1,354	186	35	291	.49	.5	.7
Quartzite	1,354-1,470	116	30	109	.04	.5	.1
Quartzite	1,470-1,615	145	20	(1/)	<.05	.5	<.1
Dolomite	1,615-1,829	214	35	(1/)	<.05	2.0	<.2

1/ Core scanned with digital magnetic susceptibility meter.

Table 2C.--Average induced magnetization, J_i, and total magnetization, J_t, of core of irregular shape from drill hole ME-4.

Rock type	Interval sampled: Depth (m)	Thickness (m)	Number of samples	J_i (A/m)	Assigned Q	J_t (A/m)
Marble	4-266	262	(1/)	<0.05	2.0	<0.2
Marble	266-278	12	105	.10	2.0	.3
Marble	278-293	15	170	.03	2.0	.1
Marble	293-335	42	(1/)	<.05	2.0	<.2
Marble	335-338	3	32	.46	2.0	1.4
Marble	338-357	19	137	.06	2.0	.2
Granite	357-362	5	33	.52	.3	.7

1/ Core scanned with digital magnetic susceptibility meter.

Granitic Rocks

Large changes in total magnetization, varying from nonmagnetic to strongly magnetic, also were found in 676 core samples of quartz monzonite and granodiorite. Almost continuous core was available from four holes shown on figure 4C: U15a drilled to 366 m (1,201 ft) depth in moderately-magnetized quartz monzonite and strongly-magnetized granodiorite, U15b-1 drilled to 549 m (1,801 ft) depth in moderately-magnetized granodiorite, UE15e drilled horizontally for a distance of 183 m (600 ft) into the side of a hill of weakly-magnetized quartz monzonite, and UE15f drilled to 100 m (328 ft) depth in moderately-magnetized quartz monzonite. Average magnetic properties are given in table 3C. Sample volumes were included to indicate sample size, and thus, the type of instrument used for measurements. Measurements on large drill core samples were made with equipment described by Jahren and Bath (1967). For small cores, magnetic susceptibilities were measured with a device similar to that described by Christie and Symons (1969) and calibrated by the method of Rosenbaum and others, 1979. Remanent magnetizations were measured with a spinner magnetometer which is commercially available.

Table 3C.--Average sample volume, induced magnetization, J_i, Koenigsberger ratio, Q, and total magnetization, J_t, of 676 core samples of cylindrical shape from drill holes U15a, U15e, U15f, and U15b-1.

				Average			
Rock type	Drill hole	Interval sampled (m)	Number of samples	Sample volume[1/] (cm^3)	J_i (A/m)	Q	J_t (A/m)
Quartz monzonite	U15a	122	5	13	0.76	([2/])	0.84
Quartz monzonite	UE15e	181	121	310	.09	([2/])	.10
Quartz monzonite	UE15f	187	124	425	.67	([2/])	.74
Granodiorite	U15a	244	19	13	1.53	([2/])	1.68
Granodiorite	U15b-1	533	351	535	.67	0.22	.82
Granodiorite	U15b-1	533	56	13	.87	.08	.94

1/ Sample volumes greater than 300 cm^3 indicate pieces of actual drill core sawed to cylinders having lengths about equal to diameters. Samples of 13-cm^3 volume were obtained by drilling 2.54-cm diameter cores from the drill core, and sawing ends off to give about 2.54-cm lengths.

2/ J_r not measured; assume Q = 0.10.

The magnetic properties of drill core indicate magnetizations increase with depth in the quartz monzonite and granodiorite stocks. Allingham and Zietz (1962) report the upper 122 m (400 ft) of quartz monzonite from drill hole U15a is moderately magnetized and the lower 244 m (800 ft) of grandiorite is strongly magnetized. Quartz monzonite from the horizontal hole, UE15e, is within 90 m (295 ft) of the surface and weakly magnetized, while quartz monzonite from the vertical hole, UE15f, is within 187 m (614 ft) of the surface and moderately magnetized. Hole U15b-1 extends to a greater depth, 533 m (1,749 ft) in granodiorite, and it was selected to provide the magnetization data that were used in computing a model for this report. About 350 large samples, averaging 535 cm^3, were collected at approximately 1.5-m (5-ft) intervals. A total of 56 small samples, approximately 13 cm^3 in volume, were collected with groups of 2 to 4 specimens separated by approximately 30 m (98 ft). Average induced magnetizations and Koenigsberger ratios are given in table 3C for the large and small samples, and individual values of induced magnetization for the large samples are plotted versus depth in figure 6C.

The line shown in figure 6C is the result of linear regression having a correlation coefficient of 0.75. The line indicates a weak near surface magnetization of 0.13 A/m and an increase of 0.00196 A/m per meter of depth. Linear regression of the small sample data yields similar results with the near surface magnetization being 0.16 A/m and the increase being 0.00225 A/m per meter of depth (correlation coefficient 0.83). Correlation coefficients for higher polynomials are negligibly larger; a fifth order fit to the large sample data produces a correlation coefficient of 0.75.

Remanent magnetization of samples from U15b-1 are low with respect to the induced component with Q averaging less than 0.25 (table 3C). Therefore, the contribution of remanence may be safely ignored for modeling purposes.

Study of opaque minerals in thirteen polished thin sections from U15b-1 indicates that the increase of induced magnetization with depth is due to an increase in the original magnetite content, and not due to deep weathering effects or to changes in size of magnetite grains. The quantity of magnetite observed ranged from 0.1 to 0.65 percent, and a linear regression of percent magnetite versus magnetic susceptibility yielded a correlation coefficient of .81. The magnetite observed in twelve thin sections collected from depths greater than 30 m (98 ft) is largely unaltered. However, the granodiorite in the remaining thin section, from a depth of 13 m (43 ft) is highly altered and approximately 30 percent of the magnetite has been replaced by hematite.

Volcanic Rocks and Alluvial Deposits

Volcanic rocks of Oligocene and Miocene age in the immediate area of the stock consist of bedded, zeolitized, air-fall, and reworked tuffs that generally have weak magnetizations, as well as ash-flow tuffs that generally have weak to moderate magnetizations. Bath (1968) reported that induced magnetizations of most volcanic units in the Test Site area are weak, and it is the strong remanent magnetizations of welded ash flows and lava flows that are responsible for many prominent aeromagnetic anomalies. No strongly-magnetized ash or lava flows occur over or near the Climax stock.

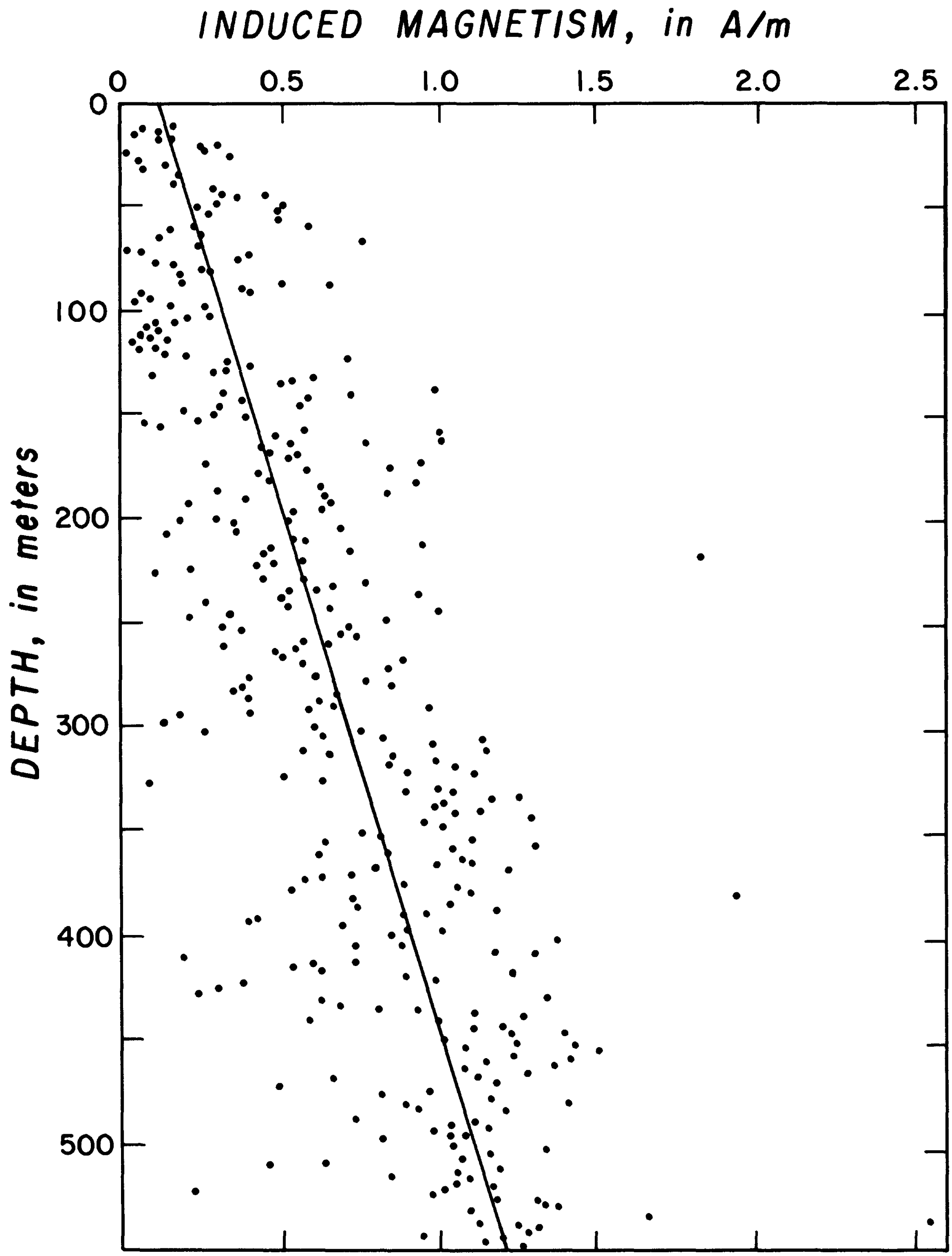


Figure 6C.--Induced magnetization of 351 large core samples of granodiorite with fitted line of linear regression showing an increase in magnetization of 1.05 A/m for a depth interval of 533 m (1,750 ft) in drill hole U15b-1.

Alluvial deposits of Holocene age consist of fragments of reworked granitic, volcanic, and sedimentary rocks. The heterogenous and haphazard manner of deposition results in cancellation of most of the contribution of remanent magnetization. Total magnetizations of alluvium are therefore almost entirely induced magnetizations that are generally categorized as nonmagnetic.

Minimum estimates of magnetization from ground magnetic anomalies indicates most near surface features in the stock area can be designated as either nonmagnetic or weakly magnetized. A 2,100-m (6,900-ft) traverse mostly over alluvium on the southeastern side of the stock illustrates the ambient level of anomaly response that is expected over nonmagnetic rock. Figure 7C shows anomalies measured 1.5 m (5 ft) above the surface along the 80.5 to 82.6 km (50 to 51.3 mi) portion of the long traverse of figure 1C. A rubidium magnetometer was carried 30 m (98 ft) behind the truck in order to eliminate magnetic "noise" caused by the truck. Part A of figure 6C shows residual anomalies that are based on a zero datum over Yucca Flat, and include regional effects of the stock and local effects of the alluvium. Part B shows amplified anomalies after regional effects of the stock have been removed. The anomaly at 80.74 km (50.2 mi) arises from weakly magnetized quartz monzonite at the alluvium-stock contact, and the anomaly at 82.44 km (51.2 mi) arises from a metal sign post. All other anomalies are assumed to be produced by alluvium at or near the surface. Almost all anomaly amplitudes over maximum slope distances are less than 15 nT, the division between nonmagnetic and weakly-magnetized rock.

OBSERVED AND RESIDUAL ANOMALIES

The data recorded by a magnetometer during an aeromagnetic or ground magnetic survey consists of the effects of the geologic feature being studied plus the combined effects of the Earth's magnetic field, and all the magnetized geologic features and man-made objects in a large area near the surface or deeply buried. Several methods have been used to identify and separate these components, and Nettleton (1976, p. 134-187) describes anomaly separation and filtering procedures in detail. In order to isolate the anomaly of interest we first define a reference surface, usually referred to as the regional anomaly, to represent effects from the long wavelength anomalies of the Earth's magnetic field and of geologic features buried at great depth. The regional anomaly then becomes the zero datum upon which residual values are based. An ideal residual anomaly map includes only the short wavelength effects of the feature, or features, under study; but in practice extraneous and overlapping effects are present.

We commonly use two methods to determine regional anomalies for aeromagnetic surveys of large areas. In one method, the regional anomaly consists of a planar surface established by a least-squares fit to data at 3-km (1.86-mi) grid intervals. This method was used in deriving figure 1C and produces contour values that are about zero over large areas of thick, nonmagnetic material. In the second method, the regional anomaly is the International Geomagnetic Reference Field (IGRF) and determined by spherical harmonic analysis of worldwide measurements on a 2^{o} grid (Barraclough and Peddie, 1978). In the area of the NTS, this method produces residual values that are about 280 nT lower than the first method. The IGRF was used in compiling figure 3C and 280nT was added to residual values to make the contours consistent with those of figure 1C.

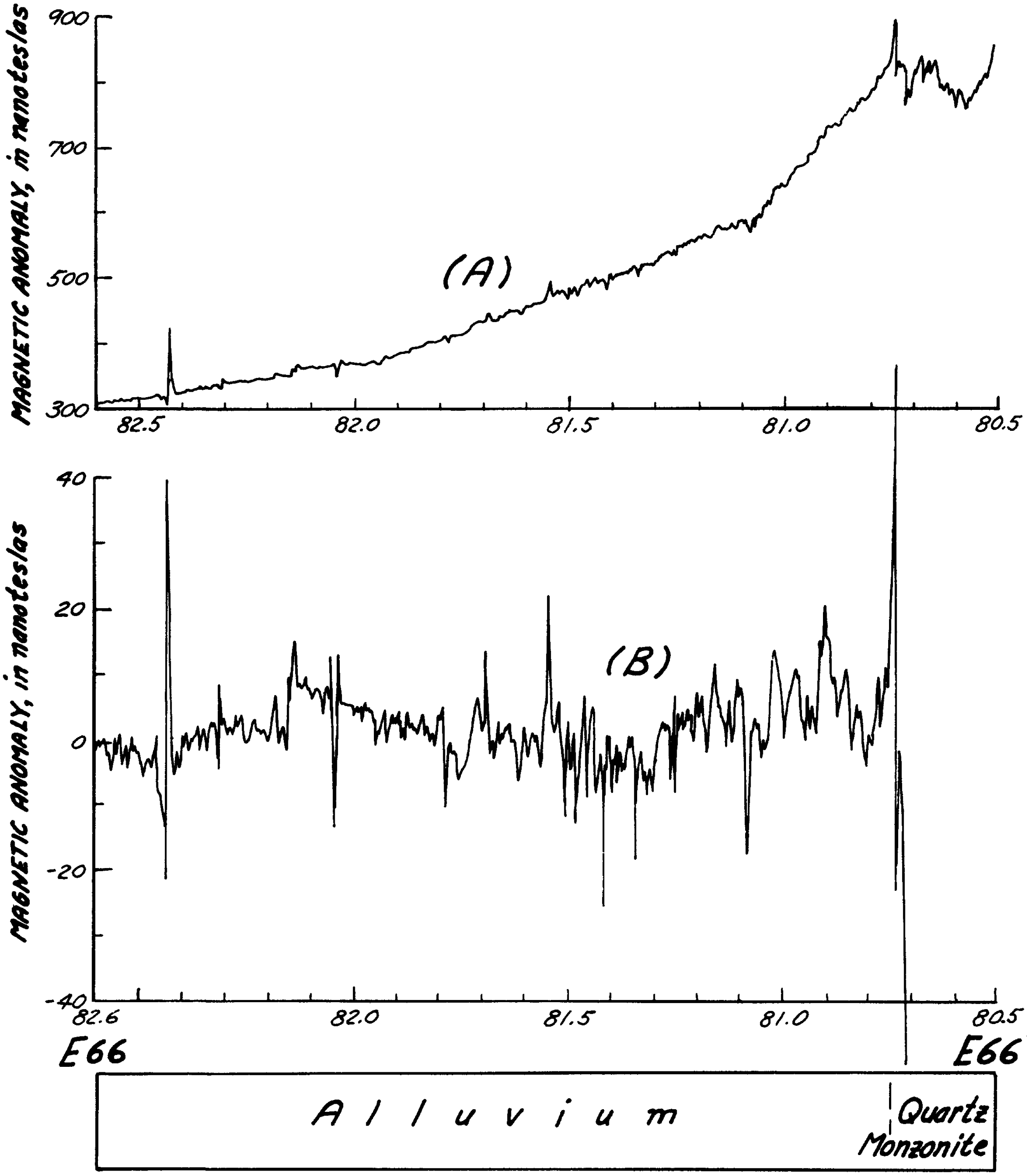


Figure 7C.--Profiles of residual ground magnetic anomalies along the same traverse E66-E66' over alluvium and quartz monzonite showing distances and amplitudes used to compute minimum estimates of magnetization. Profiles are plotted from 1200 rubidium magnetometer measurements 1.5 m (4.9 ft) above ground surface. Profile A is based on zero datum from Yucca Flat, and profile B is based on an average zero datum adjusted to fit the observed data. Distances are in kilometers from Mercury.

For quantitative interpretations of individual anomalies, further adjustment may be required to obtain values closer to zero over nearby deposits of nonmagnetic sedimentary rock. In this report, surfaces are adjusted to an assumed zero field over Yucca Flat where thick deposits of sedimentary rocks underlie relatively thin deposits of alluvium and volcanic rock. For example, a value of 40 nT was added to contours of figure 1C to prepare figure 10C, and 10nT was added to contours of figure 3C to prepare the eastern two thirds of figure 2C.

Measurements were made along a long truck-borne magnetometer traverse to investigate the field over Yucca Flat, and to establish a base station near the Climax stock. The measurement and compilation system was based on work by Kane and others (1971) and Hildenbrand and Sweeney (written commun., 1980). The traverse shown in figure 1C originates at the Mercury base station where investigations during recent years have assigned an Earth's field value of 51550 nT (nanoteslas) and a residual anomaly value of zero. The traverse goes northward on the Mercury highway, along Frenchman Flat, through Yucca Flat, across granitic exposures at Climax stock, and ends at the 85.6-km (53.2-mi) station. Figure 8C shows observed values of the Earth's field along the traverse. The solid line drawn through the anomalies is based on the planar regional anomaly of the NTS region and increases 5.63 nT/km northward and 1.72 nT/km eastward. The line crosses Yucca Flat at about the same average value as the observed anomalies, and at station 75.8 km (47.1 mi) the difference between line and observed value is about 200 nT. The station is therefore assigned a residual value of 200 nT and an Earth's field value of 51880 nT. All ground magnetic traverses measured over the stock were tied to this station.

Figure 9C shows the residual anomalies that result from subtracting regional anomaly values from observed data in part of the profile of figure 8C. The traverse starts at station 34.1 at the south end of Yucca Flat, goes northward across the Flat and stock, and ends at the 85.9 km (53.4 mi) station shown in figure 1C. The residual values were continued upward by the two-dimensional method of Henderson and Zietz (1949) to a level of 2,450 m (8,000 ft) above sea level, the elevation datum of figure 1C. The continuation smoothed and reduced the amplitudes of ground anomalies. Over Yucca Flat the values approach the zero average that has been assumed for both air and ground magnetic anomalies.

REGIONAL INTERPRETATIONS

Recently compiled aeromagnetic data reveal several new anomaly patterns, including a southeastern extension of the belt of positive anomalies that are related to exposures of intrusive rock masses within the NTS. The data are presented on figure 3C at a scale of 1:250,000, the same scale as the geologic map of Lincoln County, Nevada, by Ekren and others (1977).

A trend of positive aeromagnetic anomalies extends from the NTS southeast over known or inferred intrusive bodies for a distance of more than 65 km (40 mi) across eastern Nye and western Lincoln Counties. The anomalies previously shown on figure 2C start at Gold Meadows stock (E) and trend east 20 km (12 mi) to Climax stock (C), southeast 10 km (6 mi) to Twinridge stock (B), and southeast 15 km (9 mi) to the inferred intrusive in the Papoose Range (A).

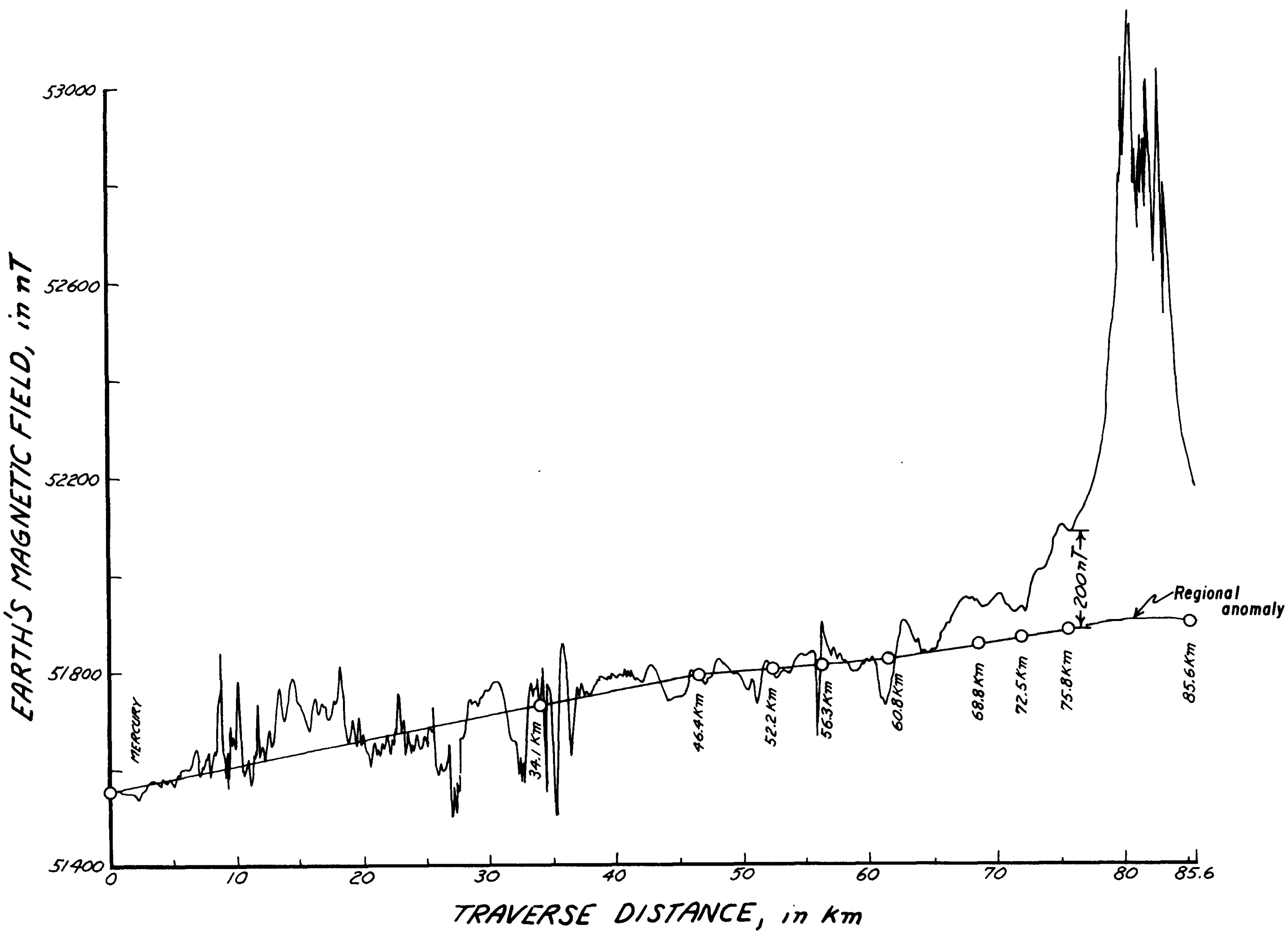


Figure 8C.--Profile of Earth's magnetic field as observed by truck-mounted magnetometer along the traverse of figure 1C extending from base station at Mercury northward 85.6 km (53.2 mi) along west side of Frenchman Flat, 13 to 26 km; through Yucca Flat, 36.6 to 75.8 km; and across granitic exposures at Climax stock, 80 to 83 km. Distances given in figure 1C are shown as circles on the regional line. The profile shows local anomalies arising from geologic features, a gradual northward increase in the Earth's magnetic field, and a line representing the planar regional anomaly of the Test Site region. The residual anomaly, difference between observed and regional anomaly, has a value of 200 nT at the 75.8 km base station.

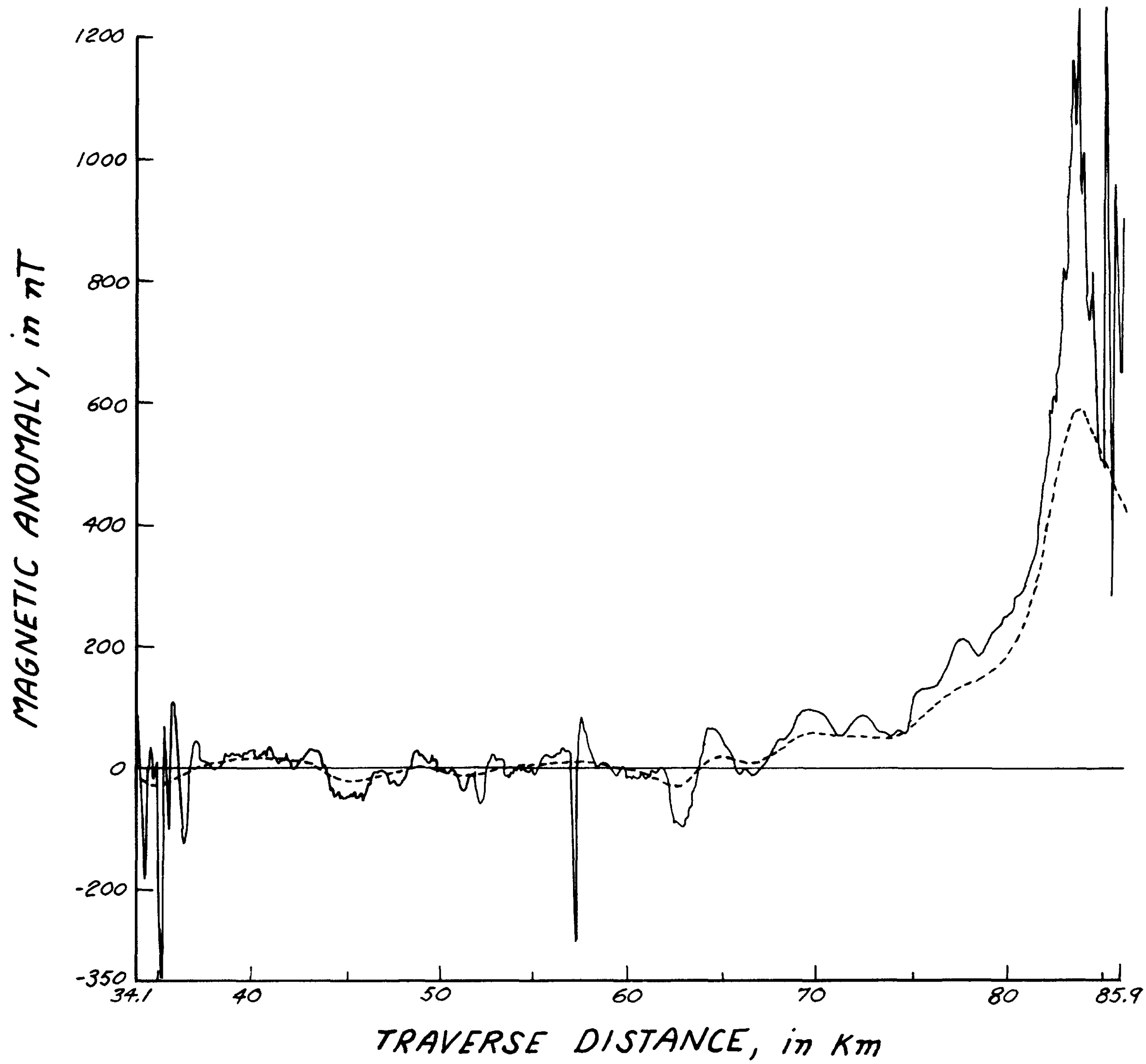


Figure 9C.--Profiles of residual magnetic anomalies, solid line; and data continued upward 914.4 m (3,000 ft), dashed line. Data are from truck-mounted magnetometer traverse of figure 1C extending from 34.1 km (21.2 mi) station northward 51.8 km (32.2 mi) through Yucca Flat, and ending at the 85.9 km (53.4 mi) station on granitic exposures on Climax stock.

The contours of figure 3C extend the trend an additional 20 km (12 mi) southeast to the anomaly maximum of 125 nT over inferred intrusive rock in the northwestern part of the Pintwater Range. The anomalies are interpreted as arising from a belt of magnetized intrusive and associated metamorphosed sedimentary rocks.

The lateral extent of the positive aeromagnetic anomaly in the northeastern corner of figure 4C suggests magnetized intrusives and associated sedimentary rocks are buried beneath the exposures of volcanic rock at the surface. Also, the map shows several belts of alined maxima and minima that strike in a northward direction. The belts are similar to those produced by a faulted volcanic ashflow at the Yucca fault in Yucca Flat (Bath, 1976), and may indicate the presence of buried faults. Data was collected along east-west flight lines, and thus emphasize effects from features that strike north-south.

GROSS CONFIGURATION OF STOCK

Figure 10C is a recompilation of the data of figure 1C at a 20-nT contour interval. The stock anomaly has nearly circular contours over an area of about 200 km^2 (77.3 mi^2), and reaches a maximum of 462 nT at the southwestern edge of the exposed portion of the stock. The compilation is based on measurements 850 m (2,789 ft) above the surface. The effect of the high measurement level is to smooth many of the local anomalies that are found in low-altitude data. Models based on high-altitude data usually represent gross configuration only, and often must be modified in areas where prominent anomalies are present in data measured closer to the ground surface.

Previous Studies

To explain the circular magnetic anomaly, Allingham and Zietz (1962) employed a three-dimensional polar chart method (Henderson, 1960) to produce a model consisting of four cylinders arranged as shown and tabulated on figure 11C. The model represents a gross configuration of the stock that conforms with granitic exposures at the surface, widens and becomes very large at depth, and has steeper slopes on the east and south than to the north and west. The cylinders have a constant magnetization of 1.54 A/m in the direction of the Earth's magnetic field. The magnetization value was determined from core samples in the lower half of drill hole U15a. Figure 11C shows the accepted configuration of the model, and the anomaly that was computed for the model. Subsequently, hole UE15d was drilled to a depth of 1,830 m (6,000 ft) southeast of the stock (fig. 11C). At this location the model of Allingham and Zietz predicts granitic rock at a depth of about 1,400 m (4,600 ft), however, none was encountered in the hole. Possible explanations for failure of the model include (1) the interval of 2,440 m (8,000 ft) from aeromagnetic datum to sea level is too great to give an accurate position for cylinder C, and (2) the granitic rock southeast of the stock is overlain by a thick section of magnetized sedimentary rock.

Whitehill (1973), on the other hand, modeled the circular anomaly with a single rectangular vertical prism. He used a computer to generate anomalies due to a large number of prisims of varying depth, length, width, thickness, and magnetization. Each prism was oriented with its long dimension N. 45° W.

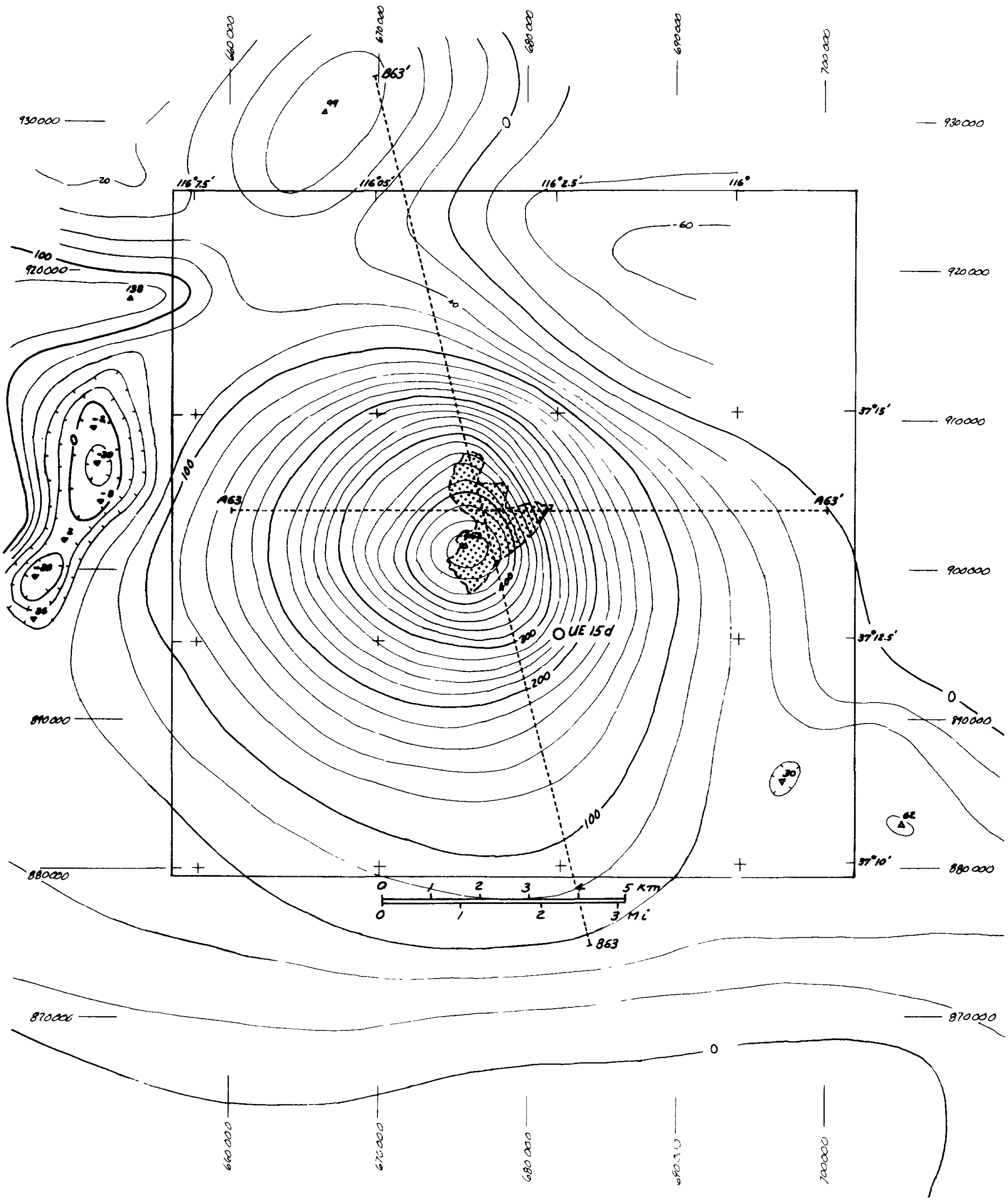
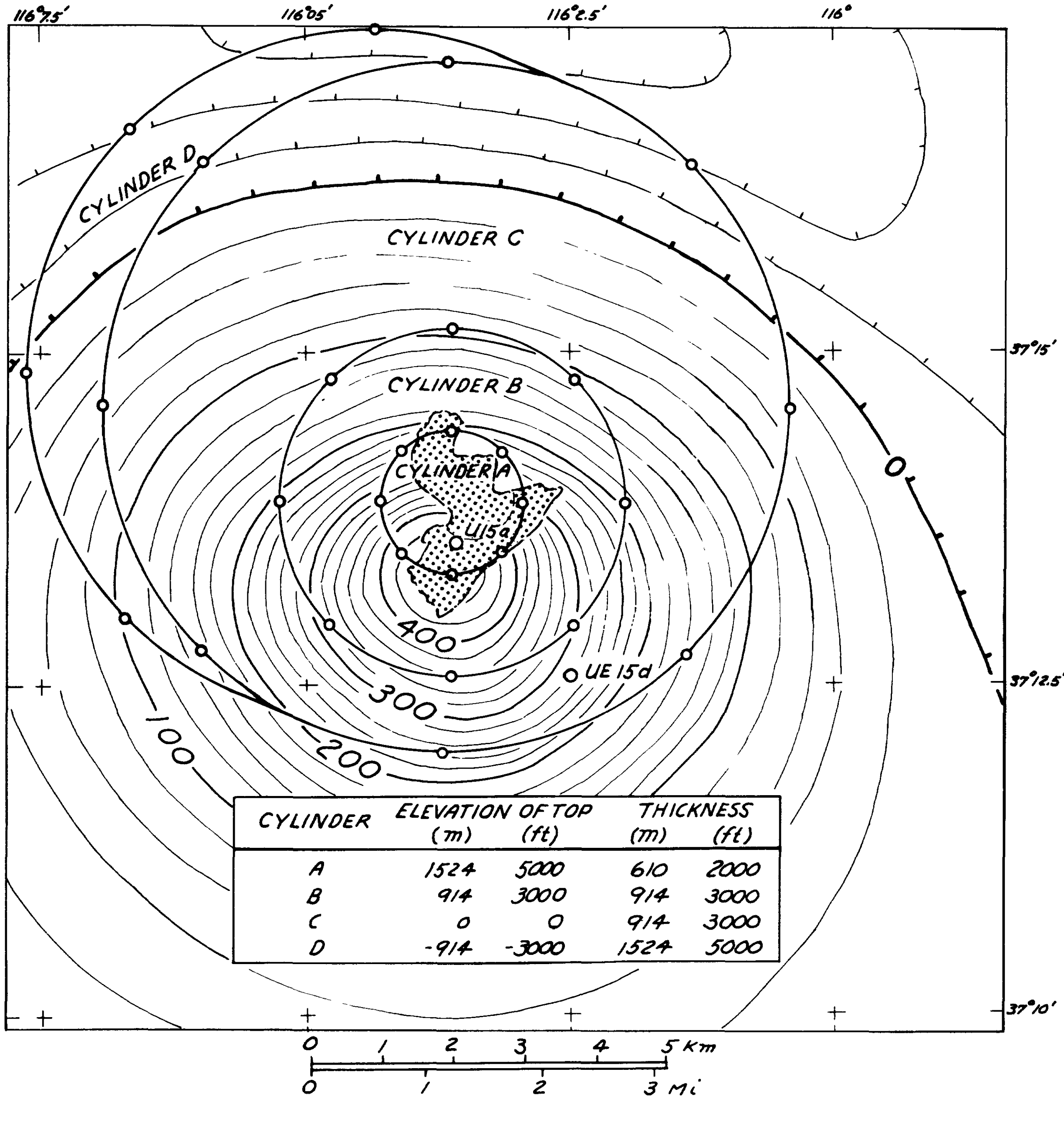


Figure 10C.--Residual aeromagnetic map showing the large circular anomaly that reaches a maximum of 462 nT over shaded outline of exposed part of the stock, and aeromagnetic traverses A63-A63' and B63-B63'. Measurements were at about 2,450 m (8,000 ft) above sea level, and countour interval is 20 nT. Triangles give locations of anomaly maxima, inverted triangles give locations of anamoly minima.



CYLINDER	ELEVATION OF TOP (m)	ELEVATION OF TOP (ft)	THICKNESS (m)	THICKNESS (ft)
A	1524	5000	610	2000
B	914	3000	914	3000
C	0	0	914	3000
D	-914	-3000	1524	5000

Figure 11C.--Outlines and tabulated dimensions of the four vertical cylinders that Allingham and Zietz (1962) used to represent the stock. Also shown and contoured at 20-nT interval is the anomaly computed from four 8-sided vertical prisms arranged to approximate the circular shapes of the four cylinders. Magnetization of all prisms is along the Earth's field at 1.53 A/m, the average intensity of magnetization for core from drill hole U15a. Drill hole UE15d penetrated volcanic and sedimentary rocks to an elevation of -440 m (-1,445 ft), or 440 m below the top of cylinder C, without entering granitic material. Shaded outline is the exposed part of the stock.

The calculated anomalies that best fit the observed anomaly were for prisms that have tops buried beneath the exposed granitic rock at the stock, and magnetizations greater than the 1.54 A/m used by Allingham and Zietz. Figure 12C shows the prism, which provided the best fit to the observed data and its computed magnetic anomaly. The southeast edge of the prisim is 1,220 m (4,000 ft) northwest of drill hole UE15d, its top is 1,173 m (3,850 ft) below granitic rock at the surface, and its magnetization is 2.27 A/m.

New Model of the Climax Stock

We have developed a new model consisting of five vertical prisms to represent the gross configuration of the Climax stock and to explain anomalies along traverses A63-A63' and B63-B63' of figure 10C. The model resulted from considerations that include the locations of granitic exposures, observed increase in magnetization with depth fig. 6C, depths estimated from slope distances of anomalies, and the model of Allingham and Zietz, and of Whitehill. Outlines and dimensions of the new model are shown in plan view on figure 13C and in section along traverse A63-A63' (fig. 13C) on figure 14C. The upper part of the model consists of three 8-sided vertical prisms, P1, P2, and P3, having outlines that closely approximate granitic exposures in plan view. The low surface magnetization of 0.13 A/m increases to 0.28 A/m in P1, 0.72 A/m in P2, and 1.39 A/m in P3. The remainder of the model consists of rectangular prism, P4, taken from Whitehill, and 8-sided prism, P5, similar to the lowermost cylinder of Allingham and Zietz. Computations with a three-dimensional forward program, and comparisons with anomalies along the two traverses, assigned a magnetization of 1.55 A/m to prisms P4 and P5. Computed anomalies for the model closely resemble the observed residual anomalies along traverse A63-A63' as shown in figure 14C (A).

Model computations and depth estimates from slope distances indicate that most of the stock anomaly arises from rocks at depths greater than 810 m (2,657 ft), the depth to the top of P4. The contribution of each of the five prisms to the 408 nT maximum on traverse A63-A63' is 5 nT from P1, 17 nT from P2, 24 nT from P3, 205 nT from P4, and 157 nT from P5. Most of the anomaly, therefore, comes from unsampled deep sources that could include strongly magnetized sedimentary rocks, as well as strongly magnetized granitic rocks.

FAULT INTERPRETATIONS

Interpretations of magnetic anomalies measured closer to the ground surface indicate major displacements of magnetized rock near the faults along the eastern and southeastern borders of stock exposures. The aeromagnetic map of figure 4C shows the circular stock anomaly 120 m (394 ft) above the surface, the mapped locations of major faults, and the positions of nine ground traverses. The residual anomalies of the map were compiled from aeromagnetic surveys flown about 120 m (394 ft) above the surface (Bath, 1976, and USGS, 1979). Unfortunately, the low-level aeromagentic data are incomplete in important areas along the eastern and southeastern sides of the stock.

The ground data were measured at 3-m (10-ft) intervals 1.5 m (5 ft) above the surface with a proton magnetometer. The ground magnetic anomalies over the stock and bordering faults are shown in east-west traverse A80-A80'

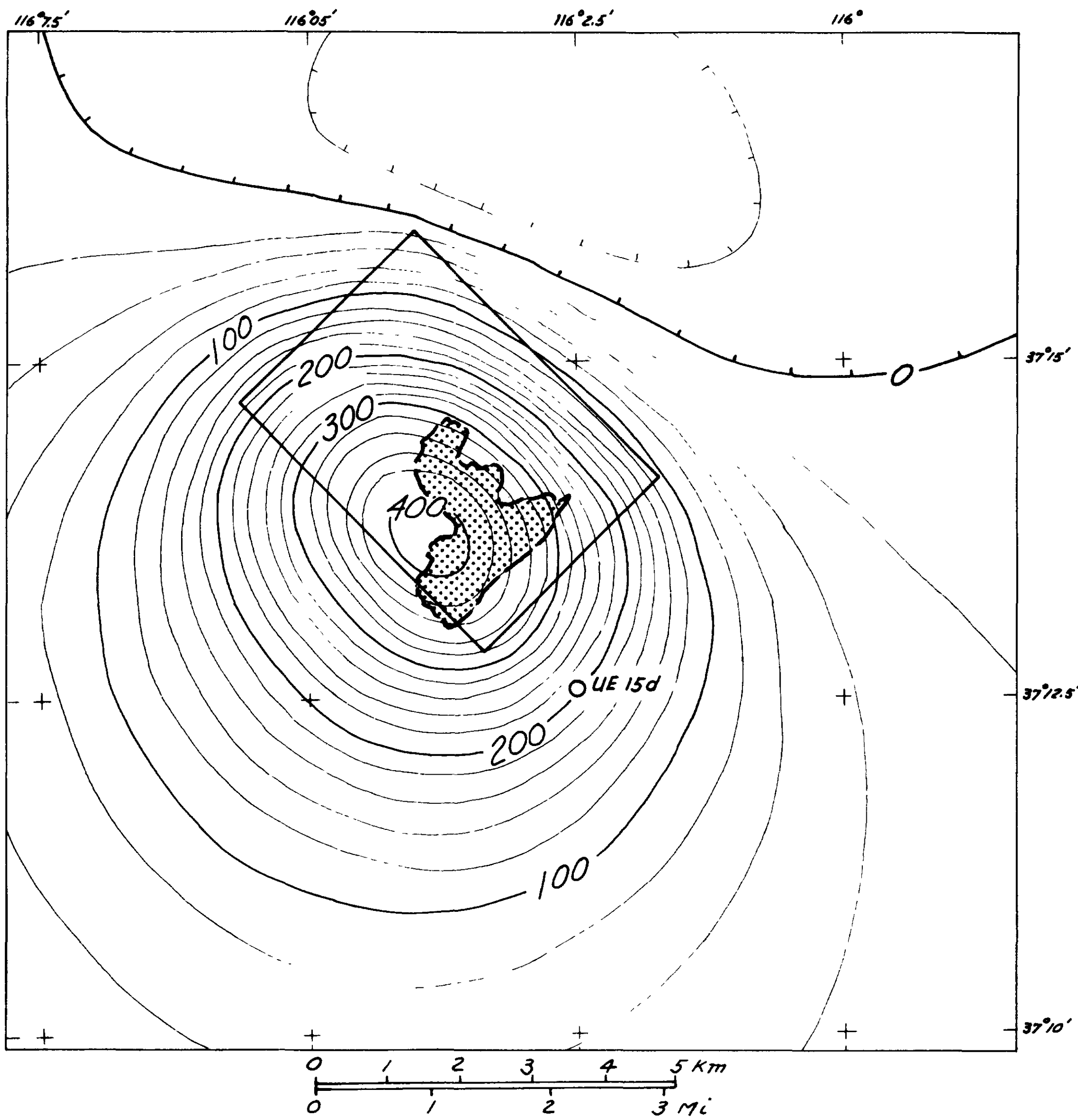
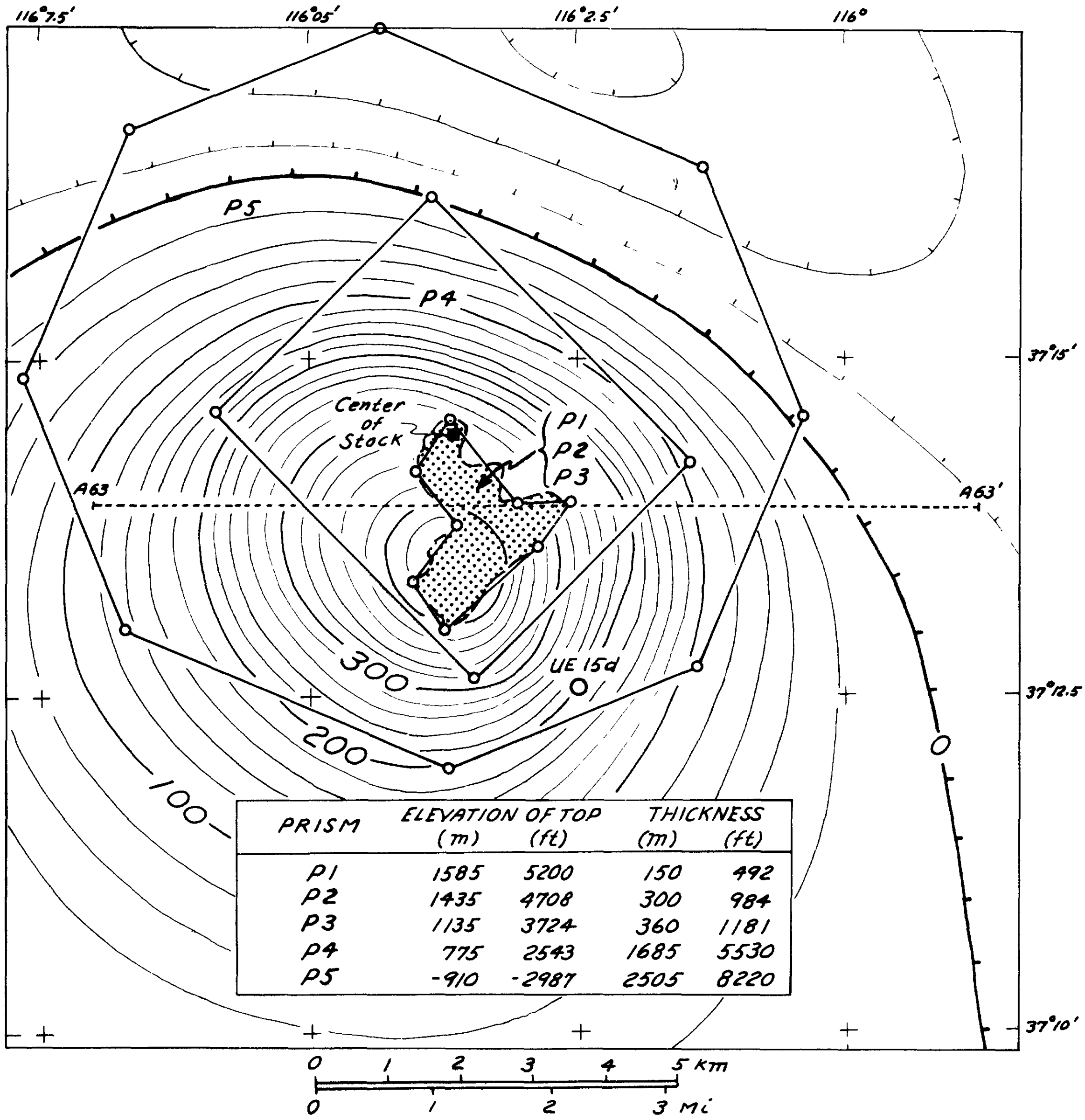


Figure 12C.--Rectangular outline of the vertical prism of Whitehill (1973) giving a computed anomaly that best fits the observed anomaly. Also shown and contoured at 20-nT interval is the anomaly computed for the prism which has a magnetization along the Earth's field at an intensity of 2.27 A/m. The prism is 4,840 m (15,900 ft) long, 3,430 m (11,250 ft) wide, and 17,200 m (56,400 ft) thick. The top of the prism has an elevation of 427 m (1,400 ft) which is 1,160 m (3,800 ft) below the elevation of the shaded outline of exposed granitic rocks. Drill hole UE15d is 1,250 m (4,100 ft) southeast of the prism.



PRISM	ELEVATION OF TOP (m)	ELEVATION OF TOP (ft)	THICKNESS (m)	THICKNESS (ft)
P1	1585	5200	150	492
P2	1435	4708	300	984
P3	1135	3724	360	1181
P4	775	2543	1685	5530
P5	-910	-2987	2505	8220

Figure 13C.--Outlines and tabulated dimensions of the five vertical prisms used to explain the anomaly of figure 10C, and to represent the gross configuration of the stock. Also shown and contoured at 20-nT interval is anomaly computed for the prisms when magnetized along the Earth's field at an intensity that increases from 0.28 A/m for prism 1 to 1.55 A/m for prisms 4 and 5. Also shown are shaded outline of the exposed part of the stock, approximate center of the stock model, and air traverse A63-A63'.

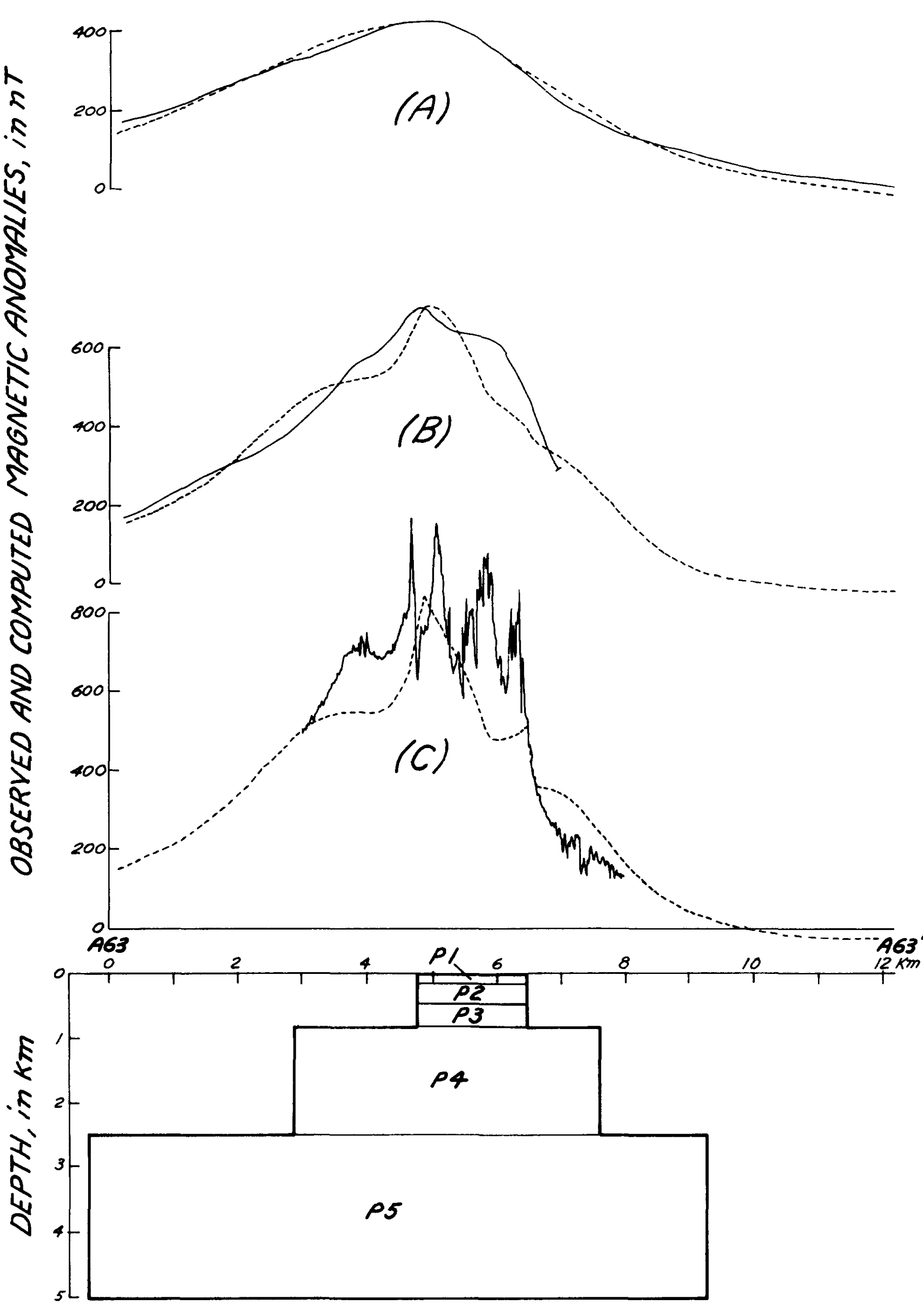


Figure 14C.--Section through the five prisms of figure 13C showing residual and computed anomalies along traverse A63-A63' at (A) 850 m (2,789 ft), (B) 120 m (394 ft), and (C) 1.5 m (5 ft) above the stock. Solid lines are residual anomalies, and dashed lines are computed anomalies.

positioned beneath air traverse A63-A63' (fig. 15C); B80-B80' parallel to and 305 m (1,000 ft) south of A80-A80' (fig. 15C); and C80-C80' to the northeast over the high topography to the north (fig. 16C). Five parallel traverses, A73-A73', B73-B73', C73-C73', D73-D73', and E73-E73', oriented N. 35° W. pass over the southeastern edge of the stock and the Boundary and Yucca faults (fig. 17C). In order to facilitate positional correlations, the ground anomalies are plotted above elevations of the topographic surface and a schematic representation of known faults and geologic units.

Slope distances and anomaly amplitudes provide a basis for estimates of magnetization, and thus for relating ground anomaly patterns to areal distributions of geologic units. Estimates are generally consistent with values from samples listed in tables 1, 2, and 3. Anomaly amplitudes are low, and application of equation (2) usually reveals nonmagnetic or weakly magnetic rocks. The only strongly magnetized rocks are in a granodiorite feature that is 200 m (656 ft) wide at the 85.0-km (52.8-mi) station on the truck-mounted magnetometer traverse shown on figure 9C. The prominent anomaly of more than 1,800 nT at the 2,900-m (9,514-ft) station of traverse C80-C80' (fig. 16C) is assumed to arise from concentrations of iron and steel objects in underground workings. Alluvium and most older sedimentary rocks are nonmagnetic, and most intrusive and all volcanic units are weakly magnetized. There are, however, local occurrences of moderately magnetized quartz monzonite, granodiorite, and sedimentary rocks.

Change of anomaly pattern, as well as distinctive anomalies are present near several faults and contacts, but many amplitudes are small because of weak magnetizations of near-surface rocks. There are minor changes over the Tippinip fault on traverses A80-A80' and B80-B80'; and over the Boundary and Butte faults on traverses A80-A80' and B80-B80'; and over the Boundary and Butte faults on traverse C80-C80'. A local positive anomaly of less than 100 nT is shown west of the Tippinip fault near station 4.0 km (2.5 mi) on traverse A63-A63' (C) of figure 14C, and near station 800 m on traverse A80-A80' of figure 15C. Also six traverses over the eastern and southeastern parts of the stock show the abrupt reductions in anomaly amplitude that are expected at stock edges or displaced magnetized rock. Anomaly decreases are present east of the Boundary fault (fig. 4C) on ground traverses A80-A80' and B80-B80' of figure 16C., and southeast of the Boundary fault (fig. 4C) on ground traverses B73-B73', C73-C73', D73-D73', and E73-E73' of figure 18C.

The computed contours and profiles of figures 13C and 14C illustrate the anomalies expected over the Climax stock, assuming it is bordered by fault-like vertical sides. Computations are for the gross configuration model of figure 13C, and the vertical sides extend to a depth of 810 m (2,658 ft), the combined thickness of prisms P1, P2, and P3. Data are computed at 850 m (2,789 ft), 120 m (394 ft), and 1.5 m (5 ft) above P1.

Boundary and Tippinip Faults

Structures near the Boundary and Tippinip faults were investigated by modifying the configuration and magnetization of the stock model (fig. 13C) in order to explain the local anomalies in ground magnetic traverses over edges of the stock. The stock model is constructed of vertical prisms that have polygonal outlines in plan view. The vertical prisms near the surface were replaced with horizontal prisms that have polygonal outlines in section view.

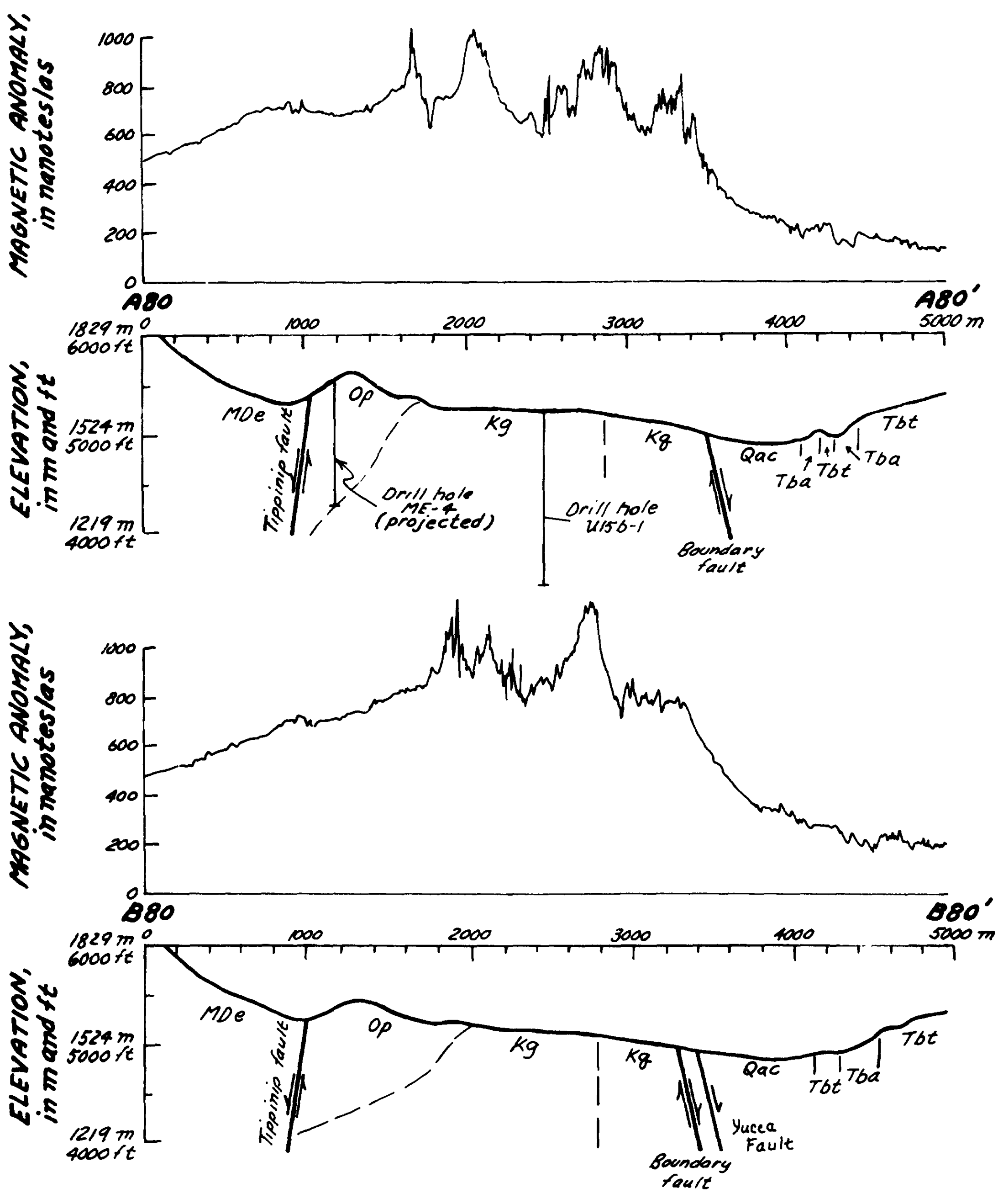


Figure 15C.--Profiles of residual ground magnetic anomalies along traverses A80-A80' and B80-B80' over Eleana Formation, MDe; Pogonip Group, Op; granodiorite stock, Kg; quartz monzonite stock, Kq; alluvium and colluvium, Qac; Tub Spring Member of the Belted Range Tuff, Tbt; air-fall, bedded, and zeolitized tuff, Tba; and Tippinip and Boundary faults. Each profile was plotted from 1,700 proton magnetometer measurements 1.8 m (6 ft) above ground surface.

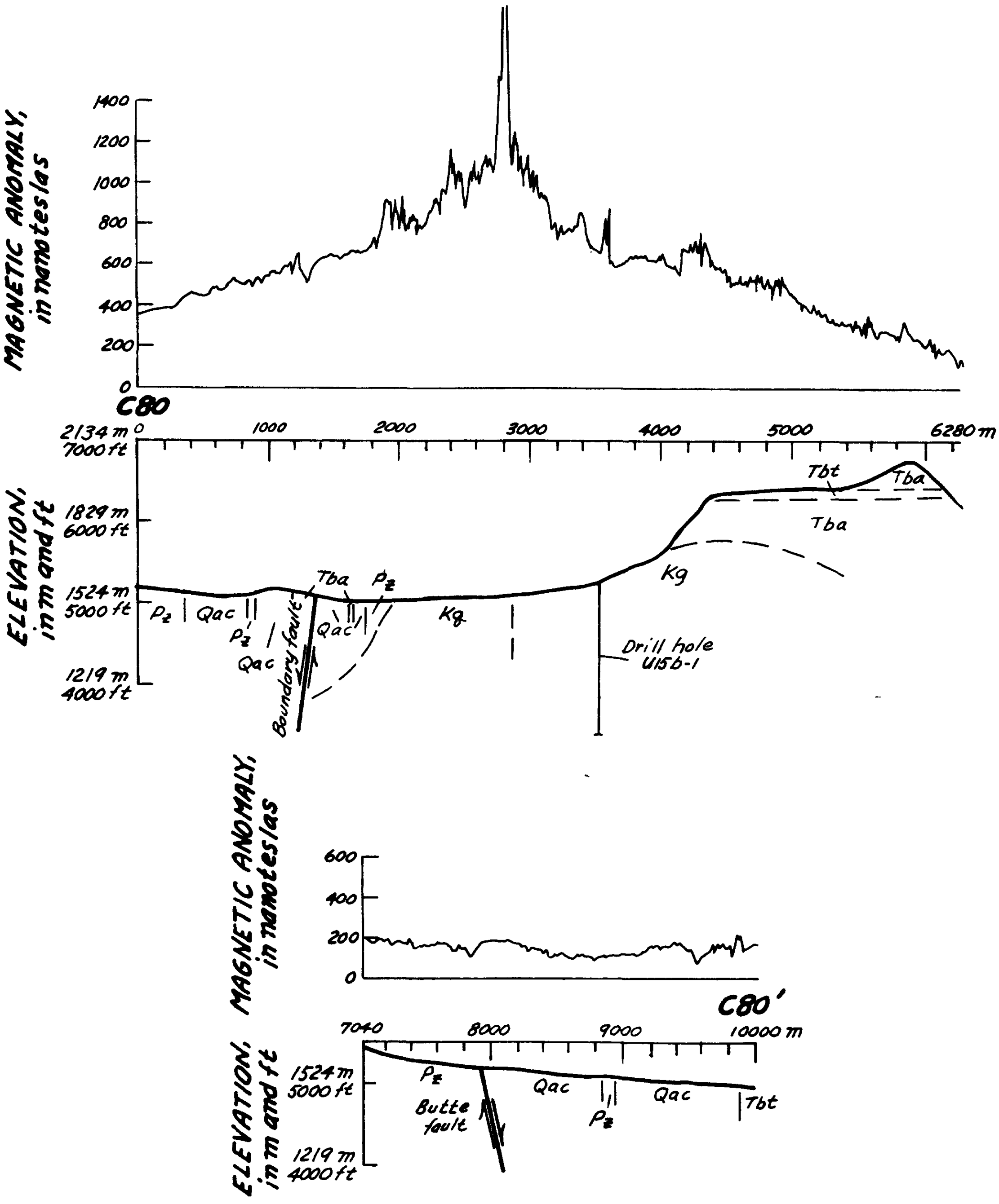


Figure 16C.--Profile of residual ground magnetic anomalies along traverse C80-C80' over Paleozoic sedimentary rocks, Pz; granodiorite stock, Kg; quartz monzonite stock, Kq; Tub Spring Member of the Belted Range Tuff, Tbt; air-fall, bedded, and zeolitized tuff, Tba; alluvium and colluvium, Qac; and Boundary and Butte faults. Profile was plotted from 3,000 proton magnetometer measurements 1.8 m (6 ft) above ground surface. No measurements were made over steep slope in interval 6,280 to 7,040 m (20,603-23,087 ft).

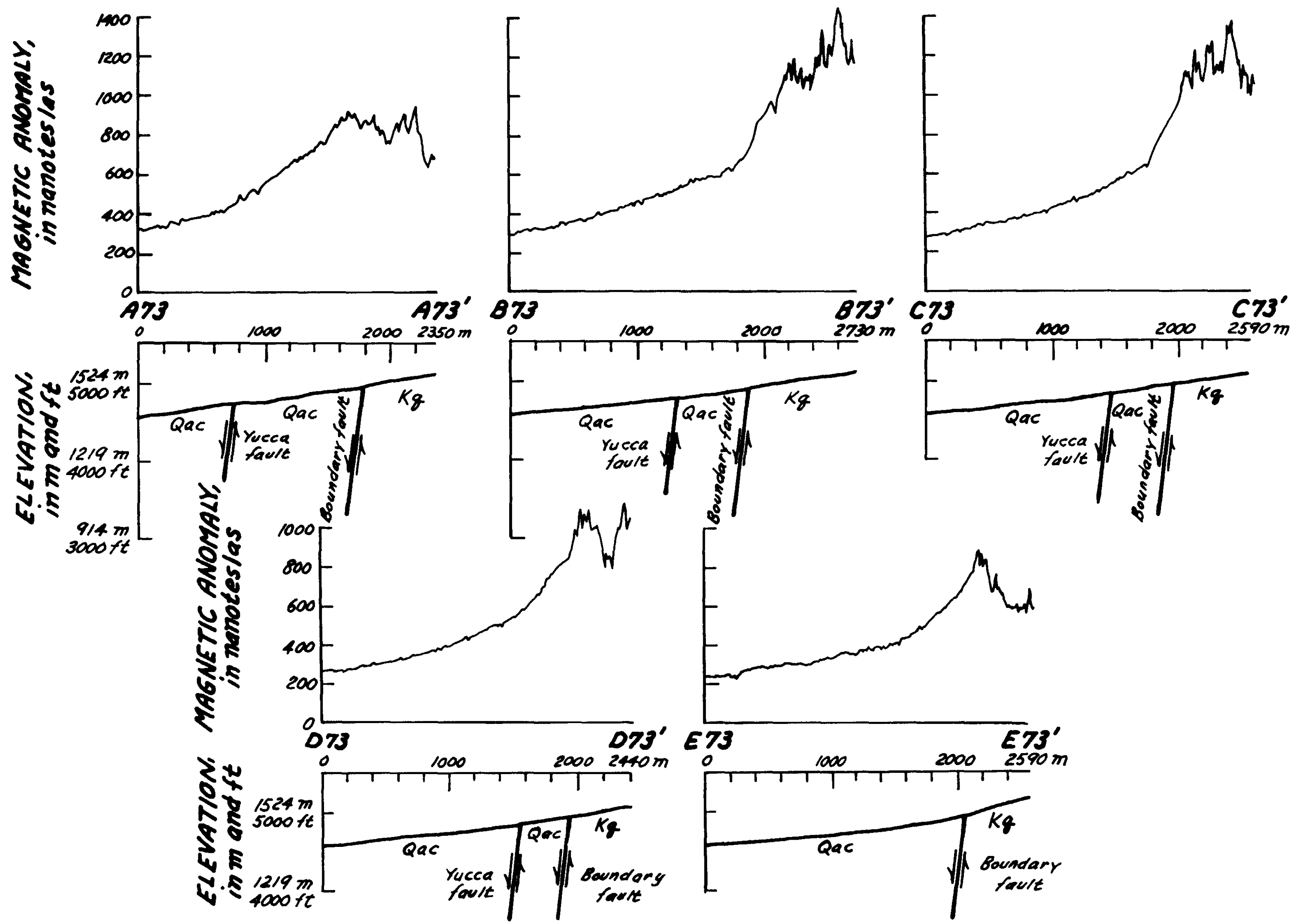


Figure 17C.--Profiles of residual ground magnetic anomalies along traverses A73-A73', B73-B73', C73-C73', D73-D73', and E73-E73' over quartz monzonite stock, Kq; alluvium and colluvium, Qac; and Yucca and Boundary faults. Profiles were plotted from 1,666 proton magnetometer measurements 1.4 m (4.6 ft) above ground surface.

This permitted use of several horizontal prisms of irregular outline to represent the relatively complex configurations of known and inferred geologic structure in section view. The cumulative effects of all vertical and horizontal prisms were then computed with a three-dimensional forward program and compared with the ground magnetic anomalies. Finally, several arrangements of prisms having different outlines and magnetizations were investigated to find the model judged most reasonable in terms of (1) comparisons of computed and measured anomalies, (2) surface and drill-hole geology, and (3) magnetic properties of core samples from nearby drill holes and magnetization estimates from ground magnetic anomalies.

The modified model of Climax stock at its southeastern edge is given on figure 18C along ground traverse C73-C73' (fig. 4C). The stock is represented by five prisms: horizontal prism P_H1 having J_t = 0.74 A/m, the average magnetization of quartz monzonite core from drill hole UE15f (table 3C); horizontal prisms P_H2, P_H3, and P_H4 having assigned magnetization of 1.55 A/m; and vertical prism P_V5 having assigned magnetization of 1.80 A/m. Southeast of the stock, alluvium is represented by horizontal prism Qac having a magnetization of 0 A/m indicated by estimates from the ground anomalies of figure 7C; volcanic rocks by horizontal prisms Tv having J_t = 0.30 A/m, the average of core from drill hole UE15d (table 1C); and metamorphosed sedimentary rocks of Precambrian age by horizontal prisms pCs having J_t = 0.10 A/m, a rough estimate from the limited core of drill hole UE15d (table 1C).

Almost all of the stock is terminated by the Boundary fault. This fault has high-angle southeastern dips of 80^o to a depth of 750 m (2,461 ft) and 70^o to a depth of 2,000 m (6,562 ft). A possible extension of the stock beyond the fault was investigated by replacing metamorphosed sedimentary rocks with granite in the wedge between the Boundary and Yucca faults. As shown on figure 18C, this resulted in poor comparison between residual and computed anomaly, and thus reduces the possibility of a significant extension to the southeast.

The modified model of Climax stock at its western edge is given in figure 19C along ground traverse A80-A80'. The stock is represented by five prisms: horizontal prism P_H1 having J_t = 0.85 A/m, the average magnetization of granite core from drill hole ME-4 (table 2C) plus the increase of 0.00196 A/m per meter of depth found in core from drill hole U15b-1 (fig. 6C); horizontal prism P_H2 having J_t = 1.30 A/m, resulting from continuing the increase of magnetization with depth; and horizontal prism P_H3, and vertical prisms P_V4 and P5, each having an assigned magnetization of 1.47 A/m. West of the stock, two groups of metamorphosed sedimentary rocks of Paleozoic age are present. The larger is represented by horizontal prism Pzs having J_t = 0.10 A/m, a rough estimate from variable core values of drill hole ME-4 (table 2C). The smaller group of unknown buried rocks is represented by the horizontal prism having an assigned J_t = 0.50 A/m and is defined by the dimensions given on figures 4C and 19C. The prism of unknown rock is required to explain the local magnetic high west of the fault.

The west edge of the stock dips 30^o westward. The distinctive anomaly near the Tippinip fault is a local high, and not the reduction in anomaly amplitude expected west of a fault having its low-standing side to the west.

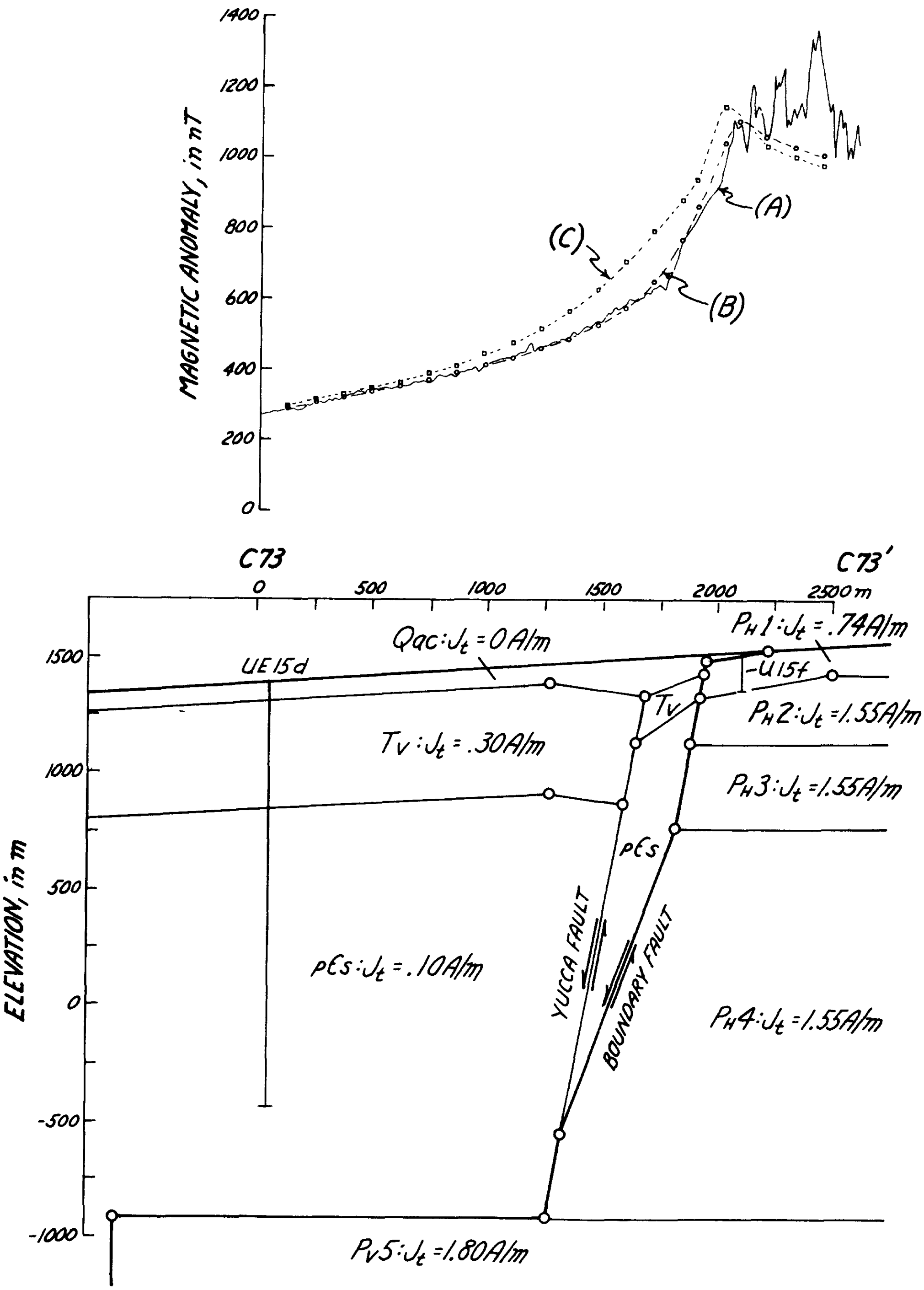


Figure 18C.--Section along ground traverse C73-C73' showing model selected to portray the southeastern edge of the stock. The stock is represented by prisms P_H1, P_H2, P_H3, P_H4, and P_v5; the Quaternary alluvium by prism Qac; the Tertiary volcanic rocks by prism Tv; and the Precambrian metasedimentary rocks by prism pCs. Also shown are Boundary and Yucca faults, and the rocks penetrated by drill holes UE15d and UE15f. Anomalies shown along the traverse are (A) measured residuals, (B) computed effects of the model, and (C) computed effects of the model with the modification of replacing metasedimentary rocks having J_t = 0.10 A/m with granitic rocks having J_t = 1.55 A/m in the wedge between Yucca and Boundary faults.

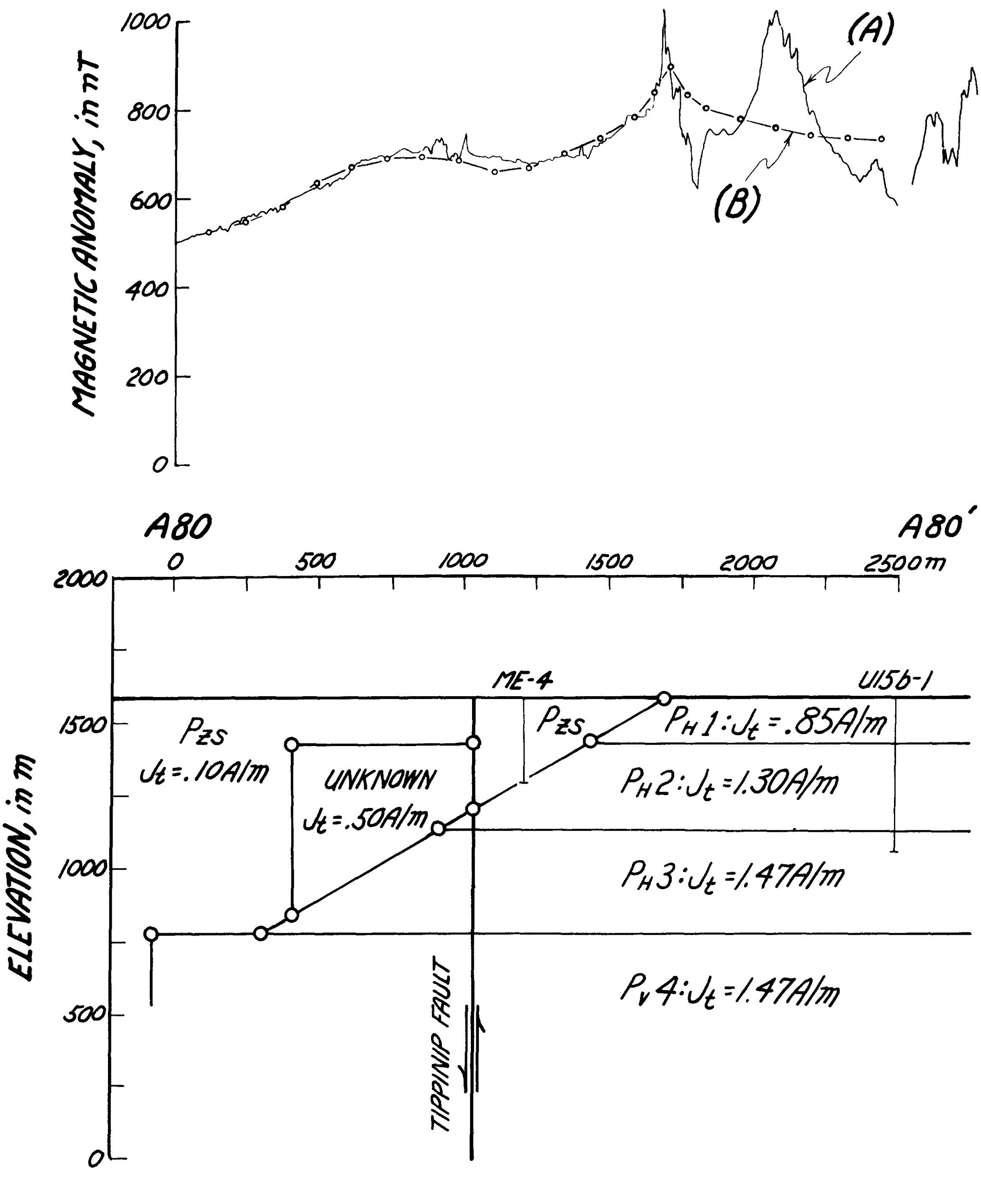


Figure 19C.--Section along ground traverse A80-A80' showing model selected to portray the western edge of the stock. The stock is represented by prisms P_H1, P_H2, P_H3, P_V4, and P5 (fig. 13C); the metasedimentary rocks by prism Pzs; and the unknown buried rocks by the prism having J_t = 0.50 A/m. Also shown is the Tippinip fault, and the rocks penetrated by drill holes ME-4 and U15b-1. Anomalies shown along the traverse are (A) measured residuals, and (B) computed effects of the model.

The unknown buried rocks may be Eleana Formation with an increased magnetite content similar to that observed near Calico Hills (Baldwin and Jahren, 1982), rather than magnetized granitic rock, and we are, therefore, unable to provide an interpretation of displaced granitic rock at the fault. The evidence for identifying the buried rock comes from amplified residual anomalies shown along traverses A80-A80' and B80-B80' on figure 20C. Slope distances indicate that near-surface Eleana Formation is magnetized just west of the Tippinip fault. Thus the Tippinip fault does not appear to bound the west edge or the stock in a fashion similar to the Boundary fault.

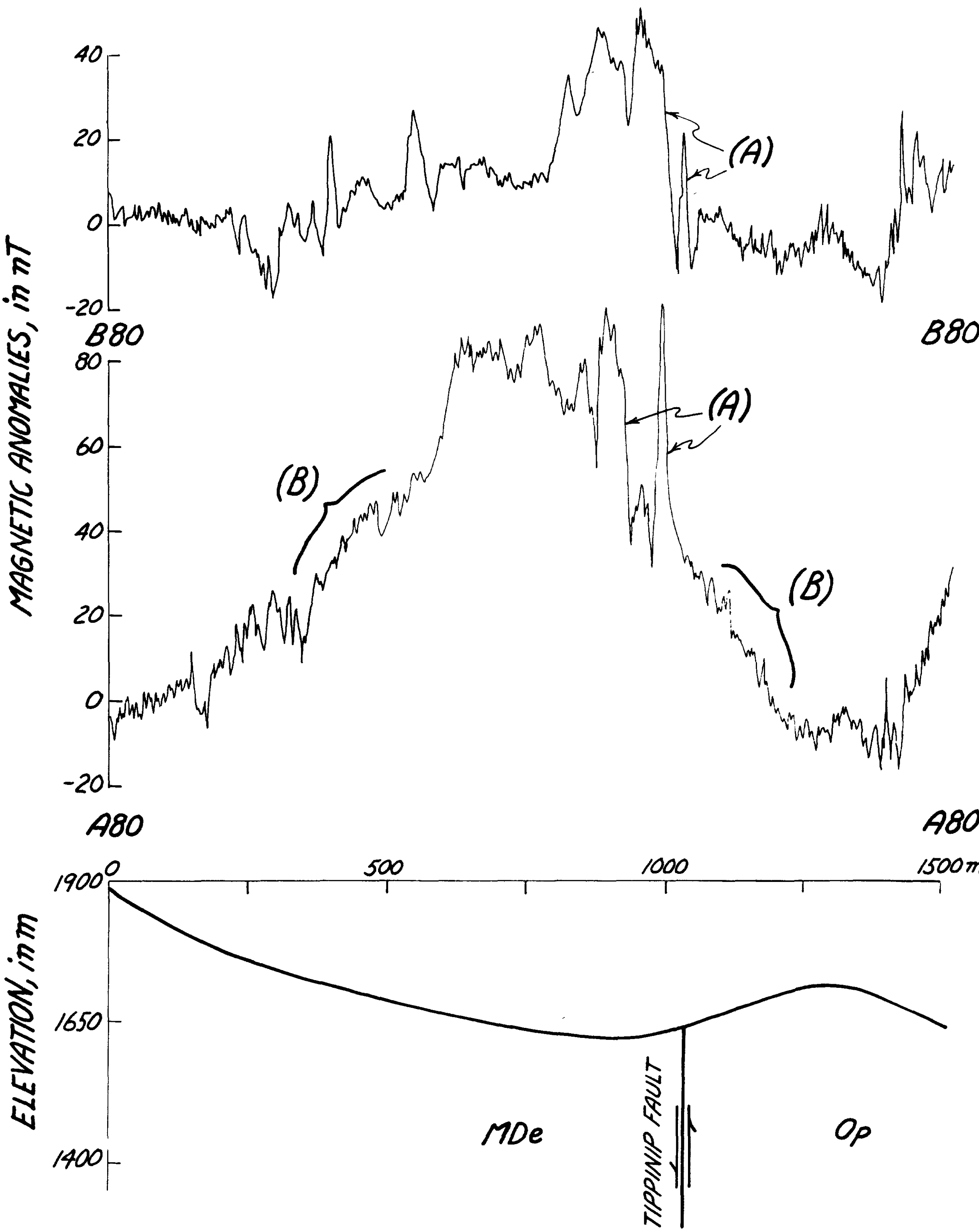


Figure 20C.--The amplified residual anomalies along traverses A80-A80' and B80-B80' showing slope distances that designate sources within 20 m (65 ft) (A) and 150 m (490 ft) (B) of the surface. Also shown are Tippinip fault, metamorphosed sedimentary rocks of the Eleana Formation, MDe, and metamorphosed sedimentary rocks of the Pogonip Group, Op. The shallow sources are just west of the Tippinip fault in the Eleana Formation, MDe.

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SUMMARY OF GEOLOGIC AND GEOPHYSICAL INVESTIGATIONS

By

Paul P. Orkild

The focus of integrated geologic and geophysical studies at the Climax stock was to define the stock boundaries and examine the geologic features pertaining to containment. The three faults (Tippinip, Boundary-Yucca, and Butte) defining the area structurally were examined in detail.

The nature of the Tippinip fault (the attitude and strike) has a little bearing on the geometry of the granite in the subsurface to the west. Surface geology (trenching) and the interpretation of magnetic data indicate that it is a benign feature which, at depth, does not affect the geometry of the granite sloping to the west. The lack of density contrast precludes the usefulness of gravity to define this fault. Field evidence indicates that the Tippinip fault had a fault motion component down to the east before the intrusion of the stock. This motion has since been reversed by the intrusion of the stock. The fault was undoubtedly a plane of weakness along which the stock was emplaced.

The Boundary fault defines the extent of granite outcrops to the southeast and east of the stock. The Yucca fault is projected to join the Boundary fault near trench 5. North of trench 5, the Boundary-Yucca faults are collectively called the Butte fault. The nature and dip of the fault planes are important in defining the boundary of the stock. These planes have been documented in seven trenches along the Boundary fault.

Initial geologic mapping was done by Houser and Poole, 1960; only minor differences were observed during recent field studies. One major difference was shallower dips on the Boundary fault, 43^{o}-59^{o}, with an average dip of 52^{o} SE instead of the recorded 75^{o} by Houser and Poole. However, it is interesting to note that the 75^{o} dip gives a better "fit" in 3-D analysis of the gravity and magnetic data.

Further examination of the Boundary fault structure in trench 5 and north of the confluence of the Boundary and Yucca faults and south in the Smokey Hills region indicates that 75^{o} to 77^{o} is a valid dip for these structures; this, combined with the magnetic and gravity interpretations, has led me to hypothesize that the faults mapped in USGS and LLNL trenches are slump features or low-angle faults of the Boundary fault system which dip into the main Boundary fault. The main trace of the Boundary fault is buried beneath young alluvium (figs. 2A and 1D). Figure 2A shows the inferred trace of the Boundary fault beneath the alluvium; this fits well with an inferred fault on 3-D gravity profile lines N899,000, N901,000, and N903,000. Figure 1D is a diagrammatic cross section of the Boundary fault system. Showing the main trace of the Boundary fault beneath alluvium, offsetting tuff and alluvium down to the east against tuffs and granite. On the footwall of the main trace of Boundary fault, outcrops of tuff were stranded on the irregular granite surface when the fault moved and, subsequently, these tuff deposits were slumped and developed the low-angle faults as seen in the USGS, LLNL, and DNA trenches.

The amount of offset on the Boundary fault, based on the stratigraphic offset of volcanic rocks which occur just beneath the Tub Spring Member on the shoulder of Oak spring Butte to the same stratigraphic horizon in and just

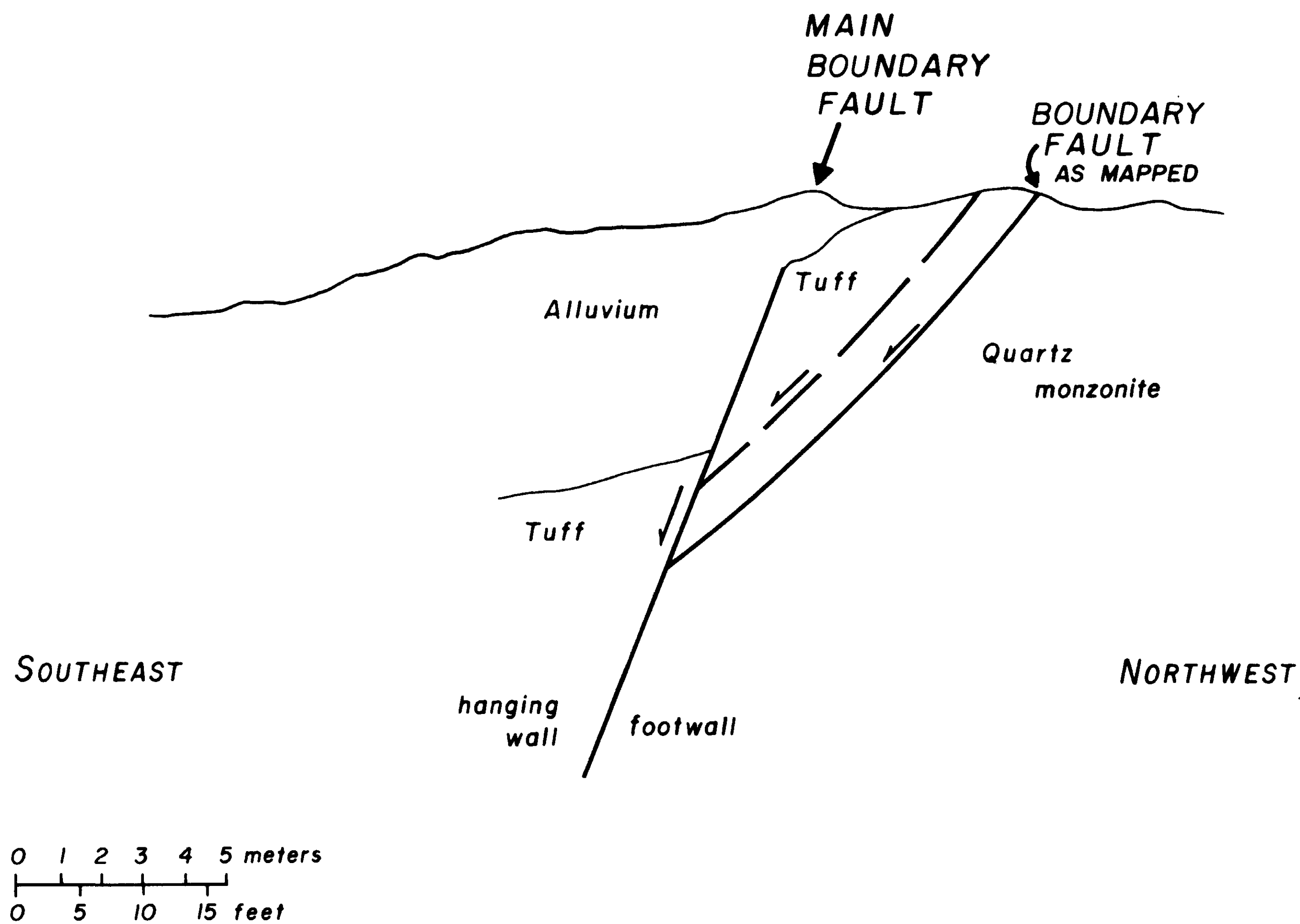

Figure 1D.--Diagrammatic cross section of Boundary fault system.

southeast of trench 5, and interpretations of gravity data, is approximately 213-243 m (700-800 ft). North of trench 5, where the Yucca and Boundary faults join, the Butte fault has a vertical post-tuff movement of 427 m (1,400 ft). A similar displacement is inferred from gravity data. The Butte fault displacement has been measured from two prominent ash-flow tuffs (Grouse Canyon and Tub Spring Members of the Belted Range Tuff), which form the cap and shoulder of Oak Spring Butte, to their down dropped counter parts east of the fault.

The amount of offset on the Boundary fault pre-volcanic rock is unknown, however, it is possible that the large displacement documented is totally post-volcanic and is related to the structural deformation of Yucca Flat basin in post-Miocene. The Yucca/Butte fault system, based on stratigraphic and drill-hole data, existed prior to the deposition of volcanic rock in the test site area. The amount of displacement had to be in excess of 610 m (2,000 ft) and possibly as much as 2,438 m (8,000 ft) based on the juxtaposition of the upper and lower plates of major thrust faults in Climax stock area. The displacement on the Boundary/Yucca fault system is further complicated by the fact that they were planes of weakness along which the stock was emplaced.

Estimates of the depth and width of buried portions of the granitic rocks of the Climax stock are based on geologic data, gravity data obtained by D. L. Healey, and interpretation of aeromagnetic and ground magnetic anomalies by G. D. Bath.

The gravity profiles define the near-surface configuration, but are unable to distinguish between the Paleozoic rocks and granitic rock at depth. The magnetic data defines the width, depth, and the gross subsurface configuration of the intrusive mass, but there is difficulty in approximating the boundaries from high-altitude aeromagnetic data. Geology defines the surface and near surface configuration. Limitations of geology, gravity, and magnetic methods prevent a unique solution by any one method, but, by combining the three, it is possible to obtain a reasonable model of the stock. This configuration is shown in figures 2D and 3D. The stock is elongated parallel to the long axis of the granitic outcrop and has steep southeast slope and moderately steep north slope. Interpretations indicate the Boundary/Yucca fault system truncates the southeast side with a displacement of approximately 2,000 m (6,500 ft). The Tippinip fault on the west flank of the stock shows no significant displacement. The model, as shown, has a total depth extent of about 4.8 km (3 mi), with the upper part of the model being approximately 6x4 km and the lower part enlarging to a diameter of at least 10 km (6 mi). The depth is a minimum estimate because it is assumed that the curie temperature occurs at about 3.4 km (2 mi) below sea level. Nonmagnetic rock probably extends to greater depths than shown on figures 2D and 3D.

Minor differences exist between geologic data and magnetic interpretations. The absence of granitic rocks between the Boundary and Yucca faults along line C73-C73' is at variance with geologic evidence to the northeast between magnetic lines D and E. Granitic rocks were penetrated at approximately 229 m (750 ft) in drill hole U15gz#24, however, to the south in the C73-C73' profile, if granitic rocks are extended southeastward into the wedge between the Boundary and Yucca faults this results in poor agreement between residual and computed anomaly as shown on figure 19C. One possibility is that U15gz#24 is located to the northwest of the concealed main trace of Boundary fault and was drilled into the footwall of the fault.

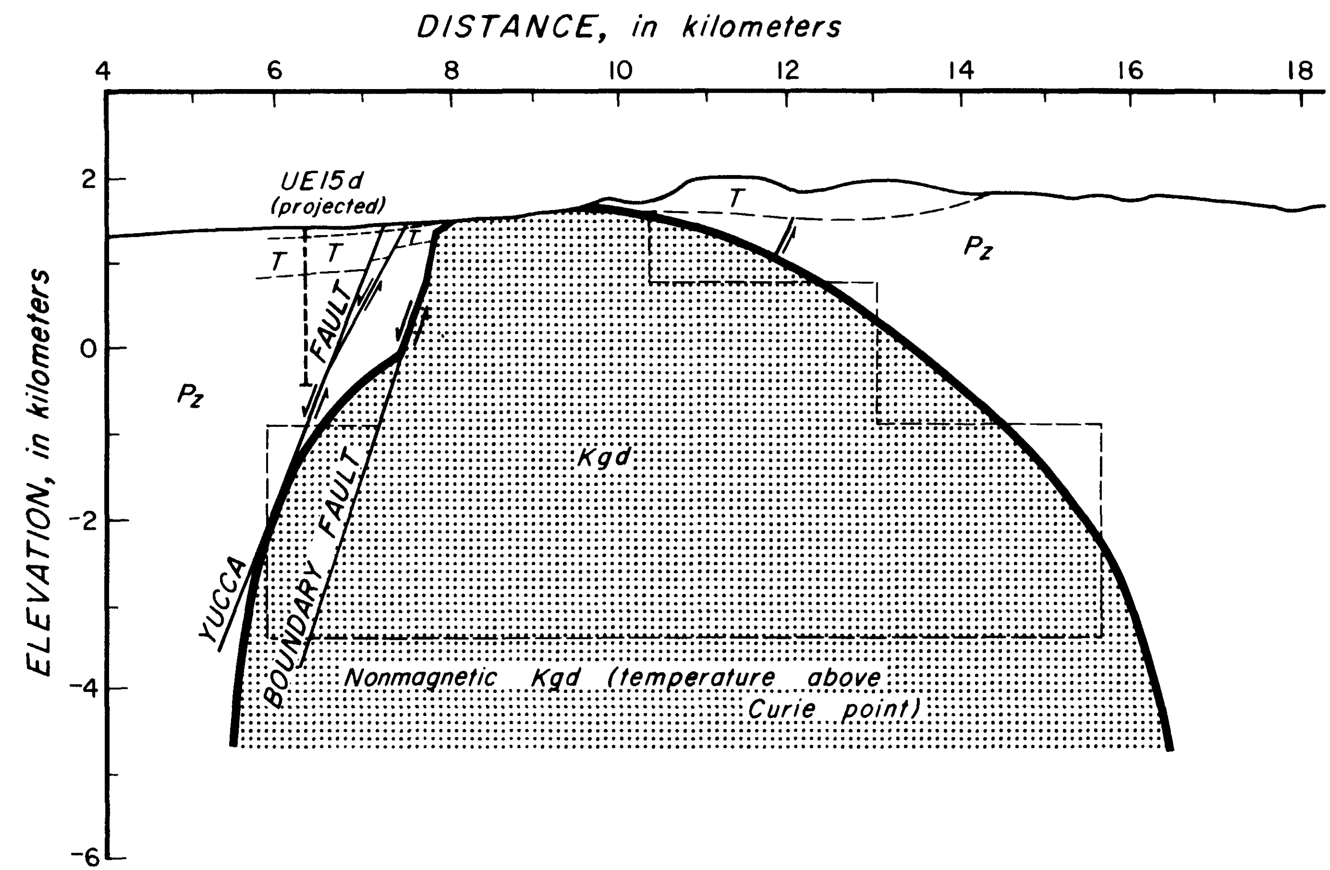

Figure 2D.--North-south section along traverse B63-B63' of figure 10C. Distance of traverse = 18.28 km (60,000 ft), but only 3.0 km to 18.28 km shown. Horizontal and vertical scale: 1" = 5,000 ft. (See plate 1A for explanation of geologic symbols.)

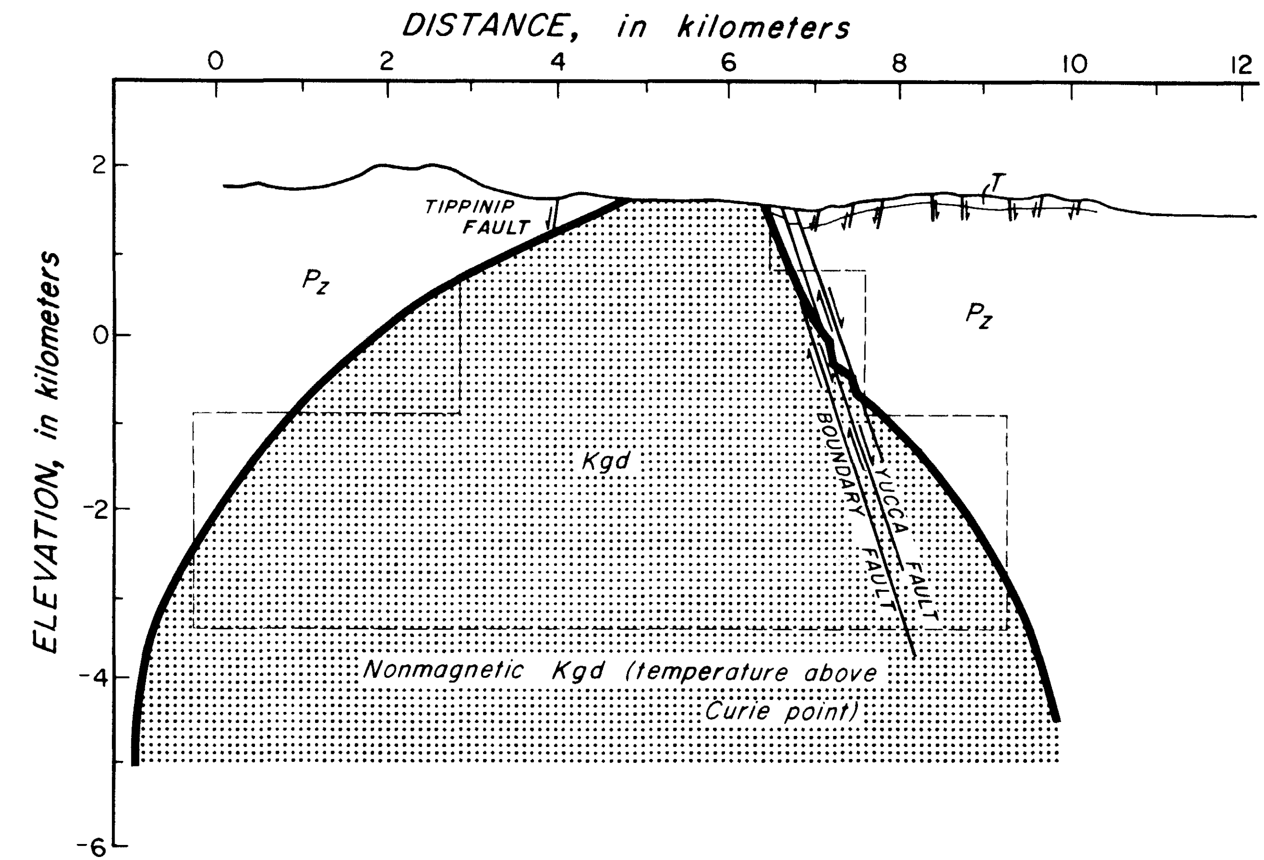

Figure 3D.--East-west section along traverse A63-A63' of figures 10C and 13C. Horizontal and vertical scale: 1" = 5,000 ft. (See plate 1A for explanation of geologic symbols.)

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