THE GEOLOGY OF ALKALI LAKE BASIN, OREGON

by

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INTRODUCTION

LOCATION. The Alkali Lake Basin lies in the north-eastern part of Lake County in south-central Oregon in what is known as the high desert province of Oregon. Its location is shown on the index map, Plate I.

It is traversed from North to South by U. S. highway #395 connecting Burns and Lakeview. It is approximately 60 miles north of Lakeview and 70 miles southwest of Burns.

SIZE. The basin referred to in this paper is the Alkali Lake fault basin proper, and no attempt was made to cover or map the entire drainage area. Any references to the basin which may be found in this article do not refer to the larger drainage basin.

The basin covers an area of approximately 250 square miles. On the east it is about 29 miles long from north to south and the northern end of the basin is about 7 miles wide, but it widens out in the central portion to approximately 15 miles at its widest part. It narrows down again in the southern portion where it is only a few miles wide.
PLATE I. Showing location of area covered in report.
PURPOSE OF INVESTIGATION. For many years considerable interest has been shown in the soda deposits at Alkali Lake and at several times in the past attempts have been made to utilize them on a commercial scale. None of these attempts, however, was very successful.

In recent years the State Department of Geology and Mineral Industries has been carrying on a continuing program of research on Oregon saline deposits, and a California company has shown considerable interest in the deposits at Alkali Lake.

For these reasons, the area was brought to the writer's attention as a very good thesis subject, especially inasmuch as there were aerial photographs available through the Soil Conservation Service which would greatly simplify the problem of mapping.

METHOD OF INVESTIGATION. The investigation was carried out both by automobile and on foot. With the exception of U. S. Highway #395, the graveled road put in by the army during their maneuvers in 1943, and the graveled road from the old C.C.C. camp just north of Grays Butte past Big Juniper Mountain, all of the roads in the area are old, secondary, dirt roads and in many cases, especially where they go through the sand dune areas, they are impassible for an ordinary type vehicle.
The extreme western part of the basin was especially inaccessible.

Use of an army type vehicle or a saddle horse would have greatly facilitated the work.
PREVIOUS WORK

The first recorded geologic investigation in this region was made in 1882 by Professor I. O. Russell. Although he did not get to Alkali Lake, he covered much of the adjoining region. His observations were published in the Fourth Annual Report of the U. S. Geological Survey.

In 1906 Gerald A. Waring made a reconnaissance survey of the region, covering most of Lake County, in order to gather information and study the water supply situation. He also made observations on the general geology of the area. His work was published in the U. S. Geological Survey Water Supply Paper 220.

In 1936 the Mineralogist Magazine published an article on Oregon saline lakes by John Melhase which was especially concerned with the Alkali Lake deposits.

The State Department of Geology and Mineral Industries published a report on Oregon saline lakes by O. M. Stafford in 1939, and again in 1947 they published a report on the Lake County salines by Dr. I. S. Allison and Ralph S. Mason.

Other articles which included material on the Alkali Lake deposits were written by Free (6, p. 26), Gale (7, p. 107-108), Phalen (12, p.129-131) and Van Winkle (p.114-115).
SUMMARY AND CONCLUSIONS

It has not been previously recognized, at least in the literature, that any sizeable portion of this area was older than Miocene, although several of the mountains and buttes in the region had been considered possibly to be of Eocene (Clarno) age. This study, however, has disclosed that a sizeable portion of the area surrounding the basin is probable Clarno material, mostly rhyolitic in nature.

The only other extensive formations in the area are the Miocene basalts and the Pleistocene lake beds.

This study also discloses the existence of a definite fault pattern in the area which seems to fit that of much of the surrounding Basin and Range Province.

The mapping of the basin has verified the existence of a suspected former outlet to the Fort Rock basin during the highest stage of the pluvial lake ancestral to Alkali Lake, about 65,000 years ago.

Although not enough work has yet been done to determine the exact amount of soda available at Alkali Lake, the present survey tends to show that the total readily available soda, which is limited to the "pothole" area, is less than has been estimated previously. The results of this survey show that the quantity of available soda ranges from at least 50,000 tons to perhaps 100,000 tons.
Any mining enterprise here, then, would appear to be limited, unless replenishment through underground seepage should be discovered to proceed rapidly enough that the operators would be assured of a continuous supply. Studies of this possibility are now underway by the State Department of Geology and Mineral Industries.

Other sources of soda in the area are of doubtful economic importance due to the special methods of recovery which would be required.

Little was done in studying the groundwater situation, but some information gathered in the course of this investigation tends to show the need for further studies in this respect, especially through the sinking of a few test wells.
GEOGRAPHY

TOPOGRAPHY. The area as a whole is a high plateau of moderate relief. The surface is broken by a widespread series of faults and locally the scarps resulting from vertical movement along these faults cause abrupt changes in the relief. Several of these are hundreds of feet high.

The lowest point in the basin (at Alkali Lake flat) is approximately 4260 feet in elevation and Grays Butte immediately to the east attains an elevation of 6173 feet. The entire eastern scarp rises from several hundred (on the north) to over 1200 feet (on the south), above the floor of the basin. The other scarps, however, are not nearly as imposing.

The most prominent features of the area are the scarps which bound the basin and the minor scarps in the bordering area.

The two buttes, situated within the basin, one to the north and the other south of Alkali Lake, respectively, Grays Butte on the east rim, Big Juniper Mountain on the east, Little Juniper Mountain on the north, and Horse Mountain on the northwest are all prominent landmarks standing at considerable heights above their surroundings.
Around the periphery of the basin, the lake terraces of which five are especially prominent, Plate III-A, form very distinctive topographic features.

The comparatively flat basin floor is interrupted at several points by wind deflation hollows, of which the Alkali Lake playa is by far the largest. These areas are bordered by residual hummocks and sand dunes. The sand dunes are especially abundant northeast of the Alkali Lake playa and form a number of longitudinal sand ridges extending in a northeast direction to the foot of the eastern scarp. The hummocks are formed in the deflation areas where some of the more hardy vegetation, usually greasewood, has protected the material from the wind.

Still another prominent topographic feature is the slump at the foot of the western or scarp face of Grays Butte, Plate III-B. This material apparently came from the top of the butte after it had been cut by the great fault and elevated along with the block which forms the eastern rim of the basin. That this slump occurred before the basin was filled to its highest water level is evident from the fact that all of the lake terraces continue unbroken around its sides. Indeed, because of its exposed position to winds from the southwest and because of the type of material of which it is composed, the terraces there are very pronounced.
PLATE II. View of Alkali Lake basin from the south.
A. The butte north of Alkali Lake. Note the two highest terraces on the left. Also, how the sand has piled up to obscure the terraces on the right (eastern side).

B. Grays Butte. Note the slump on the bottom of the righthand side of butte, and the gravel quarry in the terraces at the base of the butte.
Another feature deserving of mention is the fault splinter which can be seen at the south end of the eastern scarp. It is not shown on the geologic map, Plate XIV, as it is just below the southern limit of the sheet.

DRAINAGE. There are no permanent streams in the area but there are numerous canyons and gullies of various sizes around the edge of the basin which occasionally carry water during thundershowers and other heavy rains. All of these gullies run into the basin and there is no present outlet, all of the water being absorbed into the ground or evaporated.

There are several canyons which in former times must have carried a comparatively larger volume of water than most in the area, as shown by the depth to which they have been cut down through the plateau bordering the basin and by their length and lower gradient. One of these is directly north of Grays Butte, another, called Venator Canyon, is about six miles north of Grays Butte, a third is about six miles farther north and near the place where the main highway leaves the basin, and still another is at the north end of the basin where the old road to Wagon-tire leaves the basin.

CLIMATE. The climate of the Alkali Lake Basin area is semi-arid with the total annual rainfall usually less
than ten inches. Most of the moisture-laden clouds from the west are blocked by the Cascade Range.

As a result of the low humidity and an elevation between 4,000 and 5,000 feet, variations of temperature between night and day are marked, especially during the summer months when the temperature often rises close to 100 degrees F. during the day and drops almost to freezing at night. The mean annual temperature is between 40 and 50 degrees. Frosts occur in any month of the year.

The winters are usually comparatively cold and much of the precipitation occurs during the winter and spring months, especially in February, March and April.

VEGETATION. Sagebrush (Artemisia tridentata) and greasewood (Sarcobatus) predominate over most of the region, although the playas in the deflation basins are practically devoid of vegetation. There is some bunch grass (Agropyron caninum) but not enough to make good grazing, and with the exception of Big Juniper Mountain and some of the ridges at the north end of the basin there are very few juniper (Juniperus occidentalis) trees.

Rabbit brush (Chrysothamnus nauseosus) is fairly common, especially in the areas which have previously been under cultivation.
ROCK EXPOSURES. The basin floor is covered by lake sediments except for a few protuberances such as the two buttes which were not covered by water during even the highest stages, but were islands in the ancestral lake.

Exposures of these lake sediments can only be found at the exposed edges of the deflation basins, and then only of the top beds to a depth of fifteen to twenty-five feet or less.

The scarps bounding the basin, however, show excellent exposures of the basalts, rhyolites, and other igneous rocks and interbedded sedimentary rocks of which the plateau is composed. The basal portions of the scarps are for the most part hidden by talus and by the sands and gravels which form the lake terraces. The best exposures are generally found where deep canyons have been cut down through the scarps.
STRATIGRAPHY AND PETROGRAPHY

FORMATIONS REPRESENTED. The geological formations occurring in this area, with the possible exception of the pre-Clarno(?), are Tertiary and younger in age. The pre-Clarno(?) rocks are the oldest formation in the area. Their age is not definitely known except that they are older than the Clarno(?) formation. The formation is shown on the map as the small red patch just south of Grays Butte. The Clarno(?) formation of Eocene age is widespread over the northern part of the area and is shown on the map in brown. The next unit in the stratigraphic series, the Miocene basalts, bounds most of the southern part of the basin and is shown on the map in yellow. The Pleistocene lake beds form the floor of the basin at elevations below 4530 feet, which was the highest level of the former lake, and are shown on the map in orange.

PRE-CLARNO(?) ROCKS. The oldest rocks which, for this paper, have been designated pre-Clarno(?), appear only locally on the south flank of Grays Butte where they have been brought to the surface by the upsurge of rhyolitic lavas which formed Grays Butte and the surrounding flows.

They are shown on the geologic map, Plate XIV, by the red patch on the south side of the canyon, (Plate IV-A), which separates Grays Butte from the plateau to the south.
A. The pre-Clarno formation. Grays Butte on the extreme left.

B. Boulder conglomerate.
The steeply dipping green breccia (in foreground)
They consist of approximately 200 feet of badly weathered rhyolitic and basaltic flows, breccias, and conglomerates. They dip approximately 70 degrees to the south and are faulted in a number of places, with associated displacement of the beds, showing that they have been considerably disturbed.

Near the top of the section is exposed a series of 35 to 40 feet of breccias and conglomerates showing definite waterlaid characteristics.

The basal member of this series is an apparently local outcrop of boulder conglomerate, Plate IV-B, consisting of well rounded boulders and cobbles with fine material occupying the interstices. It is much weathered and most of the material crumbles easily, although a few boulders are still very hard and tough.

It is overlain by a 5-foot bed of breccia, composed of rounded, subrounded, and angular fragments, mostly of pebble size or smaller, but with a few ranging up to the size of a baseball. This bed shows very definite sorting, with coarse material tending to line up parallel to the bedding planes.

The next 15 feet is very similar in character, except that it contains many boulders of basalt, especially near the lower contact.
Above this is a distinctive green colored breccia, Plate V, of angular and subrounded fragments in a shaly matrix.

These breccias are succeeded by more badly weathered red-colored flows.

The talus from weathering, especially in some of the flows has obscured them to such an extent that accurate determinations are very difficult to make.

Because of their position in regard to Grays Butte which has upended them by its extrusion, and because of their much weathered character, these rocks are definitely known to be older than the Clarno(?) rocks. There are no clues, however, with which to establish their exact age.

**CLARNO(?) FORMATION.** The unit which is probably upper Eocene in age and has been mapped as the Clarno(?) formation consists of a series of rhyolite flows and related rocks. It is very extensive, being the dominant material that bounds the northern half of the basin.

These rocks cover an area on the surface which forms the eastern scarp from Grays Butte north almost to the northern end of the basin, where they have been capped by a few thin flows of Miocene basalts. They can be seen beneath the basalts at many places along the scarps at the north end of the basin and are probably connected under
ground with the Wagontire Mountain mass which Smith (14, p. 207) described as being rhyolitic and assigned to the Eocene period. He later (p. 209), however, described the Wagontire mass as a gray porphyritic andesite.

For reasons which will be given later, the writer has decided that this formation is probably equivalent to the Clarno formation and therefore has disregarded the name "Wagontire formation" which Smith gave to the Wagontire Mountain mass.

Grays Butte and Big Juniper Mountain are both rhyolitic masses and are very likely the sources of many of the surrounding flows. Grays Butte consists of light gray to pinkish rhyolite which on microscopic examination appears to be mostly devitrified glass, with phenocrysts of quartz and Sanidine.

The western half of the unnamed butte situated immediately north of the Alkali Lake playa and two small sections of the eastern half are also composed of rhyolites. These are quite variable in texture, ranging from glass and pumice to microporphyritic flow breccias. The flows of the western half seem to dip westward at a very low angle.

The rhyolite flows extend east as far as Big Juniper Mountain. On the western side of the northern part of the basin they are again the dominant scarp-forming unit.
It may be noted that Horse Mountain to the west is roughly in line with the butte north of Alkali Lake, Grays Butte, and Big Juniper Mountain, so as to suggest that it too may be rhyolitic in character and related to them in origin. In fact the alignment suggests the possibility that these prominences may delineate a great fissure from which the rhyolites were poured out over the surface.

The section of these rocks exposed along the eastern scarp north of Venator Canyon, Plate VI-A and B, shows a basalt flow at the base. Just south of there, though, the basalt member is exposed enough higher due to upthrow along a fault that an underlying rhyolite flow can be seen. This basal rhyolite is a massive, spherulitic flow which is very similar in character to the flow which forms the top bed along most of the northern part of the eastern scarp, and which is described in some detail a bit later herein.

Microscopic examination shows the basalt to be a dacytitic, holocrystalline olivene basalt. The feldspar is lathshaped labradorite. Augite is an abundant constituent and the olivene has been greatly altered to hematite. This last characteristic is also visible in the hand specimen.

Above the basalt is a 4- to 5-foot bed of breccia composed mostly of small, white colored granules of pumice with a few larger included fragments of pumice.
This bed shows a very interesting contact phenomenon which was described by Waring (19, p. 24). At its contact with the overlying flow it has been altered to a black glass which grades downward through gray, red and brown. The top six inches contains a number of small, lustrous, black, angular chunks of glass. Inside of some of these fragments can be seen inclusions of light buff-colored material, which resembles the lower part of the bed. This relation attests to the extreme heat of the overlying rhyolite flow, as is substantiated by the way the flow spread out over the surrounding countryside with no apparent change in thickness.

The rhyolite which is directly above this bed of breccia is a pinkish flow-breccia. It has a considerable number of included pumice fragments and is itself occupied by numerous small openings showing that it either was a very fluid flow containing a large amount of gases, or possibly was formed by a "nues ardentes" type of eruption where the ejected pumiceous material was thrown out over the surface and fused to form a rock which very closely resembles a flow. It is about 20 feet thick. The groundmass of this flow is essentially glass which has included a few phenocrysts of quartz and sanidine.

Above this is another rhyolite flow of a very different character. It is a thick (over 100 feet), massive flow
A. Section of eastern scarp exposed north of Venator Canyon. Note the thin white bed of breccia.

B. Same section as above but closer to Venator Canyon. A fault has cut through these flows near the middle. Note weathering of the upper flow and the delta in the foreground.
which forms the capping along the eastern scarp from Grays Butte to the north end of the basin where the main highway leaves the basin. Petrographic examination shows it to be a spherulitic rhyolite vitrophyre with the groundmass essentially devitrified glass and spherulites ranging from microscopic size to the size of a walnut. There are scattered phenocrysts of quartz and orthoclase.

The numerous vesicles and cracks in this flow are lined with crystals and druses of secondary calcite. This massive rhyolite member also contains a number of large blocks of glass and pumice inclusions. It weathers into huge spheroidal boulders which stand out along the top of the scarp to form one of the dominant characteristics of this portion of the scarp, Plate VI-B.

Overlying this, but not visible along most of the scarp is another flow of pinkish rhyolite flow-breccia. It is also a vitrophyre with phenocrysts of quartz and sanidine. This rock can be found on the surface a short distance back from the scarp in this area and is the main surface material in the vicinity of Grays Butte and Big Juniper Mountain.

Rhyolite flows closely resembling this are found in the butte north of Alkali Lake and the western scarp of the northern part of the basin. Outcrops of pumice breccia, gray to black glass, and dense white rhyolite are also
found in the western part of the butte north of Alkali Lake.

The rhyolites in the western scarp are overlain in places by an originally viscous type flow of darker colored, vesicular glass which shows a ropey structure at several places near its margin. It is probably of the same general period of eruption as the rhyolites, although somewhat later than the others. It seems to have come from the direction of Horse Mountain and ends near the western boundary of the northern part of the basin.

These rhyolites, which are exposed north of Venator Canyon, were described by Waring, (19, p. 24), who apparently mistook them for basalts, saying "This overlying rock is lighter colored and less dense than the usual basalt, and covers much of the area surrounding Alkali Lake basin, but it probably belongs to the same period of effusion as the more close-textured basalt to the south, into which it seems to grade".

Although these rocks are a considerable distance away from any definitely established Clarno rocks, they probably belong to that group. At Grays Butte the Miocene basalts disconformably overlie the upturned pre-Clarno(?) rocks which were brought up to their present position during the formation of Grays Butte, and at the north end the Clarno(?) is overlain by horizontal Miocene flows. Also, the basalt member of the Clarno(?) series, which is overlain
with only slight erosional unconformity by the breccia and upper rhyolites, shows considerably more alteration than the basalts of the Miocene, a characteristic which was used by Lowry (9, p. 44) to distinguish the Clarno basalts from the Columbia River basalts in this area.

These facts establish them as definitely older than the Miocene basalts and therefore it is reasonable to conclude that they are probably equivalent to the Clarno rocks which are so extensive in other parts of central Oregon.

It may be noted that the succession which occurs just north of Venator Canyon is similar to a sequence of Clarno beds which has been described by Lowry (9, p. 12). In the sequence which he described, massive basal basalts are overlain with slight angular as well as erosional unconformity, by a group of light-colored tuffs, above which is a group of massive rhyolite flows.

The distance between these two areas is too great to allow a direct correlation to be made or to allow the use of this similarity of sequence as the sole basis for any arguments as to the probable age of the rhyolites in the Alkali Lake basin. Also, their petrographic character, except for the basalt members, is not strikingly similar. The similarity does, however, give an indication of the similar sequence of events which caused their formation
and points to the possibility of their general if not exact equivalence.

MIOCENE BASALTS. The next stratigraphic unit in the sequence is a series of basalt flows which have been assigned to the Miocene period and are probably equivalent to the Columbia River basalts. They are shown on the map, Plate XIV, in yellow. They bound the southern part and also the extreme northern end of the basin.

The southern end of the great eastern scarp, south of Grays Butte, is composed of a series of basalt flows that tower to a height of about 1200 feet above the basin floor. The exposed section, Plate VII-A and B, shows three distinct series of flows, each separated unconformably by former erosion surfaces which are now marked by the presence of interbedded tuffs and breccias. At one place just south of Grays Butte there is exposed what appears to have been a former canyon of considerable depth which was filled with tuffaceous material before being covered by the succeeding flows.

A comprehensive microscopic study of these basalts was impossible in the short time available. Thin sections examined, however, show them to be holocrystalline olivine basalts. The abundant olivine and augite form a concertal texture in a felt of labradorite. Larger crystals of
PLATE VII.

A. The eastern scarp, south of Grays Butte.

B. The eastern scarp from the butte south of Alkali Lake. Big Juniper Mt. in the distance. Note the broad, low flexures in the middle series of flows.
plagioclase, probably albite, are common and they surround magnetite and anhedral augite crystals. The magnetite is especially abundant in this rock and appears to be both primary and secondary. The olivene shows some alteration to hematite, but most of it seems comparatively fresh.

The basalt at the north end of the basin is also an olivene basalt, in which the abundant olivene shows little alteration. It shows a jackstraw arrangement of the feldspars, with rounded olivene crystals. Augite is not common, but occurs in large, broken phenocrysts which seem to have been invaded by the spars and the olivene. The chief feldspar is labradorite.

At the north end of the basin, where a well-developed canyon enters the basin from the direction of Wagontire, a fissure dike is exposed, Plate VIII-A. The basalt can be traced up this exposed dike to the surface where it spreads out over the surface in the form of a flow. Such fissure flows are characteristic of the basalts of the Columbia Plateau which borders the area.

This basalt flow overlies a series of tuffaceous breccias which show definite waterlaid characteristics including bedding and sorting. Near the entrance to the canyon these beds have been cut and considerably disturbed by a basalt dike and a closely related eight inch elastic dike of tuffaceous material, Plate VII-B, which is very
PLATE VIII.

A. Fissure dike at north end of basin.

B. Breccias cut by basalt dike (near the center of the picture) and clastic dike (to left of rod).
similar to the material found in the clastic dikes of the deflation basins in the Fort Rock area. This clastic dike was apparently formed during the disturbance created by the intrusion of the larger basalt dike.

Again on the extreme western side of the basin in T 29 S., R 21 E., a series of tuffaceous breccias and tuffs, possibly over 100 feet thick, are overlain conformably by a single thin flow of dense dark-colored basalt. The tuffaceous breccias show distinct bedding and sorting, Plate IX, with the series near the middle grading into a coarse sandstone. The base, which is not exposed in the scarp, is a light-colored, fine-grained tuff of considerable thickness.

The eastern part of the butte north of Alkali Lake and all of the butte south of Alkali Lake are composed of black to red, vesicular, cellular, and dense basalts. Microscopic examination shows them to be olivene basalts in which the olivene has been considerably altered to hematite. The texture is ophitic. The chief feldspar is labradorite.

The extent of the alteration in these basalts is not as great as in the Clarno(?) basalts. This freshness along with the fact that the rhyolites in the northern butte appear to have been disturbed by the basalts during their eruption, and the position of the southern butte in
PLATE IX.

Waterlaid breccias at extreme western margin of basin.
relationship to the great thickness of basalts in the eastern scarp, lead us to assign the basalts to the Miocene. The evidence, although not conclusive, is at least very strongly suggestive that they belong in that stratigraphic position.

PLEISTOCENE LAKE BEDS. The only exposures of the Pleistocene lake beds occur at the edges of shallow deflation basins, so that only the top 15 to 25 feet of lake beds are available for examination. They consist of light-colored sandy and silty, slightly consolidated beds showing the crossbedding which is characteristic of shallow water deposition. Many of the sections exposed showed local slumping. Interbedded are up to 5 or more thin pumice layers ranging in thickness from mere traces to about 2 inches.

Exposures are mostly confined to the western and southern margins of the deflation hollows.

One section, about half a mile north of the spring near EM 4267 (Plate XIV) shows a layer of pumice about two inches thick which appears to be similar in character to the Crater Lake pumice which is described by Allison (1, p. 797). It apparently has been reworked, as the boundary between it and the accompanying sandy beds is irregular, and the material is weathered to some extent.
Three feet above this is another layer of approximately two inches of satiny, light-colored pumice, similar to the Newberry pumice described by Allison, which was also reworked, and between the two several indistinct ash layers. Six inches above the satiny layer is a thin (approximately ¼ inch) layer which also is satiny in appearance. The top of the lake beds is about 3 feet or so higher.

Nowhere was any biotite bearing pumice found which would have helped to establish the derivation and stratigraphic relationship of the layers and to correlate them with the Summer Lake and Fort Rock pumice falls.

At the south end of Alkali Lake playa, 100 feet east of the quarter corner between sections 18 and 19, three distinct pumice layers are visible, the uppermost being about 4 feet below the top of the lake beds, the middle one 3½ feet below this, and the lowest 2½ feet still farther down. There were several indistinct layers below these. Here, again, the associated deposits were of the characteristically crossbedded, shallow water type.

No pumice layers are visible in an exposure of 15-25 feet of lake beds shown on the southwest side of the Little Alkali Lake playa. This points to the conclusion that the northern part of the basin had already dried up
by the time of the pumice falls, whereas the southern part of the basin still contained a shallow lake. This would seem to be reasonable in view of the fact that the floor of the northern part of the basin is about 4300 feet in elevation, except for the comparatively recently wind deflated basin, while the elevation of the floor of the southern part, except for the Alkali Lake deflation basin, is about 4285 feet above sea level.

RECENT DEPOSITS. There are several very minor deposits of Recent alluvium and Recent deposits of soda in the thesis area, but as these are very limited in extent, they have not been mapped separately.

Smith (14, p. 207) has given the name of "Alkali formation" to the "potholes" and the crust of soda which occurs in this area. The writer doubts that such a minor unit should be classed as a formation, and therefore the deposit has not been mapped as such, and use of the name "Alkali formation" has been avoided. Instead, a description of the deposit is given in a later section dealing with economic geology.
GEOLOGIC STRUCTURE

REGIONAL STRUCTURE. The general structure of this region as a whole was described by Waring (19, p. 25 and 26) as follows: "Probably in few other places in the world is the geologic structure so well exhibited in the present land forms as it is in southeastern Oregon. Here the main features of relief are a direct result of deformation of the rocks. This deformation has resulted in faults which are the main structural features, as their expressions in scarps are the main topographic features.

"In most of the Great Basin region the typical Basin Range structure produced by the faulting and tilting of long narrow orographic blocks, is obscured by erosion or by earlier complex structures. But in Lake County erosion has acted very little on these great blocks, and little or no deformation preceded the faulting, so that the typical structure is evident in the present conformation on the surface.....

"Besides these tilted blocks there are low folds in the bedded lavas. In the production of these, however, the rock itself has been bent little if any. The very slight opening and closing of the multitudes of approximately vertical fractures in the beds has been sufficient to allow the low folds to be formed. In Lake County the
other structural features seem closely related to a great upward fold or anticline of this character, which has been extensively faulted in places……

"The axis of this major anticline extends from Silver Lake southwards through Goose Lake valley."

LOCAL STRUCTURE. The Alkali Lake basin is a downfaulted block or graben of the sort that is typical of the Basin and Range structure so excellently described by Gilbert, Louderback, Russell and others. The downthrow was greatest along the eastern scarp, especially at the south end, resulting in the prominent scarp which attains a height of 1200 feet just south of Grays Butte. It gradually becomes lower to the north and also runs out against the Coleman Hills several miles farther south.

This scarp appears to be a northern extension of the Abert Rim, as was noted by Melhase (11, p. 9). The two scarps are almost directly in line and are separated only by the Coleman Hills.

The movement along the faults which bound the remainder of the basin was not nearly as great, and the resulting scarps are therefore not nearly as prominent. Nevertheless, the effects of faulting dominate the landscape on all sides.

In the plateau area immediately adjacent to the
basin, especially to the north and to the southwest, are a great number of minor scarps. Raisz (13, p. 484) noted these scarps which lie at the north end of the basin and likened them to miniature Basins and Ranges.

Examination of the fault pattern shows that the strikes of these faults, with a few exceptions, lie in two general directions. One of these directions is approximately north-northwest and the other is approximately north-northeast. Even the prominent eastern scarp which trends in general nearly north-south can be seen upon close inspection to consist of a series of intersecting faults whose strikes closely approximate these same general directions, Plate I, and Plate XIV.

Several exceptions to the prevailing trends can be found on the western side of the basin, but for the most part exceptions are noticeably lacking.

Just south of Grays Butte, the steep contact between the Miocene basalts and the Clarno(?) formation is probably the result of faulting. The contact is rather sharp, the Clarno(?) rocks ending abruptly on the north side of the second ravine south of Grays Butte and the basalts forming the other side of the ravine. This relation is not visible from the basin because a finger of basalts has extended over to cover the steeply dipping
older rocks which flank Grays Butte to the south.

The Miocene basalts to the south, then, represent a series of flows which have filled a lowland, possibly a downfaulted area, while the area to the north remained high enough that it was not encroached upon by these lavas.

This inferred fault would, of course, represent an earlier period of faulting, which occurred sometime between the Eocene (Clarno?) and Miocene epochs.

Another fault which may be of this same period of faulting occurs just north of Venator Canyon, where the breccia ends abruptly. This fault appears to have a strike bearing approximately north-south, but as it is not topographically reflected at the surface because of subsequent planation by erosion, the strike cannot be determined accurately. Vertical displacement is of the order of about 40 feet, with the western block being downthrown.

The Clarno(?) formation, as shown in the eastern scarp, dips very gradually northward, apparently because of initial dip of the lavas as they spread out over the surface. They also dip somewhat to the eastward, due probably to the rotation of the block by faulting.

The basalts south of Grays Butte are nearly hori-
zontal at the top and near the base, but the intermediate series of flows shows a few broad, low "flexures", Plate VII-B, which are undoubtedly not true folds but are due instead to initial dip of the flows as they were poured out over an undulating erosional surface.

The steeply dipping pre-Clarno(?) rocks were brought up to their present position by the upsurge of lavas that formed Grays Butte. They are cut by minor faults in numerous places and are somewhat offset along these fault planes.

The rhyolites which form the western half of the butte north of Alkali Lake dip gently westward, apparently being disturbed by the upsurge of basalt which forms the eastern half of the butte.

Of the minor structural features, the series of faults, Plate XIII, which cut the Alkali Lake playa in the vicinity of the "pothole" area are the most important. They are a group of intersecting faults whose reflection on the surface is shown by the three springs and the green vegetation which marks their position. They seem to be approximately vertical faults along which little movement has taken place but which must extend at least to the bottom of the lake beds. It is probable that they are due to slight movement along earlier faults in the under-
lying bedrock. Waring (19, p. 69) estimates that the water in the main spring has come up from a depth of 700 to 800 feet. The strikes of these faults are approximately N30°W and N20°E, which shows that they also correspond to the major fault pattern of the area.

Other minor features are (1) the horst which rises above the basin floor in the northern part near the boundary between T 27 S. and T 28 S., R 25 E., (2) the fault slivers or wedges, one of which is just north of Grays Butte which was formed when a sliver of the large block to the east broke off and slipped down toward the basin but did not reach the basin floor and so forms a sort of shelf on the scarp face, the second is at the south end of the basin, and the third is southeast of the junction of the army road and the main highway.
GEOLOGIC HISTORY

PRE-CLARNO. The early history of the region included periods of intense volcanic activity which were interrupted by periods of erosion and deposition. It would appear from the weathered character of the pre-Clarno rocks that they are considerably older than the other rocks in the area. As there were no fossils or other material in the rocks which would furnish definite clues as to their age, very little can be said about their specific geologic history. The volcanic activity is marked by flows and ejected material, both rhyolitic and basaltic.

EOCENE. Again, probably in Late Eocene time, there were periods of intense vulcanism during which the Clarno- (?) rocks were poured out over the surface. First came an outpouring of rhyolites followed by an outpouring of basalt. This was followed by a period of quiescence during which the surface was moderately affected by erosion. This period was succeeded by perhaps the most violent activity that the region ever experienced when the pumice and other material which composes the breccia was thrown out and blanketed the surface. This explosive period was quickly followed by the outpouring of the succeeding
rhyolite flows. The intense heat of the magmas as they poured out over the surface is shown by their vesicular character and by the apparent fluidity of what is ordinarily a highly viscous magma as they spread out over the surface in all directions with little apparent thinning of the flows even many miles from their source.

It was at this time, also, that Grays Butte, part of the butte north of Alkali Lake, and probably Big Juniper Mountain, Horse Mountain, and Wagontire Mountain were formed.

This epoch was followed by a period of erosion and possibly of faulting during which the area to the south of Grays Butte became low-lying as compared to the area to the north. The fault that cuts the Clarino(?) rocks just north of Venator Canyon may also be of this period, although it may have been formed at a subsequent time. It was formed definitely earlier than the post-Miocene faults, as the scarp which resulted was leveled off by erosion whereas the post-Miocene fault scarps have been little modified by erosion.

**MIOCENE.** In the Miocene period came the great basalt outpourings which formed the Columbia Plateau to the north. Extensive outpourings of basalt which may not be continuous with the Columbia River basalts, but are at
least equivalent to them, occurred in this area, also. Just south of Grays Butte they are over 1000 feet thick and possibly much thicker. To the north only thin flows cover parts of the apparently high standing Clarno (?) rocks. Farther south, however, more than 2000 feet of basalts are exposed in the Abert Rim.

It was during this period, also, that the two volcanic buttes which are inside the basin, and probably the Coleman Hills, Euchre Butte, and many other prominences in the area were formed.

POST-MIOCENE FAULTING. The outstanding physiographic features of the region originated during the intense post-Miocene faulting to which the region has been subjected. This period of faulting has been dated as late Pliocene or early Pleistocene by Louderback (8, p. 33) who states: "The evidence in hand points to a late Pliocene or post-Pliocene time for the beginning of the faulting. The greater part of the faulting was completed before the late Pleistocene." Recent evidence tends to show an early Pleistocene age for most of the faulting.

According to Louderback, the faulting was begun with the uplifting and crowding of the Miocene lava plateau, probably with differential movement of the blocks
(lagging behind by some) causing the formation of the basins.

In this way, as a down-faulted block surrounded by high standing blocks, the Alkali Lake Basin was formed. As is true of many other basins of the region, the movement was greatest along the eastern margin, especially at the south end.

The eastern scarp terminates at the southern end against the Coleman Hills, Plate XI-A, and almost directly in line on the opposite side of these hills is the Abert Rim, one of Oregon’s most magnificent fault scarps. The faults forming the two scarps are undoubtedly closely related, possibly being connected. No attempt was made to trace the fault across the Coleman Hills, however, and the conclusion is drawn only from observation of the topographic relationship.

FORMATION OF PLEISTOCENE LAKES. The next event in the geologic history of the basin was the formation of the Pleistocene lakes. At first, and probably several times later, when the water was relatively shallow, there were two lakes, one in the northern part and the other in the southern part of the basin and separated by ridges of rock connecting the butte north of Alkali Lake to the
A. The Coleman Hills and Euchre Butte at the south end of the basin.

B. The Little Alkali Lake playa. Note landing strip and other playa in the distance.
western rim on one side and to Grays Butte on the other. At its highest stage, however, the surface of the lake was well above these ridges and formed one large lake.

The two buttes within the basin were islands in this lake, and there were several other islands, including the horst which is in the northern part of the basin.

This stage, marked by the highest terrace level, is shown by wave-cut cliffs and benches, by wave-deposited terraces, and by the bars at the mouths of the former streams which emptied into the lake. It is also marked by a delta at the mouth of Venator Canyon, showing that the water must have stood at this level for a comparatively long period of time.

At this stage, the 4535 foot level, the surface of the lake was up to 275 feet above the present floor of the basin. During this highest stage, an outlet connected this lake with the lake in the Fort Rock basin. The course of this outlet was through a fault trough in the plateau on the west and extended in a northwesterly direction from the southern part of the Alkali basin to Christmas Lake section of the Fort Rock basin, south of Buffalo Wells, a distance of about 9 miles.

This former outlet, which was surveyed by the writer with the aid of an aneroid barometer, has an elevation
at the highest point in the trough, which could have served as a divide, of approximately 4500 feet with a possible error in traverse of about 10 feet. This allows a range of at least 25 feet of lowering of outlet and depth of water running through the channel at this time.

This 4530-foot level undoubtedly corresponds to the Bonneville, or Tahoe, stage of about 65,000 years ago, which Allison (2, p. 64) has also assigned to the highest stages in both the Summer Lake and the Fort Rock basins.

The highest level of the pluvial lake in Fort Rock basin was determined by Allison to be about 4520 feet, which gives only about a 10-foot difference between it and Ancestral Alkali Lake.

This high stage was followed by a dry period during which the level of the lake was gradually lowered, an event which follows a pattern characteristic of all the Pleistocene lakes of the Basin and Range province.

Then came another period of comparatively moist climate, with the lake again rising to a fairly high level. This level could not be determined exactly but it is probably represented by the 4440-foot terrace which would correspond to the 4430-foot level which has been established for Fort Rock Lake of this period in the Fort Rock basin. It corresponds to the Provo or Tioga stage which has been dated at about 23,000 years ago.
A comparison of the sequence of terraces in the Fort Rock and Alkali Lake basins shows them to be very similar. The 4530-foot terrace of the Alkali Lake basin corresponds to the 4520-foot terrace at Fort Rock; the 4430-foot terrace corresponds to one at 4470 feet at Fort Rock; the 4440-foot terrace to the 4430-foot one; etc. There are 5 distinct terraces in each basin, although each has others which are less distinct.

It is not surprising, then, that the ancestral lakes in both basins were in approximately the same stages of existence, i.e., shallow water, at the time of the Crater Lake and Newberry pumice falls. The age of these pumice falls has been set at between 10,000 and 14,000 years by Allison (2, p. 64).

It is notable that the lake in the northern section of the Alkali Lake basin apparently had completely disappeared by the time of the pumice falls so that the "blowout" at Little Alkali Lake has exposed no pumice layers, although between 15 and 25 feet of lake beds have been exposed.

A visitor to this dry, rock-desert area who is acquainted with the facts regarding the former existence of these lakes may be inclined to marvel at the picture they must have presented in the past and to ponder on the changed climatic conditions necessary for their existence.
Regarding these climatic conditions, Meinzer (10, p. 549) made a study covering the whole of the Basin and Range province during 1922. His conclusions were as follows:

"The range in humidity (or aridity) among the various basins in the Pleistocene epoch was apparently as great as the difference in a given basin between the Pleistocene and the present. A considerable number of the closed basins in the province were too arid in the Pleistocene to contain lakes of any consequence, whereas a few are humid enough at present to contain perennial lakes of considerable size. The relatively humid parts of the province at the present time seem to be comparable to the most arid parts in the Pleistocene epoch."

Meinzer concluded that this would involve a mean annual temperature difference of about 15 degrees F. between the Pleistocene and the present.

The amount of precipitation involved would not be quite as important, as the cooler climate would result in much less evaporation.

Conditions, therefore, would apparently not have been as much different during the Pleistocene epoch as one might be led to suspect.

The presence of fish in the northernmost of the three springs which are in the Alkali Lake playa indicates
that the faulting which is structurally responsible for the existence of the spring had probably occurred before the lake had completely dried up and that the spring had been feeding into the lake. Otherwise all of the fish in the lake would have died and the spring would be uninhabited. Of course there is always the possibility that the spring has been stocked by man in comparatively recent times, but the fish themselves show effects of long continued isolation.

POST-PLUVIAL WIND DEFLATION. After the final extinction of the Pleistocene lakes, an event which took place about 10,000 years ago, there came a period of particularly arid climate during which the wind was able to excavate a number of basins or hollows in the loose unconsolidated lake beds which formed the basin floors. This especially was true of the neighboring Fort Rock basin which has a great number of these deflation hollows, but it is also true of the Alkali Lake basin. This period of dry climate occurred between 8,000 and 4,000 years ago. The Alkali Lake playa, because of its especially exposed position, is by far the largest of these deflation hollows. The winds, coming from the southwest, were able to sweep in over the low, distant divide on the west and reach a large portion of this
part of the basin. As this was probably the last part of the basin to be occupied by the Pleistocene lake, the beds here were especially fresh and unconsolidated and therefore especially suitable for wind erosion processes.

At first the wind may have been aided by some special structural or physiographic feature, possibly the minor faults which cut the playa near the "pothole" area. (In some of the deflation basins in the Fort Rock area the winds were aided by the disturbance of the lake beds caused by the intrusion of clastic dikes. No evidence of clastic dikes was found, however, in any of the Alkali Lake basin playas.) Another possibility is that the concentration of salines in this area had prevented the growth of vegetation which would have acted as a protective covering. A third possibility is that the drying up of shallow pools of water following wet seasons or periods had caused the formation of mud cracks so that the beds were exposed. Or the initiating factor may have been any combination of these.

Once the wind had obtained a good start, its erosional work proceeded rapidly, until the beds had been excavated to form the present playa, which covers an area of about 4 3/4 square miles to a depth of about 15 to 25 feet. This would mean the removal of over 43
million cubic yards of material. Much of this material was deposited in the form of sand dunes and longitudinal sand ridges, especially to the northeast beyond the gap between Grays Butte and the butte north of Alkali Lake. These long dune ridges extend approximately north 35° east to the delta at the mouth of Venator Canyon. This direction corresponds rather closely to the average direction of the wind (toward N. 31°41'E.) as it was determined over a short period of time by the State Highway Department engineers when they built the emergency landing field north of Alkali Lake. It also appears to correspond to the direction of the winds which swept over the Pleistocene lakes, as shown by the especially pronounced terraces against the southwestern side of the butte north of Alkali Lake and against portions of the eastern scarp where they were exposed to the waves from this direction. The natural conclusion from this is that the prevailing winds have come from this same direction for many thousands of years.

The Little Alkali Lake deflation basin, Plate XI-B, is much smaller than the Alkali Lake deflation basin. It covers an area of about 1 square mile and has also been cut to a depth of about 25 feet. It is roughly elliptical in shape, being only about 3/4 of a mile across at its widest place and about 1 3/4 miles in length.
It is protected somewhat from the southwesterly winds by the butte which is between it and Alkali Lake and by the western scarp which is not as far away from it as from the Alkali Lake playa.

Here, in contrast to the Alkali Lake area, the sand has been piled up into transverse sand ridges running northwest-southeast, normal to the direction of the winds. This is probably due to the fact that the winds are not confined, as they are to the south by the gap between Grays Butte and the butte north of Alkali Lake, with the result that the wind velocities are probably not as high.

Another deflation hollow is represented by the playa 9 miles north of Grays Butte, which is crossed by the main highway. This basin is much smaller than the Little Alkali playa. There are several other minor deflation hollows west of the Alkali Lake playa, but none of importance.

Following the dry period of 8,000 to 4,000 years ago came a period of increased precipitation during which the wind deflation ceased and lakes were formed in the small basins which the winds had previously excavated. This period has been dated by Allison (2, p. 64) at about 2,000 years ago.

This was followed by a return to drier conditions
and the partial renewal of wind erosion which has continued up to the present time.

The soda deposits were also formed during the post-pluvial period although the largest part of their collection and concentration undoubtedly occurred during the Pleistocene lake era. Their origin and formation is not fully understood at the present time, although an attempt is made, a little later herein, at evaluating the various possible explanations of their formation.
GENERAL DESCRIPTION OF SODA DEPOSITS. The greatest concentration of soda in the basin is in an area near the western margin of the playa, in sections 7, 17, and 18, R 23 E., T 30 S. The soda has been concentrated there in crater-like depressions which have been called "potholes", Plate XII. These "potholes" range in size from a few feet or less up to 30 feet or more in diameter, with the majority being about 6 or 8 feet in diameter. They range from a few inches to several feet in depth. The larger "potholes" seem to have been formed by the joining of adjacent depressions, and so are irregular in shape. Detailed measurements made by Allison (unpublished report) indicate that the thickness of the soda in individual sections of these composite "potholes" is in many cases quite different from that in the neighboring section, which would tend to substantiate the theory of coalescence. The thickness of the salt ranges from 6 inches to 51 inches in a group of 49 "potholes" in a one acre tract near the north end of the area. As the 51-inch thickness is in one of the largest "potholes" in the area, it is doubtful that any greater thicknesses are common in any of the others. The average diameter of the "holes" in this one acre tract is approximately 7 feet.
A. Typical "potholes"

B. Mud cracks near spring at south end of "pothole" area.
and the average thickness of the soda lenses is 33 inches.

Large "potholes" are not especially abundant, a few occurring about 1,000 to 1,500 feet south of the north end of the area and a number occurring at the south end. Some of those at the south end were excavated by laborers with picks and shovels in 1916 for the American Soda Products Company. They have since been replenished, apparently being fed through upward local seepage from which the salts crystallized and were deposited. One noticeable feature of these "potholes" is that the ones which contain appreciable amounts of soda are bordered by a ring of sandy earth which is about six inches or more above the general surface of the area, while the ones which are barren of soda or contain only minor amounts, do not have this characteristic "rim".

The lenses of soda are thickest near the middle and thin out towards the edges where they are usually concealed beneath the rim. They pinch out, however, approximately at the rim.

The physical, chemical, and optical properties of the bulk of the material, as determined by Allison (3, p. 8), indicate it to be natron (Na$_2$CO$_3$·10H$_2$O) with the possible presence of small amounts of trona (Na$_2$CO$_3$·NaHCO$_3$·2H$_2$O) or thermonatrite (Na$_2$CO$_3$·H$_2$O).
Another occurrence of soda is in the depression occupied in part by the spring near the south end of the "pothole" area, where a considerable crust of soda mantles a low, spongy, water-laden area bordering the spring at the western edge of the depression. The commercial possibilities of this occurrence are very doubtful. It is of interest only for the possible clue it gives to the origin of the soda in the "potholes".

A thin crust of efflorescent soda covers most of the surfaces of the playas in the area and has been considered as a possible commercial source of soda. Allison (3, p. 8) took samples of this crust and of the soft, sandy, brown material immediately underneath, which yielded 26 per cent and 18 per cent respectively of dry sodium carbonate.

ORIGIN AND FORMATION OF SODA DEPOSITS. Table 1 shows the composition of the soda in the "potholes" and crusts at Alkali Lake. From this table it can be seen that the deposit is rather remarkable in that the "potholes" contain an exceptionally high percentage of sodium carbonate \( \text{NaCO}_3 \), with small percentages of the bicarbonate \( \text{NaHCO}_3 \), common salt \( \text{NaCl} \), sodium sulphate \( \text{Na}_2\text{SO}_4 \) and potassium chloride \( \text{KCl} \). The efflorescent crust contains a higher percentage of these latter salts (of the total
# TABLE I.
## ANALYSES OF CRYSTALLINE SALTS FROM ALKALI LAKE
(in percentages by weight)

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<th>1</th>
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<th>4</th>
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<tr>
<td>Na₂CO₃</td>
<td>7.53</td>
<td>34.91</td>
<td>40.90</td>
<td>18.44</td>
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<tr>
<td>NaHCO₃</td>
<td>4.64</td>
<td>3.92</td>
<td>.74</td>
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<td>NaCl</td>
<td>5.30</td>
<td>3.67</td>
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<tr>
<td>Na₂SO₄</td>
<td>3.07</td>
<td>2.49</td>
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<td>n.d.</td>
<td>.11</td>
<td>.18</td>
</tr>
<tr>
<td>KCl</td>
<td>1.48</td>
<td>1.01²</td>
<td>.45</td>
<td>.39</td>
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<td>.00052</td>
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<td>n.d.</td>
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<td>.0001</td>
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<tr>
<td>SiO₂</td>
<td>.21</td>
<td>n.d.</td>
<td>.14</td>
<td>.20</td>
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</table>

|       |     |      |      |     |
| Difference² | 54.00 | 54.73 |      |     |
| Total      | 23.23| 100.00| 100.00| 26.38|

a. K₂SO₄ instead of KCl.

b. Essentially water of crystallization and a little insoluble matter.

1. Surface crusts, November, 1945

2. Composite of three samples representing the top two feet of solid salts in a "pothole", September 4, 1944.


4. Sample from depth of 42 inches in same "pothole" as No. 3.

Analyses 1, 3 and 4 by W. P. Smith's laboratory, Painesville, Ohio; No. 2 re-calculated from analysis by L. L. Hoagland, Ore. Dept. Geol. and Min. Ind.
amount of salts present) and a lower percentage of the carbonate and bicarbonate.

One faces a rather interesting problem, then, to determine what conditions or processes are or were in existence to cause such a concentration of salts. One logically may conclude that these salts were derived either directly, or indirectly, or both, from the decomposition and weathering of the surrounding rocks. Clarke (5, p. 161) states that alkaline carbonates have been formed from the decomposition of eruptive rocks in the Lahontan basin and surrounding areas and concentrated in the lake waters and their residues. The rocks of the drainage basin seem to be mainly rhyolites, andesites, etc., rich in alkalies and relatively poor in lime.

In this connection the following table, given by Young (20, p. 17), showing the relationship of composition to soluble weathering products of both acid and basic type rocks is significant.

The table plainly shows that for the acid type of rock, the largest part of the soluble weathering products will be Na₂O and K₂O. As the rocks which border the northern part of the basin are mainly of the acid type, it is apparent that the resulting salines should contain
TABLE II

<table>
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<th>Acid Type</th>
<th>Basic Type</th>
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<tr>
<td></td>
<td>Constituent</td>
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<td></td>
<td>in 100 lbs.</td>
</tr>
<tr>
<td>MgO</td>
<td>10.50</td>
</tr>
<tr>
<td>CaO</td>
<td>2.15</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.35</td>
</tr>
<tr>
<td>K₂O</td>
<td>4.10</td>
</tr>
<tr>
<td>S</td>
<td>0.370</td>
</tr>
<tr>
<td>Cl</td>
<td>0.015</td>
</tr>
<tr>
<td>CO₂</td>
<td>0.160</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.035</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.145</td>
</tr>
</tbody>
</table>

A high percentage of sodium. Although the basalts bordering the southern part of the basin and the extreme northern part also represent a large proportion of the rocks which border the basin, they have not been subjected to weathering nearly as long and therefore would contribute relatively much smaller amounts of soluble weathering products to the waters of the basin.

The table, however, also shows that a large proportion of the salts derived from basic type rocks are carbonates. The question then arises as to the origin of the carbonate if the basalts have been only slightly decomposed by weathering.
Clarke (5, p. 242) gives three theories to account for the formation of alkaline carbonates in natural waters and soils. The first, which has already been mentioned, is by direct derivation from volcanic rocks. The second method is by the reduction of alkaline sulphates by organic matter and subsequent absorption of carbon dioxide from the air. The third is by the double decomposition of calcium bicarbonate and sodium chloride or sodium sulphate. In the third method, the calcium is thrown down as sulphate (gypsum) or removed as more soluble calcium chloride. This is thought to be the most general method of the three for the formation of alkaline carbonates. It helps to explain the low percentages of chlorides and sulphates present in the deposits at Alkali Lake.

Yet, another possibility for the formation of the sodium carbonate is by base exchange with the sodium released by weathering replacing the calcium of calcium carbonate. The massive, spherulitic rhyolite flow which borders the northern part of the basin contains numerous cavities which have been partially filled with calcite. It is possible, then, for base exchange to occur either in the rock itself (in situ) during very slow decomposition or later on during the passage of the aqueous
solutions through or over volcanic ashes, tuffs, and related rocks.

Possibly the concentration of sodium in the "potholes" has been brought about through the deposition by local springs, two of which are found near the south end of the "pothole" area. If artesian springs are the source, the exceptional purity of the salt can be explained in part by base exchange.

Bateman (4, p. 189) states that the waters of the soda lakes of Nevada, formerly a source of commercial soda, contain about 1/5 each of sodium carbonate and sodium sulphate, and 3/5 of sodium chloride, but that the deposits of hydrated salts consist of nearly 1/2 sodium carbonate and 1/3 sodium bicarbonate, with only a little chloride and sulphate. It would appear from this that the sodium carbonate and bicarbonate were being deposited as salts, while the chloride and sulphate remained in solution.

This process of fractional crystallization seems to be a very plausible explanation of the high carbonate content of the salts in the "potholes" at Alkali Lake, as it would also explain the higher percentages of chloride and sulphate in the efflorescent crust, as this crust is a late product of evaporation. It would also explain the higher ratio of the sulphate and chloride present in
the brines which were sampled by Allison (3, p. 8), the analysis of which has been copied in Table 3, below.

**TABLE 3**

Analysis of Alkali Lake Brine

<table>
<thead>
<tr>
<th>Compound</th>
<th>Amount (grams per kilogram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na₂CO₃</td>
<td>178.02</td>
</tr>
<tr>
<td>NaHCO₃</td>
<td>nil</td>
</tr>
<tr>
<td>NaCl</td>
<td>76.15</td>
</tr>
<tr>
<td>Na₂SO₄</td>
<td>65.09</td>
</tr>
<tr>
<td>K₂SO₄</td>
<td>28.79</td>
</tr>
<tr>
<td>SiO₂</td>
<td>2.89</td>
</tr>
<tr>
<td><strong>Total dissolved solids</strong></td>
<td><strong>347.70</strong> (b)</td>
</tr>
</tbody>
</table>

(a) Saturated brine from a "pothole", taken September 4, 1944.

(b) Determined directly, not a summation.

Allison (3, p. 8) advances the theory that the "pothole" depressions and rims may possibly have originated as artesian spring pits and associated mounds on the lake floor which later were modified by the pressure of crystal growth, by rainwash, and by deflation of dry salts from the rim. The rims which have formed around the "potholes" that contain appreciable amounts of soda can be explained by the pressure of crystal growth.

Another theory was advanced by Melhase (11, p. 9)
who thought that the masses of crystalline salts had assumed the form of inverted cones which grew by surface accretion and that the weight of these conical plugs caused them to sink into the underlying mud "until the apices of the larger ones may be 15 to 20 feet below the surface and the displaced mud forms an elevated rim about each plug".

The mechanics of this theory appears to be extremely doubtful, inasmuch as the specific gravity of the soda is about the same as the specific gravity of the mud, and the soda would be too soluble to allow the mud to become very pasty without re-solution of the sodium carbonate at points of pressure. Also, detailed measurements which were made by Allison (unpublished report), shows that the thickness of soda in the largest of the "potholes" to be less than 6 feet, and that the bottoms of the "plugs" are not conical surfaces but are instead convex surfaces.

In regard to the artesian spring pit theory of origin for "potholes", it should be mentioned that the surface of the soda in the "potholes", except for a fluffy crust, is a foot or so below the general surface of the area. This means that they are about the same level as the water which issues from the two springs at the south end of the area. Apparently a condition of hydrostatic equilibrium exists in the area.
Allison (3, p. 9), Smith (11, p. 213) and Stafford (12, p. 4) noted that sodium carbonate was being brought to the surface through underground seepage, thus bringing about replenishment of the supply in the "pot-holes" which had been excavated. Allison also noted that the water from test holes sunk in the bottom of one of these pits showed a higher concentration of salts after 24 hours than after only one hour. This suggests progressive solution of the salts from the playa muds by upward-moving, comparatively fresh underground waters.

**ECONOMIC FACTORS CONCERNING SODA DEPOSITS.** The soda at Alkali Lake has been owned by the American Soda Products Company through mining claims which they purchased in 1916 and had patented in 1918. In 1916 this company mined some soda from "potholes" at the south end of the area and erected several buildings nearby. The soda was mined and loaded by laborers using picks and shovels. The project was shortly abandoned.

The total available content of the "potholes" has been variously estimated at from 75,000 to 1,250,000 tons of soda. (This latter figure probably includes the widespread efflorescence which covers the playa, the recovery of which would be of doubtful economy.)
Allison (3, p. 11) made an estimate which he based upon the previously mentioned detailed measurements of a one acre tract and slightly less detailed measurements of 28 acres of "potholes". His figure of 75,000 to perhaps 200,000 tons was based on the estimate of 200 to 400 acres as the total area containing "potholes".

With the aid of an enlarged aerial photograph and a field traverse through the main "pothole" area, the writer was able to map this area and to determine that the total acreage was about 150 acres. Another 50 acres was allowed as the maximum probable acreage outside of this main area which would contain "potholes". Using these figures and Allison's figures for the area in which detailed measurements were made, the total quantity of available soda would appear to range from at least 50,000 to possibly 100,000 tons.

The most important factor controlling the economic possibilities of this deposit is the factor of transportation. The nearest railroad is at Lakeview, Oregon, a distance of 60 miles from Alkali Lake. It would be necessary to haul the soda this distance by truck. From Lakeview it would be another 275 miles to Portland, the nearest logical market.

Stafford (17, p. 3) estimated that the total cost
of transportation would be over $8.00 per ton. The market price then was reported at roughly $25.00 per ton delivered at Portland. This would mean that the soda would have to be produced for $17.00 per ton in order that the project could meet present competition from California producers who virtually control the western market at present. As these estimates were made in 1939, likely the present cost of transportation (1947) would be higher, although this may be offset by a higher delivery price.

Probably the soda could be mined with machinery at a cost considerably under this figure. There is to be considered, however, the additional factor of the amount of included mud and earth, which would have to be removed. Allison (unpublished report) estimated the amount of included mud and water to be about 10 or 15 per cent. Unless special care were taken in the handling of the soda, this figure would be increased by pollution with the dirt and mud from outside sources. The problem, then, would be to remove the included material from the soda at a cost which would still allow a profit for the operation. It might be possible, however, to wash the soda with saturated solution of sodium carbonate, in the same manner as common table salt is sometimes washed to
remove impurities.

Whatever the methods that could be devised for the treatment of the "ore", a plant for handling it would be needed. This plant could not feasibly be located at Alkali Lake if much of a water supply is needed, as the known supply at Alkali Lake is very limited, unless the supply could be increased by drilling a properly located well. This possibility should be investigated further. If, on the other hand, the plant were located at Portland, the included foreign material would have to be shipped this distance, which would affect the cost of delivery appreciably. Lakeview might prove to be an ideal location for a plant, as a water supply would be available and the soda would have to be handled there at least once, anyway, as it was transferred from the trucks to the railroad cars.

The other sources of soda in the area are of doubtful economy as they would require special methods of recovery. Some consideration has been given to the "harvesting" of the efflorescent crusts which cover the playas, as reported by Allison (3, p. 4), the proposal envisioning the use of some type of scraper, revolving broom, or suction apparatus, or a combination of these. These crusts contain several tons of soda to the acre, but no definite figure has yet been obtained as to yield
under actual operating conditions. Another possible source under consideration is the brines which occupy some of the "potholes" and occasional pools of water which form on the surface of the playas during wet periods.

HYDROLOGY. No attempt was made to study the Alkali Lake basin with particular respect to the water supply situation. A few details were discovered during the investigation, however, which appear to be worthy of mention.

First, the three springs which emerge along the faults that cut the Alkali Lake playa near the "pothole" area have had a continuous flow during the past few years, which according to the natives of the area have been exceptionally dry years. The largest and most northern of the three springs issues from a hole about a dozen or so feet in diameter, and a number of feet in depth. The depth is not definitely known, but it is probably less than 20 feet, although the writer was unable to touch the bottom with a 10-foot pole. This spring is unusual in that it contains a considerable number of fish (Siphan-jelie bicolor oregonensis) whose ancestors probably inhabited the former lake. The presence of these fish in the spring attest to its permanency, showing that it must have had a continuous flow for many years, or even
millenia, although conceivably they have been planted by
man in fairly recent times.

Likely a well could be properly located and drilled
so as to tap this aquifer and make more efficient use of
the supply which is present. One cannot tell otherwise
whether the springs are being fed by the full capacity
of this aquifer, or are merely tapping a small portion
of the available supply. Probably much of this under-
ground water rises along the faults which cut the under-
lying formations. One important factor is that any
water found by drilling probably would have artesian flow,
thereby removing the necessity for pumping.

Another detail which was discovered is that the north-
erm part of the basin is underlain by a potentially good
water bearing stratum, as shown by the section of pre-
Clarno(?) rocks exposed at Venator Canyon where a basalt
flow and an overlying bed of breccia are both capped and
underlain by rhyolites which are essentially more impervi-
ous rocks. As these strata dip at a low angle to the south-
ward, due to the down-faulting and tilting of the block
which underlies the basin, and the beds appear to terminate
against Grays Butte, the butte north of Alkali Lake, and
the ridge connecting them, the prospects of a water-bearing
structure underlying this part of the basin are very favor-
able. Also, a similar structure may be present in
the lake beds just above the underlying volcanic strata. Of course the underlying strata possibly have been cut by faults so extensively that these faults may allow the water to escape as fast as it arrives. The prospects of finding water in this portion of the basin, however, merit further consideration.

It should be mentioned that the present known water supply is not being utilized to the fullest possible extent. A well was drilled at the emergency landing strip a few miles north of Alkali Lake and water is reported to have been found at a depth of 180 feet. Another well drilled at the site of the former Civilian Conservation Corps camp just north of Grays Butte was able to furnish enough water to maintain a considerable number of men who were stationed there. Three wells that have been drilled near the State Highway Department maintenance station at Alkali Lake furnish an abundant supply for the three families who now live there.

It seems, therefore, that the water supply could be increased greatly. Just exactly how much of a supply could be developed is unknown and would require further investigation, especially through the drilling of a few test wells in properly located places, but the structural setting as a whole is very favorable for an increased recovery of underground water.
APPENDIX

Explanation of Plate XIII.
(Map of "pothole" area)

The map of the "pothole" area, Plate XIII, is essentially a reproduction of an enlargement made from an aerial photograph of the area. The enlargement was made by the United States Soil Conservation Service and is approximately a 5X enlargement. Distortion occurs, of course, due to the fact that the area was not in the center of the photograph, and so the scale shown on the map is not accurate for all portions of it. The scale shown is based upon a plane-table survey made in the summer of 1946, which crossed the "pothole" area, except for the extreme south end, from north to south. It is therefore fairly accurate for that portion of the map.

Several small areas which contain "potholes" are at the south end of the playa but as no aerial photographs were taken of this area and as they are not extensive enough to be considered important, they were not mapped.

Only the larger "potholes" are shown on the map, but they give a fairly accurate picture of the general distribution of the "potholes" throughout the area.
Explanation of Plate XIV.
(Geologic Map of Alkali Lake Basin)

The accompanying geologic map was made with the aid of aerial photographs taken by the Soil Conservation Service in 1939. Ground control was based upon surveys and bench marks established by the U. S. Coast and Geodetic Survey in 1920 and by the State Highway Department in 1931-32, and also upon triangulations made by the writer and Mr. Paul W. Hughes during the summer of 1946.

In the southern part of the map, the southern half of T. 30 S., R. 21, 22, 23, and 24 E., and all of T. 31 S., R. 22, 23 and 24 E. are based upon surveys made by the U. S. General Land Office. Township 30 S., R. 23 E., and T. 31 S., R. 23 E. had been contoured, but several corrections were made by the writer in the field.

Field data for the map were obtained by the writer during the summer of 1946 and the spring of 1947. Only the contacts between the formations along the eastern scarp and between the lake beds and the older formations were located precisely. The extreme inaccessibility of parts of the area prevented compilation of a complete geologic map of the entire basin in the limited time available for field work.


