Stratigraphic and Structural Evolution of the Kramer Sodium Borate Ore Body, Boron, California

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ABSTRACT

The Kramer sodium borate ore body consists of a lenticular sedimentary facies of borax and kernite crystals together with varying amounts of interstitial and interbedded claystone. This sodium borate facies has been divided into seven stratigraphic units. The sodium borate facies is successively enveloped by a ulexite facies, a colemanite facies, and a barren claystone facies. Together, these four facies constitute the Shale member of the Kramer beds. The term Kramer beds is locally used to designate all of the conformable Miocene strata, including the borates, between the base of the Quaternary alluvium and the base of the Saddleback basalt. The borax is believed to have been precipitated in a permanent shallow lake, fed from nearby thermal springs containing anomalous amounts of sodium and boron. AsS and Sb_2S_3 were most abundant in the lake during a late stage of borax deposition. Successive beds of borax crystals protected by layers of mud were progressively deposited as the lake remained structurally low due to movement along a fault scarp at its south edge. The ore body has been deformed by faults and associated folds which developed in several stages. Minor faulting and folding took place in the borax lake contemporaneously with borax deposition. Some of the borax was altered to kernite after burial beneath a great thickness of fluvial sediments. Later, some of the kernite reverted back to borax when regional uplift and erosion and a renewal of local faulting and folding resulted in a reduction of temperature and redistribution of excess water within the ore body.

INTRODUCTION

The Kramer borate deposit is in the northwestern Mojave Desert of California, approximately 100 miles northeast of Los Angeles, immediately north of the town of Boron (Fig. 1). The deposit derives its name from the mining district in which it lies. The deposit is presently being mined from the Boron open pit, which supplies a major portion of United States borate production.

This paper deals with previously unpublished stratigraphic and structural studies of the borate deposit, based primarily on mapping undertaken during the last three years. This basic work is still in progress and will be completed before mineralogic and geochemical studies of a detailed nature are undertaken. The work completed to date has resulted in a series of detailed geologic maps of the ore body which are presently being utilized in open pit design and other mining operations.

The ore body consists of a roughly lenticular crystalline mass of borax ($NA_2B_4O_7 \cdot 10H_2O$), and kernite ($NA_2B_4O_7 \cdot 4H_2O$), containing interbedded claystone, and completely enveloped by ulexite-bearing shales (Gale, 1946). Stratigraphic and structural studies indicate that the Kramer borates were deposited in a small structural, nonmarine basin, elongated in an east-west direction and limited on the south by a fault scarp.

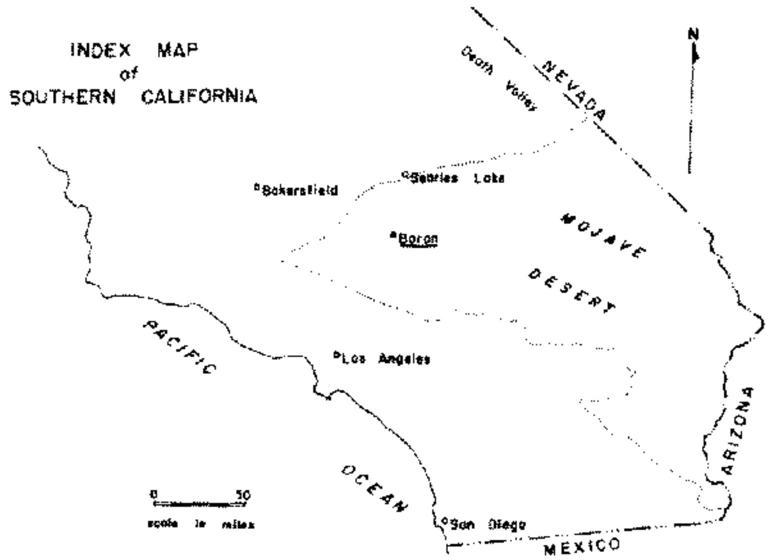

Figure 1. Location map.

Gale (1946) assigned the Kramer borates and associated shales, together with the underlying basalt and overlying arkose, to the Kramer Lake Bed member of the Pliocene Ricardo Formation. This correlation was made on the basis of lithologic similarities and geographic proximity to the Ricardo sediments and volcanics which crop out about 29 miles northwest of the Kramer deposit. The Kramer borates and associated sediments were later placed in the Pliocene (?) upper part of the Tropico Group (Dibblee, 1958).

Recently, however, well-preserved mammalian remains have been uncovered in sediments overlying the borate deposits in the Boron open pit mine. These fossils have been identified as a pre-Ricardo fauna, with an age no younger than early Middle Miocene (Whistler and Tedford, 1964). The term Ricardo can therefore no longer be used for any of the beds associated with the Kramer deposit, and Dibblee's age correlation within his Tropico Group must be revised.

Figure 2. Exposure of the Kramer beds on the north side of the Boron open pit.

GENERAL STRATIGRAPHY OF THE KRAMER BEDS

The term Kramer beds is being used locally by U.S. Borax geologists to designate all the similar dipping Miocene strata, including the borates that lie between the base of the Quaternary alluvium and the base of the Saddleback basalt in the structural basin. The saddleback basalt is unconformably underlain by older Tertiary arkoses, tuffs, and shales.

We have divided the Kramer beds into three distinct members, the Saddleback basalt member, the Shale member, and the Arkose member, in ascending order. Figure 3 is a generalized stratigraphic section of the Kramer beds near the central part of the ore body.

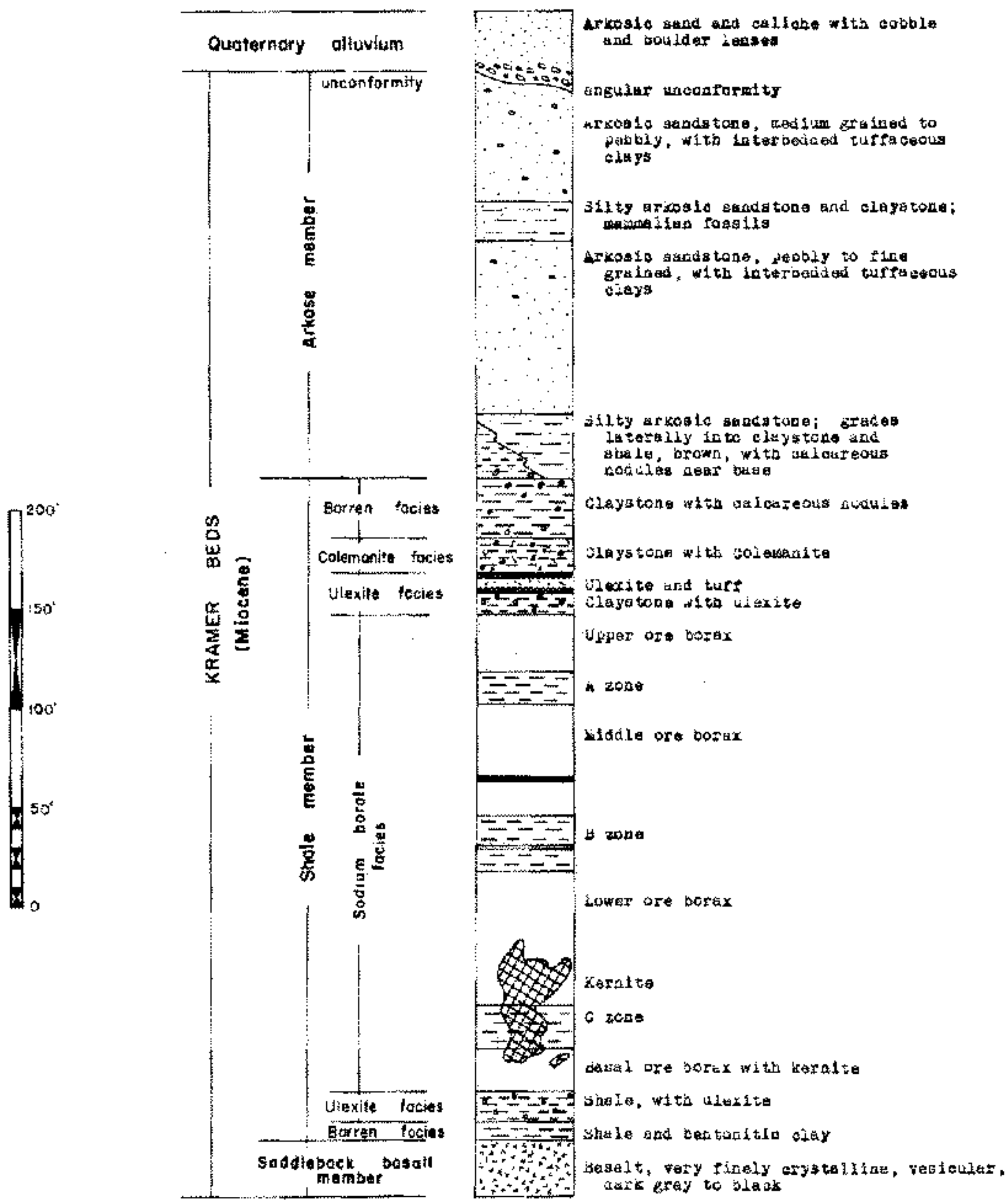

Figure 3. Generalized stratigraphic section of the Kramer beds.

<u>Saddleback basalt member</u>.

The basal member of the Kramer beds consists of one or more flow sheets of vesicular basalt. The basalt is known to range in thickness from less than 20 feet to 250 feet, and is missing at a few localities near the southern edge of the basin. Small amounts of ulexite are occasionally found as fracture and vesicle fillings in the basalt near faults. The top of the basalt is somewhat weathered but is roughly conformable with the overlying Shale member of the Kramer beds. The basalt crops out in ridges northwest, north, and northeast of the local basin.

<u>Shale member</u>.

The Shale member (Fig. 4) consists of four lacustrine facies that are differentiated on the basis of the occurrence of borate minerals into: a colemanite facies, ulexite facies, sodium borate facies, and barren claystone facies. The Shale member interfingers with green arkose and arkosic conglomerate along the abrupt southern edge of the local basin of deposition.

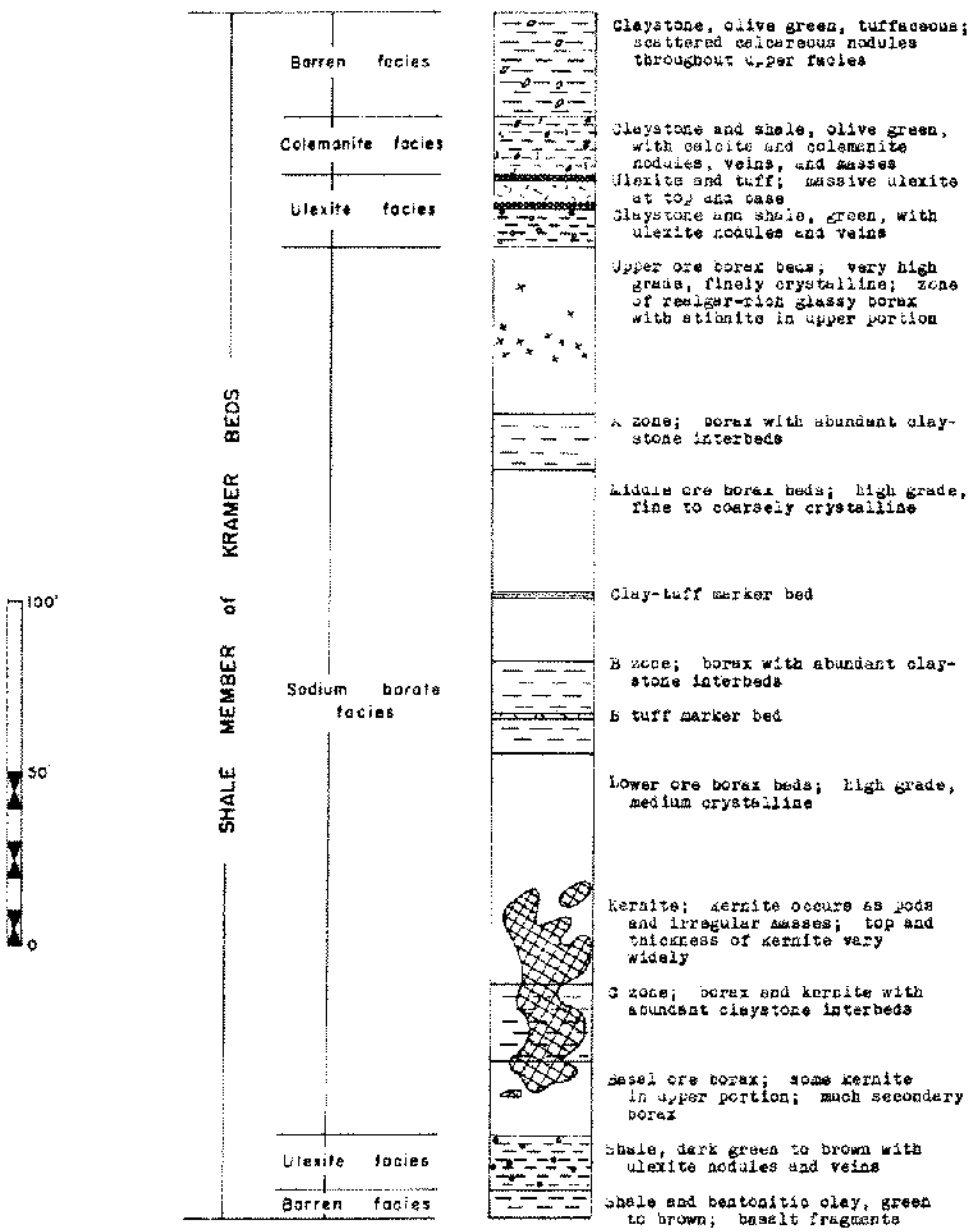

Figure 4. Generalized stratigraphic section of the Shale member.

A lenticular facies of borax and kernite crystals with varying amounts of interstitial and interbedded claystone is present in the south central part of the basin. This facies constitutes the Kramer sodium borate ore body, which is discussed in detail below.

The sodium borate facies is successively enveloped by the ulexite ($NaCaB_5O_9 \cdot 8H_2O$) facies, the colemanite ($Ca_2B_6O_{11} \cdot 5H_2O$) facies, and the barren claystone facies. The gray-green to dark green claystone and shale beds common to all four facies are montmorillonitic, and occasionally tuffaceous. Individual tuffaceous beds have been traced from one facies into the laterally adjacent facies.

The ulexite facies consists of claystone, shale, and tuff with ulexite occurring in beds, nodules, and veins. Claystone and shale are much more abundant in the ulexite facies than in the sodium borate facies. Several massive beds of ulexite, up to 2 feet in thickness, are present in the central part of the basin. These beds are located stratigraphically above the sodium borate facies and are associated with gray tuff.

The colemanite facies is found laterally and gradationally beyond the limits of the ulexite facies and in a thin interval overlying the ulexite facies. In the central part of the basin, colemanite appears to have replaced parts of the uppermost massive ulexite bed. Colemanite occurs as nodules and stringers in shale and claystone with minor associated calcite and limestone. Almost no colemanite is present in the lower part of the Shale member, underlying the ulexite facies, at least in the central part of the basin.

Around the outer part of the local basin of deposition, the Shale member of the Kramer beds consists entirely of the barren facies: the colemanite bearing shales of the colemanite facies grade outwardly into green shale and claystone which contain some calcareous nodules but are barren of borates. Along the abrupt southern termination of the basin, the barren facies interfingers with green arkose and arkosic conglomerate. The base of the barren claystone facies, immediately above the Saddleback basalt, frequently consists of several feet of brown claystone and shale and in places contains abundant ostracods.

Arkose member.

The lacustrine Shale member of the Kramer beds is conformably overlain by brown, poorly to moderately consolidated arkose, silty arkose, tuffaceous arkose, and conglomerate. This unit also contains minor interbeds of siltstone, shale, and acidic tuff. The present thickness of the Arkose member varies from less than 50 feet in structurally high areas to over 1000 feet in structurally low areas. The original thickness of the member prior to fault movement, uplift, and erosion was probably much greater. The Arkose member is separated from the 10 to 50 feet of overlying Quaternary alluvium by a distinct angular unconformity.

DETAILED STRATIGRAPHY OF THE SODIUM BORATE FACIES

The sodium borate facies (the Kramer ore body) consists mainly of a stratified mass of borax crystals with varying amounts of interstitial and interbedded green montmorillonitic claystone. The sodium borate facies is roughly lenticular, ranging in thickness from a few feet at its outer limits to several hundred feet in its central part. The boundaries between the sodium borate facies and the enveloping ulexite facies are sharp rather than gradational. Although minor local erosion at the top of the borax is suggested in some areas, these boundaries are generally the result of abrupt facies change rather than erosion or solution. Tuffaceous claystone beds have been traced across the abrupt boundaries of borax into the ulexite facies without interruption, except for a slight change in dip (Fig. 5).

The borax crystals are commonly euhedral to sub-euhedral, and range in length from less than 1/8 inch to over 1 inch. Stratification by crystal size is common. Borax crystals comprise over 80 per cent of some high-grade beds, with claystone present only in the crystal interstices. In low-grade beds, borax occurs as disseminated crystals in the claystone matrix. Stringers and pods of glassy, secondary borax occur locally.

The numerous green to brown claystone beds intercalated with the borax range from less than 1/2 inch to over 2 feet in thickness. Claystone beds less than 3 inches thick are by far the

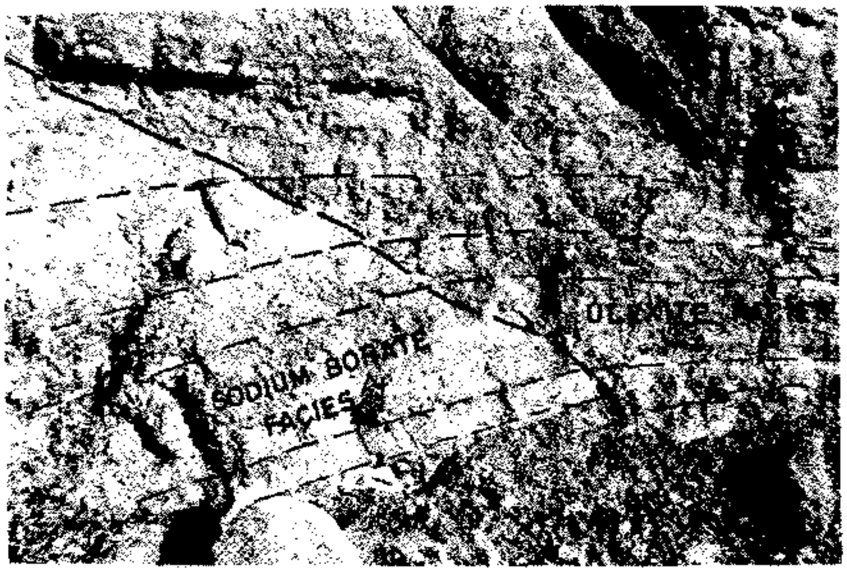

Figure 5. Claystone beds, shown as fine-dashed lines, extending across the abrupt boundary between the borax facies and the ulexite facies.

most common. The vertical spacing between claystone interbeds is mainly irregular; however, some intervals of borax have a banded appearance resulting from regularly spaced claystone beds which may represent seasonal or other cyclic conditions of deposition. We use some of the prominent claystone beds as stratigraphic markers. Most of the claystone beds contain vertical fractures filled with secondary borax. Near the edges of the ore body these fractures may contain asbestiform ulexite rather than borax. At some localities near faults, where the beds dip steeply, the vertical fractures have been widened so that segments of the claystone bed are separated by a foot or more of borax. This "drifting" of claystone segments may be in part diagenetic.

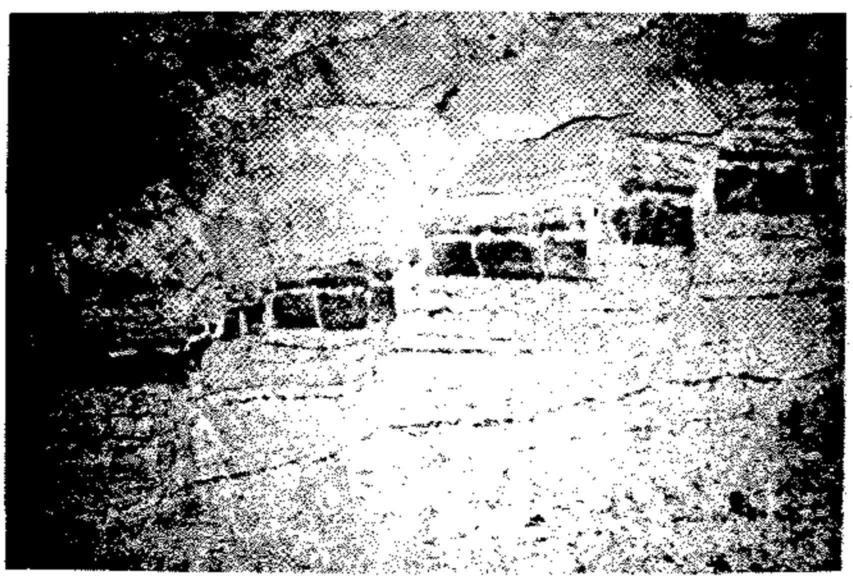

Figure 6. Step faulted claystone interbed in the lower ore. The 5-inch thick claystone bed contains borax filled vertical fractures.

X-ray diffractometer studies by the U. S. Geological Survey indicate that the interbedded claystones contain montmorillonite, dolomite, hydrous mica, and feldspars. A small percentage of Li_2O is likewise contained in the claystones (Schreck, 1960).

Part of the sodium borate facies consists of kernite, a secondary mineral formed by the dehydration of borax due to an increase in temperature (Gale, 1946; Schaller, 1930). In a study of the temperature, pressure, and other factors affecting the borax to kernite conversions, it has been concluded that the bulk of the transition took place at about 58° ±5° C at a depth of 2500 ±500 feet (Christ & Garrels, 1959).

The distribution of kernite is generally limited to the stratigraphically lower parts of the sodium borate facies; however, these are not necessarily the present structurally lower parts.

The claystone beds associated with the coarsely crystalline kernite are commonly broken and distorted. At the margins of the main kernite occurrences in the ore body, kernite is found in isolated pods and crystal masses (Fig. 7). These pods commonly have a halo of secondary glass borax formed from rehydrated kernite (Muessig and Allen, 1957). In many places claystone

Figure 7. Claystone rimmed kernite pods in bedded primary borax. The kernite is partly rehydrated and has a halo of secondary borax.

forms a rim around the kernite pods which themselves contain very little clay. Borax masses adjacent to the main kernite occurrences frequently exhibit "poddy" texture, inherited from kernite which has been completely rehydrated. Some of this secondary borax exhibits relic kernite cleavage.

No kernite has been observed in the top and bottom few feet of the sodium borate facies, even in areas of maximum kernite development. Two explanations for the absence of kernite and presence of secondary sucrosic borax at these localities are suggested: (1) surplus water, produced by the dehydration of borax to kernite, or from residual brines, accumulated adjacent to the relatively impervious clays of the ulexite facies, thereby preventing the formation of kernite but resulting in sucrosic recrystallized borax; (2) at some period of time after the formation of kernite, uplift and fracturing resulted in a minor redistribution of surplus water in the ore body; much of this surplus water accumulated adjacent to the ulexite-bearing claystone at the top and especially the bottom of the sodium borate facies, and caused the kernite near these contacts to be rehydrated to sucrosic borax. Both of these processes for the formation of secondary borax may have been involved at different stages in the history of the ore body, but further work is necessary.

Our stratigraphic study of the sodium borate facies was initiated by the detailed measurement and description of vertical sections in the open pit and in underground workings. Samples from numerous core holes through the ore body were then logged to obtain control for a series of structural and isopachous maps of the various stratigraphic horizons and units.

We have divided the sodium borate facies into seven stratigraphic units. Four of the units contain relatively little interbedded and interstitial claystone, while three units contain relatively abundant interbedded and interstitial claystone. The four high-grade units (Upper ore, Middle ore, Lower ore, and Basal ore) typically contain over 75% borax. The three relatively low-grade units (A zone, B zone & C zone) typically contain less than 60% borax. Only in the thick central portion of the sodium borate facies are all the units present. Stratigraphic control is maintained by the use of a number of tuffaceous claystone and claystone marker beds within the sodium borate facies.

The seven units are briefly described in ascending order as follows:

Basal ore.

The Basal ore is limited to the southern and eastern parts of the ore body and is the thinnest and least extensive of the higher grade sodium borate units. The upper part of the Basal ore is usually composed of kernite with minor borax. The lower 5 to 10 feet is borax, generally recrystallized with a glassy to sucrosic texture.

C zone.

The C zone is the lowermost major unit of abundant claystone in the sodium borate facies and ranges up to 28 feet in thickness in the central part of the ore body. The upper part of the C zone contains about 10 feet of massive claystone with relatively sparse amounts of sodium borates. The remainder of the unit contains varying amounts of kernite and borax with abundant interbedded claystone. Probertite crystals ($NaCaB_5O_9 \cdot 5H_2O$), commonly in the form of rosettes, are sparsely present in the claystone interbeds where kernite is the predominate sodium borate. Where primary borax is predominant, the associated claystone may contain some ulexite crystals.

Lower ore.

The Lower ore, which is over 90 feet thick in some areas, is the thickest and most extensive of the four high-grade units. Its maximum development is in the south-central part of the sodium borate body. Kernite, where present, is most commonly limited to the lower half of the Lower ore. No kernite is present in the Lower ore in the western and northern part of the ore body. Realgar occurs sparsely scattered in the borax at several stratigraphic horizons.

B zone.

The middle unit of abundant claystone in the ore body has been designated as the B zone, which is over 27 feet thick in the central part of the sodium borate facies. The lower part of the unit includes a light brown silty to argillaceous tuff approximately 1 1/2 feet in thickness and containing a network of thin borax veins. This bed, which we designate as the B tuff marker, is one of the two most easily recognizable and persistent marker beds in the sodium borate facies. Kernite is known to occur stratigraphically as high as the B zone in limited areas in the south-central part of the ore body.

Middle ore.

The Middle ore ranges in thickness from a featheredge to over 65 feet, and constitutes the second most extensive of the four high-grade sodium borate units. The Middle ore persists to the north beyond the pinchout of both the Lower and Upper ores; however, the Lower ore persists to the south and east well beyond the Middle ore. Most of the Middle ore is primary borax; kernite is present in only a few areas in the south-central part of the ore body. A part of the upper half of the Middle ore has a brownish color. Further work is needed to determine whether slight amounts of arsenic, antimony, or iron minerals are the primary cause of this coloration.

A persistent and easily identifiable stratigraphic marker bed, which we call the clay-tuff marker, lies 10 to 20 feet above the base of the Middle ore. It consists of 3 to 6 inches of green claystone underlain by 3 to 6 inches of tan to gray, fine- to medium-grained, arkosic, micaceous tuff. The upper 1/2 inch of the tuff is silty and exhibits ripple marks at some localities. The clay-tuff marker affords the horizon most easily used for structural studies of the ore body (Fig. 8).

A zone.

The 15- to 20-foot unit of abundant claystone, which separates the Middle ore from the Upper ore, has been designated as the Z zone. The top of the A zone has been placed at the "U4 marker," a green 1 1/2-foot claystone bed which contains a brown tuffaceous stratum. The A zone contains small amounts of realgar associated with the claystone and borax.

Upper ore.

The uppermost unit consists of high-grade borax and ranges up to 80 feet in thickness. The area of maximum Upper ore thickness coincides with the area where the total sodium borate facies is thickest. The Upper ore is absent in the easternmost and southernmost parts of the sodium borate ore body. The Upper ore is characterized by its very high grade and by its relatively finely crystalline texture. Some intervals contain 1-inch bands of almost pure borax alternating with finely tuffaceous or argillaceous borax. At several localities in the underground workings, small tight folds and recumbent folds, suggestive of the plastic flow folds common in halite beds, have been observed in finely crystalline borax. Most of the borax is primary; no kernite has been observed in this unit.

The Upper ore contains a 2- to over 20-foot thick interval of borax containing relatively large amounts of realgar and stibnite. The borax and associated claystone are colored red to orange by the disseminated realgar. Stibnite occurs as small scattered rosettes within the borax and claystone. The arsenic zone occurs as a fairly consistent stratigraphic unit in the Upper ore, adjacent to and between two shale beds designated as the U-1 and U-2 markers. The arsenic zone is absent (or lies outside the sodium borate facies) where the Upper ore is less than 15 feet thick. Because of this stratigraphic relationship, the sulfides appear to have been deposited syngenetically with the Upper ore.

STRUCTURE

The structurally deepest part of the borate basin is near its southern limits. The abrupt southern edge of the borate basin is believed to have been formed by the "Western Borax" Fault (named by Gale, 1946). Although the fault trace is not exposed, its presence is indicated by the abrupt absence of the Kramer Shale member a short distance south of the borate deposits. Furthermore, coarse conglomerate and arkose interfinger with the Kramer Shale member along the southern edge of the borate basin, indicating considerable relief along the Western Borax Fault scarp during Kramer time. In contrast, the structural rise out of the basin is gradual to the north, and the coarse conglomerate has not been recognized in drill holes.

The Kramer beds, including the borate deposits, have been moderately folded and faulted. Steeply dipping strata are present near the principal fault and fold trends. Both vertical and horizontal displacement has taken place along some faults. A major structural element in the southern part of the sodium borate facies is the Portal Fault. North of the Portal Fault, the ore body is cut by eight northwest trending faults and folds. The structural elements affecting the western and

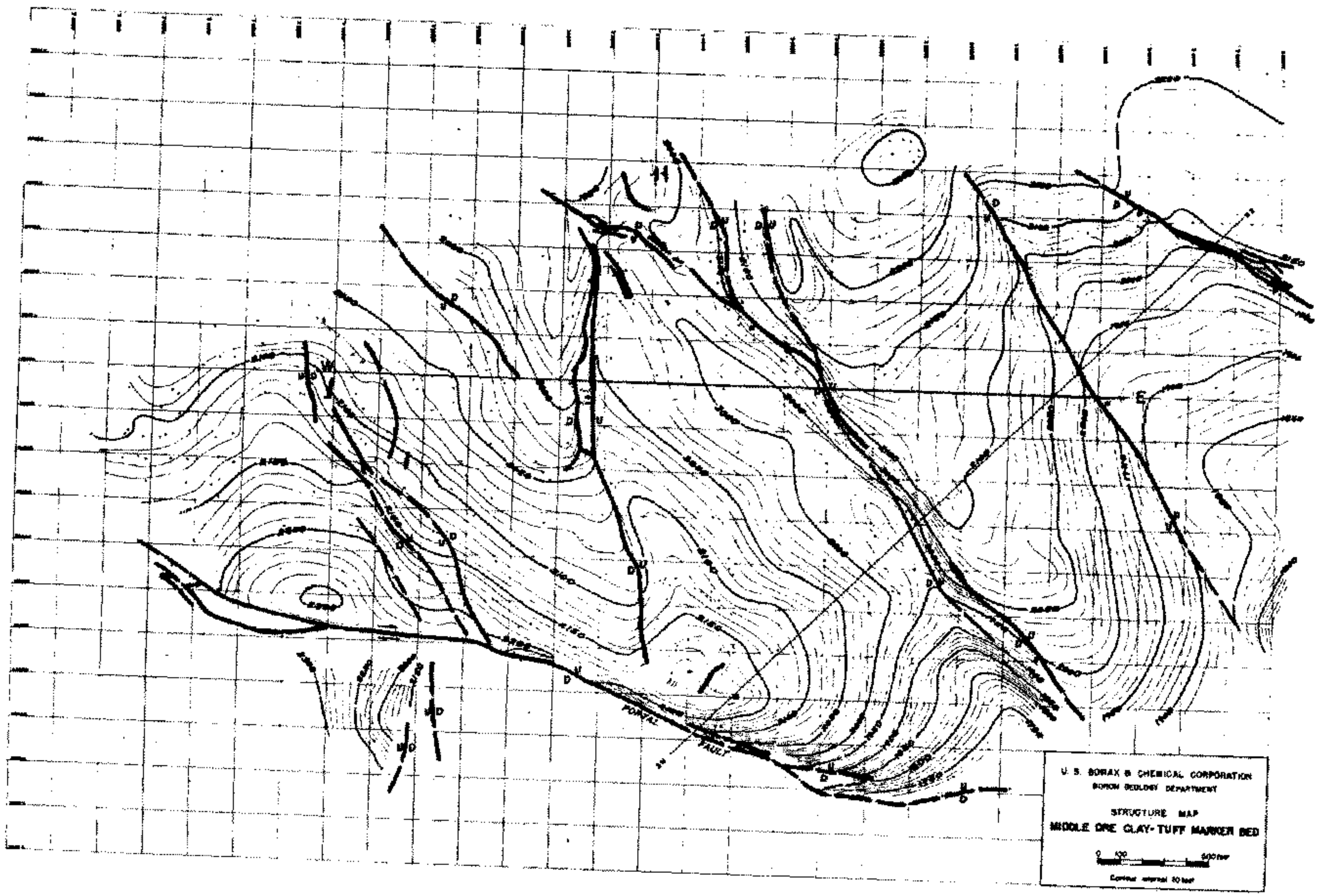

Figure 8. Structure map on Middle ore clay-tuff marker bed.

central parts of the sodium borate facies are shown in Fig. 8, which is a structure contour map of the Middle ore clay-tuff marker. These same structural elements, with slightly greater structural relief, are illustrated by a structure map drawn on the top of the Saddleback basalt member (Fig. 9).

The Portal Fault.

The Portal Fault trends slightly north of west and displaces the Kramer beds both vertically and horizontally. In the south-central part of the ore body, vertical displacement, including the effect of drag folding, is at least 400 feet down on the south. In this general area, the dip of the fault plane varies, but the net effect is that of a high-angle normal fault. Vertical displacement rapidly decreases to the west, where the fault branches. In this area, the Shale member of the Kramer beds south of the Portal Fault is tilted upward until it subcrops below the Quarternary alluvium. Therefore, some borates southwest of the existing ore body were removed by erosion.

In the western part of the ore body, the stratigraphy and mineralogy on the south side of the Portal Fault differ from that on the north side of the Fault. The borate beds on the south side bear a greater resemblance to those found in deeper areas to the east than they do to the borate beds typical of the western part of the ore body. These differences, together with lithologic differences in the section overlying the borates, suggest a right lateral displacement of over 2,000 feet. A structure map drawn on the top of kernite illustrates this displacement (Fig. 10).

Northwest trending faults and folds.

Five northwest trending fault and fold structures, which affect the central and western parts of the sodium borate facies north of the Portal fault, are shown in Fig. 8. Three structures of similar trend are present east of the area shown on this map. A few northeast trending faults with minor displacement are present in the ore body, but these are subordinate to the dominant northwest fracture pattern. In the areas between the principal fault and fold structures, the dip of the Kramer beds ranges from nearly horizontal to over 20°.

The predominant faults are normal with dips ranging from 30° to vertical. Some of the northwest trending structures are actually faulted asymmetric or monoclinal folds. Several faults appear from drill hole data to have a vertical displacement in excess of 100 feet, but our mapping in the mine workings indicates that much of this displacement of borax strata is due to steep dips adjacent to the faults. Strike-slip displacement along some of the faults is indicated by nearly horizontal to low-angle striations on the fault planes; however, the similar appearance of correlative beds on both sides of the faults indicates that strike-slip displacement is probably minor, at least on the four westernmost structures.

Structural mapping on different stratigraphic horizons in the Kramer beds indicates an increase in fault displacement with depth along some of the northwest trending structures. This is evident from a comparison of Figs. 8 and 9 and from the cross sections (Fig. 11).

Thinning of the borax beds adjacent to northwest trending faults or faulted folds is evident at many localities. This thinning is illustrated by the isopach map of the Upper ore of the western and central parts of the sodium borate facies (Fig. 12) and by the structure cross sections. Some of the thinning is only apparent and is the result of dip-slip separation of beds along low-angle fault planes; however, true stratigraphic thinning is also evident along the principal fault and fold structures, especially on the upthrown blocks.

The thinning of borax on upthrow blocks and the indications of greater fault displacement with depth are considered to be evidence of some structural movement contemporaneous with borax deposition.

We have observed no relic borax structures, masses of secondary ulexite, or collapsed breccia immediately above the areas of thin borax which might indicate that the thinning is the result of post-burial dissolution by circulating ground water.

Although small flow folds have been observed in finely crystalline borax at several localities, plastic flow similar to that common in halite beds does not appear to be a major cause of variation in the thickness of the ore body.

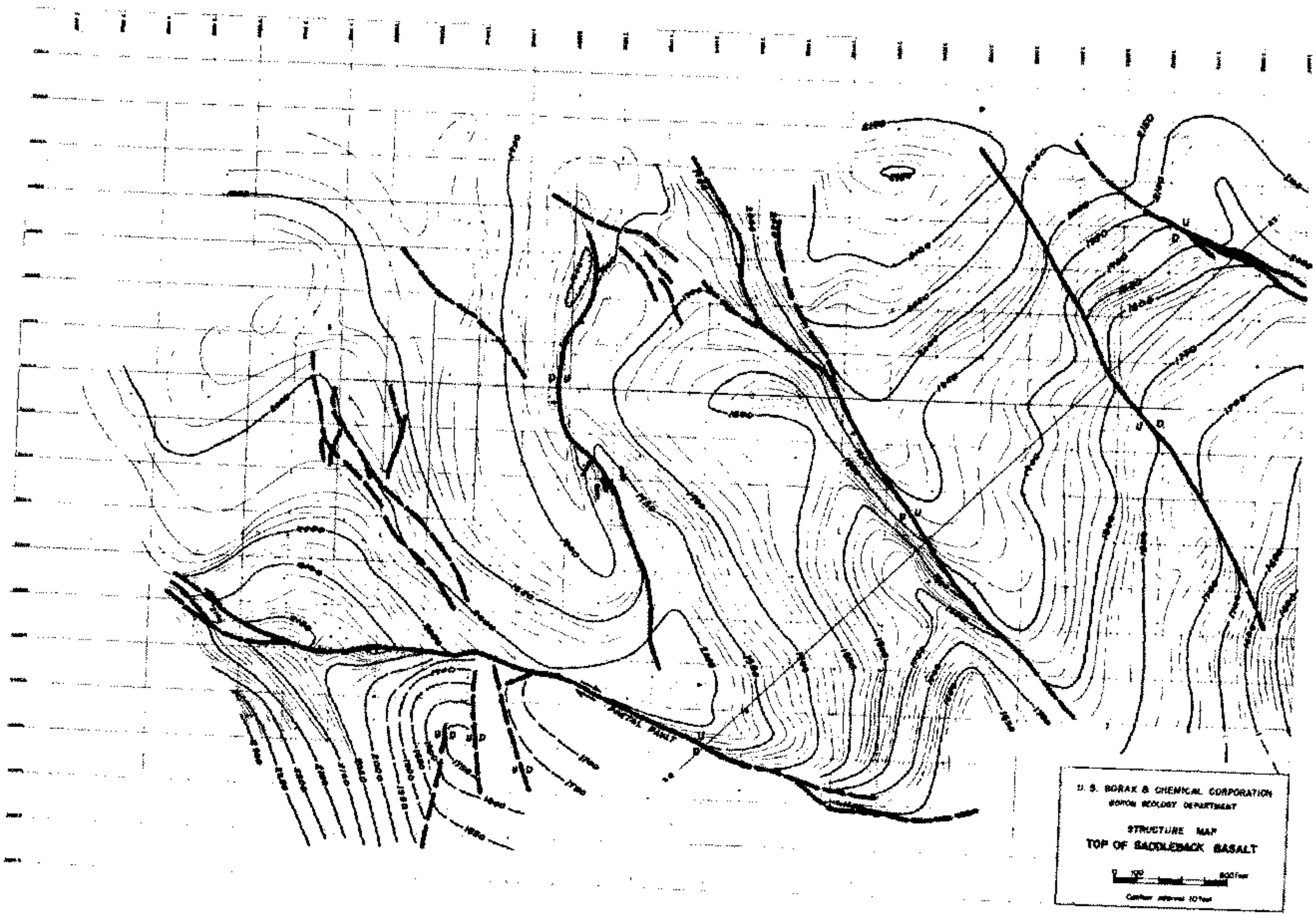

Figure 9. Structure map on top of the Saddleback basalt member.

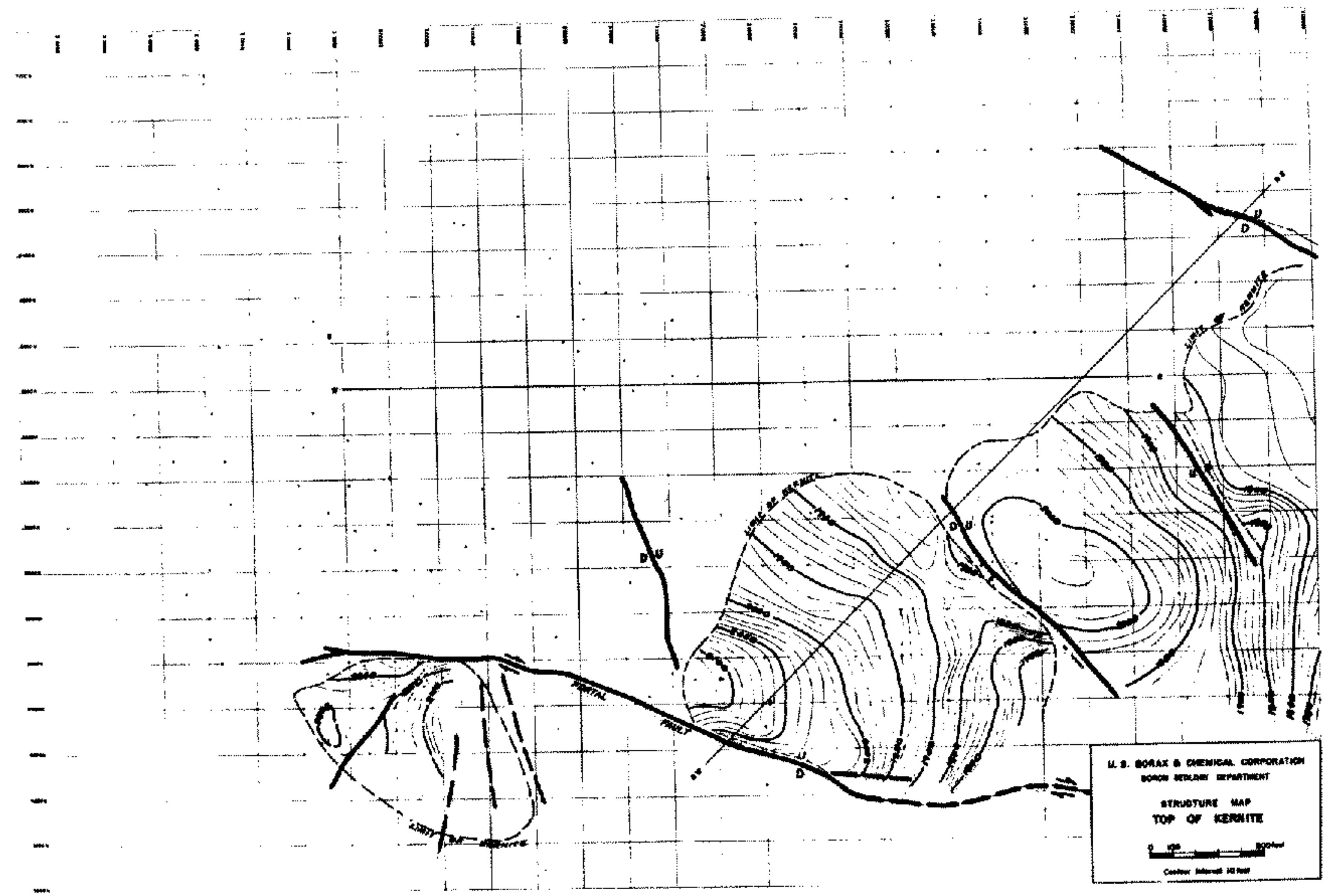

Figure 10. Structure map on top of kernite.

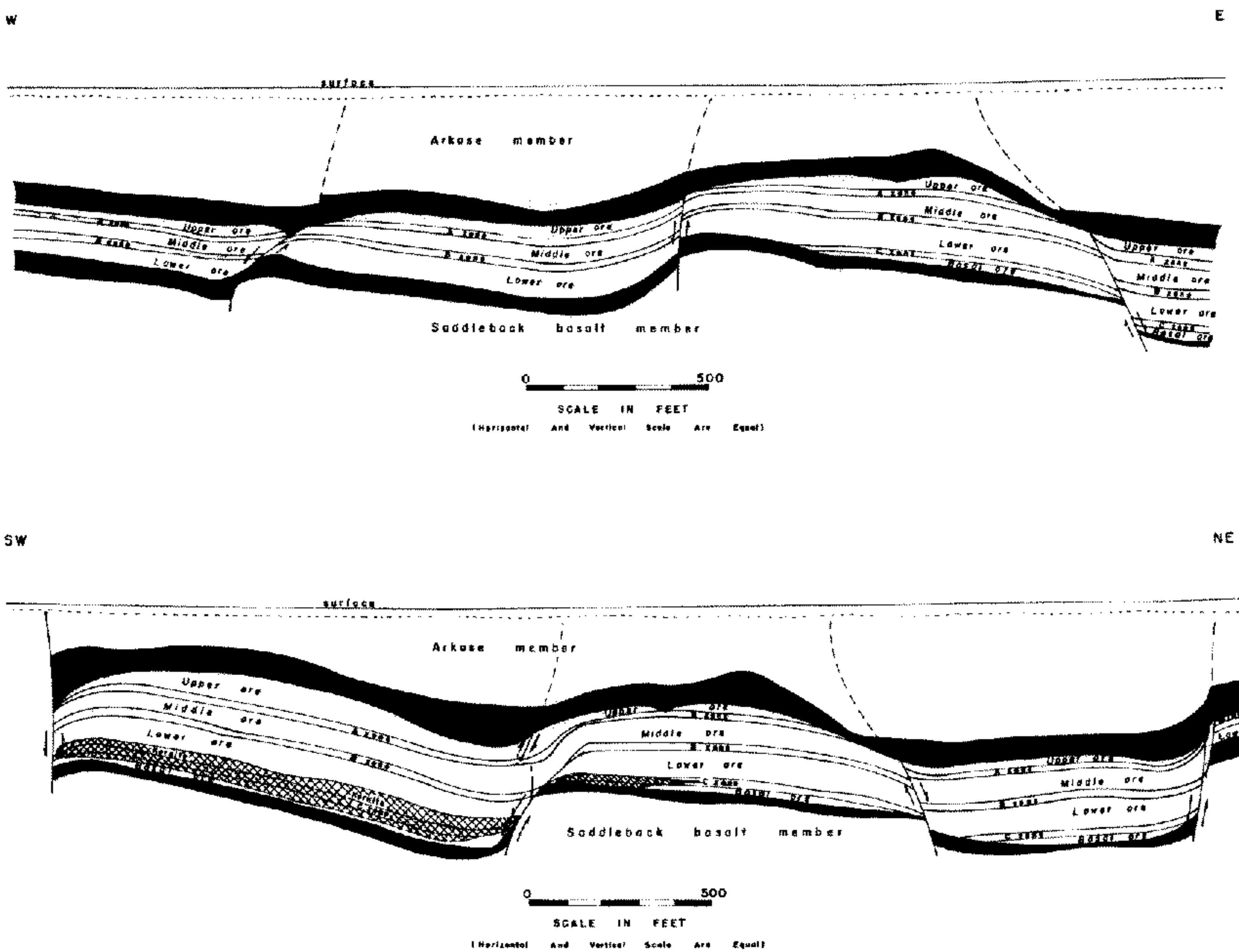

Figure 11. Cross sections of parts of the Kramer borate deposit. Lines of section shown on Figure 8. Darkened areas above and below the ore body represent the ulexite, colemanite, and barren claystone facies.

Figure 12. Isopach map of the Upper ore.

After the deposition of the Upper ore, the supply of boron and sodium-bearing thermal spring water diminished while the proportion of calcium-bearing surface water increased, resulting in the precipitation of ulexite in mud even in the central portion of the playa basin. The permanent borax lake was gone.

Events after the deposition of borates.

The playa continued to exist for a period of time after the final deposition of borates. Volcanic ash and some $CaCO_3$ were deposited along with the muds during this stage.

At some time following the burial of the borates, some of the outer portions of the ulexite facies were altered to colemanite through the action of calcium-bearing ground waters. This may have taken place shortly after burial or at a much later date.

During late "Kramer" time the lake beds were buried under a great thickness of fluvial arkosic and tuffaceous sediments. The lower borax beds in the deeper parts of the ore body were partially altered to kernite during this period of maximum burial when the borax was subjected to maximum temperatures.

Transition of borax to kernite occurred stratigraphically as high as the Middle ore in some of the deeply buried southern parts of the ore body, but most of the kernite crystallization took place in the Basal ore, C zone, and Lower ore beds. Intercalated claystone beds were broken and distorted during the conversion process. Small amounts of probertite crystallized in the associated claystones, as a result of dehydration of ulexite and/or the release of calcium from the claystone. Some borax was dissolved as a result of increased temperatures and surplus water produced may never have formed as kernite, but later precipitated as veins, beds, and lenses of secondary borax when temperatures were reduced.

Late in the Middle Pliocene, the Kramer beds were uplifted, folded, and faulted. Folding of the borax beds and the greater part of the dip-slip and strike-slip displacement now evident along the northwest trending faults and the Portal Fault probably took place during this time. Minor faults and fractures in the borax appear to have developed more abundantly in the thin outer parts of the ore body than in the thick central portion. In the central and western parts of the ore body, the Kramer beds were uplifted on the north side of the Portal Fault. There is evidence that right lateral strike-slip displacement also took place on the Portal Fault. Some of the kernite-bearing borax from the deep south-central part of the ore body was moved westward at least 2,000 feet along the south side of the fault to a position in the southwesternmost part of the ore body.

Uplift and tilting of the Kramer beds resulted in the erosion of a thick sequence of upper Kramer sediments after the Middle Pliocene orogeny of the Mojave block and during the Quaternary. Most of the sodium borate facies were preserved, but that which was displaced farthest to the west on the south side of the Portal Fault was exposed and removed by erosion. When erosional stripping of the beds above the sodium borate facies resulted in a reduction of temperature, some of the kernite reacted with surplus water and reverted back to secondary sucrosic borax.

Following the latest period of Quaternary uplift and erosion, the Recent alluvium was deposited on the beveled Kramer strata.

ACKNOWLEDGMENT

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STRUCTURAL AND DEPOSITIONAL HISTORY AND ITS EFFECTS UPON THE SODIUM BORATE FACIES

Our detailed stratigraphic and structural studies to date have led to the following conclusions regarding the history of the Kramer beds, and particularly the sodium borate facies:

Events immediately prior to and during the deposition of borax.

No later than early Middle Miocene, the Saddleback basalt was extruded on older Tertiary sediments in the area of the future borate basin. This area was already topographically low due to downward movement along the "Western Borax" Fault immediately to the south. Soon after the extrusion of basalt, the topographically low area became a playa basin. The deepest part of the basin was close to its southern border, which was formed by the fault scarp. To the north, east, and west the rise out of the basin was more gradual.

In the structural setting described above, boron and sodium, derived from local thermal springs, combined with calcium from surface water and formed ulexite in the playa muds. (A local thermal spring source for the borate deposits at Kramer has been suggested by Gale, Muessig, and others.) This belief, which we support, is based primarily on the presence of volcanic rocks in the Kramer beds, the association of syngenetic arsenic and antimony sulphides with the borax, the limited suite of evaporitic minerals, and the observation of recent borax deposition at other localities.

A permanent shallow lake soon developed in the central portion of the playa basin. The lake, fed almost entirely from the local thermal springs, contained a great abundance of sodium and boron. The cooling lake brine became saturated with respect to borax, which was precipitated in great abundance in the muds. Muessig (written communication, 1956) has suggested that borax, whose solubility is much more sensitive to temperature changes than other evaporites, probably crystallized at times of decreased temperatures. The solubilities of other salts such as NaCl are not much affected by small temperature changes, and if present in the lake, they remained in solution in the surface waters until they were removed by overflow at a low outlet. The primary precipitation of borax in the lake probably occurred at temperatures in the range (25°-35° C (Christ & Garrels, 1959, p. 517).

During the period of borax, ulexite, and lake mud deposition, the local basin remained structurally low as a result of continued downward movement along the "Western Borax" Fault to the south. Thus, successive beds of borax crystals protected by layers of mud were progressively built up as the basin sank. In the outer portions of the playa, the lake water mingled with calcium-bearing surface and ground waters, resulting in the precipitation of ulexite rather than borax along the margins of the central borax lake.

At three different times during the deposition of borax, temporary slight climatic changes or slight decreases in available boron resulted in the formation of the low-grade A, B, and C zones. During deposition of the B zone, and again during the early deposition of Middle ore, layers of arkosic to silty volcanic ash settled in the borax lake.

The center of borax deposition shifted and the size of the lake varied as the basin was filled with sediments and borax. The first borax deposition was restricted to the southern and eastern portions of the ore body. The borax lake probably reached its maximum development in area in "Lower ore time." During "Middle ore time," the lake retracted slightly from the south and east and shifted slightly farther north. The area covered by the lake was considerably reduced in "Upper ore time," having retracted from the east, south, and north.

From time to time anomalous amounts of AsS and Sb_2S_3 were precipitated in the lake along with the borax. The greatest precipitation of AsS and probably of Sb_2S_3 occurred during the late stages of borax deposition. The local thermal springs were probably the source of arsenic and antimony.

Minor faulting and folding along northwest trending lineaments took place in the borax lake contemporaneously with borax deposition. These vertical movements resulted in less deposition of borax adjacent to faults, especially on the upthrown side.

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