TEXAS SALT DOMES:
Natural Resources, Storage Caverns, and Extraction Technology

Steven J. Seni, William F. Mullican III, and H. Scott Hamlin

Contract Report for Texas Department of Water Resources
under Interagency Contract No. IAC (84-85)-1019

28 figs. 5 tables 3 appendices

161 p.

167 p.

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
University Station, P.O. Box X
Austin, Texas 78713-7508

TEXAS SALT DOMES:
Natural Resources, Storage Caverns, and Extraction Technology

Steven J. Seni, William F. Mullican III, and H. Scott Hamlin

Contract Report for Texas Department of Water Resources
under Interagency Contract No. IAC (84-85)-1019

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
University Station, P.O. Box X
Austin, Texas 78713-7508

CONTENTS

INTRODUCTION 1

TEXAS SALT DOMES. 2

SOLUTION-MINED CAVERNS 7
    Public information 8

CAVERN CONSTRUCTION 9
    Casing program 10
    Salt-dissolution process 12
    Blanket material and function 13
    Sump 13

CAVERN GEOMETRY 15
    Direct circulation 15
    Reverse circulation 16
    Modified circulation. 16

CAVERN FAILURES 20
    Mechanisms of cavern failure 27

SALT-DOME RESOURCES 28
    Salt-dome storage 29
    Salt resources 39
        Rock-salt mine 42
        Solution-brine well 42
    Petroleum resources. 45
        Shallow salt-dome oil fields 45
        Cap-rock reservoirs 47
        Salt-dome flank reservoir 52
        Deep-seated dome crest reservoir 54
        Petroleum resources of salt domes in the
            Rio Grande and East Texas Basins 56
    Sulfur resources 57
        History and technology 57
        Characteristics of cap-rock sulfur deposits 60
    Cap-rock resources 60
        Crushed stone 66
        Other resources 66

ACKNOWLEDGMENTS 68

REFERENCES. 69

APPENDIX 1. Structure-contour map of Texas salt domes constructed on a topographic base. 74

APPENDIX 2. Railroad Commission of Texas Authority Numbers for storage-well permits. 159

APPENDIX 3. Railroad Commission of Texas Rule 74 procedures and requirements for storage-well operations 160

Figures

1. Salt basins and diapir provinces in the United States. 3
2. Location map for Texas salt domes. 4-5
3. Typical casing string detail for solution-mined cavern in salt. 11
4. Casing configuration for direct circulation. 14
5. Phased expansion of solution cavern with direct circulation. 17
6. Casing configuration for reverse circulation.. 18
7. Evolution of brine and storage caverns, Pierce Junction salt dome. 19
8. Cross section of Blue Ridge salt dome showing geometry of salt mine and storage cavern that failed. 25
9. Histogram of 1983 storage capacity in Texas salt domes and proposed Strategic Petroleum Reserve caverns. 30
10. Map of salt domes showing active, abandoned, and pending storage facilities. . 32-33
11. Cross section of Bryan Mound salt dome (north-south) showing geometry of present Strategic Petroleum Reserve caverns. 34
12. Cross section of Bryan Mound salt dome (east-west) showing geometry of present and proposed Strategic Petroleum Reserve caverns. 35
13. Cross section of Big Hill salt dome (north-south) showing geometry of proposed Strategic Petroleum Reserve caverns and Union Oil Co. storage cavern. 36
14. Cross section of Big Hill salt dome (east-west) showing geometry of proposed Strategic Petroleum Reserve caverns. 37
15. Map of Boling salt dome showing locations of oil fields, sulfur production, Valero Gas Co. gas-storage caverns, and United Resource Recovery, Inc., lease area. . . 40
16. Cross section of Boling salt dome (east-west) showing location of sulfur production, geometry of Valero Gas Co. gas-storage caverns, and proposed location and geometry of United Resource Recovery, Inc. waste-storage caverns. 41
17. Map of salt domes showing active rock-salt mines and solution-brine wells. . . . 43
18. Yearly oil production from Spindletop salt-dome oil field. 46

19. Map of piercement salt domes showing oil fields that have produced more than 10 million barrels of oil. 48

20. Graph showing depth to the crest of Texas salt domes and their cumulative oil production through 1975. 49

21. Map of Boling salt dome showing locations of oil fields. 50

22. Cross section of (Moores) Orchard salt dome showing upturned strata on the flank of the dome and the crest of the dome truncated by erosion. . 53

23. Map of Yegua and Frio reservoirs over the crest of deep-seated salt domes.. . . . 55

24. Casing string detail for cap-rock sulfur-production well. 58

25. Graph showing the chronology of sulfur mining in Texas salt domes. 61

26. Map of salt domes showing active and abandoned sulfur mining. 62-63

27. Cross section of Boling salt dome showing cap rock and zone of sulfur mineralization. 64

28. Map of Texas salt domes showing area of sulfur mineralization. 65

Tables

1. List of salt domes with cavern failures, mechanisms, and consequences. 21

2. List of salt domes with storage, operating company, Railroad Commission of Texas applicant, number of caverns, capacity, and product stored.. 38

3. List of salt domes with salt production, method, status, company, and history. . . 44

4. List of salt domes with large oil fields and production status. 51

5. List of salt domes with sulfide mineral occurrences and documentation. 67

INTRODUCTION

This report reviews natural resources associated with salt domes in Texas. Salt domes provide a broad spectrum of the nation's industrial needs including fuel, minerals, chemical feedstock, and efficient storage space. This report focuses on the development, technology, uses, and problems associated with solution-mined caverns in salt domes. One proposed new use for salt domes is the permanent isolation of toxic chemical waste in solution-mined caverns. As the Texas Department of Water Resources (TDWR) is the State authority responsible for issuing permits for waste disposal in Texas, TDWR funded this report to judge better the technical merits of toxic waste disposal in domes and to gain a review of the state of the art of applicable technology.

Salt domes are among the most interesting and intensively studied structural-stratigraphic geologic features. Individual domes may be the largest autochthonous structures on earth. Yet many aspects of salt-dome genesis and evolution, geometry, internal structure, and stratigraphy are problematic. Details of both external and internal geometry of salt stocks and their cap rocks are vague, and information is restricted to the shallow parts of the structure. These facts are all the more surprising considering that salt diapirs dominate the fabric of the Gulf Coastal Province, which is one of the most explored and best known geologic regions on earth.

This report includes information on present and past uses of Texas salt domes, their production histories, and extractive technologies (see also Halbouty, 1979; Hawkins and Jirik, 1966; and Jirik and Weaver, 1976). Natural resources associated with salt domes are dominated by petroleum that is trapped in cap rocks and in strata flanking and overlying salt structures. Sulfur occurs in the cap rock of many domes. Some cap rocks also host potentially valuable Mississippi Valley-type sulfide and silver deposits. Salt is produced both by underground mining of rock salt and by solution brining.

The caverns created in salt by solution mining also represent a natural resource. The relative stability, economics, location, and size of these caverns makes them valuable storage vessels for various petroleum products and chemical feedstocks.

TEXAS SALT DOMES

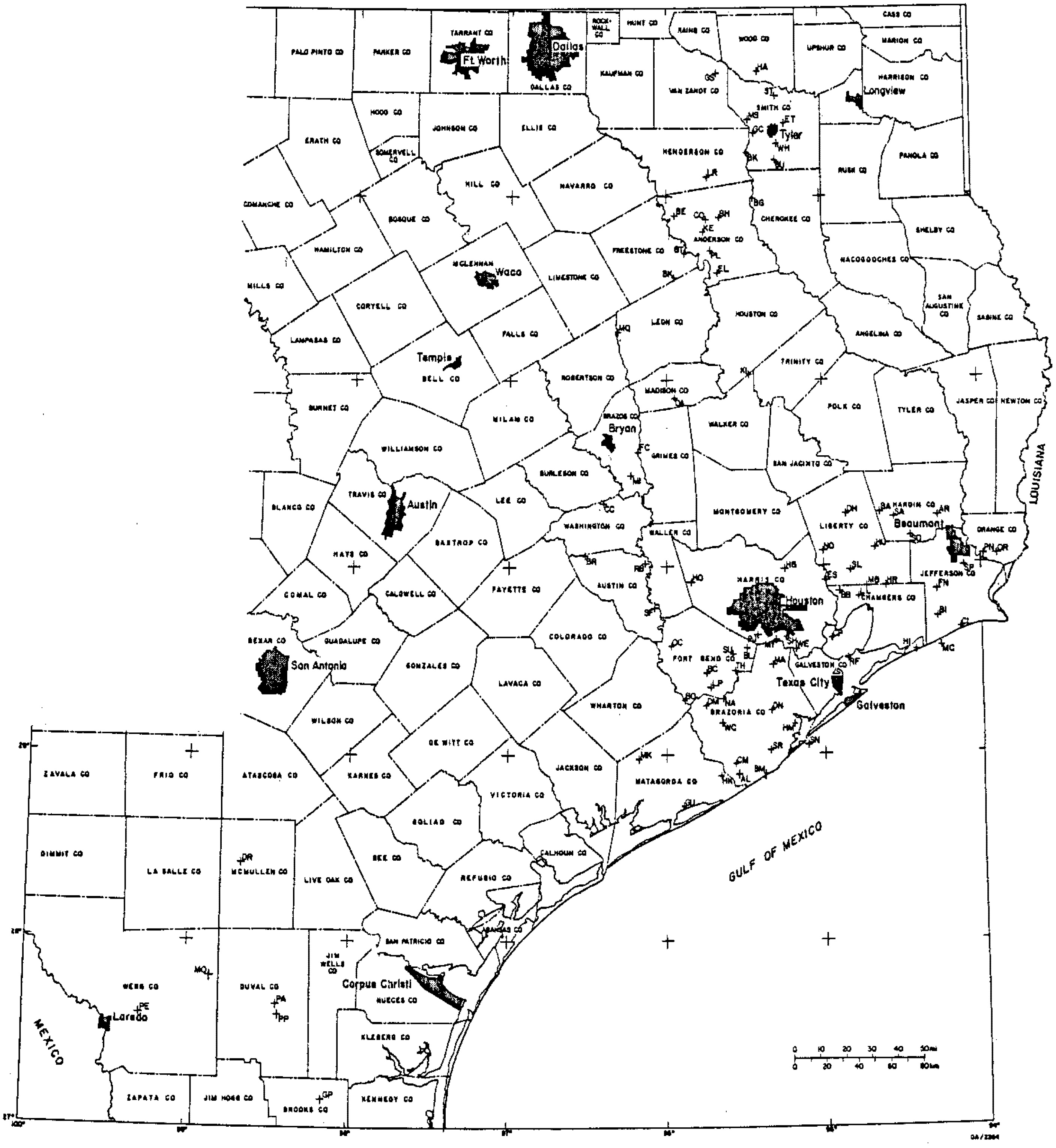
Texas salt structures are clustered in the Gulf Coast, Rio Grande, and East Texas Salt Basins. Shallow piercement salt domes form diapir provinces within the larger salt basins (fig. 1). A regional map shows the distribution of salt domes in the three salt basins (fig. 2). Structure-contour maps (sea-level datum) of individual domes were prepared and plotted on a map with surface topographic contours (appendix 1).

Physically, salt domes are composed of three elements--the salt stock, the cap rock, and the host strata. The central core of the salt dome is a subcylindrical to elongate salt stock. Typically, the cap rock immediately overlies the crest of the salt stock and normally drapes down the uppermost flanks of the stock. An aureole of sediments surrounds the salt stock. Drag zones, gouge zones, and diapiric material transported with the salt stock are included in the aureole.

Salt diapirs are the mature end members of an evolutionary continuum of salt structures. Diapirs begin as low-relief salt pillows that are concordant with surrounding strata. The flanks of the salt pillow steepen with continued growth, and overlying strata are stretched and faulted. Salt becomes diapiric when the relation of salt and surrounding strata becomes discordant. At that point, the salt structure may be intrusive with respect to surrounding strata or it may be extruding at the surface. The phase of active diapirism is typically accompanied by rapid rates of sedimentation. Subsequent to active diapirism, dome evolution enters a slower phase of growth characterized by slow rates of upward movement or by crest attrition owing to salt dissolution in excess of growth.

Dome-growth history is an important aspect in understanding the many problems associated with dome stability (Jackson and Seni, 1983). A complete understanding of dome

Figure 1. Salt basins and diapir provinces in the United States (modified from Smith and others, 1973).



TEXAS SALT DOMES

Figure 2. Location map for Texas salt domes.

(continued)

Figure 2 (cont.).

Code	Dome Name	County
AL	Allen	Brazoria
AR	Arriola	Hardin
BB	Barbers Hill	Chambers
BA	Batson	Hardin
BE	Bethel	Anderson
BC	Big Creek	Fort Bend
BI	Big Hill	Jefferson
BL	Blue Ridge	Fort Bend
BG	Boggy Creek	Anderson/Cherokee
BO	Boling	Wharton/Fort Bend
BR	Brenham	Austin/Washington
BK	Brooks	Smith
BH	Brushy Creek	Anderson
BM	Bryan Mound	Brazoria
BU	Bullard	Smith
BT	Butler	Freestone
CP	Cedar Point	Chambers
CL	Clam Lake	Jefferson
CC	Clay Creek	Washington
CM	Clemens	Brazoria
CO	Concord	Anderson
DM	Damon Mound	Brazoria
DN	Danbury	Brazoria
DH	Davis Hill	Liberty
DA	Day	Madison
DR	Dilworth Ranch	McMullen
ET	East Tyler	Smith
EL	Elkhart	Anderson
ES	Esperson	Harris/Liberty
FN	Fannett	Jefferson
FC	Ferguson Crossing	Brazos/Grimes
GC	Girlie Caldwell	Smith
GS	Grand Saline	Van Zandt
GU	Gulf	Matagorda
GP	Gyp Hill	Brooks
HA	Hainesville	Wood
HR	Hankamer	Chambers/Liberty
HK	Hawkinsville	Matagorda
HI	High Island	Galveston
HO	Hockley	Harris
HM	Hoskins Mound	Brazoria
HU	Hull	Liberty
HB	Humble	Harris
KE	Keechi	Anderson
KI	Kittrell	Houston/Walker
LR	La Rue	Henderson
LP	Long Point	Fort Bend
LL	Lost Lake	Chambers
MA	Manvel	Brazoria
MK	Markham	Matagorda
MQ	Marquez	Leon
MC	McFaddin Beach	State waters
MI	Millican	Brazos
MO	Moca	Webb
MB	Moss Bluff	Chambers/Liberty
MS	Mount Sylvan	Smith
MY	Mykawa	Harris
NA	Nash	Brazoria/Fort Bend
ND	North Dayton	Liberty
OK	Oakwood	Freestone/Leon
OR	Orange	Orange
OC	Orchard	Fort Bend
PA	Palangana	Duval
PL	Palestine	Anderson
PE	Pescadito	Webb
PP	Piedras Pintas	Duval
PJ	Pierce Junction	Harris
PN	Port Neches	Orange
RB	Raccoon Bend	Austin
RF	Red Fish Reef	State waters
SF	San Felipe	Austin
SN	San Luis Pass	State waters
SA	Saratoga	Hardin
SO	Sour Lake	Hardin
SH	South Houston	Harris
SL	South Liberty	Liberty
SP	Spindletop	Jefferson
ST	Steen	Smith
SR	Stratton Ridge	Brazoria
SU	Sugarland	Fort Bend
TH	Thompson	Fort Bend
WE	Webster	Harris
WC	West Columbia	Brazoria
WH	Whitehouse	Smith

growth requires detailed knowledge of dome geometry, stratigraphy, and structure and stratigraphy of surrounding strata, geohydrology (both past and present), and surficial strata. Such detailed studies have been completed for salt domes in the East Texas Basin (Jackson and Seni, 1984; Seni and Jackson, 1983a, b). Currently, the required data base for understanding growth history of the domes in the Houston Salt Basin is only partly assembled. Public data on the geometry of the salt stock have been collected. Much work remains to understand the geology of cap rocks and surrounding strata.

The influence of dome growth on the topography of the modern surface over the crests of salt structures is one aspect of dome-growth history that is available for domes in both the Houston and the East Texas Salt Basins. The topography of the modern surface over the crests of diapirs is readily influenced by diapir growth or dissolution. Positive topographic relief (in excess of regional trends) over the dome crest is linked to uplift or to active diapir growth. In contrast, subsidence of the topographic surface over the dome crest is linked to attrition or dissolution of the dome crest. Comparison of the topographic relief over domes in the salt basins indicates the relative importance of growth or dissolution processes. For salt domes in the Houston Salt Basin with crests shallower than 4,000 ft, 63 percent of the domes show evidence of positive topographic relief over their crests, whereas only 8 percent of these domes show evidence of subsidence at the depositional surface. In contrast, in the East Texas Salt Basin, 81 percent of the shallow domes (those with crests shallower than 4,000 ft) show evidence of subsidence over the crest, whereas no domes in the East Texas Salt Basin express evidence of uplift. Clearly, strata over the crests of domes in the East Texas Salt Basin have responded differently to processes at the diapir crest than have domes in the Houston Salt Basin. Supradomal topography over domes in the East Texas Basin reflects the dominance of dissolution and crest attrition processes, whereas the dominance of uplift is shown over domes in the Houston Salt Basin.

SOLUTION-MINED CAVERNS

Salt caverns were originally an unrecognized resource formed when salt was removed by dissolution to produce brine principally as a chemical feedstock. Along the Texas coast, a large petrochemical industry evolved because abundant petroleum reserves were associated with Texas coastal salt domes. This close association between salt domes and the petroleum industry in turn promoted both brine and storage industries near the domes. Texas domes are now being considered as chemical waste repositories. The petroleum-refining industry would be the source of much of that chemical waste.

Natural resources from Texas salt domes have been efficiently exploited with a multiple-use philosophy. Permanent disposal of toxic-chemical waste in solution-mined caverns may remove a given region of the dome from resource development forever. Multiple use of domes in the future would then be restricted.

Brining and solution mining are two different operations that form two types of caverns. Brining is used here to describe operations in which the primary economic product is the Na^+ and Cl^- in the brine. Caverns that form around brine wells are incidental to the production of brine. The cavern is just the space from which salt was dissolved during brine production. Solution mining is used here to describe the process of forming an underground cavern specifically for product storage. In this case the brine is typically discarded either into the cap rock or the saline aquifers.

Both brining and solution mining operate on a large scale in Texas. Of 13 domes with a history of brining operations, 7 are active. Similarly, of 18 domes with a history of storage, 16 are active. Two additional domes have proposed storage operations approved by the Texas Railroad Commission (RRC). According to Griswold (1981), approximately 900 cavities have been solutioned in the United States (circa 1981). Statistics from the Gas Processors Association (GPA) reveal that in 1983, 47 percent of the national storage capacity of light hydrocarbons was in Texas salt domes (GPA, 1983).

The primary objectives differ for brine operations and solution mining for storage. Currently, many former brine caverns serve as storage caverns. Simultaneous product storage and brining began in Texas at Pierce Junction salt dome (Minihan and Querio, 1973). The difference between salt dissolutioning to produce brine and creating space for storage may be subtle but variations in operating parameters often produce vastly different salt-cavern geometries. The primary objective in brining is lessening pumping costs and increasing brine production. Solution mining for storage is primarily directed toward a controlled cavern shape yielding maximum cavern stability. The mechanisms by which differences in operating parameters affect cavern shape and stability will be described in sections titled Cavern Geometry, Cavern Failures, and Mechanisms of Cavern Failure.

As with many fledgling industries, initial solution-mining operations were originally seat-of-the-pants. Experience was gained from the early operations, and many new techniques were employed to complete successfully and set casing in problem holes, to control and monitor cavern development, and to predict eventual cavern shapes and stabilities. Some predicted conditions later proved wrong, however. Despite industry safeguards, a total of 10 brine and storage caverns have failed in Texas.

Both long-term and short-term cavern stability is a critical issue for the storage industry and especially for the permanent disposal of chemical waste. Despite concerted research effort in this area, even industry leaders admit "no universally accepted technique to predict cavern closure (or stability) has been developed" (Fenix and Scisson, Inc., 1976a).

Public Information

At this point a caveat is warranted. The total number and capacities of solution-mined caverns in Texas is unknown. Most individual companies treat information on cavern capacities as classified data. Much research time and effort were spent at the RRC examining original documents requesting storage permits. Railroad Commission of Texas authority numbers are included in appendix 2 to aid future research efforts. Early regulatory practices of the RRC were laissez-faire. The original permit specifically allowed any and all improvements including the creation of additional storage caverns and space as desired. Other caverns that received permit approval were never completed. Some caverns have been abandoned as a result of technological or economic problems. Thus although a comprehensive list of caverns approved by the RRC was obtained, its exact equivalence with currently active caverns and their present use is not assured. Capacities of storage for Texas salt domes are from the Gas Processors Association (1983), which lists present storage capacities for light hydrocarbons. Storage of natural gas and crude oil was not listed by the Gas Processors Association. Much additional storage capacity primarily resulting from brining is undocumented.

The RRC created the Underground Injection Control Section and strengthened application procedures and reporting requirements for constructing underground hydrocarbon storage facilities after a storage cavern failed at Barbers Hill salt dome. Beginning April 1, 1982, all storage wells must be tested for mechanical integrity at least once every 5 years. Rule 74 is the document that details State requirements for underground hydrocarbon storage. It is reproduced in appendix 3.

CAVERN CONSTRUCTION

A salt cavern is solution mined by drilling a hole to expose salt, circulating fresh or low-salinity water to dissolve salt, and then displacing the resulting brine. With time, the hole enlarges and becomes the cavern. Constructing a solution-mined cavern in salt requires thick salt, a supply of fresh or low-salinity water, and a means of disposing or using the brine (Fenix and Scisson, 1976a). With some exceptions, solution-mined wells are drilled and cemented with what is generally the same technology as that is used in completing oil-, water-, and brine-disposal wells. The unique set of conditions generated during cavern dissolution requires some specialized procedures. Hole straightness is critical because this affects cavern geometry and location. Massive drill collars are used to reduce the "walk-of-the-bit," or the tendency of the bit to trace a helicoidal path during drilling. Drilling in salt also requires special salt-saturated drilling muds for preventing hole enlargement by unwanted salt dissolution.

The casing program is the single most important aspect for successfully drilling and completing a well for solution mining. Industry experts agree that most cavern failures and all reported instances of catastrophic product loss resulted from some form of casing failure (Fenix and Scisson, 1976a; Van Fossan, 1979).

Casing Program

Casing programs for solution-mined wells are designed to (1) prevent contamination of surrounding formations by drilling fluids, (2) prevent sloughing of surrounding formations into the drillhole, (3) anchor the casing, tubing, and braden-head assembly firmly into the salt, and (4) prevent loss of storage products. Casing programs have become more complex with time. A typical casing program is shown in figure 3. Early casing programs in brine wells used two or three casing strings and one production tubing. Modern casing programs use up to seven casing strings and up to three production tubing strings.

Conductor pipe is the first and largest diameter (30 to 42 inch) casing. Conductor pipe is commonly used in the Gulf Coast area where it is simply driven 50 to 300 ft into the ground until rejection. After drilling through fresh-water aquifers in the upper section, surface casing is set and cement is circulated to the surface up the annulus between the surface casing on one side and exposed formations and conductor casing on the other. Typically the surface casing is set at the top or slightly into the cap rock. Intermediate casing is set through the cap rock and from 100 to 500 ft into the top of the salt. Intermediate casing is used to isolate lost-circulation zones that commonly occur in the cap rock. Two intermediate casing strings may be cemented through the cap rock where lost-circulation zones cause severe problems. The intermediate casing is set at a depth in salt sufficient to ensure a good cement-formation bond. Salt-saturated muds are used when drilling into salt. Similarly, intermediate casing is cemented

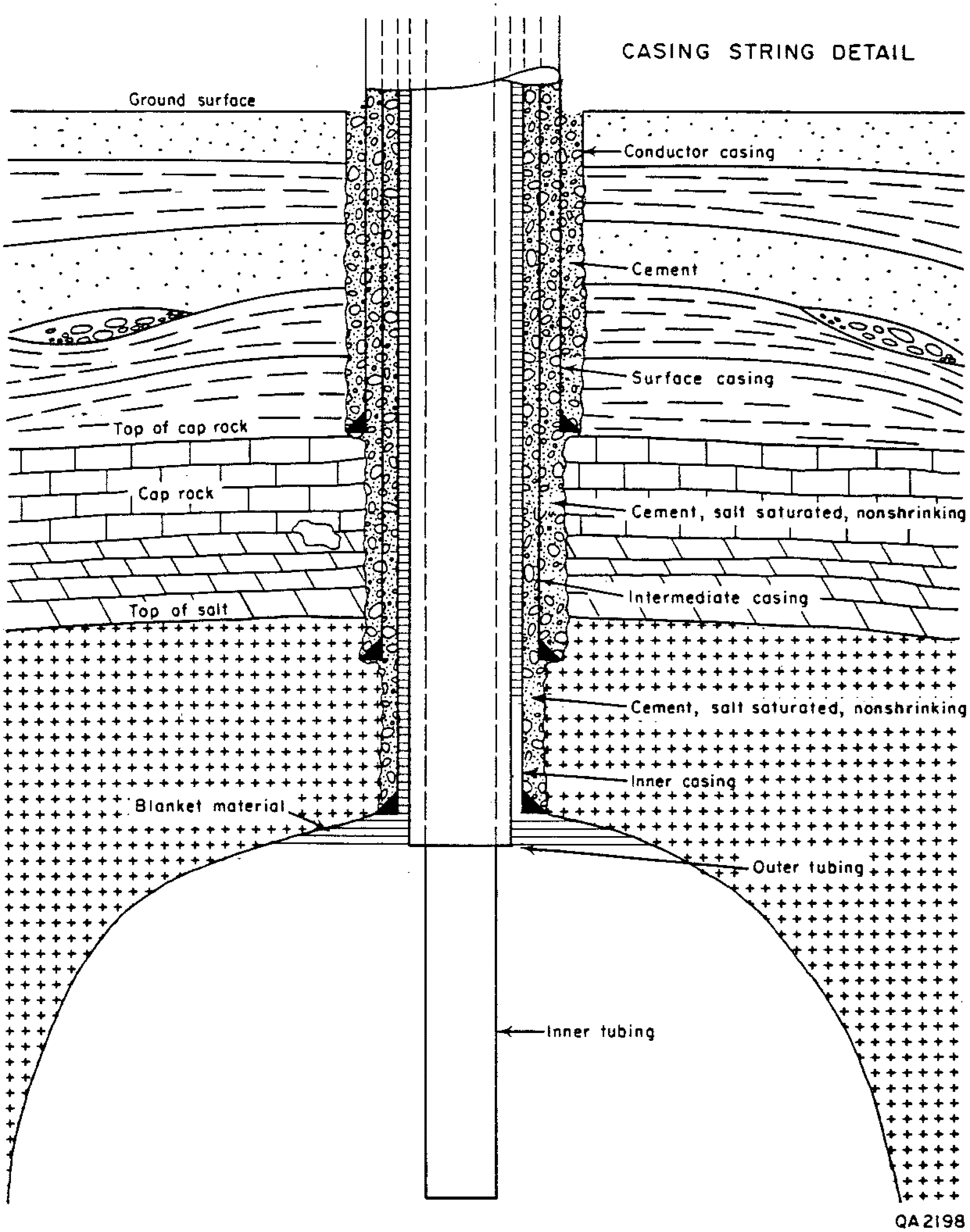


Figure 3. Typical casing string detail for solution-mined cavern in salt (after Fenix and Scisson, 1976a).

with specialized salt-saturated and nonshrinking cements. Clearly, a secure cement-formation bond is critical for cavern integrity. Cement is circulated to the surface.

Inner or Product casing is set if the depth of the top of the cavern is significantly deeper than the bottom of the intermediate casing. Again, salt-saturated, nonshrinking cements are circulated at least to the intermediate casing and preferably to the surface.

Salt-Dissolution Process

Two processes--diffusion and circulation--cause salt to dissolve. Diffusion is the ionic movement of Na^+ and Cl^- ions away from the salt face toward regions of lower ionic pressure in the water. This process is very slow and is not considered the primary mechanism of cavern formation (Bays, 1963). In contrast, circulation implies mass movement of unsaturated fluid to the salt face. The saturation can then be increased as circulation brings additional unsaturated fluid to the salt face. Low-pressure jetting techniques (Van Fossan and Prosser, 1949) are used to create a predictable circulation pattern.

Temperature, gravity, and pressure all influence the circulation process. Thermal convection of the brine within the cavern is due to temperature differences between cold, dense injection water and hotter, stabilized cavity water. Thermal convection is actually a gravity phenomenon of short duration. Temperature and circulation equilibria are achieved within 24 to 72 hours in a stable cavern (Bays, 1963). Gravity is the most important factor controlling fluid movement within a cavern. Injected fresh waters are lighter than brines that are saturated. Thus, injected waters will rise through the brines. Fluids at the base of the cavern are nearly saturated, and fluids at the top of a cavity are rarely more than 10 to 15 percent saturated and may be essentially fresh. Pressure gradients imposed by brine-lift pumps also cause circulation within a cavern. However, as cavern size increases, the circulation effects of pressure differentials become insignificant (Bays, 1963).

Blanket Material and Function

The blanket is inert material at the top of the cavern. The main function of the blanket is preventing unwanted salt dissolution at the top of the cavern around the casing seat. The blanket also prevents corrosion of the product casing. Many materials have been used as blankets including air, diesel oil, crude oil, butane, propane, and natural gas. The blanket must be lighter than water and must not dissolve salt. The blanket material is injected in the annulus between the last or innermost casing string and the outermost wash or blanket tubing. Thus brine is prevented from contacting the casing seat.

Raising or lowering the blanket tubing controls the position of the blanket. The location of the blanket can locally produce a desired cavern shape by dictating where dissolution is allowed to take place. This technique is typically used at the beginning and end of cavern construction, first to wash the sump and finally to dome the cavern roof. A sump is produced at the bottom of the borehole by using a long blanket tubing to depress leaching to the base of the hole. Once the cavern has been leached, blanket control can shape the cavern roof into a dome or arch for added stability. By periodically withdrawing the blanket tubing and raising the level of the blanket during a wash cycle, a flat roof is progressively shaped into a domed or arched roof.

Sump

A sump or local depression is mined at the bottom of solution caverns to collect the relatively insoluble constituents of salt domes that remain after the salt is dissolved and removed (fig. 4). A typical Gulf Coast salt dome contains from 1 to 10 percent anhydrite, which is the chief insoluble mineral. Country rock, sandstone, and shale are insoluble constituents that may be encountered in the salt stock. These insoluble materials generally become more abundant as the periphery of the salt stock is approached. The volume of the

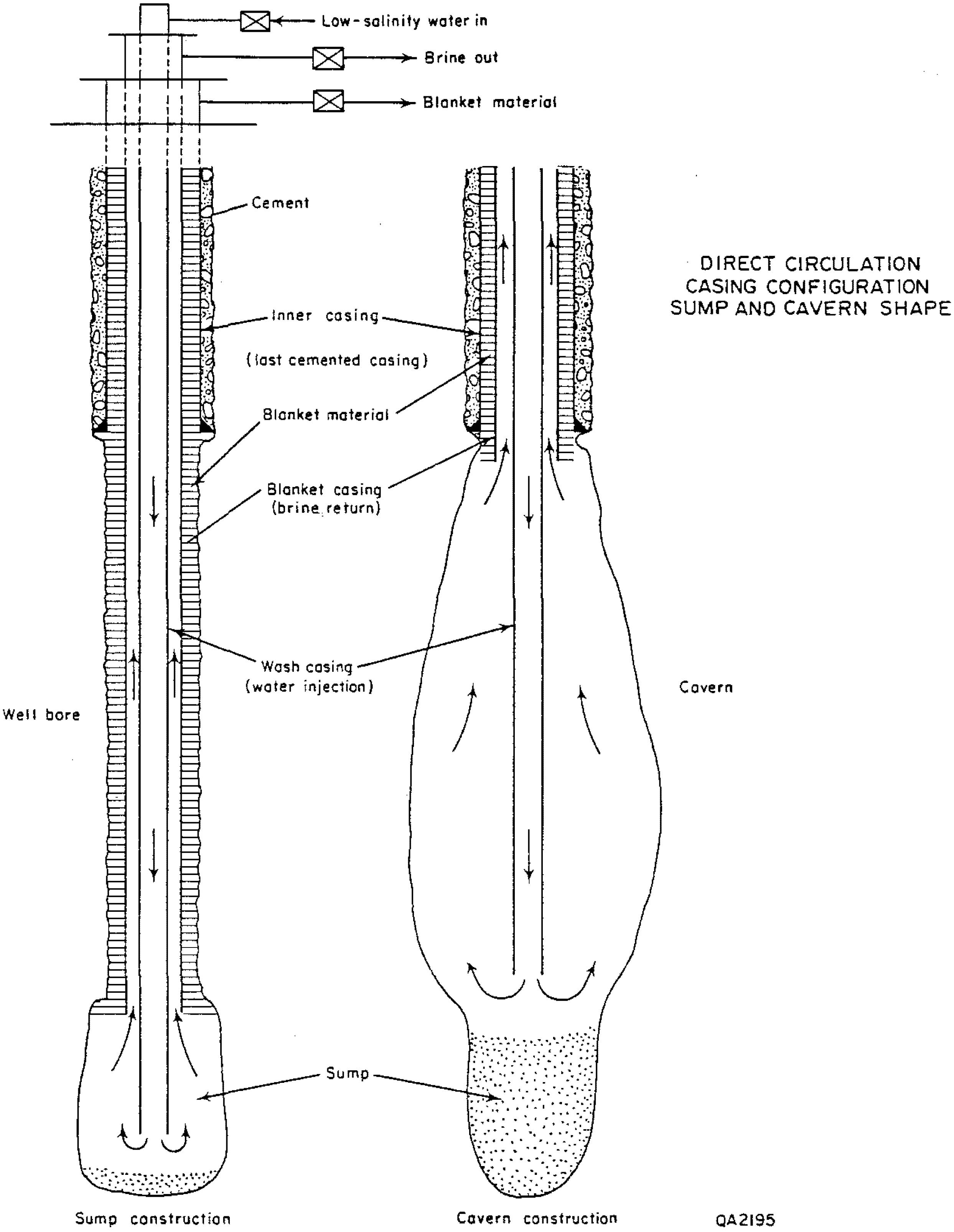


Figure 4. Casing configuration for direct circulation (after Fenix and Scisson, 1976a).

sump is dictated by the volume of the cavern and by the insoluble percentage. A core of the salt mass is normally used to determine percentage of insoluble constituents.

CAVERN GEOMETRY

The two basic techniques to control the shape of the caverns are direct circulation and reverse circulation. The techniques are differentiated by the location of the fresh-water injection and brine-return tubing within the cavern. Additionally the thickness and location of the blanket controls cavern shape during the initial and final stages of cavern mining. Final cavern shape is also influenced by variables that cannot be controlled. Such variables include salt-stock inhomogeneities, percentage and distribution of insoluble constituents, salt solubility, and space limitations with respect to the edge of the salt stock, property lines, or adjacent caverns.

Caverns that were solution mined for storage are typically leached with direct circulation, whereas brining operations typically use reverse circulation. The leaching technique for a single cavern may vary with time to adjust to changing uses or to modify original cavern shapes. The leaching technique is an important factor in cavern stability because each technique produces a "typical" shape. Clearly cavern stability is, in part, a function of cavern shape (Fossum, 1976).

Direct Circulation

A cavern is leached by direct circulation when fresh or low-salinity water is injected down the wash tubing and exits near the base of the cavern (fig. 4). Brine is returned up the annulus between the wash tubing and blanket casing located near the top of the cavern. The freshest water enters the system near the base of the cavern; thus, most of the dissolution is concentrated there. A pressure differential between the injection and brine return helps drive the progressively more saline water upward toward the brine return point. Characteristically with direct circulation, the discharged brine is less saturated with Na^+ and Cl^- than is the brine discharged during reverse circulation.

A cavern formed by direct circulation is typically tear-drop shaped because fresh water is injected at the base of the cavern and the brine is returned at the top. Cavern geometries after phased expansion using direct circulation are shown in figure 5.

Reverse Circulation

A cavern is leached by reverse circulation when fresh water is injected down the annulus between the blanket casing and the wash tubing. The fresh-water injection point is at the top of the cavern. The brine returns up the wash tubing for which the opening is located near the base of the cavern (fig. 6). The typical geometry of a cavern leached by reverse circulation is "flower pot" with a characteristically broad and flat roof. Density differences between fresh water at the top and brine at the base allow brine to sink toward the base of the cavern. The lighter fresh injection water is forced to circulate near the top of the cavern, thus forming the broad cavern roof. With increasing dissolution, the fresh water becomes denser and sinks toward the base of the cavern.

Brining operations favor leaching by reverse circulation because operating costs are lessened as only the densest brines are produced at the base of the cavern. Less wash water is required per volume of produced brine than for direct circulation, which typically produces brines that are less dense. Careful blanket control is often used to shape the flat roof into the arch. This process adds stability and lessens the probability of roof caving.

Modified Circulation

Caverns may also be mined with modified circulation in which leach conditions are modified during the formation of the cavern. For instance, a sump may be formed by direct circulation; then the rest of the cavern is formed by reverse circulation by raising the wash casing and reversing the position of the fresh-water injection and brine return. Similarly,

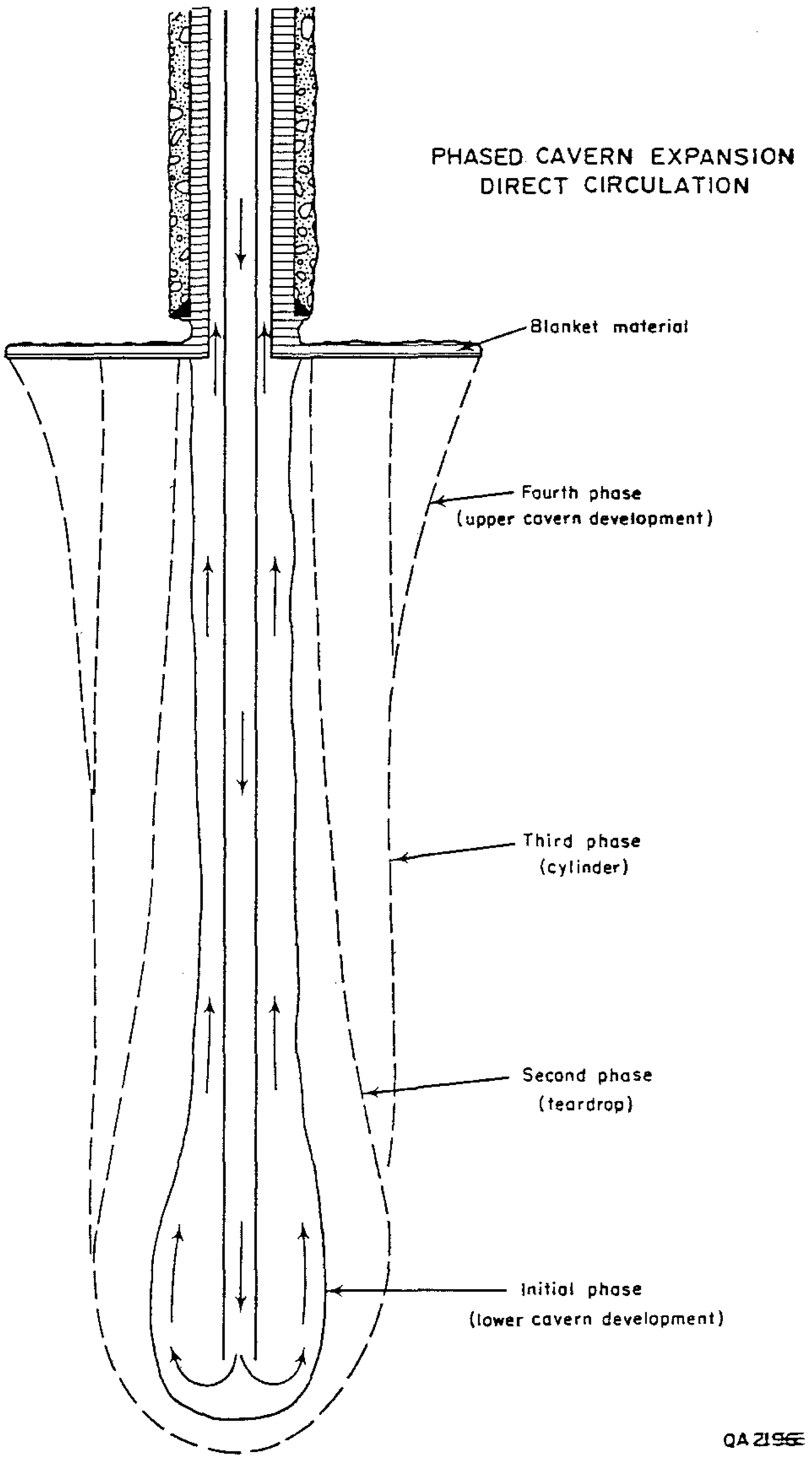


Figure 5. Phased expansion of solution cavern with direct circulation (after Fenix and Scisson, 1976a).

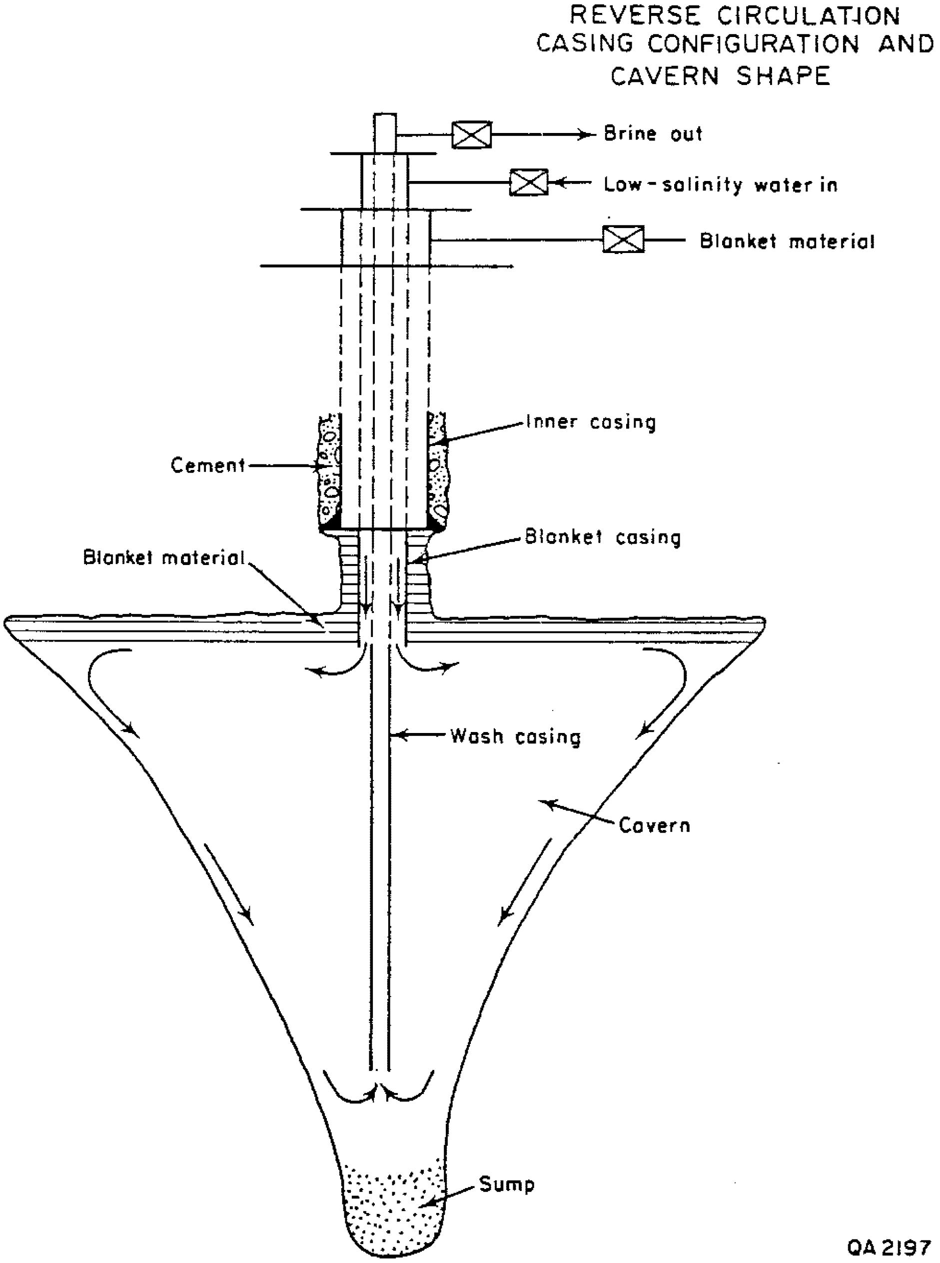


Figure 6. Casing configuration for reverse circulation (after Fenix and Scisson, 1976a).

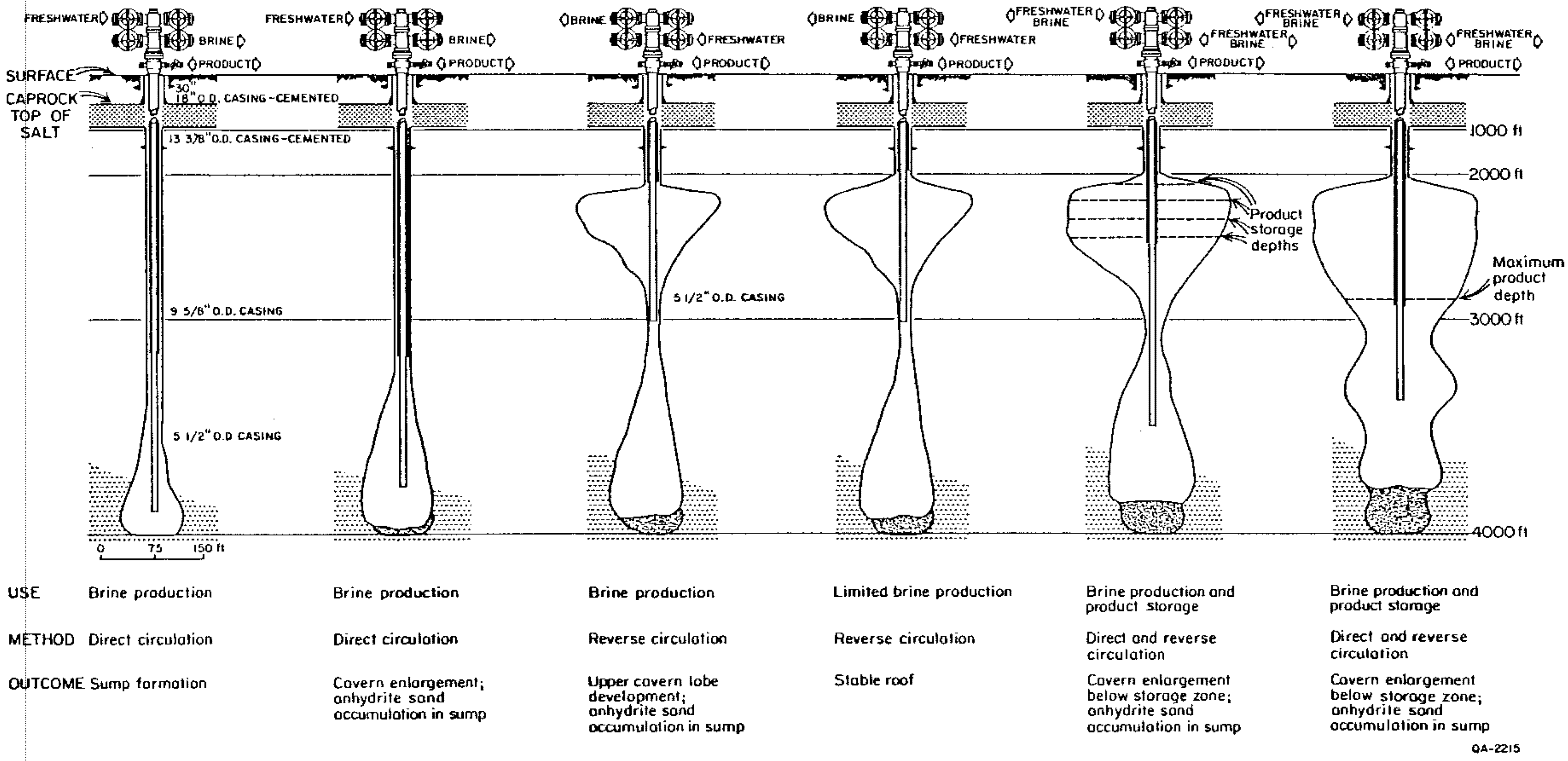


Figure 7. Evolution of brine and storage caverns, Pierce Junction salt dome (after Minihan and Querio, 1973).

changes in the use of a cavern may dictate modifications in the leach technique. Figure 7 shows a cavern that initially was a brine cavern and then was used simultaneously for brine production and product storage (Minihan and Querio, 1973). Clearly, by varying the positions of the blanket strings and wash tubing and switching injection and return points, new cavern geometries were created that facilitated new uses of the dome.

CAVERN FAILURES

At least 10 solution caverns in Texas salt domes have failed. Failure is here defined as the loss of integrity of an individual cavern. Storage caverns (in contrast to brine caverns) have also failed in salt domes in Louisiana and Mississippi (Science Applications, Inc., 1977). The consequences of failure of a storage cavern are much greater than failure of a brine production cavern because of the value of the product that is lost and the cost of abatement procedures. Brine caverns show a much greater failure rate than do storage caverns. However, many brine caverns have been converted to storage caverns. Thus, any consideration of the stability of storage caverns must include brine caverns as well.

Three types of known cavern failures in Texas include (1) loss of stored products, (2) surface collapse, and (3) cavern coalescence. Table 1 lists cavern failures, possible mechanisms, and consequences.

There are approximately 254 caverns in Texas salt domes. On the basis of failure of 10 modern caverns (post-1946), the probability (p) of failure of a given cavern is approximately 4 percent (p=0.039). Statistics based on the years of cavern operation also yield indications of the useful life of a cavern. Railroad Commission of Texas permits indicate that the 254 Texas caverns have a cumulative operational history of 4,717 cavern-years. With 10 failures, the average operational life of an individual cavern is 472 years.

Two cavern failures in Texas salt domes resulted in catastrophic loss of liquid petroleum gas (LPG) at Barbers Hill salt dome in 1980 and at Blue Ridge salt dome in 1974. The failure of a storage cavern at Barbers Hill salt dome released LPG into subsurface formations below the

Table 1. List of salt domes with cavern failures, mechanisms, and consequences.

Failure mechanism	Dome	Storage cavern	Brine-well cavern	Rock-salt mine	Comments
Closure	Eminence salt dome, Mississippi	Natural gas storage cavern			Eminence salt dome--very deep cavern, depth 5,700 to 6,700 ft; cavern closure up to 40 percent in first year; cavern bottom rose 120 ft; closure related to rapid pressure declines used to produce natural gas (i.e., cavern is operated "dry" without brine).
			No data--creep closure probably common		
				Minor problem with creep-related closure and creep rupture of walls and roof	
Loss of integrity	Barbers Hill salt dome, Texas	LPG storage cavern			Barbers Hill salt dome--catastrophic loss of LPG in 1980; LPG lost to subsurface formations, and at surface over dome; town of Mount Belvieu evacuated; problem inferred to be casing seat failure.
	Blue Ridge salt dome, Texas	LPG storage cavern			Blue Ridge salt dome--catastrophic loss of LPG in 1974; LPG lost to subsurface formations and at surface over dome; minor flash fire--explosion injured 4 workmen during utility construction; RRC ordered cavern plugged and abandoned.
			Common		
				Not applicable	

Table 1. List of salt domes with cavern failures, mechanisms, and consequences (cont.).

Coalescence	Pierce Junction salt dome, Texas	5 LPG storage caverns comprise 2 multicavern systems			Pierce Junction salt dome--timing of coalescence is not known; caverns previously were brine producers; caverns currently used for LPG storage.
	Bayou Choctaw salt dome, Louisiana		3 brine caverns coalesced		Caverns abandoned.
	Sulfur Mines salt dome, Louisiana		3 brine caverns coalesced		Caverns abandoned.
				Not applicable	
Surface collapse	Palestine salt dome, Texas		16 collapse structures at surface over dome		Historic brine-well operations from 1904-1937 resulted in very common surface collapse over old brine wells; 3 collapse structures formed since 1937.
	Grand Saline salt dome, Texas		1 collapse structure		Collapse occurred in 1976 over probable brine well.
	Blue Ridge salt dome, Texas		1 collapse structure		Collapse occurred in 1949 at brine well that formerly was a rock-salt mine.
	Bayou Choctaw salt dome, Louisiana		1 collapse structure		Collapse occurred in 1954 over brine well; water-filled sinkhole.
	Jefferson Island salt dome, Louisiana			Major disaster--mine flooded and abandoned	Oil-drilling rig probably breached mine opening; Lake Peigneur flooded into mine; disaster occurred 1980.

Table 1. List of salt domes with cavern failures, mechanisms, and consequences (cont.).

	Belle Island salt dome, Louisiana	Major disaster--mine flooded and abandoned	Water leak around mine shaft resulted in surface collapse in 1973.
Other	Winnfield salt dome, Louisiana	Major disaster--mine flooded and abandoned	Water leak issuing from mine wall flooded mine in 1965; water sand at cap-rock-salt-stock interface is inferred source of water.

city of Mount Belvieu (Underground Resource Management, 1982), causing evacuation of the residents. The Warren Petroleum Co. assumed financial responsibility for the abatement and monitoring program. Over 400 shallow relief wells were drilled to vent the escaped LPG (Underground Resource Management, 1982). Although the Warren Petroleum Co. has not made public the cause of the leak, a failure in the casing seat is suspected. The defective cavern has since been returned to service after remedial work on the casing resulted in a successful integrity test.

Failure of a storage cavern at Blue Ridge salt dome also resulted in the escape of LPG. Four workmen installing a utility conduit were injured in an explosion and flash fire suspected to have been caused by leaking LPG. At that time, the cavern was owned by Amoco and used by Coastal States to store LPG. In 1975 the Railroad Commission of Texas issued special order 03-64,673, rescinding the authority to store LPG in that cavern (RRC Authority Number 03-34,658). That cavern is now abandoned. Figure 8 is a cross section of the upper part of Blue Ridge salt dome showing dome shape and the location and geometry of the salt mine and cavern.

Failure of brine caverns at Grand Saline, Blue Ridge, and Palestine salt domes have caused localized surface collapse. Sixteen collapse structures mar the surface above Palestine salt dome and are attributed to historic brine production (Fogg and Kreitler, 1980). The brine caverns that collapsed at Palestine salt dome have not been included in the statistics of cavern failures because those caverns were constructed with no regard for their stability, and construction techniques pre-date modern practices beginning in the late 1940's and 1950's.

From 1904 to 1937, Palestine Salt and Coal Company used brine wells to produce salt from Palestine salt dome. The collapse structures form circular water-filled depressions with diameters of 27 to 105 ft and depths of 2 to 15 ft (Fogg and Kreitler, 1980). Each collapse structure is assumed to mark the location of a former brine well. Powers (1926) described the brine operation as follows: Wells were drilled 100 to 250 ft into salt. Water from the "water sand" between the cap rock and the salt stock flowed into the well, dissolved the salt, and brine

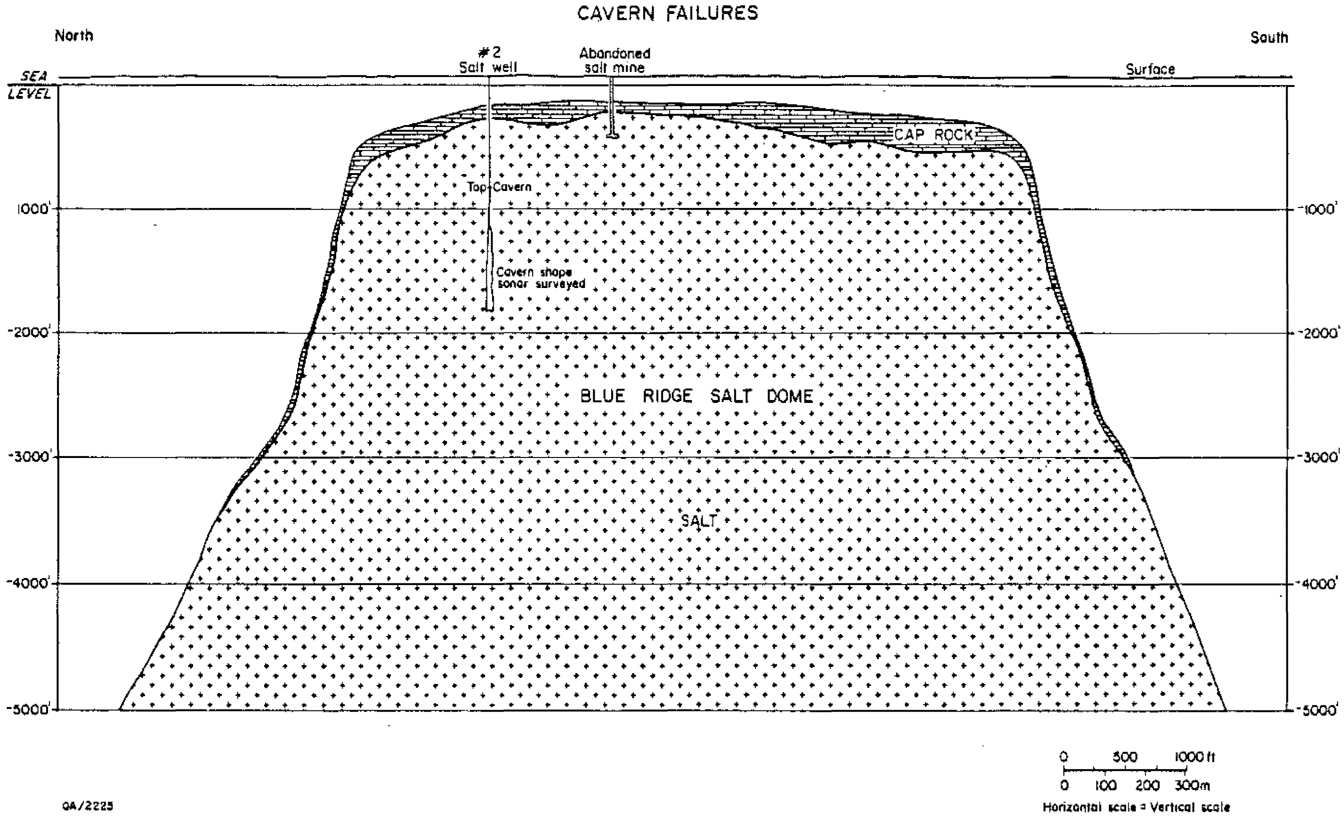


Figure 8. Cross section of Blue Ridge salt dome showing geometry of salt mine and storage cavern that failed.

was then displaced by compressed air. The cap rock was undermined by the large brine cavern below it. The cap rock eventually collapsed forming a large sinkhole (Hopkins, 1917). A new brine well was simply offset a safe distance. Although brining operations ceased in 1937, three collapsed structures have formed since 1978 (Fogg and Kreitler, 1980).

In 1975, a circular collapse structure formed at Grand Saline, Texas. Although the exact origin in unknown, the collapse structure is inferred to overlie an old brine production well (Martinez and others, 1976; Science Applications, Inc., 1977). In 1949, a spectacular collapse occurred at Blue Ridge salt dome (Science Applications, Inc., 1977). An old rock-salt mine operated by Gulf Salt Co. had been converted into a brine production well. Without warning, the main building and well assembly collapsed around the original mine shaft and well bore. The brine cavern is inferred to have dissolved to the cap rock. A "water sand" composed of loose anhydrite grains at the cap-rock - salt-stock interface may have contributed water to help undermine the cap rock. The cap rock and overlying strata then collapsed into the brine cavity after removal of too much underlying support.

Railroad Commission of Texas records (Authority Number 03-60,093) indicate that five former brine caverns at Pierce Junction salt dome have coalesced to form two independent caverns. These caverns currently are used as storage caverns. When the caverns coalesced is unknown. Although five individual caverns have coalesced, integrity within each of the two multicavern systems has been maintained.

Conspicuous examples of cavern failures and surface collapses have been reported in Louisiana and Mississippi (Science Applications, Inc., 1977; Griswold, 1981; Fenix and Scisson, 1976b). One brine cavern has collapsed and formed a water-filled sinkhole at the surface over Bayou Choctaw salt dome (Science Applications, Inc., 1977). Two other caverns at Bayou Choctaw are abandoned because the caverns have dissolved to the cap rock. Three additional caverns, separated by at least 200 ft of pillar salt in plan, are now hydraulically connected (Griswold, 1981; Fenix and Scisson, 1976b). Rock-salt mines have also failed by flooding at Winnfield, Avery Island, and Jefferson Island salt domes. A jet of water issuing from a mine wall caused the flooding and abandonment of Winnfield mine in 1965 (Martinez and others, 1976).

The Jefferson Island disaster of 1980 is an instructive example of the consequences of possible inadvertent breach into a mined opening in salt (Autin, 1984). Diamond Salt Company was operating a rock salt mine at Jefferson Island salt dome when a Texaco oil exploration rig (spudded from a barge in Lake Peigneur) was searching for flank oil production in sandstone pinch-outs near the salt stock. The chain of events that led to the draining of Lake Peigneur into the salt mine is paraphrased here on the basis of a description of the event by Autin (1984).

> During the morning of the disaster, the Texaco drill bit became stuck in the hole at a depth of 1,245 ft, and mud circulation was lost. Efforts to free the bit and reestablish mud circulation failed. The drill rig began to tilt and rapidly overturned. Within 3 hours the drill rig, the support barge, and Lake Peigneur all disappeared down into a rapidly developing sinkhole. At approximately the same time, the 1,300-ft-level of the mine was flooded. All mine personnel were evacuated safely.

Mechanisms of Cavern Failure

Most cavern failures result from integrity loss at the casing seat. Cavern coalescence is another common mode of cavern failure, especially with brine caverns. The casing system is vulnerable at zones of lost circulation during cavern construction and during product cycling. Clearly, the cemented zone, production tubing, and casing strings are the weak link in any cavern system because many problems that begin there can quickly evolve into severe problems, including eventual cavern collapse.

Blanket control protects salt from being dissolved behind the casing seat. This dissolution, if left unchecked, can lead to loss of the casing seat, loss of tubing, and eventual cavern collapse.

Another point of attack on the integrity of a cavern system is within the cap rock. The cap rocks of many salt domes are characterized by lost-circulation zones. These zones compose vuggy areas with open caverns up to tens of feet in vertical extent. The vuggy zones are concentrated in the transition and anhydrite zones of the cap rock. Many cap rocks also contain a zone of loose anhydrite sand at the cap-rock - salt-stock interface. Presence of this zone at the cap-rock - salt-stock interface is critical because it indicates active salt dissolution with the accumulation of loose anhydrite sand as a residuum and the presence of an active brine-circulation system.

Lost-circulation zones weaken the integrity of any cavern system in two ways. During drilling, the difficulty of maintaining mud circulation forces the use of many circulation-control measures. Drilling may continue "blind," that is without mud returns, until salt is encountered. Then a temporary liner is set through the lost-circulation zone. Alternatively, cement may be pumped down the tubing to plug the lost-circulation zone. The cement is then drilled out, and if circulation is lost again the process is repeated until circulation is reestablished.

Even with modern drilling techniques, lost-circulation zones can cause problems severe enough to force hole abandonment. In 1974, a hole was lost while drilling a gas-storage well at Bethel salt dome (RRC Authority Number 06-05,840). Circulation was lost within the cap rock and was not reestablished even though 1,300 sacks and 80 yd^3 of cement were added. Ground subsidence then caused the rig to tilt, and the hole was abandoned.

Vuggy zones in cap rock are areas of natural cap-rock and salt dissolution. Therefore cement-formation bonds are vulnerable to attack by natural dissolution. The natural brine-circulation system also may attack the cement itself and reduce its useful life. The brine is very corrosive, and its long-term effects on cements and casings are inadequately known.

Van Fossan (1979) has listed various mechanisms whereby product loss may occur through loss of cavern integrity.

SALT-DOME RESOURCES

Valuable natural resources are associated with the salt stock, cap rock, and favorable geological structures and reservoirs associated with the growth and emplacement of the dome. Dome salt is an important chemical feedstock. Salt is extracted both by underground mines and by solution-brine wells. Storage space, available in cavities formed by brining operations, was initially an unrecognized resource, but now many cavities in domes are created exclusively for storage space and the brine is discarded. The cap rock is quarried as a source of road metal, and cap-rock sulfur is mined by the Frasch process. Petroleum in salt-dome-related traps is by far the most valuable salt-dome-related resource.

The long-term trends for petroleum and sulfur production are in decline owing to depleted reserves and few new discoveries. Salt production is stable to slightly growing, but production is constrained by demand. Demand for storage space is growing rapidly especially with the requirements of the Strategic Petroleum Reserve (Fenix and Scisson, 1976b, c, d; U.S. Federal Energy Administration, 1977a, b, c; Hart and others, 1981). Conceivably, the storage space within a dome may be the most valuable salt-dome-related resource.

Salt-Dome Storage

Texas is the national leader in storage capacity for hydrocarbons in salt domes. In 1983, Texas salt domes housed 47 percent of the nation's total stored light hydrocarbons (liquified petroleum gas, or LPG). Texas salt domes are also becoming a major repository for the Strategic Petroleum Reserve (SPR) (fig. 9). Crude oil for the SPR is currently being stored at Bryan Mound salt dome, and additional storage capacity is under construction at Big Hill salt dome (Hart and others, 1981). Storage of toxic-chemical waste in solution-mined caverns is also being considered at Boling salt dome (United Resource Recovery, 1983).

The most common hydrocarbons stored in Texas salt domes are light hydrocarbons, natural gas, and crude oil. Rarely fuel oil may be stored near a plant to generate power during a gas curtailment. Light hydrocarbons, such as ethane, propane, butane, and isobutane, comprise the bulk of stored products. They are gases under atmospheric pressure and room temperature, but are liquids under the slight confining pressure. Light hydrocarbons were the first products stored in salt-dome caverns because the demand for the products was strongly cyclical with the seasons. In 1983, approximately 219,464,000 barrels of light hydrocarbons were stored in Texas

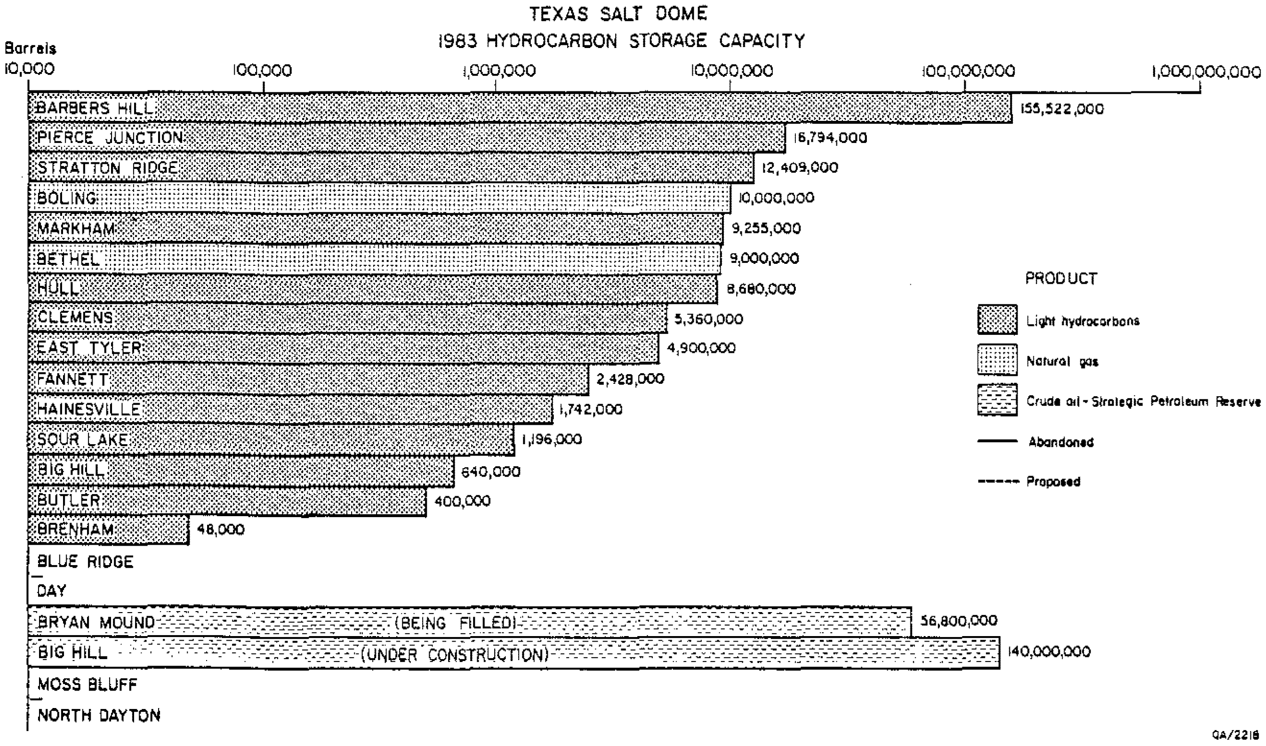


Figure 9. Histogram of 1983 storage capacity in Texas salt domes and proposed Strategic Petroleum Reserve caverns.

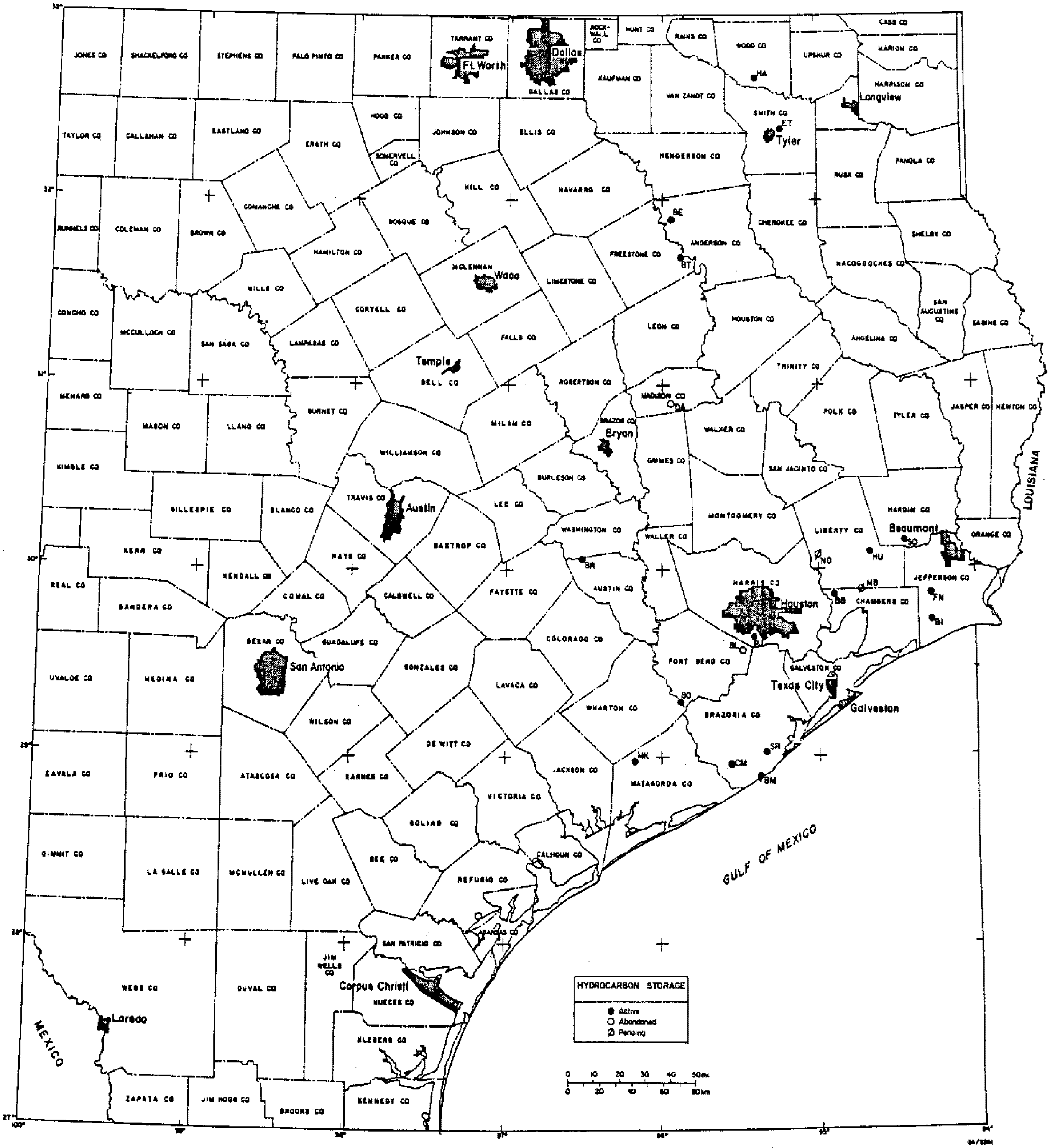
salt domes (Gas Processors Association, 1983). Of the total storage capacity in Texas for light hydrocarbons, 77 percent is in salt domes, and the remainder is in bedded salt in West Texas.

Whether a dome is a good candidate for storage is typically determined by its location near industrial suppliers and pipelines. Geologic characterization of candidate domes was done primarily to obtain site information for casing details. Geologic deficiencies such as small dome size and cap-rock-lost-circulation zones were viewed as minor engineering problems to be dealt with and not as site selection criteria. Figure 10 shows domes with active, abandoned, and pending storage facilities. Table 2 is a list of pertinent information on the domes with a history of hydrocarbon storage.

Barbers Hill salt dome houses the greatest concentration of storage facilities in the world. Nine separate companies store light hydrocarbons in the dome. The 1983 capacity for light hydrocarbons storage at Barbers Hill salt dome was 155,522,000 barrels (Gas Processors Association, 1983). There are approximately 137 caverns in Barbers Hill salt dome.

Congress in 1975 passed the Energy Policy and Conservation Act, which established the Strategic Petroleum Reserve to protect the nation against future oil supply interruptions. The size of the reserve was expanded to 1 billion barrels by President Carter's National Energy Plan. Crude oil for the SPR is currently being stored in preexisting brine caverns at Bryan Mound salt dome, and new caverns are being constructed at Big Hill salt dome.

Present capacity at Bryan Mound salt dome is 56.8 million barrels in four caverns originally mined for brine. Figures 11 and 12 are cross sections of the dome showing the geometries and locations of the caverns. Their irregular shape is typical of caverns originally mined for brine. Projections include construction of an additional 120 million barrels of storage space at Bryan Mound salt dome. Cavern construction for the SPR is underway at Big Hill salt dome. Fourteen caverns will be constructed, each with a capacity of 10 million barrels. Figures 13 and 14 are cross sections showing the proposed geometries and locations of the SPR caverns at Big Hill salt dome and the location and geometry of a storage cavern used by Union Oil Co. to store light hydrocarbons.



HYDROCARBON STORAGE IN SALT DOMES OF TEXAS

Figure 10. Map of salt domes showing active, abandoned, and pending storage facilities.

(continued)

Figure 10 (cont.).

Code	Dome Name	County
BB	Barbers Hill	Chambers
BE	Bethel	Anderson
BI	Big Hill	Jefferson
BL	Blue Ridge	Fort Bend
BO	Boling	Wharton/Fort Bend
BR	Brenham	Austin/Washington
BM	Bryan Mound	Brazoria
BT	Butler	Freestone
CM	Clemens	Brazoria
DA	Day	Madison
ET	East Tyler	Smith
FN	Fannett	Jefferson
HA	Hainesville	Wood
HU	Hull	Liberty
MK	Markham	Matagorda
MB	Moss Bluff	Chambers/Liberty
ND	North Dayton	Liberty
PJ	Pierce Junction	Harris
SO	Sour Lake	Hardin
SR	Stratton Ridge	Brazoria

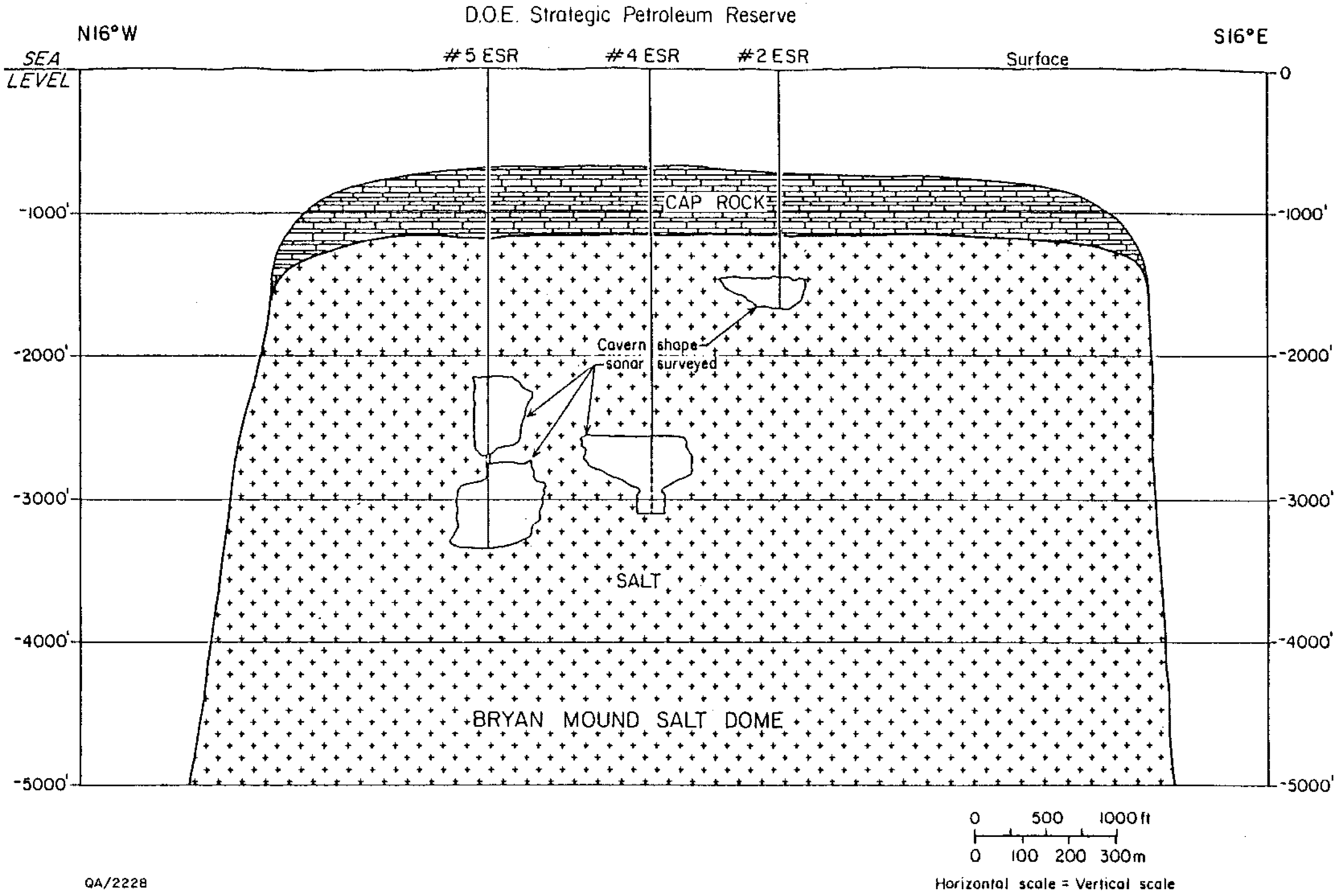


Figure 11. Cross section of Bryan Mound salt dome (north-south) showing geometry of present Strategic Petroleum Reserve caverns.

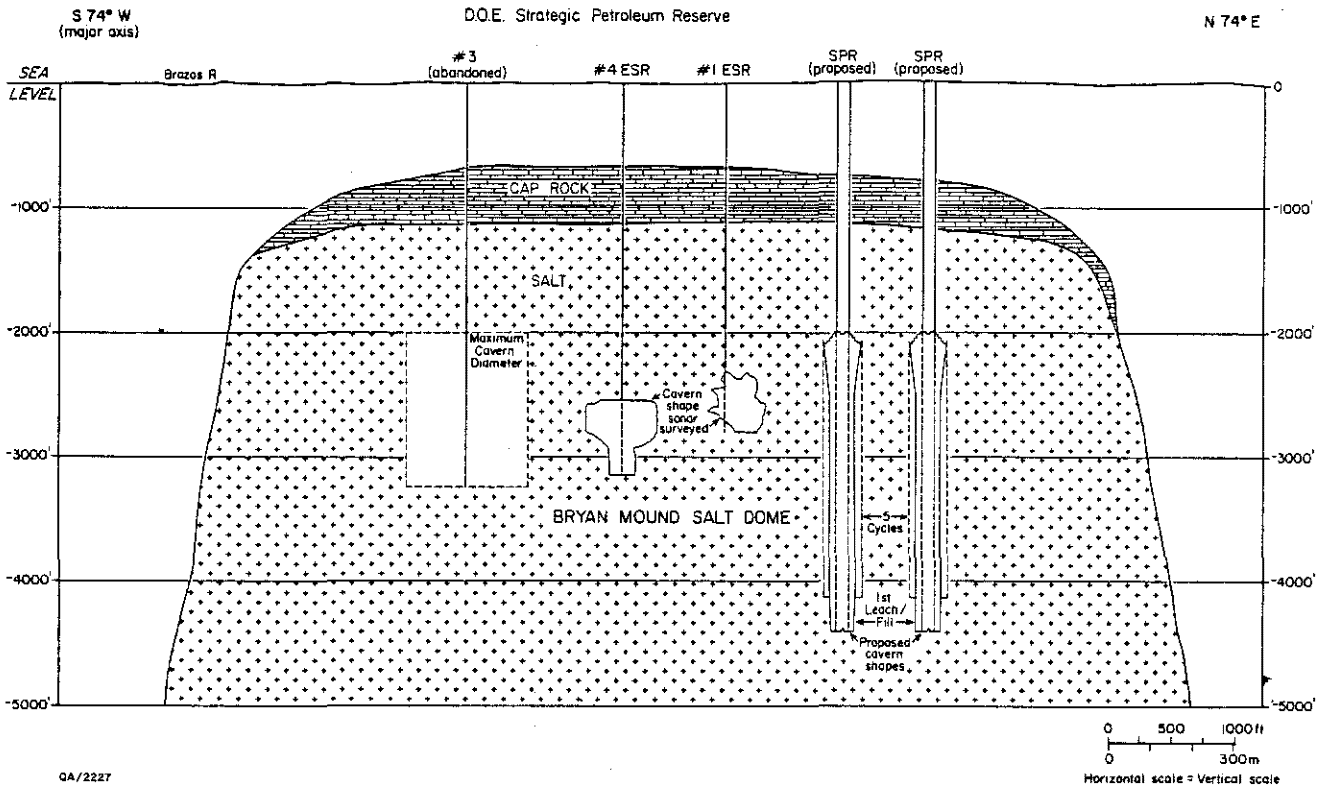


Figure 12. Cross section of Bryan Mound salt dome (east-west) showing geometry of present and proposed Strategic Petroleum Reserve caverns.

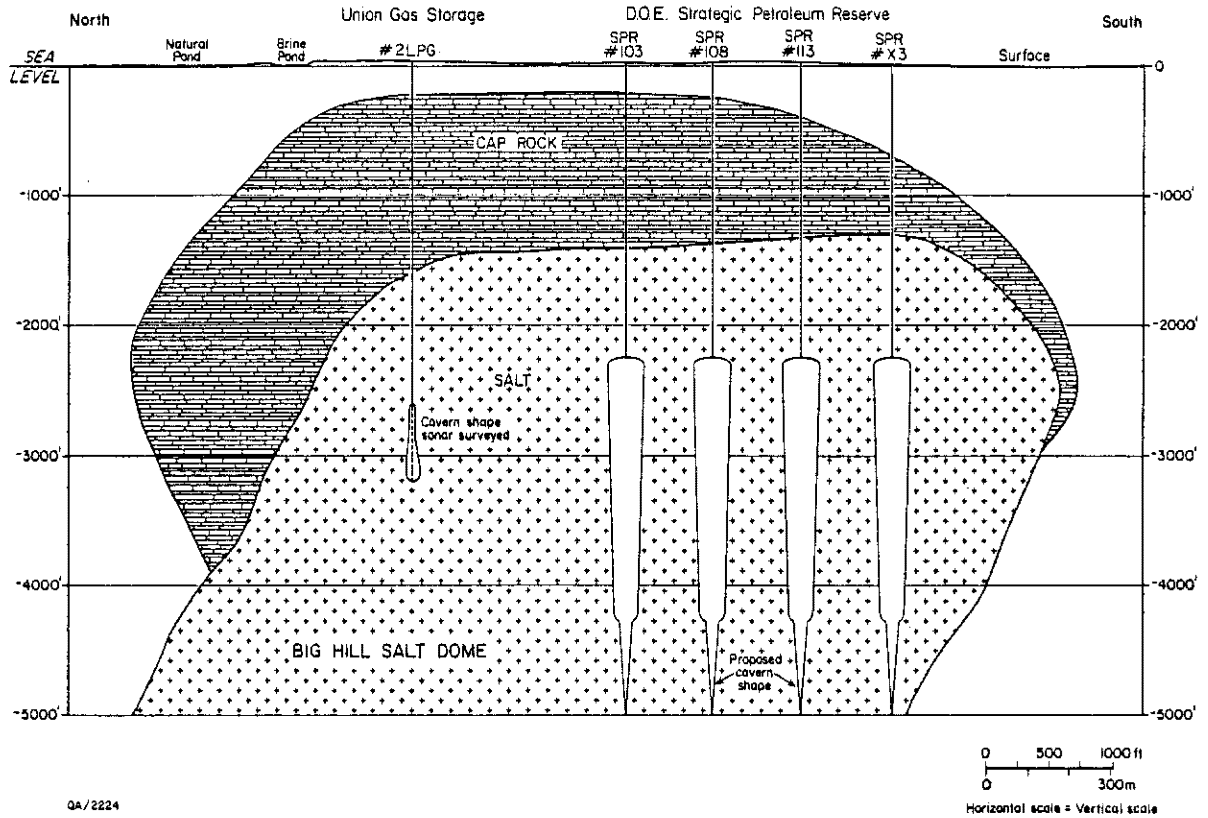


Figure 13. Cross section of Big Hill salt dome (north-south) showing geometry of proposed Strategic Petroleum Reserve caverns and Union Oil Co. storage cavern

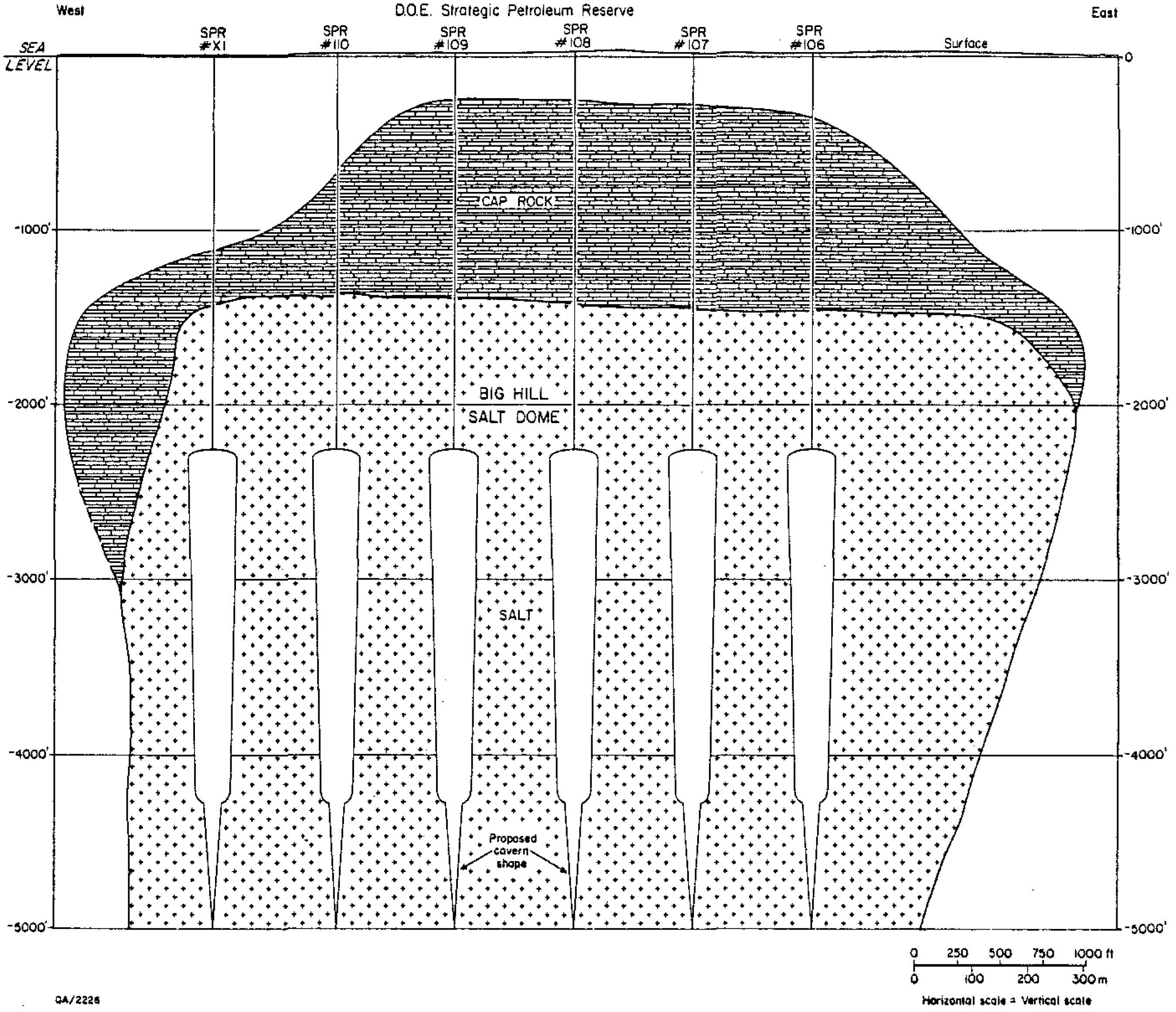


Figure 14. Cross section of Big Hill salt dome (east-west) showing geometry of proposed Strategic Petroleum Reserve caverns.

Table 2. List of salt domes with storage, operating company, Railroad Commission of Texas applicant, number of caverns, capacity, and product stored.

NAME OF SALT DOME	CURRENT OPERATOR OF STORAGE FACILITIES	ORIGINAL APPLICANT	NUMBER OF CAVERNS	STORAGE CAPACITY IN BARRELS	PRODUCT STORED
BARBERS HILL	TEXAS EASTERN	TEXAS NATURAL GASOLINE	27	30978000	LIGHT HYDROCARBONS
BARBERS HILL	DIAMOND SHAMROCK	DIAMOND SHAMROCK	10	34700000	LIGHT HYDROCARBONS
BARBERS HILL	WARREN	WARREN	29	45032000	LIGHT HYDROCARBONS
BARBERS HILL	X-RAL	X-RAL	16	22065000	LIGHT HYDROCARBONS
BARBERS HILL	TENNECO	TENNESSEE GAS TRANSMISSION	18	9822000	LIGHT HYDROCARBONS
BARBERS HILL	EXXON	HUMBLE OIL AND REFINING	7	5710000	LIGHT HYDROCARBONS
BARBERS HILL	ENTERPRISE	ENTERPRISE	13	13300000	LIGHT HYDROCARBONS
BARBERS HILL	CONOCO	CONOCO	3	1200000	LIGHT HYDROCARBONS
BARBERS HILL	ARCO	TEXAS BUTADIENE AND CHEMICAL CORP.	14	4914000	LIGHT HYDROCARBONS
BETHEL DOME	BI-STONE FUEL	BI-STONE FUEL	3	9000000	NATURAL GAS
BIG HILL	UNION	PURE OIL CO..	2	640000	LIGHT HYDROCARBONS
BIG HILL	DEPARTMENT OF ENERGY	DEPARTMENT OF ENERGY	14	0	CRUDE OIL
BLUE RIDGE	ABANDONED	TULOMA-AMOCO	3	0	LIGHT HYDROCARBONS
BOLING	VALERO	LO-VACA GATERING CO.	4	10000000	NATURAL GAS
BRENHAM	SEMINOLE PIPELINE CO.	SEMINOLE PIPELINE CO.	1	48000	LIGHT HYDROCARBONS
BRYAN MOUND	DEPARTMENT OF ENERGY	DOW CHEMICAL	4	56300000	CRUDE OIL
BRYAN MOUND	DEPARTMENT OF ENERGY	DEPARTMENT OF ENERGY	12	0	CRUDE OIL
BUTLER DOME	U.P.G.	FREESTONE UNDERGROUND STOR.	3	490000	LIGHT HYDROCARBONS
CLEMENS	PHILLIPS PETROLEUM	PHILLIPS PETROLEUM	17	5360000	LIGHT HYDROCARBONS
DAY	ABANDONED	PURE OIL	1	0	LIGHT HYDROCARBONS
EAST TYLER	TEXAS EASTMAN	WARREN PETROLEUM	10	4900000	LIGHT HYDROCARBONS
FANNETT	WARREN PETROLEUM	GULF OIL	5	2428000	LIGHT HYDROCARBONS
HAINESVILLE	BUTANE SUPPLIES	ENTERPRISE PETROLEUM GAS CORP.	3	1742000	LIGHT HYDROCARBONS
HULL	MOBIL	MAGNOLIA PETROLEUM CORP.	11	3630000	LIGHT HYDROCARBONS
MARKHAM	TEXAS BRINE	TEXAS BRINE	9	1800000	LIGHT HYDROCARBONS
MARKHAM	SEADRIFT PIPELINE	SEADRIFT PIPELINE	6	7455000	LIGHT HYDROCARBONS
MOSS BLUFF	MOSS BLUFF STORAGE VENTURE	MOSS BLUFF STORAGE VENTURE	5	0	LIGHT HYDROCARBONS
NORTH DAYTON	ENERGY STORAGE TERMINAL INC.	ENERGY STORAGE TERMINAL INC.	2	0	LIGHT HYDROCARBONS
PIERCE JUNCTION	ENTERPRISE	WANDA PETROLEUM AND ELLIS TRANSPORT	10	4060000	LIGHT HYDROCARBONS
PIERCE JUNCTION	COASTAL STATES CRUDE GATHERING	COASTAL STATES CRUDE GATHERING	7	12734000	LIGHT HYDROCARBONS
SOUR LAKE	TEXACO	THE TEXAS CO.	8	1196000	LIGHT HYDROCARBONS
STRATTON RIDGE	SEMINOLE PIPELINE	SEMINOLE PIPELINE	4	152000	LIGHT HYDROCARBONS
STRATTON RIDGE	AMOCO	FENIX AND SCISSON	7	5257000	LIGHT HYDROCARBONS
STRATTON RIDGE	DOW	DOW	22	7000000	LIGHT HYDROCARBONS

```
LIST/TITLE L(18)NAME OF SALT DOME,B(1),R(30)CURRENT OPERATOR OF          +
 LIST/TITLE L(18)NAME OF SALT DOME,B(1),R(30)CURRENT OPERATOR OF          +

STORAGE FACILITIES           ,B(1),R(36)ORIGINAL APPLICANT             ,B(1),
 STORAGE FACILITIES           ,B(1),R(36)ORIGINAL APPLICANT             ,B(1),

R(7)NUMBER +OF  +CAVERNS,B(1),R(10)STORAGE  +CAPACITY +IN BARRELS,B(3),
 R(7)NUMBER +OF  +CAVERNS,B(1),R(10)STORAGE  +CAPACITY +IN BARRELS,B(3),

R(18)PRODUCT STORED   /C1,C226,C227,C228,C229,C236,OB LOW C1 WH C226 EXISTS:
 R(18)PRODUCT STORED   /C1,C226,C227,C228,C229,C236,OB LOW C1 WH C226 EXISTS:
```

Two domes in Texas--Bethel and Boling salt domes--store natural gas. Natural gas is significantly different from other products stored in salt domes because of its high pressures during storage and rapid pressure declines during production. At Bethel salt dome, natural gas is stored in caverns under a cavern-storage pressure of 3,500 pounds per square inch gauged (psig). The depth of the cavern is between 4,300 and 4,800 ft.

Boling salt dome is a good example of a salt dome with multiple use of the available resources (fig. 15). Oil is produced from oil fields over the cap rock, within the cap rock, and from flank reservoirs. Boling salt dome has been the world's largest single source of sulfur. Valero Gas Co. has recently expanded its natural-gas storage facility at Boling to four caverns.

A cross section of Boling salt dome shows the geometry of the upper part of the salt dome illustrating cap rock, sulfur production, the location and size of two Valero storage caverns, and the proposed locations of a field of toxic-chemical waste caverns by United Resource Recovery, Inc. (fig. 16). Several aspects are important. The Valero caverns are located about 10,000 ft from the Texas Gulf Sulfur producing zone. Despite the 10,000 ft of separation, however, during construction of the Valero storage cavern no. 3, problems occurred that apparently are directly related to sulfur production. The well encountered, within the cap rock, a zone bearing high-pressure "mine waters" that caused the well to "kick." Texas Gulf Sulfur personnel were needed to cap the well. Although there is a large separation between the sulfur-mining operations and the active and proposed storage operations, the impact of the sulfur-mining operation extends far across the salt dome. Additionally, the proposed toxic-waste caverns are located near the periphery of the dome. Characteristically the internal constituents of salt domes--anhydrite and other country rock--increase toward the margins of salt stocks.

Salt Resources

Texas salt domes constitute an immense reservoir of salt that has risen through gravity deformation from great depths to lie within man's reach. Salt is a major industrial commodity that is used as a chemical feedstock, for road deicing, and for human and animal consumption.

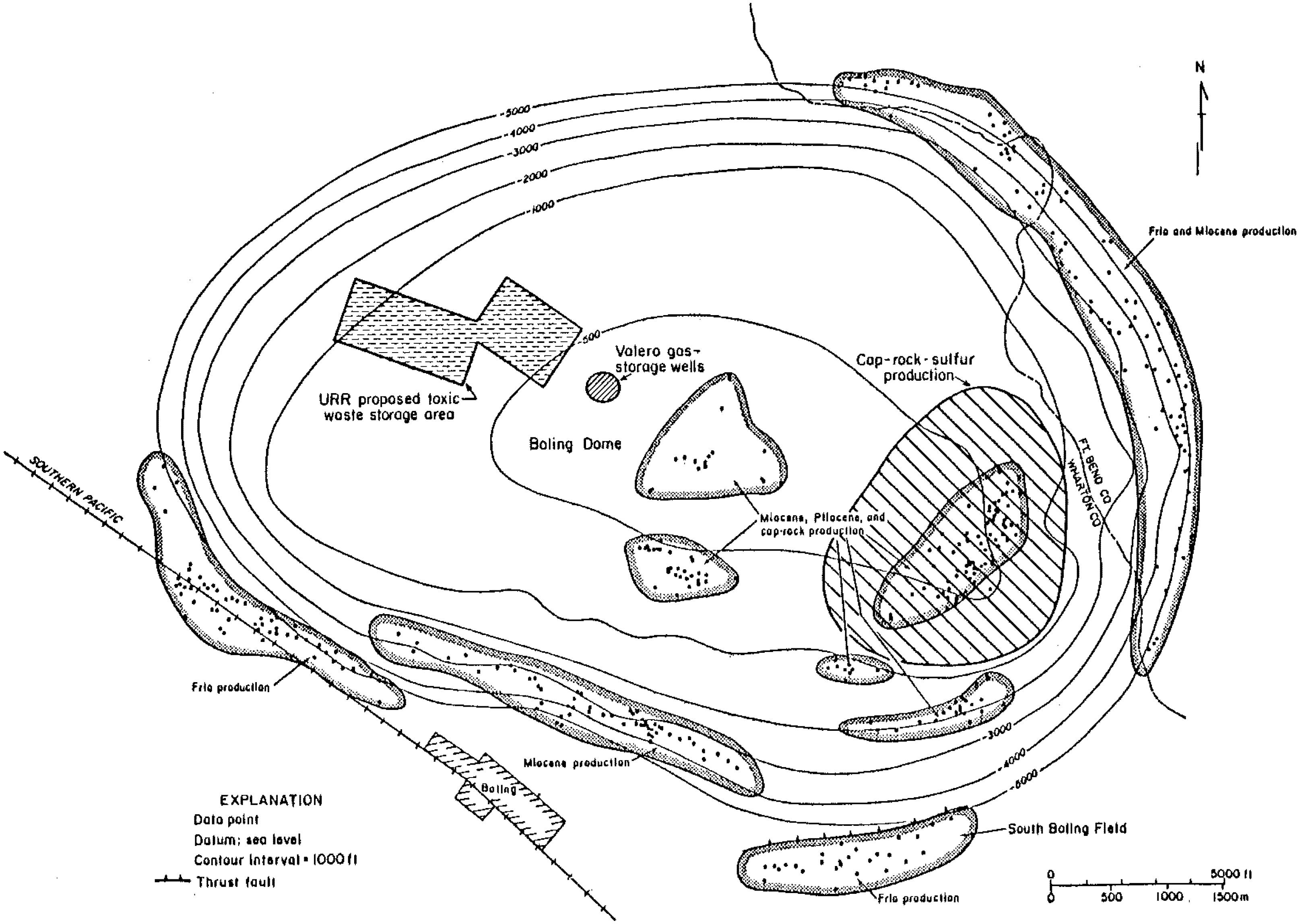


Figure 15. Map of Boling salt dome showing locations of oil fields, sulfur production, Valero Gas Co. gas-storage caverns, and United Resource Recovery, Inc., lease area (modified from Galloway and others, 1983).

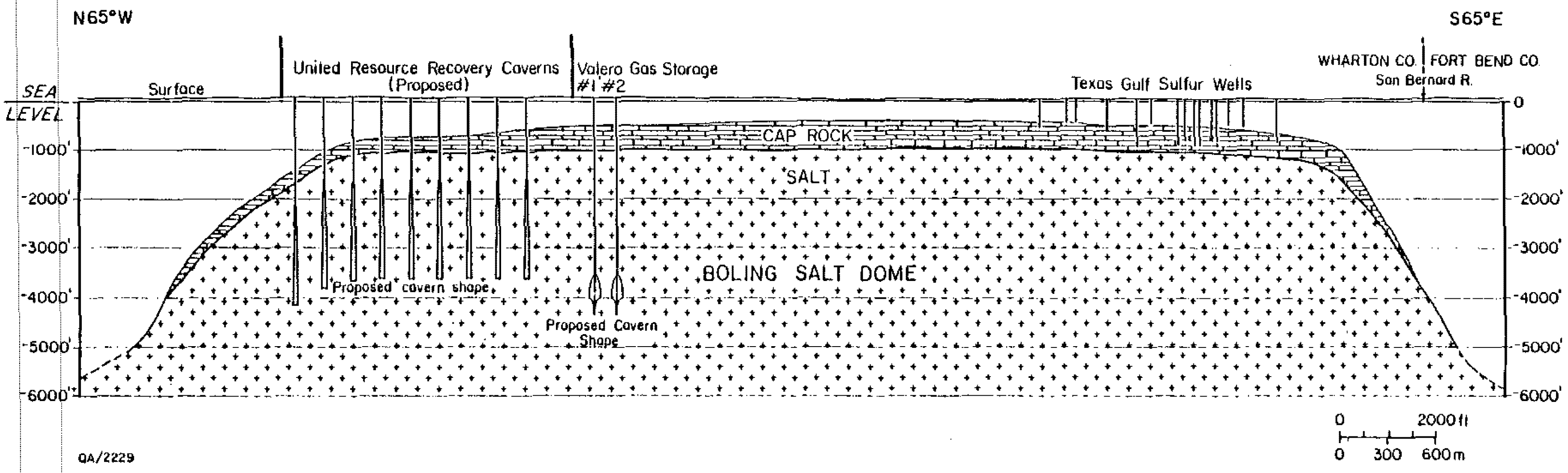


Figure 16. Cross section of Boling salt dome (east-west) showing location of sulfur production, geometry of Valero Gas Co. gas storage caverns, and proposed location and geometry of United Resource Recovery, Inc., waste-storage caverns.

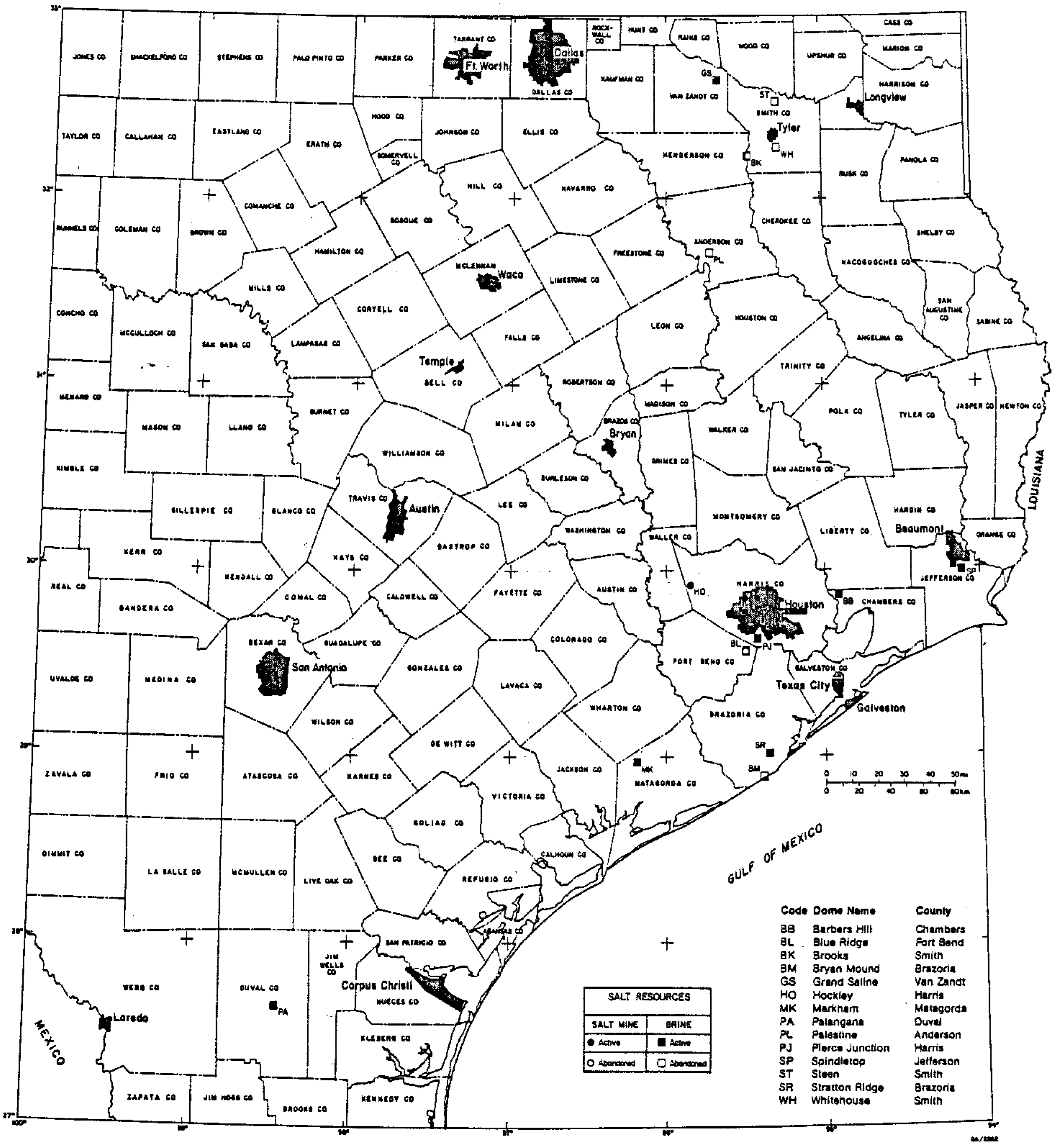
Salt is produced from Texas salt domes by conventional underground mining and by solution-brine wells. Estimates indicate that salt reserves will be adequate for 381 years (Griswold, 1981) to 26,000 (Hawkins and Jirik, 1966). The smaller figure is more reasonable on the basis of less recoverable salt at shallower depth, growth in salt demand, and preemption of some domes by storage requirements. Figure 17 shows those domes with active rock-salt mines and brine operations. Table 3 lists pertinent information on the operations at those domes.

Rock-Salt Mine

Currently, two active underground salt mines exist in Texas salt domes, the Kleer mine at Grand Saline salt dome and the United Salt mine at Hockley salt dome. According to Science Applications, Inc. (1977), Blue Ridge salt dome also housed a rock-salt mine that was later converted to a solution-brine mine. The well and mine opening collapsed in 1949. Both the Hockley and the Grand Saline salt mines are relatively small, and the operations are constrained by demand. Production is from one level in each of the mines. The primary use for the mined granulated and compressed rock salt is as a dietary supplement for animals (that is, salt lick).

Solution-Brine Well

Solution-brine wells for the production of chemical feedstock are active at seven salt domes in Texas including Barbers Hill, Blue Ridge, Markham, Palangana, Pierce Junction, Spindletop, and Stratton Ridge salt domes. Historically, the Indians first used natural brines from East Texas salt domes as a source of salt and brine for tanning hides. In the past, salt caverns, which were created as the brine was produced, constituted an unrecognized resource. Many brine caverns have been converted to store light hydrocarbons. Currently, the DOE is using four large storage caverns in Bryan Mound salt dome, created by Dow Chemical Co. during past brining operations, for crude-oil storage in the SPR. The present capacity of the former brine caverns at Bryan Mound is 56.8 million barrels.



Code	Dome Name	County
BB	Barbers Hill	Chambers
BL	Blue Ridge	Fort Bend
BK	Brooks	Smith
BM	Bryan Mound	Brazoria
GS	Grand Saline	Van Zandt
HO	Hockley	Harris
MK	Markham	Matagorda
PA	Palangana	Duval
PL	Palestine	Anderson
PJ	Pierce Junction	Harris
SP	Spindletop	Jefferson
ST	Steen	Smith
SR	Stratton Ridge	Brazoria
WH	Whitehouse	Smith

SALT RESOURCES FROM SALT DOMES OF TEXAS

Figure 17. Map of salt domes showing active rock-salt mines and solution-brine wells.

Table 3. List of salt domes with salt production, method, status, company, and history.

```
 NAME OF SALT DOME      MINERAL     STATUS OF    REPORTING ORGANAZATION     NAME OF COMPANY     MINING HISTORY
                                    PRODUCTION     OR MINING METHOD
***
* BARBERS HILL         BRINE       ACTIVE       BRINE WELLS               DIAMOND SHAMROCK
* BLUE RIDGE           BRINE       ACTIVE       BRINE WELLS               UNITED SALT
* BLUE RIDGE           ROCK SALT   ABANDONED    SALT MINE                 UNITED SALT
* BROOKS DOME          BRINE       ABANDONED    L.S.U.-1976               UNKNOWN             1865
* BRYAN MOUND          BRINE       ABANDONED    BRINE WELLS               DOW CHEMICAL
* GRAND SALINE DOME    ROCK SALT   ACTIVE       SALT MINE                 MORTON SALT
* GRAND SALINE DOME    BRINE       ABANDONED    BRINE WELLS               MORTON SALT         1845
* HOCKLEY              ROCK SALT   ACTIVE       SALT MINE                 UNITED SALT         1929-PRESENT
* MARKHAM              BRINE       ACTIVE       BRINE WELLS               TEXAS BRINE CORP.
* PALANGANA DOME       BRINE       ACTIVE       BRINE WELLS               P.P.G.IND.INC.
* PALESTINE DOME       BRINE       ABANDONED    L.S.U.-1976               UNKNOWN             1865
* PIERCE JUNCTION      BRINE       ACTIVE       BRINE WELLS               TEXAS BRINE CORP.
* SPINDLETOP           BRINE       ACTIVE       BRINE WELLS               TEXAS BRINE CORP.
* STEEN DOME           BRINE       ABANDONED    L.S.U.-1976               UNKNOWN             1865
* STRATTON RIDGE       BRINE       ACTIVE       BRINE WELLS               DOW CHEMICAL
* WHITEHOUSE DOME      BRINE       ABANDONED    L.S.U.-1976               UNKNOWN
___
```

```
LIST/TITLE L(18)NAME OF SALT DOME,B(4),R(9)MINERAL  ,B(4),R(10)
 LIST/TITLE L(18)NAME OF SALT DOME,B(4),R(9)MINERAL  ,B(4),R(10)
___
STATUS OF  +PRODUCTION,B(4),R(22)REPORTING ORGANAZATION+
 STATUS OF  +PRODUCTION,B(4),R(22)REPORTING ORGANAZATION+
___
OR MINING METHOD     ,B(4),R(18)NAME OF COMPANY  ,B(4),R(14)MINING HISTORY/
 OR MINING METHOD     ,B(4),R(18)NAME OF COMPANY  ,B(4),R(14)MINING HISTORY/
___
C1,C199,C200,C201,C202,C203,OB LOW C1 WH C199 EQ ROCK SALT OR C199 EQ BRINE:
 C1,C199,C200,C201,C202,C203,OB LOW C1 WH C199 EQ ROCK SALT OR C199 EQ BRINE:
```

Petroleum Resources

Oil discovered in 1901 at Spindletop salt dome gave birth to the modern petrochemical industry. The petroleum production of many Gulf Coast salt domes is truly staggering. Cumulative production from the salt-dome-related oil reservoirs (those greater than 10 million barrels cumulative production) is 3.46 billion barrels (Galloway and others, 1983). Oil is not found in the salt stock but in surrounding strata. Intrusion of the salt diapir can form a wide range of structural and stratigraphic traps for petroleum. Highly productive zones around salt domes include cap rocks, dome flanks, and supradomal crests.

An oil play is an assemblage of geologically similar reservoirs exhibiting similar trapping mechanisms, reservoir rocks, and source rocks (Galloway and others, 1983). Four major oil plays are associated with Gulf Coast salt domes. They include cap rock, Yegua salt-dome flanks, Yegua deep-salt-dome crests, and Frio deep-salt-dome crests.

This discussion of petroleum resources associated with salt domes centers on diapirs in the highly productive Gulf Coast (Houston Salt Basin) of Texas. Shallow piercement oil fields will be discussed generally, and then specific examples of the major oil plays associated with salt domes will be discussed in turn. Much of this discussion is based on two sources: a recent publication by Galloway and others (1983), which has proved to be a valuable guide to oil in Texas, and a book by Halbouty (1979), which is the standard oil-related salt-dome text.

Shallow Salt-Dome Oil Fields

Shallow salt-dome fields were the first oil fields discovered in the Gulf Coast area. Many fields discovered 70 and 80 years ago are still producing. This productive longevity stems in part from diapirism and faulting, which segmented reservoirs thus creating a diverse range of traps at many different stratigraphic levels. The yearly oil production of Spindletop salt dome illustrates that production has been prolonged and periodically increased dramatically by discovery of new types of salt dome traps (fig. 18).

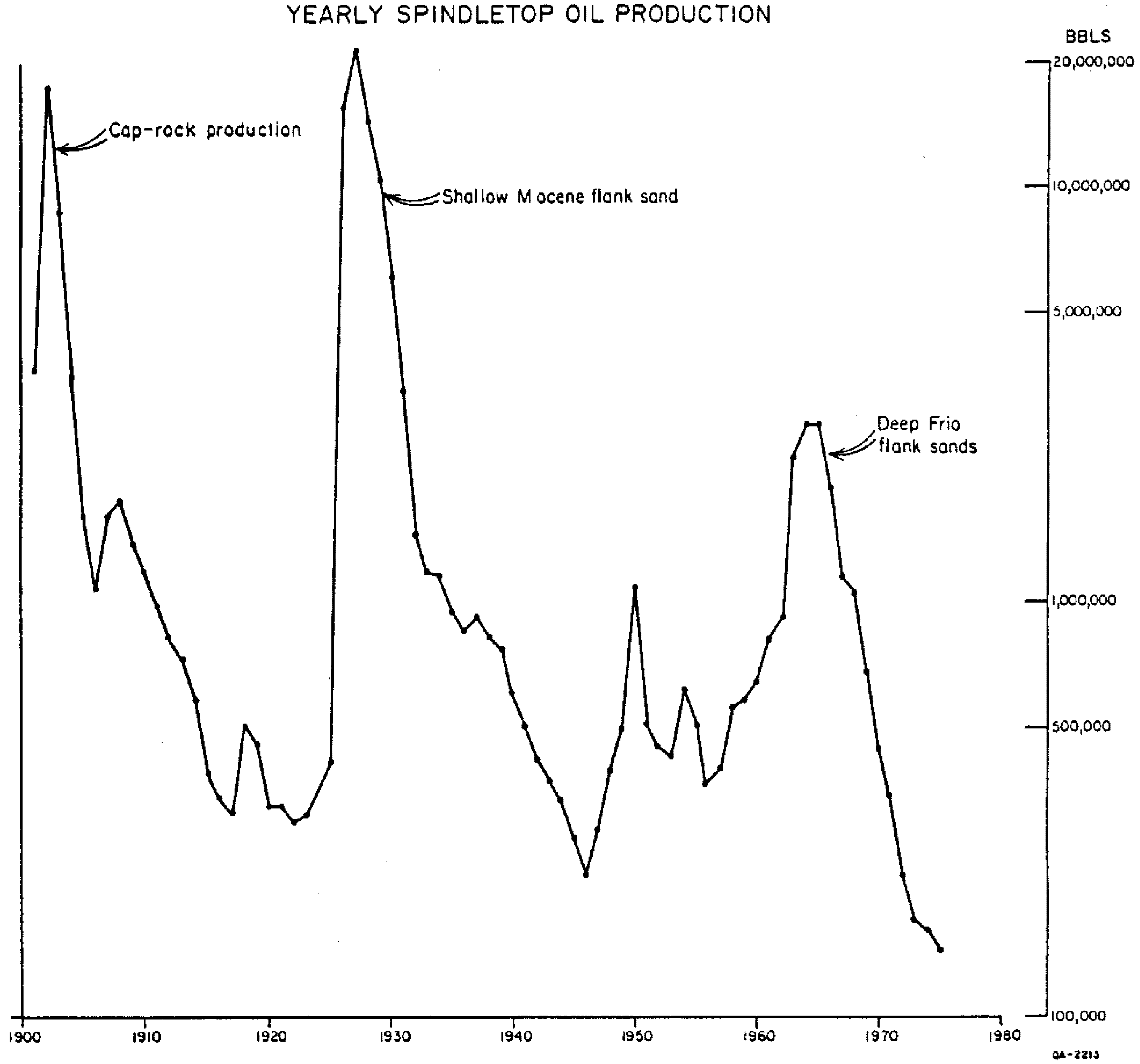


Figure 18. Yearly oil production from Spindletop salt-dome oil field (data from Halbouty, 1978).

Shallow-piercement-salt domes with cumulative oil production greater than 10 million barrels are located on figure 19. These domal fields are listed in table 4 with discovery dates, depth to cap rock and salt, productive area, and production figures (Galloway and others, 1983). Most oil has been produced from traps in cap rock, in strata truncated or pinched out against dome flanks, and in strata arched over dome crests. Although some very shallow diapirs are highly productive, there is a correlation between greater depth of burial of the dome and greater oil production (fig. 20). According to statistics from Halbouty (1979), known salt domes with crests greater than 4,000 ft deep have approximately twice the cumulative production of domes with crests buried less than 4,000 ft (80 million barrels vs. 38 million barrels).

Strata of Eocene through Pliocene age host most of the production associated with Gulf Coast salt domes. The Wilcox Group and the Yegua, Frio, and Fleming Formations compose the host strata. Major reservoirs and trap types discussed below are cap rock, dome flank (Yegua), and deep-salt-dome crest (Yegua and Frio). Boling salt dome is a good example of a shallow piercement dome with a large number of oil fields (fig. 21). Production is from supradomal sands, cap rock, and flank traps in Miocene, Heterostegina Limestone, and Frio reservoirs. Cumulative production through 1981 is 35.7 million barrels.

Cap-Rock Reservoirs

Four of the oldest fields in the Gulf Coast area--Spindletop, Sour Lake, Batson, and Humble--produce oil from calcite cap rock overlying shallow piercement salt domes. A total of eight shallow Gulf Coast diapirs had significant oil production from their cap rock. Most cap rocks have been exploited and their oil exhausted. Minor cap-rock production from Day salt dome in Madison County, however, was initiated in 1981. The location of some cap-rock fields over Boling salt dome is shown in figure 21.

Cap-rock fields typically showed prolific initial production and then rapid production decline (fig. 17). Production is from microscopic to cavernous porosity. Porosity values up to 40 percent are reported (Galloway and others, 1983).

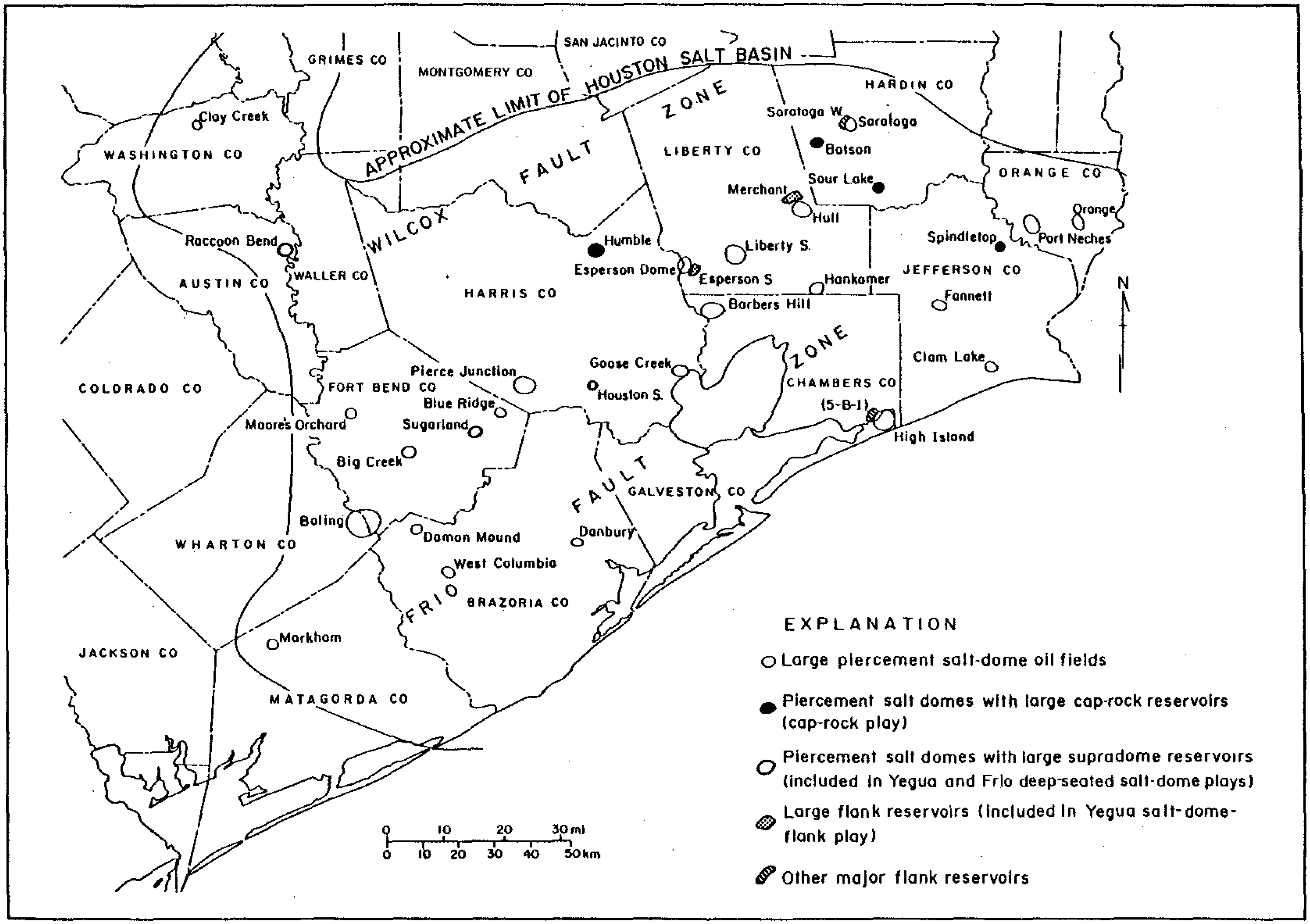


Figure 19. Map of piercement salt domes showing oil fields that have produced more than 10 million barrels of oil (after Galloway and others, 1983).

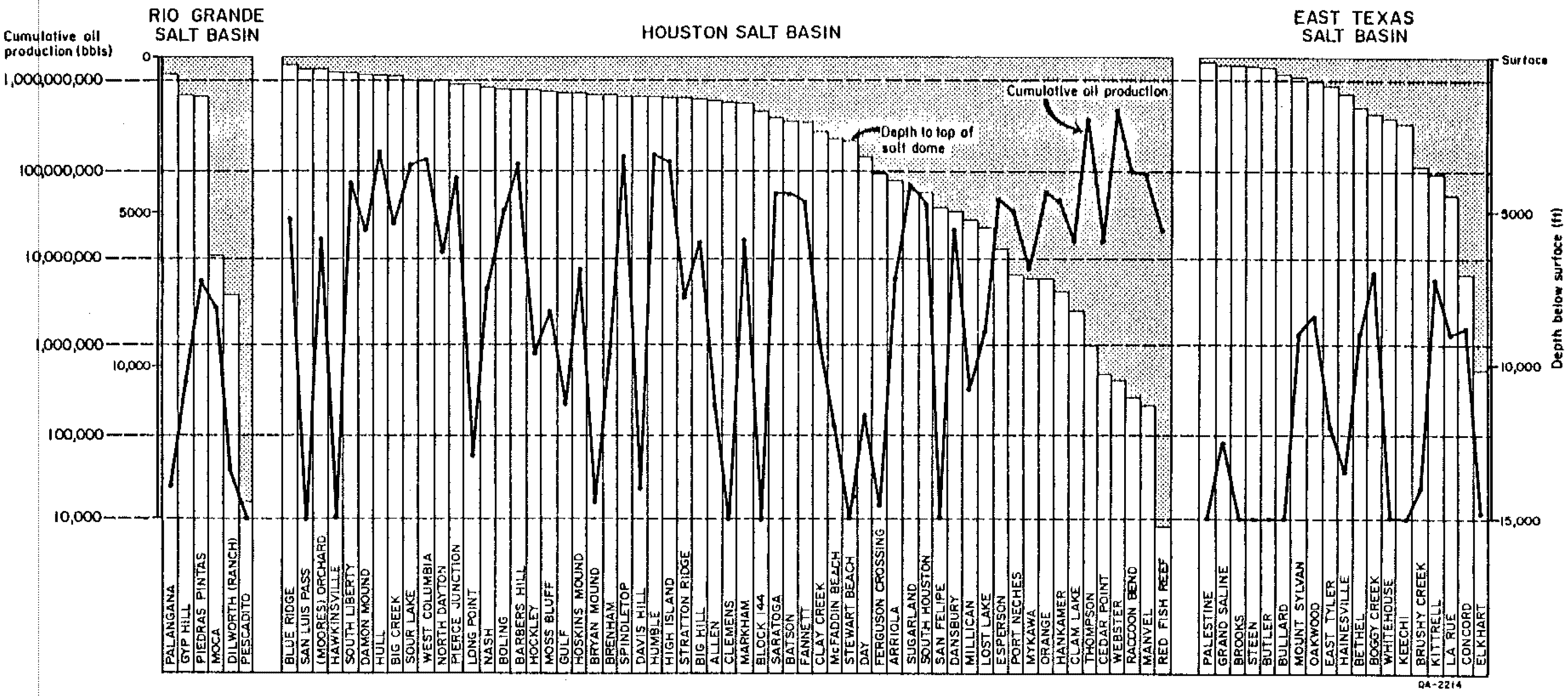


Figure 20. Graph showing depth to the crest of Texas salt domes and their cumulative oil production through 1975 (modified from Halbouty, 1979).

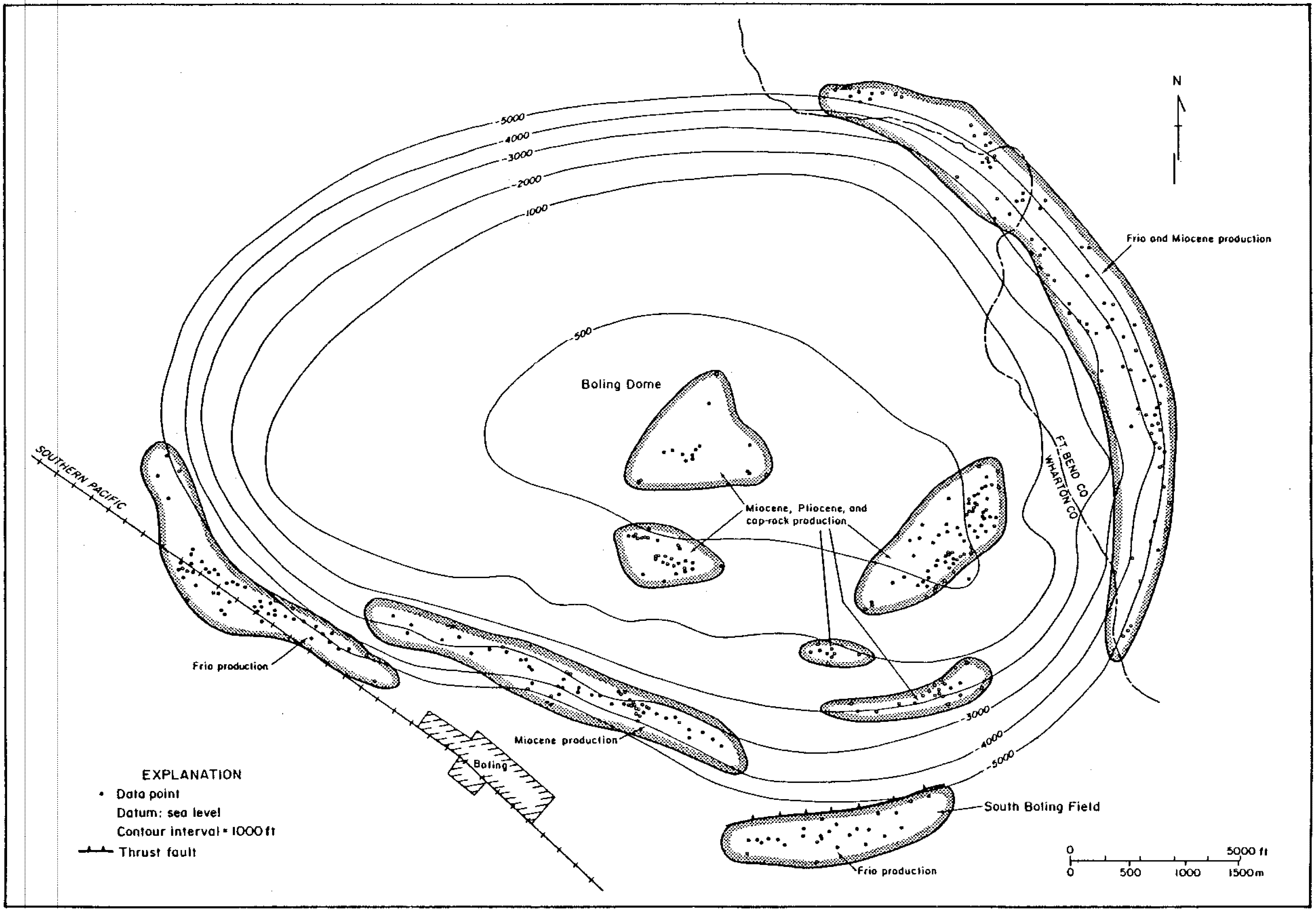


Figure 21. Map of Boling salt dome showing locations of oil fields (after Galloway and others, 1983).

Table 4. List of salt domes with large oil fields and production status.

Field	Discovery date	Top cap (ft)	Top salt (ft)	Production			Cumulative production (million barrels)	Estimated ultimate recovery (million barrels)
				Supradome	Cap	Flank		
Barbers Hill	1916	350	1,000	No	No	Frio, Miocene	128.0	129.3
Batson	1903	1,080	2,050	Miocene	Yes	Miocene, Frio, Yegua	60.6	61.0
Big Creek	1922	450	635	Miocene, Frio	No	Vicksburg	24.6	27.0
Blue Ridge	1919	143	230	No	No	Miocene, Frio, Vicksburg	24.1	24.3
Boling	1925	383	975	Miocene	Yes	Miocene, Frio	35.7	36.2
Clam Lake	1937	none	8,173	Miocene	No	No	18.7	19.4
Clay Creek	1928	1,800	2,400	Wilcox, Sparta and Queen City	No	No	12.8	13.2
Damon Mound	1915	surface	529	No	No	Frio, Miocene	21.6	21.9
Danbury	1930	none	4,948	Miocene	No	Frio	21.6	21.9
Esperson	1929	none	6,170	Miocene, Frio, Vicksburg	No	Yegua	50.5	51.9
Fannett	1927	741	2,080	Miocene?	No	Frio	51.0	52.9
Goose Creek	1908	> 5,000	?	Frio, Miocene	No	No	134.7	135.2
Hankamer	1929	7,535	7,582	Miocene, Frio	No	No	48.8	51.0
High Island	1922	150	1,228	No	No	Miocene, Frio	132.0	134.2
Hull	1918	260	595	No	Yes	Miocene, Frio, Yegua	183.5	185.9
Humble	1905	700	1,214	Pliocene, Miocene	Yes	Frio, Yegua	168.2	169.5
Liberty South	1925	275	480	No	No	Miocene, Frio, Vicksburg, Yegua	86.1	88.0
Markham	1908	1,380	1,417	Miocene	Yes	Frio	17.6	17.7
Moore's Orchard	1926	285	369	No	No	Miocene, Frio, Yegua	21.8	22.1
Orange	1913	none	7,120	Miocene, Frio	No	Hackberry	61.8	62.8
Pierce Junction	1921	630	860	No	No	Miocene, Frio, Vicksburg, Jackson, Yegua	88.3	88.9
Port Neches	1928	none	6,948	Miocene, Frio	No	Hackberry	31.7	32.4
Saratoga	1901	1,500	1,900	Miocene	No	Yegua	59.2	61.1
Sour Lake	1902	660	719	Miocene	Yes	Frio, Jackson?, Yegua	123.8	126.8
Spindletop	1901	700	1,200	Miocene	Yes	Miocene, Frio	153.2	153.9
West Columbia	1904	650	768	No	Yes	Miocene, Frio	162.2	163.6
							1,922.1	1,952.1

The genesis of cap rock is complex. Cap rock typically occurs at the crest of shallow piercement salt domes and may extend for some distance down the dome flanks. Mineralogically, most cap rocks are composed of a basal anhydrite zone, a middle gypsum or transition zone, and an upper calcite zone. The anhydrite is a dissolution residuum that accumulated as ground water dissolved anhydrite-bearing salt at the dome crest and flank. Gypsum then formed by hydration of anhydrite. Calcite is formed by sulfate reduction of gypsum with bacterial reaction with oil. The calcite zone is the typical oil reservoir in the cap rock.

Cap rocks are complex karstic features. They accumulated as a dissolution residuum and may themselves be undergoing dissolution. To this day, cap rocks are exceptionally difficult zones to complete and case a well through. Lost-circulation zones cause major problems involving mud circulation and complete cementation of casing strings. Active circulation of brine in cap-rock pores also provides a geochemical environment that is corrosive to casing and cements.

Some Gulf Coast cap rocks record evidence of erosion over the dome (Hanna, 1939). The cap rock of Orchard salt dome is thin over the dome crest but is up to 1,000 ft thick (stratigraphically) on the dome flanks (fig. 19). Pleistocene sands and gravels truncate Miocene strata around the dome periphery and apparently have stripped calcite cap rock from the dome crest.

Salt-Dome Flank Reservoirs

Important oil production from sandstones flanking salt domes was initiated at Spindletop dome in 1925 (Halbouty, 1979) (fig. 18). These flank reservoirs typically are thin sandstones steeply inclined upward toward the diapir flank. The sandstones may be truncated by the dome or pinch out toward the dome (fig. 22). Commonly, radial faults segment the sand bodies into discrete fault blocks.

Delta-front sheet sandstones of the Yegua Formation constitute the most important dome flank reservoir (Galloway and others, 1983). Major Yegua flank sands are reservoirs at Hull,

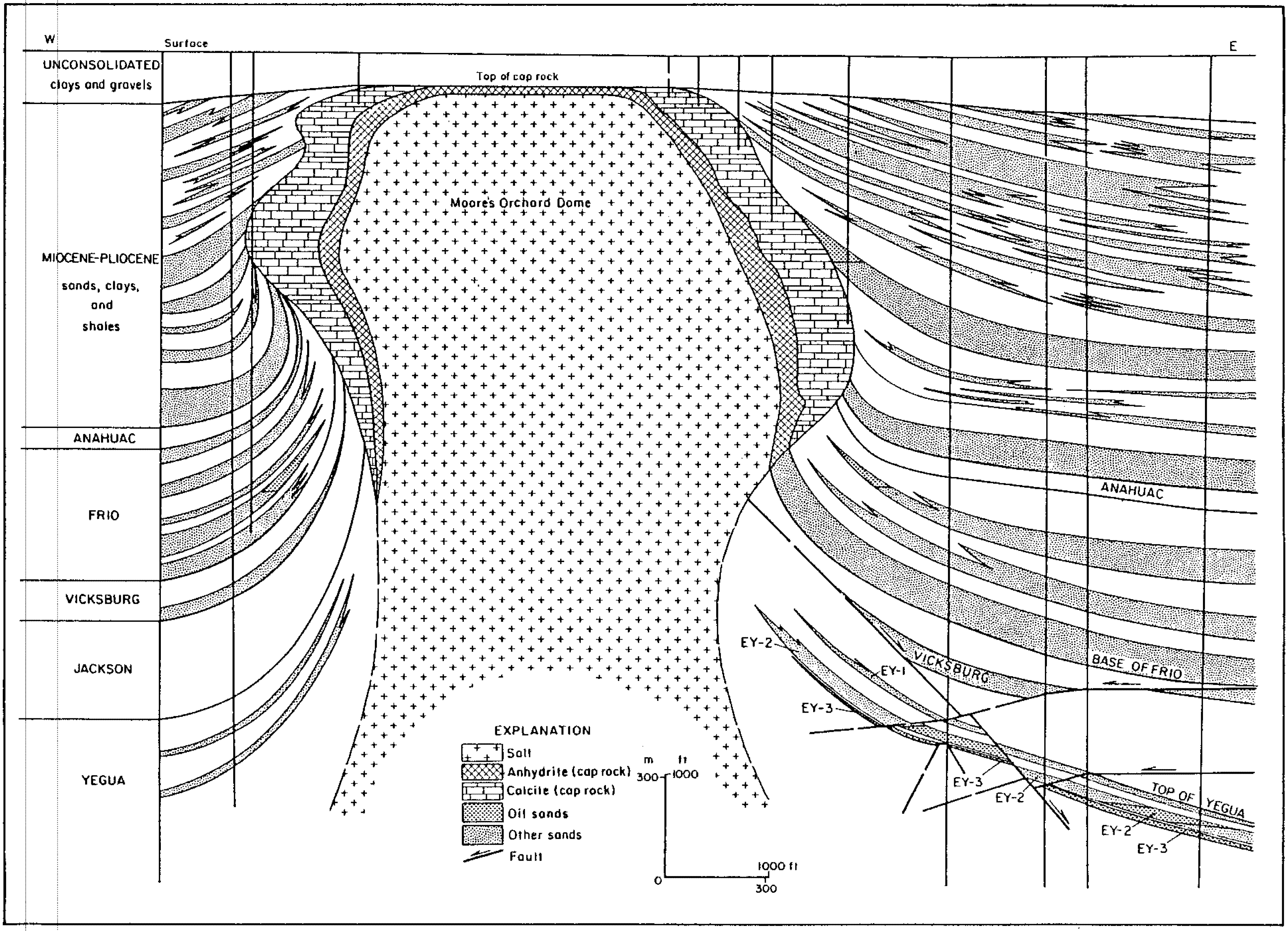


Figure 22. Cross section of (Moores) Orchard salt dome showing upturned strata on the flank of the dome and the crest of the dome truncated by erosion (after Galloway and others, 1983).

Esperson, and Saratoga salt domes. An example of the geometry of these flank sands and reservoirs is illustrated by Orchard (Moores Orchard) salt dome (fig. 22). The steep inclination of the flank sands makes them elusive targets, but this inclination also yields thick oil columns, efficient gravity segregation, and efficient water drives for impressive single-well production statistics.

Deep-Seated Dome Crest Reservoirs

Yegua and Frio sandstones arched over the crest of deep-seated salt domes produce the greatest cumulative amount of salt-dome-related oil in the Texas Gulf Coast (Galloway and others, 1983) (fig. 23). Most fields overlie known deep-seated salt domes such as Raccoon Bend (Yegua production) and Thompson, Manvel, Webster, and Cedar Point (Frio production). Other fields such as Katy may overlie non-piercing salt structures (Halbouty, 1979) or turtle-structure sediment-cored anticlines (Winker and others, 1983; Galloway and others, 1983).

Faults play a variable role in oil trapping and compartmentalization of reservoirs. For example, the Frio deep-seated dome crest trend is along the Vicksburg and Frio growth-fault trends. In contrast to the ubiquitous radial faults associated with shallow piercement salt domes, deeply buried salt domes normally have fewer associated faults as at Sugarland salt dome.

The average depth of reservoir rocks in the Yegua trend is approximately 5,000 ft. The reservoir sandstones are a complex of deltaic sand bodies including distal fluvial, distributary-channel-fill, and crevasse-splay facies (Galloway and others, 1983). The average depth of reservoir rocks in the deep Frio trend is approximately 6,000 ft. Reservoir rocks include a wide range of deltaic facies including delta-front, delta-margin, distributary-channel-fill, and destructional barrier facies (Galloway and others, 1983). The reservoir-drive mechanism is an efficient water drive commonly assisted by gas-cap expansion. Most of the larger fields are unitized with reservoir-wide secondary gas injection.

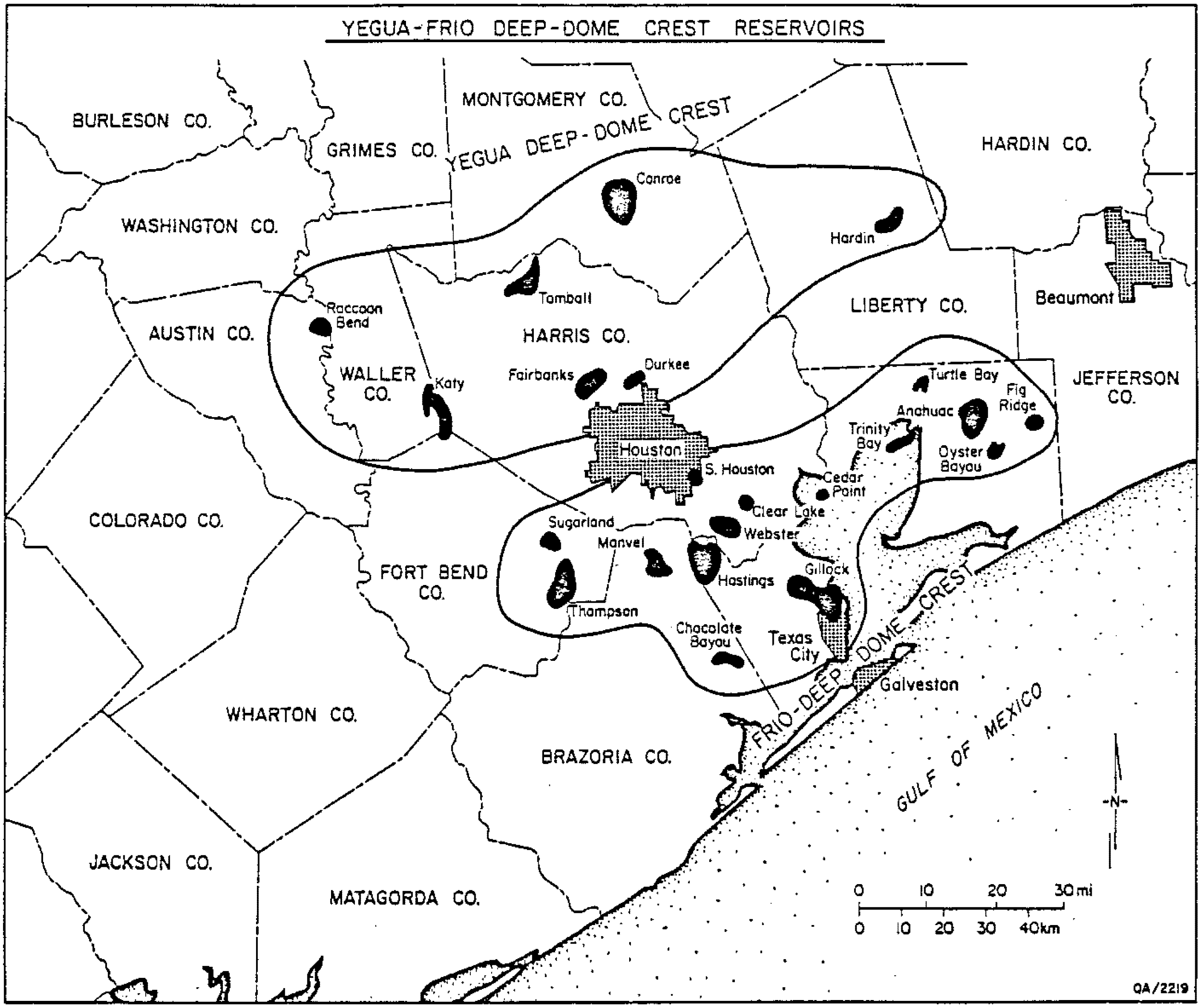


Figure 23. Map of Yegua and Frio reservoirs over the crest of deep-seated salt domes.

Petroleum Resources of Salt Domes in the East Texas and Rio Grande Basins

Oil production from East Texas and Rio Grande salt diapirs is much less than production from diapirs in the Houston Salt Basin (fig. 20). No fields around diapirs in the East Texas or the Rio Grande Basins have produced greater than 10 million barrels of oil. Shallow salt domes (less than 6,000 ft) have produced less than 1 percent of the oil from the central part of the East Texas Basin (Wood and Giles, 1982).

The East Texas Basin on the whole is an extraordinarily oil-rich basin. The East Texas oil field alone has produced 4.68 billion barrels of oil. Deeply buried non-piercing salt structures are highly productive in the East Texas Basin. Hawkins and Van salt structures have produced 734 million and 485 million barrels of oil, respectively. The question remains, why are diapirs in the interior basins so barren in comparison with coastal diapirs?

Several factors have acted to minimize the entrapment of oil in interior salt diapirs. Diapirs in interior basins have greater structural maturity than do coastal diapirs. This structural maturity is characterized by steep flanks of the diapir and a surrounding rim syncline. Most diapirs in the East Texas Basin are surrounded by strata that dip toward the diapir or are flat lying. In contrast, the flanks of many coastal diapirs are less steep, and strata typically are inclined upward toward the dome. The increased maturity of East Texas diapirs results in the structural closure being minimized around the domes.

The domes of the East Texas Basin are also much older than coastal diapirs. Most coastal domes probably became diapirs in the Oligocene or Miocene, 10 to 35 million years ago. In contrast, East Texas domes became diapirs from 80 to more than 112 million years ago (Seni and Jackson, 1983b). Thus, if large amounts of oil had accumulated over the crests of early pillows that later evolved into East Texas diapirs, the hydrocarbons would have had a long period of time to leak during dome uplift, during erosion of previously deposited strata over the dome crest, or both.

Sulfur Resources

Historically, a major proportion of the world supply of sulfur came from Texas salt domes. Sulfur production began in Texas at Bryan Mound salt dome. Sulfur has been produced commercially from the cap rocks of 15 Texas salt domes. Currently, Boling salt dome contains the only active cap-rock-sulfur mine in Texas (fig. 15). Texas cap-rock sulfur mining has declined owing to exhaustion of reserves, lack of new cap-rock discoveries, and price competition from sulfur produced by secondary recovery of sulfur from sour gas and petroleum refining.

This section will present the history and technology of sulfur mining and the geology of cap-rock sulfur deposits.

History and Technology

Sulfur was first discovered in 1867 in cap rock of coastal salt domes at Sulfur Mines salt dome in Louisiana. Louisiana Petroleum and Coal Oil Co. was searching for oil and instead discovered a thick deposit of native (free elemental) sulfur in cap rock at a depth of 650 ft. For 20 years, a number of ventures designed to mine the sulfur by underground methods failed. H. Frasch patented in 1890 a revolutionary sulfur-mining technology that is still used today with minor modifications. Basically the Frasch process uses hot water to melt the sulfur and compressed air to help lift the sulfur to the surface. Standard oil-field technologies are used to drill a hole to the base of the sulfur-bearing zone. Three stands of pipe are then set concentrically into the hole--the outer casing, the middle sulfur-production string, and the inner compressed-air line (fig. 24).

Casing (usually with diameter of 6 to 8 inches) is cemented into the hole. Two separate sets of perforations are made through the casing at the top and near the bottom of the sulfur-bearing zone. According to Ellison (1971), the upper set of perforations is 8 to 10 ft above the base of the productive zone, and the lower set is 1 to 5 ft above the base. A ring-shaped seal is placed in the annulus between the sulfur-production string and the casing string between the

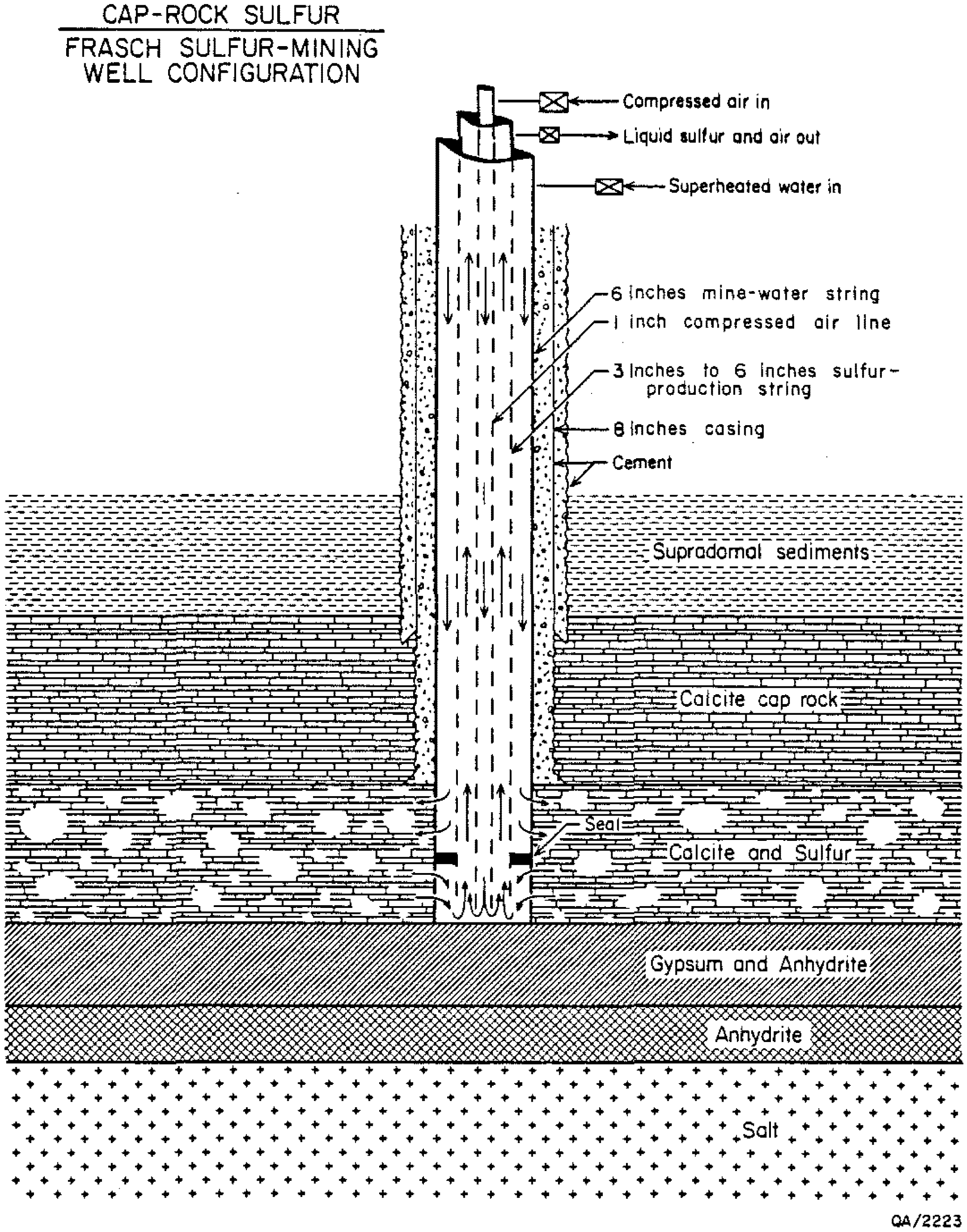


Figure 24. Casing string detail for cap-rock sulfur-production well (after Myers, 1968).

upper and lower sets of perforations. The seal prevents communication between the upper and the lower perforations within the annular space.

Superheated (300° to 325°F) and pressurized (125 to 100 psi) water is injected down the annulus between the casing and the sulfur-production string. The hot water exits through the upper set of perforations. The sulfur melts as the superheated water enters the sulfur-bearing zone. Molten sulfur is heavier than water and therefore sinks to the lower part of the sulfur-bearing zone. Pressure differentials drive the molten sulfur through the lower set of perforations into the casing. The seal forces the sulfur into the sulfur-production string. Compressed air at 500 to 600 psi is injected into the innermost compressed-air string. This helps force the sulfur to the surface by lowering the bulk density of the molten sulfur-air mixture.

Sulfur, having a purity of 99.5 percent, solidifies at the surface in large vats. Some operations directly ship the molten sulfur in insulated vessels.

Two ancillary operations during sulfur production involve recycling of the injected water and mitigating surface subsidence owing to sulfur removal. "Bleed-water" wells are drilled to produce and recycle excess water that was injected to melt the sulfur. Once the water has cooled below the melting point of sulfur, it must be recycled. By drilling "bleed-water" wells beyond the productive area, costs can be lowered and water flow is improved (Hawkins and Jirik, 1966).

Surface subsidence over areas of sulfur production is a problem common to many sulfur-mining areas. The removal of sulfur opens a series of void spaces in the cap rock. The collapse of these voids causes the subsidence over the mining operations. The closing of voids is beneficial in that less water is needed to mine the remaining sulfur. Many sulfur operations now pump special muds into the zone where sulfur has been produced to fill the voids and prevent surface subsidence. A 2 mi^2 area over Boling salt dome has subsided up to 20 ft. An extensive system of levees protects the area from flooding. In addition to flooding, subsidence may cause damage to well bores, casing, and surface facilities.

Characteristics of Cap-Rock Sulfur Deposits

Native (free) sulfur has been reported in cap rock of 25 Texas salt domes. Fifteen of these domes have undergone commercial sulfur production (figs. 25 and 26). Only Boling salt dome has active sulfur production. Boling salt dome has been continuously active since 1929 (fig. 24) and is the world's largest single sulfur source. A cross section of Boling salt dome, its cap rock, and sulfur zone is shown in figure 27.

Cap rock is a particularly complex area of a salt dome. Cap-rock thickness ranges from a feather edge to more than 1,000 ft. Cap-rock depth ranges from above sea level to depths greater than 4,000 ft. Sulfur typically occupies vugular porosity at the base of the calcite zone. The thickness of the sulfur-bearing zone may exceed 300 ft. Sulfur is typically found on the outer periphery, or shoulder, of shallow piercement salt domes (fig. 28) (Myers, 1968). Some small domes have sulfur deposits across the entire crestal area. Even though the larger domes, such as Boling salt dome, have sulfur over only a portion of their crests, the larger domes have mineralization over a much larger area and generally of greater thicknesses. In the Gulf Coast area, the depth of sulfur mining is typically from 900 to 1,700 ft. Orchard salt dome exhibits the greatest depth of sulfur production at 3,200 ft.

Cap-Rock Resources

The cap rock hosts and also comprises most of the other resources associated with salt domes. The cap rock is an exceedingly complex environment as demonstrated by its variable stratigraphy including calcite, gypsum (transition), and anhydrite zones. In addition to the cap-rock petroleum and sulfur resources already discussed, some cap rocks of Texas domes contain uranium (Palangana salt dome), Mississippi Valley-type sulfide deposits (Hockley salt dome), and silver minerals (Hockley salt dome). The cap rock is a valuable commodity as crushed stone in the rock-poor coastal regions. Just as the caverns in salt domes were an unrecognized resource for a long time, lost-circulation zones have been converted into convenient disposal zones for brine leached from storage cavern projects.

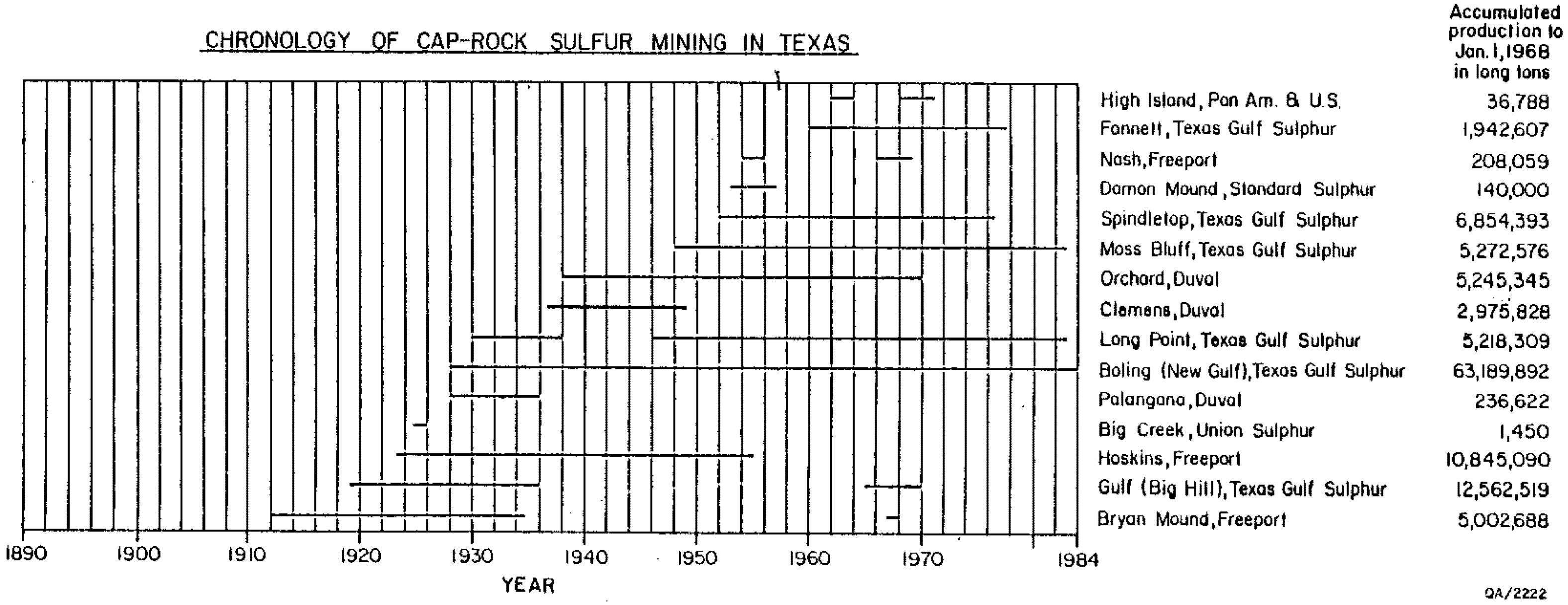
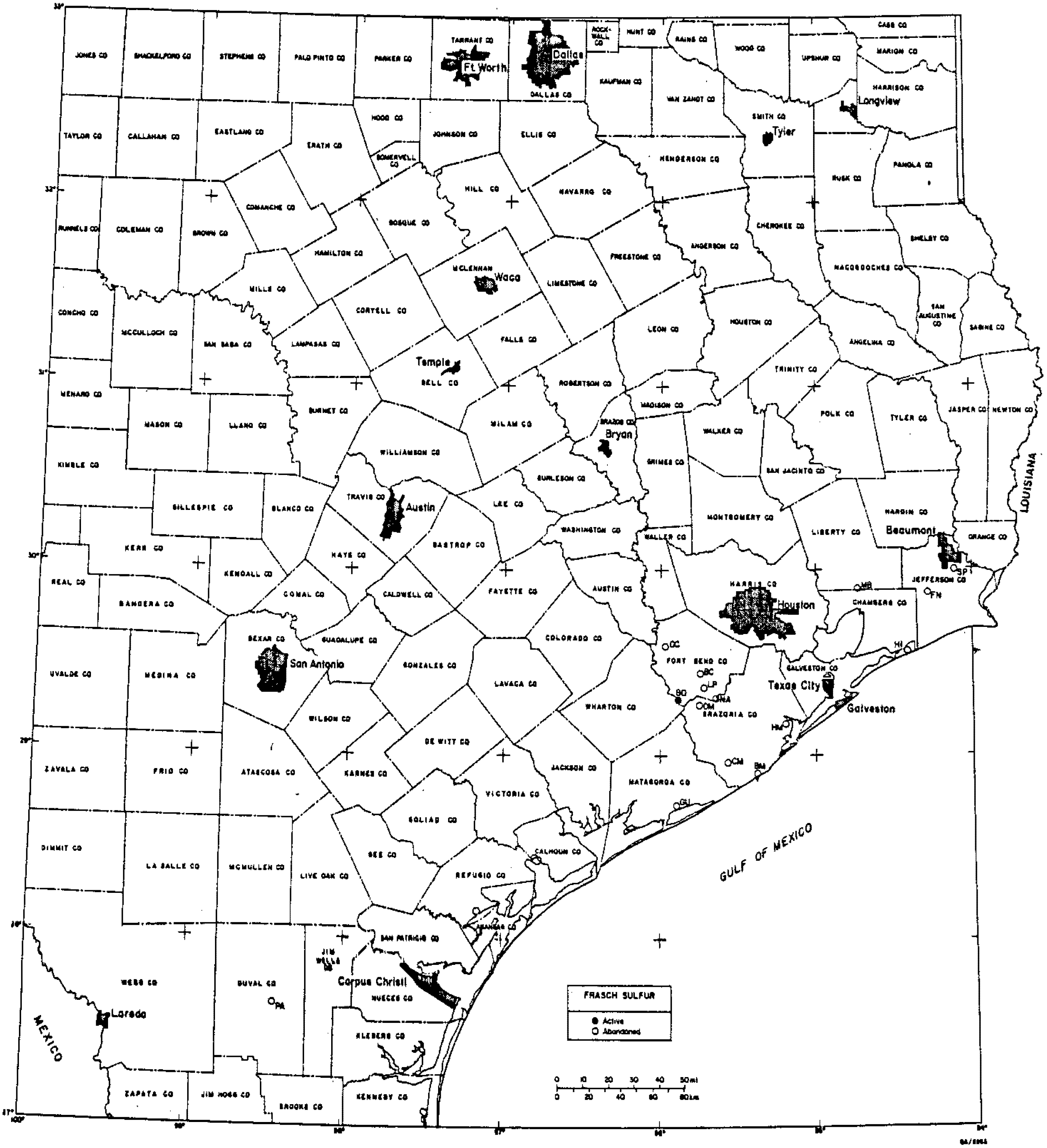


Figure 25. Graph showing the chronology of sulfur mining in Texas salt domes (modified from Ellison, 1971).



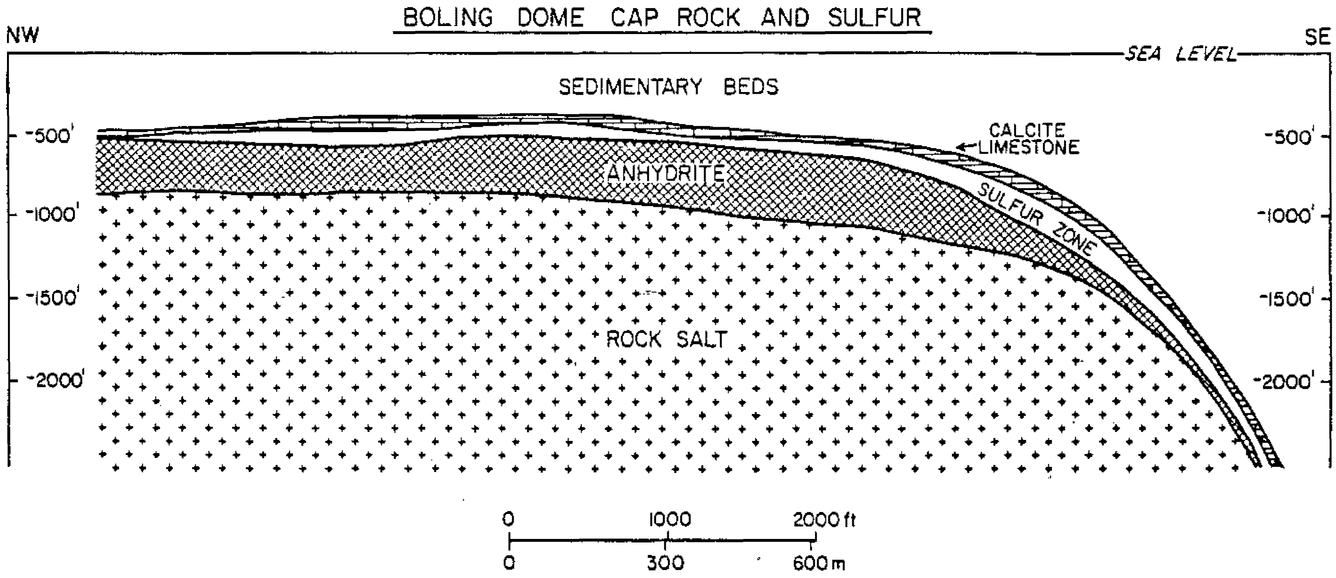
FRASCH SULFUR FROM SALT DOMES OF TEXAS

Figure 26. Map of salt domes showing active and abandoned sulfur mining.

(continued)

Figure 26 (cont.).

Code	**Dome Name**	**County**
BC	Big Creek	Fort Bend
BO	Boling	Wharton/Fort Bend
BM	Bryan Mound	Brazoria
CM	Clemens	Brazoria
DM	Damon Mound	Brazoria
FN	Fannett	Jefferson
GU	Gulf	Matagorda
HI	High Island	Galveston
HM	Hoskins Mound	Brazoria
LP	Long Point	Fort Bend
MB	Moss Bluff	Chambers/Liberty
NA	Nash	Brazoria/Fort Bend
OC	Orchard	Fort Bend
PA	Palangana	Duval
SP	Spindletop	Jefferson



QA/2220

Figure 27. Cross section of Boling salt dome showing cap rock and zone of sulfur mineralization (after Myers, 1968).

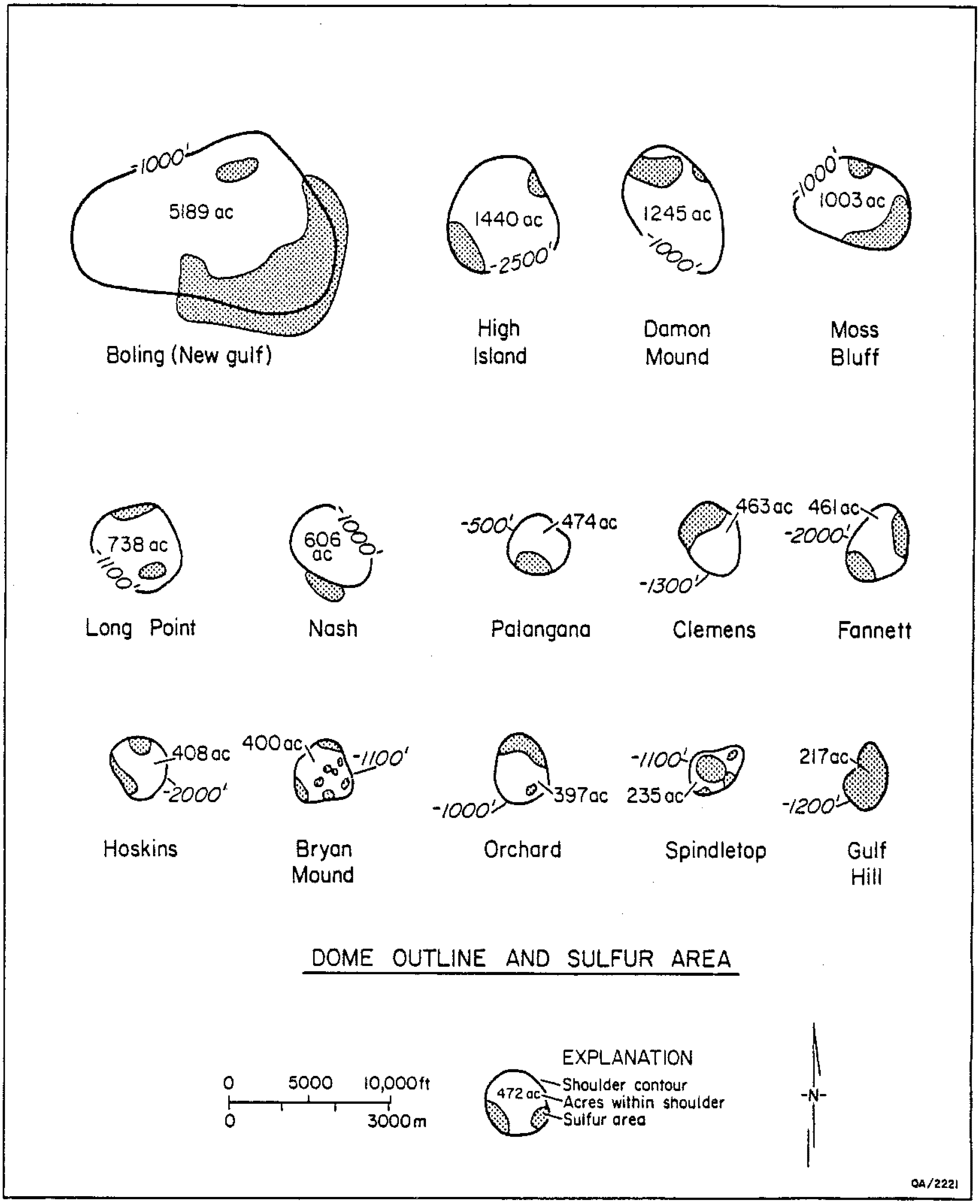


Figure 28. Map of Texas salt domes showing area of sulfur mineralization.

Crushed Stone

Cap rock has been mined from conventional above-ground quarries at Gyp Hill and Damon Mound salt domes. Only the quarry at Damon Mound is currently active. Cap rock has also been exploited on a small scale by underground mining at Hockley salt dome. False-cap-rock, or mineralized supracap, sandstones are now quarried at Butler salt dome. Most of the cap rock is used as road metal and base fill.

Other Resources

Mississippi Valley-type sulfide deposits and uranium have been reported (Smith, 1970a, b) and locally have been explored for in Gulf Coast cap rocks (Price and others, 1983). There has been no commercial production, however. The recent recognition that cap rocks may host Mississippi Valley-type sulfide deposits has generated intense interest in cap-rock genesis and fluid flow around salt domes. Price and others (1983) reported extensive sulfide mineralization and local silver minerals from an annular zone around the periphery of the cap rock. They related the deposition of the sulfide minerals to reduction in the cap rock environment by petroleum and possibly by H_2S, and to periodic expulsion of deep-basin brines that were the mineralizing fluids. Smith (1970a, b) listed 18 Texas coastal domes for which occurrence of sulfide minerals had been reported. Table 5 lists such Texas salt domes, type of sulfide mineral, and documentation.

Table 5. List of salt domes with sulfide mineral occurrences and documentation.

NAME OF SALT DOME	NAME OF SULFIDE	PRODUCTION STATUS	DOCUMENTATION REFERENCE	MINING COMMPANY
***				
* BIG HILL	GALENA	OCCURRENCE	SMITH-1970,A,B-	NA
* BLUE RIDGE	PYRITE	OCCURRENCE	SMITH-1970,A,B-	NA
* BOLING	SPHALERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* BOLING	BARITE	OCCURRENCE	SMITH-1970,A,B-	NA
* BOLING	CELESTITE	OCCURRENCE	SMITH-1970,A,B-	NA
* BOLING	GALENA	OCCURRENCE	SMITH-1970,A,B-	NA
* BOLING	HAVERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* BOLING	PYRITE	OCCURRENCE	SMITH-1970,A,B-	NA
* CLEMENS	HAUERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* DAMON MOUND	MARCASITE	OCCURRENCE	SMITH-1970,A,B-	NA
* DAMON MOUND	MELANTERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* FANNETT	HAVERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* FANNETT	ALABANDITE	OCCURRENCE	SMITH-1970,A,B-	NA
* FERGUSON CROSSING	GALENA	OCCURRENCE	SMITH-1970,A,B-	NA
* FERGUSON CROSSING	SPHALERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* GULF	GALENA	OCCURRENCE	SMITH-1970,A,B-	NA
* GULF	HAVERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* GULF	PYRITE	OCCURRENCE	SMITH-1970,A,B-	NA
* GULF	SPHALERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* HIGH ISLAND	GALENA	OCCURRENCE	SMITH-1970,A,B-	NA
* HIGH ISLAND	HAUERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* HIGH ISLAND	SPHALERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* HOCKLEY	SPHALERITE	EXPLORATION	CORE-PRICE ET AL-1983	MARATHON MINERALS
* HOCKLEY	GALENA	EXPLORATION	CORE-PRICE ET AL-1983	MARATHON MINERALS
* HOCKLEY	MARCASITE	EXPLORATION	CORE-PRICE ET AL-1983	MARATHON MINERALS
* HOCKLEY	PYRITE	EXPLORATION	CORE-PRICE ET AL-1983	MARATHON MINERALS
* HOSKINS MOUND	GALENA	OCCURRENCE	SMITH-1970,A,B-	NA
* HOSKINS MOUND	HAUERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* HOSKINS MOUND	SPHALERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* HOSKINS MOUND	PYRRHOTITE	OCCURRENCE	SMITH-1970,A,B-	NA
* HUMBLE	GALENA	OCCURRENCE	SMITH-1970,A,B-	NA
* MOSS BLUFF	HAUERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* ORCHARD	SPHALERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* ORCHARD	GALENA	OCCURRENCE	SMITH-1970,A,B-	NA
* PALANGANA DOME	SPHALERITE	OCCURRENCE	SMITH-1970,A,B-	NA
* PALANGANA DOME	GALENA	OCCURRENCE	SMITH-1970,A,B-	NA
* PIERCE JUNCTION	GALENA	OCCURRENCE	SMITH-1970,A,B-	NA
* SOUR LAKE	PYRRHOTITE	OCCURRENCE	SMITH-1970,A,B-	NA
* SOUR LAKE	PYRITE	OCCURRENCE	SMITH-1970,A,B-	NA
* SPINDLETOP	PYRITE	OCCURRENCE	SMITH-1970,A,B-	NA

```
list/title l(18)name of salt dome,b(3),r(15)name of sulfide,
 LIST/TITLE L(18)NAME OF SALT DOME,B(3),R(15)NAME OF SULFIDE,
 ----
b(3),r(12)production  +status    ,b(3),r(25)documentation reference,
 B(3),R(12)PRODUCTION  +STATUS    ,B(3),R(25)DOCUMENTATION REFERENCE,
 ----
b(3),r(20) mining commpany    /c1,c199,c200,c201,c202,ob low c1
 B(3),R(20) MINING COMMPANY    /C1,C199,C200,C201,C202,OB LOW C1
 ----
wh c200 eq exploration or c200 eq occurrence:
 WH C200 EQ EXPLORATION OR C200 EQ OCCURRENCE:
```

ACKNOWLEDGMENTS

Thanks are extended to Texas Railroad Commission personnel Mark Browning (Central Records) and J. W. Mullican (Underground Injection Control), who provided easy access to records and files. Discussions with the following industry representatives were very helpful: Kermit Allen, Jose Machado, and Edward Voorhees (Fenix and Scisson, Inc.), Neils Van Fossan (Texas Brine Company), Ferris Samuelson (Texas Gulf Sulfur), Carl Brassow (United Resource Recovery, Inc.), Jack Piskura (Pakhoed, Inc.), and Bill Ehni and Mark Katterjohn (Geotronics Corporation). Word processing was done by Joann Haddock, under the supervision of Lucille C. Harrell. Mark Bentley, Tom Byrd, Jeff Horowitz, Jamie McClelland, and Richard Platt drafted the figures, under the supervision of Dick Dillon.

REFERENCES

Autin, W. J., 1984, Observations and significance of sinkhole development at Jefferson Island: Louisiana Geological Survey Department of Natural Resources Geological Pamphlet No. 7, 75 p.

Bays, C. A., 1963, Use of salt solution cavities for underground storage: Northern Ohio Geological Society, 1st International Symposium on Salt, Cleveland, Ohio, p. 564-578.

Ellison, S. P., Jr., 1971, Sulfur in Texas: The University of Texas at Austin, Bureau of Economic Geology, Handbook No. 2, 48 p.

Fenix and Scisson, Inc., 1976a, Review of applicable technology--solution mining of caverns in salt domes to serve as repositories for radioactive wastes: Prepared for U.S. Energy Research and Development Administration, Office of Nuclear Waste Isolation, Oak Ridge, Tennessee, Y/OWI/SUB-76/92880, 122 p.

________ 1976b, Final report, Project 1, investigation of new leached caverns in salt domes, vol. 1: Prepared for U.S. Federal Energy Administration, Washington, D. C.

________1976c, Final report, Project 1, investigation of new leached caverns in salt domes, vol. 2: Prepared for U.S. Federal Energy Administration, Washington, D.C.

________1976d, Final report, Project 2, engineering feasibility study of underground storage in existing leached caverns in salt formations: Prepared for U.S. Federal Energy Administration, Washington, D.C.

Fogg, G. E., and Kreitler, C. W., 1980, Impacts of salt-brining on Palestine Dome: in Kreitler, C. W., and others, Geology and geohydrology of the East Texas Basin: a report on the progress of nuclear waste isolation feasibility studies (1979): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 80-12, p. 46-54.

Fossum, A. F., 1976, Structural analysis of salt cavities formed by solution mining: I. Method of analysis and preliminary results for spherical cavities: Prepared for U.S. Energy Research and Development Administration, Office of Nuclear Waste Isolation, Oak Ridge, Tennessee, ORNL/SUB-4269/19, 26 p.

Galloway, W. E., Ewing, T. E., Garrett, C. M., Tyler, N., and Bebout, D. G., 1983, Atlas of major Texas oil reservoirs: The University of Texas at Austin, Bureau of Economic Geology Special Publication, 139 p.

Gas Processors Association, 1983, North American storage capacity for light hydrocarbons and U.S. LP-gas import terminals 1983: Tulsa, Oklahoma, 26 p.

Griswold, G. B., 1981, Solution mining in salt domes of the Gulf Coast Embayment: Richland, Washington, Pacific Northwest Laboratory, prepared for Office of Nuclear Waste Isolation, PNL-3190.

Halbouty, M. T., 1979, Salt domes; Gulf region, United States and Mexico, 2d ed.: Houston, Texas, Gulf Publishing, 561 p.

Hanna, M. A., 1939, Evidence of erosion of salt stock in Gulf Coast salt plug in late Oligocene: American Association of Petroleum Geologists Bulletin, v. 23, no. 4, p. 604-607.

Hart, R. J., Ortiz, T. S., and Magorian, T. R., 1981, Strategic petroleum reserve (SPR) geological site characterization report, Big Hill salt dome: Sandia National Laboratories, Albuquerque, New Mexico, SAND81-1085.

Hawkins, M. E., and Jirik, C. J., 1966, Salt domes in Texas, Louisiana, Mississippi, Alabama, and offshore tidelands: a survey: U.S. Bureau of Mines Information Circular 8313, 78 p.

Hopkins, O. B., 1917, The Palestine salt dome, Anderson County, Texas: U.S. Geological Survey Bulletin 661, contributed to Economic Geology, pt. 2, Mineral Fuels, p. 253-270.

Jackson, M. P. A., and Seni, S. J., 1983, Suitability of salt domes in the East Texas Basin for nuclear-waste isolation: final summary of geologic and hydrogeologic research: The University of Texas at Austin, Bureau of Economic Geology, milestone contract report for the U.S. Department of Energy under Contract No. DE-AC97-80ET46617, 247 p.

Jackson, M. P. A., and Seni, S. J., 1984, The domes of East Texas: in Presley, M. W., ed., The Jurassic of East Texas: East Texas Geological Society, p. 163-239.

Jirik, C. J., and Weaver, L. K., 1976, A survey of salt deposits and salt caverns, their relevance to the strategic petroleum reserve: Federal Energy Administration, Report FEA/S-76/310, 64 p.

Martinez, J. D., Thoms, R. L., Kupfer, D. H., Smith, C. J., Jr., Kolb, C. R., Newchurch, E. J., Wilcox, R. E., Manning, T. A., Jr., Romberg, M., Lewis, A. J., Rovik, J. E., 1976, An investigation of the utility of Gulf Coast salt domes for isolation of nuclear wastes: Louisiana State University Institute for Environmental Studies, Baton Rouge, Report No. ORNL-SUB-4112-25, prepared for U.S. Department of Energy, 329 p.

Minihan, T. J., and Querio, C. W., 1973, Simultaneous storage of LPG and production of brine, Pierce Junction Dome, Houston, Texas: Northern Ohio Geological Society, 4th Symposium on Salt, Cleveland, Ohio, v. 2, p. 285-290.

Myers, J. C., 1968, Gulf Coast sulfur resources: in Brown, L. F., Jr., ed., Fourth Forum on Geology of Industrial Minerals: The University of Texas at Austin, Bureau of Economic Geology Special Publication, p. 57-65.

Powers, S., 1926, Interior salt domes of Texas: American Association of Petroleum Geologists Bulletin, v. 10, no. 1, p. 1-60.

Price, P. E., Kyle, J. R., and Wessel, G. R., 1983, Salt-dome related zinc-lead deposits: in Kisvarsanyi, G., and others, eds., Proceedings, International Conference on Mississippi Valley-Type Lead-Zinc Deposits: University of Missouri, Rolla, p. 558-571.

Science Applications, Inc., 1977, The mechanisms and ecological impacts of the collapse of salt dome oil storage caverns: McLean, Virginia, Report No. 5-210-00-567-04.

Seni, S. J., and Jackson, M. P. A., 1983a, Evolution of salt structures, East Texas diapir province, part 1: sedimentary record of halokinesis: American Association of Petroleum Geologists Bulletin, v. 67, no. 8, p. 1219-1244.

_________ 1983b, Evolution of salt structures, East Texas diapir province, part 2: patterns and rates of halokinesis: American Association of Petroleum Geologists Bulletin, v. 67, no. 8, p. 1245-1274.

Smith, A. E., Jr., 1970a, Minerals from Gulf Coast salt domes, part I: rocks and minerals, v. 45, no. 5, p. 299-303.

Smith, A. E., Jr., 1970b, Minerals from Gulf Coast salt domes, part II: rocks and minerals, v. 45, no. 6, p. 371-380.

Smith, G. I., Jones, C. L., Culbertson, W. C., Ericksen, G. E., Dyni, J. R., 1973, Evaporites and brines: in Brobst, D. A., and Pratt, W. P., eds., United States Mineral Resources: U.S. Geological Survey Professional Paper 820, p. 197-216.

U.S. Federal Energy Administration, 1977a, Strategic petroleum reserve, final environmental impact statement for Cote Blanche Mine: FEA/S-77/016, FES 76/77-7.

_________ 1977b, Strategic petroleum reserve, final environmental impact statement, Bryan Mound salt dome: FEA/S-76/502, FES 76/77-6.

_________ 1977c, Strategic petroleum reserve, final environmental impact statement (final supplement to FEA FES 76/77-6), Bryan Mound salt dome, Brazoria County, Texas: DOE/EIS-0001.

Underground Resource Management, 1982, Hydrogeologic investigation in the vicinity of Barbers Hill salt dome: Austin, Texas, Job No. 82-807, 104 p.

United Resource Recovery, Inc., 1983, Application of United Resource Recovery, Inc., to dispose of waste by well injection at the Boling salt dome: Submitted by Keysmith Corp., Austin, Texas, 121 p.

Van Fossan, N. E., 1979, Mechanisms of product leakage from solution caverns: Northern Ohio Geological Society, 5th Symposium on Salt, Cleveland, Ohio, v. 2, p. 213-230.

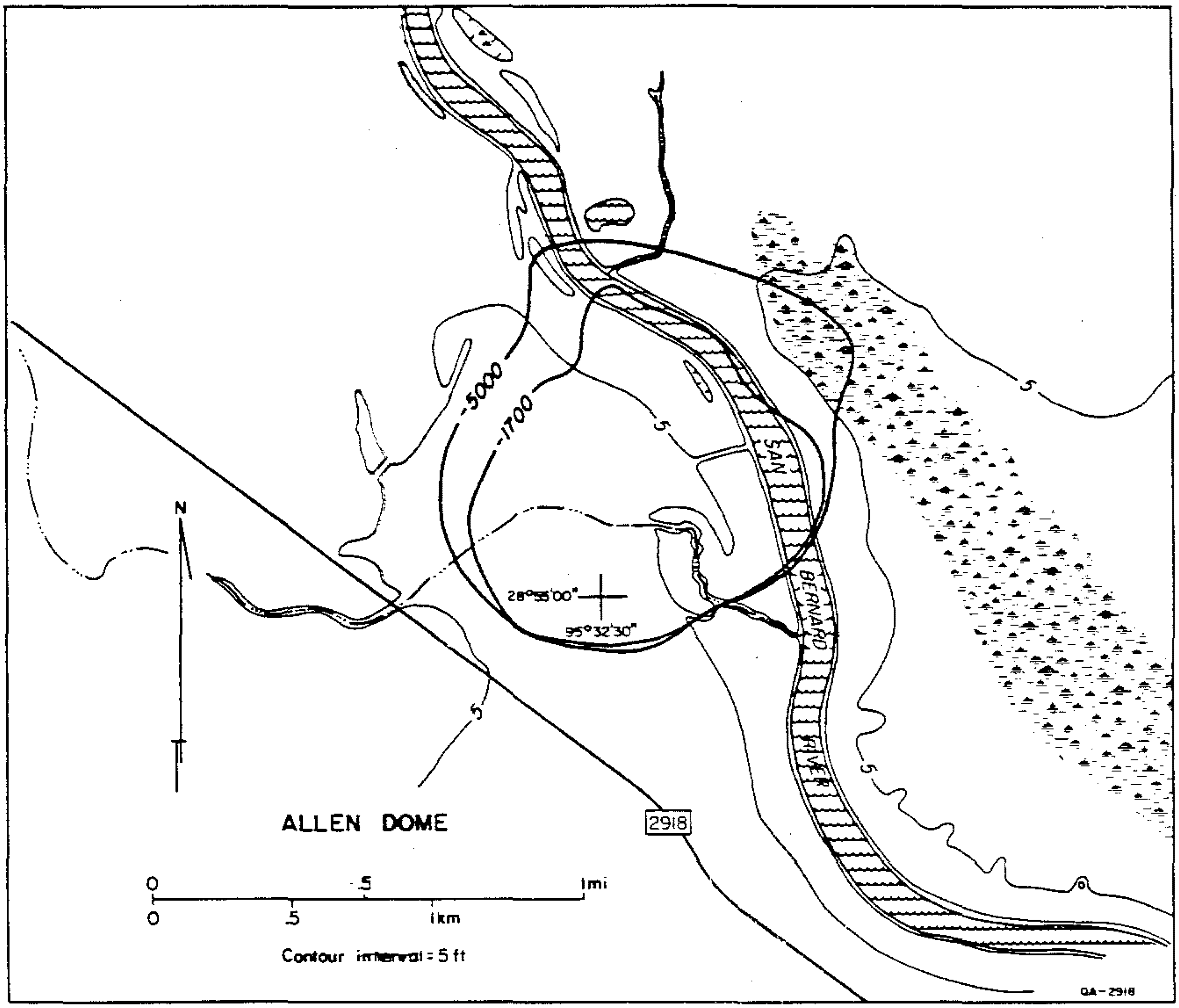
Van Fossan, H., and Prosser, L. E., 1949, The application of free jets to the mixing of fluids in bulk: London, Institute of Mechanical Engineers Proceedings, v. 160, p. 224-251.

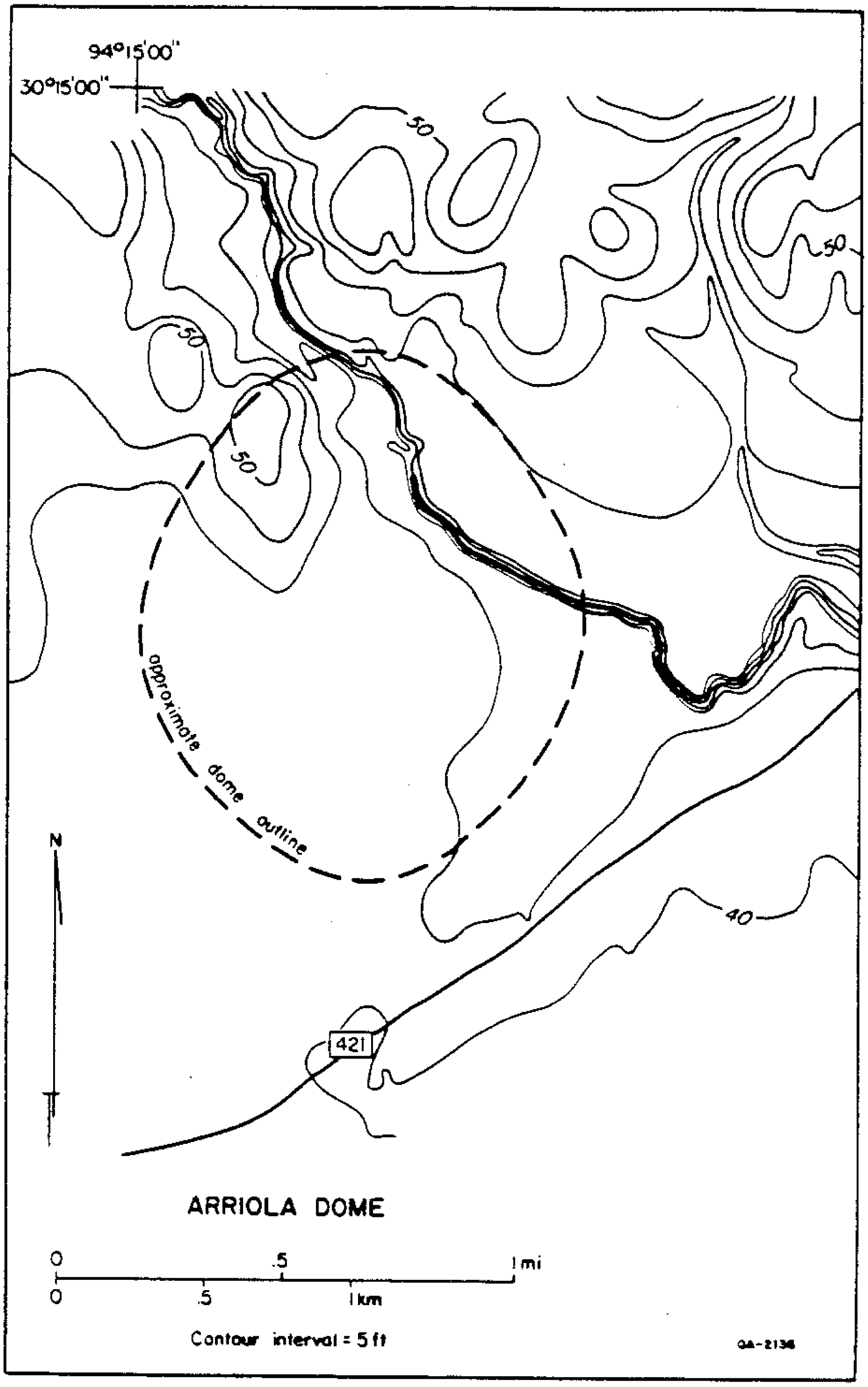
Winker, C. D., Morton, R. A., Ewing, T. E., and Garcia, D. D., 1983, Depositional setting, structural style, and sandstone distribution in three geopressured geothermal areas, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 134, 60 p.

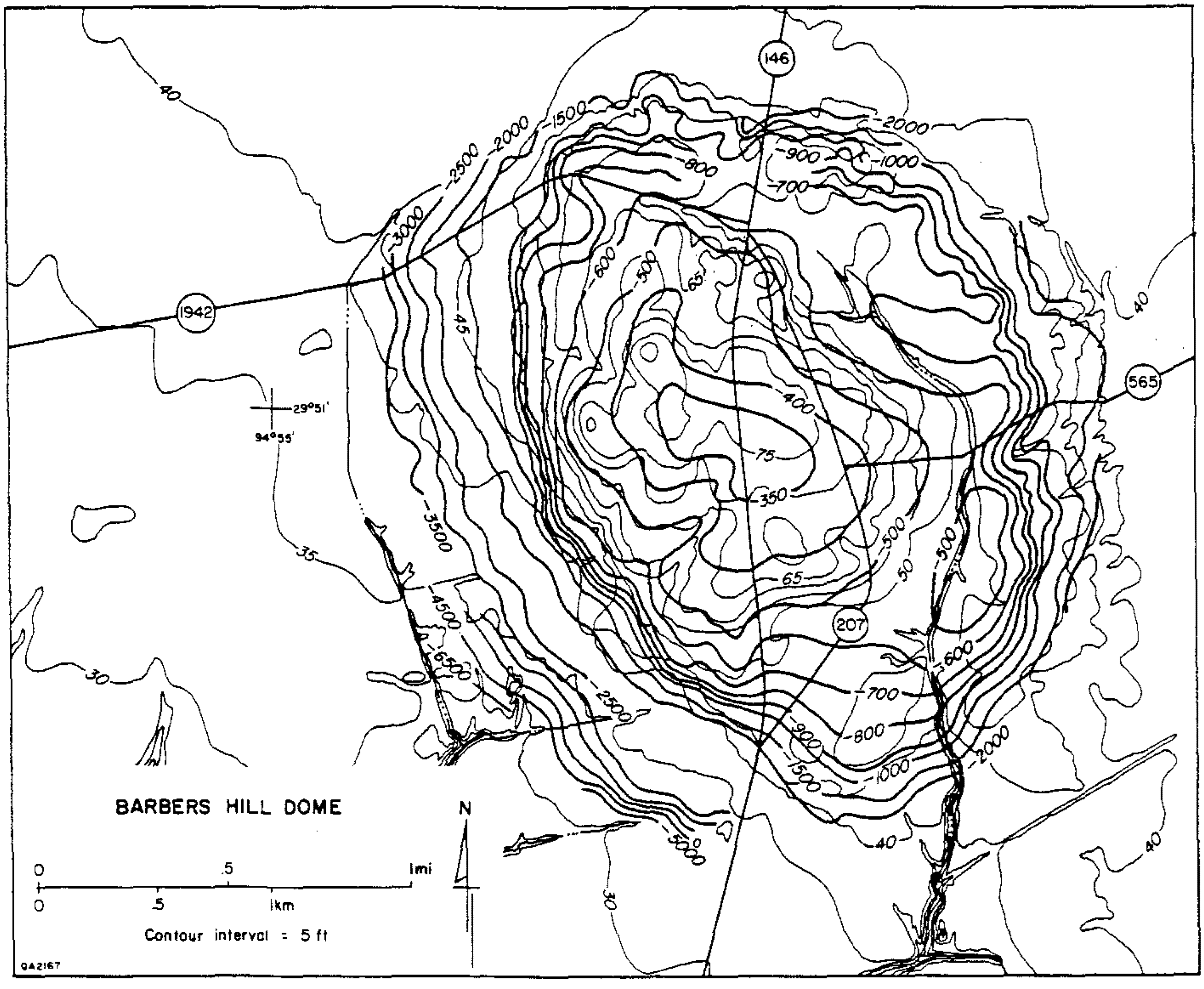
Wood, D. H., and Giles, A. B., 1982, Hydrocarbon accumulation patterns in the East Texas salt dome province: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 82-6, 36 p.

APPENDIX 1: Texas salt domes: natural resources, storage caverns, and extraction technology.

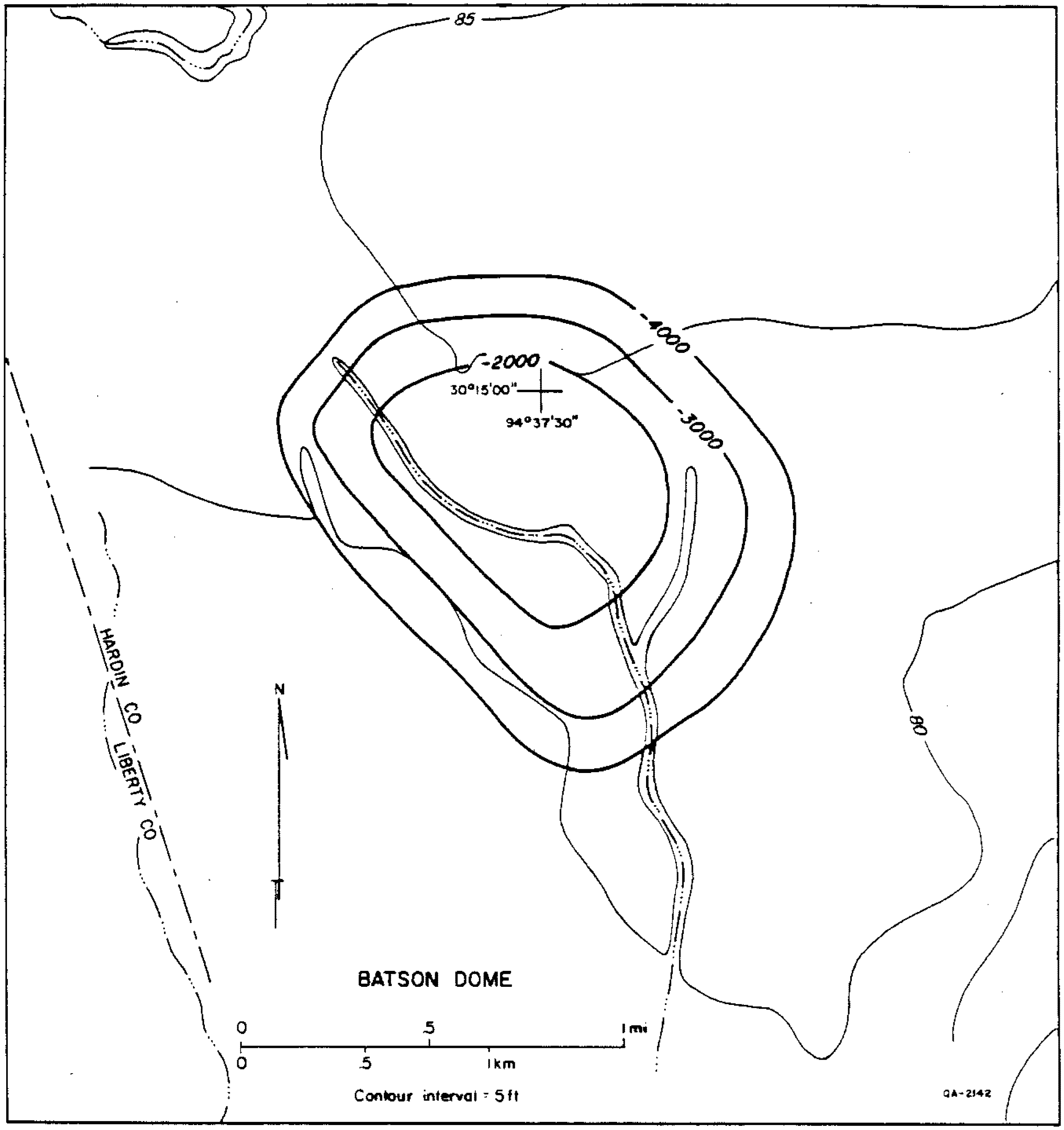
Structure-contour maps of Texas salt domes. Heavy lines are salt structure contours; light lines are surface topographic contours.

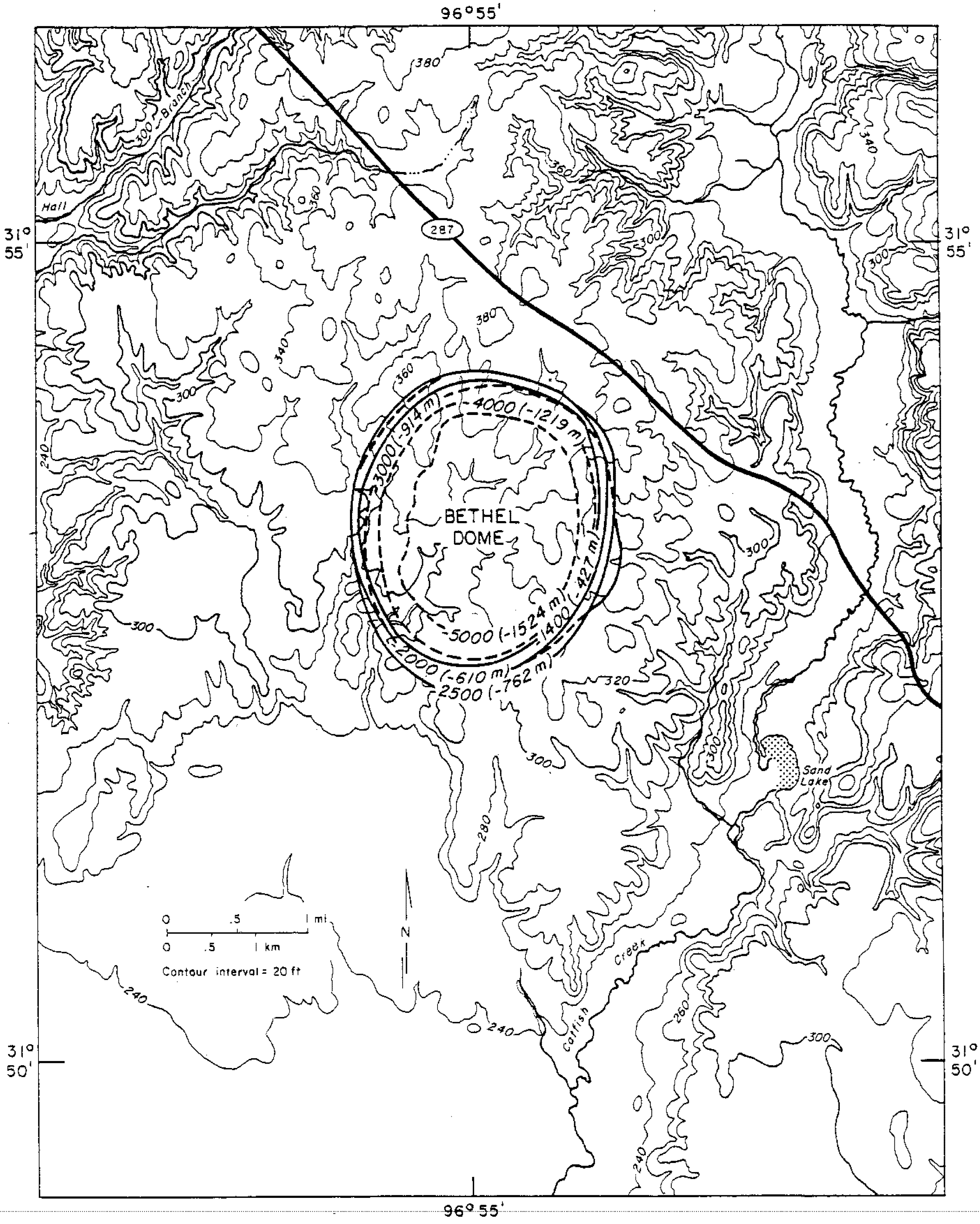

-5000
-1700
5
SAN BERNARD RIVER
N
28°55'00"
95°32'30"
2918
ALLEN DOME
0 .5 1mi
0 .5 1km
Contour interval = 5 ft
QA-2918

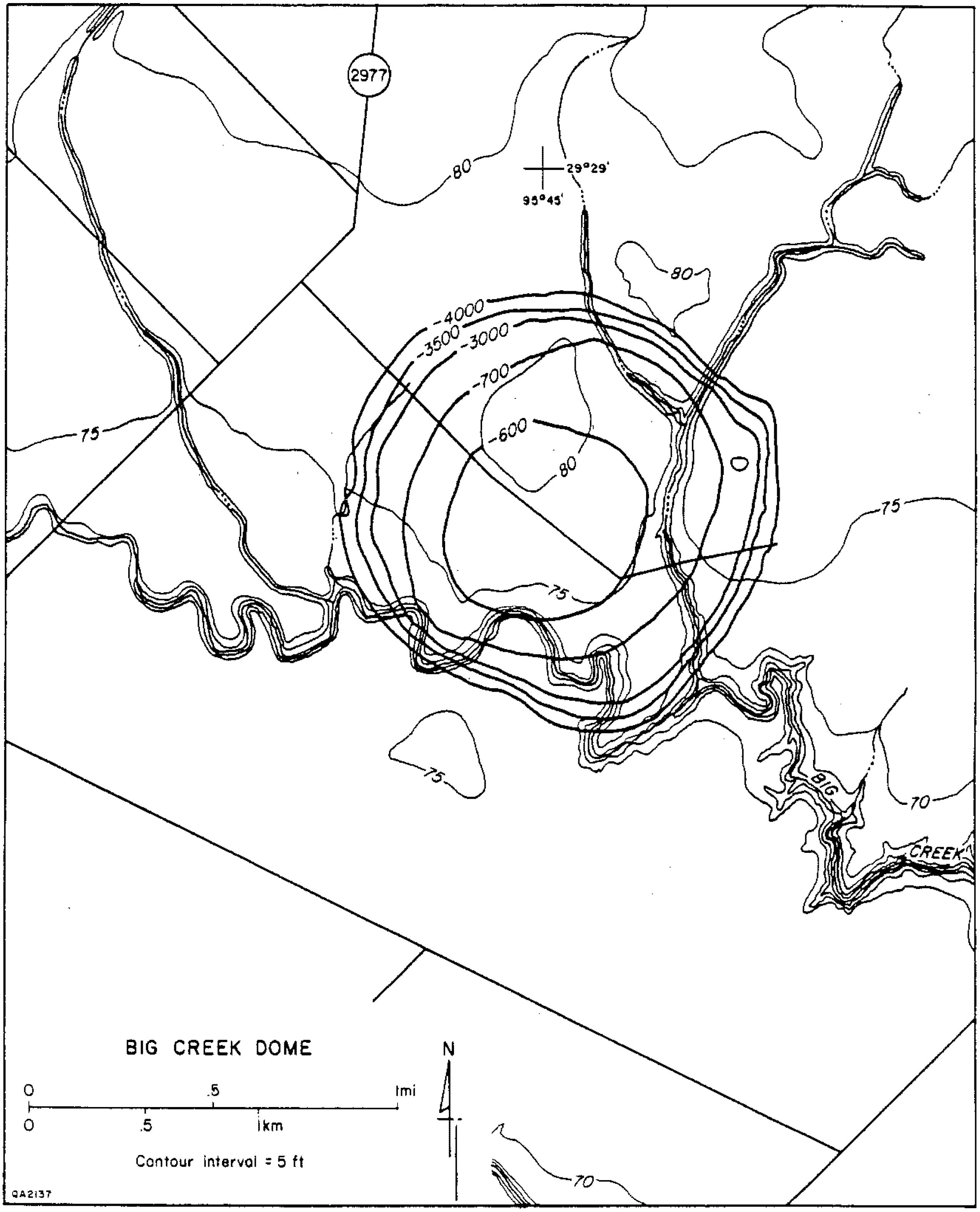

94°15'00"
30°15'00"
50
50
50
50
40
approximate dome outline
N
421
ARRIOLA DOME
0
.5
1 mi
0
.5
1 km
Contour interval = 5 ft
QA-2136



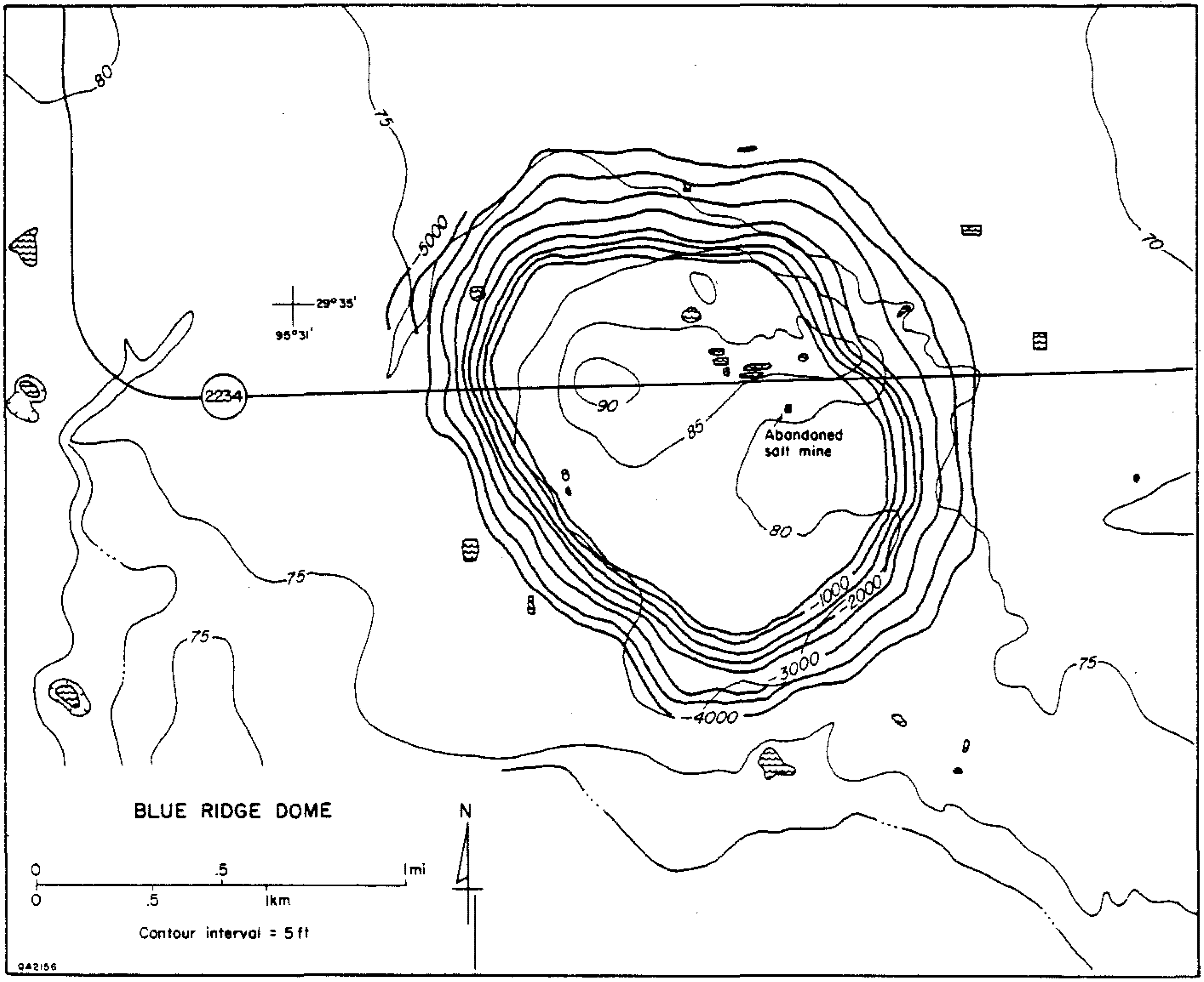
BARBERS HILL DOME

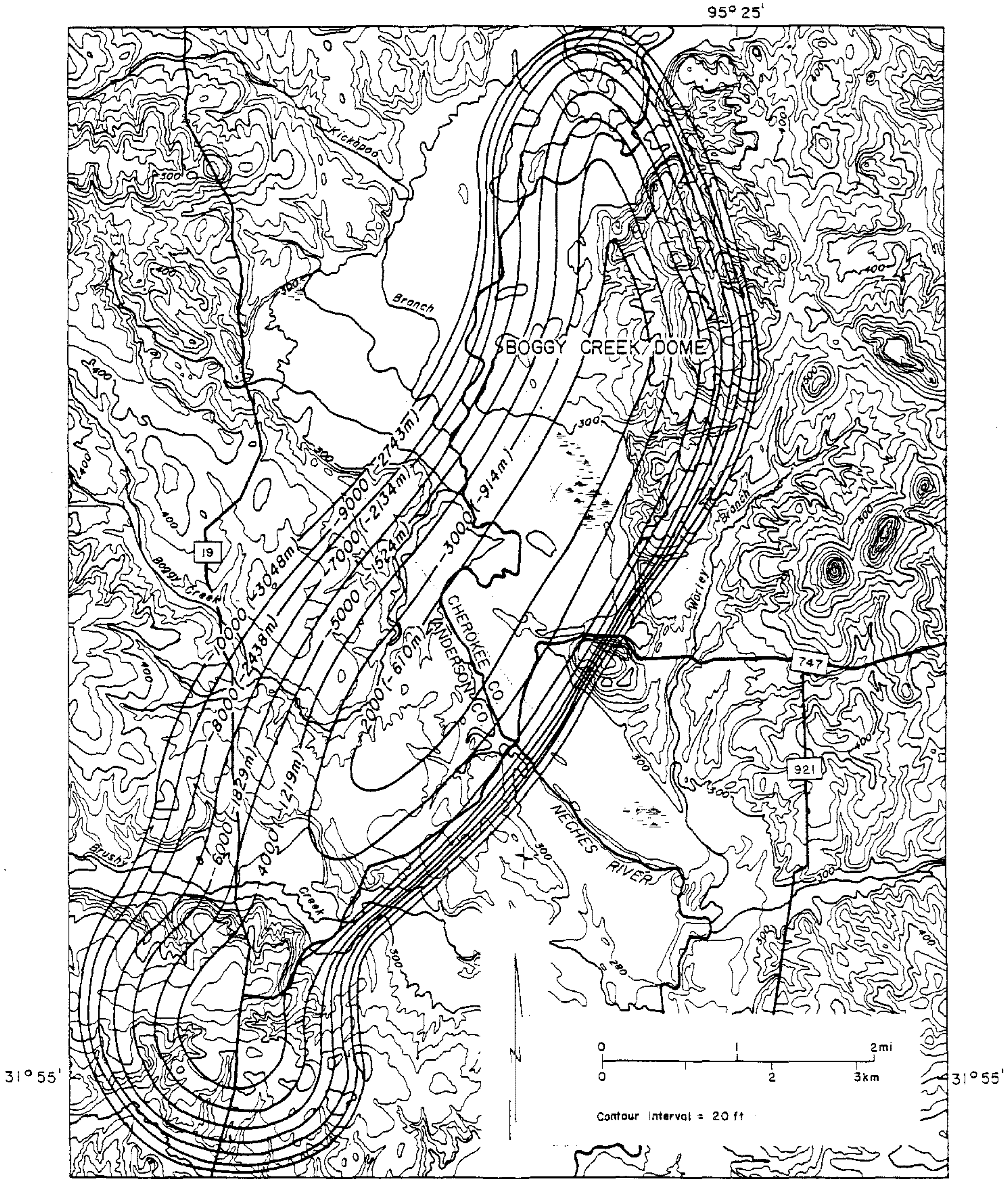

85
-4000
-2000
30°15'00"
94°37'30"
-3000
80
HARDIN CO
LIBERTY CO
N
BATSON DOME
0
.5
1 mi
0
.5
1 km
Contour interval = 5 ft
QA-2142

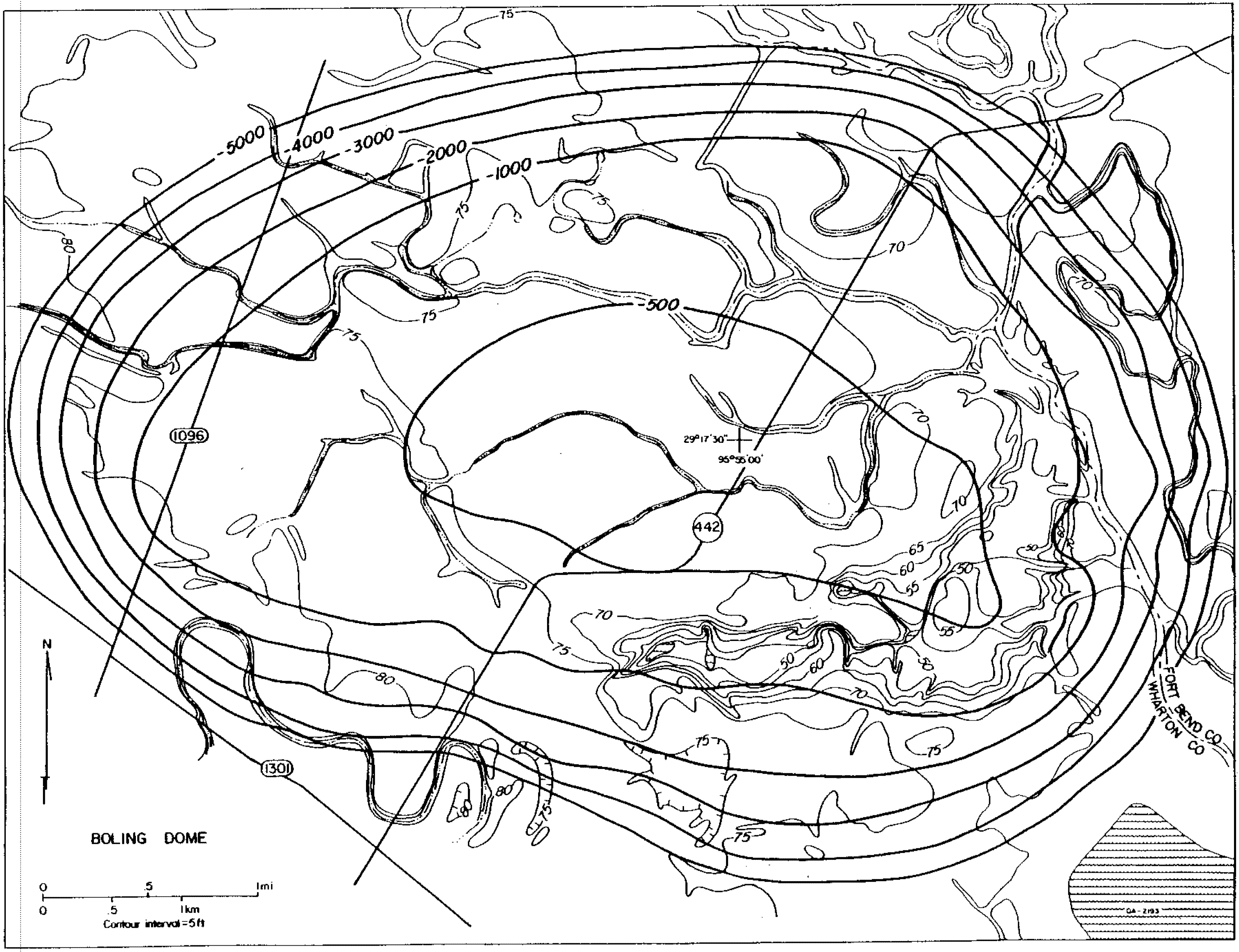

96°55'
31° 55'
31° 55'
31° 50'
31° 50'
96°55'
Hall
300
Branch
380
360
287
380
340
300
300
340
360
300
240
300
BETHEL DOME
4000 (-1219 m)
3000 (-914 m)
5000 (-1524 m)
1400 (-427 m)
2000 (-610 m)
2500 (-762 m)
320
300
300
Sand Lake
280
0 .5 1 mi
0 .5 1 km
Contour interval = 20 ft
N
240
240
Catfish Creek
260
300
240


BIG CREEK DOME


29°46'
94°15'
10
10
10
10
5
-4500
-5000
-4000
-3000
-3500
-2500
-2000
-1500
30
20
10
-4000
-5000
-1500
4500
-3500
3000
-2000
2500
BIG HILL DOME
0 .5 1mi
0 .5 1km
Contour interval = 5 ft
N
QA2146

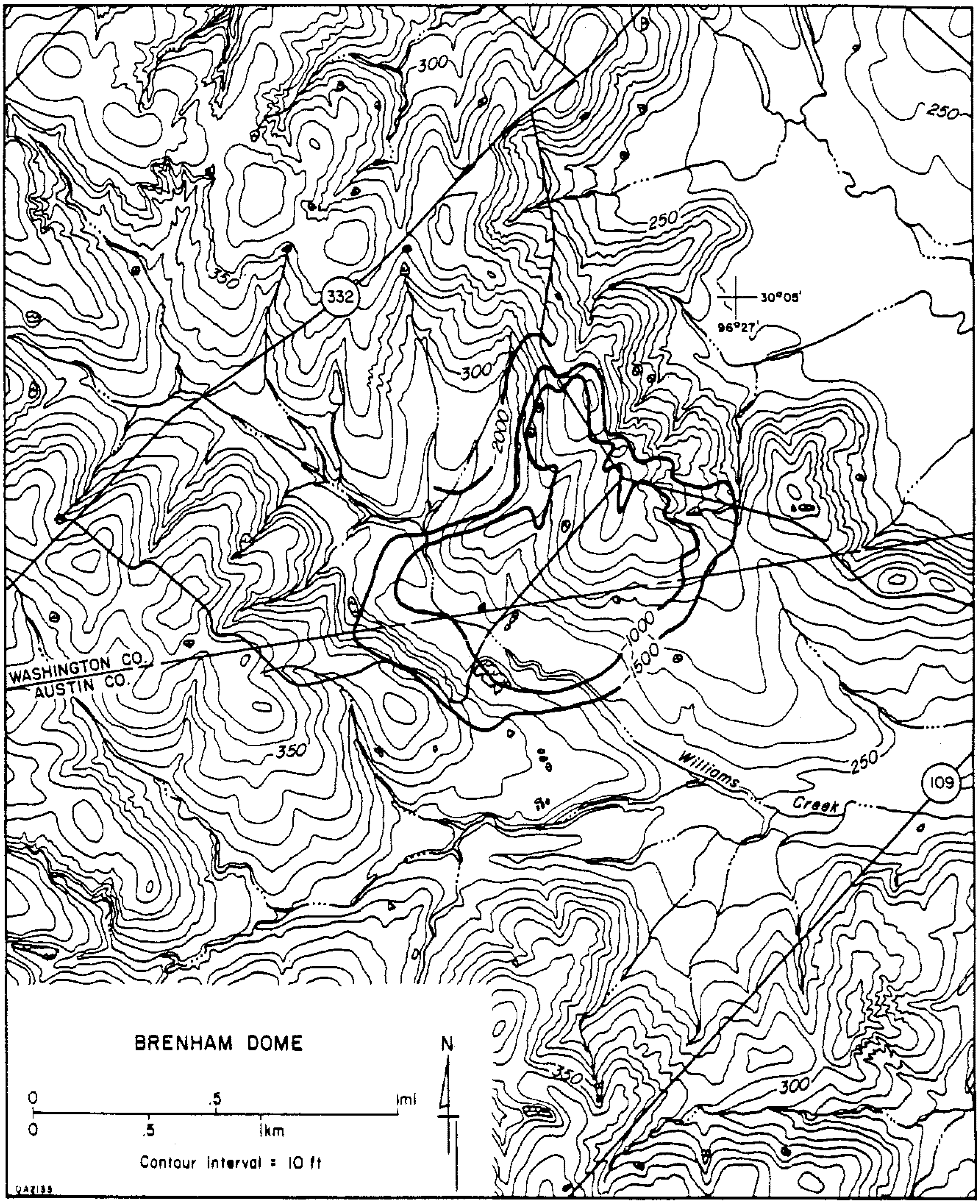

80
75
70
5000
29°35'
95°31'
2234
90
85
Abandoned salt mine
80
75
75
75
-1000
-2000
-3000
-4000
BLUE RIDGE DOME
N
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
QA2156

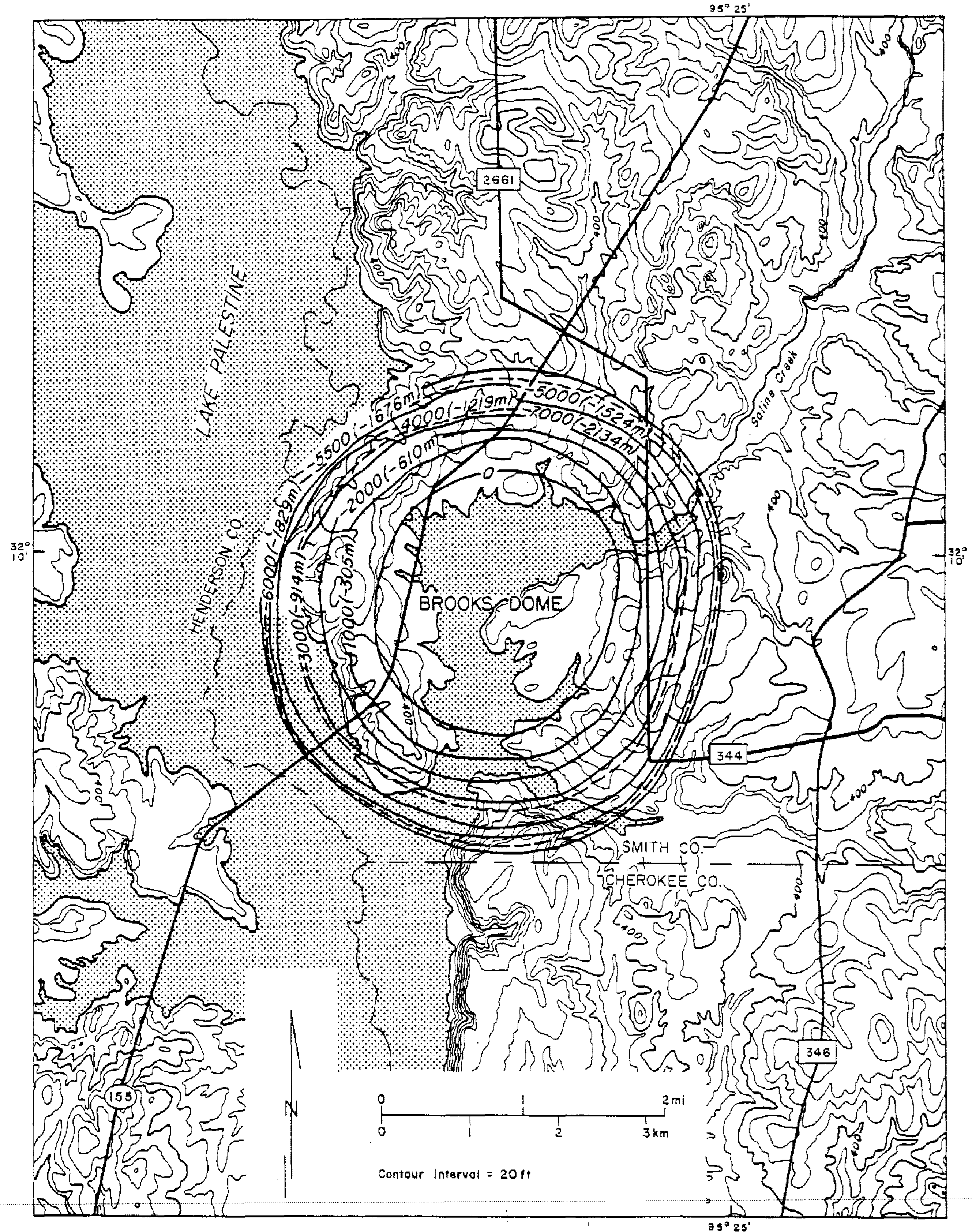

95° 25'
31° 55'
BOGGY CREEK DOME
Kickapoo
Branch
Boggy Creek
Brushy Creek
Worley Branch
NECHES RIVER
CHEROKEE CO.
ANDERSON CO.
19
747
921
-2000 (-610m)
-3000 (-914m)
-4000 (-1219m)
-5000 (-1524m)
-6000 (-1829m)
-7000 (-2134m)
-8000 (-2438m)
-9000 (-2743m)
-10000 (-3048m)
300
400
280
N
0 1 2mi
0 2 3km
Contour Interval = 20 ft

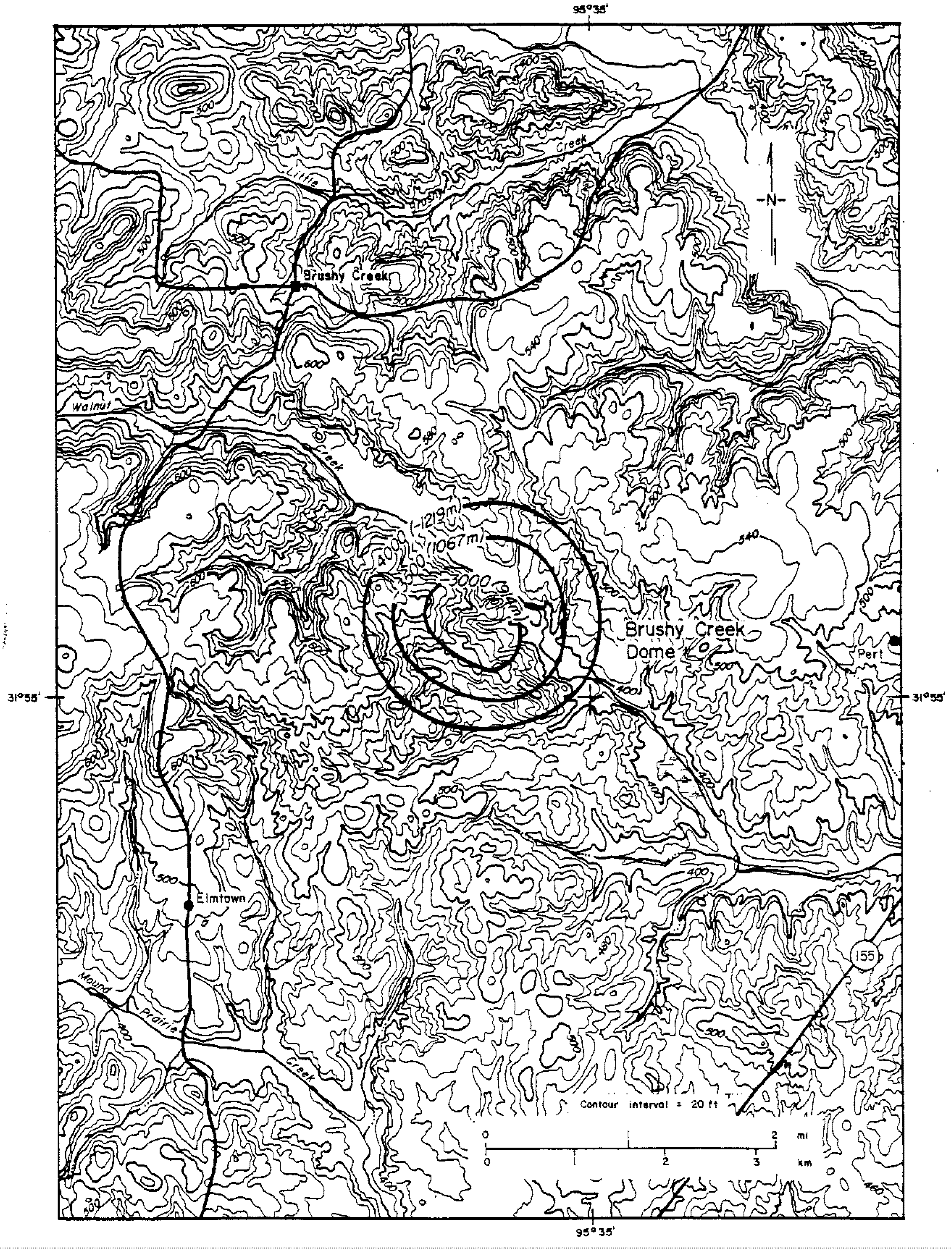


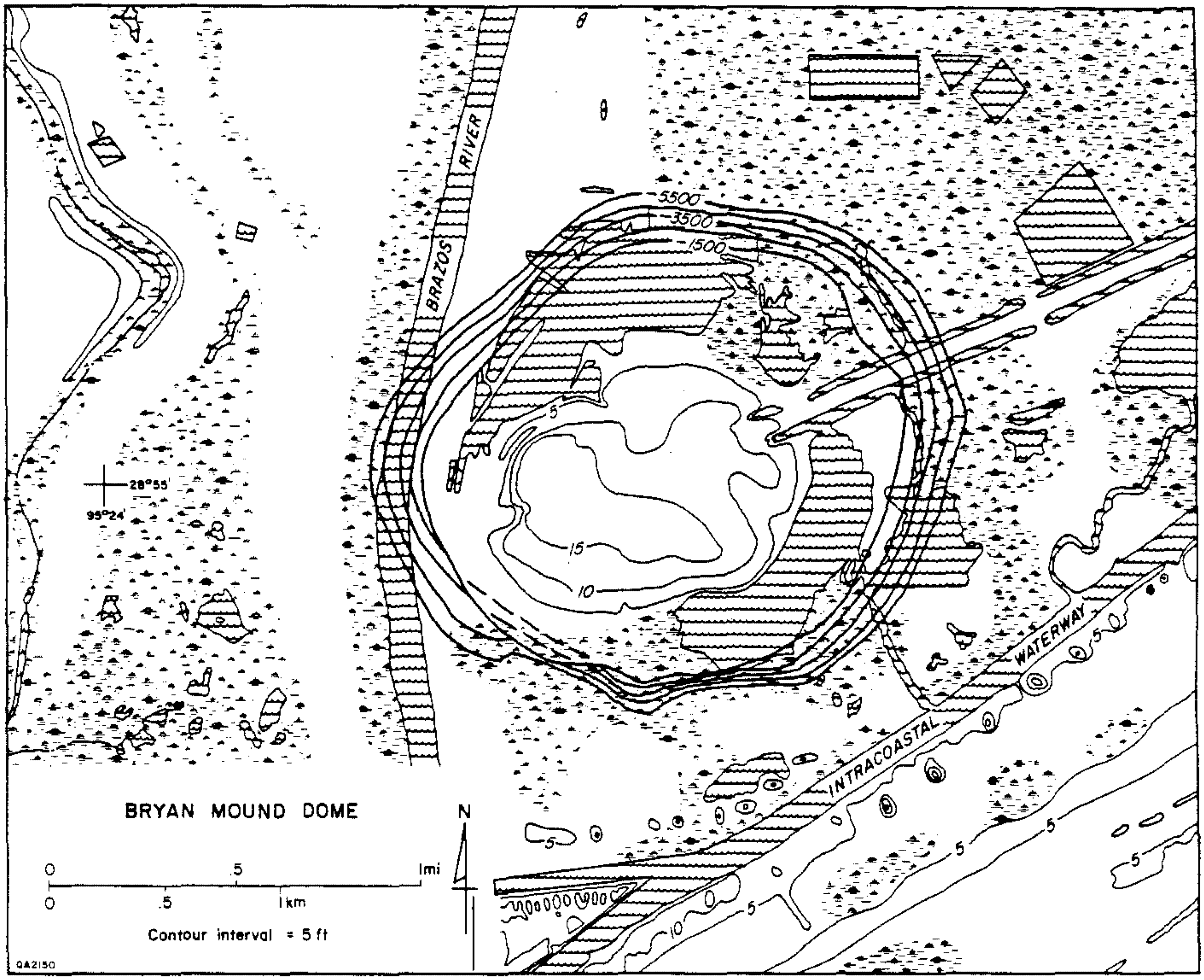
BOLING DOME

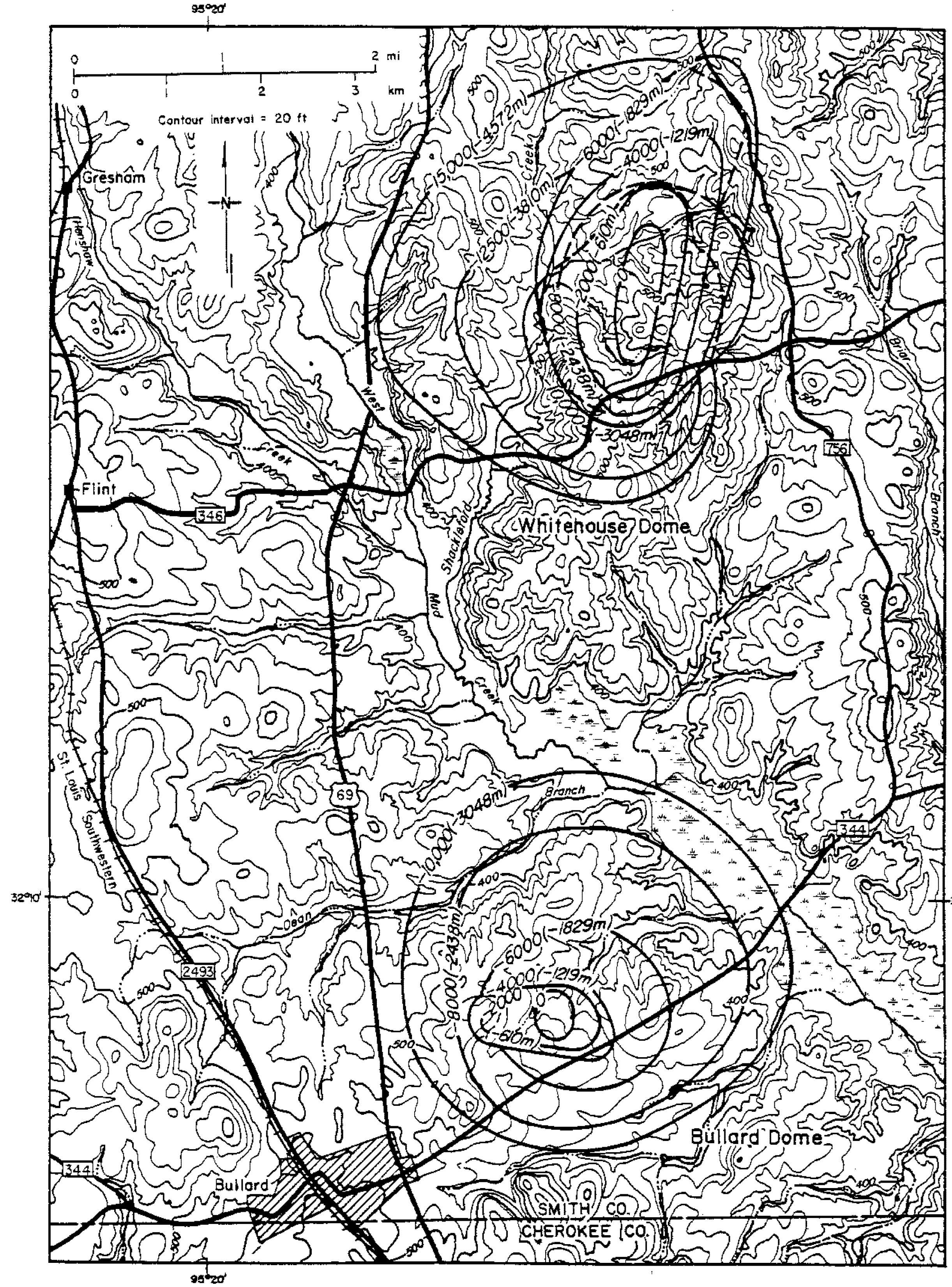
-5000
-4000
-3000
-2000
-1000
-500
75
70
65
60
55
50
80
1096
442
1301
29°17'30"
95°55'00"
FORT BEND CO
WHARTON CO
N
0 .5 1mi
0 .5 1km
Contour interval=5ft
QA-2193


BRENHAM DOME
0
.5
1mi
0
.5
1km
Contour interval = 10 ft
N
WASHINGTON CO.
AUSTIN CO.
332
109
Williams Creek
30°05'
96°27'
300
250
350
2000
1000
1500
0
QA2135

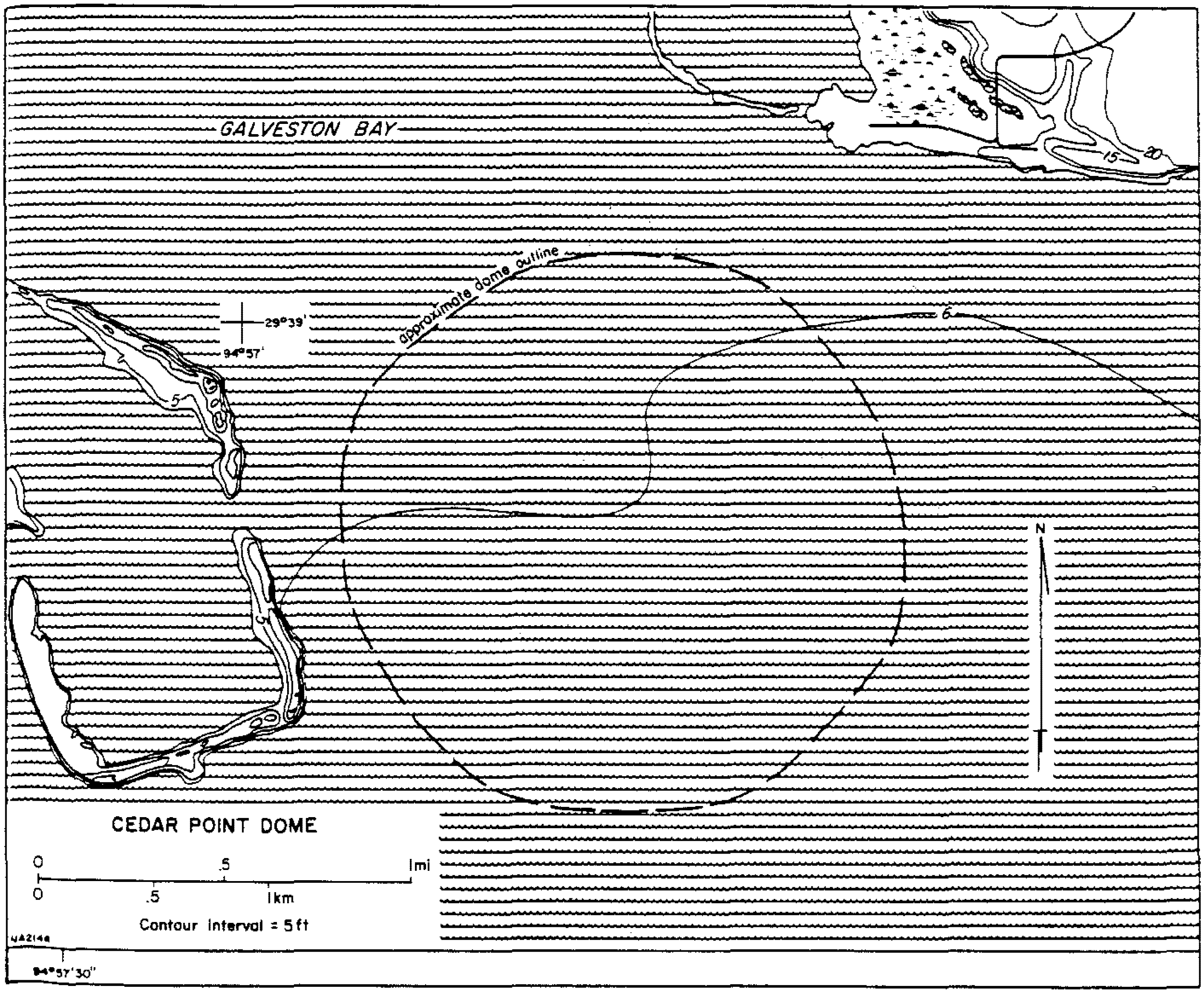

95° 25'
32° 10'
32° 10'
LAKE PALESTINE
HENDERSON CO.
2661
400
Salina Creek
-5000(-1524m)
-4000(-1219m)
-7000(-2134m)
-5500(-1676m)
-2000(-610m)
-6000(-1829m)
-3000(-914m)
-1000(-305m)
0
BROOKS DOME
344
SMITH CO.
CHEROKEE CO.
155
346
N
0 1 2 mi
0 1 2 3 km
Contour Interval = 20 ft
95° 25'


95°35'
31°55'
31°55'
95°35'
Little Brushy Creek
Brushy Creek
Walnut Creek
-4000 (-1219m)
-3500 (1067m)
-3000 (914m)
Brushy Creek Dome
Pert
Elmtown
Mound Prairie Creek
155
N
Contour interval = 20 ft
0 1 2 mi
0 1 2 3 km
400
460
500
540
600

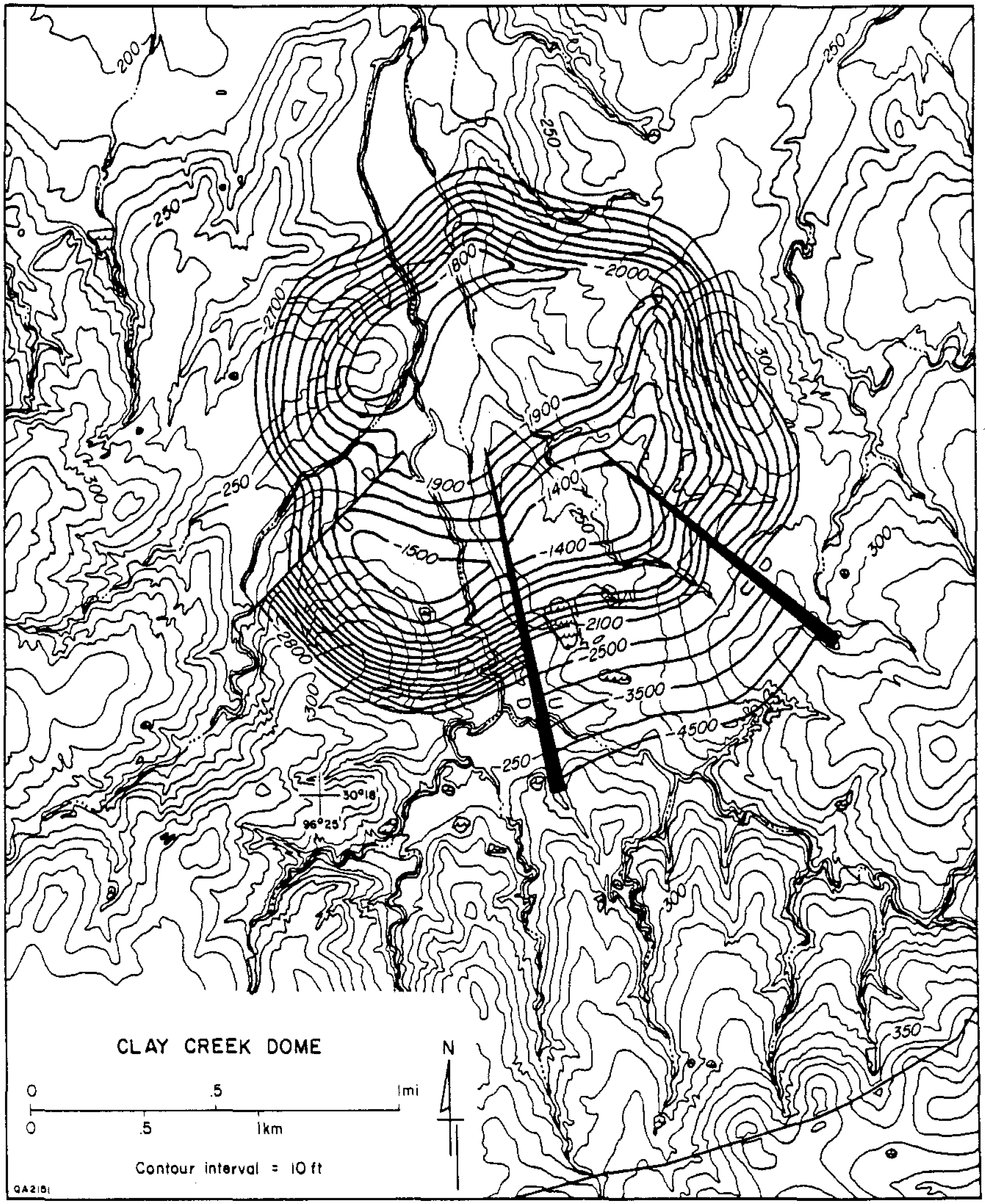

BRYAN MOUND DOME
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
QA2150
N
28°55'
95°24'
BRAZOS RIVER
INTRACOASTAL WATERWAY
5500
3500
1500
5
10
15

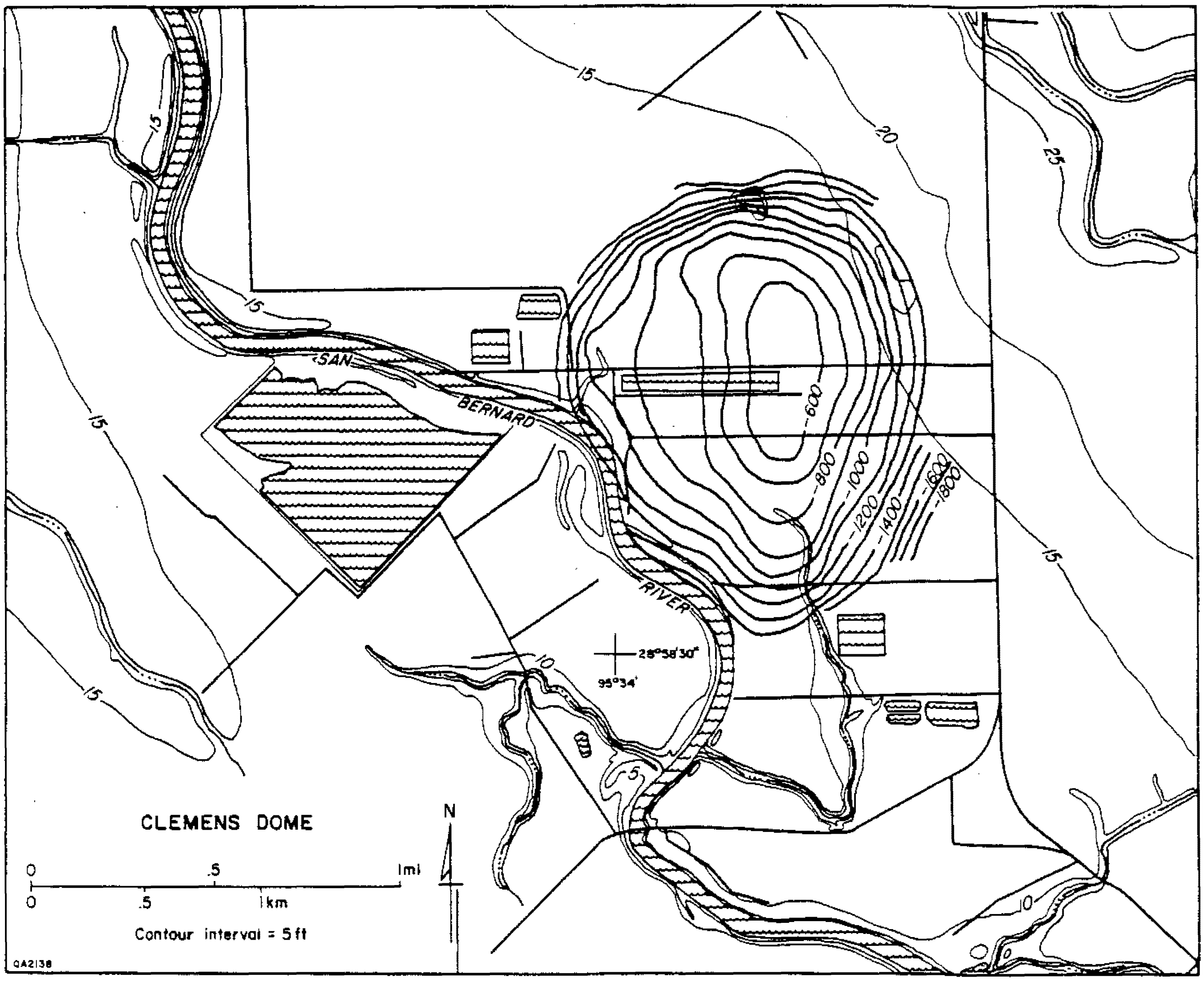

95°20'
0
1
2 mi
0
1
2
3
km
Contour interval = 20 ft
N
Gresham
(Henshaw)
Flint
346
Creek
West
Creek
-15,000(-4572m)
-12,500(-3810m)
-6000(-1829m)
-4000(-1219m)
-2000(-610m)
-8000(-2438m)
-10,000
-3048m
Whitehouse Dome
Shackelford
Mud
Creek
756
Briar
Branch
69
St. Louis Southwestern
Branch
-10,000(-3048m)
344
Dean
-6000(-1829m)
-4000(-1219m)
-2000
-610m
-8000(-2438m)
2493
Bullard Dome
344
Bullard
SMITH CO.
CHEROKEE CO.
32°10'
32°10'
400
500
95°20'


Cedar Lake Slough
225
TRINITY RIVER
220
210
ANDERSON COUNTY
FREESTONE COUNTY
Gaston Branch
-5000 (-1524m)
-4000 (-1219m)
-3000 (-914m)
-2000 (-610m)
-1000 (-305m)
0
Saline Branch
BUTLER DOME
Blue Lake
8000 (-2438m)
7000 (-2134m)
-6000 (-1829m)
250
300
350
275
79
84
Caney Cr.
N
0 2000 4000 ft
0 500 1000m
Contour interval = 10ft
31°40'
95° 52' 30"


GALVESTON BAY
approximate dome outline
6
29°39'
94°57'
5
15
20
N
CEDAR POINT DOME
0 .5 1mi
0 .5 1km
Contour interval = 5ft
QA2144
94°57'30"

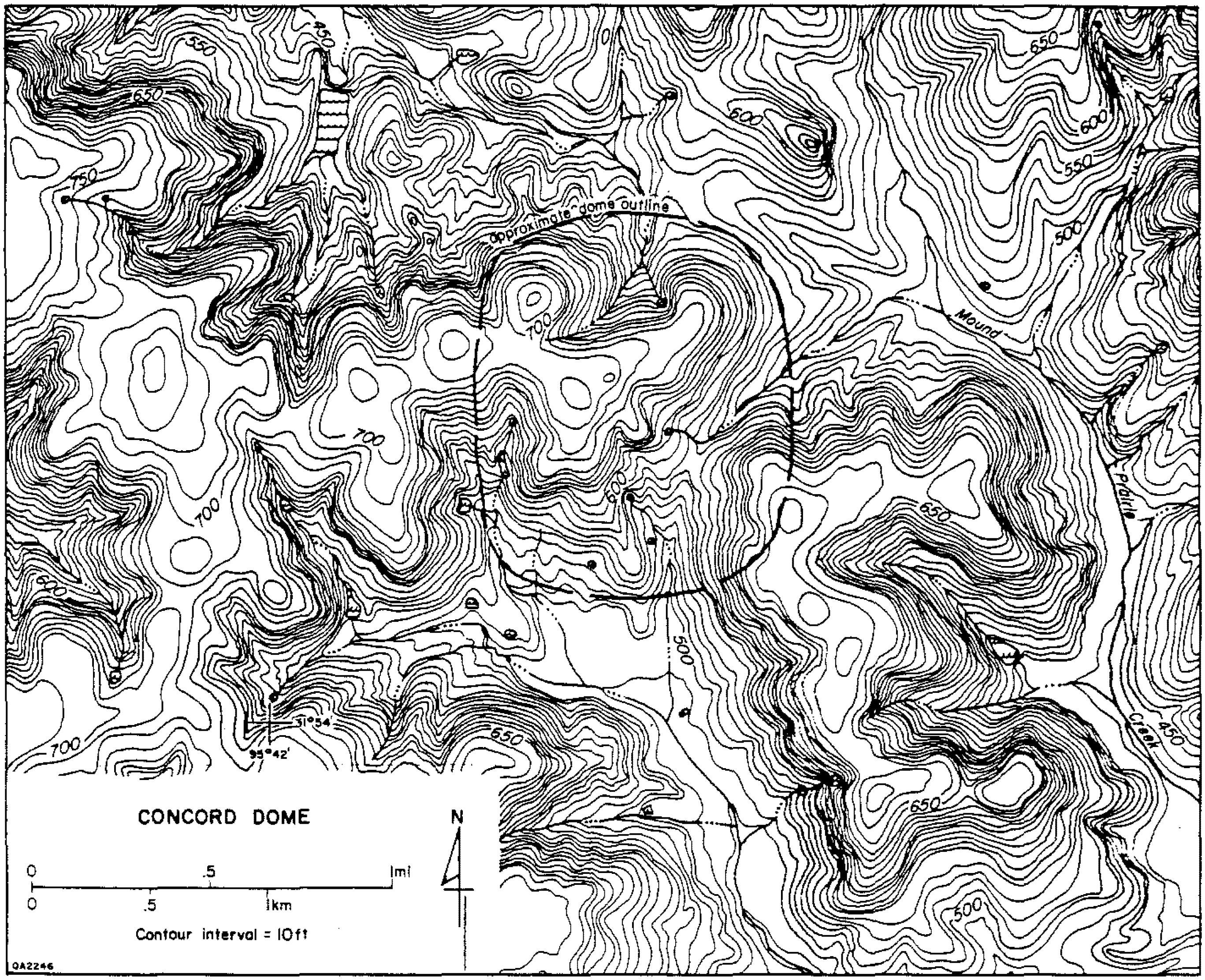

INTRACOASTAL WATERWAY
5
29°42'30"
94°07'30"
approximate dome outline
N
CLAM LAKE
CLAM LAKE DOME
0
.5
1 mi
0
.5
1 km
Contour interval = 5 ft
QA-2140

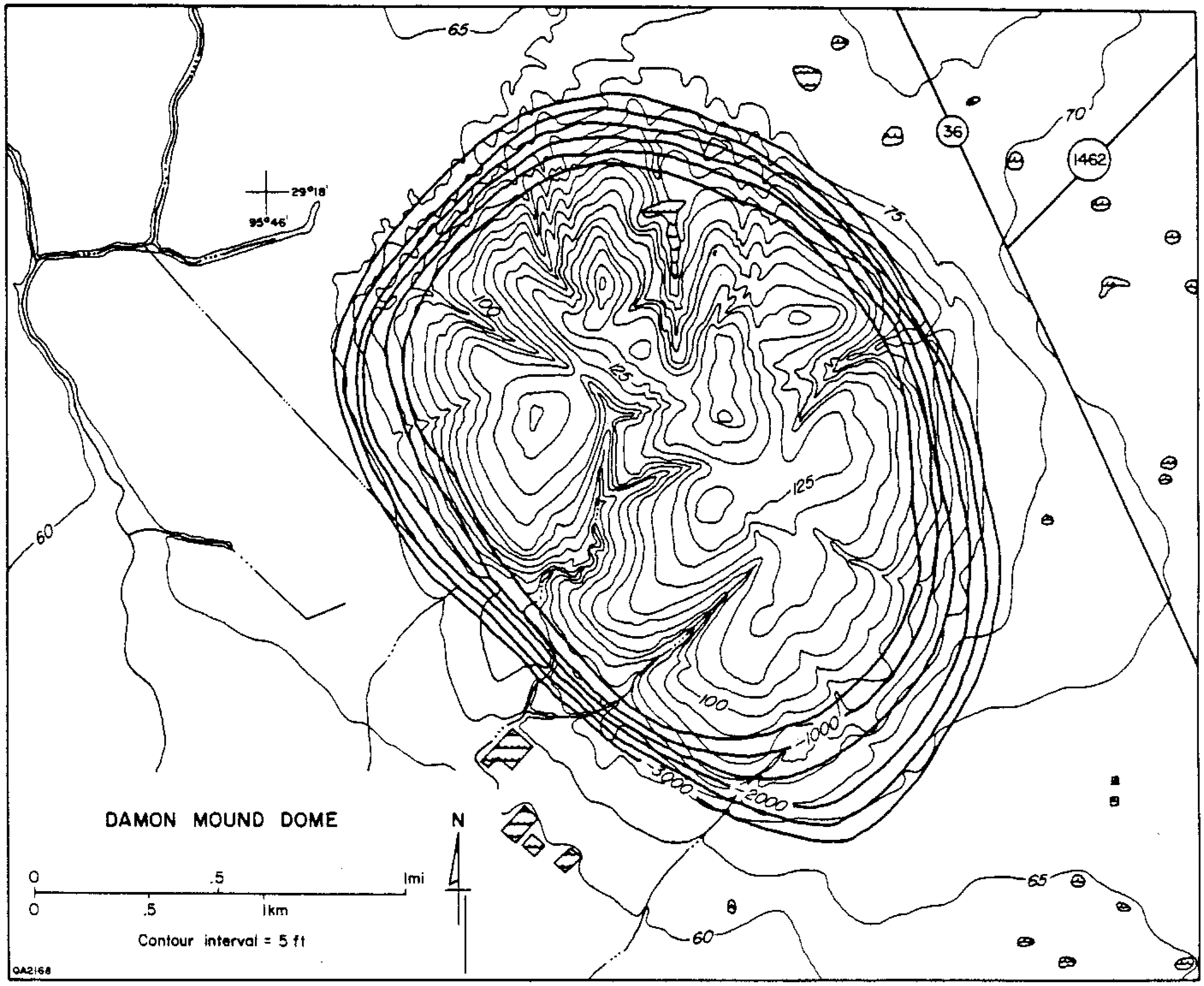

CLAY CREEK DOME
0
.5
1mi
0
.5
1km
Contour interval = 10 ft
N
QA2151
200
250
250
250
250
300
300
300
300
350
2700
2800
1800
2000
1900
1900
1400
1400
1500
2100
2500
3500
4500
30°18'
96°25'
D
U

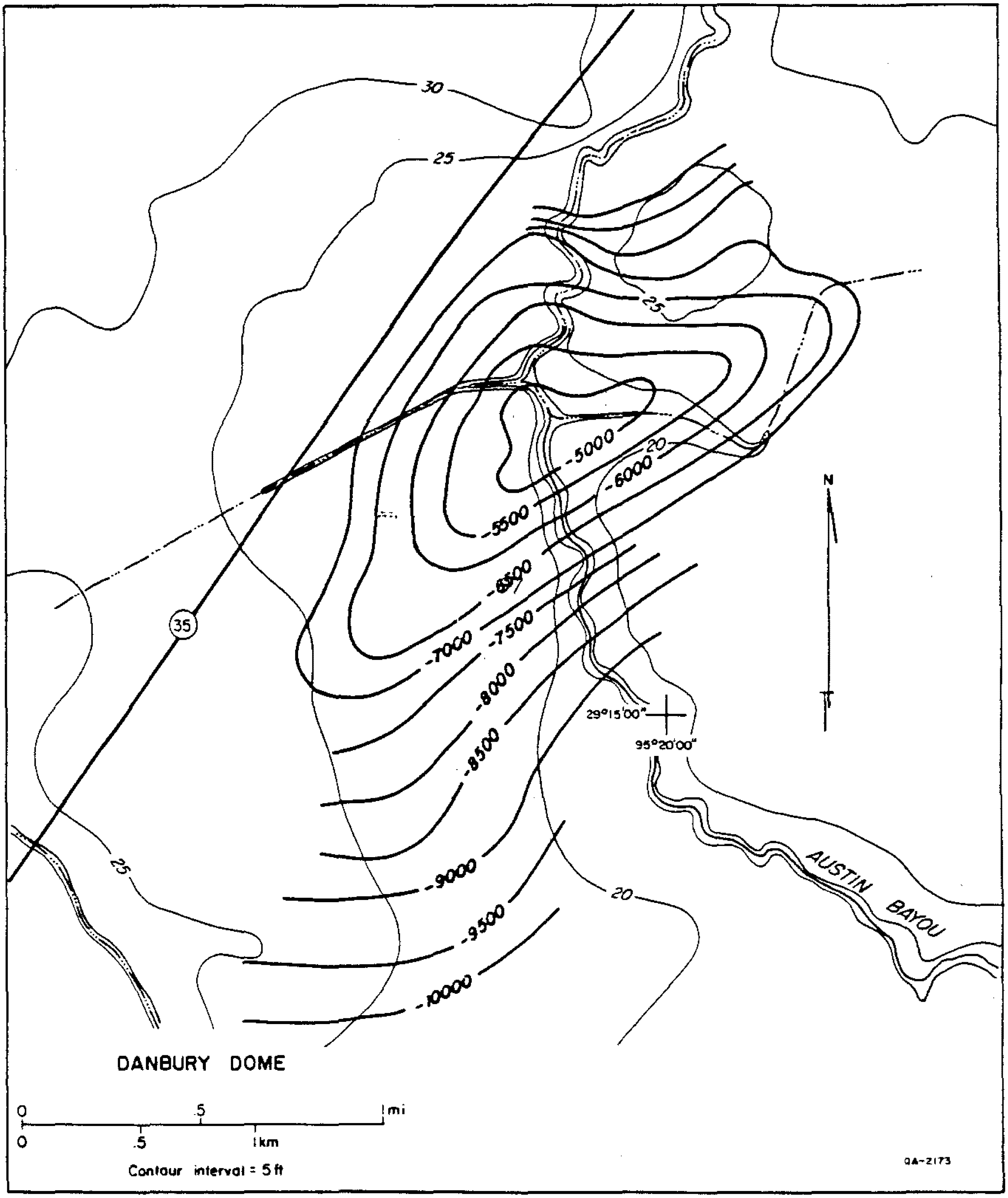


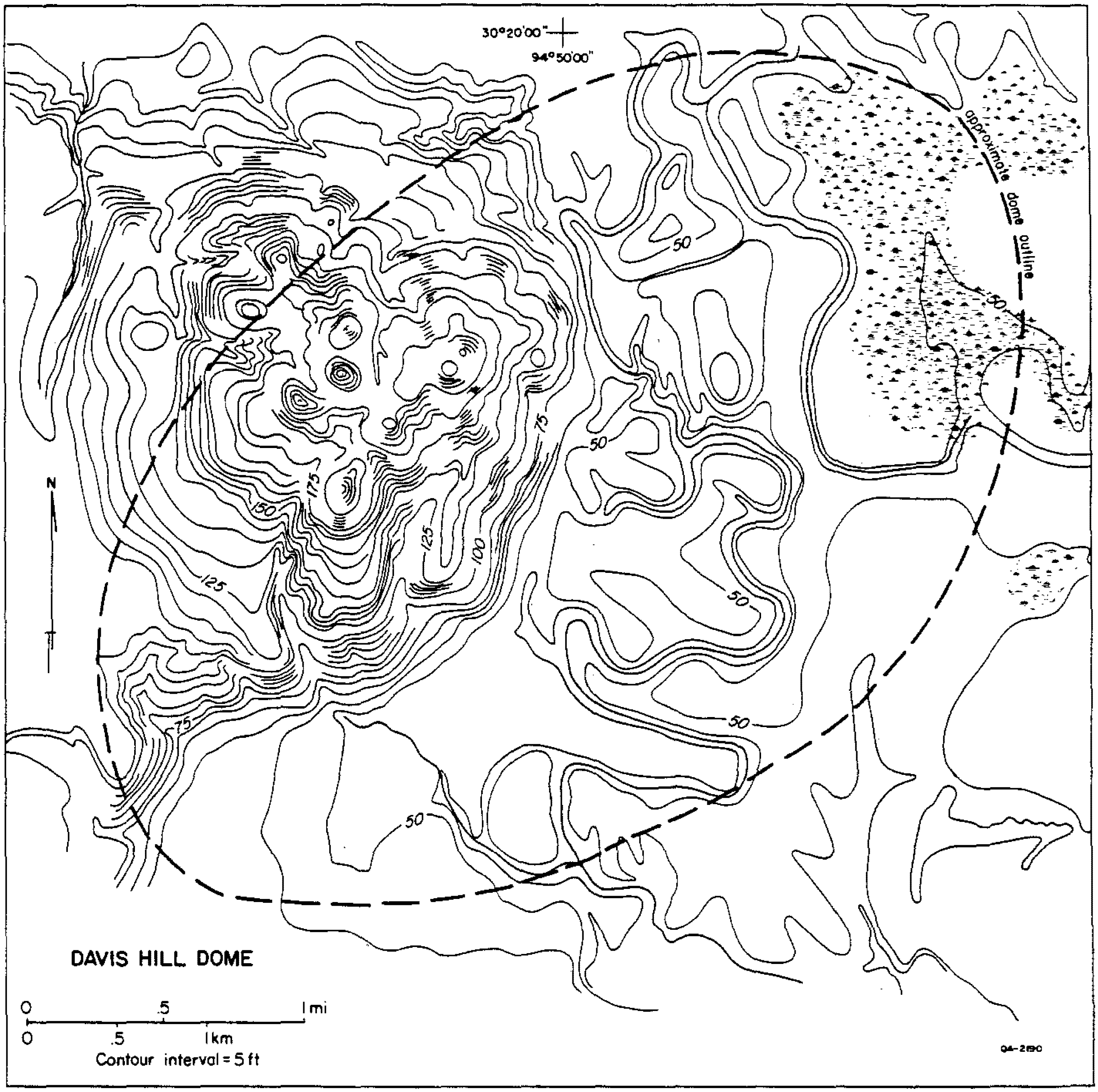
CLEMENS DOME

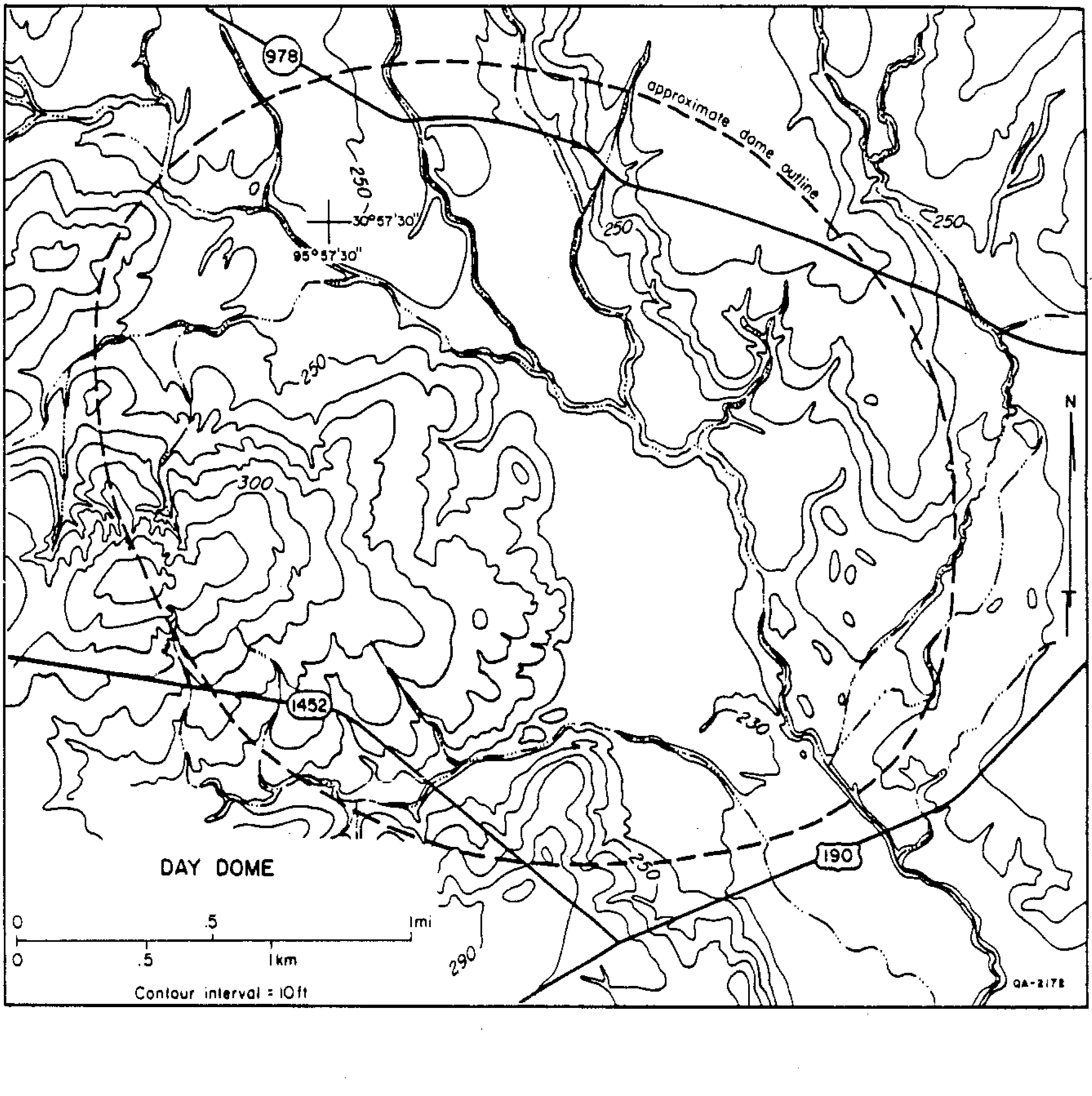
Contour interval = 5 ft


CONCORD DOME
0 .5 1mi
0 .5 1km
Contour interval = 10ft
N
QA2246
approximate dome outline
Mound
Prairie
Creek
31°54'
95°42'
750
700
650
600
550
500
450

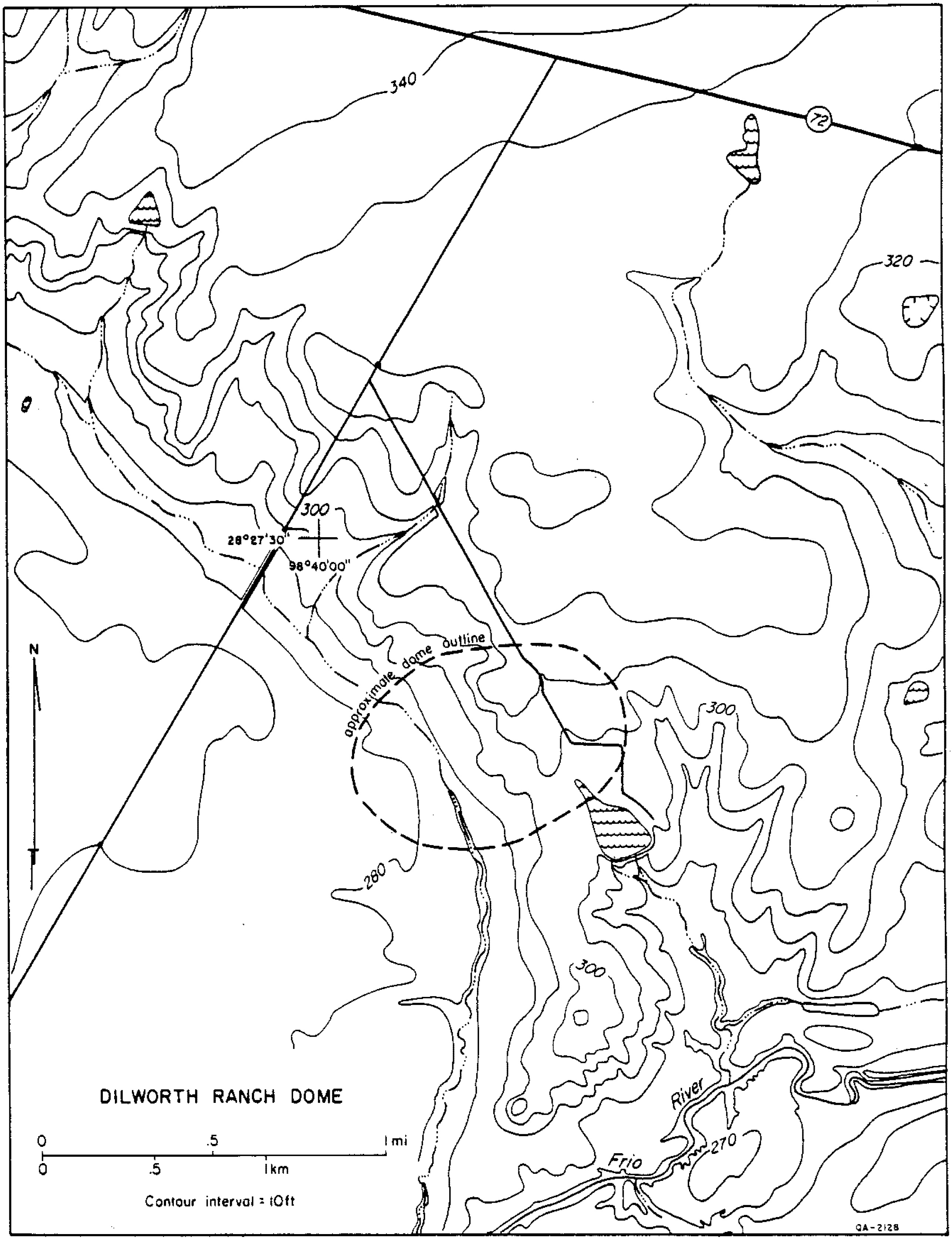

65
70
75
36
1462
29°18'
95°46'
60
100
125
125
100
1000
2000
3000
DAMON MOUND DOME
N
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
65
60
QA2168

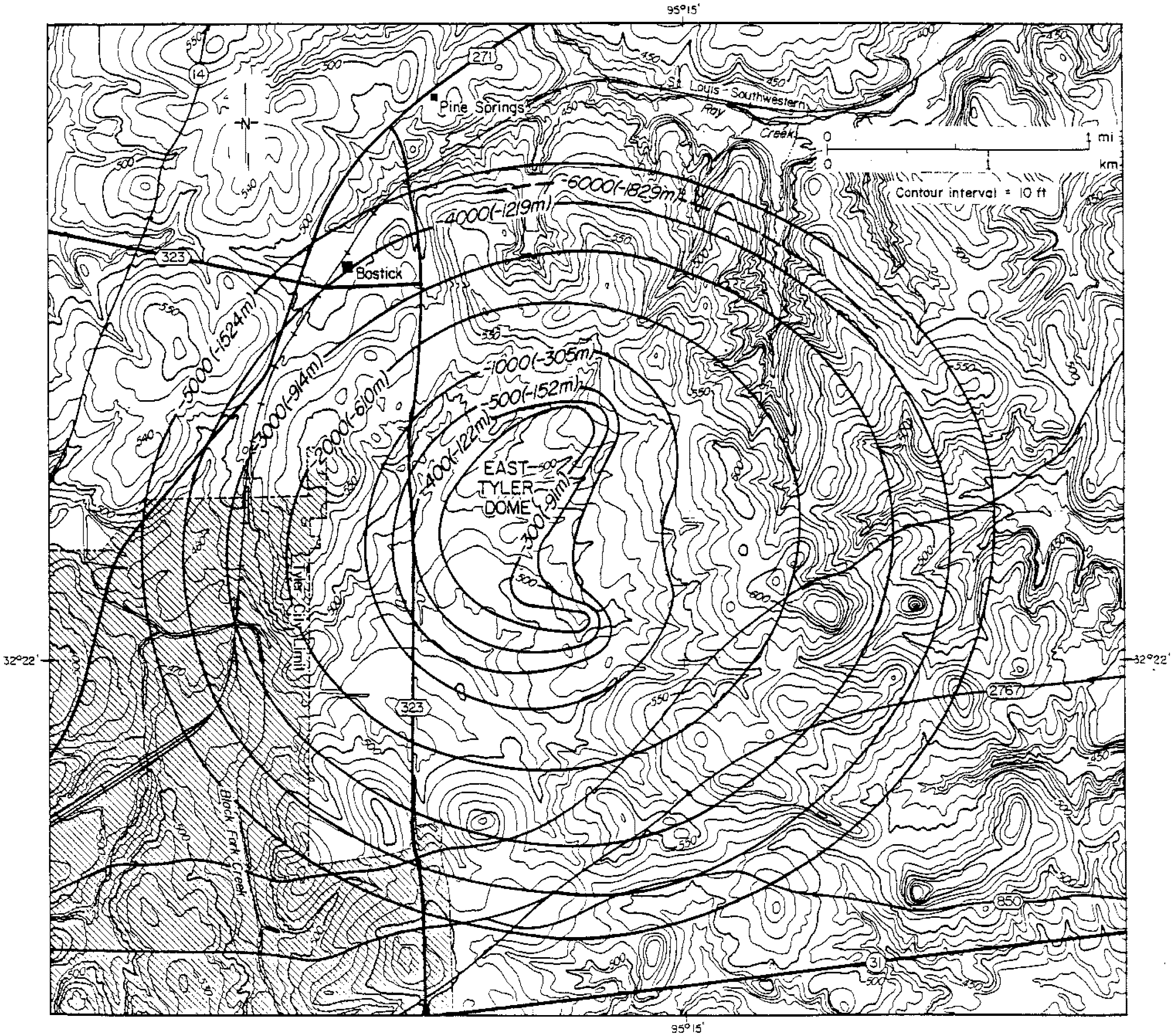

30
25
25
25
20
20
-5000
-5500
-6000
-6500
-7000
-7500
-8000
-8500
-9000
-9500
-10000
35
N
29°15'00"
95°20'00"
AUSTIN BAYOU
DANBURY DOME
0
.5
1 mi
0
.5
1 km
Contour interval = 5 ft
QA-2173

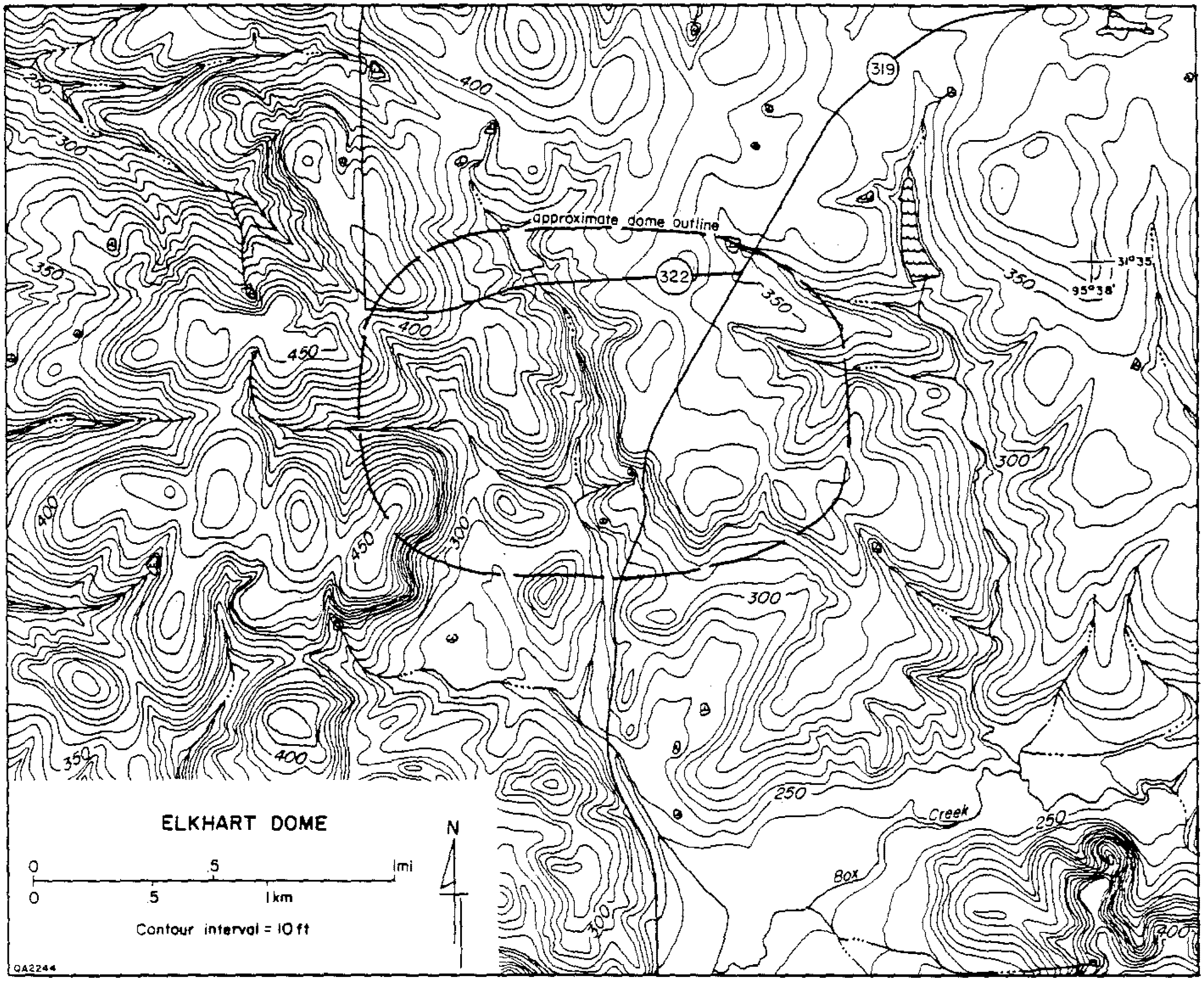

30°20'00"
94°50'00"
approximate dome outline
50
75
100
125
150
175
N
DAVIS HILL DOME
0 .5 1 mi
0 .5 1 km
Contour interval = 5 ft
94-2190

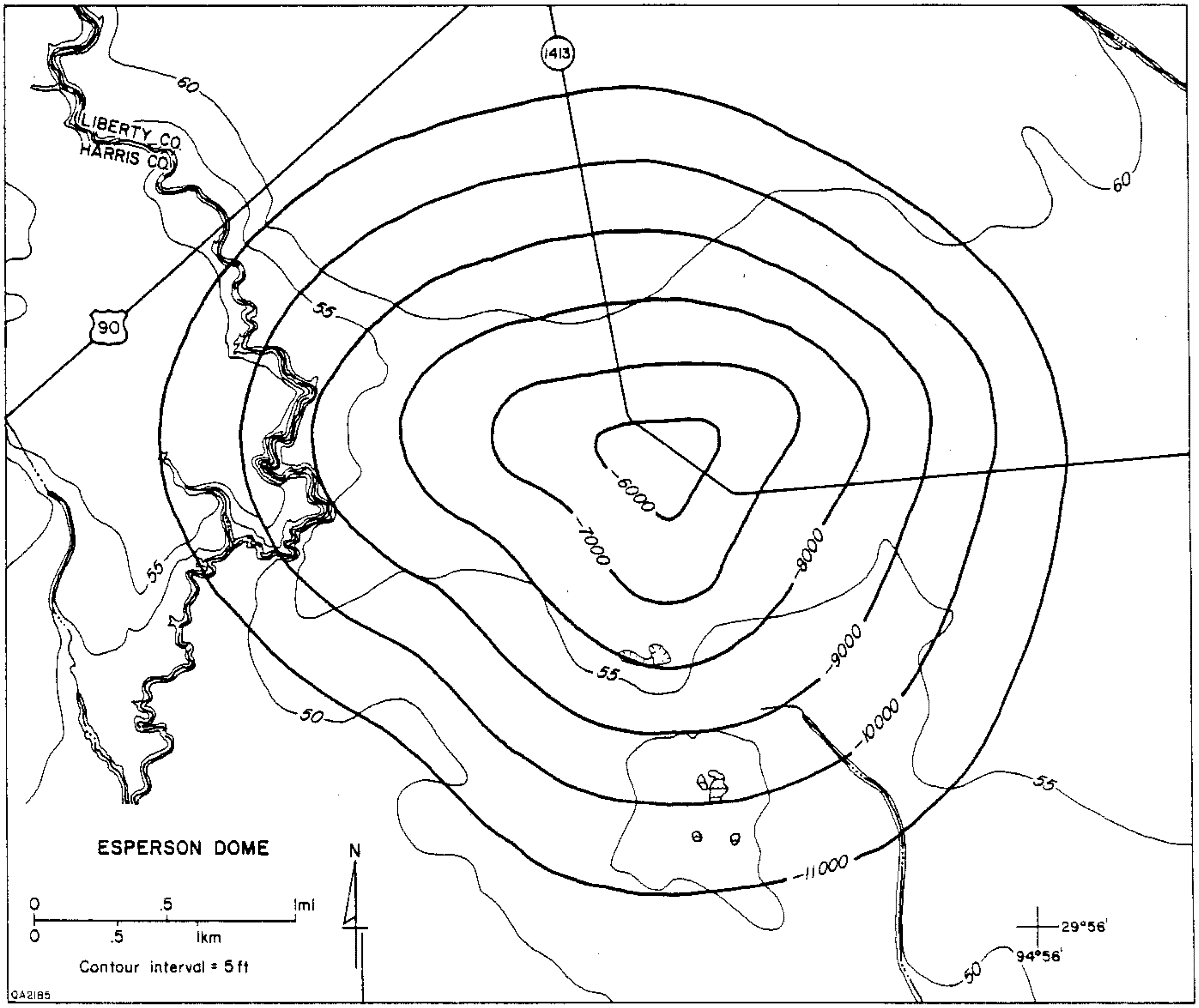


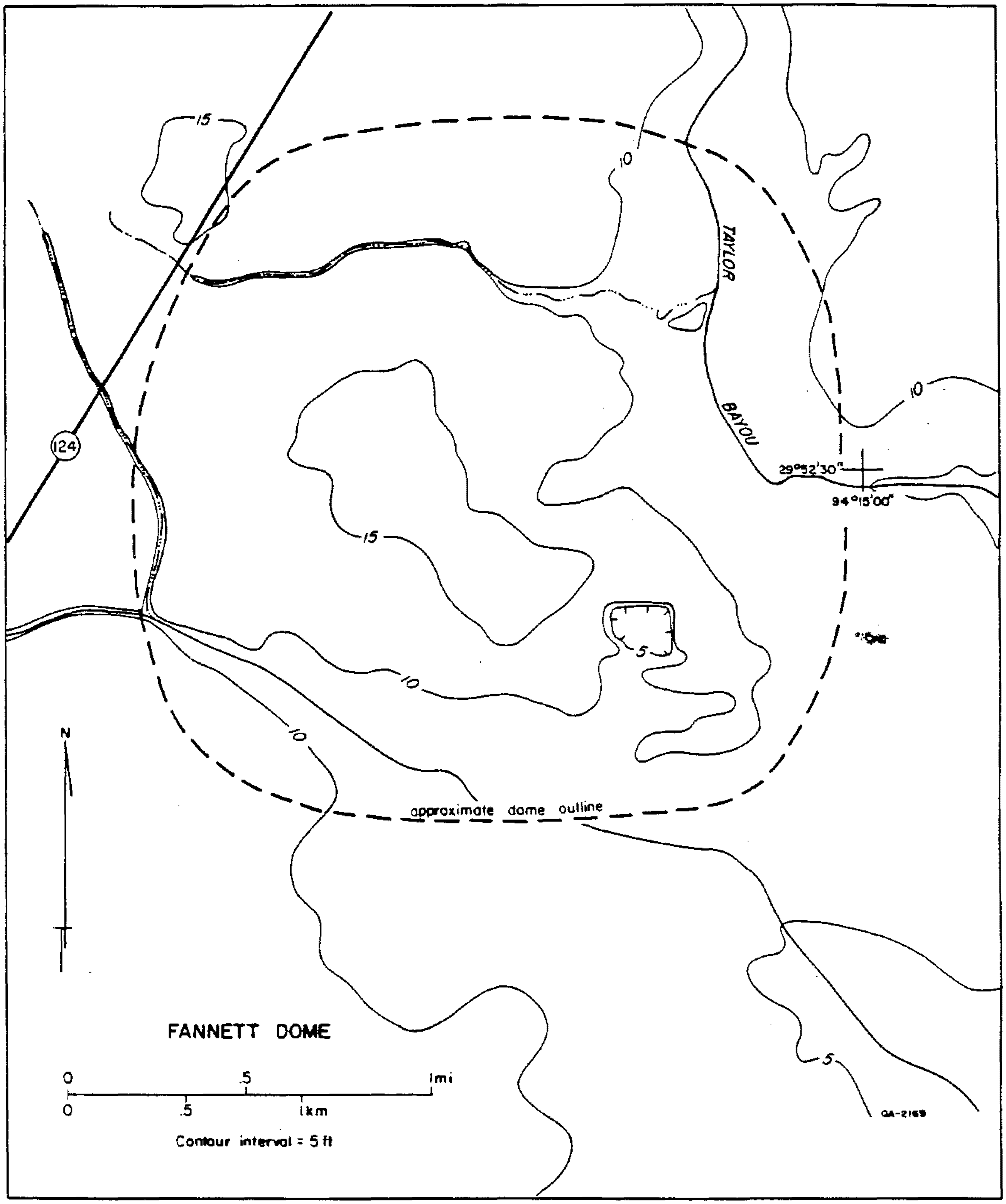
978
approximate dome outline
250
30°57'30"
95°57'30"
250
250
250
300
1452
230
190
250
290
DAY DOME
0
.5
1mi
0
.5
1km
Contour interval = 10 ft
N
QA-2178


340
72
320
300
28°27'30"
98°40'00"
approximate dome outline
300
N
280
300
River
Frio
270
DILWORTH RANCH DOME
0
.5
1 mi
0
.5
1 km
Contour interval = 10 ft
QA-2128

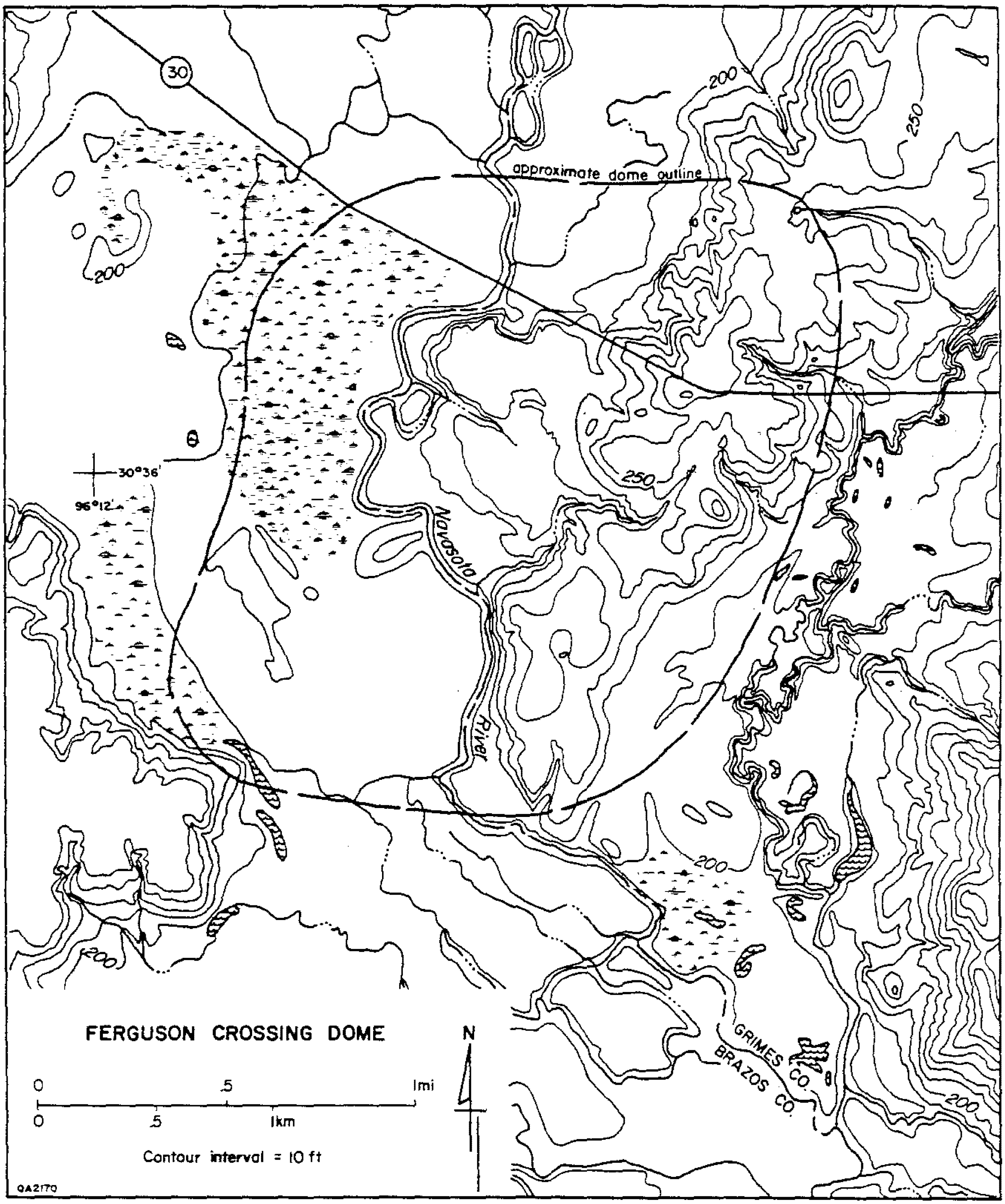

95°15'
N
Pine Springs
St. Louis - Southwestern
Ray Creek
0 1 mi
0 1 km
Contour interval = 10 ft
-6000(-1829m)
-4000(-1219m)
Bostick
-5000(-1524m)
-3000(-914m)
-2000(-610m)
-1000(-305m)
-500(-152m)
-400(-122m)
-300(-91m)
EAST TYLER DOME
Tyler City Limit
Black Fork Creek
14
271
323
2767
850
31
32°22'
32°22'
95°15'


ELKHART DOME
0
.5
1mi
0
.5
1km
Contour interval = 10 ft
N
QA2244
approximate dome outline
319
322
31°35'
95°38'
250
300
350
400
450
Box
Creek

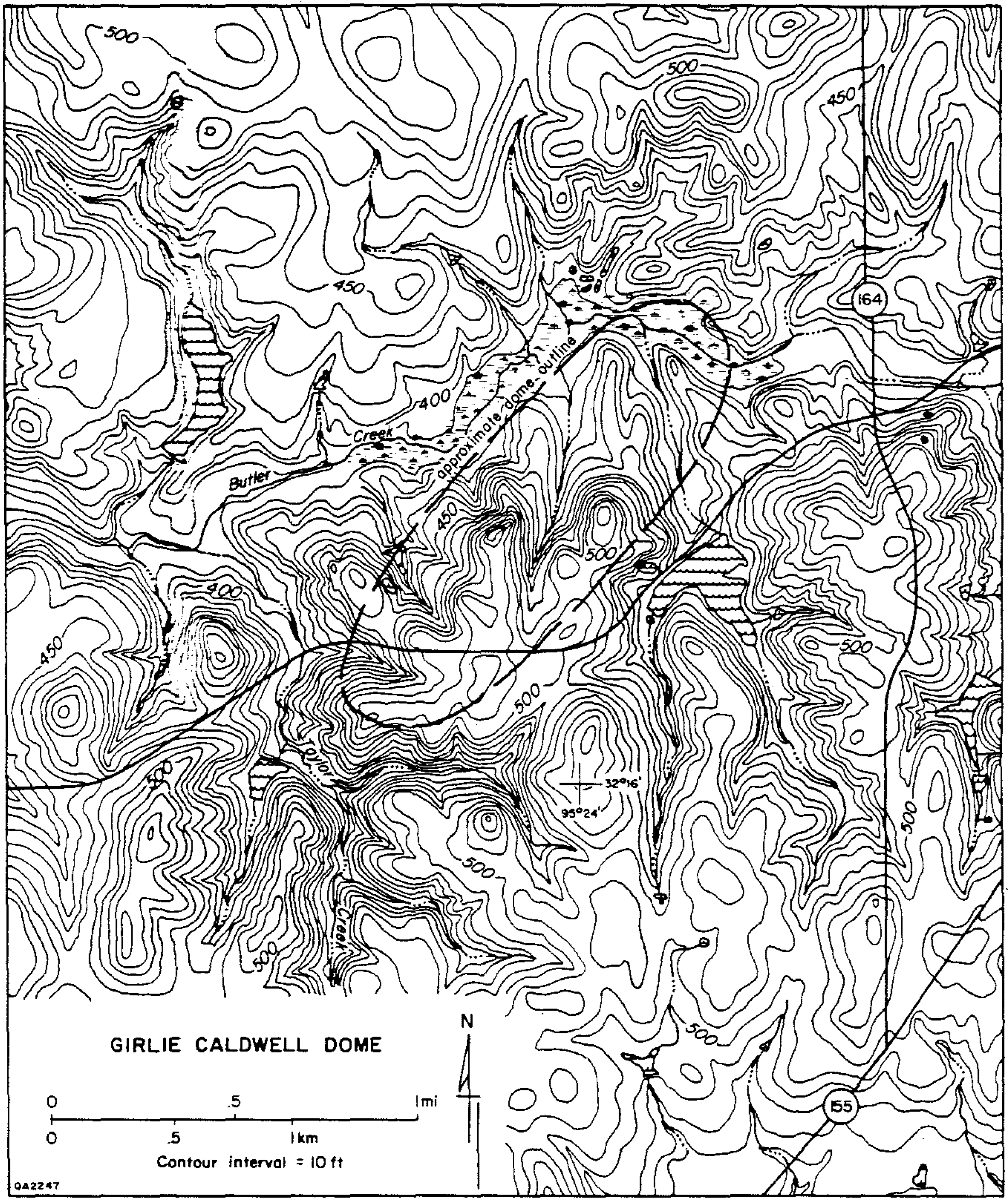

1413
60
LIBERTY CO.
HARRIS CO.
90
55
60
-6000
-7000
-8000
-9000
-10000
-11000
55
55
50
55
50
ESPERSON DOME
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
N
29°56'
94°56'
QA2185

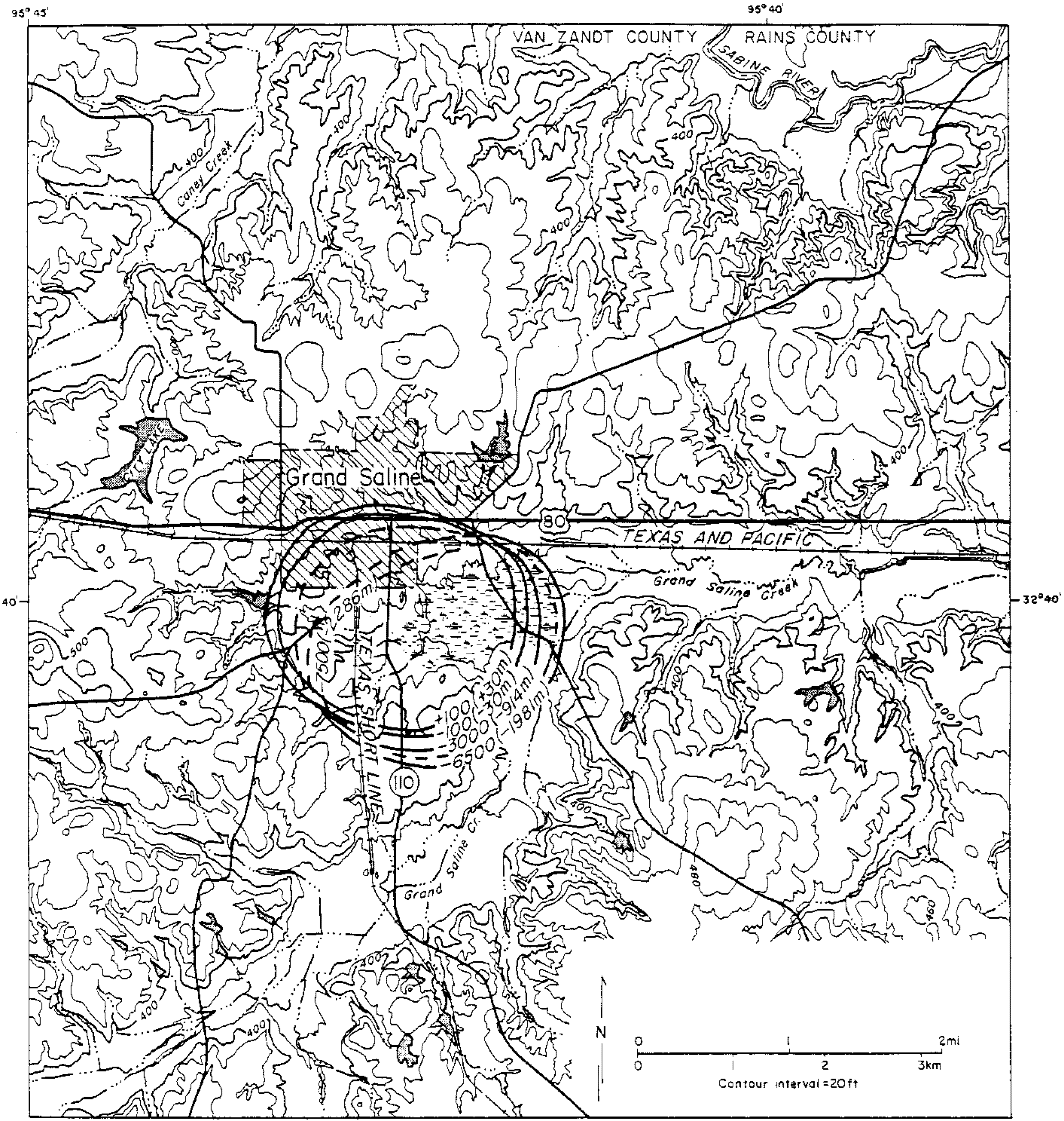


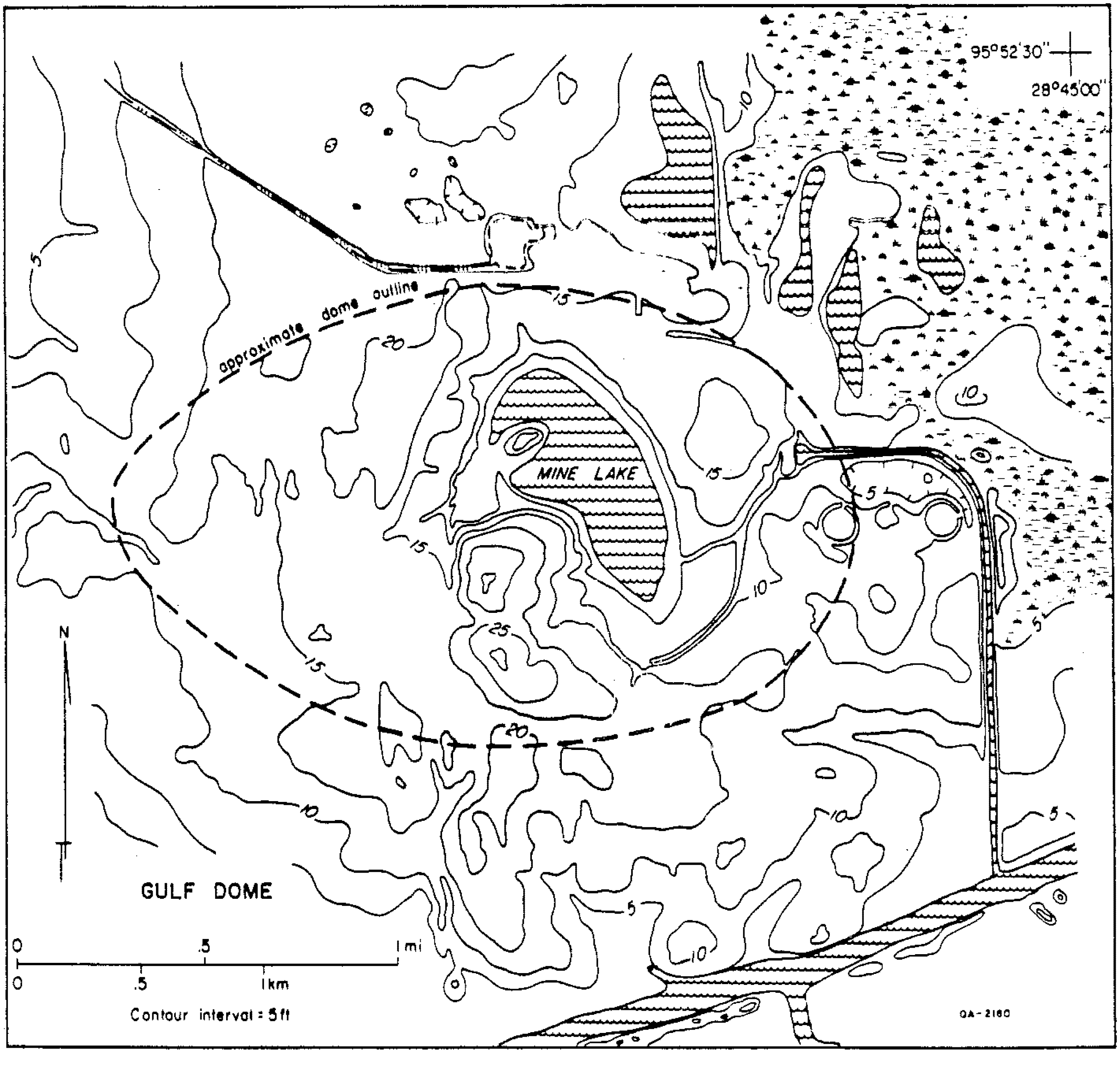
FANNETT DOME

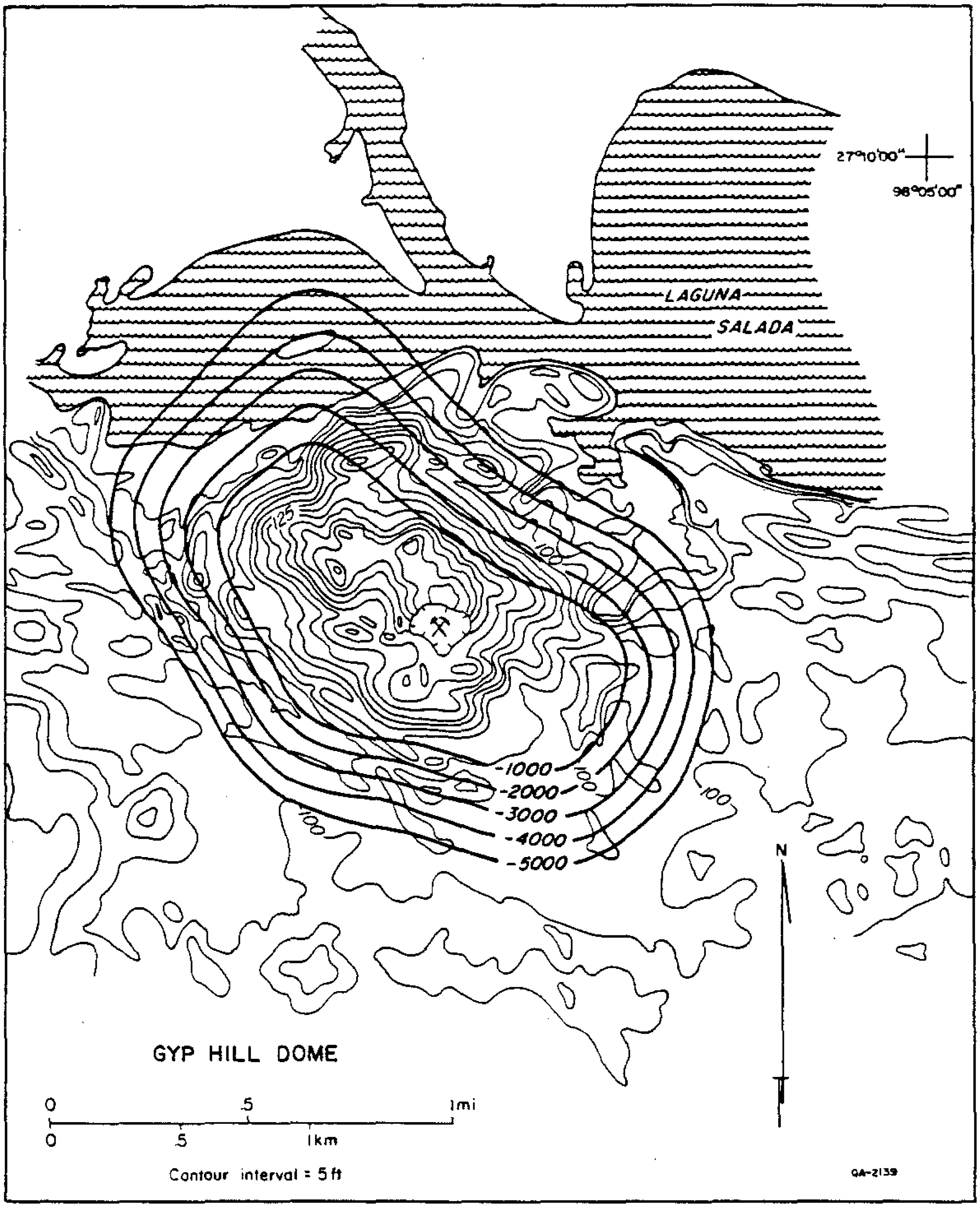


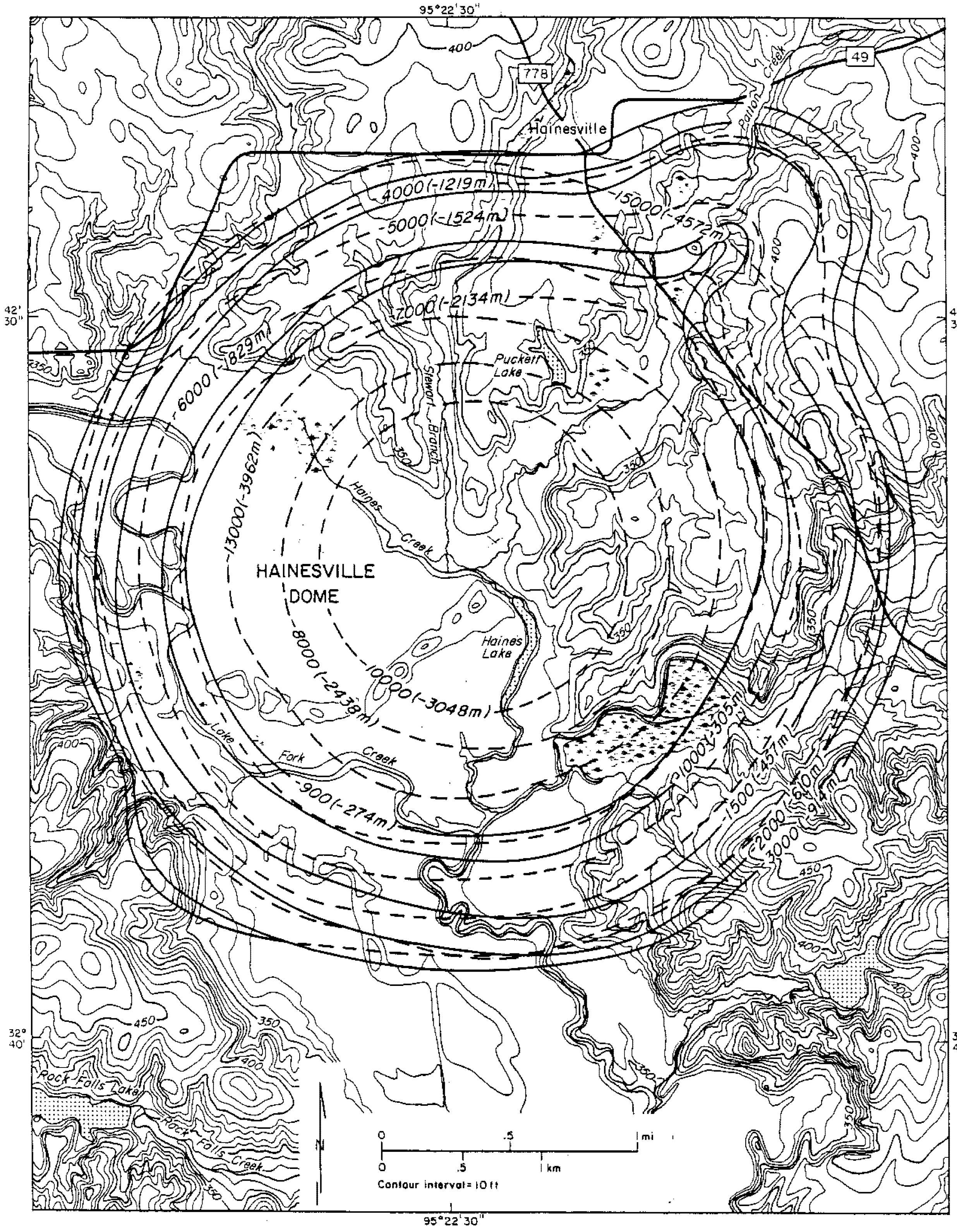
FERGUSON CROSSING DOME

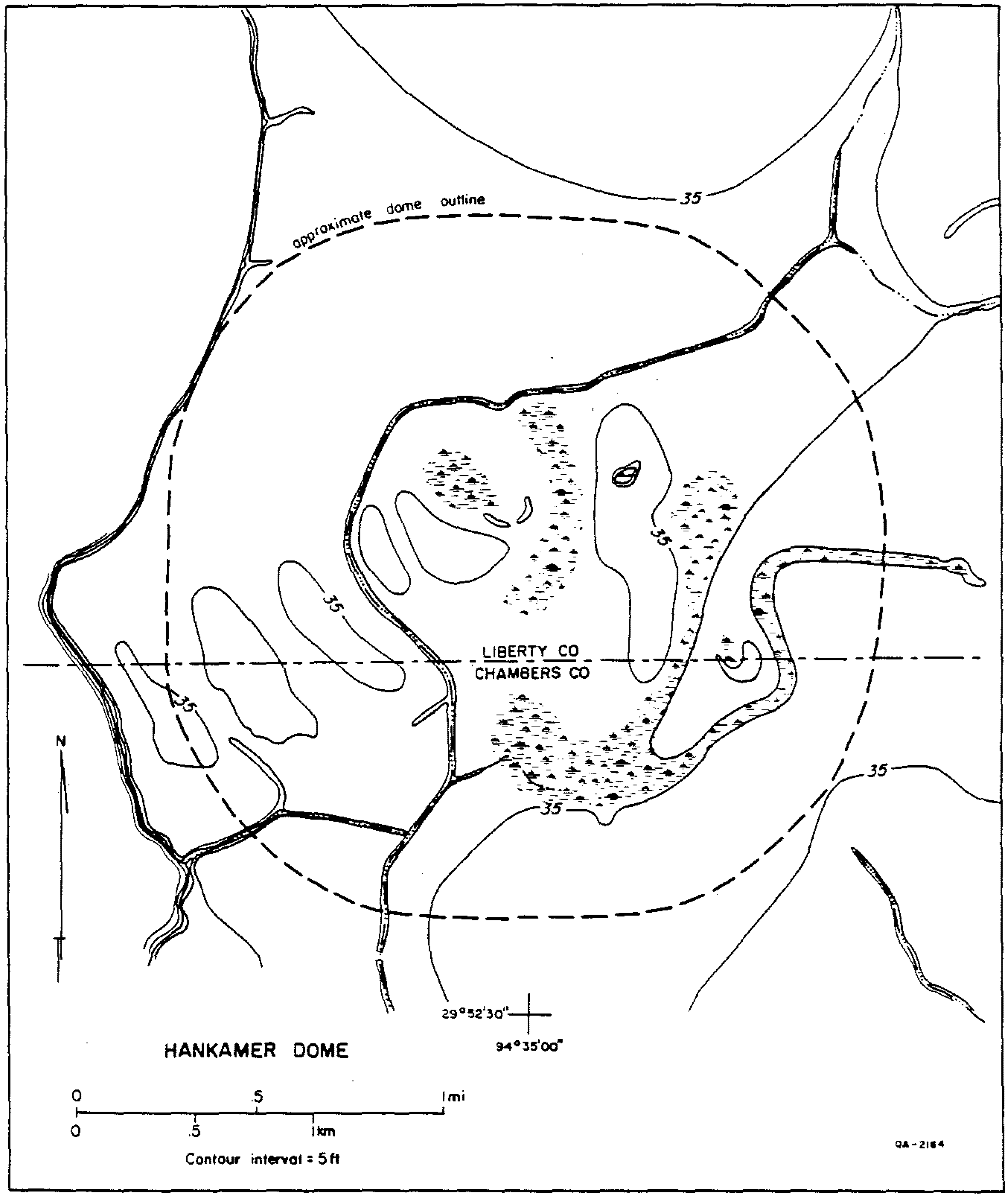

500
500
450
450
400
Butler Creek
approximate dome outline
164
450
500
400
450
500
500
Taylor Creek
32°16'
95°24'
500
500
500
500
155
GIRLIE CALDWELL DOME
N
0 .5 1 mi
0 .5 1 km
Contour interval = 10 ft
QA2247

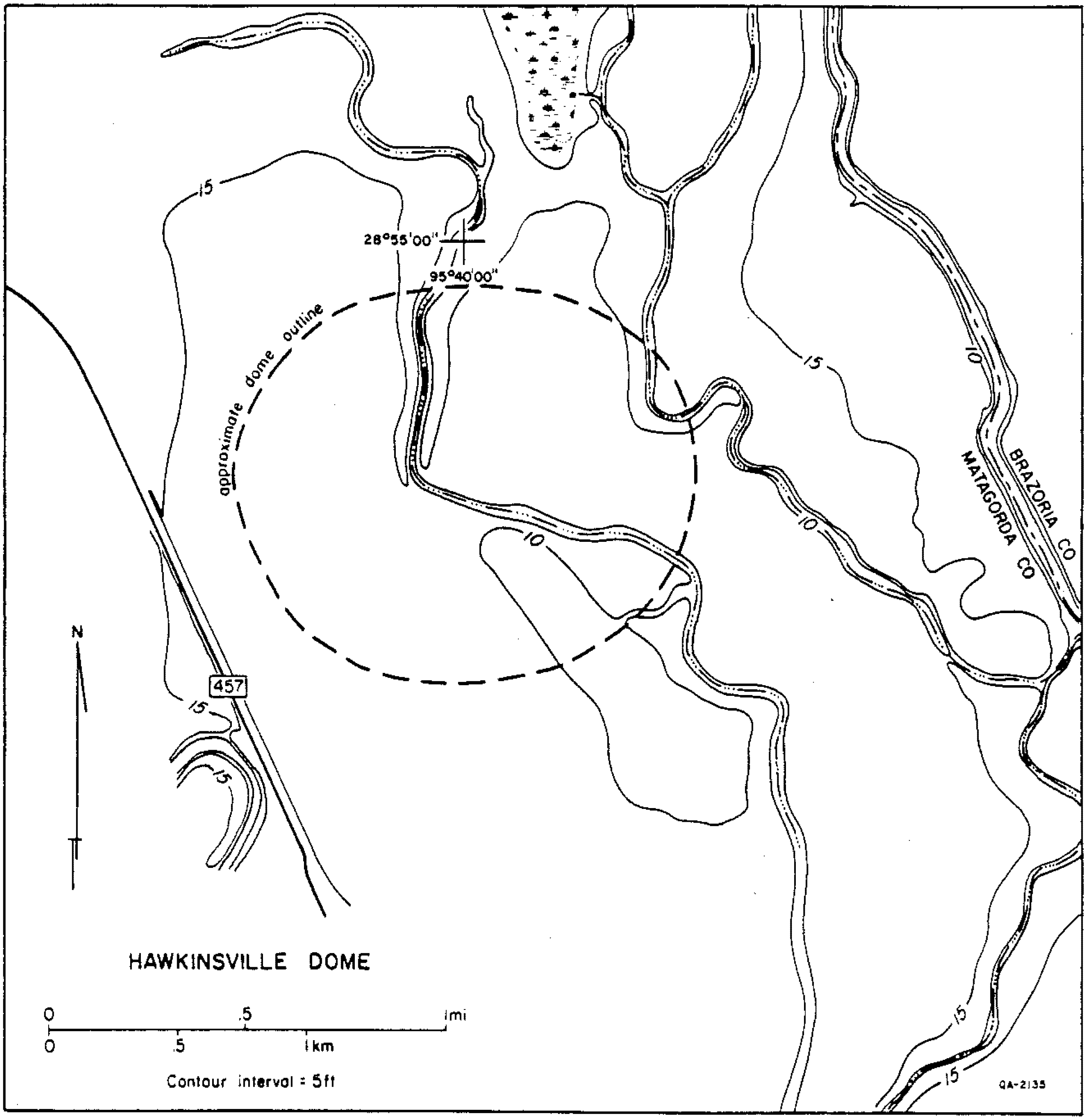

95° 45'
95° 40'
VAN ZANDT COUNTY
RAINS COUNTY
SABINE RIVER
Caney Creek
400
Grand Saline
80
TEXAS AND PACIFIC
Grand Saline Creek
32° 40'
32° 40'
500
-286m
-7500
TEXAS SHORT LINE
+100 (+30m)
-100 (-30m)
-3000 (-914m)
-6500 (-1981m)
110
Grand Saline Cr.
480
N
0 1 2mi
0 1 2 3km
Contour interval = 20 ft


95°52'30"
28°45'00"
approximate dome outline
MINE LAKE
GULF DOME
N
5
10
15
20
25
0 .5 1 mi
0 .5 1 km
Contour interval = 5 ft
QA-2160

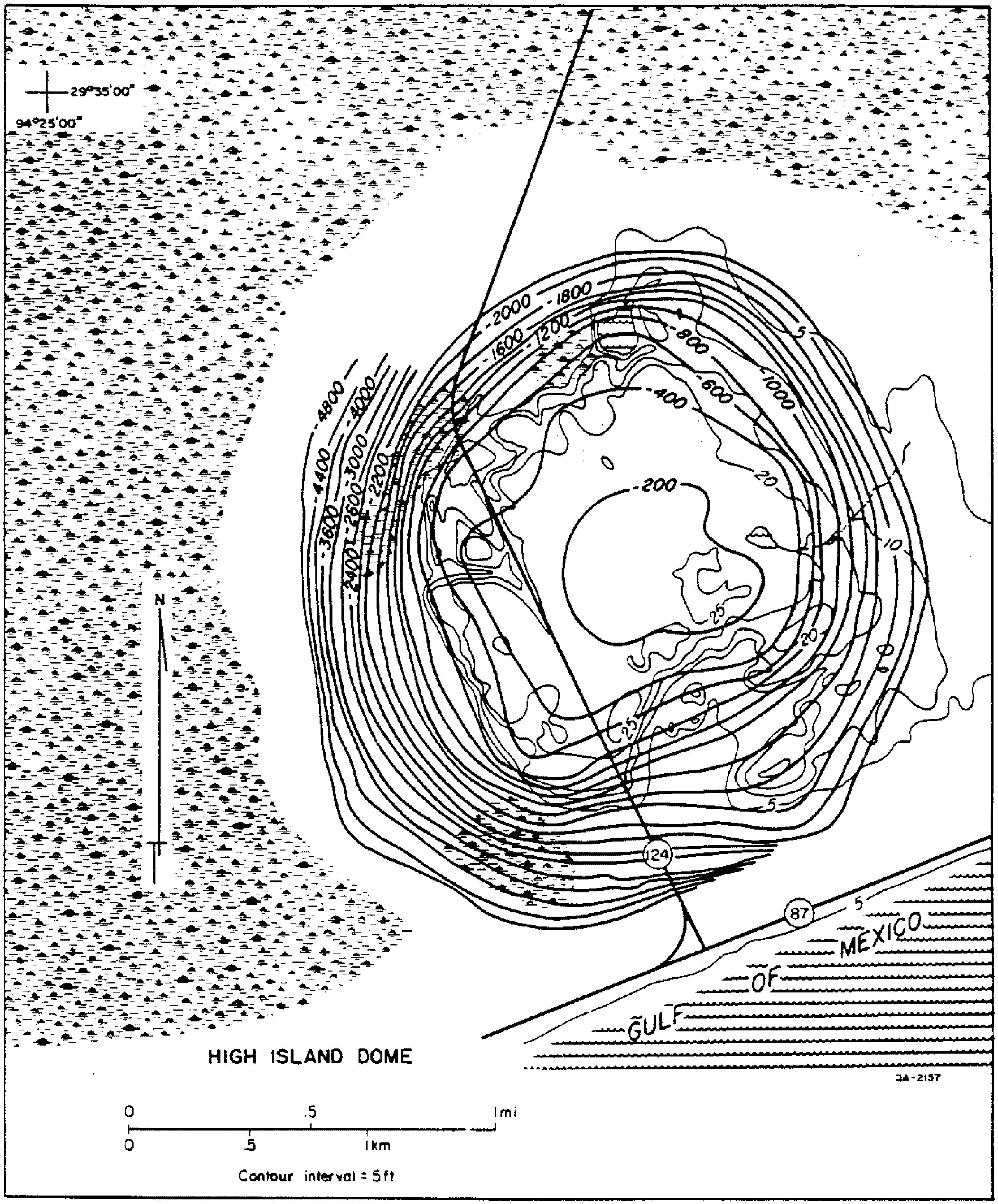

27°10'00"
98°05'00"
LAGUNA
SALADA
125
100
-1000
-2000
-3000
-4000
-5000
N
GYP HILL DOME
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
QA-2139


95°22'30"
400
778
49
Hainesville
Patton Creek
4000(-1219m)
-5000(-1524m)
-15000(-4572m)
7000(-2134m)
Puckett Lake
Stewart Branch
6000(-829m)
350
-13000(-3962m)
Haines Creek
HAINESVILLE DOME
8000(-2438m)
-10000(-3048m)
Haines Lake
-1000(-305m)
-1500(-457m)
-2000(-610m)
-3000(-914m)
450
Lake Fork Creek
-900(-274m)
Rock Falls Lake
Rock Falls Creek
42' 30"
32° 40'
0 .5 1 mi
0 .5 1 km
Contour interval=10 ft
95°22'30"


35
approximate dome outline
35
35
35
LIBERTY CO
CHAMBERS CO
35
35
35
N
29°52'30"
94°35'00"
HANKAMER DOME
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
QA-2164

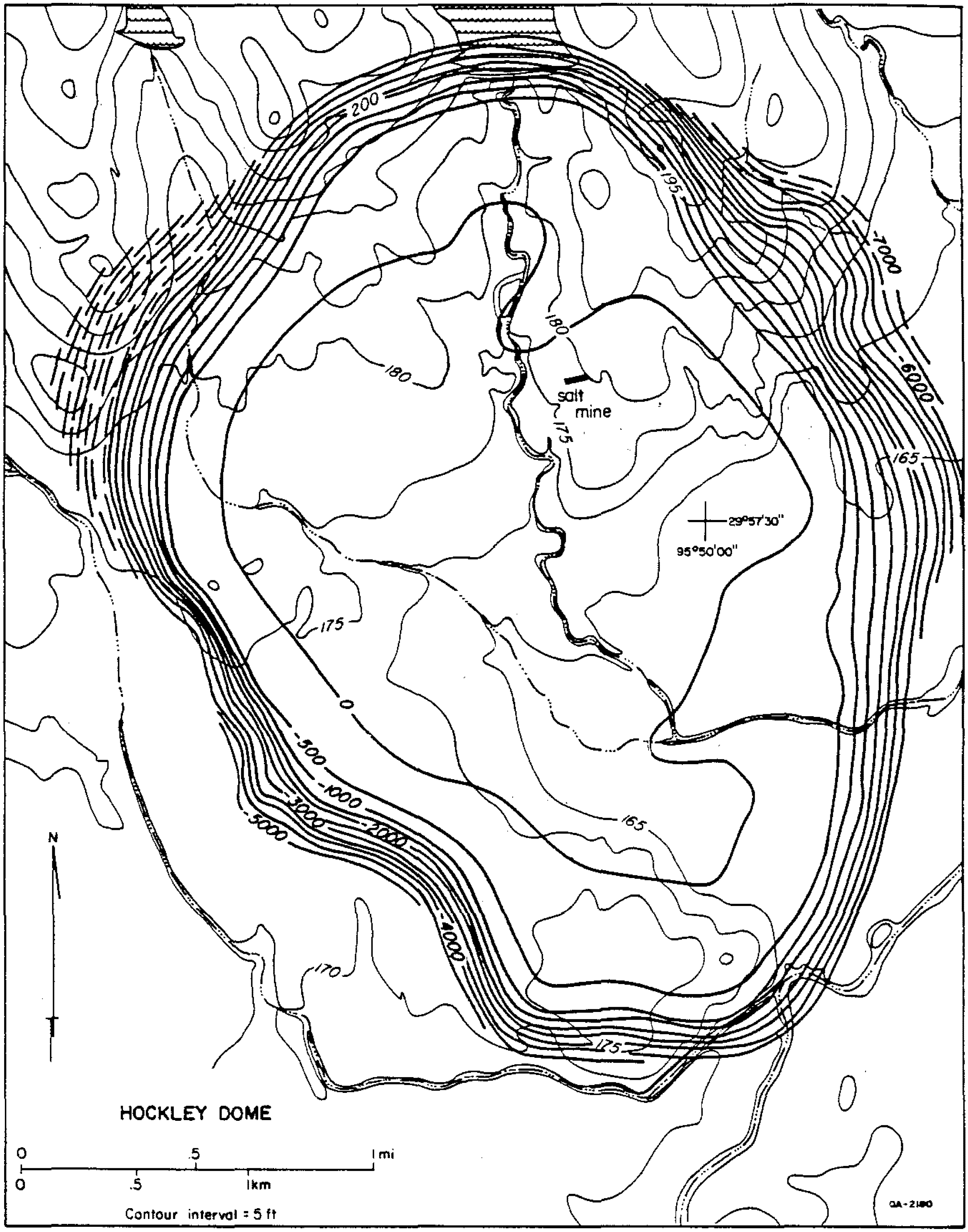


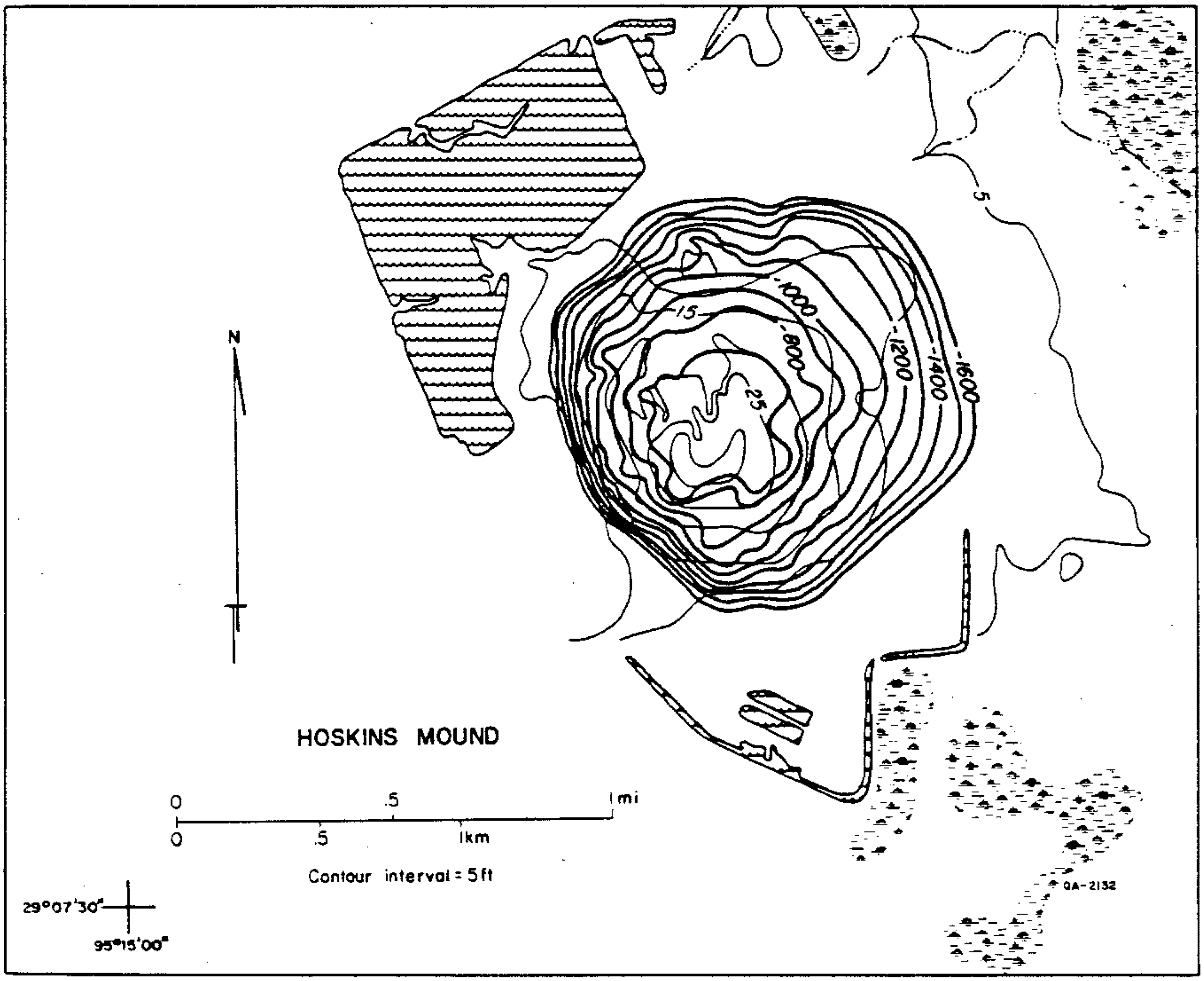
HAWKINSVILLE DOME

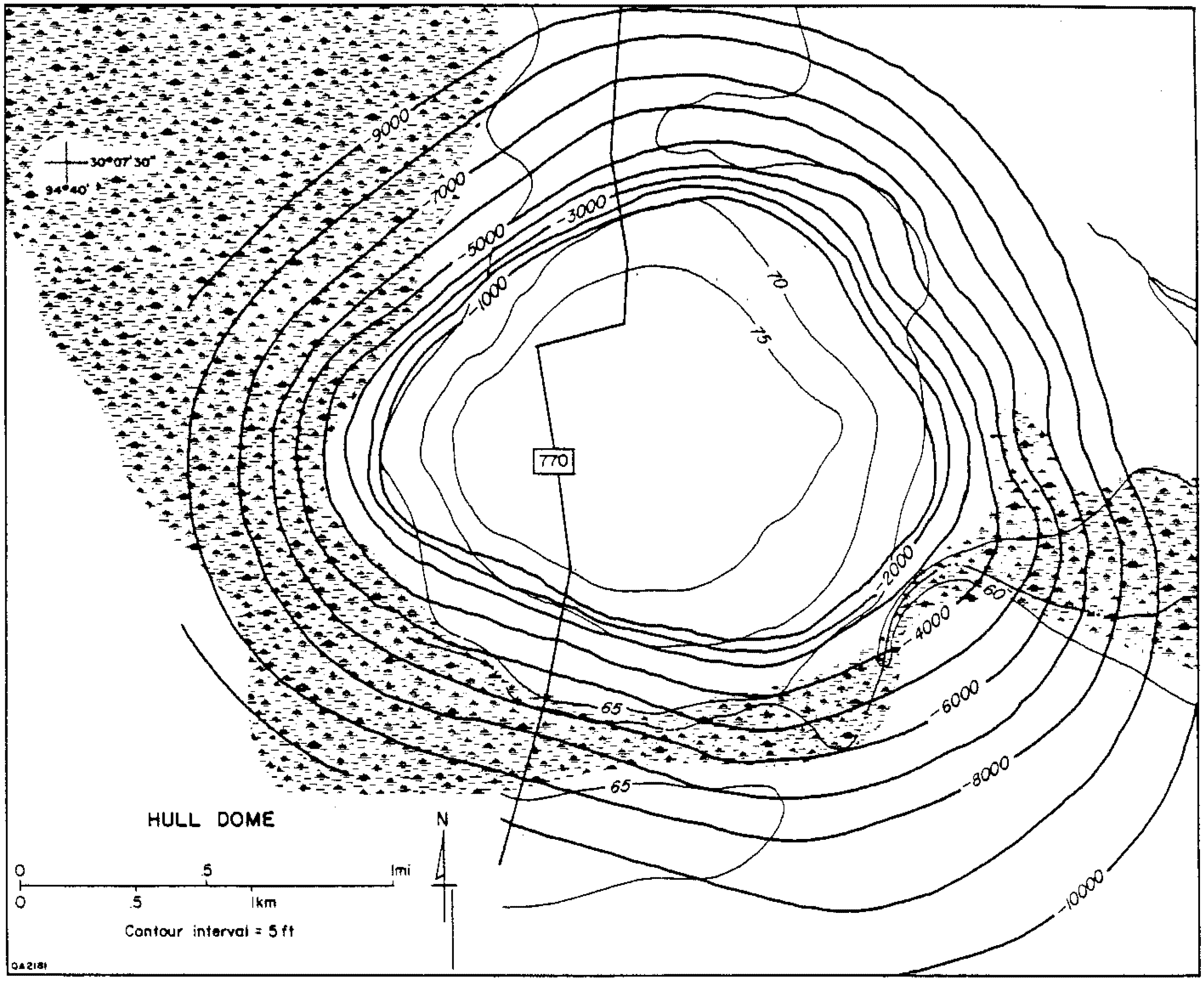


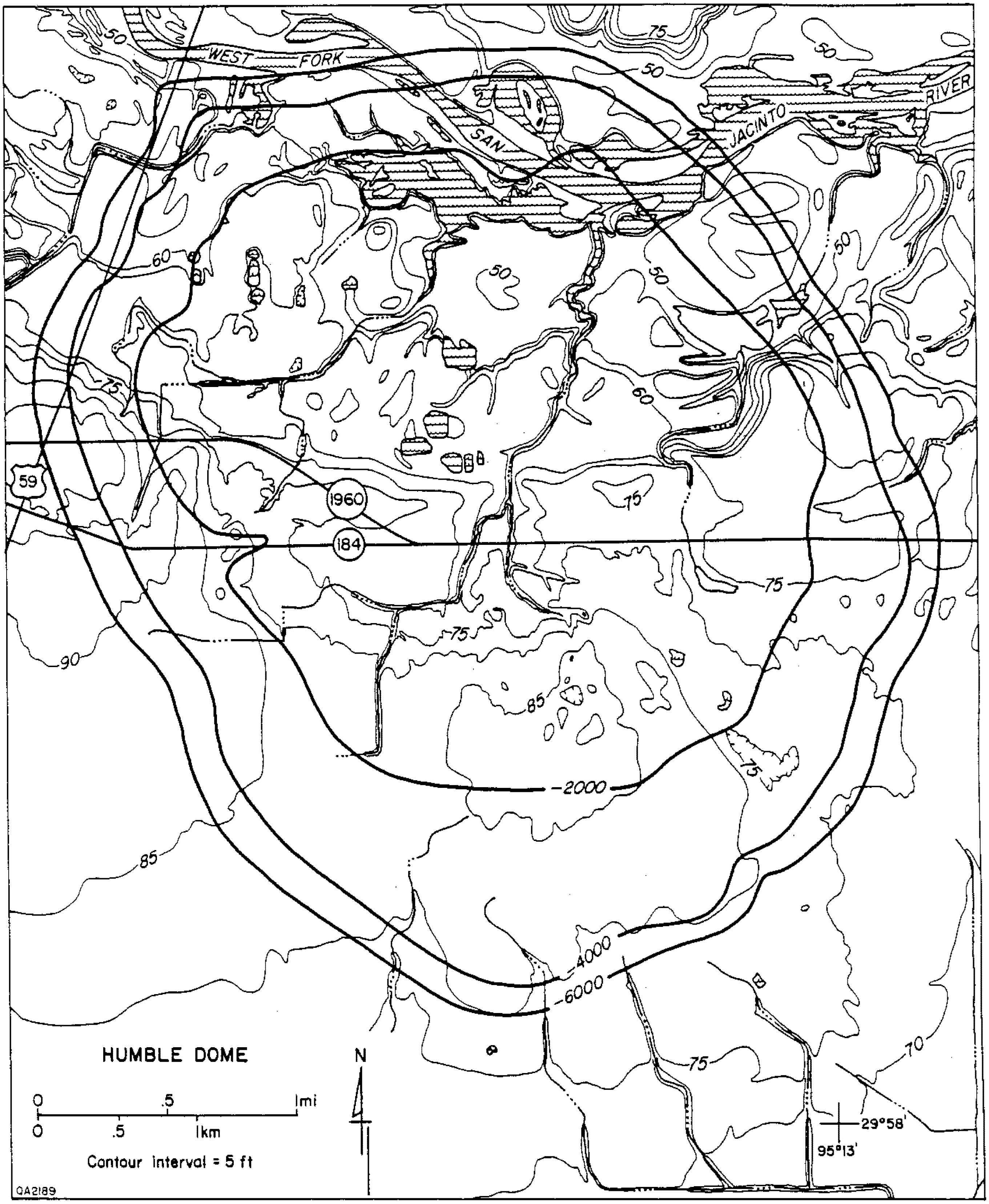
HIGH ISLAND DOME

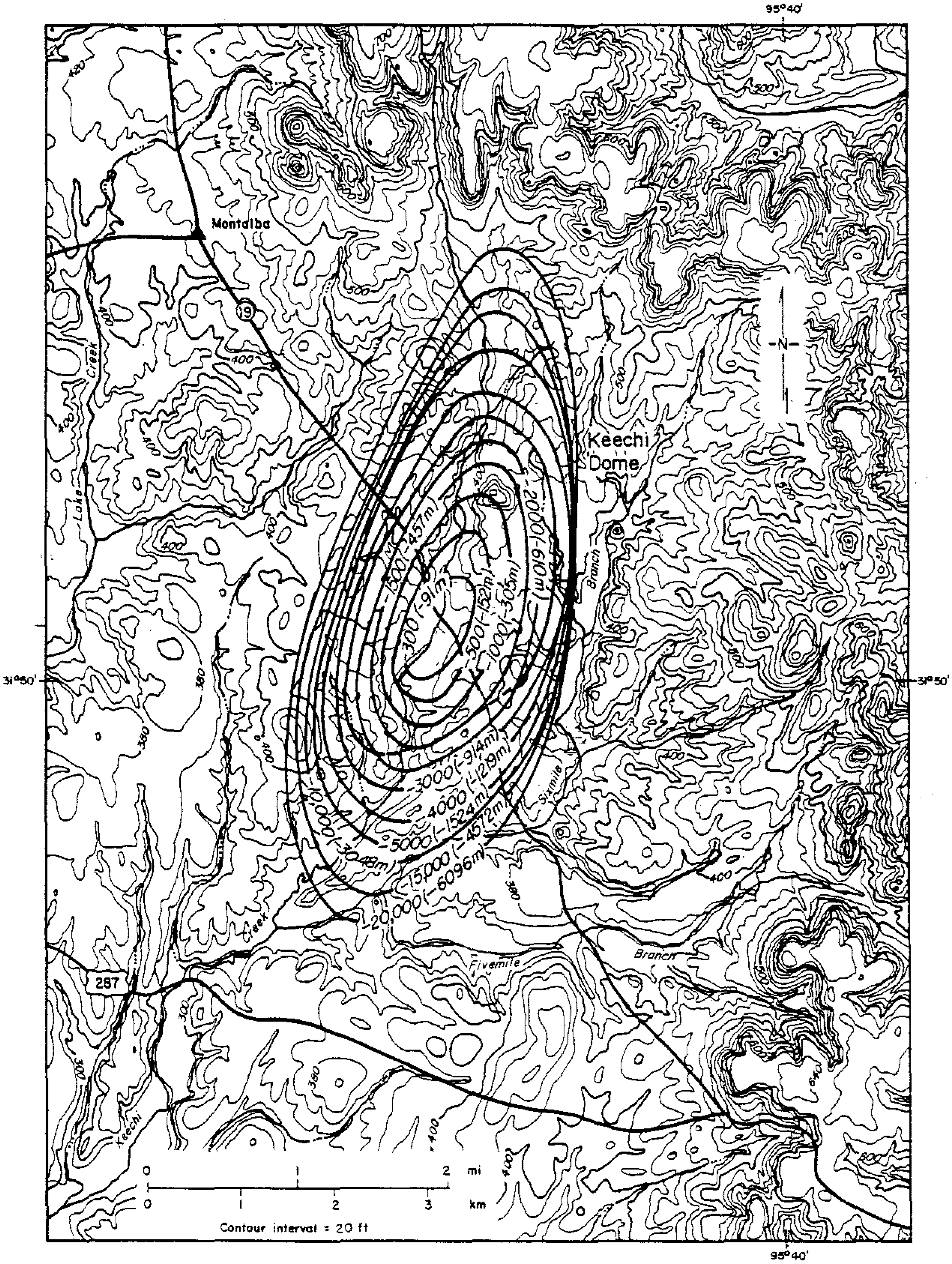
Contour interval = 5 ft

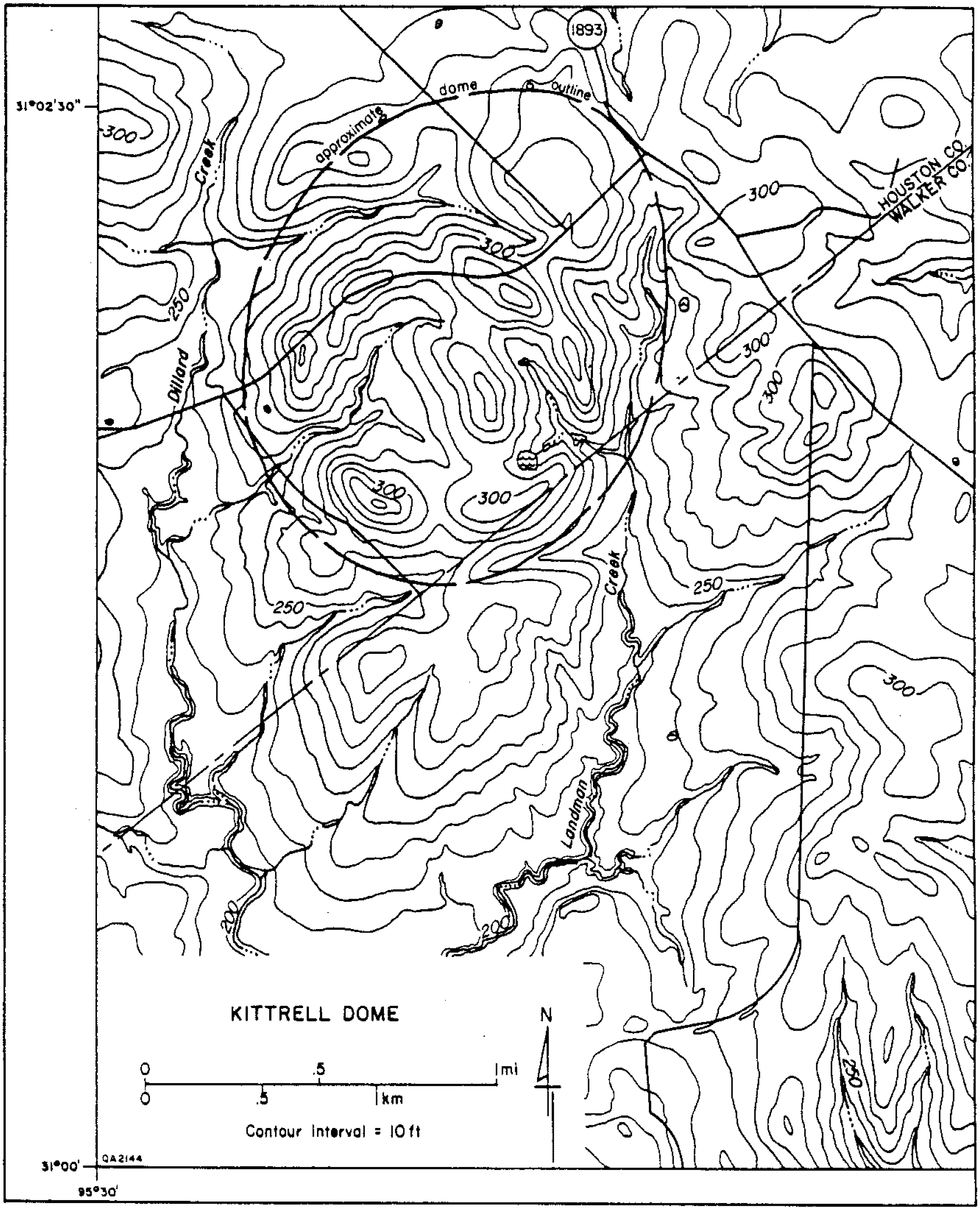

200
195
-7000
-6000
165
180
180
salt mine
175
29°57'30"
95°50'00"
175
0
-500
-1000
-2000
-3000
-5000
-4000
165
170
175
N
HOCKLEY DOME
0
.5
1 mi
0
.5
1 km
Contour interval = 5 ft
QA-2180

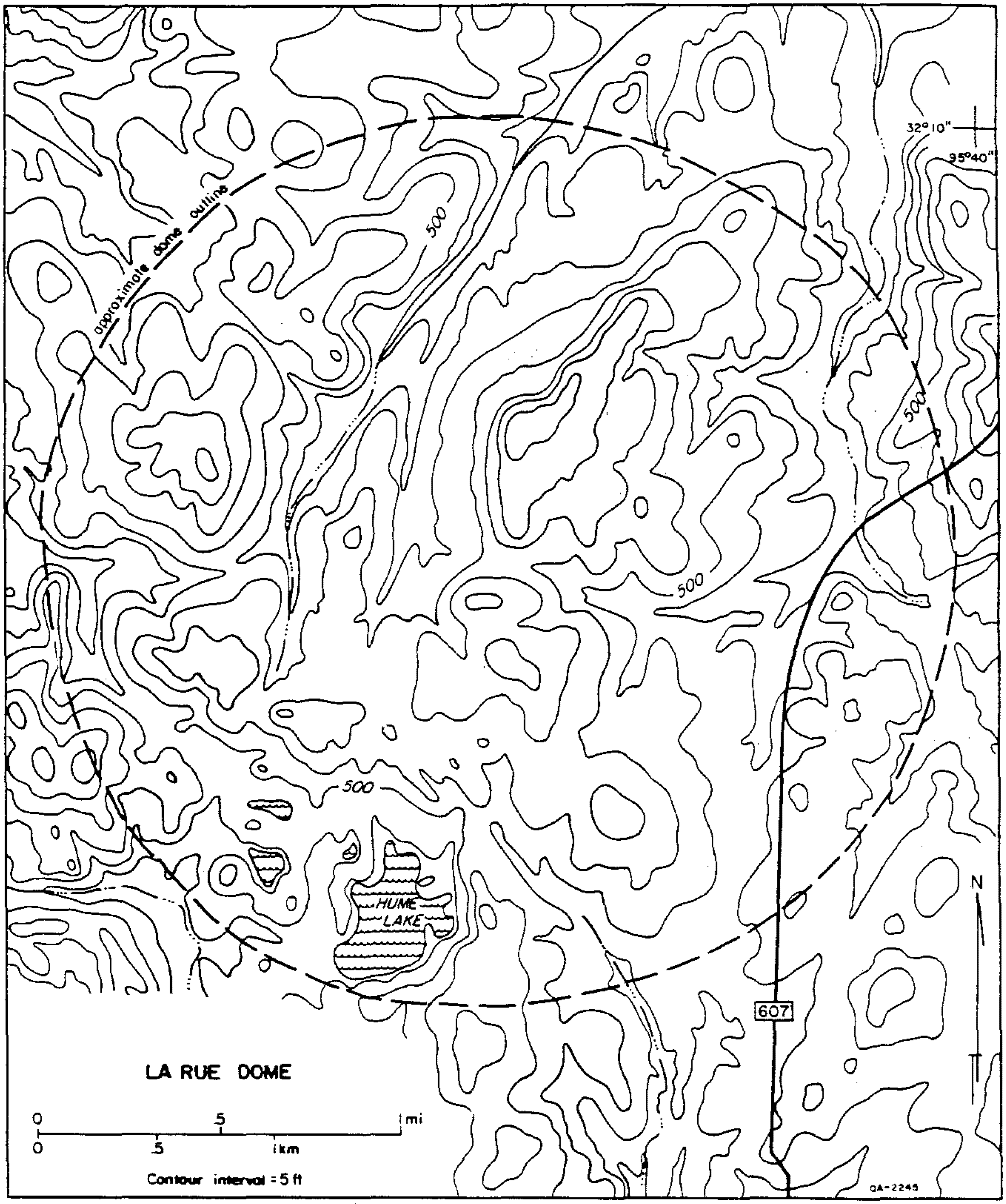

N
5
15
25
-800
-1000
-1200
-1400
-1600
HOSKINS MOUND
0
.5
1 mi
0
.5
1km
Contour interval = 5 ft
29°07'30"
95°15'00"
QA-2132

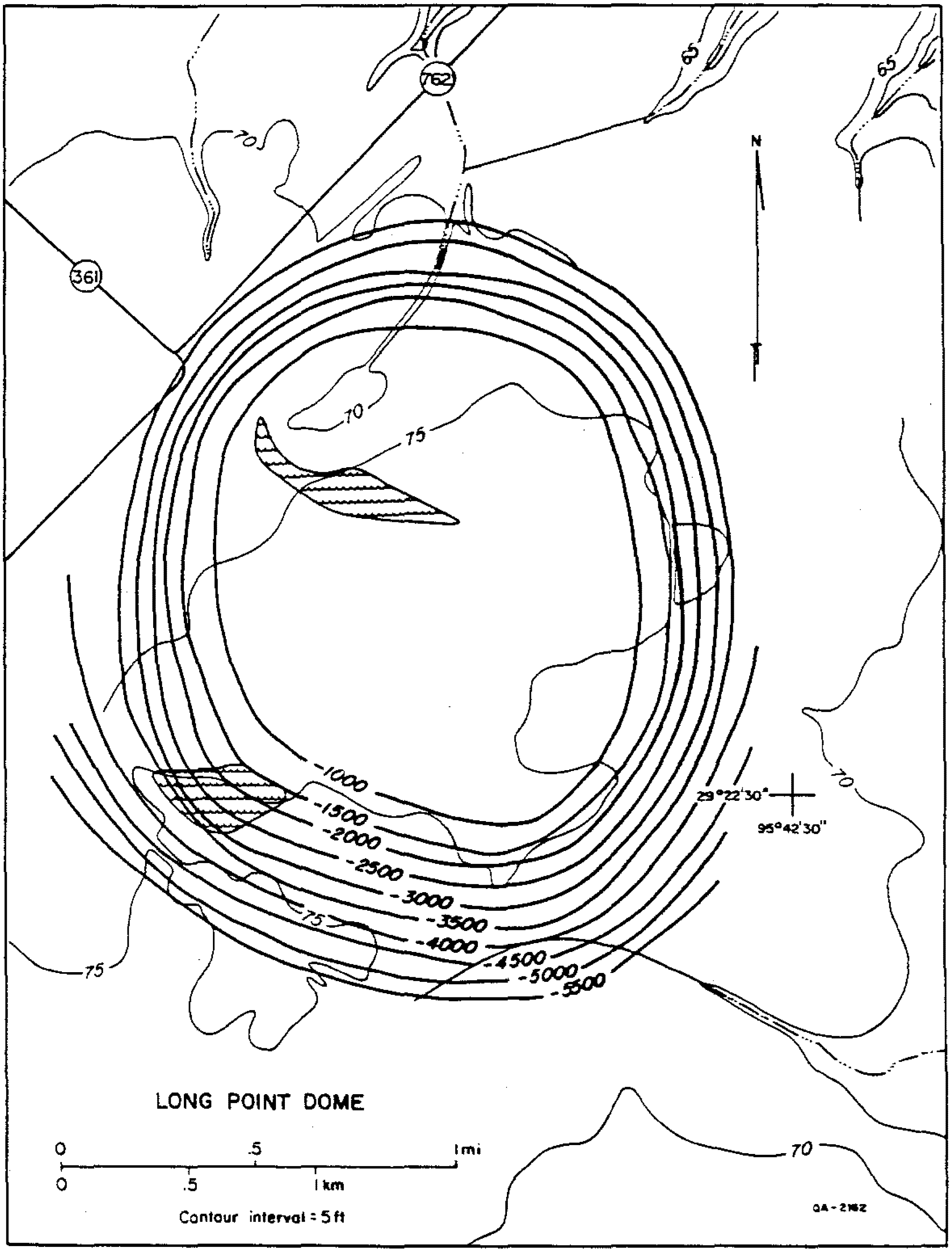

30°07'30"
94°40'
-9000
-7000
-5000
-3000
-1000
70
75
770
-2000
60
-4000
-6000
-8000
65
65
-10000
HULL DOME
N
0 .5 1mi
0 .5 1km
Contour interval = 5 ft
QA2181

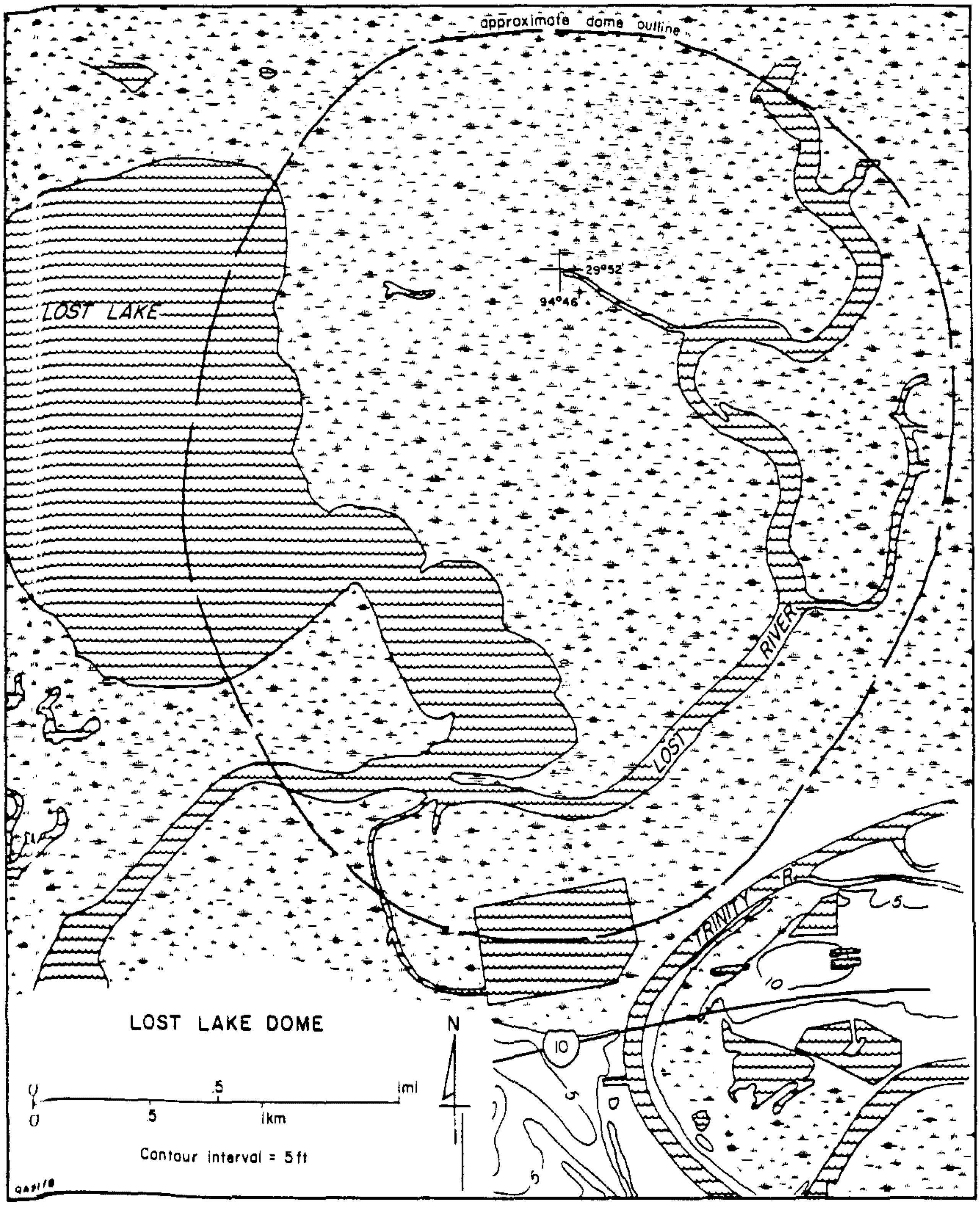

WEST FORK
SAN
JACINTO
RIVER
50
75
60
90
85
70
-2000
-4000
-6000
59
1960
184
HUMBLE DOME
0 .5 1mi
0 .5 1km
Contour interval = 5 ft
N
29°58'
95°13'
QA2189

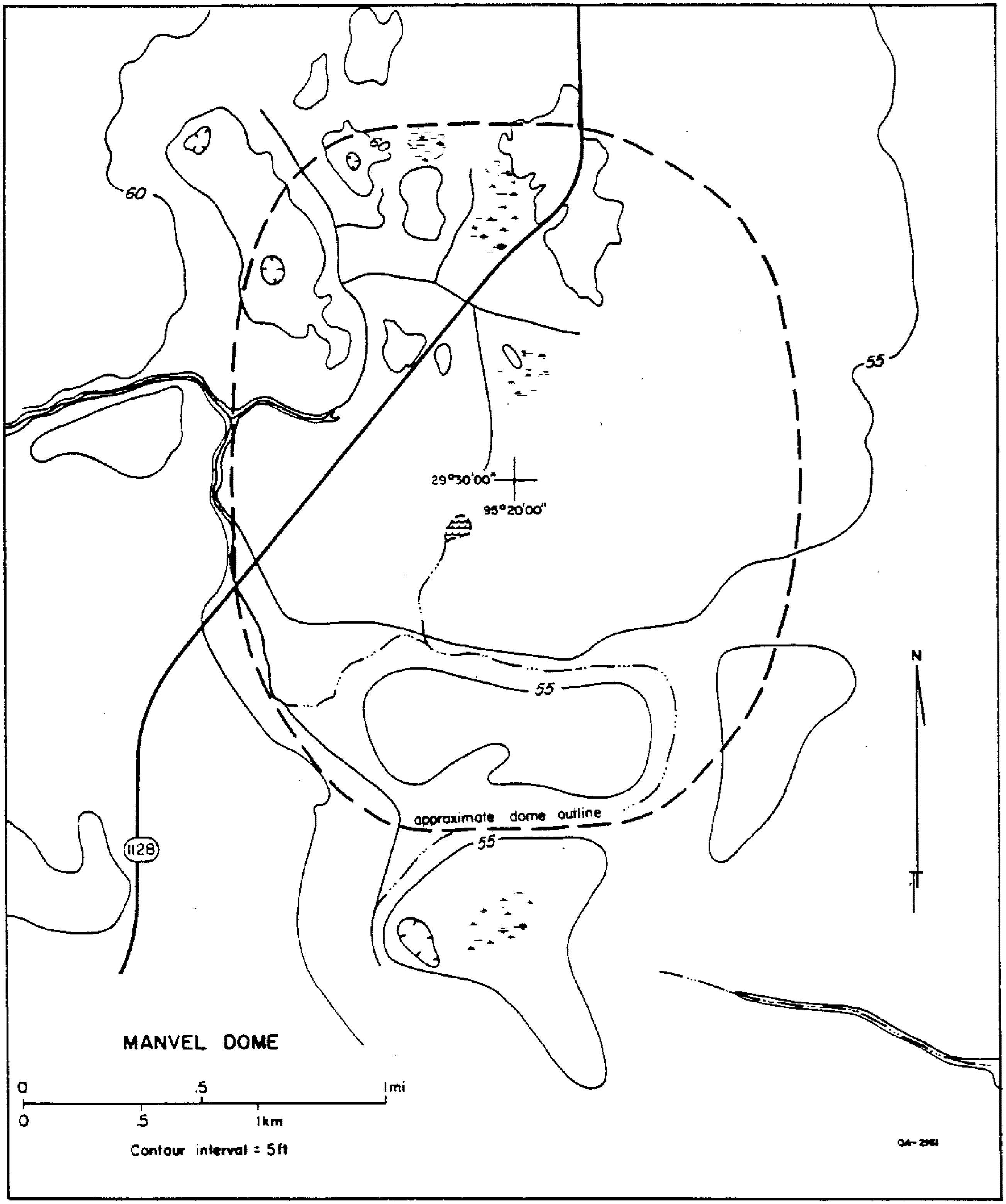

95°40'
420
700
800
500'
Montalba
19
Creek
Lake
400
500
-N-
Keechi Dome
Branch
-300(-91m)
-500(-152m)
-1000(-305m)
-1500(-457m)
-2000(-610m)
-3000(-914m)
-4000(-1219m)
-5000(-1524m)
-10,000(-3048m)
-15,000(-4572m)
-20,000(-6096m)
31°50'
380
Sixmile
Creek
Fivemile
Branch
287
300
Keechi
640
0
1
2 mi
0
1
2
3
km
Contour interval = 20 ft
95°40'

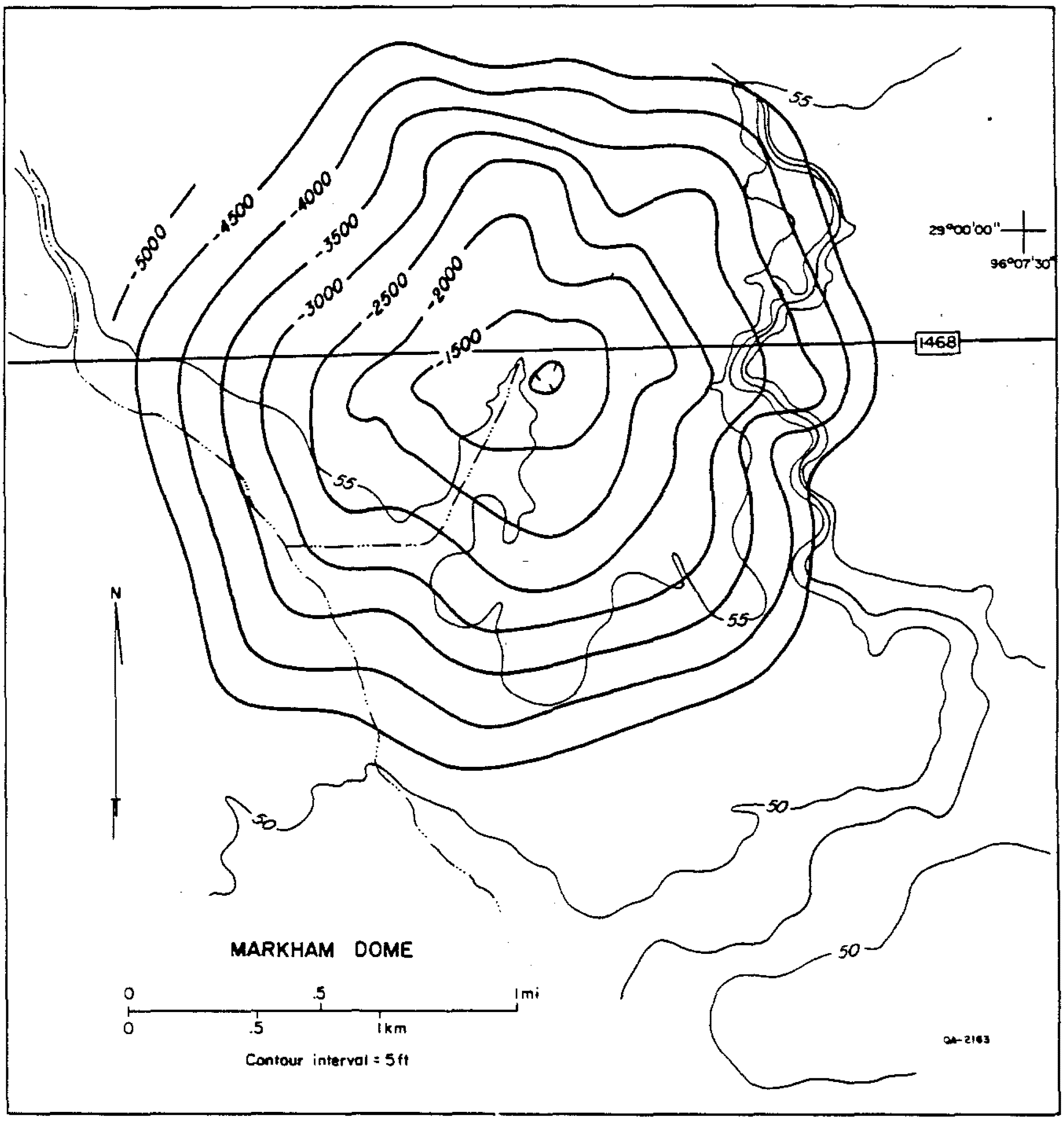

31°02'30"
approximate dome outline
1893
300
250
200
Dillard Creek
Landman Creek
HOUSTON CO.
WALKER CO.
KITTRELL DOME
0 .5 1 mi
0 .5 1 km
Contour Interval = 10 ft
N
QA2144
31°00'
95°30'


D
approximate dome outline
500
500
500
500
32°10"
95°40"
HUME LAKE
607
N
LA RUE DOME
0 .5 1 mi
0 .5 1 km
Contour interval = 5 ft
QA-2245

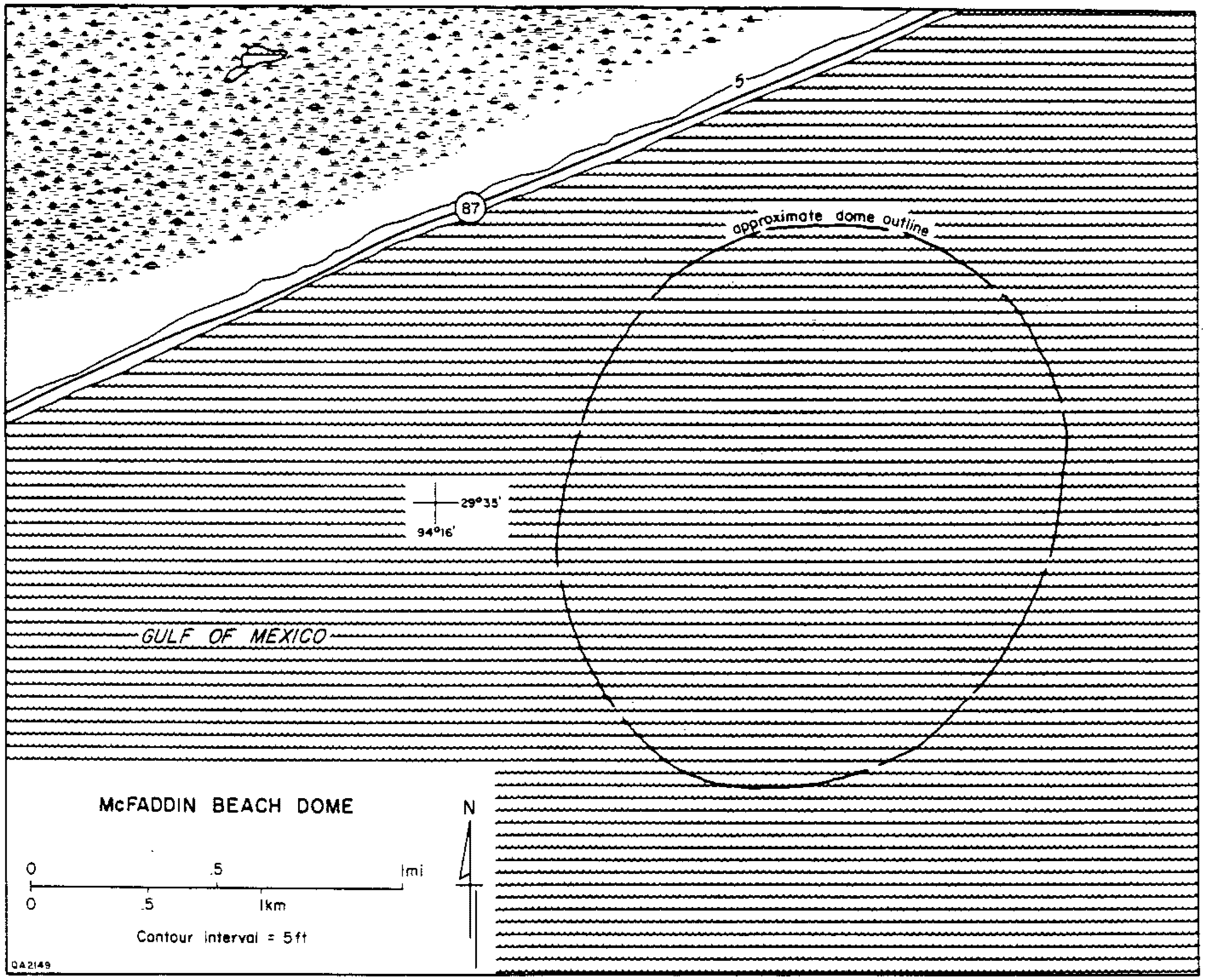

762
361
65
65
70
N
70
75
-1000
-1500
-2000
-2500
-3000
-3500
-4000
-4500
-5000
-5500
75
75
70
29°22'30"
95°42'30"
70
LONG POINT DOME
0
.5
1 mi
0
.5
1 km
Contour interval = 5 ft
QA-2162

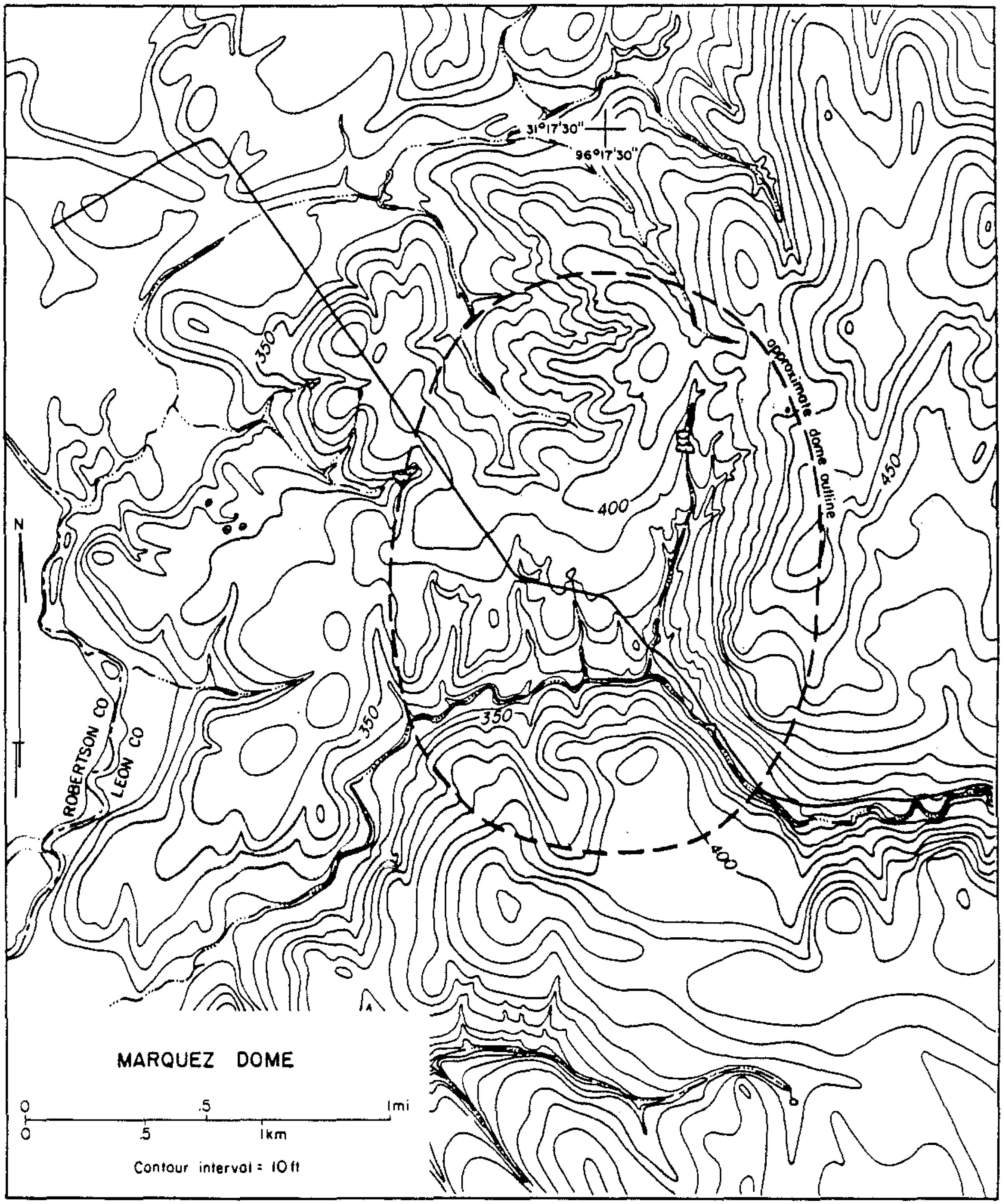

approximate dome outline
LOST LAKE
29°52'
94°46'
LOST RIVER
TRINITY R.
10
5
LOST LAKE DOME
N
0 .5 1 mi
0 .5 1 km
Contour interval = 5 ft

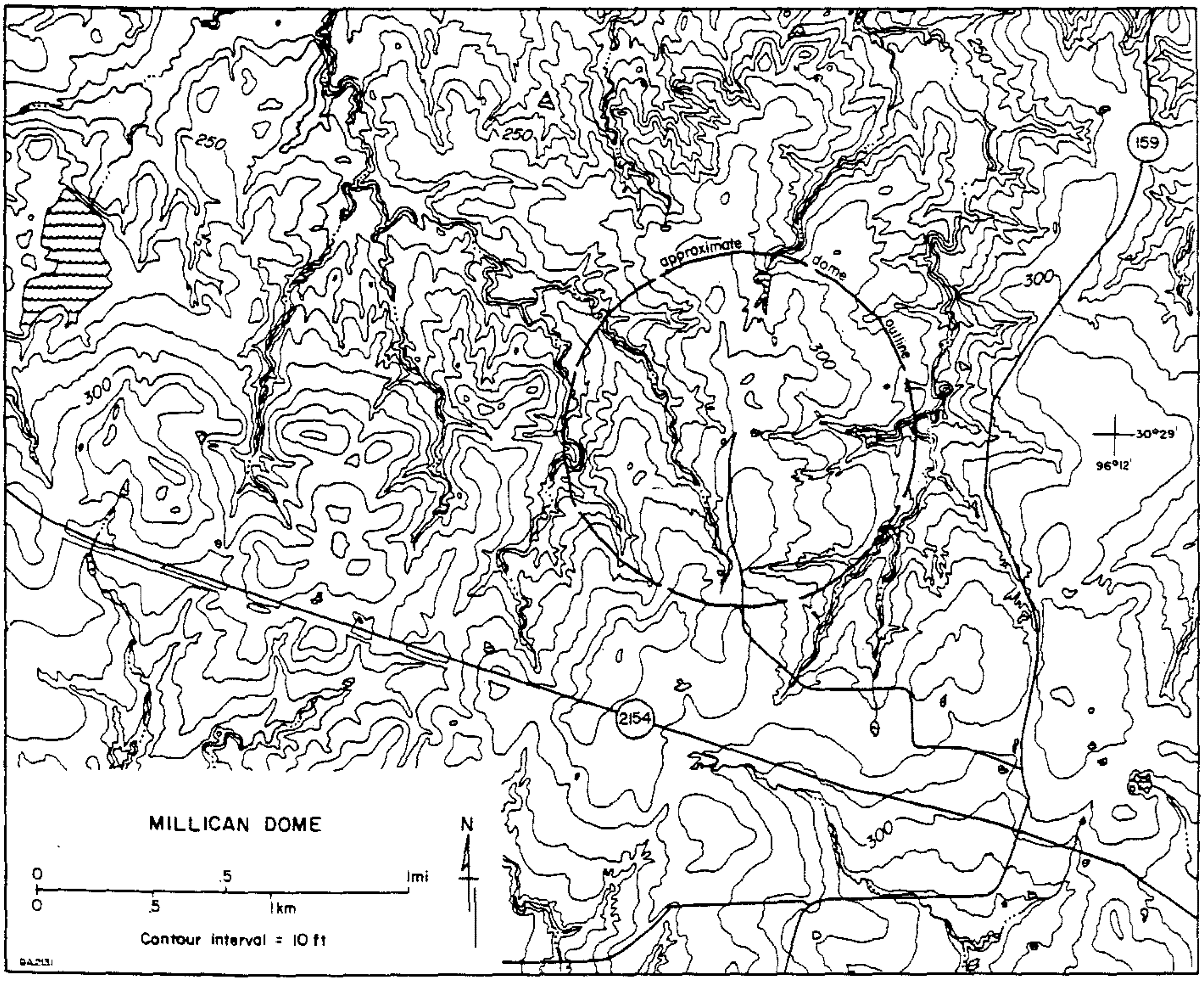

60
60
55
29°30'00"
95°20'00"
55
approximate dome outline
55
1128
N
MANVEL DOME
0 .5 1mi
0 .5 1km
Contour interval = 5ft

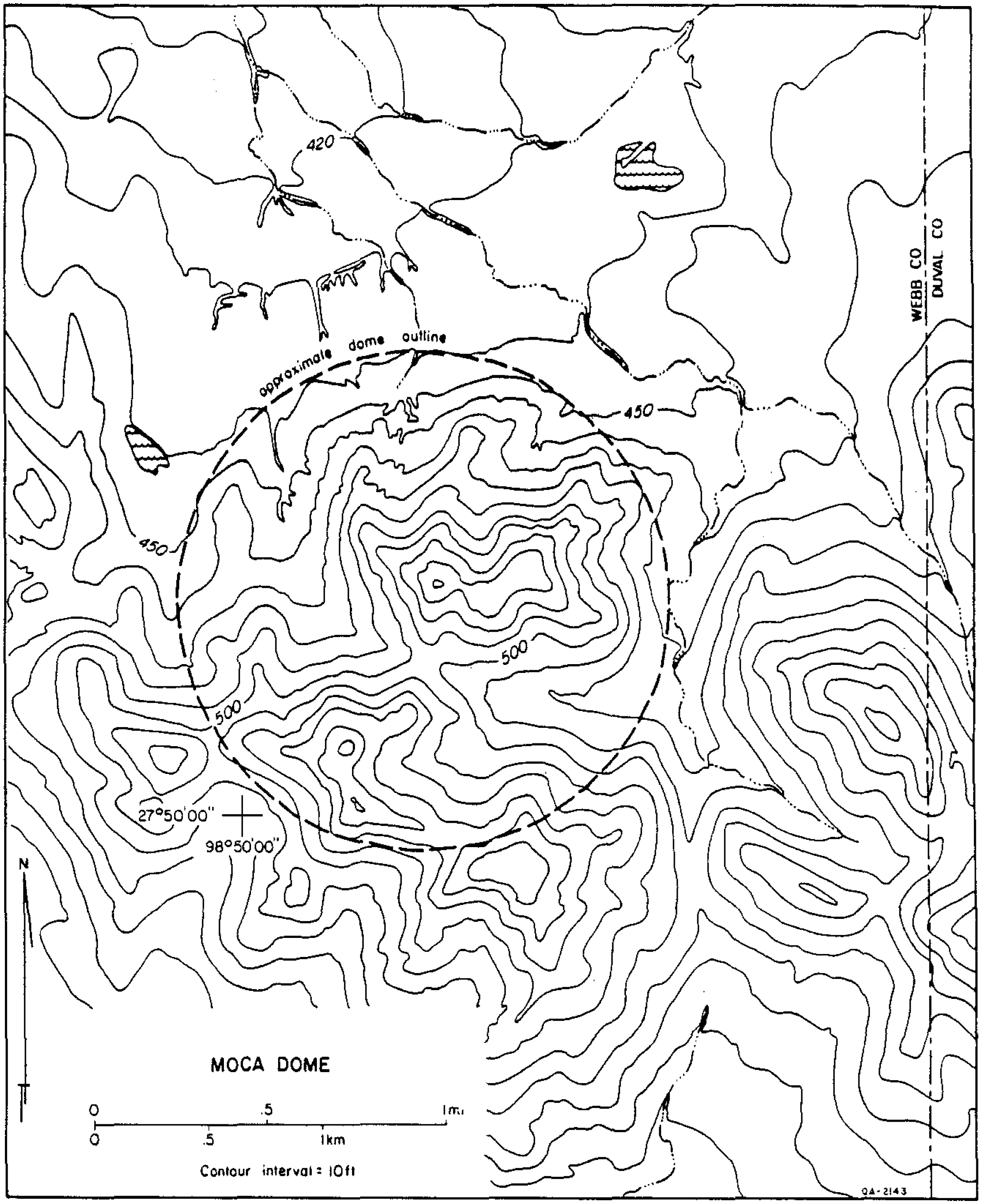


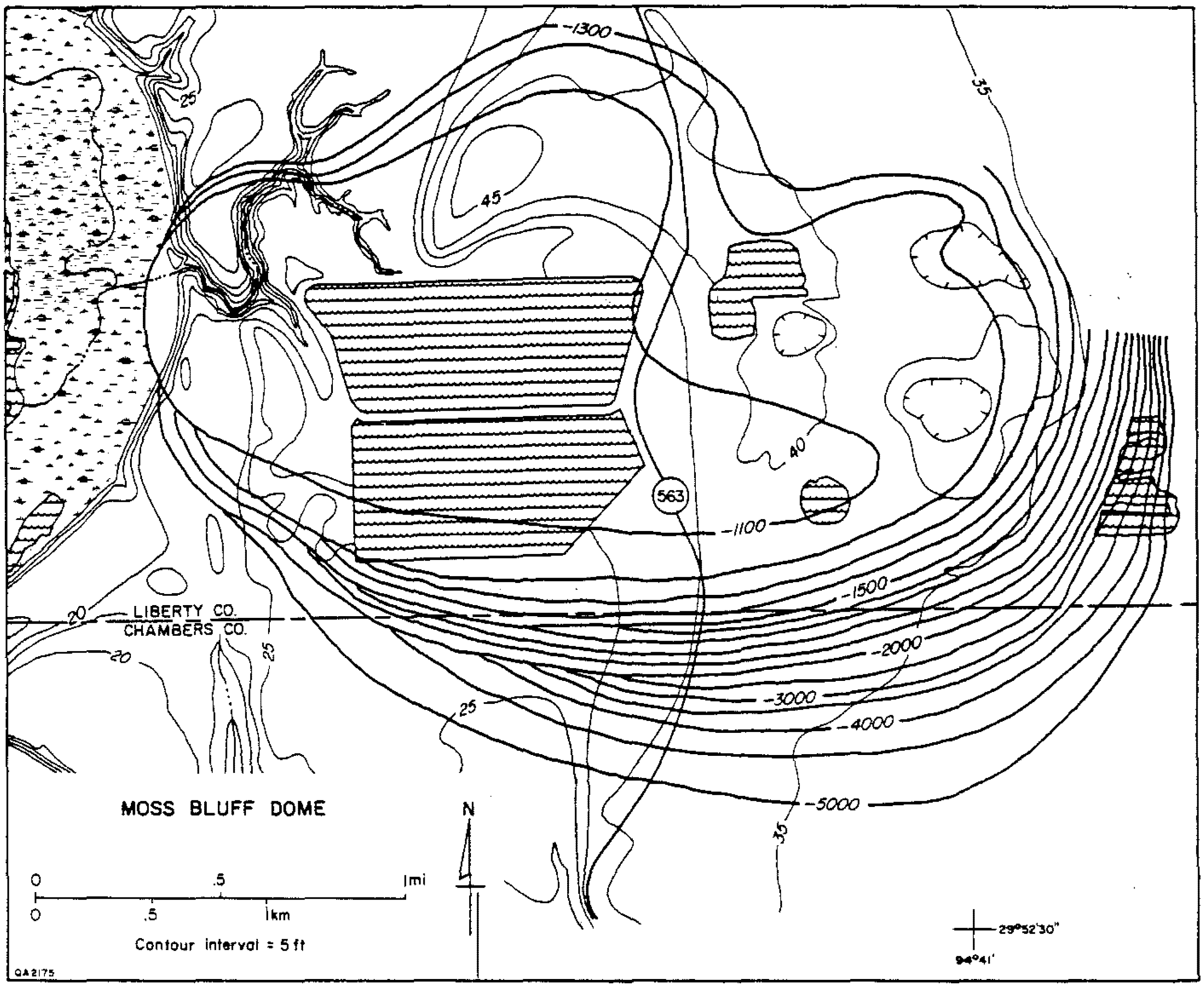
MARKHAM DOME

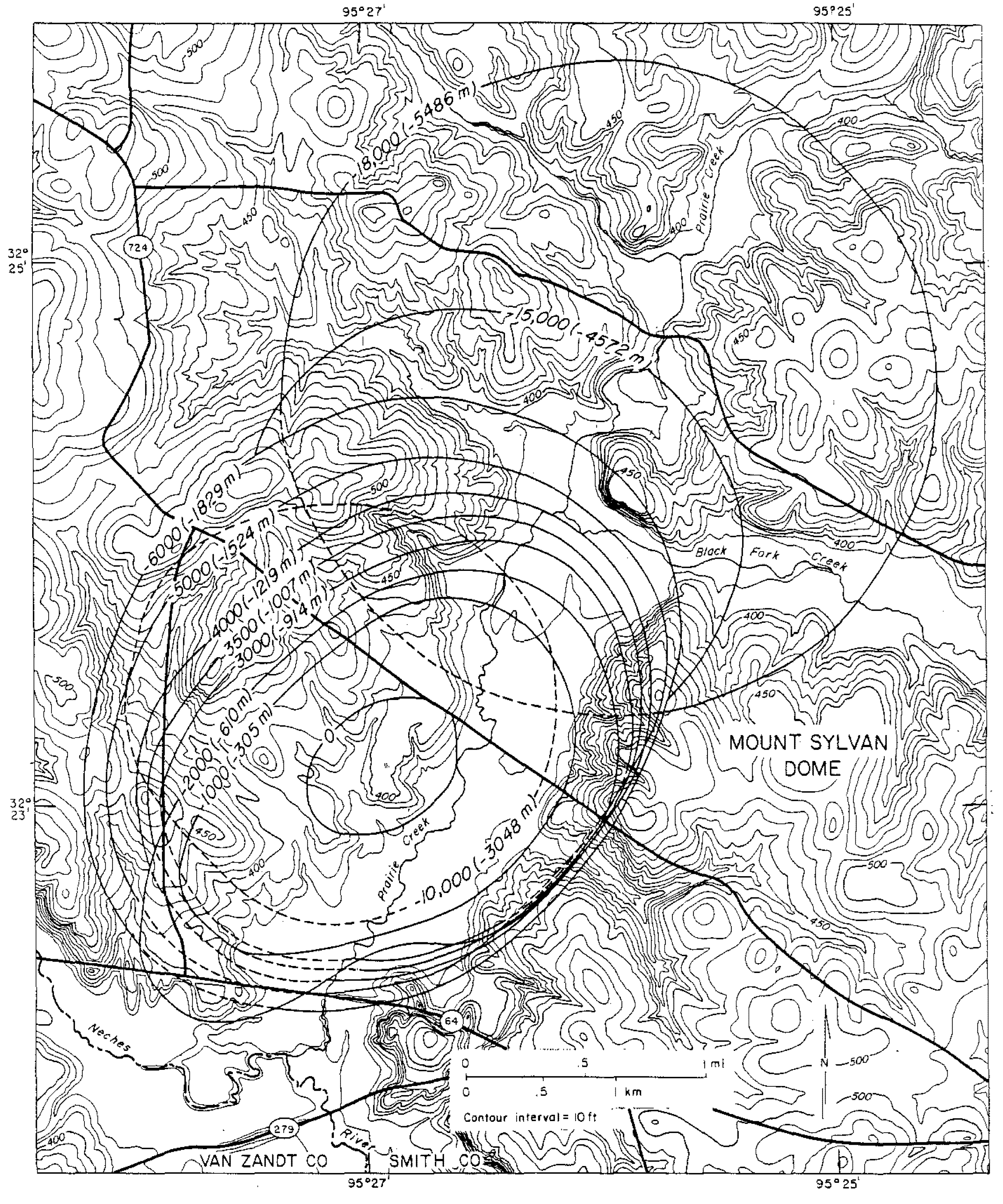

5
87
approximate dome outline
29°35'
94°16'
GULF OF MEXICO
McFADDIN BEACH DOME
0
.5
1mi
0
.5
1km
Contour interval = 5ft
N
QA2149

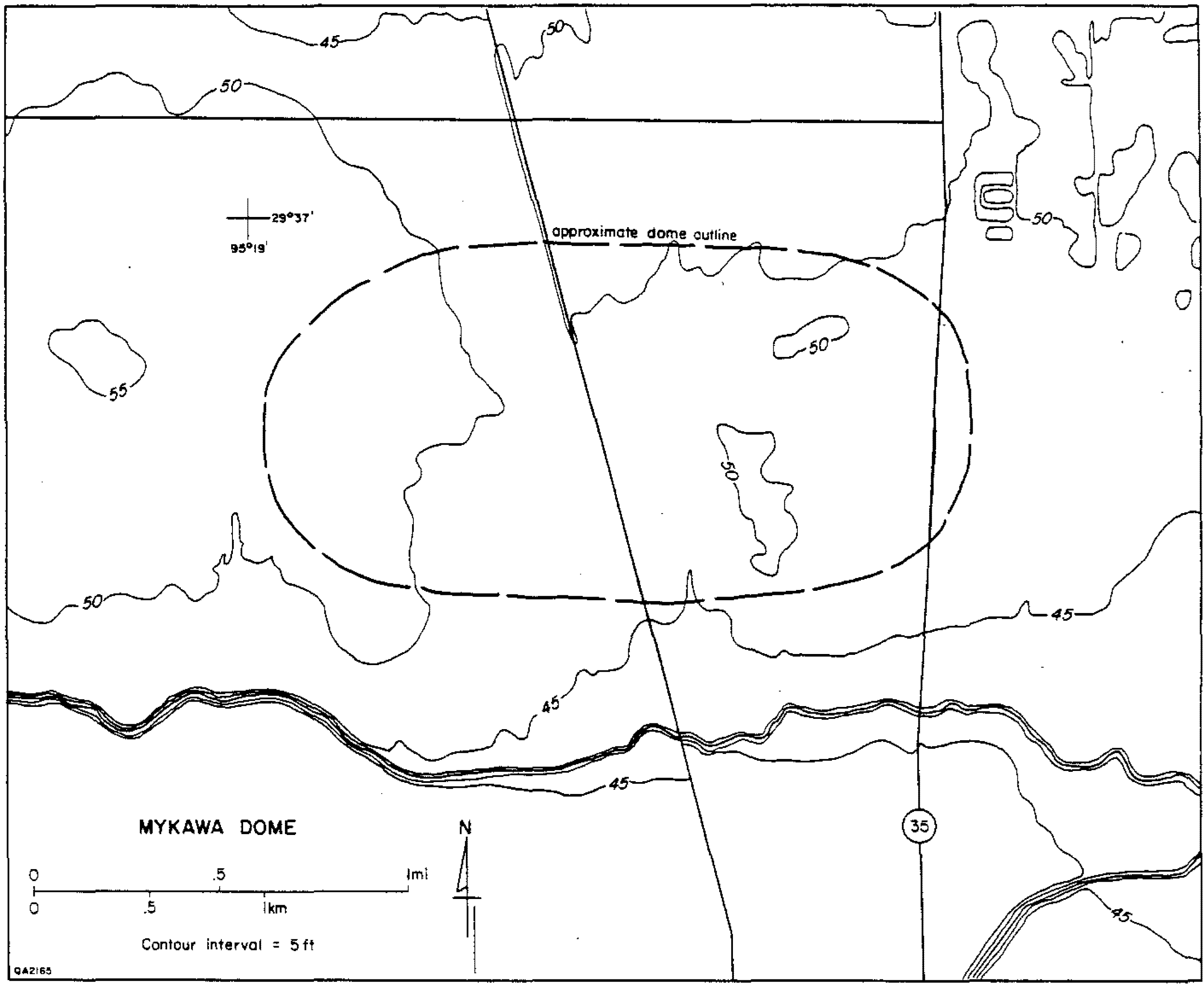

31°17'30"
96°17'30"
approximate dome outline
350
400
450
350
350
400
N
ROBERTSON CO
LEON CO
MARQUEZ DOME
0 .5 1mi
0 .5 1km
Contour interval = 10 ft

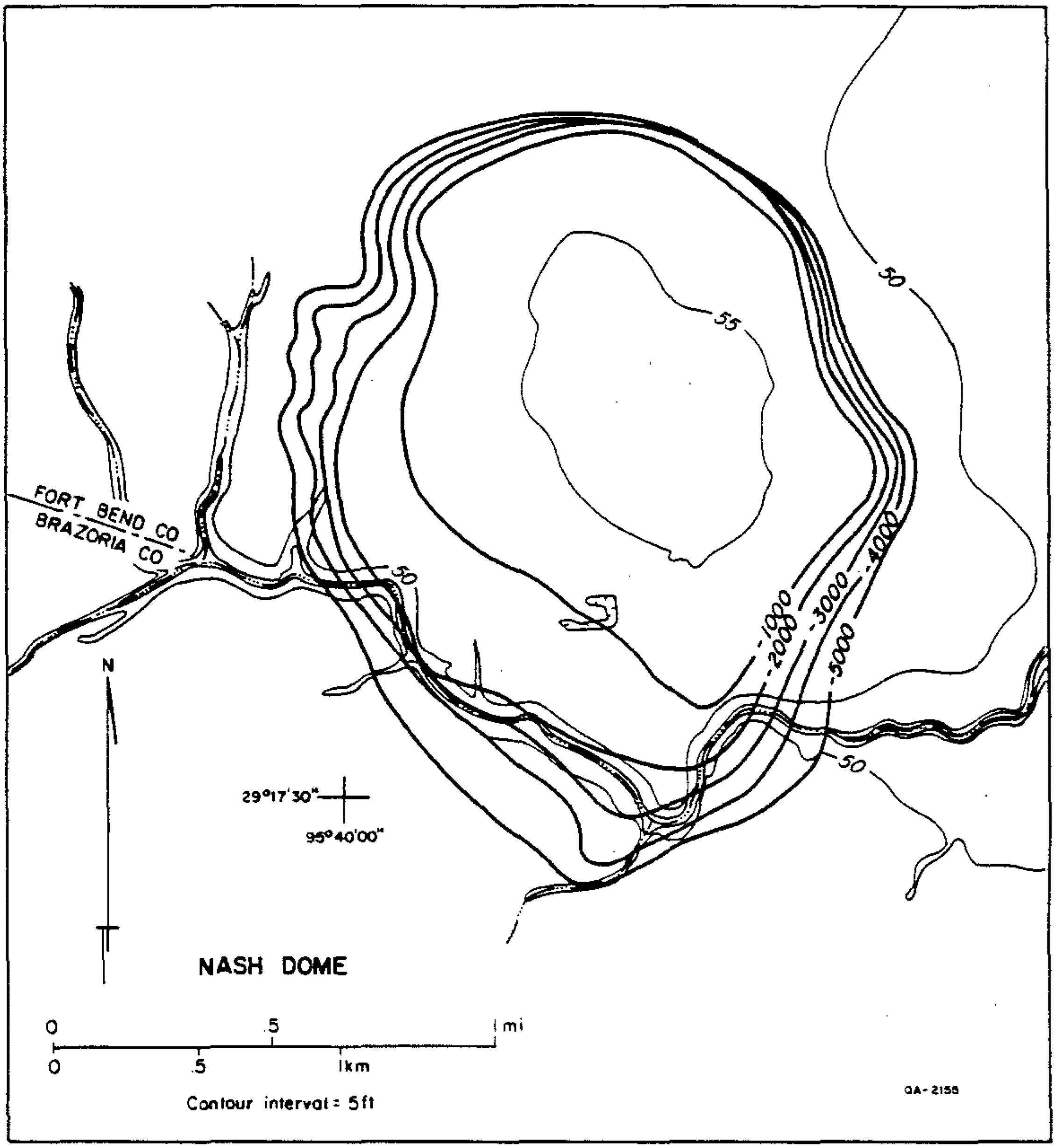

250
250
250
159
approximate dome outline
300
300
300
300
30°29'
96°12'
2154
MILLICAN DOME
0
.5
1mi
0
.5
1km
Contour interval = 10 ft
N


420
approximate dome outline
450
450
500
500
WEBB CO
DUVAL CO
27°50'00"
98°50'00"
N
MOCA DOME
0
.5
1mi
0
.5
1km
Contour interval = 10ft
QA-2143

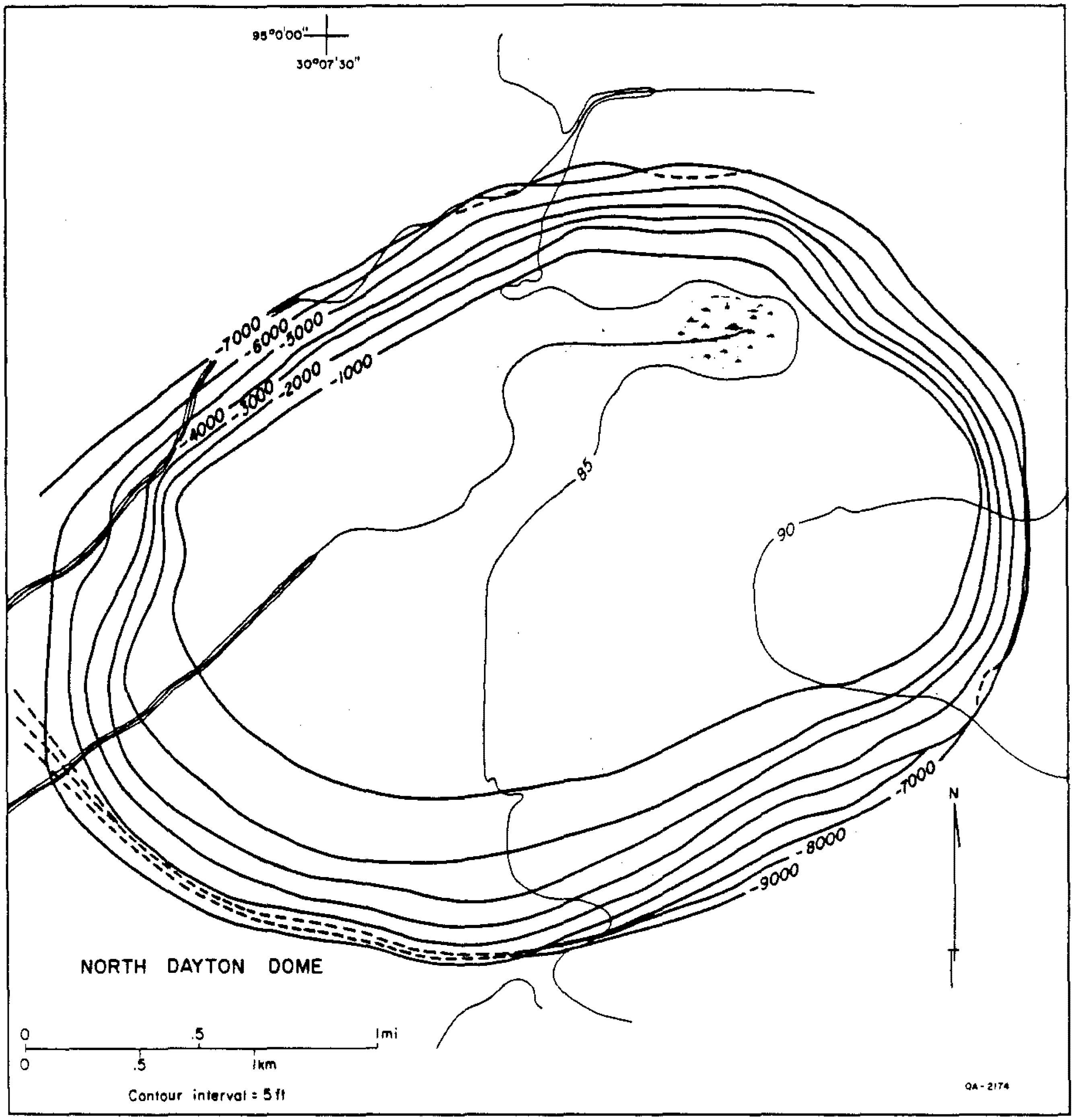

MOSS BLUFF DOME
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
N
QA2175
LIBERTY CO.
CHAMBERS CO.
563
-1100
-1300
-1500
-2000
-3000
-4000
-5000
20
25
35
40
45
29°52'30"
94°41'

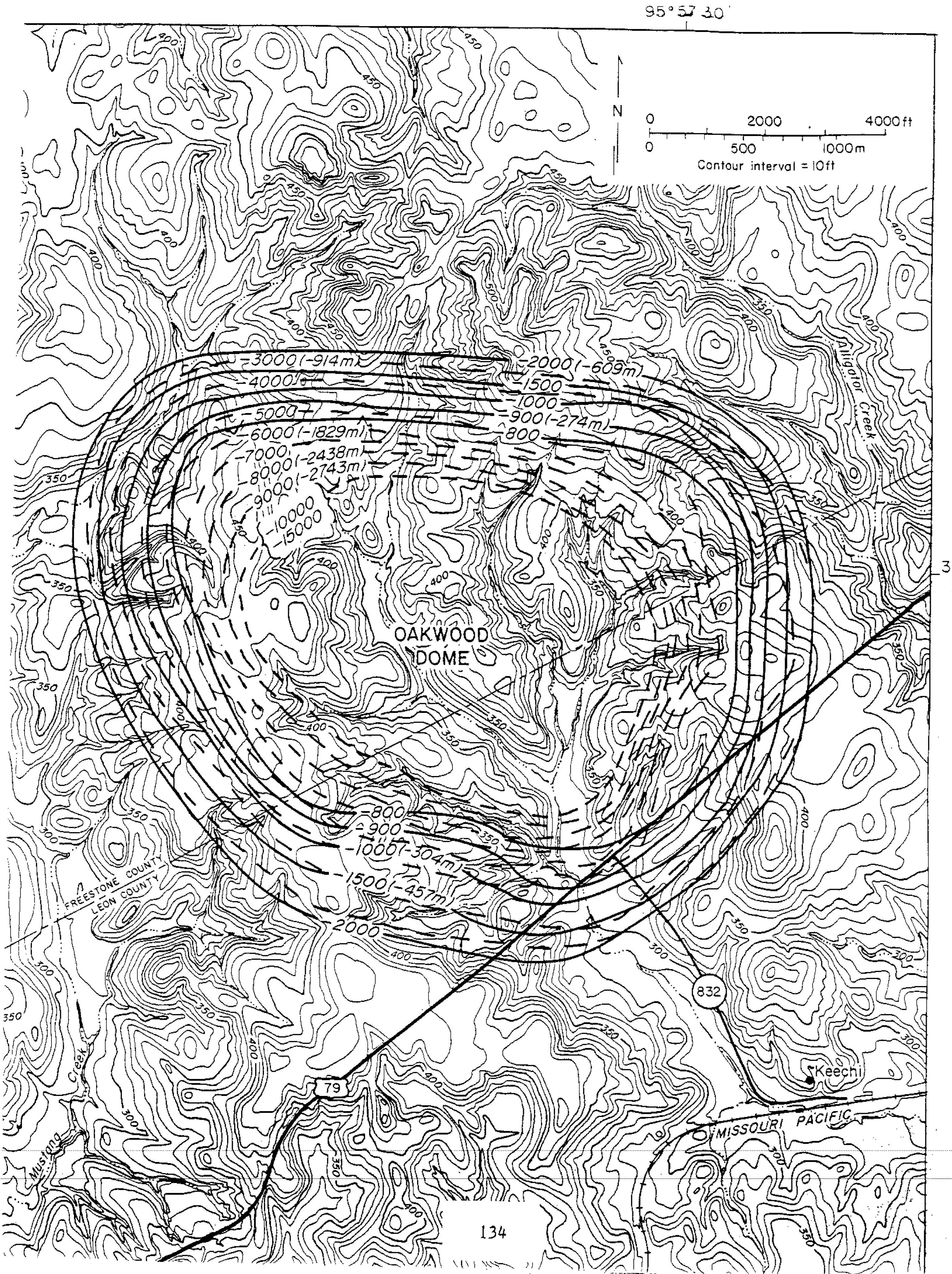

95°27'
95°25'
32° 25'
32° 23'
-18,000 (-5486 m)
-15,000 (-4572 m)
-6000 (-1829 m)
-5000 (-1524 m)
-4000 (-1219 m)
-3500 (-1067 m)
-3000 (-914 m)
-2000 (-610 m)
-1000 (-305 m)
0
-10,000 (-3048 m)
MOUNT SYLVAN DOME
Prairie Creek
Black Fork Creek
Neches River
724
64
279
VAN ZANDT CO
SMITH CO
500
450
400
0 .5 1 mi
0 .5 1 km
Contour interval = 10 ft
N

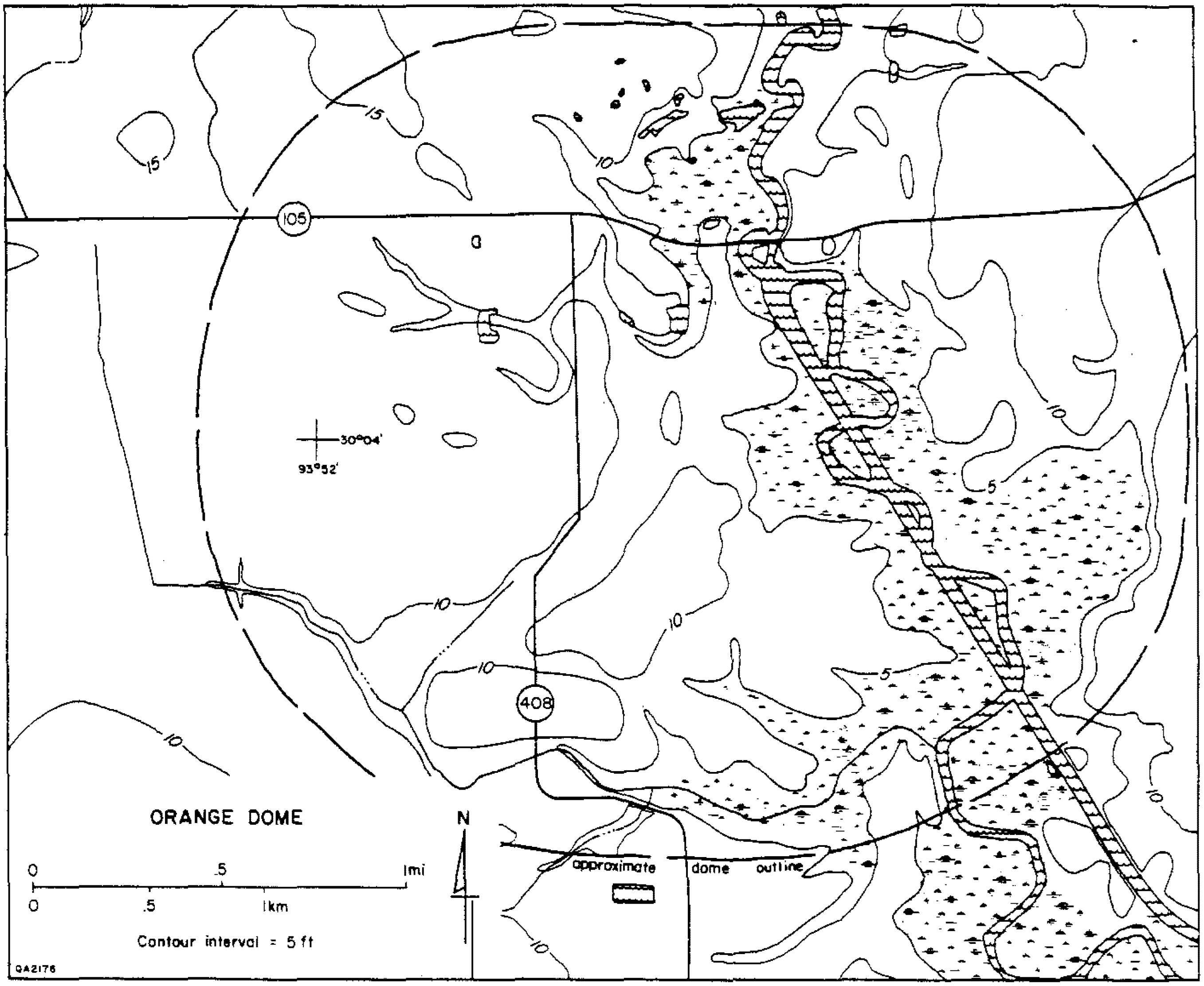
45
50
50
29°37'
95°19'
approximate dome outline
50
55
50
50
50
45
45
45
45
MYKAWA DOME
N
35
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
QA2165

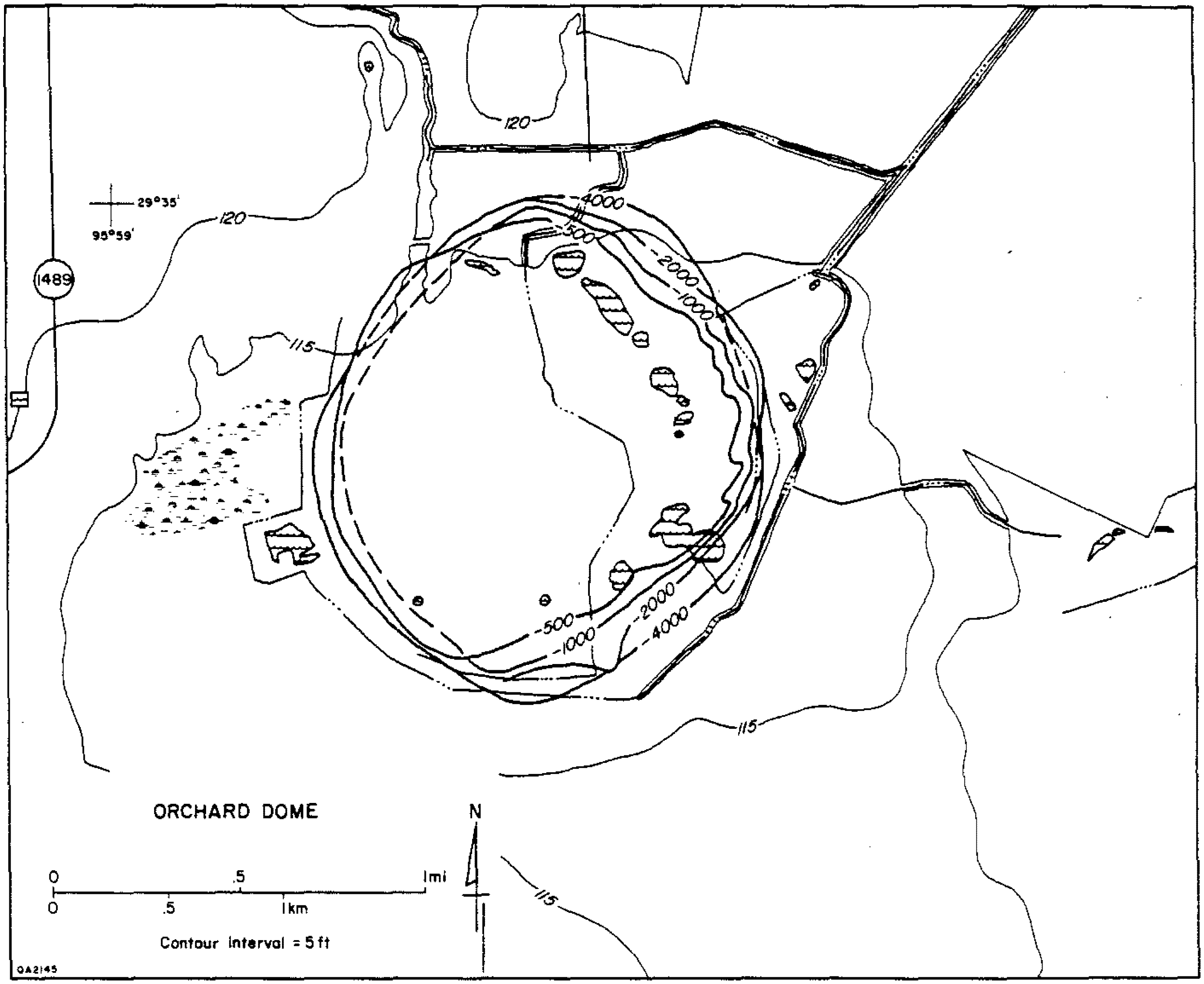


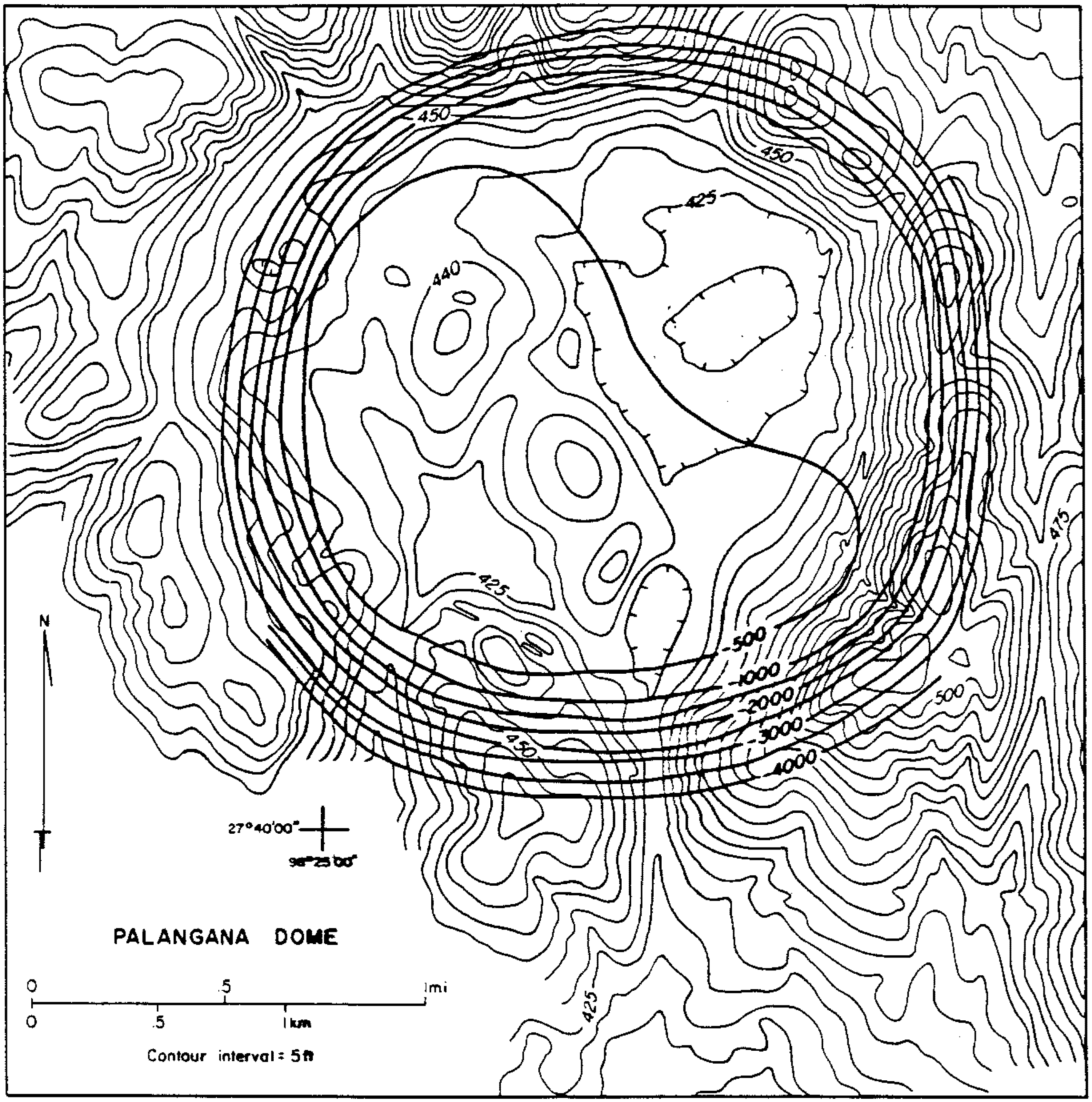
FORT BEND CO
BRAZORIA CO
N
29°17'30"
95°40'00"
50
55
50
50
-1000
-2000
-3000
-4000
-5000
NASH DOME
0 .5 1 mi
0 .5 1 km
Contour interval = 5 ft
QA-2155

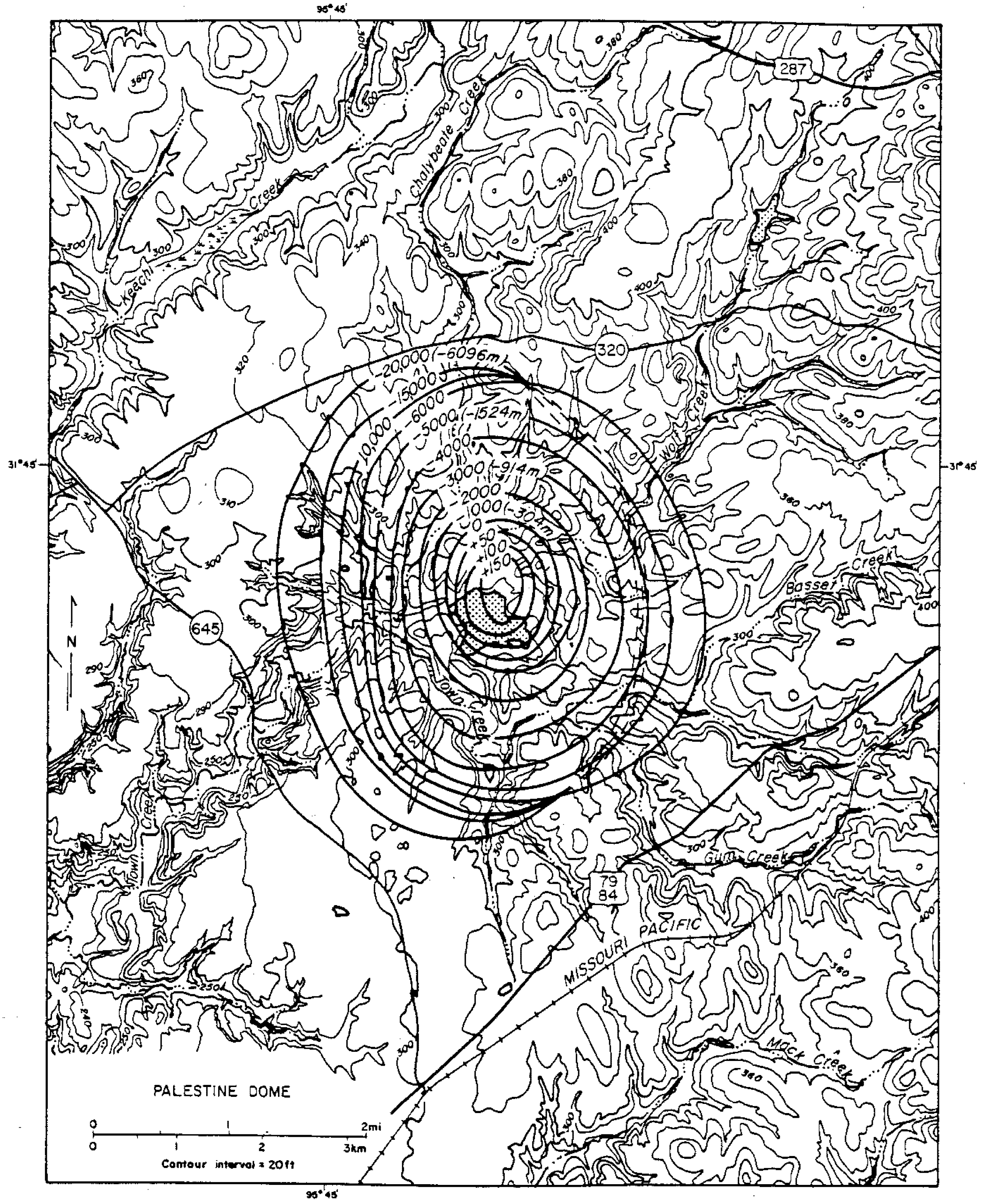

95°0'00"
30°07'30"
-7000
-6000
-5000
-4000
-3000
-2000
-1000
85
90
-7000
-8000
-9000
N
NORTH DAYTON DOME
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
QA-2174

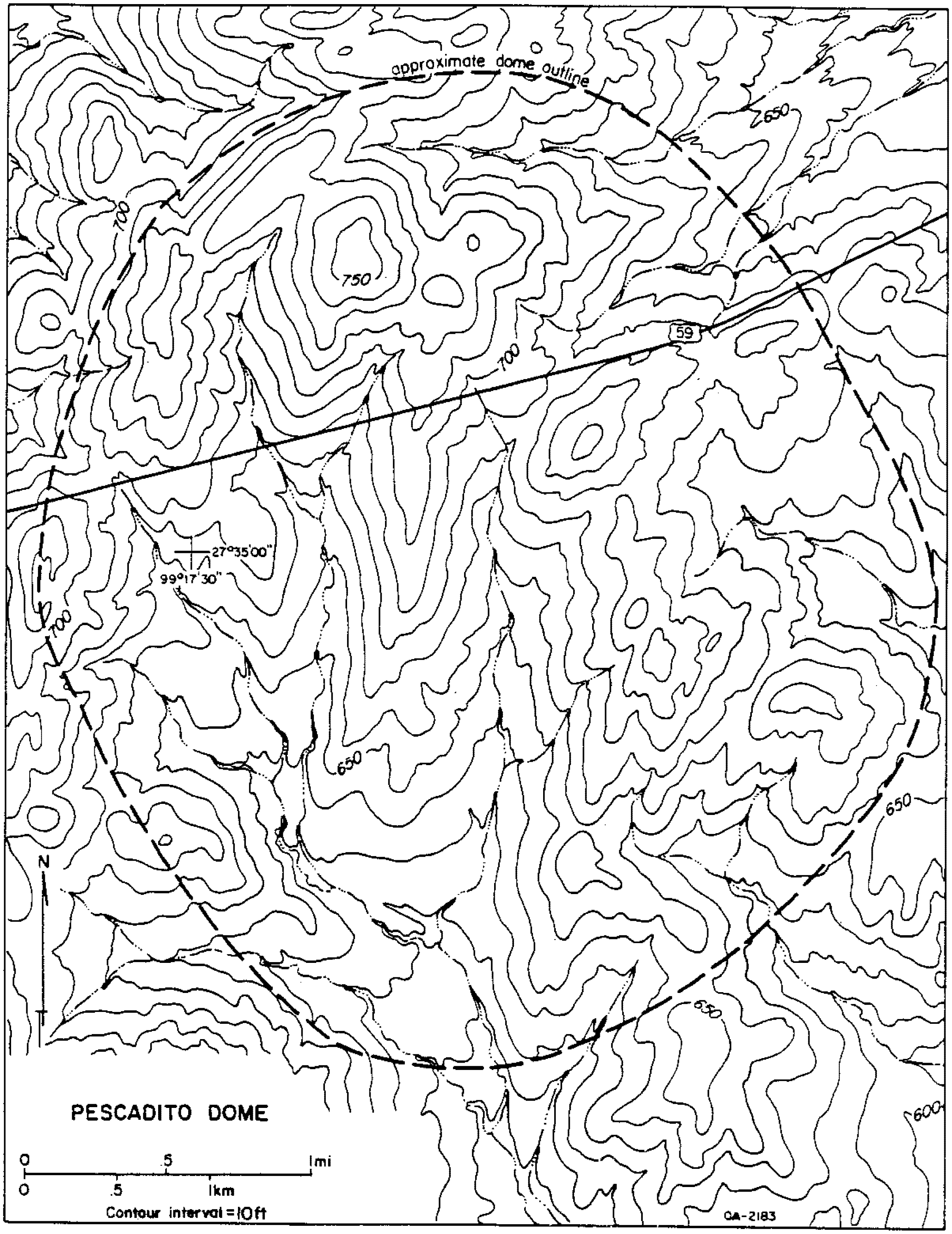

95°57'30"
N
0 2000 4000 ft
0 500 1000 m
Contour interval = 10 ft
-3000 (-914m)
-2000 (-609m)
-4000
-1500
-1000
-5000
-900 (-274m)
-6000 (-1829m)
-800
-7000
-8000 (-2438m)
-9000 (-2743m)
-10000
-15000
Alligator Creek
31°3 30"
OAKWOOD DOME
-800
-900
-1000 (-304m)
-1500 (-457m)
-2000
FREESTONE COUNTY
LEON COUNTY
832
Mustang Creek
79
Keechi
MISSOURI PACIFIC
300
350
400
450
500

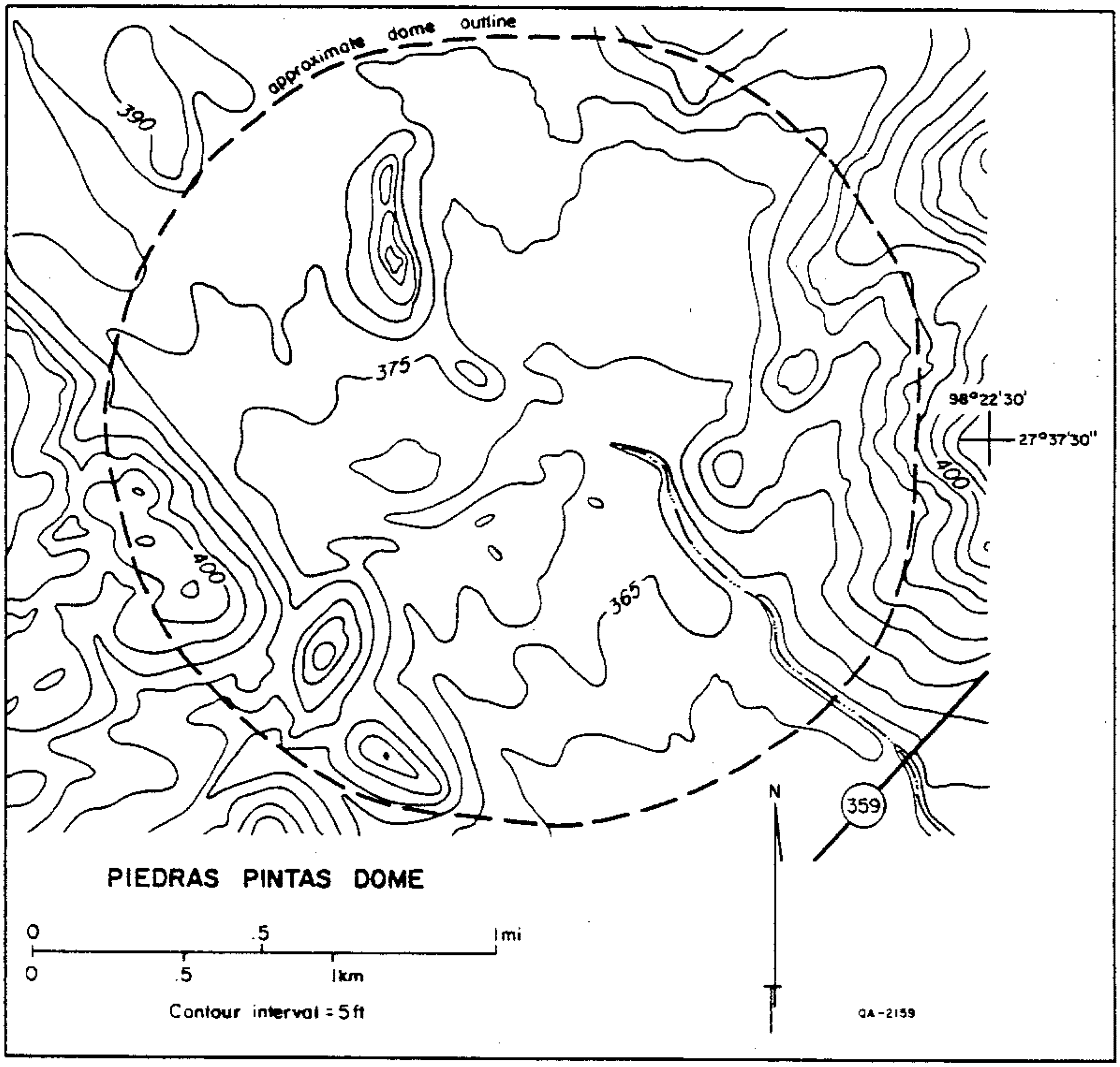

ORANGE DOME
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
QA2176
N
approximate dome outline
105
408
15
15
10
10
10
10
10
10
10
5
5
30°04'
93°52'

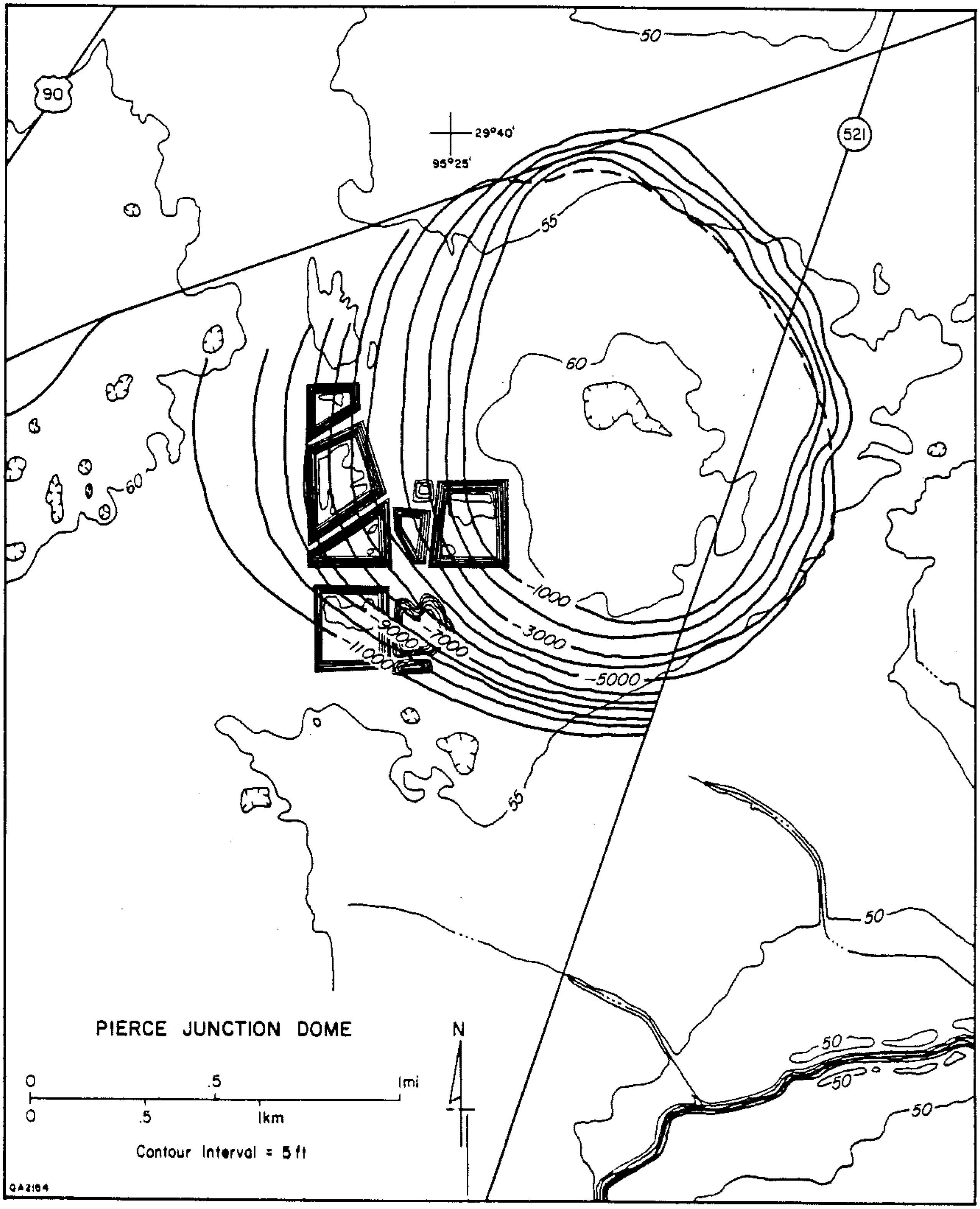

120
120
29°35'
95°59'
1489
115
4000
500
2000
1000
500
1000
2000
4000
115
115
ORCHARD DOME
N
0
.5
1mi
0
.5
1km
Contour Interval = 5 ft
QA2145

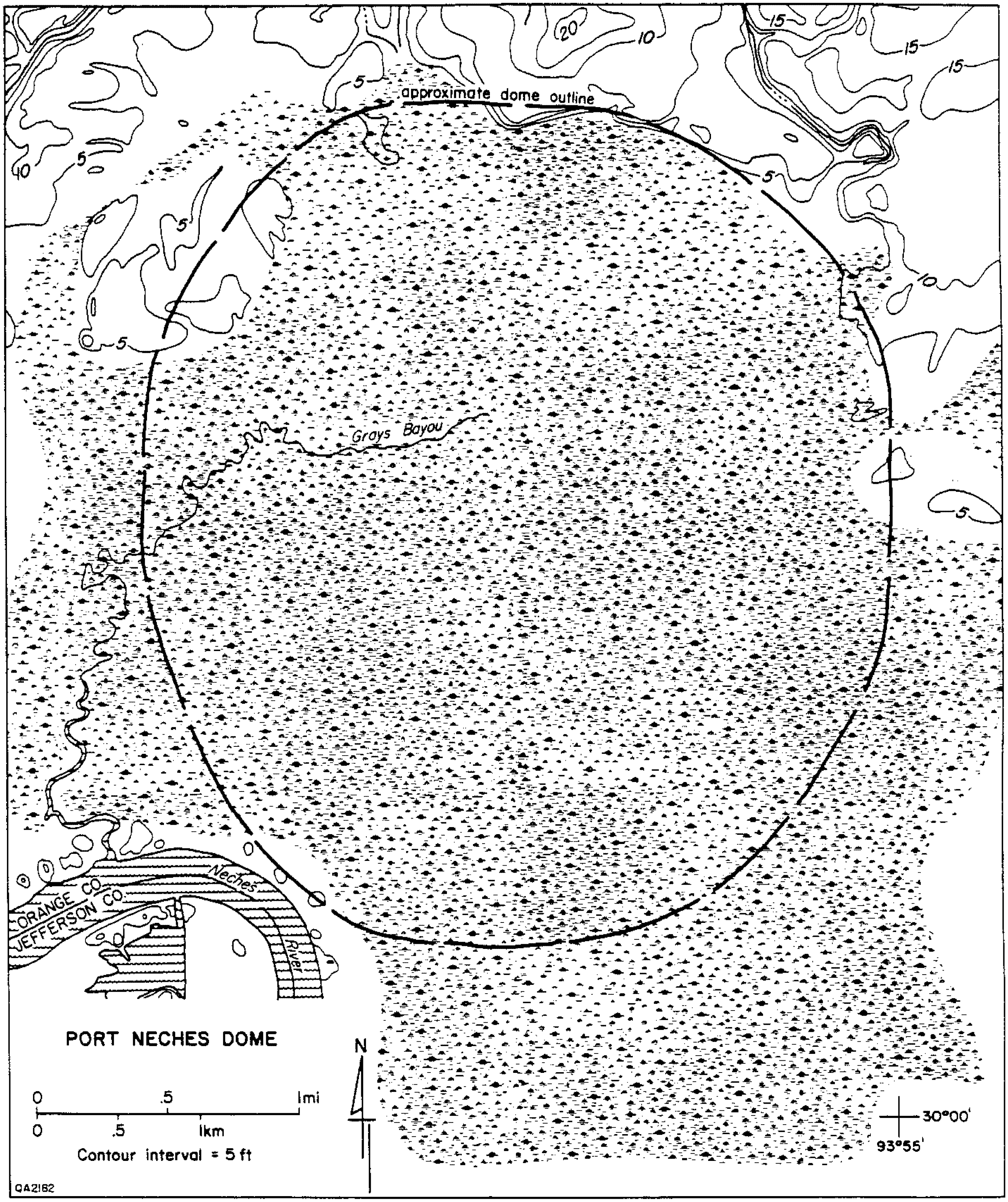

450
450
425
440
425
475
500
1000
2000
3000
4000
500
450
425
N
27°40'00"
98°25'00"
PALANGANA DOME
0 .5 1mi
0 .5 1km
Contour interval = 5ft

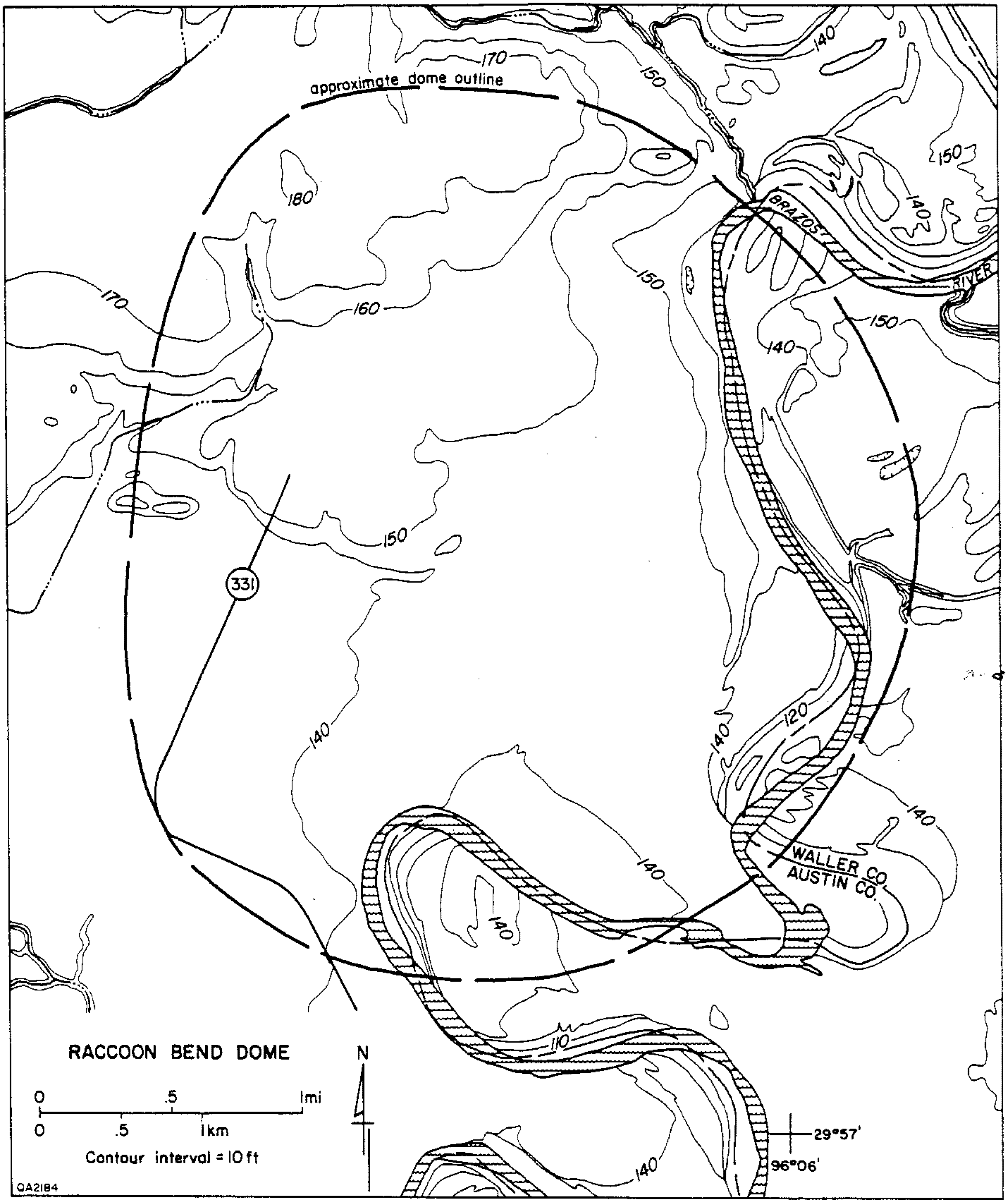

96°45'
31°45'
PALESTINE DOME
0 1 2mi
0 1 2 3km
Contour interval = 20ft
N
Keechi Creek
Chalybeate Creek
Wolf Creek
Town Creek
Basset Creek
Gum Creek
Mack Creek
MISSOURI PACIFIC
287
320
645
79
84
-20,000 (-6096m)
-15000
-10,000
-6000
-5000 (-1524m)
-4000
-3000 (-914m)
-2000
-1000 (-304m)
0
+50
+100
+150
250
290
300
310
320
340
360
380
400

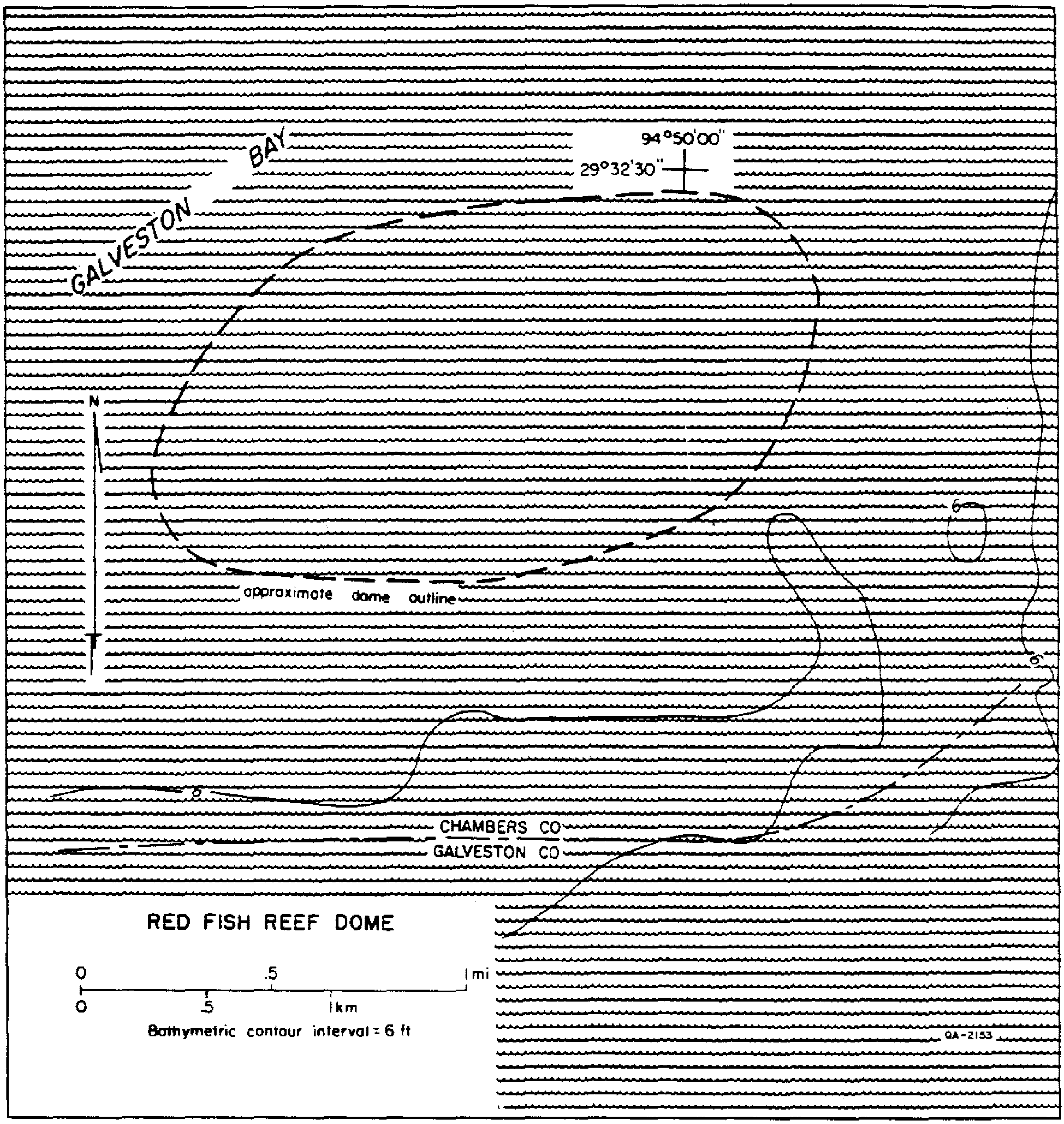

approximate dome outline
650
700
750
700
59
27°35'00"
99°17'30"
700
650
650
650
600
N
PESCADITO DOME
0 .5 1mi
0 .5 1km
Contour interval = 10 ft
QA-2183

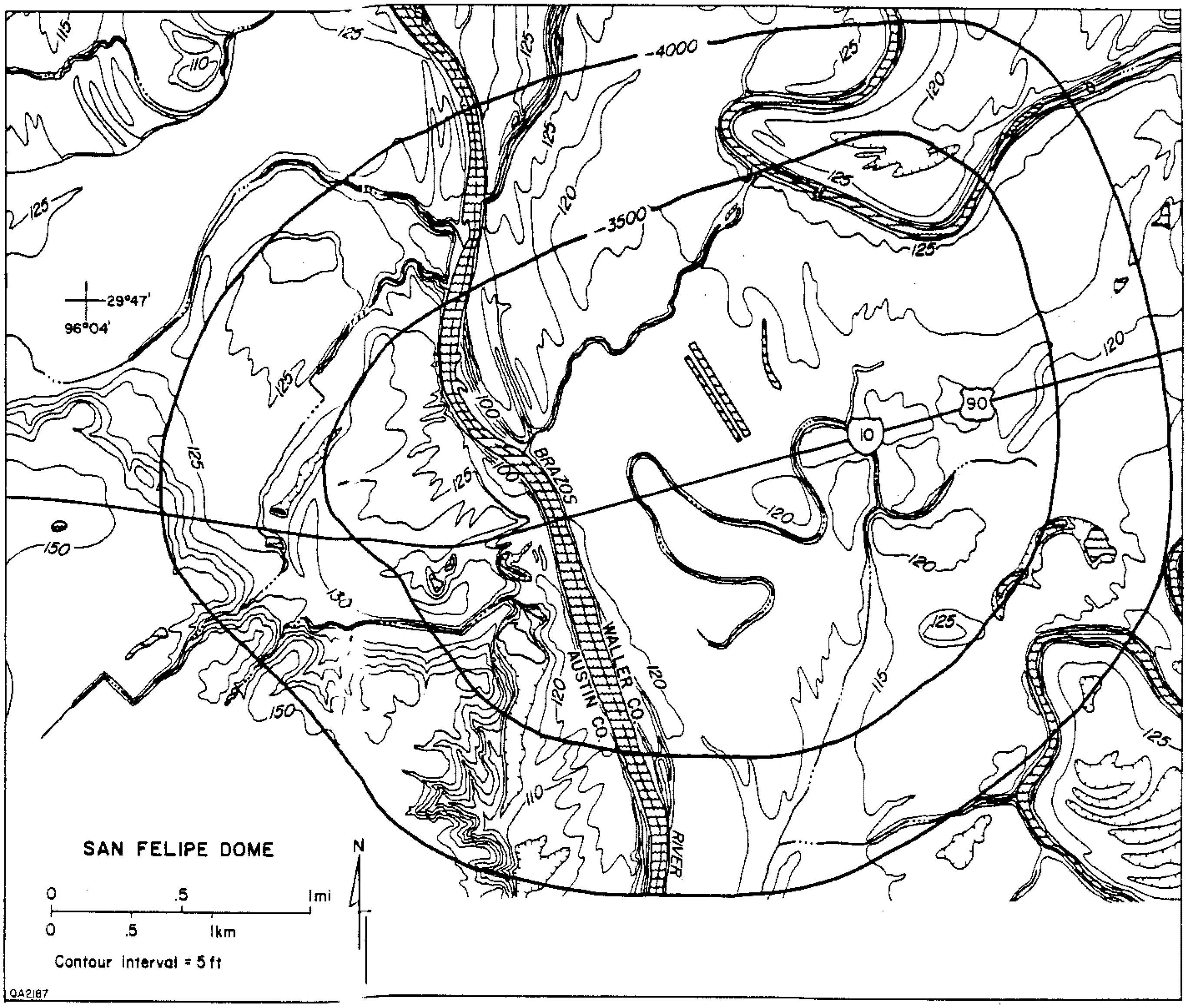

approximate dome outline
390
375
400
365
400
98°22'30'
27°37'30"
359
N
PIEDRAS PINTAS DOME
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
QA-2159


PIERCE JUNCTION DOME
0
.5
1mi
0
.5
1km
Contour Interval = 5 ft
N
QA2184
90
521
29°40'
95°25'
50
55
60
60
-1000
-3000
-5000
-7000
-9000
-11000
55
50
50
50
50

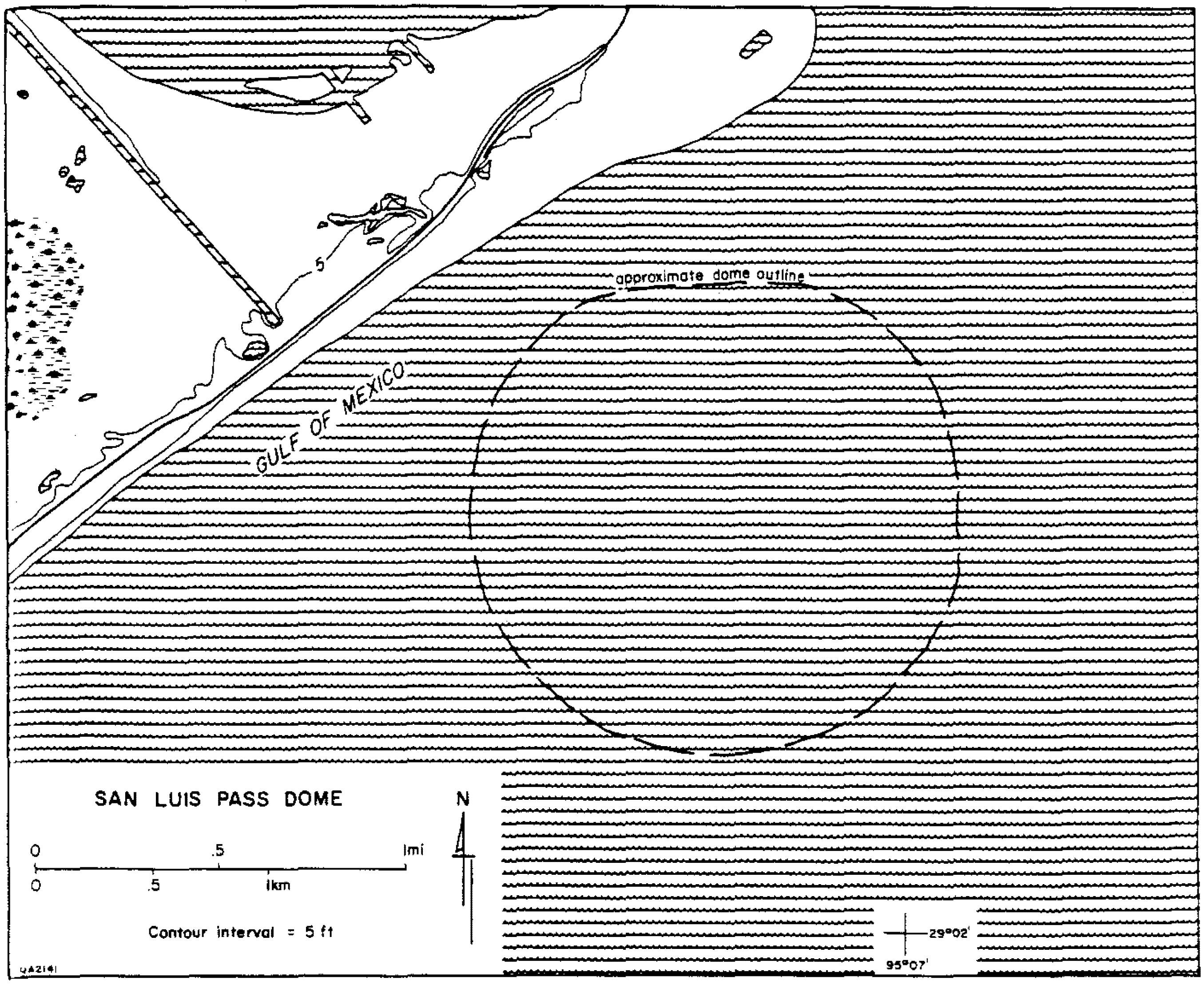

PORT NECHES DOME
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
QA2182
N
30°00'
93°55'
approximate dome outline
Grays Bayou
Neches River
ORANGE CO.
JEFFERSON CO.
5
10
15
20

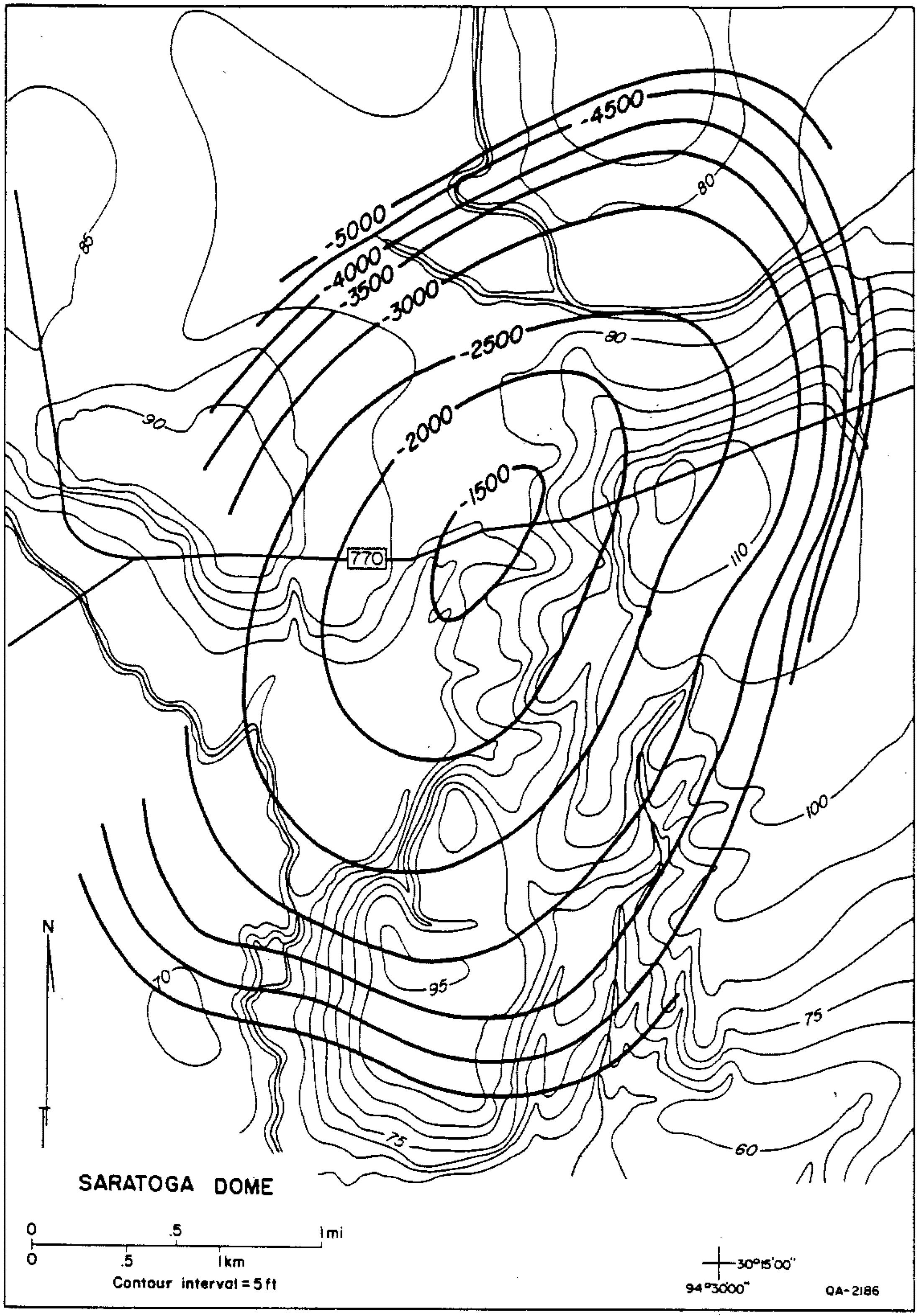

approximate dome outline
170
150
140
150
140
180
170
160
150
150
140
150
331
140
120
140
140
WALLER CO.
AUSTIN CO.
140
140
110
140
29°57'
96°06'
BRAZOS
RIVER
N
RACCOON BEND DOME
0 .5 1mi
0 .5 1km
Contour interval = 10 ft
QA2184

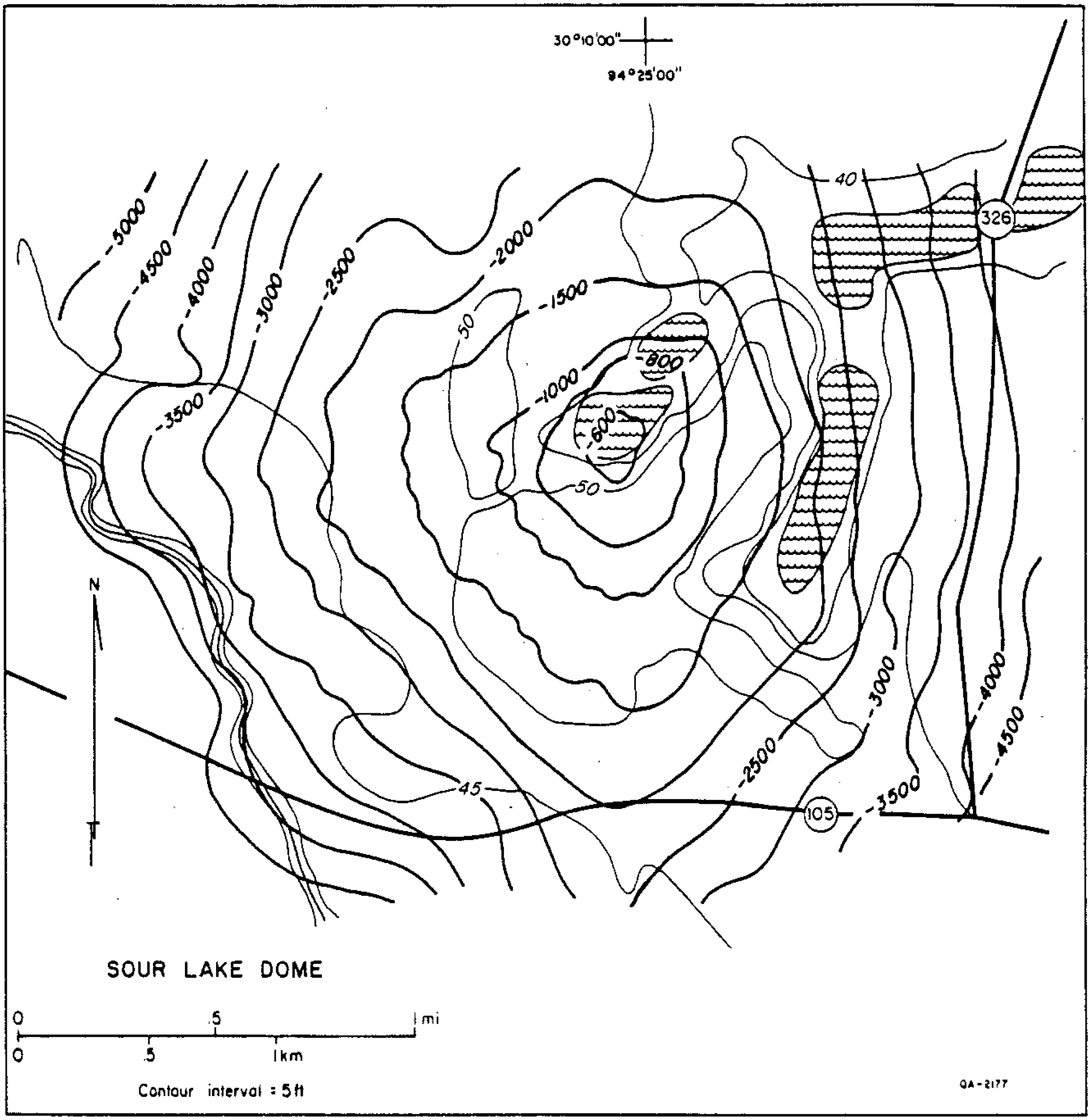

GALVESTON BAY
94°50'00"
29°32'30"
N
approximate dome outline
6
6
6
CHAMBERS CO
GALVESTON CO
RED FISH REEF DOME
0 .5 1 mi
0 .5 1 km
Bathymetric contour interval = 6 ft
QA-2153

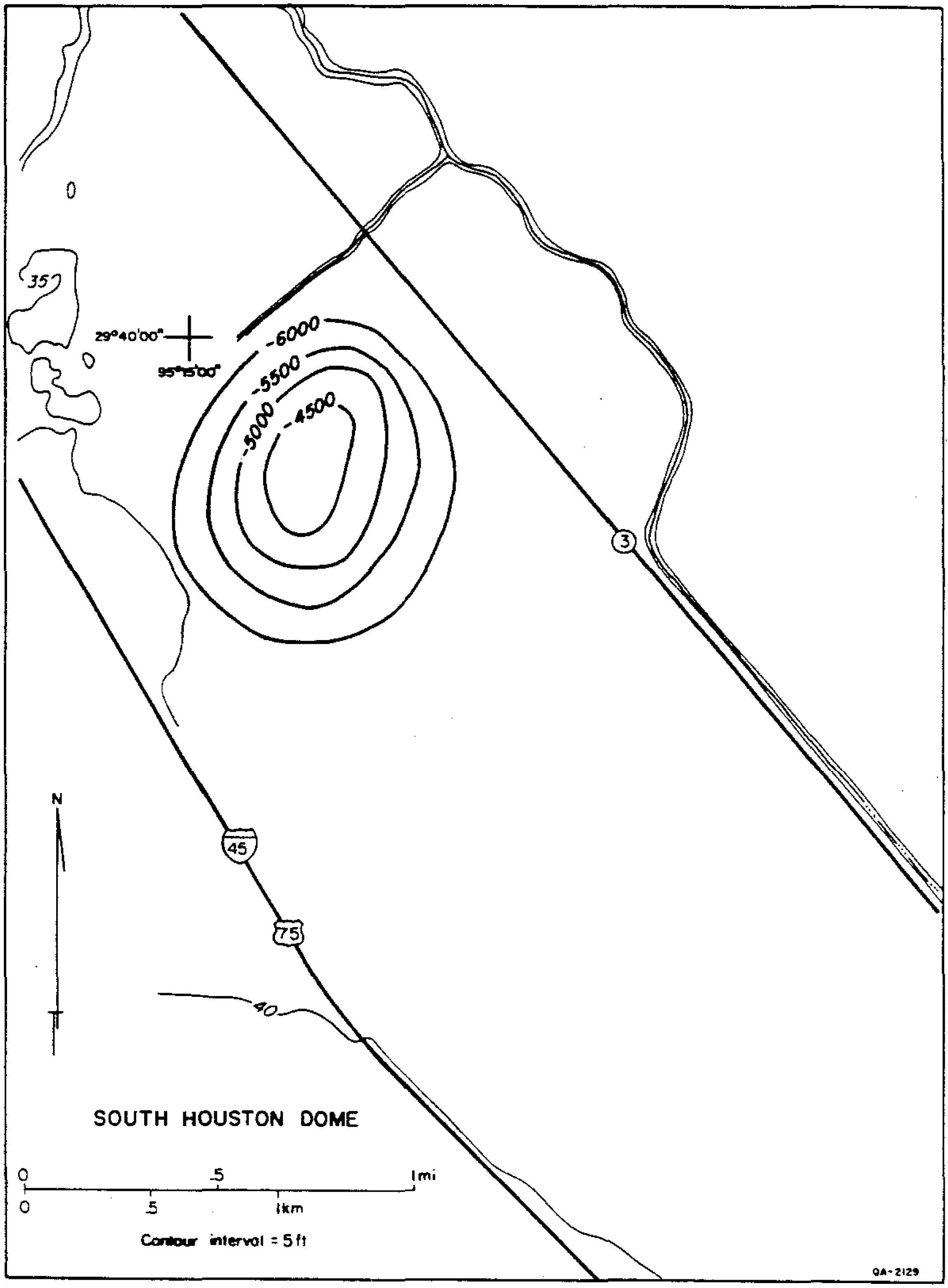


115
110
125
-4000
125
120
125
120
-3500
125
120
125
125
29°47'
96°04'
125
100
125
100
BRAZOS
10
90
120
120
120
150
130
125
WALLER CO.
AUSTIN CO.
120
120
115
150
110
RIVER
125
SAN FELIPE DOME
N
0 .5 1mi
0 .5 1km
Contour interval = 5 ft
QA2187

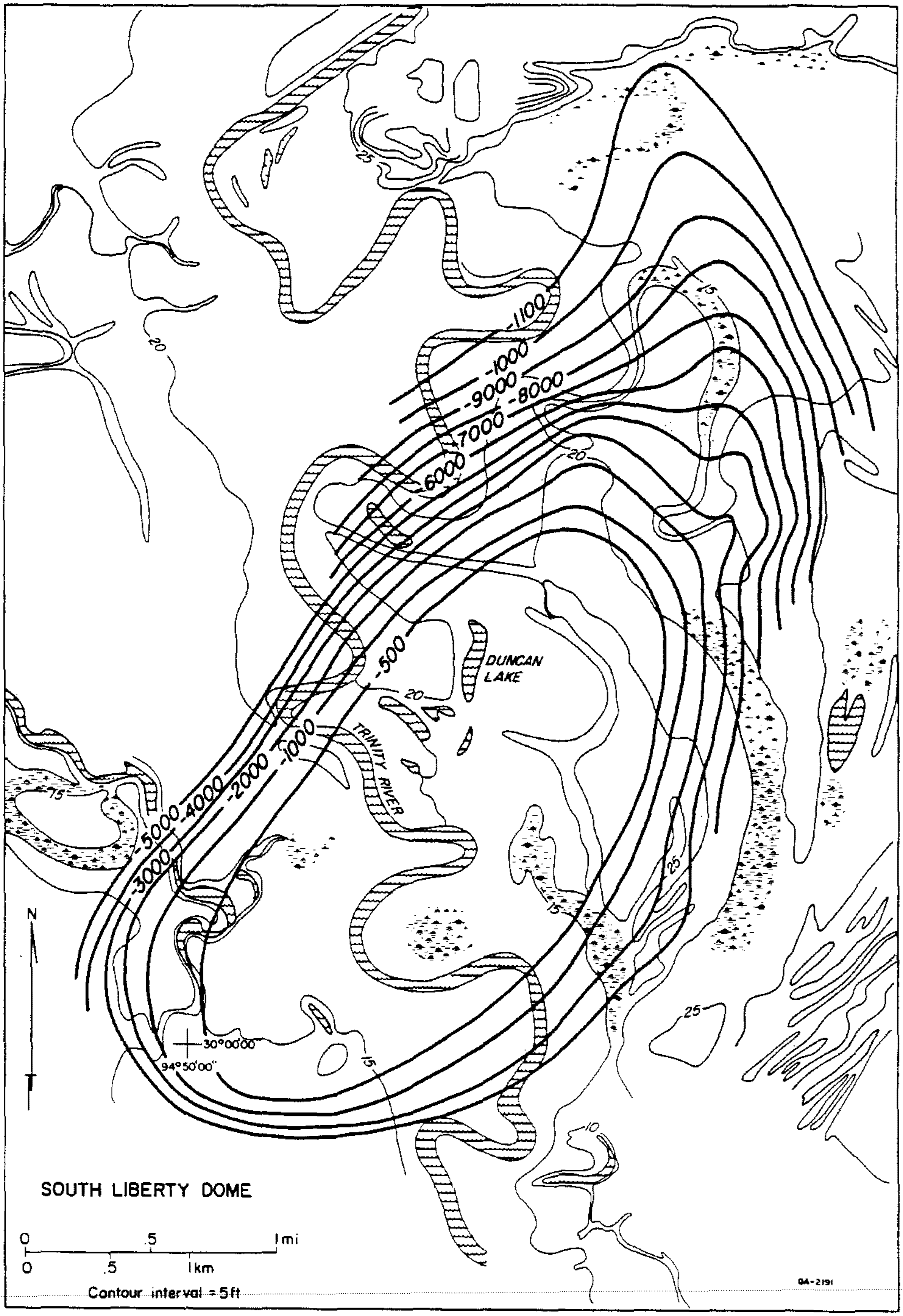

approximate dome outline
GULF OF MEXICO
5
SAN LUIS PASS DOME
0
.5
lmi
0
.5
lkm
Contour interval = 5 ft
N
29°02'
95°07'
QA2141


SARATOGA DOME
-5000
-4500
-4000
-3500
-3000
-2500
-2000
-1500
770
80
85
90
110
100
95
70
75
60
N
0
.5
1 mi
0
.5
1 km
Contour interval = 5 ft
30°15'00"
94°30'00"
QA-2186


30°10'00"
94°25'00"
-5000
-4500
-4000
-3000
-2500
-2000
-1500
-1000
-800
-600
-3500
50
50
50
40
45
326
105
-3000
-2500
-3500
-4000
-4500
N
SOUR LAKE DOME
0
.5
1 mi
0
.5
1 km
Contour interval = 5 ft
QA-2177

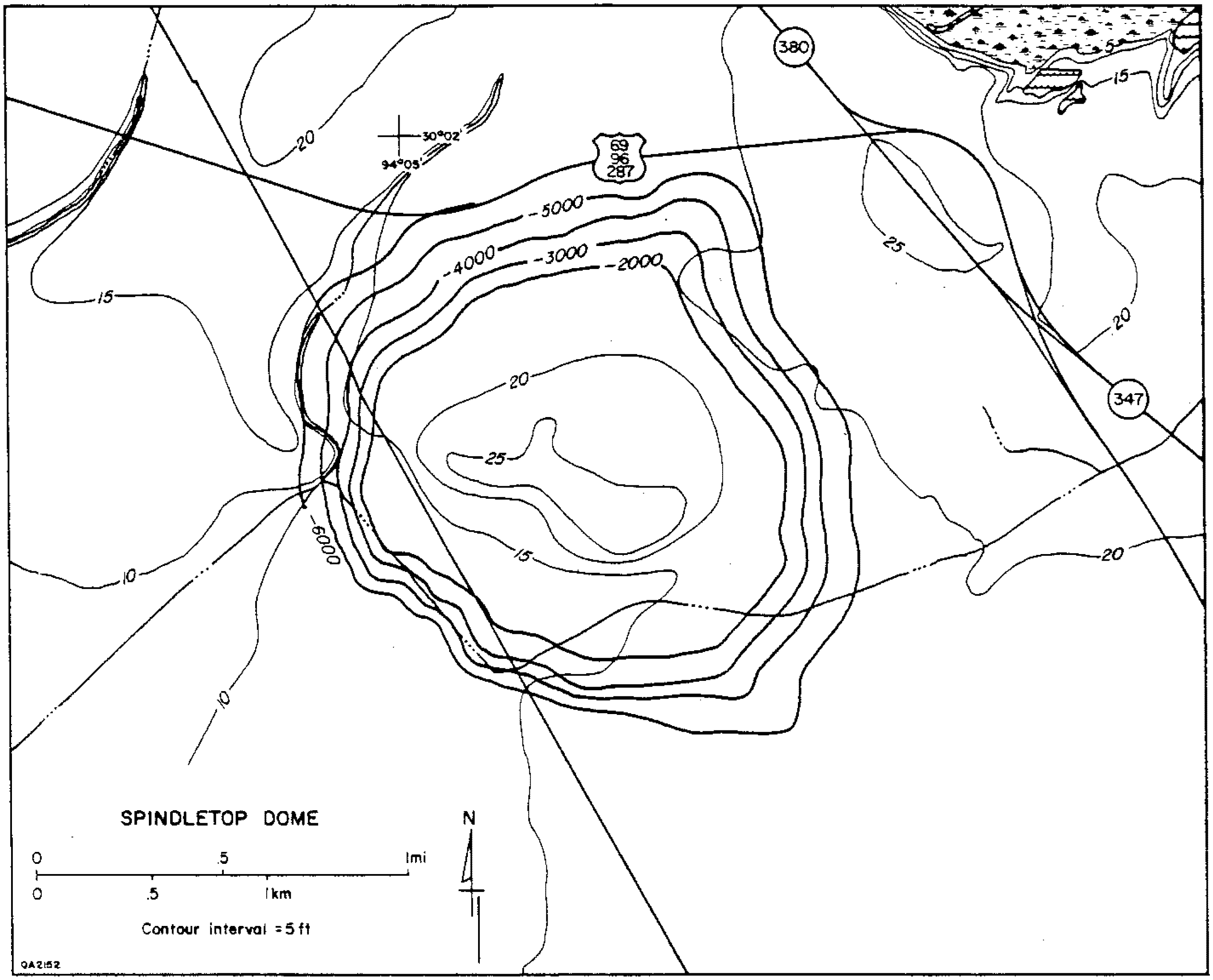


SOUTH HOUSTON DOME

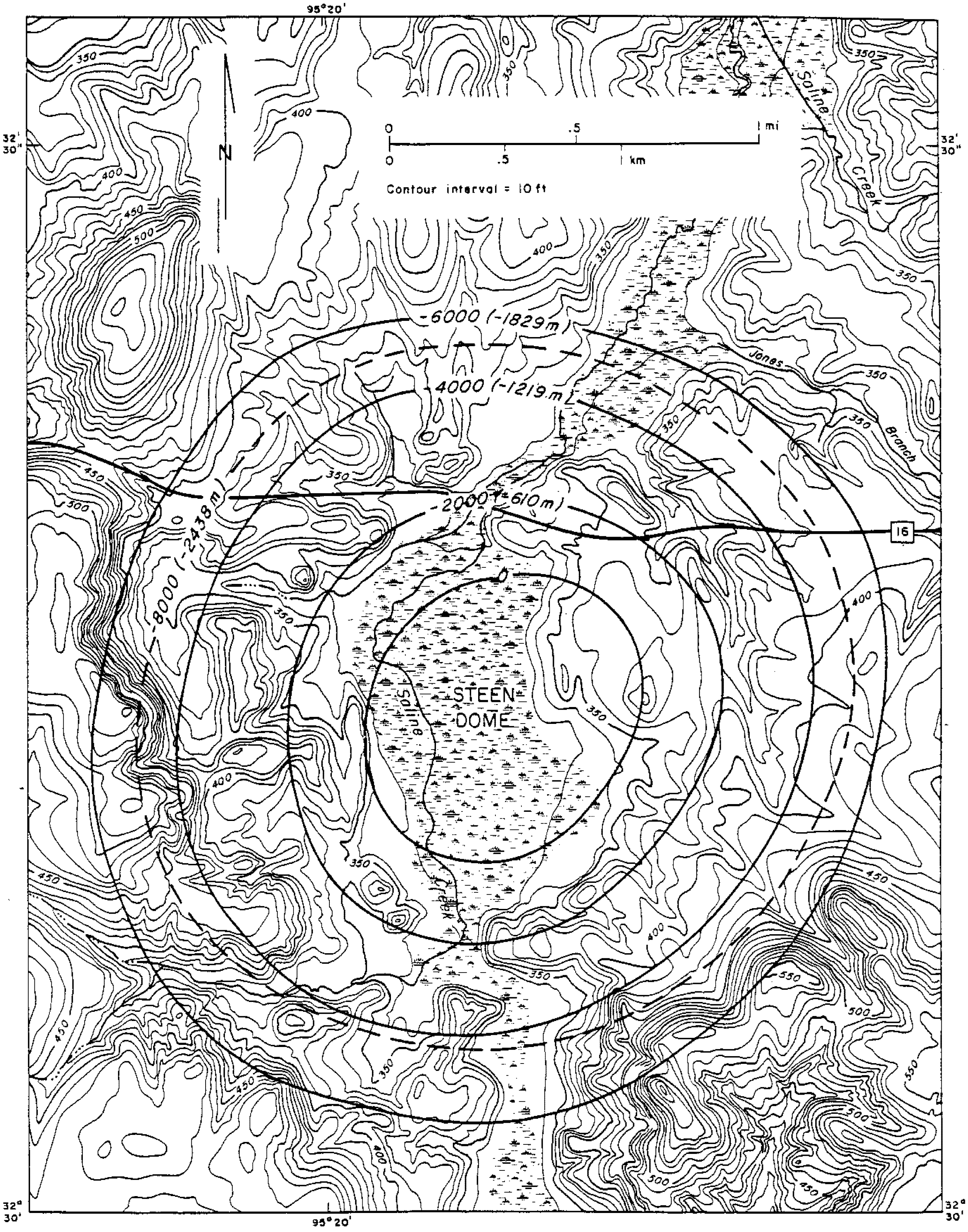


SOUTH LIBERTY DOME

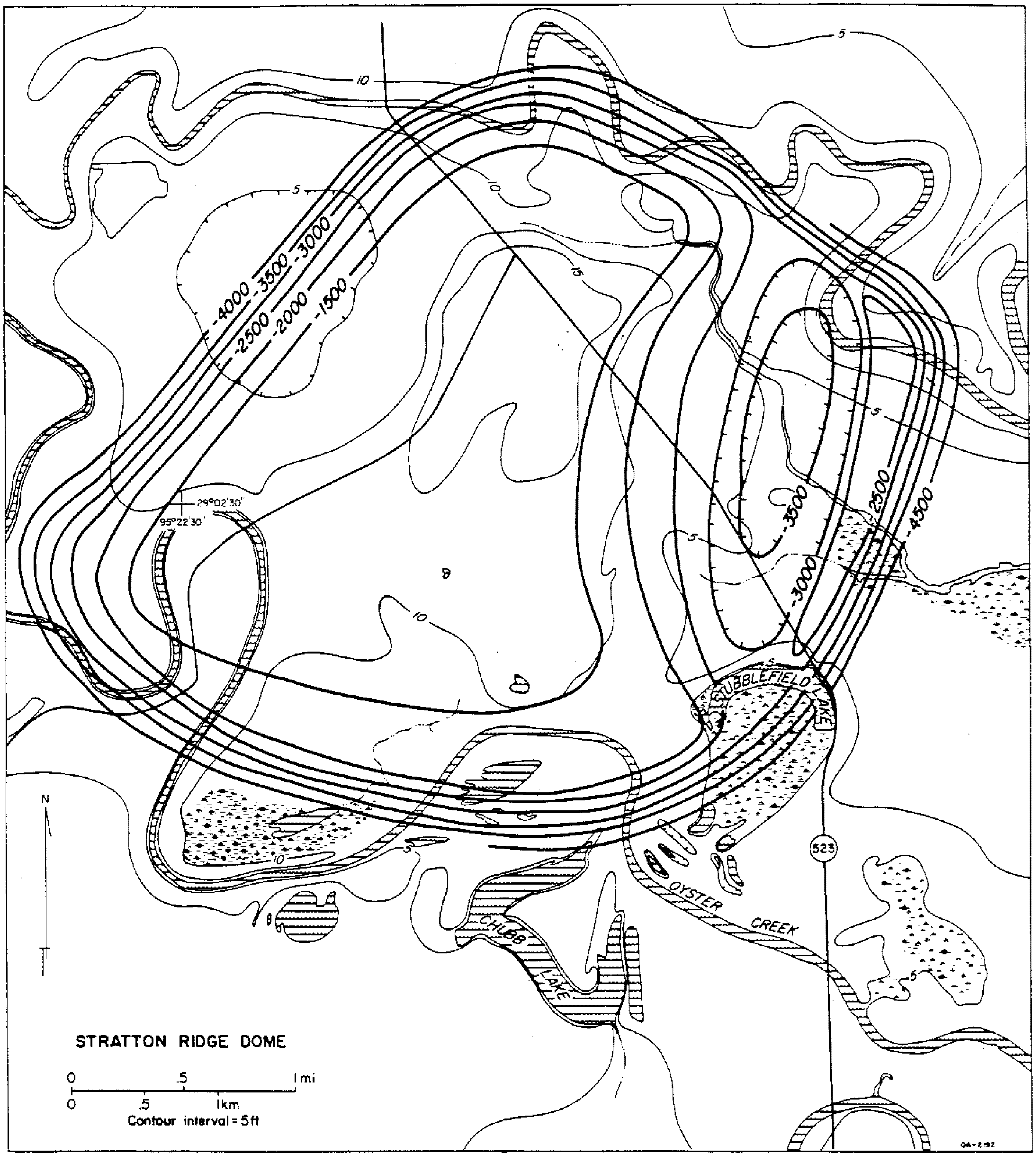
Contour interval = 5 ft



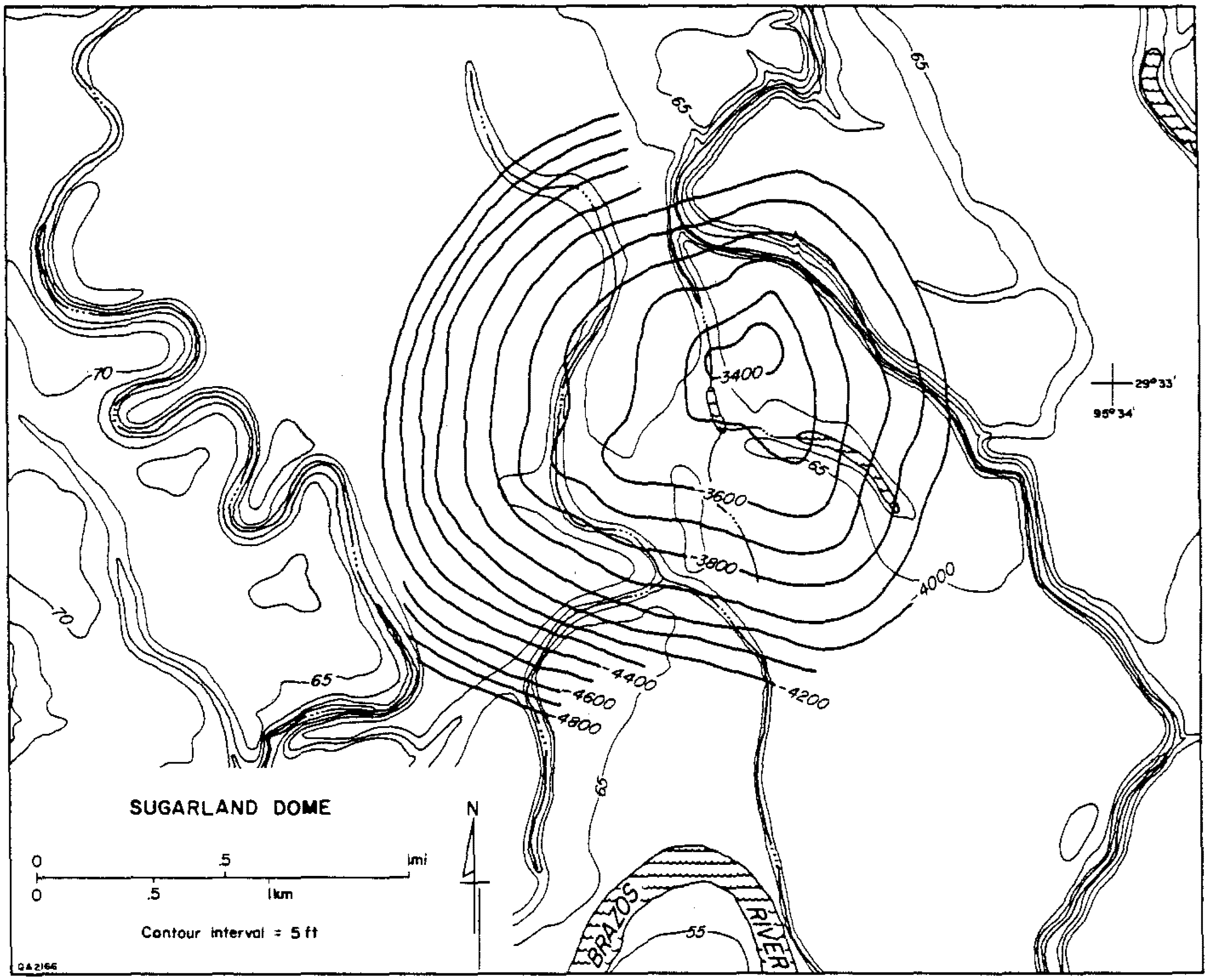
SPINDLETOP DOME
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
N
QA2152
30°02'
94°05'
69
96
287
380
347
-2000
-3000
-4000
-5000
-6000
5
10
10
15
15
15
15
20
20
20
20
25
25

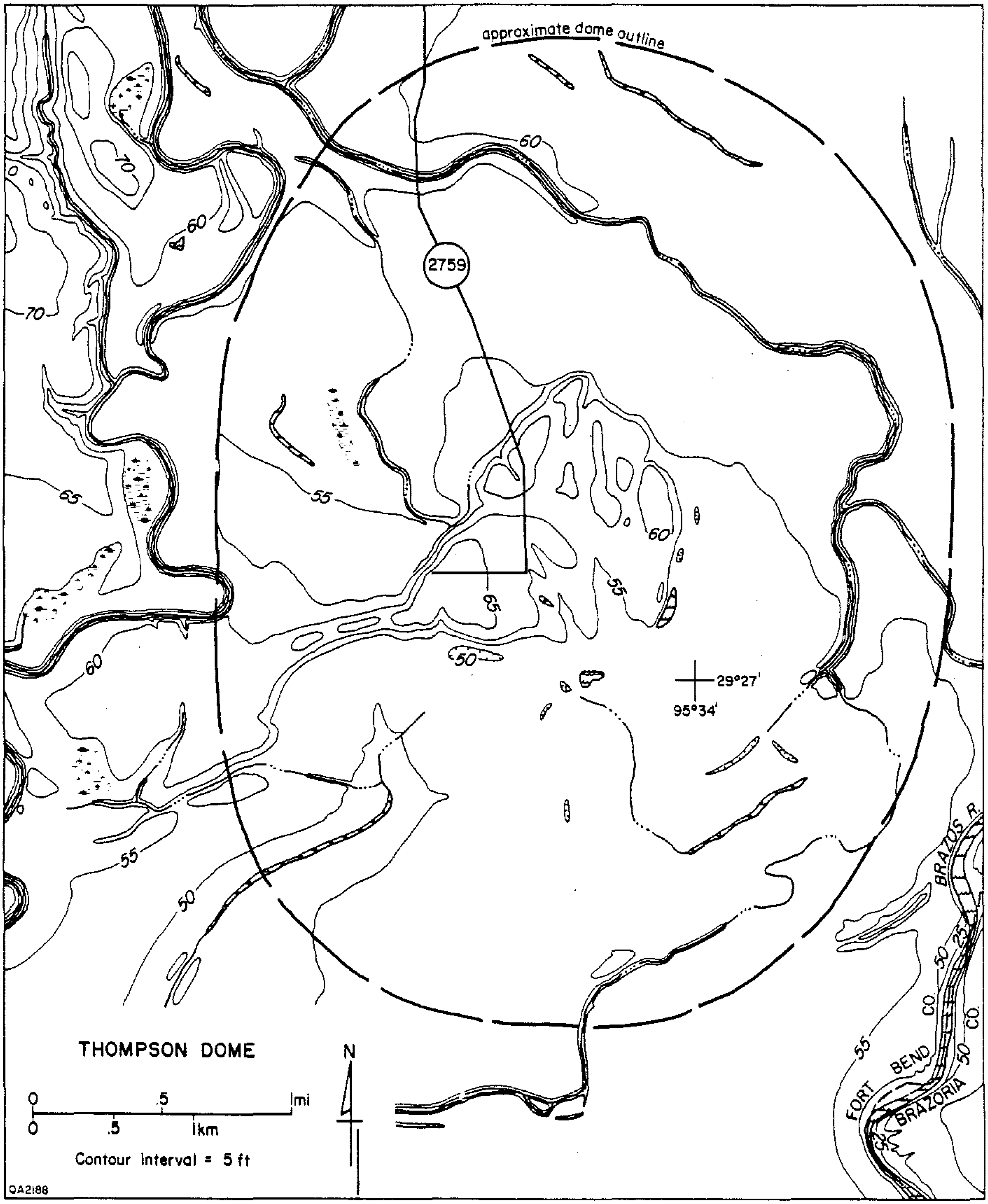


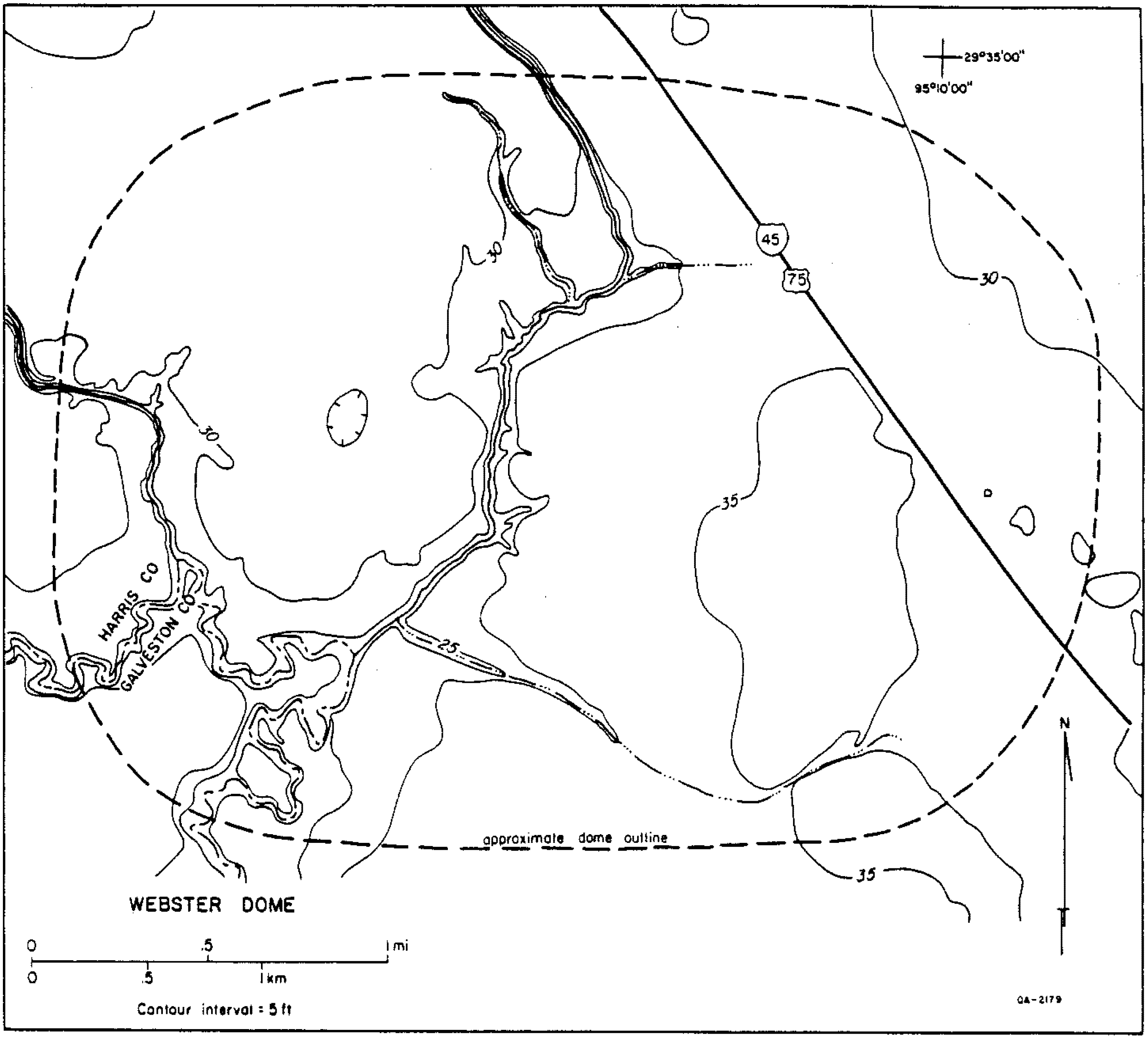
95°20'
32' 30"
32° 30'
N
0 .5 1 mi
0 .5 1 km
Contour interval = 10 ft
Saline Creek
Jones Branch
-6000 (-1829 m)
-4000 (-1219 m)
-2000 (-610 m)
-8000 (-2438 m)
16
STEEN DOME
Saline Creek
350
400
450
500
550



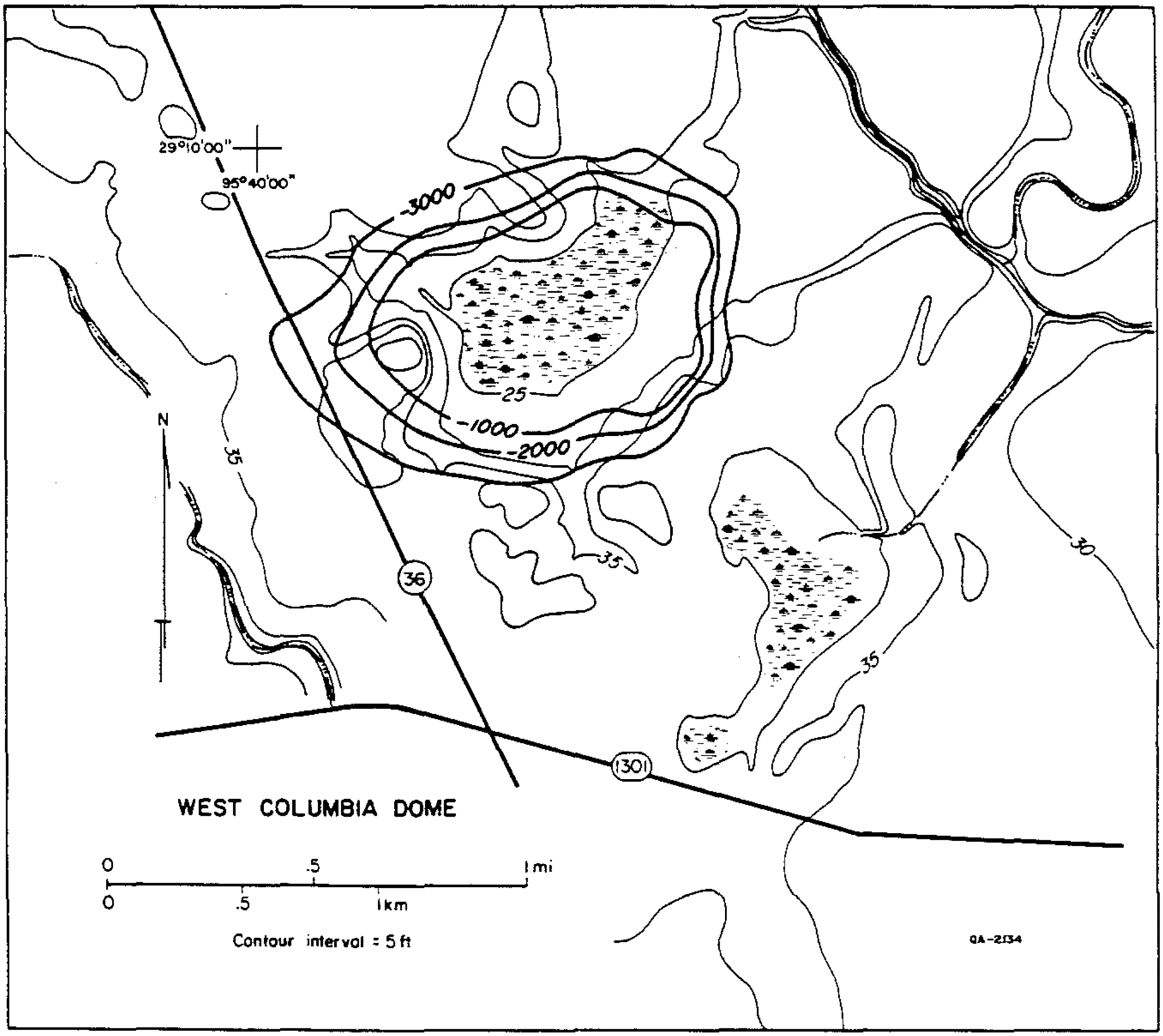
10
5
10
15
-4000
-3500
-3000
-2500
-2000
-1500
5
29°02'30"
95°22'30"
10
5
-3500
-3000
-2500
-4500
5
STUBBLEFIELD LAKE
523
OYSTER CREEK
CHUBB LAKE
10
5
N
5
STRATTON RIDGE DOME
0 .5 1 mi
0 .5 1 km
Contour interval = 5 ft
QA-2192

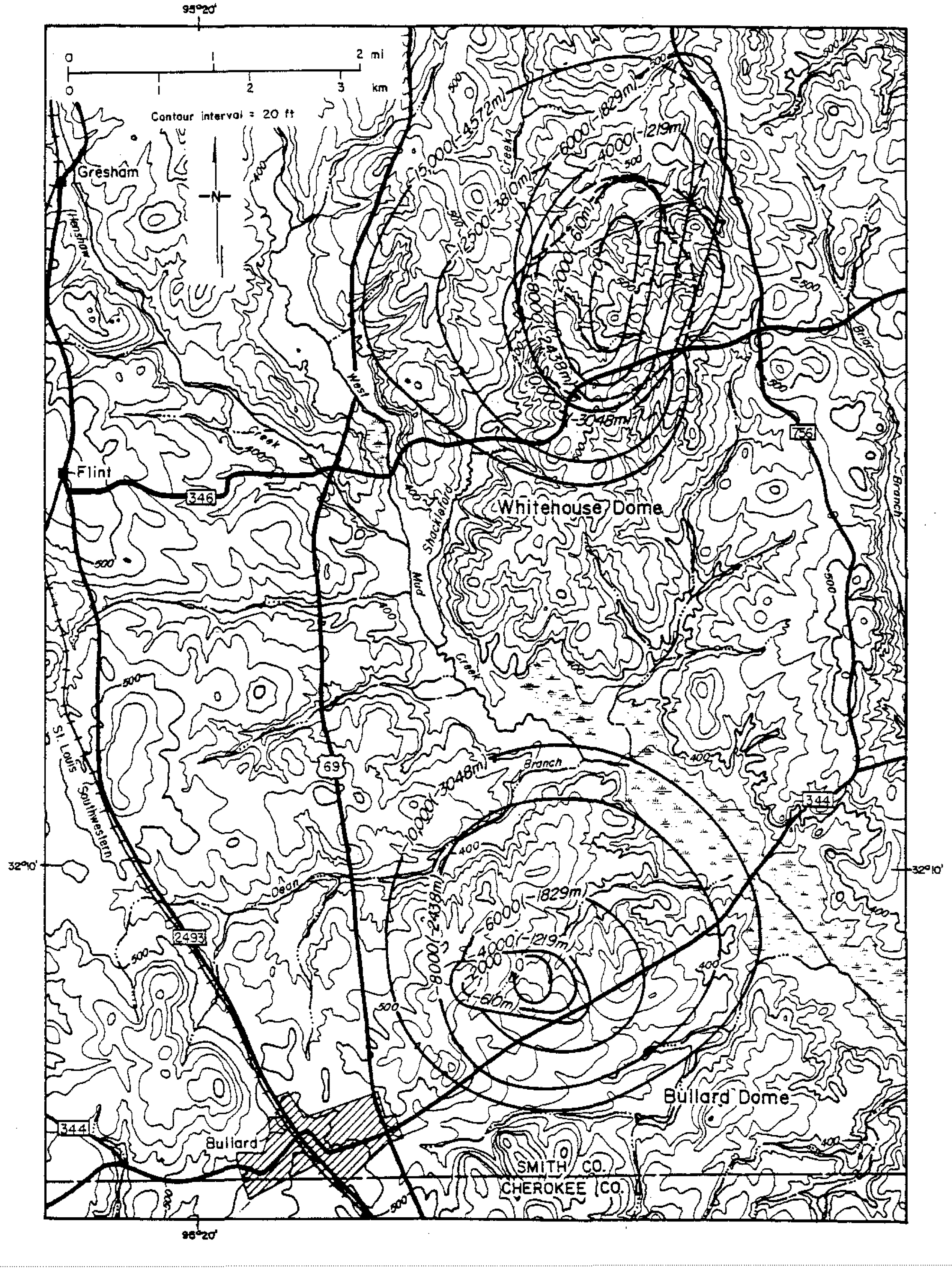

SUGARLAND DOME
0
.5
1mi
0
.5
1km
Contour interval = 5 ft
N
QA2166
29°33'
95°34'
65
65
70
70
65
65
65
55
-3400
-3600
-3800
-4000
-4200
-4400
-4600
-4800
BRAZOS
RIVER

approximate dome outline
60
70
60
70
2759
55
65
60
55
65
50
60
29°27'
95°34'
55
50
BRAZOS R.
25
50
CO.
CO.
55
FORT BEND
50
BRAZORIA
55
THOMPSON DOME
0
.5
Imi
0
.5
Ikm
Contour interval = 5 ft
N
QA2188



29°35'00"
95°10'00"
45
75
30
30
30
35
35
25
HARRIS CO
GALVESTON CO
approximate dome outline
N
WEBSTER DOME
0 .5 1 mi
0 .5 1 km
Contour interval = 5 ft
QA-2179


29°10'00"
95°40'00"
-3000
25
-1000
-2000
N
35
35
36
30
35
1301
WEST COLUMBIA DOME
0 .5 1 mi
0 .5 1 km
Contour interval = 5 ft
QA-2134


95°20'
0 1 2 mi
0 1 2 3 km
Contour interval = 20 ft
N
Gresham
Henshaw
Flint
346
Creek
400
500
West
Creek
Mud
Shackleford
Creek
Whitehouse Dome
-15,000(-4572m)
-12,500(-3810m)
-6000(-1829m)
-4000(-1219m)
-2000(-610m)
-8000(-2438m)
-10,000(-3048m)
756
Briar
Branch
69
Branch
-10,000(-3048m)
344
St. Louis Southwestern
Dean
2493
-8000(-2438m)
-6000(-1829m)
-4000(-1219m)
-2000(-610m)
0
Bullard Dome
Bullard
344
SMITH CO.
CHEROKEE CO.
32°10'
32°10'
95°20'

APPENDIX 2. Railroad Commission of Texas Authority Numbers for storage-well permits.

NAME OF SALT DOME	CURRENT OPERATOR OF STORAGE FACILITY	ORIGINAL APPLICANT	RAILROAD COMMISSION AUTHORITY NUMBERS
***			
* BARBERS HILL	TEXAS EASTERN	TEXAS NATURAL GASOLINE	03-27865,03-40761,03-40760
* BARBERS HILL	DIAMOND SHAMROCK	DIAMOND SHAMROCK	03-59299
* BARBERS HILL	WARREN	WARREN	03-63536
* BARBERS HILL	X-RAL	X-RAL	03-64977
* BARBERS HILL	TENNECO	TENNESSEE GAS TRANSMISSION	03-33873,03-77018,03-77903,03-32960
* BARBERS HILL	EXXON	HUMBLE OIL AND REFINING	03-45459,03-65222
* BARBERS HILL	ENTERPRISE	ENTERPRISE	03-70198,03-69581,03-77044
* BARBERS HILL	CONOCO	CONOCO	03-63409,03-76800
* BARBERS HILL	ARCO	TEXAS BUTADIENE AND CHEMICAL CORP.	03-33063
* BETHEL DOME	BI-STONE FUEL	BI-STONE FUEL	06-62759
* BIG HILL	UNION	PURE OIL CO.	03-34046,03-33628
* BIG HILL	DEPARTMENT OF ENERGY	DEPARTMENT OF ENERGY	03-79466
* BLUE RIDGE	ABANDONED	TULOMA-AMOCO	03-34676,03-35658,03-64673
* BOLING	VALERO	LO-VACA GATERING CO.	03-73654
* BRENHAM	SEMINOLE PIPELINE CO.	SEMINOLE PIPELINE CO.	03-76656
* BRYAN MOUND	DEPARTMENT OF ENERGY	DOW CHEMICAL	03-67732
* BRYAN MOUND	DEPARTMENT OF ENERGY	DEPARTMENT OF ENERGY	03-70337
* BUTLER DOME	U.P.G.	FREESTONE UNDERGROUND STOR.	05-23215
* CLEMENS	PHILLIPS PETROLEUM	PHILLIPS PETROLEUM	03-31930,03-32483
* DAY	ABANDONED	PURE OIL	
* EAST TYLER	TEXAS EASTMAN	WARREN PETROLEUM	06-22995
* FANNETT	WARREN PETROLEUM	GULF OIL	03-23675,03-29708,03-30296,03-31943
* HAINESVILLE	BUTANE SUPPLIES	ENTERPRISE PETROLEUM GAS CORP.	06-23529
* HULL	MOBIL	MAGNOLIA PETROLEUM CORP.	03-27136
* MARKHAM	TEXAS BRINE	TEXAS BRINE	03-64975
* MARKHAM	SEADRIFT PIPELINE	SEADRIFT PIPELINE	03-45456
* MOSS BLUFF	MOSS BLUFF STORAGE VENTURE	MOSS BLUFF STORAGE VENTURE	03-72099
* NORTH DAYTON	ENERGY STORAGE TERMINAL INC.	ENERGY STORAGE TERMINAL INC.	03-80865
* PIERCE JUNCTION	ENTERPRISE	WANDA PETROLEUM AND ELLIS TRANSPORT	03-33874,03-60093
* PIERCE JUNCTION	COASTAL STATES CRUDE GATHERING	COASTAL STATES CRUDE GATHERING	03-26489,03-64779
* SOUR LAKE	TEXACO	THE TEXAS CO.	03-23381,03-23803,03-30937,03-23476
* STRATTON RIDGE	SEMINOLE PIPELINE	SEMINOLE PIPELINE	03-76306
* STRATTON RIDGE	AMOCO	FENIX AND SCISSON	03-62057
* STRATTON RIDGE	DOW	DOW	03-26779,03-45413,03-60633,03-60845;03-74630

```
LIST/TITLE L(17)NAME OF SALT DOME,B(1),R(30)CURRENT OPERATOR OF        +
 LIST/TITLE L(17)NAME OF SALT DOME,B(1),R(30)CURRENT OPERATOR OF        +

STORAGE FACILITY          ,B(1),R(35)ORIGINAL APPLICANT          ,B(1),
 STORAGE FACILITY          ,B(1),R(35)ORIGINAL APPLICANT          ,B(1),

R(48)RAILROAD COMMISSION AUTHORITY NUMBERS         /
 R(48)RAILROAD COMMISSION AUTHORITY NUMBERS         /

C1,C226,C227,C230,OB LOW C1 WH C226 EXISTS:
 C1,C226,C227,C230,OB LOW C1 WH C226 EXISTS:
```

APPENDIX 3. Railroad Commission of Texas Rule 74 procedures and requirements for storage-well operators.

RAILROAD COMMISSION OF TEXAS
OIL AND GAS DIVISION

JAMES E. (JIM) NUGENT, Chairman
MACK WALLACE, Commissioner
BUDDY TEMPLE, Commissioner

BOB A. MASON, P.E.
Director
JERRY W. MULLICAN
Director of Underground
Injection Control

[illegible] CAPITOL STATION — P. O. DRAWER 12967 AUSTIN, TEXAS 78711

NOTICE OF RULE AMENDMENT

Attached is an amendment to Rules 9 and 46, and a new Rule 74, adopted on December 21, 1981. These rules will become effective on April 1, 1982.

Glenn Jordan
Glenn Jordan, Legal Counsel
Underground Injection Control

An Equal Opportunity Employer

Railroad Commission of Texas
Oil and Gas Division
051.02.02.074

051.02.02.074

RULE 74. UNDERGROUND HYDROCARBON STORAGE.

(a) Permit required. No person may create, operate, or continue to use or maintain an underground hydrocarbon storage facility without obtaining a permit from the commission. Permits from the commission issued before the effective date of this rule shall continue in effect until revoked, modified, or suspended by the commission. FORM

(b) Application.

(1) An application for a permit to dispose of saltwater or other mineralized water arising out of or incidental to the creation, operation, or maintenance of the underground storage facility shall be filed with the commission in accordance with the appropriate commission rules.

(2) An application for a permit to create, operate, or maintain an underground hydrocarbon storage facility shall be filed in the Austin office of the commission and shall contain the necessary information to demonstrate compliance with the laws of Texas and the rules of the commission. H-4

(c) Geological requirement.

(1) Underground hydrocarbon storage facilities shall only be created, operated, or maintained in formations which are confined by impervious strata so as to prevent the waste of hydrocarbons, the uncontrolled escape of hydrocarbons to the surface, and the escape of hydrocarbons into freshwater formations.

(2) The applicant must submit a letter from the Texas Department of Water Resources, Austin, Texas, with the application, stating the depth to which freshwater strata occurs at each storage facility.

(d) Notice and hearing.

(1) The applicant shall give notice by mailing or delivering a copy of the application to the surface owner of the tract under which the

---

Railroad Commission of Texas
Oil and Gas Division
051.02.02.074

facility is located and to each adjoining offset operator, on or before the date the application is mailed to or filed with the commission.

(2) Notice of the application shall be published by the applicant in three consecutive publications in a newspaper of general circulation for the county where the facility will be located in a form approved by the director of underground injection control (hereinafter "director"). The applicant shall file in Austin proof of publication prior to the hearing or administrative approval.

(3) An application for a new underground hydrocarbon storage project will be considered for approval only after notice and hearing. After hearing, the examiner shall recommend a final action by the commission.

(4) An application for an expansion of a previously approved project may be considered for administrative approval if the commission receives no protest.

(A) If the commission receives a protest from a person notified pursuant to paragraph (1) or other interested person within 15 days of receipt of the application or after publication that the proposed plan as contained in the application will cause damage to oil, gas, geothermal resources, freshwater resources, or otherwise cause harm, then a hearing will be held on the application after the commission provides notice of hearing to all interested persons.

(B) If the commission receives no protest, the director may administratively approve the application. If the director denies administrative approval, the applicant shall have a right to a hearing on the matter. After hearing, the examiner shall recommend a final action by the commission.

(e) Subsequent commission action. A permit may be modified, suspended, or terminated after notice and opportunity for hearing if:

FORM

(1) A substantial change of conditions occurs in the operation, maintenance, or construction of the facility, or there are substantial changes in the information originally furnished;

(2) Freshwater is likely to be polluted as a result of continued operation of the facility;

(3) There are substantial violations of the terms and provisions of the permit or of commission rules;

(4) The applicant has misrepresented any material facts during the permit issuance process; or

(5) Injected fluids or gases are escaping from the storage facility.

(f) Transfer. An underground hydrocarbon storage permit may be transferred only upon written approval. The permitted operator shall file an application with the director for approval of the transfer of the permit for the facility. The director may require a hearing on the matter. After hearing, the examiner shall recommend a final action by the commission. P-4

(g) Casing. Wells used for injection and removal of hydrocarbons from the storage facility shall be cased and the casing strings cemented to prevent stored hydrocarbons from escaping to the surface, into freshwater strata, or otherwise escaping and causing waste or endangering the public health.

(h) Monitoring and reporting.

(1) All operators of hydrocarbon storage wells shall monitor the injection pressure and volumes of fluids or gases injected and removed for each storage well on at least a monthly basis. Injection pressure and volumes injected shall be reported annually to the commission on the prescribed form. All monitoring records, including volumes withdrawn, shall be retained by the operator for at least five years. H-10 Operators storing crude

oil must also comply with other Commission rules including the filing of reports required under those rules.

(2) The operator shall report immediately to the appropriate district office any significant loss of fluids or gases, any significant mechanical failure or any other signficant problem. The operator shall confirm this report in writing within five days.

(i) Testing.

(1) Each storage well shall be tested for mechanical integrity at least once every five years. The testing shall be in a manner approved by the director.

(2) The operator shall notify the appropriate district office at least five days prior to testing. Testing shall not commence before the end of the five-day period unless authorized by the district director.

(3) A complete record of all tests shall be filed in duplicate in the district office within 30 days after the testing.

(j) Plugging. Upon abandonment, all wells used for the injection or removal of hydrocarbons from the facility shall be plugged in accordance with Statewide Rule 14.

(k) Penalties.

(1) Violations of this rule will subject the operator to penalties and remedies specified in Title 3 of the Texas Natural Resources Code.

(2) The certificate of compliance for any underground hydrocarbon storage facility may be revoked in the manner provided in Statewide Rule 68 for violation of this rule.