CELESTITE MINERALIZATION
AT
ENON LAKE, CAPE BRETON COUNTY, NOVA SCOTIA

by

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FRONTISPIECE

View to south of open pit from South Lake.

The sedimentary country rocks are commonly ferruginous maroon in colour.

Celestite ore appears as continuous bed, on which a hammer is seen at upper right corner, underlain by ferruginous calcareous siltstone or ferruginous silty limestone and grey limestone.

ABSTRACT

Drill cores from 80 bore holes were examined at the mine site and studied with thin sections of the ore-bearing rocks in the laboratory.

The celestite deposits occur at the base of the Windsor group which unconformably overlies the Devonian igneous basement complex. Correlation of the several lithounits of the Windsorian reveals abrupt lateral and vertical changes of lithofacies. All celestite mineralization is confined lithologically within limestone or calcareous beds as a few layers or lenses; most is below calcium sulphate or below equivalent stratigraphic horizons although some occurs in limestone interbeds within calcium sulphate. Generally ore in a rock unit occurs more extensively along the flanks of its paleotopographic ridge. Most abundant is bedded celestite, up to 95 per cent by weight and up to 9 feet in thickness; next in importance are open space fillings. Veins or calcareous patches in calcium sulphate are insignificant. No hydrothermal effect was observed around celestite mineralization.

The history of the celestite mineralization at Enon Lake is deduced as follows: During the sedimentation of Windsorian, the evaporation of water in isolated sea bodies led to gradual increase in the concentration of strontium which finally attained saturation point and started to coprecipitate with calcium carbonate, to form bedded celestite. Strontium precipitation with carbonate or silty carbonate attained a maximum just before the brine became saturated in calcium sulphate. In places allochemical limestone was deposited, deformed, and filled by celestite which had been precipitated following the limestone. During diagenesis, some post-depositoinal features were formed.

Future exploration for celestite should concentrate on carbonate or calcareous beds underlying calcium sulphate, or underlying stratigraphically equivalent beds. Along the flanks of paleotopographic highs is more preferable than highs or valleys.

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CHAPTER 1

INTRODUCTION

OBJECTIVE AND OUTLINE OF STUDY

The major problem involved in the study of celestite deposits at Enon Lake, Loch Lomond, Cape Breton is to determine the history of celestite mineralization in an attempt to analyze structural and mineralogical factors which controlled ore localization. Are the celestite deposits of epigenetic origin and restricted to certain stratigraphic horizons by the physical and chemical properties of the horizons? Are the celestite deposits confined to these horizons in the sense that they represent the initial precipitate? Are they the products of diagenetic migration or modification?

Field and laboratory work has been carried out to find answers to these questions.

Field work has consisted of an examination of about 15,000 feet of drill core with emphasis placed on the mineralized zones totalling several hundred feet. Laboratory work has consisted of drawing cross sections and maps of ore grade, and analyzing the fabric and mineral composition of the ore-bearing limestones and evaporites as revealed in thin sections and hand specimens. Qualitative chemical investigations using X-ray fluorescence and X-ray diffraction were employed as needed.

LOCATION OF THE DEPOSITS

The Enon Lake celestite deposit is located on the eastern side of

Enon Lake, Loch Lomond District, Cape Breton County, Nova Scotia. It is 31 miles from Sydney and 9 miles south of the community of Big Pond. Enon Lake is 159 feet above sea level and roughly rectangular, with its long direction northeasterly. It is two miles long and a mile and half a mile wide.

Celestite occurs in the Windsor group of lower Mississippian age, and possibly extends northeast and southwest on the east side of Enon Lake, following the Windsor sedimentary bedding.

The Enon Lake celestite is probably the largest single celestite deposit in the world. The concentrator was started up in 1971 operating on a stockpile of development ore. The average grade of this material was 50 per cent celestite. Mill feed from 1971 development work averaged 60 per cent celestite. It is expected that production will rise to 100,000 tons per year from the 1971 figure of 60,000 tons (Crowell, 1971).

PREVIOUS GEOLOGICAL WORK

A detailed study of the celestite deposits at Enon Lake had not been attempted previously. The celestite deposits were discovered in 1962, by A. D. Hudgins (Crowell, 1971). In 1963 they were indicated on a newly issued map which illustrates the occurrence of industrial minerals in Nova Scotia.

Celestite crystals are generally known as one of the minor constituents of calcium sulphate. N. R. Goodman (1952) found celestite cyrstals in thin sections of gypsum and anhydrite from several areas in Nova Scotia.

Dawson (1855) was the first author to recognize the correlation of the Carboniferous system through the Maritime Provinces. In his "Acadian Geology", he described the Carboniferous system as follows: (Dawson, 1891, p. 129)

> "When fully developed, the whole Carboniferous series may be arranged in the following subordinate groups of formations, the limits of which are, however, in most cases not clearly defined: -
>
> 1. The Upper Coal Formation, containing coal formation plants, but not productive coals.
> 2. The Middle Coal Formation, or coal formation proper, containing the productive coal-beds.
> 3. The Millstone Grit Series, represented in Nova Scotia by red and grey sandstone, shale, and conglomerate, with a few fossil plants and thin coal seams, not productive.
> 4. The Carboniferous Limestone, with the associated sandstones, marls, gypsum, etc., and holding marine fossils, recognised by all palaeontologists who have examined them as Carboniferous.
> 5. The Lower Coal Measures, holding some, but not all, of the fossils of the Middle Coal Formation, and thin coals, not productive: but differing both in flora and fauna from the Upper Devonian, which they overlie unconformably."

The first three units are Upper Carboniferous and the last two are Lower Carboniferous. The lower two units of Dawson's classification are essentially the same as used today under different names. The Lower Coal Measures are the Horton Group and the Carboniferous Limestone is the Windsor Group (Kelley, 1967).

In 1930 and 1931, W. A. Bell described the Grantmire member of the Windsor Group in this area and recognized it as representing a transgressive overlap onto pre-Carboniferous rocks during Lower to Upper Windsor time.

In 1952, N. R. Goodman described Nova Scotian calcium sulphate deposits in detail and concluded that they were laid down from a concentration of sea water in lagoons that were rhythmically replenished with sea water.

L. J. Weeks (1954) conducted a large scale mapping project in southeast Cape Breton Island during the period from 1944 to 1949. The investigation was promoted by the presence of massive lead-zinc-copper ore deposits at Stirling.

Recently the results of various detailed studies of stratigraphy, sedimentation, and depositional history concerning the Windsorian stage in the Fundy Basin have been published by many authors: Stacy, M.C., 1953; Swift, Donald J. P., 1965; Kelley, D. G., 1965, 1967; Belt, E. S., 1965; Shea, F. S., 1966; Moore, R. G., 1967; Howie, R. D., and Cumming, L. M, 1963; Campbell, F. H. A. and Schenk, P. E., 1967; Schenk, P. E., 1967, 1969.

The main contribution by Schenk is the realization of lateral facies changes and cyclic sedimentation of the Windsorian stage due to the depositional and diagenetic environmental characteristics.

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CHAPTER II

REGIONAL GEOLOGY OF THE CELESTITE DEPOSITS

GEOLOGY OF SOUTHEAST CAPE BRETON

The area lies entirely within the Canadian Appalachian geosynclinal province, as does the whole of Cape Breton Island. The rocks of the immediate mining area are Carboniferous, lying unconformably upon a Devonian basement complex of altered igneous rocks.

The oldest rocks in the area, assigned to the Archean, are the Fourchu Group of the East Bay Hill. The name Fourchu is applied to a group of volcanic and sedimentary rocks that lie beneath the Lower Cambrian (?) Morrison River formation. These rocks are well exposed near the village of Fourchu and have been metamorphosed to various degrees. Volcanic breccia and tuff are most common and sedimentary rocks include shale and, more rarely, sandstone or greywacke. Lava flows were noted in a few places. Weeks (1954) reports that the original stratigraphy cannot be observed in Fourchu rocks, and determination of the strike and dip of bedding can be made only on a few narrow bands of bedded sedimentary rocks or water-laid tuffs.

Cambrian rocks, of the Bourinot Group, appear as the oldest rocks in the southeastern part of the Enon Lake area. The rocks of the Bourinot group may be divided lithologically into three classes, which have no stratigraphic significance: the most common are lava flows with their associated pyroclastic rocks; reworked volcanic debris, greywackes with conglomerate and shale are a second class, and orthoquartzites form the third.

LEGEND

PALEOZOIC

PENNSYLVANIAN

▒ Sandstone, shale, conglomerate.

MISSISSIPPIAN

▤ WINDSOR GROUP
Marginal basin beds: conglomerate, limestone, sandstone, gypsum, shale; includes undifferentiated Grantmire formation, conglomerate, sandstone.

▦ Central basin beds: limestone, siltstone, sandstone, shale, gypsum.

∘ HORTON GROUP
Conglomerate, sandstone, siltstone, shale.

DEVONIAN

+ Diorite, quartz diorite, andesite.

▴ Undivided granitic rocks.

SILURIAN OR DEVONIAN (?)

∴ MIDDLE RIVER GROUP
Conglomerate, arkosic sandstone, quartzite.

CAMBRIAN

MIDDLE CAMBRIAN

░ BOURINOT GROUP
Volcanic tuff, breccia; lavas; sandstone, shale, minor greywacke.

LOWER CAMBRIAN

☰ MacCODRUM AND CANOE BROOK FORMATIONS
Shale, claystone.

PROTEROZOIC (?)

▓ MORRISON RIVER FORMATION
Red sandstone, conglomerate; minor white quartzite and grey shale

PROTEROZOIC

≋ FOURCHU GROUP
Volcanic breccia, tuff, lavas; sandstone, shale; chlorite schist.

Fault (defined, approximate, assumed) 〰〰〰 〰 ~ ~
Approximate magnetic declination, 25° 43' W.

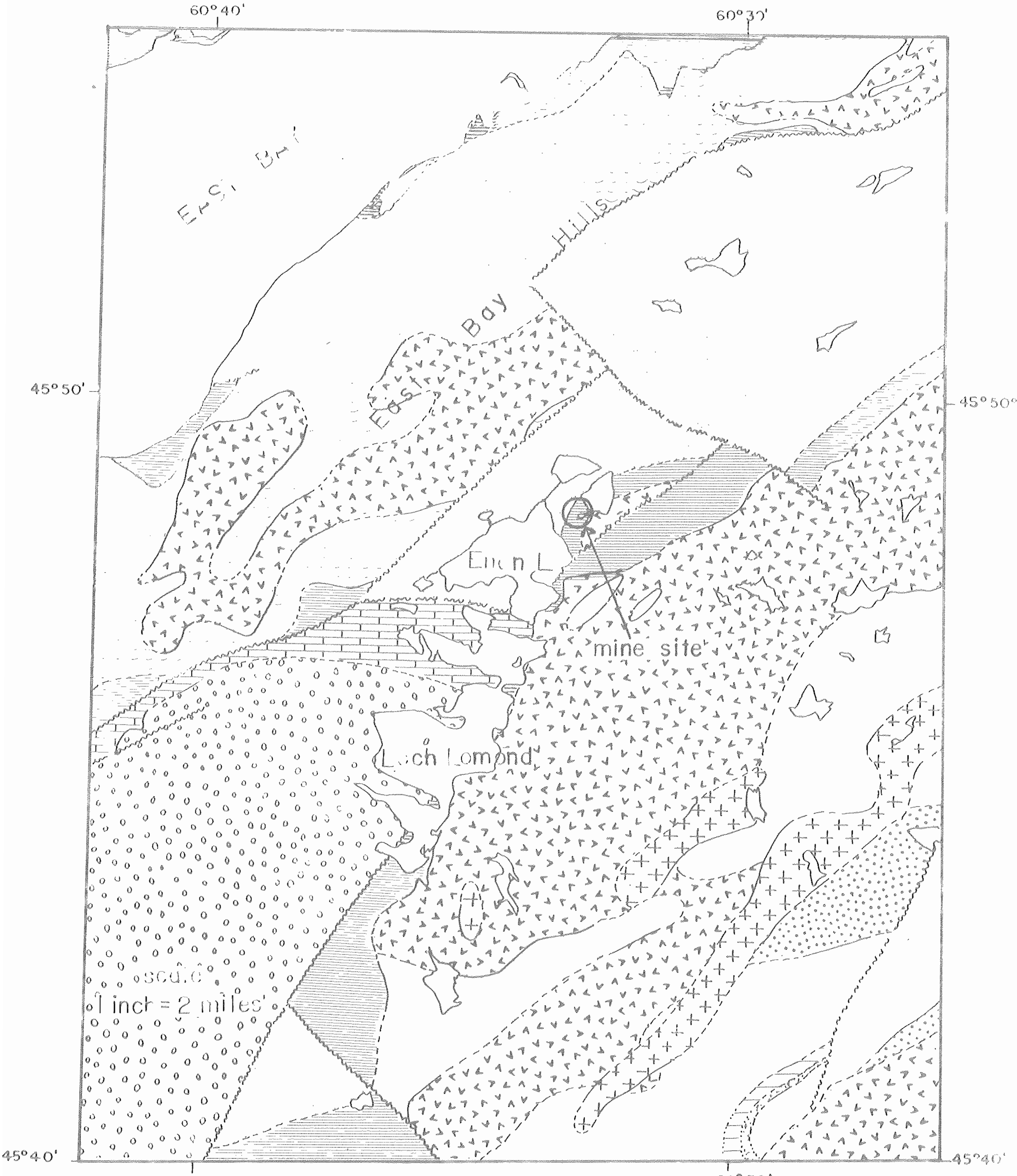


PLATE 1 Geological Map of Enon Lake Area
(from Weeks, 1954)

Rocks of Ordovician age have not been found in the southeastern part of the Island. Silurian or Devonian sedimentary rocks, called the Middle River Group, overlie the Bourinot group unconformably in the southeastern area of the Enon Lake area.

The Devonian rocks in the area are mainly intrusive rocks which are overlain by Mississippian rocks. The intrusive rocks are widespread in the area and range in composition from granite to gabbro; granitic batholiths and stocks are predominant. Weeks (1954) assigned the granitic rocks to a single period of intrusion. In the Lake Ainslie map area, Norman (1935) interpreted the granitic rocks as differentiates of one magma. Samples from the southeastern part of Cape Breton Island were dated at 365 million years by Fairbairn, et al. (1960). However, at least two ages of granite are present on Cape Breton Island, one perhaps associated with the Taconic orogeny, the other with the Acadian. The earliest one has a minimum age of 500 million years (Kelley, 1967).

The Mississippian period in the Maritime Province is represented by two sequences of sedimentary rocks, the Lower Mississippian Horton Group and the Upper, Windsor Group. Mississippian sediments of Cape Breton Island were deposited on the eastern edge of a large basin that from time to time may have occupied many thousands of square miles of eastern Canada. Parts of the Mississippian basin emerged as landmasses at various times. These landmasses were probably ridges that trended parallel to the northeast regional structure. Localized folding and faulting accompanied deposition of the Mississippian, so that both conformable and unconformable contacts exist between the two groups.

Local folding and faulting also resulted in the occurrence of erosion simultaneously with nearby deposition (Kelley, 1967).

The Lower Mississippian Horton group consists of conglomerate, sandstone, siltstone, and shale. Outcrops of the Horton group are widespread southwest of Loch Lomond.

The Upper Mississippian Windsor group consists of thick sequences of massive red siltstone, shale, sandstone, limestone, gypsum, anhydrite and conglomerate, the total thickness approximating 2500 feet. Outcrops of the Windsor group are found as a belt a half mile wide extending northeasterly and southwesterly from the east side of Enon Lake. Another belt of Windsor group rocks is found on the south side of the East Bay of Bras d'Or Lake.

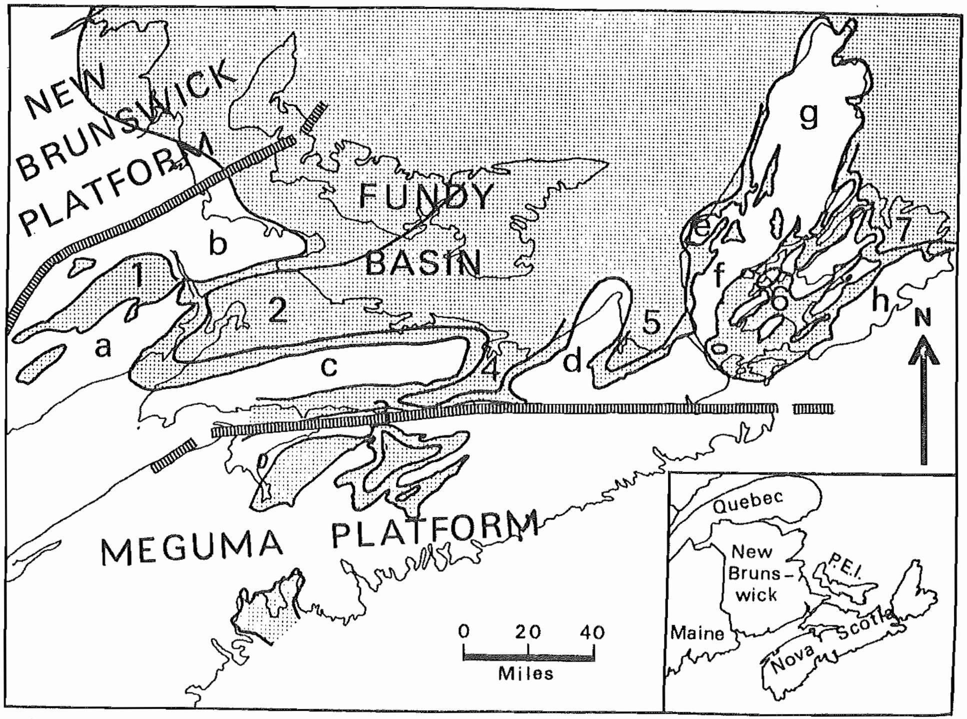


FIG. 1. Location map showing distribution and thickness of the Windsor Group within the Fundy basin—a complex rift-valley system. Structural (bathymetric?) basins are: (1) Moncton; (2) Cumberland; (3) Minas; (4) Stellarton; (5) Antigonish; (6) Bras d'Or; and (7) Sydney. Horsts (source areas) are: (a) Caledonian; (b) un-named; (c) Cobequid; (d) Antigonish–Pictou; (e) Mabou; (f) "Southwest"; (g) "Cape Breton Highland"; and (h) Sydney massifs. Contour lines limiting and within present basins are isopachs of 0 and 2000 ft respectively. (Modified from Howie and Cumming 1963.)

(from Schenk, 1969)

The Maritime Windsor basin, the so-called Fundy basin, of Eastern Canada covered an area now occupied by parts of the provinces of New Brunswick, Nova Scotia, Prince Edward Island, Newfoundland and Quebec, and probably extended to the northeast. "The Fundy basin is subdivided by a number of horsts, each of which served at some time as the source for most of the very thick Carboniferous succession in the intervening linear sub-basins" (Schenk, 1969. See Figure 1).

"The land area of what is today the eastern part of Cape Breton Island probably had considerable relief during deposition of the basal limestone of the Windsorian. This is indicated by the coarseness of the conglomerate both beneath and correlative with the basal Windsor limestone along the edge of the Horton basin" (Kelley, 1967).

Enon Lake is situated on the extreme eastern margin of the Bras d'Or sub-basin of the Windsorian Fundy basin. The sedimentary sequence containing the celestite deposits of the area contains the extreme marginal sedimentary deposits in that sub-basin. This is also suggested by the sedimentological qualities and irregularities: the absence of the Windsorian basal limestone (subzone A and possible subzone B, as defined by Bell, 1929), the thick coarse conglomerate, appreciable topographical relief of the basin bottom, the rapid lateral changes in the rock units, and the small scale overlap.

Sedimentary rocks of Pennsylvanian age occur in the northeast part of Enon Lake. The Pennsylvanian rocks consist of sandstone, conglomerate, grit, shale and coal.

Rocks of Permian age are not found in the area.

The rocks in the area have undergone several periods of folding and deformation. The earliest period of folding followed the Taconic orogeny at the close of the Ordovician and deformed the Fourchu group and later Cambrian beds. Intense regional deformation occurred again during the Acadian orogeny, of probable Lower and Middle Devonian time. Finally, the youngest of which we have any record is the orogeny, believed to be the Appalachian, that deformed the Carboniferous beds of the region. There was also extensive erosion, producing peneplanation, probably by the end of the Cretaceous.

The faults of the area do not cross on the entire region. There is no direct evidence to support the existence of faults of earlier age than those accompanying the Acadian orogeny, although it is possible that such are covered by later deposits. The faults may be grouped into three: those that affect Middle River beds but do not disturb Carboniferous strata and believed to be connected with the Acadian orogeny; the L'Ardoise thrust block, which affects Carboniferous strata; and block faults that also affect Carboniferous beds (Weeks, 1954).

The last phase of the geological history in the area is concerned with the outstanding effects of Wisconsin glaciation, fluvial and lacustrine deposits. In the lowland these Pleistocene and recent unconsolidated materials are as thick as 50 feet.

CHAPTER III

GEOLOGY OF THE MINE AREA

SUMMARY

The celestite deposit that is being mined occurs at the base of the Windsor group which unconformably overlies the Devonian igneous basement complex. The basement complex at the mine site consists of altered granitic and dioritic rocks. Its surface was rough and rocks of the basement were invaded by some thin diabase dikes.

At the mine site, which is 1,600 by 2,600 feet, 80 bore holes were logged during the summer of 1970. No bore holes cut the Horton group; instead they penetrate directly from the Windsor into the igneous basement beneath.

The Windsor group in the mine area generally has conglomerate immediately over basement. The basal conglomerate varies from 0 to 32 feet in thickness and consists of fragments of the igneous rocks which occur below the conglomerate.

The bulk of the Windsor group is limestone, conglomerate, siltstone, gypsum and anhydrite. The stratigraphic section of the mine area has been subdivided into several lithologic units: Siltstone and Limestone, Upper Conglomerate, Middle Limestone, Calcium Sulphate, Middle Conglomerate, Lower Limestone, Basal Conglomerate and Basement. (See cross sections I, II, III, IV, V and VI). The thickness of the Windsor group at the mine site ranges up to 510 feet in core. Some core logs are given below.

The lithologic facies change very rapidly laterally. It is the general trend that the conglomerate facies changes, laterally as well as vertically, to siltstone facies with an intermediate facies of sandstones. In places, tens of feet of conglomerate in one diamond drill hole are almost absent in another only 200 feet away and limestone appears instead. These facies changes in clastic sedimentary beds reflect the paleoenvironments in the basin in which they were deposited and the source area from which the sediments were derived. The evaporites, gypsum and anhydrite, reflect evaporation from a restricted basin.

Celestite, limestone, calcareous siltstone, conglomerate, gypsum and anhydrite are interrelated in their occurrence in the Windsor group.

The celestite deposits appear as bedded forms in the Lower Limestone, the Calcium Sulphate and the Middle Limestone and also show post-depositional features such as vug fillings and veins. The celestite deposits extend for a distance of over one mile to the south of Lake Uist and possibly much further.

DESCRIPTION OF ROCK UNITS

BASEMENT

Out of 72 bore holes (DDH 26 to 98) which were available during the summer of 1970, 32 had been drilled to the basement.

Diamond Drill Hole Number 85
Location: 16 + 00 W, 10 + 00 N.
Collar Elevation: 176.6 feet.
Completed Depth: 388 feet.

Depth, ft.

Overburden

from	to	
0	61	Overburden; pebbles of pinkish granite, greenish granite, limestone, siltstone.

Siltstone and Limestone

61	64.5	Siltstone, light green, calcareous, interbedded with thin green shale.
64.5	66.5	Conglomerate consisting of fragments of granite, syenite and some greenstone.
66.5	77	Dolostone, grey.
77	91	Silty limestone, ferruginous, vugs lined by calcite, trace of galena.

Upper Conglomerate

91	93	Conglomerate, light green, calcareous.
93	95.3	Siltstone, calcareous, greenish grey.
95.3	104	Conglomerate, calcareous.
104	111	Siltstone, calcareous.
111	116	Conglomerate, calcareous.
116	119.2	Dolostone, grey.
119.2	190	Conglomerate, calcareous, ferruginous, maroon and greenish, with interbeds of siltstone and trace of celestite.
190	197.4	Siltstone, ferruginous, calcareous.
197.4	200	Conglomerate, calcareous.
200	211	Brecciated dismicrite with interstices filled by ferruginous and greenish siltstone.
211	244	Conglomerate, ferruginous matrix predominant downward, occasionally calcite forming matrix.

Middle Limestone

244	254.4	Brecciated dismicrite filled by ferrugionous siltstone, grey, fossiliferous.
254.4	258	Conglomerate with a matrix of ferruginous siltstone. (This apparently is a small local patch of conglomerate; it is not found in adjacent holes.)

Depth, from	ft. to	
	Calcium Sulphate	
258	261.3	Gypsum, white to grey, massive, calcareous cryptocrystalline.
261.3	266.3	Celestite ore zone, dark reddish, calcareous, 62 per cent celestite.
266.3	282	Siltstone, dark grey and ferruginous, with 10 per cent interbeds and veins of gypsum.
282	290	Gypsum, silty; gypsum 80, selenite 5, anhydrite 5, and silt 10 per cent.
290	295.5	Anhydrite, white, with rosettes of grey selenite, 15 per cent; 294.5 to 295.5, celestite 13 per cent.
295.5	297.5	Anhydrite 50, gypsum 20, selenite 2, celestite 13, and hematitic materials 15 per cent.
297.5	299	Anhydrite, celestite 13 per cent.
299	303	Mixture of anhydrite, dark brown gypsum, hematite, trace of limonite; anhydrite 30, gypsum 30, celestite 13, and hematite 27 per cent.
303	305	Anhydrite with rosettes of selenite.
305	307.6	Gypsum, cryptocrystalline, with a minor amount anhydrite and hematite.
307.6	310.7	Ochre with varying amounts of gypsum, selenite and anhydrite; celestite 12 per cent.
310.7	317	Gypsum, cryptocrystalline, with 10 per cent anhydrite; 315.0 to 317, celestite 12 per cent.
317	320	Ochre with 25 per cent of gypsum, celestite 12 per cent.
320	322.4	Gypsum, anhydrite and hematite, 60 to 65, 10 to 20, 5 to 8 per cent respectively; minor celestite.
	Lower Limestone	
322.4	323.4	Ochre; celestite 20 per cent.
323.4	369	Biodismicrite to biopeldismicrite, buff to grey, stylolitic, with trace of galena and chalcopyrite; abundant calcite as vug fillings; celestite as follows:

from 323.4	to 324.8	32 per cent
324.8	328.1	13.6
328.1	336.9	4
336.9	339.9	17.6
339.9	343.6	24
343.6	351.5	9
361.0	369	7

Depth, from	ft. to	
	Basal Conglomerate	
369	385	Conglomerate, pebbles of granite, syenite, greenstone, hornblende syenite etc. with a matrix generally of fine-grained rock fragments, sand and silt; silty partings.
	Basement	
385	388	Basement; hornblende syenite, brecciated ferruginous.

Diamond Drill Hole Number 63
Location: 8 + 00W, 2 + 00S.
Collar Elevation: 199.1 feet.
Completed Depth: 242 feet.

Depth, from	ft. to	
	Overburden	
0	58	Overburden
	Siltstone and Limestone	
58	61	Limestone, white to grey; shale partings.
61	67	Siltstone, ferruginous.
	Upper Conglomerate	
67	90	Conglomerate, with pebbles from 0.2 to 2 inches, composed of syenite, diorite, granite, limestone, in a matrix of siltstone and calcite.
90	120	Siltstone, calcareous, ferruginous, with interbedded limestone; 5 per cent of small igneous pebbles.
	Middle Limestone	
120	123	Limestone, crumpled.
123	127	Siltstone, ferruginous, calcareous.
127	128	Limestone, crumpled.
128	147	Siltstone, calcareous. Celestite at 145 feet, 2 inches thick, 50 per cent.

Depth, from	ft. to	
	Lower Limestone	
147	174	Limestone, biodismicrite, dark grey, partly hematitic. Trace of celestite, 3 per cent.
174	186	Limestone, biodismicrite, carbonaceous, black. Celestite, 179.5 to 180.5 feet 10 per cent, at 183 feet, 3 inches thick 10 per cent.
	Basal Conglomerate	
186	196	Conglomerate.
196	202	Siltstone, calcareous, ferruginous.
202	206	Conglomerate.
	Basement	
206	208	Granite.
208	213	Diabase.
213	242	Granite.

The basement complex at the mine site consists of granitic and dioritic rocks which have been intensely altered. Rocks of the basement were invaded by some thin diabase dikes.

The granitic rocks range in colour from pale pink and greenish pink to grey, and in composition from granite to granodiorite. There is also a rock which closely resembles rhyolite. No contact between rhyolitic rocks and granitic rocks was observed but, in composition, a gradual change from granite through porphyritic granite to rhyolite was noticed. In places, granitic porphyry gradually changed to rhyolite and some granite contains sparse small phenocrysts. This might suggest that rhyolite is a marginal chill phase of the granite.

The granite is commonly medium-grained with abundant visible quartz. There are minor amounts of biotite, chlorite, epidote, pyrite, hematite, and limonite. The rock is so intensely altered to fine-grained micaceous mineral that it is difficult to determine the composition of feldspar. There is about twice as much K-feldspar as plagioclase, which is mainly oligoclase.

The rhyolite varies considerably in grain size with phenocrysts of feldspar and quartz, which are seen in thin section to be up to 4 millimetres in a groundmass of between 0.1 and 0.2 millimetres in size. All the feldspars are altered to sericite, muscovite, quartz and calcite. Quartz crystals show very irregular boundaries with the groundmass and show rounded surfaces instead of crystal faces.

According to Weeks (1954), "Rosiwal analyses of medium-grained granite and the coarsest rhyolite obtainable in southeastern Cape Breton Island indicate a remarkable similarity in composition, the notable differences being an increase of quartz and decrease of mafic minerals in the rhyolite, as indicated in Table 1."

Table 1.

(from Weeks, 1954)

Comparison of Rosiwal Analyses of Granite and Rhyolite

Rock	Quartz	K-feldspar	Plagioclase	Other minerals
	Per cent	Per cent	Per cent	Per cent
Granite, Enon	18.2	46.6	25.4	10.3
Rhyolite, Big Glen	25.0	46.9	26.5	1.7

Diorite, gabbro, and their fine-grained equivalents, are less widely distributed. The rocks range from greenish grey to nearly black. Diorite is fine to medium grained. Thin sections show that the plagioclase has been considerably altered to a fine-grained micaceous mineral (sericite?). The gabbro is a dark grey to black rock, and consists mainly of hornblende, in crystals up to one and a half millimetre long, and plagioclase in laths a half millimetre long.

Diabase dikes cut the basement complex, and possibly intruded Windsorian sedimentary rocks too. Diabase was not found in Windsorian sedimentary rocks in the mining area, but highly metamorphosed limestone pebbles in the conglomerate suggest that possibly some of the dikes may be Windsorian or post-Windsorian and may have produced metamorphism of the Windsor limestones. It is also possible that the pebbles may be George River limestones. Some contacts between diabase and granite contain ferruginous fault gouge which can be traced upward to Windsorian sedimentary rocks. The fault gouge does not show contact metamorphism and indicates that the faults formed along the contacts. These small faults are probably subsidary to the main northeasterly fault system which appears east of Enon Lake.

Celestite, as lenticular veinlets, was observed in thin sections of granite. Many fractures are developed in altered granite and filled by iron oxides. Celestite followed such a fracture discontinuously.

BASAL CONGLOMERATE

In the Enon Lake area the basal member of the Windsor group is represented by a maroon and greenish conglomerate unit which overlies pre-Carboniferous basement. In places, arkose sandstone beds are interbedded in the conglomerate. The thickness of this basal conglomerate ranges up to 32 feet and is dependent on the topography of the basement upon which it was deposited. The thicker parts of the basal conglomerate occur as the filling of small hollows in the basement surface. Some of the higher spots on that surface were not completely buried by the conglomerate and in these areas, the Lower Limestone was deposited directly upon the basement.

The term Grantmire Formation was first used by Bell (1938) to designate a basal member of the Windsor group and was defined as thick deposits of conglomerate which lie below marine limestone or sandstone of lower Windsor age and form the base of the series. Because this definition restricts the use of the term, Weeks (1954) redefined the Grantmire as a formation comprising all Windsor Conglomerate members that form the base of the group, regardless of whether they are lower or upper Windsor in age.

According to the definition of Weeks, the unit here called the Middle Conglomerate also can be called as Grantmire where the Middle Conglomerate was deposited directly on the basement. In order to avoid confusion, the term Grantmire is not employed here, but the conglomerate is called Basal, Middle or Upper Conglomerate within the mining area.

Fragments in the conglomerate consist of granite, quartz porphyry and diabase. They vary from 3 mm to 60 mm in size. They are mostly subangular or subrounded but some rounded fragments are also observed. Sparse disseminations of pyrite, chalcopyrite, and galena are observed in the fragments. The sulphides generally occur in fine-grained granite and fine grained diorite pebbles. Pyrite was observed in the matrix, but not chalcopyrite or galena. The matrix of the conglomerate is maroon and greenish white siltstone and sandstone. In places celestite appears as a cementing material in sandstone and conglomerate.

LOWER LIMESTONE

Lower Limestone is the main host rock of the celestite mineralization. Lower Limestone overlies Basal Conglomerate and underlies Calcium Sulphate or Middle Conglomerate. The thickness of Lower Limestone varies from place to place and reflects paleotopography of the depositional basin. The thickest deposits are in former hollows and deposition gradually buried the higher parts of the bottom of the basin. The maximum thickness of Lower Limestone so far found within the mine area is 100 feet, measured in bore hole 73.

Lower Limestone may be divided into several different facies: silty micrite, silty dismicrite, sparite, pelsparite, silty pelsparite, biopelsparite, calcareous siltstone. They change vertically, laterally and gradually or abruptly into one another.

Generally, the upper half of the Lower Limestone is composed of silty micrite, and a considerable amount of high grade celestite ore occurs as layers in this upper silty micrite. Celestite mineralization in the lower part of the Lower Limestone occurs mostly as lower grade open-space-fillings. Biopelsparite is the most important host rock for celestite mineralization of this latter type.

Celesite mineralization will be discussed in more detail in later chapters.

MIDDLE CONGLOMERATE

The Middle Conglomerate contains fragments of diorite, granite and limestone in a ferruginous silty matrix. Fragments range up to 60 mm in size. Maximum thickness of Middle Conglomerate so far found within the mine area is 49 feet, measured in bore hole 70.

In places, celestite mineralization occurs as open-space-filling and disseminations, up to 4 to 5 per cent, in the conglomerate. Disseminations of chalcopyrite and pyrite are also observed.

Stratigraphic relations between Middle Conglomerate and Calcium Sulphate are complicated. (See Plate 2.) In Cross Section II, Middle Conglomerate appears as a marker bed and can be followed as a distinct conglomerate from hole 38 to hole 74. Thereafter it grades into sandstone in holes 68 to 54 and it pinches out before reaching hole 69. The Middle Conglomerate directly overlies igneous basement at bore hole 38. Between holes 39 and 54, it overlies Lower Limestone and underlies Middle Limestone. At bore hole 19 where the Middle Conglomerate is absent, the Calcium Sulphate appears between Basal and Middle Limestone. In Cross Section I, conglomerate is present in hole 34 (in the eastern part of the section) and it grades into the same sandstone noted above in hole 54. Eastward, it again pinches out. It appears, then, that the Middle Conglomerate forms a narrow band, trending northward with its western margin near holes 39, 74 and 34, and with the eastern margin marked by holes 38, 78 and near 28. (It is missing from hole 33, where it should appear in the overburden. Core from hole 16 was not preserved.) In Cross Section V, a conglomerate appears in holes 47, 93, and 48, but apparently grades into a thin sand in hole 44. This conglomerate ends against a basement high to the north. Although it is the second conglomerate above the basement, it is probably not the equivalent of the Middle Conglomerate as described above. In hole 44, the thin sand which is its equivalent is about 20 feet below the Middle Conglomerate.

CALCIUM SULPHATE

General Statement

Gypsum deposits have been known in the Windsor formation in Nova Scotia from the time of the earliest settlers. Although the commercial use of the Windsorian gypsum was first prophesied by Richard Smith and Richard Brown in 1829, little detailed geological or mineralogical work had been done on them until Goodman investigated individual occurrences in 1952.

It is possible that sulphate might have a genetic inter-relationship, syngenetically or diagenetically, with the celestite deposits. For this reason, origin of the Windsorian evaporite requires a careful study in more detail.

Genesis of Nova Scotia gypsum

Goodman (1952) modified the generally accepted view concerning the origin of the gypsum beds. He concluded that calcium sulphate deposits were laid down from concentrated sea water in lagoons which were rhythmically replenished with marine waters. This cycle deposited alternating limestone and calcium sulphate. The temperature of the water in the lagoons, or at the bottom of the lagoon, was sufficiently high for anhydrite to be the stable form. With the removal of the lagoonal waters the high temperatures could not be maintained and the upper horizon was rapidly altered to gypsum by the action of the connate waters trapped by the deposited anhydrite crystals. Subsequently the deposits were subjected to, and deformed by, the several periods of diastrophism which were operative in Nova Scotia since the deposition of the Windsor

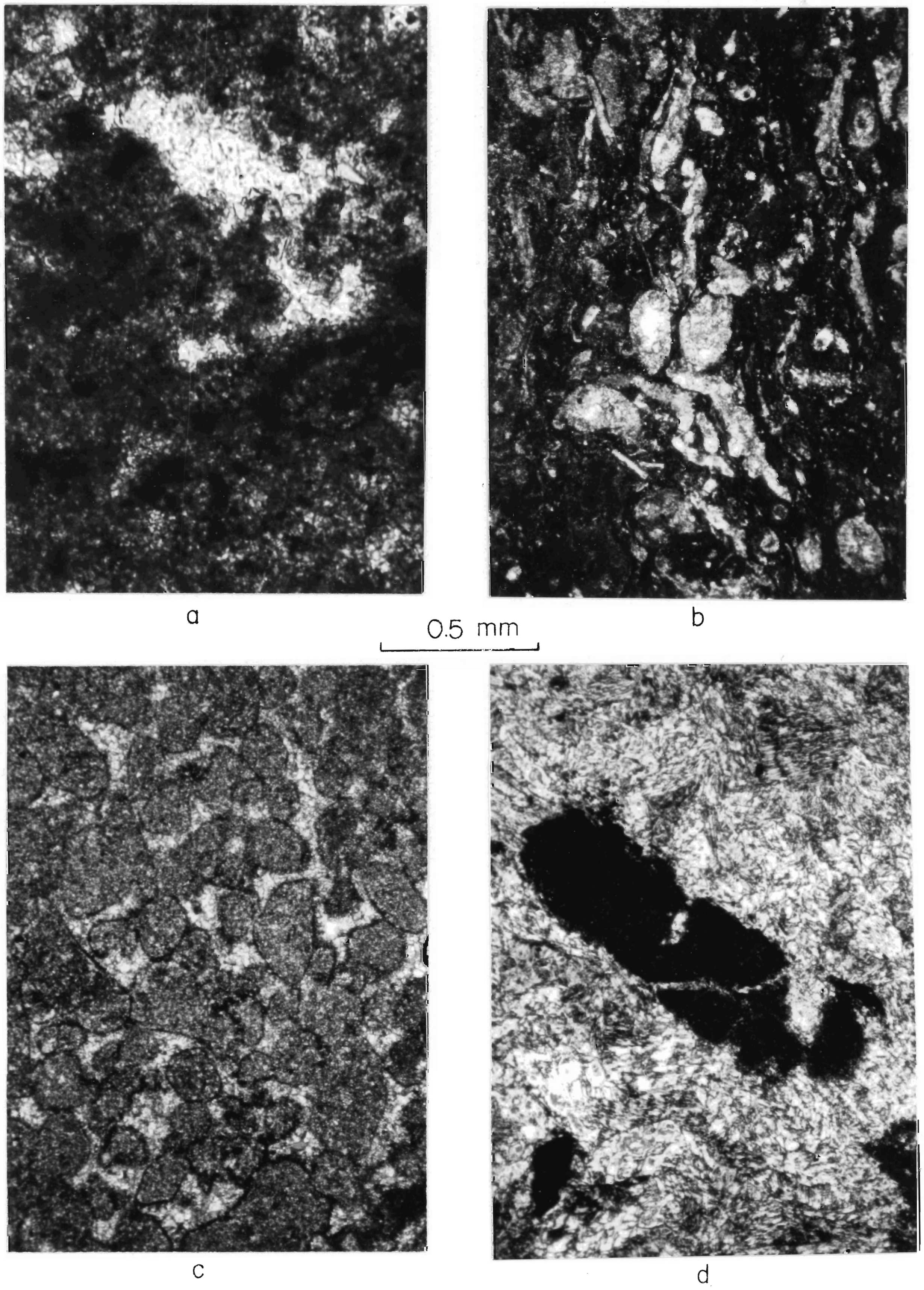
a. Photomicrograph of dismicrite. Sample S-310, DDH 75, 296 feet, Lower Limestone. Microcrystalline limestone (micrite) has been disturbed and the resulting openings are filled with irregular "eyes" of sparry calcite.

b. Photomicrograph of biomicrite. Sample S-87, DDH 57, 245.5 feet, Lower Limestone. Fossils are replaced by clear secondary calcite.

c. Photomicrograph of pelsparite. Sample S-108, DDH 59, 86.5 feet, limestone fragment in Upper Conglomerate. Constituent pellets are coated by limonite and hematite and contain some recrystallized calcite.

d. Photomicrograph of gypsum and calcite in it. Sample S-61, DDH 57, 182 feet, Calcium Sulphate. Fibrous alabastrine secondary gypsum replaced calcite along the boundary. Calcite is also broken and traversed by gypsum.

Plate 17


a
0.5 mm
b
c
d

evaporite beds.

Schenk (1969) argued that calcium sulphate is mainly diagenetic and supratidal, precipitated within, not on, subaerial salt flat carbonate from brine drawn from the lagoon, heated under the black algal mats, and evaporated beneath the hot arid salt flat.

Goodman and Schenk concerned themselves with the Windsorian evaporite throughout Nova Scotia, though Schenk's data were based mainly upon detailed study of a few localities. In the Enon Lake mining area, the evaporite may have features that are local and not present elsewhere in Nova Socita, such as the relation to the celestite deposits which occur below or within the evaporite sequence. Because the investigation on the evaporite is restricted to the mining area, the results of this study might not be applicable to evaporite of other areas.

Description of the Unit

Beds of gypsum, selenite, anhydrite, gypsiferous siltstone and ochre make up the impure Calcium Sulphate unit. Pure gypsum or anhydrite, however, is observed in places at the middle of the Calcium Sulphate unit, as shown in Plate 18. Near the upper and lower limits of Calcium Sulphate, the amount of impurities due to silt and/or ochre increases, while the middle part of the Calcium Sulphate unit is generally nearly pure. Minor amounts of gypsum are also observed as nodules and veinlets near the Calcium Sulphate unit in the Lower Limestone and Middle Limestone.

Thin limestones and calcareous siltstones are in many places interbedded in Calcium Sulphate. Some of them are mineralized. Northwestward

a. Photograph of ochre, anhydrite and impure gypsum. DDH 85, around 280 feet. From right: 1st core - hematite-limonite ochre zone with white anhydrite, 2nd and 3rd cores - white cryptocrystalline anhydrite with rosettes of selenite, 4th core - impure silty gypsum with secondary gypsum veins.

b. Photograph of ferruginous siltstone and secondary gypsum with relics of anhydrite. DDH 85, around 310 feet. From top: 1st core - impure gypsum, ferruginous, calcareous, silty, 2nd core - secondary gypsum showing relics of primary anhydrite, 3rd and 4th cores - ferruginous silty limestone containing secondary gypsum veins. Pale blue celestite grains are also disseminated in 4th.

* Note: these cores are as they normally occur.

Plate 18

a

b

the thickness of one interbedded limestone increases and around bore holes 82, 85, 92 and 89 interbedded limestone and calcareous siltstone divide the Calcium Sulphate into two separate layers. The thickness of the interbed ranges up to 19 feet. In part it is highly mineralized.

In places a few ferruginous beds are observed at the base of the Calcium Sulphate. These are not continuous but they are mineralized. Some nodules or patches of celestite are also found in the evaporite sequence.

Thickness of evaporite is variable and reflects the bottom topography of the evaporating basin. The maximum thickness of evaporite is measured as 120 feet at bore hole 57.

Generally, the evaporite bed can be divided into three parts: upper gypsum, middle anhydrite, lower gypsum as seen in cross section III. In places the boundary between the parts is nearly parallel to the surface of the evaporite, but generally it is irregular. In some bore holes, such as 70 and 50, the middle anhydrite bed is absent and anhydrite appears as a minor constituent in the gypsum.

Gypsum of the upper gypsum bed varies from white or grey to pink in colour. Under the microscope, gypsum appears as fibrous alabastrine secondary gypsum with an average length of 0.03 mm. Cloudy intergranular superindividuals are often observed with an average size of 1.5 mm by 0.4 mm made up of aggregates of fine fibrous grains, 0.01 - 0.02 mm long. Boundaries among superindividuals are not always distinguishable.

The amounts of middle anhydrite in the evaporite range up to about 70 per cent, as in bore hole 97. Rocks shown in cross section III contain a higher percentage of anhydrite in the evaporite than do those shown in cross section I.

Anhydrite, under the microscope, shows a mosaic texture of interlocking subhedral to anhedral grains having stumpy rectangular or lath-shaped habit. Anhydrite varies from 0.03 to 0.05 mm in size.

Gypsum of the lower gypsum bed is similar, lithologically and texturally, to that of the upper gypsum bed.

Anhedral calcite particles and rhombs of dolomite crystals are disseminated in calcium sulphate in many places. Subhedral and anhedral celestite grains, 0.2 - 0.3 mm in size, were also observed. Many are traversed and broken by calcium sulphate.

In places gypsum and anhydrite are much contorted.

Impure Calcium Sulphate overlies Lower Limestone in the west half of the mining area, but eastward the Middle Conglomerate intervenes and evaporite is absent finally in the east half of the area. The Calcium Sulphate underlies Middle Limestone. Paleotopographic map of Calcium Sulphate basin and isopach map of total calcium sulphate are seen in plate 14 and 15. The Evaporite may extend further to the northwest.

Although the bottom topography of the evaporite beds is irregular, the surface topography of the evaporite generally appears as a flat surface with a dip of about 10° NW and a strike of N 16°E. This surface can be considered as a paleo-horizon in the evaporite basin.

MIDDLE LIMESTONE

Middle Limestone overlies Calcium Sulphate in the west half of the mining area. Eastward, the Middle Conglomerate intervenes and finally Middle Limestone overlies Middle Conglomerate in the east half of the area where Calcium Sulphate is absent. Middle Limestone underlies Upper Conglomerate. The thickness of Middle Limestone ranges up to 55 feet.

Middle Limestone may be divided into a few different limestone facies: dismicrite, silty dismicrite, biodismicrite, biomicrite and pelsparite. In places siltstone and hematitic ochre occur as interbeds in the limestone. Partly they are continuous but generally they change abruptly into other facies vertically and laterally.

Middle Limestone contains celestite mineralization near the base; silty dismicrite is the predominant host rock for such mineralization. These are relatively higher grade ores. The thickness of the mineralized zone ranges up to 14 feet, but the ore is much less continuous than ore in Basal Limestone. Ore distribution in Middle Limestone is seen on Plate 12 and in the cross sections. It appears as lenticular bodies.

UPPER CONGLOMERATE

Upper Conglomerate overlies Middle Limestone and underlies Siltstone and Limestone. The thickness of Upper Conglomerate increases westward and ranges up to 150 feet, while eastward the Upper Conglomerate has been thinned by recent erosion and is overlain by overburden. Bore holes 28 and 27 on the eastern margin of the area do not contain Upper Conglomerate. Basement topography is no longer reflected in the deposition of the Upper Conglomerate.

Conglomerate contains chiefly subrounded to subangular fragments of granite, syenite, and siltstone. Either a light greenish or a ferruginous siltstone forms the matrix. Siltstone also appears as thin interbeds in the conglomerate. In places calcite cementing is observed. Downward, the amounts of limestone fragments increase. Brecciated limestone is also interbedded.

A few celestite-bearing fragments are observed, and are thought to be derived from earlier mineralization of limestone; practically no epigene celestite mineralization is believed to have occurred in Upper Conglomerate.

SILTSTONE AND LIMESTONE

Around bore holes 85, 92 and 95, Upper Conglomerate is underlain by a formation of alternating greenish and maroon siltstone and grey to black limestone. The thickness of the siltstone and limestone unit ranges up to 170 feet at bore hole 91, but, due to erosion, the true thickness of this formation is not preserved anywhere.

Thin conglomerate and dolostone layers are interbedded in the unit. Argillaceous partings are frequently observed in black limestone. Part of the limestone is crumpled.

In places, argillaceous limestone contains trace amounts of galena as disseminations; in some other places small amounts of galena occur as lining of vugs.

Throughout the investigation of the Windsorian sedimentary rocks at the mine site, a few metamorphosed limestone pebbles are found in conglomerates and a few discontinuous dolomite lenses in a few places, but no metamorphic effect was observed. If siltstone or limestone were slightly metamorphosed by low temperature hydrothermal solution, such minerals as chlorite, sericite, or epidote would be expected; no such minerals are observed however.

CORRELATION OF UNITS

Cross Section I was drawn along the bore holes 79, 77 ....34, 28, and 27 so that it reveals a vertical profile along the dip direction of the sedimentary bedding. Overburden, Siltstone and Limestone, Upper Conglomerate, Middle Limestone, Calcium Sulphate, Middle Conglomerate, Lower Limestone, Basal Conglomerate, Basement and their stratigraphic relations are displayed. Because it is believed that the Calcium Sulphate was laid down as evaporite in sea water isolated in a lagoon, that unit must have been originally nearly horizontal. Accordingly, it has been used as a datum surface in correlating the drill hole data.

The lateral changes of lithofacies are abrupt. Thickness of each rock unit is also variable, reflecting basement relief; generally, thicker sediments accumulated in the hollows of the basement. Deposition of

Calcium Sulphate is found only in a valley or basin of basement. Bore hole 73 at the bottom of a valley contains 80 feet of Lower Limestone, whereas bore hole 77 along the flank of a hill, 400 feet away to the west, shows only 8 feet of Lower Limestone. Influence of the basement relief on the sedimentation was continued through deposition of the Middle Limestone, and then the relief became too small to be reflected in the Upper Conglomerate.

Bore holes 77 and 75 are located on the flank of a basement ridge with a slope of 12°, dipping eastward. The difference of basement elevation between them appears as much as 44 feet. This slope continues to the bottom of a valley at bore hole 73 with a consistent gradient. On the other hand, the general trend of bedding from bore hole 28 to bore hole 77 shows a dip of 10° sloping westward.

The Upper Conglomerate and the surface of the Calcium Sulphate also show a dip similar to that of the general mineralization trend. (If the Calcium Sulphate originally had a nearly horizontal surface, then the dip is post deposition, and the flank of basement along the bore holes 79, 77, 75 and 73 had a still steeper dip during the deposition of Windsorian sediments than it now does.)

Cross Section II reveals a vertical profile parallel to the strike direction of sedimentary bedding along the bore holes 38, 39.........54 and 69, which contain no calcium sulphate. In this section the thickness of the Middle Conglomerate is generally uniform, though the conglomerate thins to the northwest.

CHAPTER IV

STRUCTURAL AND STRATIGRAPHIC CONTROL OF ORE

GENERAL STATEMENT

In the mining area the celestite deposits occur at the base of the Windsor group, where major ore occurs as flat lenses in particular stratigraphic units. One hypothesis is that the celestite deposits are no more than strontium sulphate precipated chemically from an isolated body of sea water, or lagoon, and that their localization was controlled by the particular paleobasin and its bottom topography. An alternate hypothesis argues that the celestite deposits were introduced to a particular stratigraphic range which was favourable structurally, lithologically and chemically for the precipitation of celestite from strontium-bearing solutions. These arguments led the author to analyze the relations between ore localization and the structure and stratigraphy.

In order to test for paleoenvironmental, structural, or stratigraphic controls on ore localization in the area, some ore distribution maps and sub-surface structure contour maps have been drawn.

DISTRIBUTION OF CELESTITE

First of all, the total amounts of $SrSO_4$ from each bore hole were measured and plotted as thickness on a bore hole map. This figure can be interpreted as the thickness that would be present if all the celestite actually in the interval were concentrated into a layer of pure celestite.

The chemical data for $SrSO_4$ content were obtained from the mine office and modified after microscopic observation. (See Plate 2).

An example of the calculation of $SrSO_4$ is given below:

Table 2.

An example of the calculation of $SrSO_4$ for Ore Distribution Map

DDH 74

from	to	$SrSO_4$		thickness	
122.3 ft.	126.0 ft.	4.8/100	x	3.7 ft.	= 0.18 assay-ft.
126.0	129.0	8.0/100	x	3.0	= 0.24
129.0	132.0	74.0/100	x	3.0	= 2.22
132.0	135.0	57.0/100	x	3.0	= 1.71
135.0	138.0	60.0/100	x	3.0	= 1.80
					6.15

It should be noted that the total ore distribution map shows the total amounts of $SrSO_4$ for each bore hole, but not ore grade. Generally, higher amounts of $SrSO_4$ mean higher grade ore in the bore holes, but there are some exceptions. For an example, a bore hole may show considerable amounts of $SrSO_4$, but penetrate only a few thick limestone beds containing lower grade ore. These are shown on cross sections.

The ore distribution in each rock unit containing celestite mineralization (Lower Limestone, Calcium Sulphate and Middle Limestone) was also mapped, following the same procedure used to plot total ore distribution:

a). Ore Distribution in Lower Limestone. (Plate 10)

b). Ore Distribution in Calcium Sulphate. (Plate 11)

c). Ore Distribution in Middle Limestone. (Plate 12)

DISTRIBUTION IN RELATION TO PALEOTOPOGRAPHY

Contours of the total ore distribution (Plate 2) exhibit a thick and thin morphologic form extending northwestward, N55° to 75°W, the elongation trending parallel to the dip of the Windsorian sedimentary bedding. The greater amounts of ore are represented by the thicker morphologic forms and the lesser amounts of ore by the thinner. There is a gradual radial depletion of ore quantity from the major ore zones.

The three major ore zones are indicated by the bore holes as follows:

Group I, Major Ore Zones

1). bore holes 44, 74, 78, 83 and 26.

2). bore holes 92, 85 and 89.

3). bore holes 66, 98 and 81.

There are also several subsidiary ore bands extending at a right angle from the major ore zones as follows:

Group II, Subsidiary Ore Bands

1). bore holes 35 and 100.

2). bore holes 68, 96 and 54.

3). bore holes 90, 41 and 38.

4). bore holes 66, 63, 19 and 58.

5). bore holes 97, 80, 77 and 81.

There are also a few corresponding barren bands, between minor ore bands of Group II, coincidental with:

1). bore holes 33 and 16.

2). bore holes 71, 56 and 60.

3). bore holes 48, 93 and 47.

Group III, Minor oval zone of low ore volume

1). surrounding bore hole 82.

These zones suggest control of ore in two directions: the major ore zones of Group I are parallel to the dip of the Windsorian sedimentary bedding and the subsidiary ore bands of Group II are parallel to the strike of the bedding. In this respect the major ore zone along the bore holes 85 and 89 might be considered as a subsidiary ore band from the major ore zone, which is probably extended northwest from bore hole 85.

Structure contour map of the surface of basement displays a considerable range of relief. These topographic features were generally preserved and reflected in the strata deposited on and around them, although abrupt lateral change of lithofacies and thickness gradually altered the topography of the paleobasin. Finally, the basement topography was not reflected any longer after Upper Conglomerate deposition. Each rock unit containing celestite mineralization was therefore deposited in a paleobasin with its own peculiar topography.

At first the total ore distribution and structural contour map of the surface of basement were compared in an effort to find any relationship between the basement topography and the ore localization. This was possible only in the western half of the area where the bore holes extended to the basement; in the eastern half, the holes were bored only to the Basal Conglomerate which overlies the basement. The only noticeable relation between the basement topography and the ore localization was that the minor oval zone of low ore volume surrounding bore hole 82 coincides with a basement saddle. However, the comparison of the total ore distribution map with structure contour map of Lower Limestone basin shows some relations between them. (See Plates 10 and 13). Generally, the ore zones coincide with the flanks of a paleotopographic ridge. On the other hand, barren bands coincide with major valleys or ridges.

The ore distribution in each rock unit and the structure contour map of the base of each unit were then compared. Each comparison made more apparent the general dependence of ore localization on the paleotopography of the basin as follows:

Comparison of Ore Distribution in Lower Limestone (Plate 10) with Structural Contour Map of the Base of Lower Limestone (Plate 13).

Most of the mineralization is confined to Lower Limestone and ore distribution in the Lower Limestone appears to be similar to total ore distribution. Some differences are, however, noticed in the northwest of the area, and only these will be discussed here.

In the northwest of the area, one major ore zone is indicated along the holes 97, 85, 92, 95, 73, 98, and 66. This could be considered as two ore zones (one along the holes 97, 85, 92 and 95, and the other along the holes 73, 98, and 66) which are connected between the holes 75 and 73.

The one along the holes 97, 95, 92 and 95 coincides with the flank of a paleotopographic high. The other, along the bore holes 73, 98 and 66, coincides with a minor ridge of the paleotopography.

Comparison Ore Distribution in Calcium Sulphate sequence (Plate 11) with Structure Contour Map of the Base of Calcium Sulphate (Plate 14).

Two major ore zones and one minor oval zone are indicated on Plate 11. The one major ore zone around the bore holes 57 and 55 coincides with the flank of a paleotopographic high. The minor oval zone surrounding hole 77 coincides with a saddle of paleotopography. Absence of paleotopographic information around hole 89 prevents comparison of ore distribution along the holes 85 and 89 with the paleotopography.

Comparison of Ore Distribution in Middle Limestone (Plate 12) with Structure Contour Map of the Base of Middle Limestone (Plate 16).

Two ore zones are indicated on Plate 12: one along the holes 80, 78, and 81, the other around the hole 54. The ore zone along the holes 80, 78, and 81 coincides with a flank of paleotopographic high. The other oval zone around the hole 54 coincides with a minor valley.

DISTRIBUTION IN RELATION TO STRATIGRAPHY

In an attempt to find any stratigraphic and lithological relationships suggesting control of ore distribution, six cross sections were made. (See Cross Sections I to VI and Plate 2 for their location).

Cross Section I shows that the celestite mineralization is confined within the base of the Windsorian sedimentary rocks, with a range of 100 feet from the basement. While this is generally true for the area contoured on Plate 2, there is the possibility that is does not hold to the northwest, where we have no information.

Most of the celestite occurs in the Lower Limestone as a few layers or lenses. Some of the high grade celestite mineralization, however, is found in the Middle Limestone overlying the Calcium Sulphate and in the limestone interbedded in the Calcium Sulphate. It is not clear from Section I whether the celestite mineralization above the Calcium Sulphate is connected to that in the Lower Limestone below the Calcium Sulphate through mineralization in the limestone interbedded within it. This is partly because celestite mineralization in the Lower Limestone is also not uniform but changes abruptly in height, width and tenor of ore. The Lower Limestone itself is variable in thickness as mentioned above.

Some bore holes contain one mineralization zone in the Lower Limestone, whereas others have two or three. The vertical interval between two ore zones is also variable but generally reflects the thickness of the Lower Limestone. Some, if not all, of the ore zones seem to be connected laterally. Bore hole 75 contains three highly mineralized zones above the Calcium Sulphate and one low grade ore zone near the base of the Lower Limestone below the Calcium Sulphate. On the other hand, bore hole 73, 200 feet away to the eastward, does not show any mineralization above the Calcium Sulphate, but it has two low grade ore zones in the Lower Limestone - one near the top and the other near the base of that member. The Calcium Sulphate between the Middle Limestone and the Lower Limestone forms a continuous bed even though the thickness is variable.

The lack of information in the space between holes 75 and 73 is critical in any evaluation of ore genesis. If it is proved that ore zone above the Calcium Sulphate can be traced to any ore zone in the Lower Limestone by a connection through the Calcium Sulphate, it will be diagnostic evidence for an epigenetic origin of the celestite mineralization. No evidence for such a connection between them has been observed, if one exists.

Even in the Lower Limestone, discontinuity of ore zones is observed, as can be seen between bore holes 70 and 57. Unlike other bore holes, these two show conglomerate interbedded in the Lower Limestone. Bore hole 57 contains mineralized zones between the Calcium Sulphate and conglomerate interbedded in the Lower Limestone but continuation of the ore is not found at bore hole 70. The celestite deposits seem to occur as lenses rather than as distinct strata.

Eastward, where the Calcium Sulphate is absent, celestite mineralization occurs in one zone in the Middle Limestone above the Middle Conglomerate and in another in the Lower Limestone below it.

Some relations between ore localization and the base of each mineralized rock unit (which might give some explanation of ore genesis) can be observed on Cross Section I.

Mineralization continues westward from outcrop in the east to bore hole 54 and it nearly pinches out at bore hole 56. Mineralization continues again westward from bore hole 55 to hole 77, even though marked changes in height, width and tenor of ore are observed. But ore finally pinches out abruptly between bore holes 77 and 79. Bore hole 77 contains three high grade ore zones: from the top downward 5.5 feet thick (27 to 47 per cent of $SrSO_4$), 2 feet (60 per cent) and 2.2 feet (60 per cent). Bore hole 79 is located only 200 feet westward from bore hole 77, but does not show any celestite mineralization. No abrupt change in lithofacies which might explain this sudden change in mineralization is observed between two bore holes. The basement at bore hole 56 forms a minor ridge between bore holes 55 and 54. This might imply that the general mineralization trend was interrupted against a flank with a slope direction opposite to the general mineralization trend. It is also noteworthy that bore holes 73 and 70 at the bottom of a valley do not contain any high grade mineralization but only two thick zones of slight mineralization.

Cross Section II shows that most of the celestite occurs in the Lower Limestone as a few layers or lenses. Eastward some of the high grade celestite mineralization, however, is found in the Middle Limestone overlying the Middle Conglomerate. The celestite mineralization continues with a relatively consistent tenor of ore along a flank between bore holes 39 and 54, but it pinches out abruptly against a paleotopographic high between bore holes 38 and 39 in the west, and towards the bottom of the paleobasin between bore holes 54 and 69 in the east. The celestite mineralization in Middle Limestone at bore holes 96 and 54 also pinches out against a paleotopographic high between bore holes 68 and 96 in the west, and towards the bottom of the paleobasin in the east.

Cross Section IV along the bore holes 26, 36 ...58 and 50 appears as another example which suggests that the general mineralization trend was interrupted against a paleotopographic flank with a direction of slope opposite to the general mineralization trend.

Cross Sections III, V and VI confirm that celestite mineralization is confined lithologically to limestones or calcareous beds, whether the Middle Limestone, the Lower Limestone, or limestone interbedded in the Calcium Sulphate. It is also confirmed that, structurally, ore occurs more extensively along the flank of a paleotopographic ridge which has the same direction of dip as the overlying rock unit, and that it pinches out against paleotopographic ridge or high and towards valley or bottom of the paleobasin.

DISCUSSION

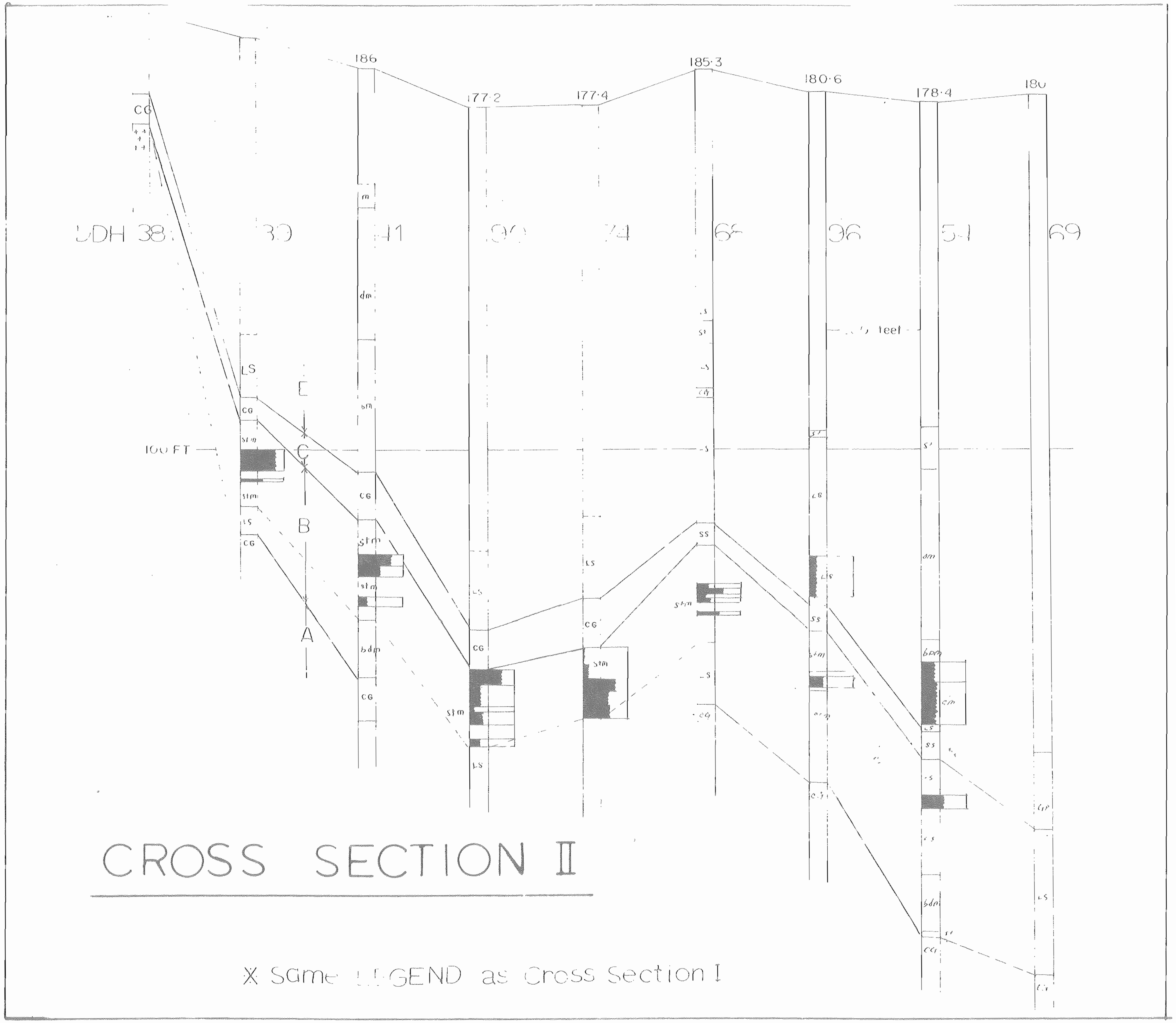
General conclusions reached from the preceding discussion may be summarized as follows:

Celestite mineralization is confined lithologically to limestones or calcareous beds, whether the Middle Limestone, the Lower Limestone, or limestone interbedded in the Calcium Sulphate. Localization of celestite is controlled in two directions: the major ore zones are parallel to the direction of the dip of the Windsorian sedimentary bedding and the subsidiary ore bands are parallel to the direction of the strike of the bedding. Ore occurs more extensively along the flank of a paleotopographic ridge which has the same direction of dip as the overlying rock unit, and it pinches out against paleotopographic ridge or high and towards the valley or bottom of the paleobasin.

Some ore zones, however, depart from these general trends of localization described above. As an example in Cross Section I, high grade ore in Middle Limestone at bore hole 77 and 75 pinches out suddenly towards bore hole 73, even though no paleotopographic or lithologic differences are observed between them. This could be explained by an hypothesis as follows:

The localization was modified by minor migration after deposition of primary ore. (This will be substantiated by microscopic evidences in a later chapter.) The ore-bearing solution migrated, following the general trend of mineralization westerly and downward, and reached the flank of the basement ridge near bore holes 75 and 77. The migration was continued upward along the surface of the ridge. Above the Calcium Sulphate, near the basement of bore hole 77, the ore-bearing solution met another rock unit that had favourable physiochemical conditions for precipitation of $SrSO_4$. Finally the solution mineralized the zone above the Calcium Sulphate at bore holes 77 and continued eastward to ore zones above the Sulphate of bore hole 75, but mineralization did not reach bore hole 73, either due to lack of $SrSO_4$ in solution or to unfavourable physiochemical conditions for precipitation of celestite.

It should be mentioned that this is proposed only at bore holes 77 and 75, and the mineralization above the Calcium Sulphate at other places may have a different genesis. The mineralization above Calcium Sulphate such as a hole 54 seems to have occurred in a small hollow of the paleobasin during the deposition of Middle Limestone.



CROSS SECTION II

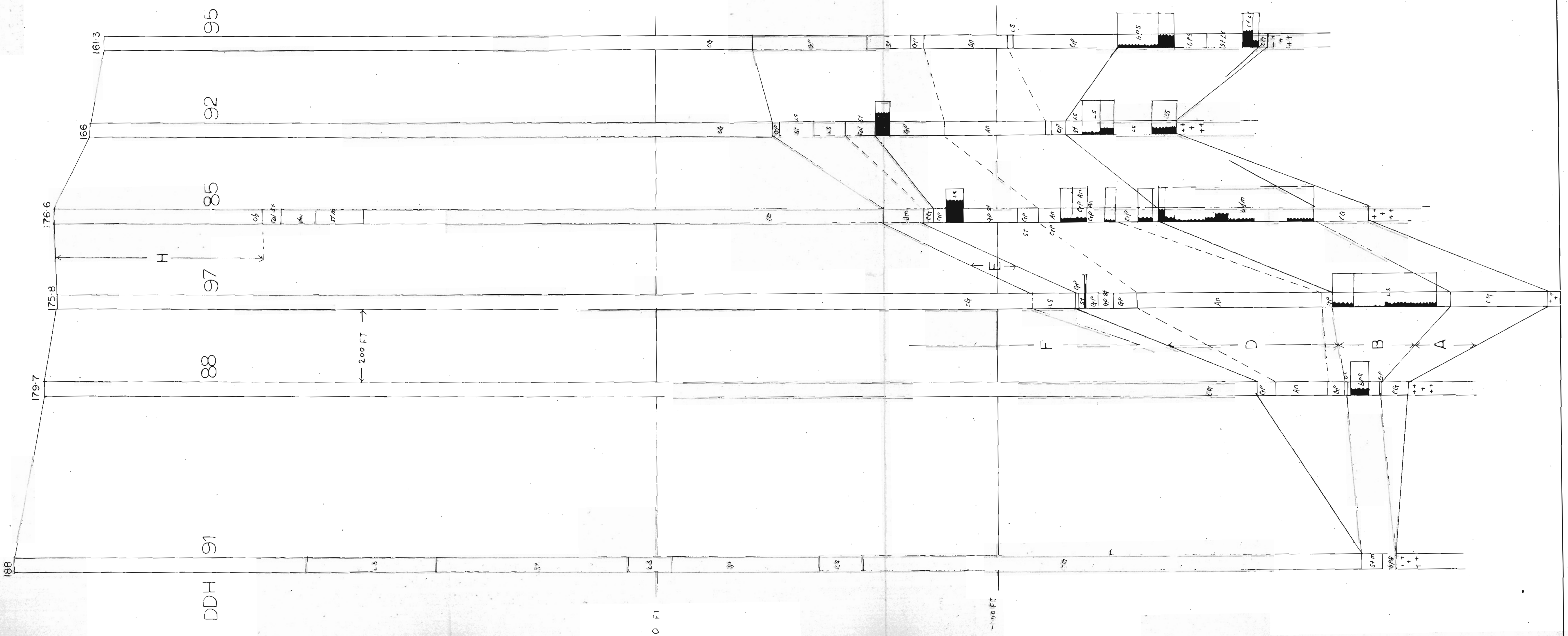
X Same LEGEND as Cross Section I

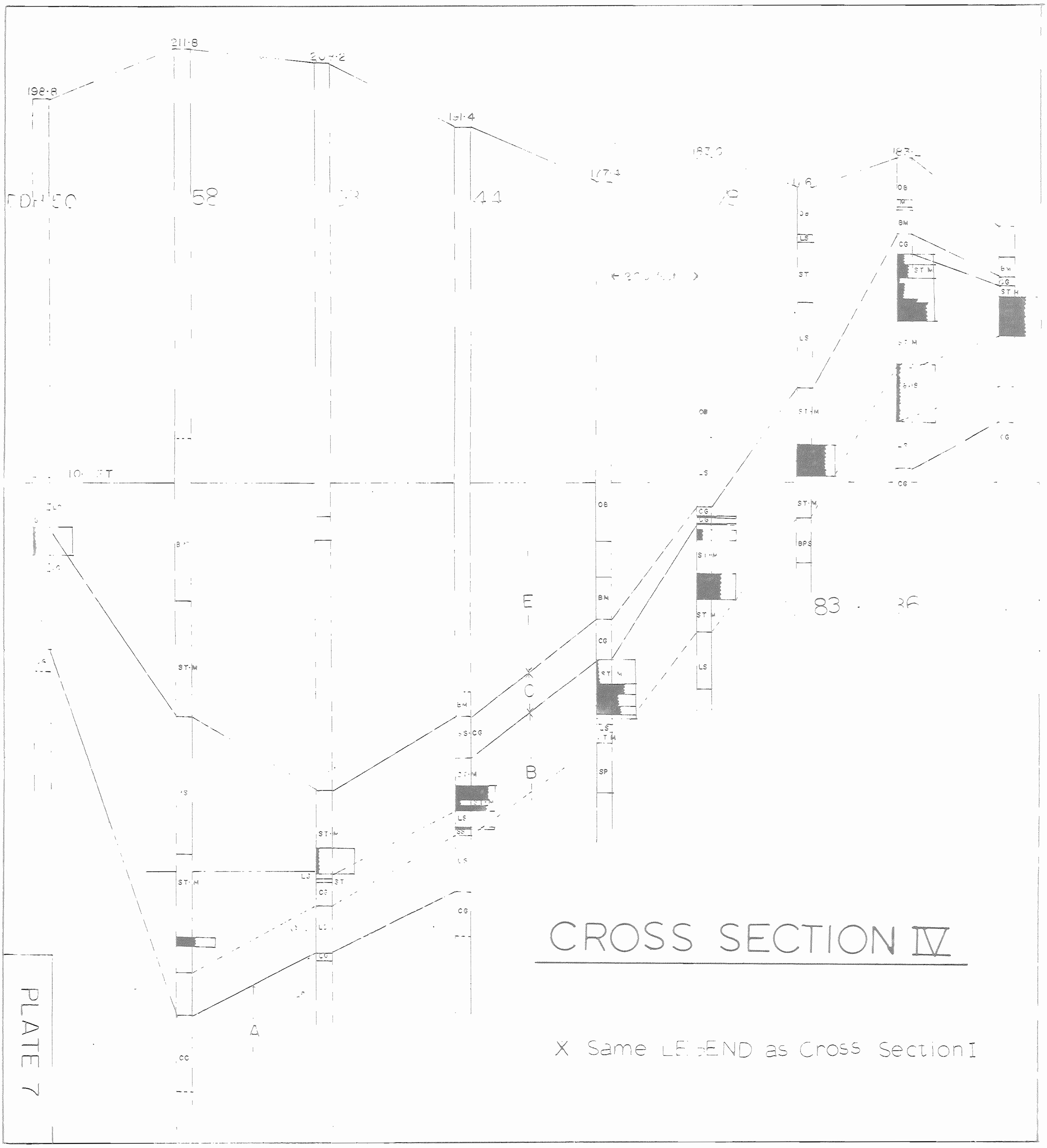
PLATE 5

PLATE 6

CROSS SECTION III

※ Same LEGEND as Cross Section I



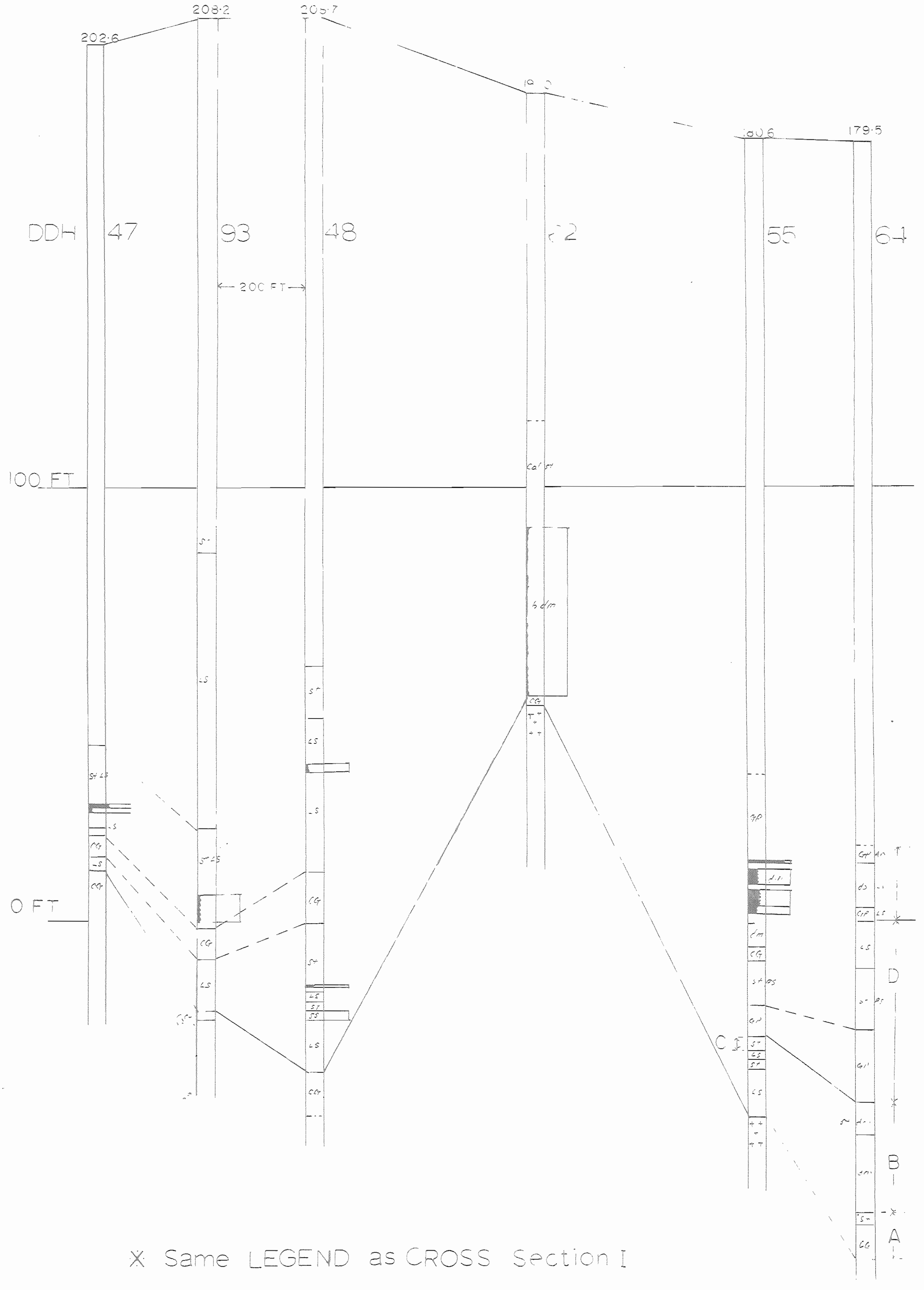


CROSS SECTION IV

X Same LEGEND as Cross Section I

PLATE 7

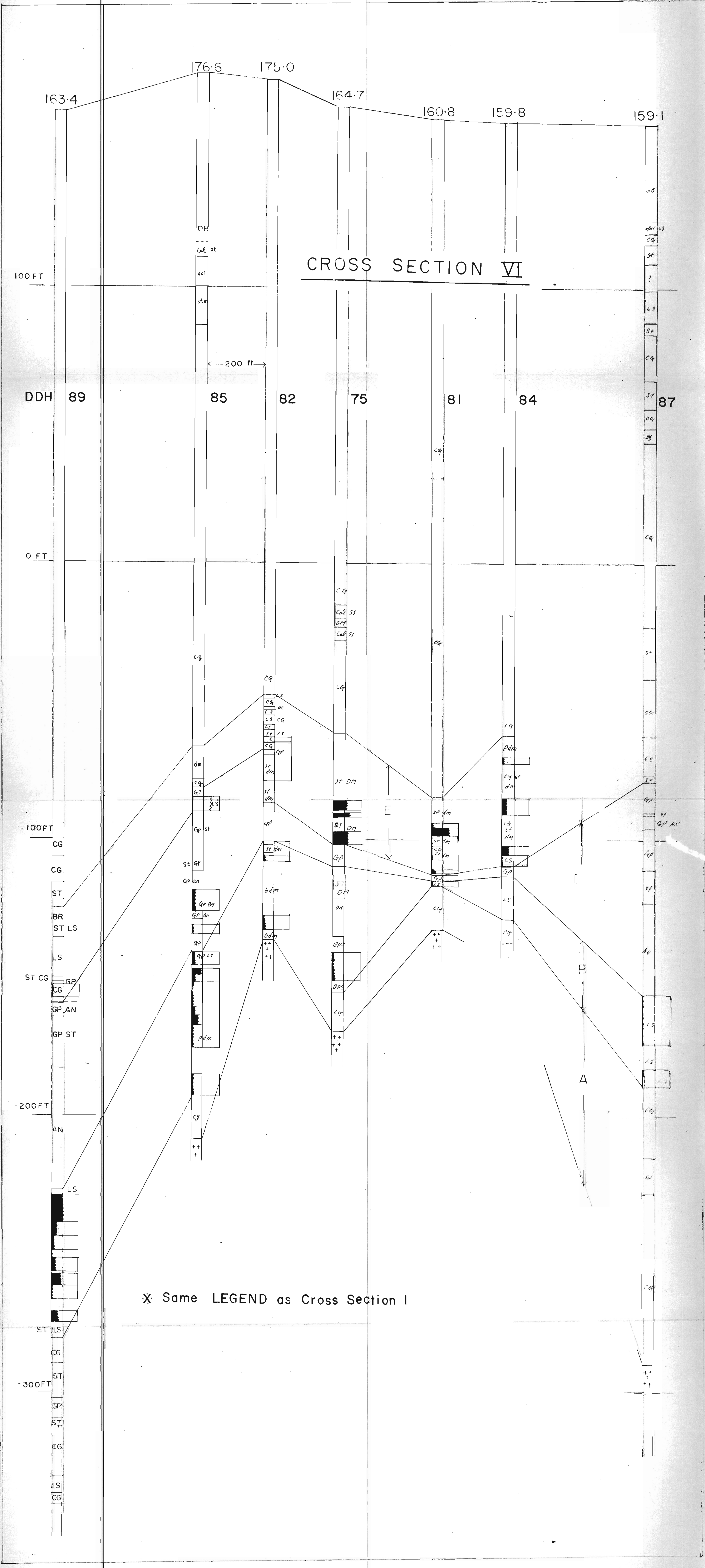
CROSS SECTION V



✕ Same LEGEND as CROSS Section I

PLATE 8

CROSS SECTION VI



✕ Same LEGEND as Cross Section I

CHAPTER V

MINERALOGY AND TEXTURAL RELATIONS IN THE ORE

GENERAL STATEMENT OF PROBLEM

Through investigation of structural and stratigraphic relationships with celestite localization, it was found that all the celestite mineralization is confined within limestone or calcareous beds regardless of their stratigraphic position, whether in Lower Limestone, in Middle Limestone or limestone interbedded in Calcium Sulphate. This implies that celestite mineralization was controlled by some mineralogical factors, by some chemical factors represented in rocks by the mineral assemblages, or by some physicochemical conditions which might be deduced from the minerals now present. In an effort to recognize such factors which might give some indication of ore genesis, and act as a mineralogical guide for future exploration, the occurrence of celestite was examined in some 400 thin sections. The typical relations found are described below as they occur in hole 57.

DESCRIPTION OF TYPICAL MINERAL RELATIONS (MICROSCOPIC)

(Bore hole 57. Collar elevation 166.3 feet. See Cross Section I.)

Sample S-62. 188.5 feet. Celestite-limestone nodule in Calcium Sulphate: (See Plate 19-a).

Celestite-limestone nodules are enclosed in white microcrystalline gypsum. They are broken and filled by selenite, which is also found along the boundary of nodules. Size of nodules ranges from a few millimetres to larger than 10 cm. Nodules contain: maroon and grey fine-grained celestite, 70 to 80 per cent; cryptocrystalline calcite, 10 to 20 per cent, and some selenite as just mentioned. Calcite appears to fill interstices of the celestite.

In thin section, gypsum appears as fibrous alabastrin secondary gypsum with an average length of 0.03 mm. A few units that appear to be euhedral gypsum "crystals" (0.2 - 1.0 mm) are observed in a groundmass of fine-grained gypsum. These "crystals" are in fact, composed of aggregates of very small gypsum grains. Selenite, 0.2 to 0.7 mm in size, shows anhedral, interlocking and interstitial textures. Anhydrite and celestite inclusions are found in a groundmass of gypsum. Many are traversed by gypsum veinlets and their faint primary outlines of inclusions can be traced. These appear as residual primary minerals. Anhydrite inclusions are in the form of stumpy rectangles, narrow laths or needles with an irregular eroded boundary, and they range from 0.02 mm to 0.5 mm in length. Celestite inclusions in gypsum are similar stubby rectangular or lath forms with eroded boundaries.

Celestite nodules are composed of anhedral interlocking granular celestite from 0.2 to 1.0 mm in size. Isolated celestite crystals in the gypsum appear as subhedral or euhedral. The celestite nodule is partly replaced by myriads of minute particles, 0.01 mm, mostly calcite and hematite or limonite. Rhombic dolomite is also observed. In places, celestite disappears due to extensive replacement by calcite and a microcrystalline mass of carbonate remains.

Sample S-64, 195 feet. Disseminated celestite in limestone interbedded in Calcium Sulphate.

Grey cryptocrystalline limestone is slightly brecciated and fractures are filled by argillaceous materials. Fine pyrite and sphalerite (?) coat fractures.

In thin section, the present appearance of disseminated celestite is regarded as a result of extensive replacement by minute carbonate particles as seen on Plate 19-b and -c. Ragged patches of celestite are considered to have been a single crystal originally because they have the same optical orientation and continuity of cleavages. Celestite remaining after replacement by calcite appears as irregular patches and rhombic forms. This rhombic form of celestite shows celestite cleavage. No evidence is observed to prove that this form of celestite is pseudomorphic after calcite; instead, the numerous inclusions of calcite and the rhombic outline of the celestite appears to be a euhedral face of a celestite crystal.

Consequently, this interbedded limestone containing 10 per cent of disseminated celestite was probably higher grade celestite ore, originally, but extensively replaced by microcrystalline calcite.

Sample S-68, 223 feet. High grade celestite bed in the transition zone between Calcium Sulphate and Lower Limestone.

Bluish-grey medium-grained (1 to 2 mm) the celestite bed appears to be nearly pure ore in the transition zone between Calcium Sulphate and

Lower Limestone. (See Plate 19-d).

In thin section, one finds that anhedral celestite was only very slightly replaced by calcite. Calcite particles appear interstially and as inclusions in the celestite. Minute inclusions of anhydrite, gypsum, celestite and sulphides (pyrite and sphalerite) are also observed. Sulphide generally appears in the interstices between calcite grains. The sharp corner of one euhedral celestite crystal was seen enveloped by anhedral celestite grains, in which calcite inclusions show rhombic arrangement. Sulphide and hematite are scattered through the celestite, as well as some sulphides under crystallographic control of celestite. Size of sulphide inclusions ranges up to 0.3 mm.

Sample S-69, 224.5 feet. As sample S-68.

Fractures are developed in celestite ore and filled by selenite.

In thin section, general features are similar to those of sample S-68. Celestite has more irregular anhedral boundaries than in S-68. Glide twinning is well developed. (Plate 20-a).

Sample S-71, 227 feet. Dirty grey brecciated limestone containing celestite fragments.

Limestone appears to be brecciated and filled by matrix of calcite. Subrounded fragments of calcite and celestite are generally no larger than 8 mm in size, but a celestite fragment 4 cm in size is seen in core samples S-71.

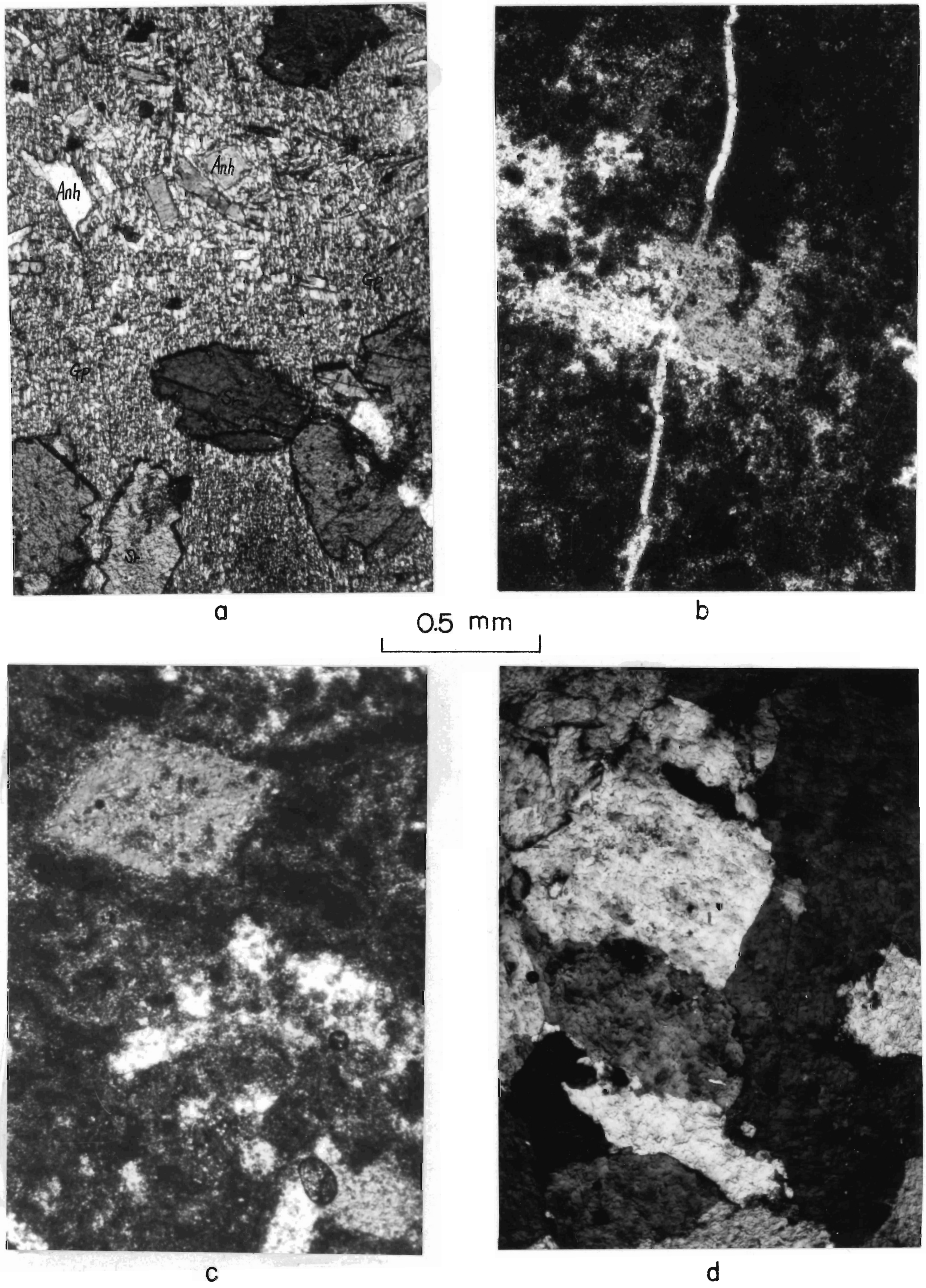
a. Photomicrograph of gypsum containing celestite, and anhydrite. Sample S-62, DDH 57, 185.5 feet, Calcium Sulphate. Sr - celestite, Anh - anhydrite, Gp - gypsum.

b. Photomicrograph of celestite vein. Sample S-64, DDH 57, 195 feet, in limestone interbedded in Calcium Sulphate.

c. Photomicrograph of celestite with rhombic form. Sample S-64, DDH 57, 195 feet, in limestone interbedded in Calcium Sulphate. This rhombic grain of celestite has the two diagonal cleavages at 90°± to one another, characteristic of celestite; they are not in the orientation appropriate to calcite. This is considered to be a euhedral face of celestite crystal. Inclusions of calcite are shown in celestite. Calcite replaced rhombic celestite below, leaving vague euhedral outline. "Aggregates" of celestite grains within the outline are in optical continuity.

d. Photomicrograph of massive bedded celestite. Sample S-68, DDH 57, 223 feet as Plate III-a. Anhedral, granular. Optically randomly oriented.

Plate 19


Anh
Anh
Gp
Gp
Sr
Sr
a
0.5 mm
b
c
d

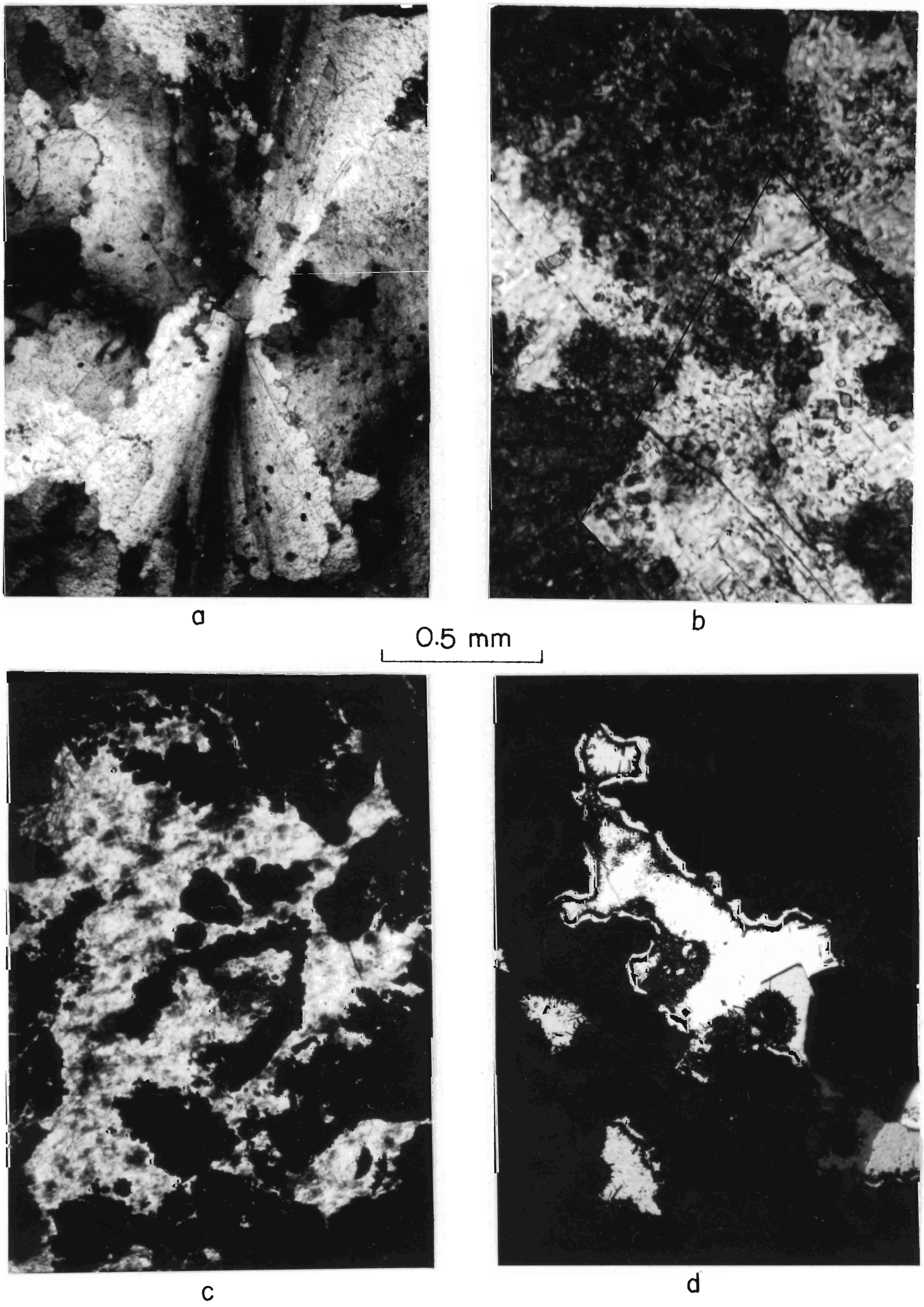
a. Photomicrograph of celestite showing glide twinning. Sample S-69, DDH 57, 224.5 feet in Lower Limestone.

b. Photomicrograph of celestite partly replaced by calcite. Sample S-107, DDH 58, 241.5 feet, in Lower Limestone. A single crystal of celestite was irregularly replaced by calcite and broken. Carbonate inclusions are shown in celestite. Most of them are calcite but some of the rhombic grains may be dolomite. White, Sr- celestite. Black - calcite.

c. Photomicrograph of celestite in limonite-hematite ochre. Sample S-8, DDH 36, 42.2 feet.

d. Photomicrograph of quartz in ochre. Sample S-264, DDH 298.2 feet. Quartz contains rim of limonite (?) and acicular crystals of limonite (?) along the rim.

Plate 20


a
b
0.5 mm
c
d

In thin section, the brecciated limestone contains carbonates, 75 to 80 per cent, celestite, 5 to ?0 per cent, gypsum 3 to 5 per cent and iron minerals, 2 to 3 per cent. The amount of matrix ranges up to 50 per cent. Under the microscope, S-71 appears very impure, due to widely distributed iron minerals, mostly pyrite and limonite staining, which contaminate all the fragments and the matrix. Fragments of carbonates consist of anhedral recrystallized calcite. Though sought, no strontianite was identified. It is possible that some has been misidentified as calcite with low birefringence. Pyrite ranges from very fine up to 0.3 mm; the grains are mostly anhedral.

Celestite is found as parts of calcite fragments, as celestite fragments and in the matrix. Celestite in calcite-celestite fragments appears interstial to the calcite grains. Gypsum is found as fracture fillings.

Sample S-72, 228 feet. Calcareous celestite ore, with about 30 per cent celestite.

Carbonates appear as limestone patches or interstitial calcite in celestite ore. In thin section, limestone patches appear as pelletiferous micrite.

Under the microscope, the occurrence of celestite in S-72 can be texturally divided into masses of anhedral celestite and disseminated euhedral-subhedral celestite. In masses, interlocking anhedral celestite suffered from very slight calcite replacement. Only trace amounts of minute calcite, iron minerals, anhydrite and gypsum inclusions are observed. In some places, different sizes of celestite grains show different size ranges, with finer-grained ranges, 0.06 to 0.1 mm and coarser-grained ranges, 0.2 to 0.4 mm. Thickness of coarser-grained zones is about 1.5 mm and of the finer is about 0.5 mm. Interstitial secondary calcite is also observed. Generally, celestite boundaries contacted by interstitial secondary calcite are euhedral or subhedral. Occurrence of euhedral celestite is different from anhedral celestite masses. Euhedral celestites appear to be separated and isolated from each other.

Sample S-77, 239.2 feet. Celestite bed with celestite vein.

A thin celestite interbed is observed in limestone. Thickness of the bed varies from 5 mm to 25 mm. Some of the limestone inclusions in the celestite bed are broken. A thin celestite vein, 1 mm in thickness, is perpendicular to the celestite bed and the limestone bedding.

In thin section, the boundary between the celestite bed and limestone is sharp, and no alteration is observed along the boundary. The thin cross-cutting celestite vein contains increased amounts of celestite close to the celestite bed, but gradually changes to calcite away from the bed. Celestite in the vein does not contain any calcite inclusions, while it does so in the celestite bed.

Sample S-78, 242.2 feet. Vug filling and fossil replacement by celestite.

Secondary calcite and celestite occur as fillings of vugs and as replacement of fossils. In thin section, a recrystallization band of limestone is observed along the boundary of vugs. Celestite in vug fillings is subhedral or euhedral, whereas fossil replacement celestite is mostly anhedral.

Sample S-88, 270.2 feet. Celestite ore in calcareous siltstone.

S-88 contains celestite, 65 to 75 per cent, calcite, 5 to 7 per cent, silt, 5 to 10 per cent, clay minerals, 10 to 15 per cent and trace amounts of iron minerals. Celestite shows anhedral interlocking texture with interstices filled by clay, silt, calcite and iron minerals. Minute carbonate inclusions are widely distributed in celestites. In places, this sample is similar to the anhedral celestite masses of S-72.

Sample S-89, 271 feet. Celestite ore in calcareous arkosic sandstone.

S-89 contains celestite, 45 to 55 per cent, calcite, quartz, altered feldspar, and altered granite fragments. Clastic fragments range in size from 0.03 mm to 2 mm; some of the granite fragments range up to 1 cm. Calcite occurs in the interstices of the clastic grains. Celestite, 0.3 to 2 mm in size, appears as fresh, anhedral, interstitial, and interlocking grains. Only a few minute carbonate inclusions are observed in the celestite.

Sample S-91, 278.2 feet. Celestite interbed in silty limestone.

In thin section, both euhedral and subhedral celestite grains are present; they are separated and isolated in a matrix of silty limestone.

The amount of celestite gradually decreases in both directions from a maximum 60 per cent until finally the rock is barren. Neither a sharp boundary between the celestite zone and silty limestone nor interstitial texture of celestite is observed. It appears to be syngenetic celestite.

Though not recognized in any of the typical specimens described above, barite was found by X-ray analysis of powders. The mine office reports 2 to 3 per cent in some places. It is, of course, not possible, as a practical matter, to distinguish celestite from barite by optical methods. All quantitative data on celestite here presented are based upon chemical analyses supplied by the mine office.

DESCRIPTION OF TYPICAL CELESTITE BODIES

All the celestite from other bore holes also appears as one or other of those types described above. Occurrences of celestite can be grouped as follows: (See Plate 21).

(1) Bedded celestite.

(2) Celestite as open-space-filling.

(3) Celestite replacement of fossils.

(4) Celestite-calcite veins.

(5) Celestite in calcium sulphate.

All the celestite-bearing thin sections are classified on Table 3. The table may be usefully compared with cross sections.

a. Alternating beds of limestone, and maroon ferruginous beds containing celestite. Sample S-324, DDH 82, 307 feet, in Basal Limestone. Limestone beds do not contain any celestite but the amount of celestite in ferruginous beds ranges up to 50 per cent.

b. Bedded celestite. Sample S-68, DDH 57, 223 feet, between Calcium Sulphate and Basal Limestone. Celestite 85 per cent, calcite, limonite, hematite, etc., 15 per cent.

c. Celestite-calcite vein cutting limestone bedding. Sample S-79, DDH 57, 242.5 feet, in Basal Limestone. Vein contains celestite 35 per cent and calcite 65 per cent.

d. Bedded celestite. From outcrop around DDH 28, in Basal Limestone. Euhedral celestite crystallization in cavity is shown.

e. Celestite as open-space-filling and Celestite replacement of fossils. Sampel S-133, DDH 67, 163 feet, in Basal Limestone. Pale blue, celestite.

f. Celestite patches or nodules in Calcium Sulphate. Sample S-60, DDH 57, 188.5 feet, Calcium Sulphate. White, gypsum. Bluish, celestite nodule. Nodules contain 60 to 80 per cent of celestite and are traversed by gypsum.

Plate 21: Occurrences of Celestite.

(1). BEDDED CELESTITE

The various types of celestite mineralization mentioned above appear stratiform when considered on a large scale. The majority of the high grade celestite mineralization occurs as continuous beds, but the proportion of celestite may range from low values up to 90 per cent or more. The open space fillings and replacement of fossil, etc. are also confined to a well-defined stratigraphic zone of lithological units. These latter types of celestite, however, are detached bodies and do not form continuous beds in the strict sense.

Bedded celestite occurs as interbeds in limestone and calcareous siltstone. It contains disseminations of calcite, dolomite, silt and iron minerals, but is up to 95 per cent $SrSO_4$ by weight. The celestite layers vary from half an inch to nine feet in thickness and the thickness of an individual layer is irregular. In places the bands are not continuous, but break off suddenly, and commence again further on, at or near the same level.

All the higher grade ore deposits can be included in this "bedded celestite" type. This type of ore also shows a range of grade. The variation of tenor appears to be partly, but not always, a primary feature. That is, the original primary grade of the ore depended upon the proportion of carbonate deposited simultaneously with the celestite. In some cases, however, celestite was replaced by calcite to produce a later change in the grade.

TABLE 3

Occurrence of Celestite, Thin Section Observation.

(1) Bedded celestite

DDH No.	Sample No.	Level ft.	Replacement stage	Per cent $SrSO_4$	Crystal shape	Other minerals
36	S- 7	37.5	0	80	an.	he. li.
	8	42.2	0	30	an. sub.	he.
85	S- 32	265.3	1	70	an. sub.	he.
	44	302.7	0	70	an.	he. li. ah. st.
	48	320.1	0	60	an. sub.	li. he. st.
28	S- 56	61.0	1	30	sub. eu.	st.
	57	63.5	1	50	sub. eu.	st.
	59	72.0	0	80	sub.	cl. st.
57	S- 64	195.0	2	10	an.	py.
	68	223.0	0	90	an. sub.	
	69	224.5	0	90	an.	gp.
	71	227.0	2	5	an.	gp. st. py.
	72	228.0	1	30	an. sub.	eu.
	74	230.0	1	80	an. sub.	gp.
	77	239.2	1	30	an. sub.	
	88	270.2	1	80	an.	cl. st.
	91	278.2	1	30	sub. eu.	cl. st.
58	S-105	229.5	1	30	an. sub.	st. cl.
41	S-166	111.0	1	90	an. sub.	
	167	113.0	1	60	an. sub.	st.
80	S-215	264.6	2	50	an.	dol. li. he.
	216	268.5	1	65	an.	dol. li. he.
	217	271.0	1	15	an. sub.	dol. li. he. st.
	218	272.7	1	7	sub.	he. li. gp. st.
70	S-251	333.0	1	15	an. sub.	st.
75	S-307	252.0	1	70	an. sub.	he.
	308	263.0	1	70	an. sub.	he. li.
62	S-324	307.0	0	10	an. sub.	he. li.
66	S-329	187.5	1	20	an. sub.	st.

TABLE 3 (continued)

DDH No.	Sample No.	Level ft.	Replacement stage	Per cent $SrSO_4$	Crystal shape	Other minerals
55	S-345	171.5	1	70	an. sub.	eu. li.
54	S-347	83.0	1	1	an.	py.
83	S-375	68.5	0	95	an.	
	376	72.5	0	70	sub. an.	cl.
	377	82.0	1	tr.	an. sub.	cl.
61	S-395	212.5	0	90	an.	

Abbreviations:

an. - anhedral
sub. - subhedral
eu. - euhedral
he. - hematite
li. - limonite

py. - pyrite
ah. - anhydrite
gp. - gypsum
st. - silt
cl. - clay

Replacement stage: see page 68

0 - Celestite ore of stage 0 includes all the fresh celestite which scarcely suffered from replacement by carbonate, but a few calcite and dolomite inclusions are observed in many places (Plate 19-d and 20-a).

1 - Replacement by carbonate begins with increase of calcite and dolomite inclusions and interstitial particles in the celestite. Carbonate particles occupy the spaces between celestite grains. Increase in the proportion of such grains, at the expense of celestite produces some euhedral celestite residuals. This is the feature of stage 1. (Plate 19-c). Continuing replacement results in development of irregular to subhedral celestite grains. (Plate 19-b). This is the last feature of stage 1

2 - In stage 2, the celestite is in irregular masses, and no suggestion of euhedral outline is now preserved. (Plate 19-b).

(2) Celestite as open-space-filling

DDH No.	Sample No.	Level ft.	Texture	Host Rock	
36	S- 4	25.0	I	cong.	
	9	47.5		dol. ps.	
	11	57.3		dol. bps.	X
	14	76.4		dol. dm.	

TABLE 3 (continued)

DDH No.	Sample No.	Level ft.	Texture	Host Rock	
85	S- 49	333.0	V	bdm.	
	50	341.0	I	bps.	X
	51	348.0	V	bps.	X
57	S- 78	242.2	V	ps.	
	89	271.0	I	cong.-ss.	
58	S-107	241.5	I, V	dm.	
67	S-128	130.5	V	bdm.	X
	129	133.5	V	dol. dm.	
	130	135.5	V	och.	X
	131	143.7	I	bps.	X
	132	153.0	I	bps.	X
	133	163.0	V	bdm.	
	134	167.0	V	bps.	
	135	170.0	V	bdm.	
	136	183.0	V	bps.	
	137	186.5	V	bps.	
88	S-198	384.0	I	ps.	
	201	392.0	V	ps.-dm.	
80	S-220	305.0	I, V	ps.-dm.	
49	S-234	63.5	V	he. dm.	
70	S-239	166.5	I	bdm.	
	242	272.0	I	ss.	
	244	291.0	I, V	dm.	
	245	302.0	I	bps.	
	252	338.0	I	st. bps.	X
	253	343.0	I	bps.	
73	S-265	278.0	I	dm.-ps.	
	266	283.0	I	dm.-ps.	
	267	288.0	I	bps.	X
	269	298.0	V	bps.-bdm.	
	270	313.0	I	bdm.-bps.	
	271	322.5	I	bps.	X
	292	343.0	I	st. bps.	
	293	347.0	I	st. bps.	
	294	355.0	I	st. bps.	
	295	363.0	I	cong.	
	298	376.5	V	ig. basement	

TABLE 3 (continued)

DDH No.	Sample No.	Level ft.	Texture	Host Rock	
75	S-310	296.0	V	bdm.-bps.	
	312	314.5	I	bps.	
85	S-315	282.5		och.	
	316	283.5	V	bps.	
	317	285.0	V	bps.-bdm.	
	318	290.0	V	bdm.	
	319	294.0	V	bdm.	
	320	300.0	V	bdm.-bps.	
	321	310.0	I, V	bdm.-bps.	
66	S-327	185.5	V	bps.	
	328	186.4	I, V	bps.	
65	S-333	169.0	V	dol. dm.	
	334	169.5	I	ps.	
56	S-338	131.5		dm.	
	339	132.5		dm.	
	340	133.8		dm.	
	341	147.0	V	bps.	
	342	148.7	V	ps.	
	343	150.2	V	bdm.-bps.	X
54	S-354	126.0	I	bdm.-bps.	X
	355	127.5	I, V	dm.-ps.	
	356	132.5	V	dm.	
	358	141.1	I	bps.	
96	S-370	112.5	I, V	bdm.-bps.	
	374	133.0	I, V	och.	
78	S-381	381.0	I	cong.	
89	S-387	400.0	I	bps.	
	388	405.0	I	bps.	X
61	S-394	209.7	I	bps.	X
98	S-402	239.8		dm.	
	403	256.0	I	bps.	X
	406	288.6	I	ss.	
	408	294.0	I	st. ps.	

TABLE 3 (continued)

DDH No.	Sample No.	Level ft.	Texture	Host Rock
92	S-409	314.0	I, V	bdm.-bps.

Abbreviations:

I	- interstice-filling	ss.	- sandstone
V	- vug-filling	cong.	- conglomerate
ps.	- pelsparite	och.	- ochre
bps.	- biopelsparite	st.	- silty
bdm.	- biodismicrite	dol.	- dolomitic
X	- replacement of fossils (Type 3)		

(4) Celestite-calcite vein

DDH No.	Sample No.	Level ft.	Host Rock
57	S- 77	239.2	ps.
	79	243.7	bps.
75	S-301	185.5	st. dm.
66	S-327	185.5	bps.
92	S-410	321.0	ig. basement

(5) Celestite in calcium sulphate

DDH No.	Sample No.	Level ft.	Occurrence	Crystal shape
85	S- 31	258.5	sg.	an. sub. eu.
	42	296.4	ag.	an. sub.
	44	302.7	ag.	an.
57	S- 60	171.0	ag.	an.
	62	185.5	ag. sg.	an. sub. eu.
	73	222.7	ag.	an. sub.
80	S-219	280.0	sg.	an. sub.

TABLE 3 (continued)

Abbreviations:

sg. - as separate grains

ag. - as aggregate

Stages of Replacement

The increase of replacement by carbonate decreases celestite ore grade. Intensity of celestite replacement by carbonate can be divided into three stages: stage 0, stage 1 and stage 2.

Celestite ore of stage 0 includes all the fresh celestite which scarcely suffered from replacement by carbonate, but a few calcite and dolomite inclusions are observed in many places. Calcite is the chief carbonate to replace the celestite, but a lesser amount of rhombic dolomite particles is also observed in many samples. Most of the celestite of stage 0 appears as anhedral forms, as seen in Plate 19-d.

Replacement by carbonate begins with increase of calcite and dolomite inclusions and interstitial particles in the celestite. Carbonate particles occupy the spaces between celestite grains. Increase in the proportion of such grains, at the expense of celestite (i.e. by replacement of celestite) produces some euhedral celestite residuals (Plate 19-c). This is the feature of stage 1. Continuing replacement results in development of irregular to subhedral celestite grains. (Plate 20-b). This is the last feature of stage 1. Some "aggregates" of celestite grains are in optical continuity and vague euhedral to subhedral outlines can still be recognized. (As outlined in Plate 20-b). In stage 2, the celestite is in irregular masses, and no suggestion of euhedral outline is now preserved. (Plate 19-b). Celestite ore of stage 0 ranges up to 95 per cent in $SrSO_4$, but that of stage 2 ranges up to 30 per cent only.

Epigenetic Features of Bedded Celestite

It also should be noticed that some of bedded celestite shows epigenetic features as follows:

Many continuous celestite beds are stained or cemented by iron oxides (limonite and hematite) which are present in variable amounts. Iron staining and cementing also follow bedding and show definite zoning.

Sample S-324, Plate 21-a is a type-sample in small scale of continuous celestite beds containing iron minerals, up to 50 per cent. Celestite-bearing bands are alternated with limestone bands. Maroon ferruginous celestite beds and greyish limestone beds have similar thickness, 4 to 5 mm. A sequence of photomicrographs of hand specimen S-324, taken across the banding, is shown on Plate 22. It shows an alternation of three celestite bands and three limestone bands. Limestone appears as biomicrite with minor amounts of indistinctive pellets and sparite. Iron staining is also observed. Calcite veins containing celestite appear to cut the limestone band and connect two celestite bands. No celestite mineralization was found in limestone bands. Boundaries between limestone bands and celestite bands are irregular and often marked by iron minerals. Thin rims, 0.1 to 0.15 mm, of recrystallized calcite are also observed along the boundaries.

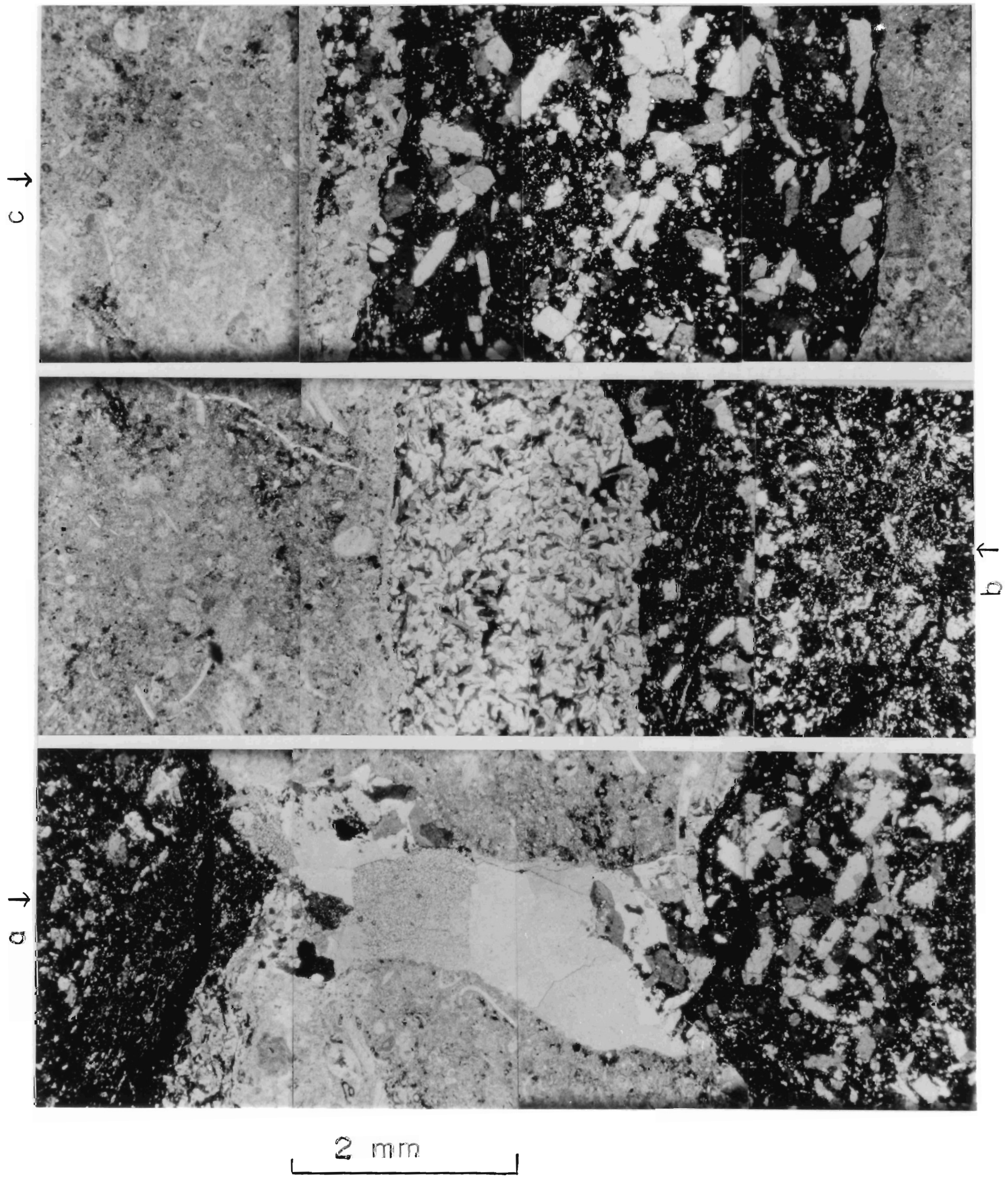
Celestite band can be divided into two: a celestite zone with iron cementing and a purer celestite zone without iron minerals or with less than 5 per cent of iron minerals. The boundary between them is irregular

Plate 22. Photomicrograph of alternating of fossiliferous limestone, ferruginous celestite zone and purer celestite zone. DDH #57, 188.5 feet as Figure 5-d.

a. Ferruginous zone containing anhedral celestite, lighter colour, white or grey. Fossiliferous limestone with calcite vein. A few grey euhedral and subhedral celestite grains are seen in calcite vein. And ferruginous celestite zone containing subhedral and anhedral celestite crystals.

b. Continuation of ferruginous celestite zone from a. Pure celestite zone, subhedral laths are interlocked each other. The interstitial anhedral celestites filled them so that a mozaic texture is shown. Thin recrystallization band of limestone is seen along the boundary between fossiliferous limestone and pure celestite zone.

c. Continuation of fossiliferous limestone from b. Ferruginous celestite zone. Contact between fossiliferous limestone and ferruginous zone appears as post depositional feature. And fossiliferous limestone.


c
b
a
2 mm

but sharp and marked by calcite replacement. No depositional feature is observed from the boundaries between limestone band and celestite band, and between two celestite zones.

Celestite Zone with Iron Cement:

The ferruginous celestite zone contains iron minerals, 40 to 50 per cent, celestite, 30 to 40 per cent, calcite 5 to 7 per cent, silty size quartz, 2 to 3 per cent and trace amounts of dolomite and sepiolite. Subhedral and euhedral celestite crystals are separated and isolated by iron cementing, whereas anhedral crystals form interlocking masses. Subhedral and euhedral celestite crystals are lath forms 0.3 to 0.5 mm in length and 0.1 to 0.15 mm in width. These lath-form crystals are sub-oriented following banding. Minor amounts of calcite and of quartz inclusions are observed in celestite. Generally celestite crystals are more concentrated in the middle of a ferruginous celestite band than at the margin.

Pure Celestite Zone:

The purer celestite zone contains celestite, 85 to 90 per cent, cementing-iron minerals, 2 to 3 per cent and calcite that replaces celestite along the contact with the ferruginous celestite zone, 4 to 5 per cent. Subhedral laths of celestite are interlocked with each other. The interstitial anhedral celestite filled them so that a mosaic texture is shown. Subhedral crystals have an average grain size of 0.2 mm in length and 0.05 mm in width. No orientation of crystals is observed in purer celestite zone.

Textures mentioned above suggest some genetic explanation of this type of celestite mineralization. The celestite band of this type of ore might have a different history of mineralization from primary continuous bedded celestite. Both celestite zones just described are not depositional but appear to be introduced by some solution. If they were depositional, the boundary between a celestite band and a limestone band should be gradual as seen in other continuous celestite beds. The thin recrystallized calcite rim between a celestite band and a limestone band implies some relation between limestone host rock and celestite-bearing solution. Calcite grains containing celestite also suggest possible transportation of celestite by solution. Furthermore, in another thin section, sample S-218, DDH No. 80, 272.7 feet, a ferruginous celestite bed appears to cut bedding of barren limestone.

The two different celestite zones might have formed at different stages of introduction. This is suggested by a sharp boundary between them and by calcite replacing celestite in the purer celestite zone along the contact between them. It is proposed that the purer celestite zone was formed first and then the ferruginous celestite zone by a much more ferruginous solution. Calcite replacing celestite along the contact between the two zones could be explained as the result of reaction with a solution depositing calcite in the purer celestite zone. Suborientation of coarser subhedral and euhedral celestite crystals in the ferruginous celestite zone also might be the result of recrystallization due to the solution.

The formation of celestite mineralization in the ferruginous beds remains a problem. It is possible that the celestite was transported from elsewhere and deposited in the ferruginous bed, or it might have been present as a primary mineral in the bed. In the latter case, of course, the celestite would be of syngenetic origin. In Plate 22 section a, the small (1 to 2 mm) calcite veinlet in the fossiliferous limestone contains some celestite. It is obvious, therefore, that there has been at least a little post-depositional movement of celestite as well as of calcite.

(2) CELESTITE AS OPEN-SPACE-FILLING

Celestite is observed as open-space-filling in many places in cavernous limestone, silty limestone, calcareous siltstone and in conglomerate. This type of mineralization is also confined to well-defined stratigraphic zones in Basal Limestone and Middle Limestone.

Generally, celestite as open-space-filling forms ores of relatively low grade. The tenor of open-space-filling celestite ranges up to 35 per cent $SrSO_4$.

Replacement of celestite by calcite in open-space filling is rare or non-existent. Some calcite and dolomite inclusions, however, are observed in places.

Open spaces may be divided into two types, interstices and vugs. Interstices are best developed in biopelsparite. Consequently, celestite filling of interstices took place most extensively in biopelsparite, particularly in that which is fractured and fragmented. Interstice-fillings are mostly celestite, and calcite is very minor. Vugs are most abundant in dismicrite. They are generally filled by calcite, although some vugs are filled by calcite and lesser amounts of celestite.

Crystals of calcite are observed in many places in open spaces. Calcite crystals developed perpendicular to the walls of the open spaces and formed a thin cavity lining, 0.01 to 0.1 mm in thickness. Neither recrystallization nor alteration of limestone is observed along the open space boundaries.

Trace amounts of aragonite and strontianite are also observed as open-space filling. (There is some doubt, because calcite so oriented as to show low bi-refringence might have been mistaken for strontianite.)

Generally celestite as open-space-filling occurs at a lower stratigraphic level than bedded celestite.

Open-space-filling is generally considered as diagnostic evidence for epigenetic origin. Celestite as open-space-filling in fractured and fragmented biopelsparite suggests an alternative hypothesis concerning the origin of celestite mineralization as follows: Allochemical limestone containing fossil fragments and pellets was deposited. Later deformation resulted in fracturing and fragmentation of biopelsparite, and celestite, coprecipitated with calcium carbonate, was carried into the open spaces by ground water.

(3) CELESTITE REPLACEMENT OF FOSSILS

Some fossil fragments are composed of the usual calcite or aragonite.

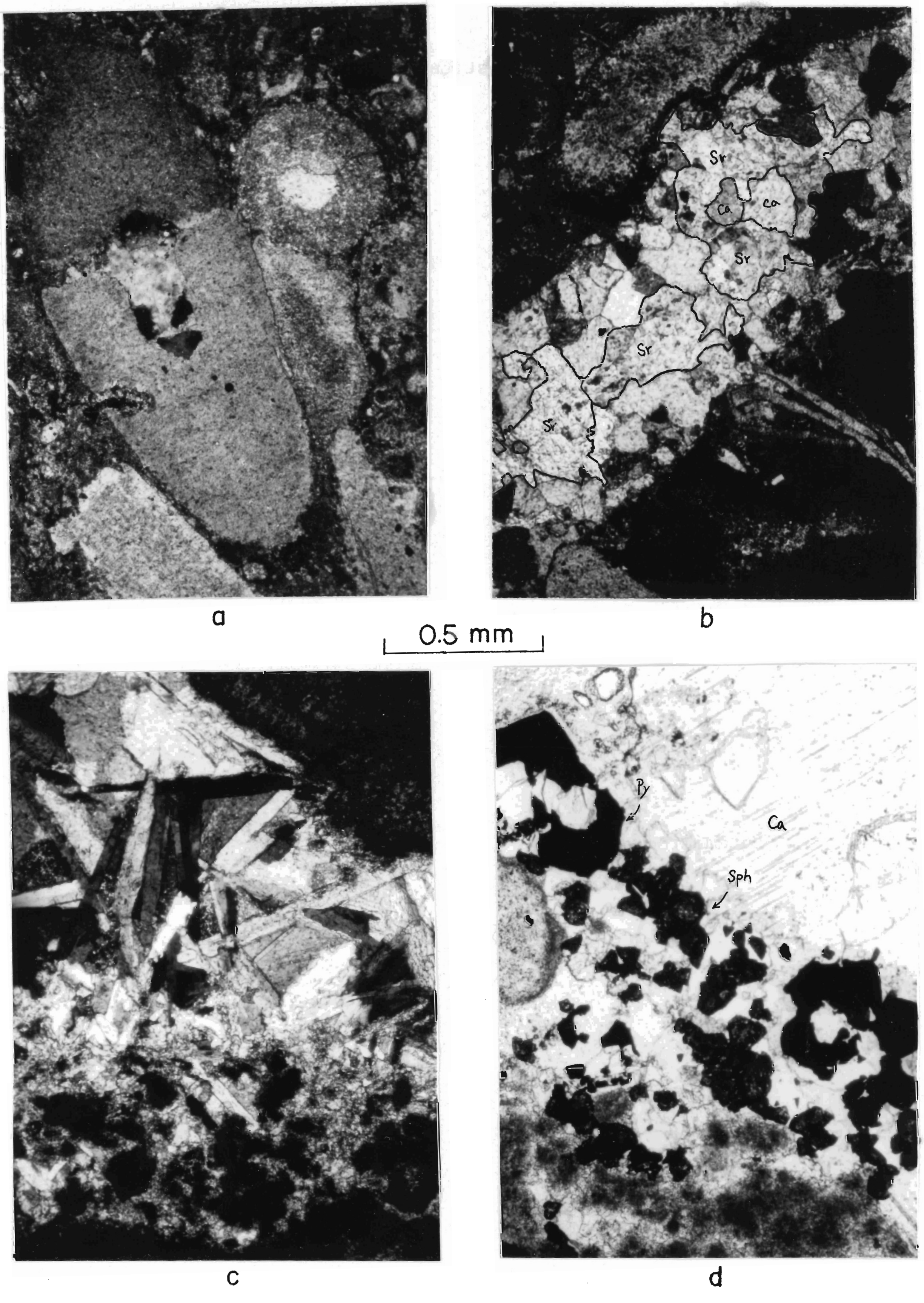
a. Photomicrograph of celestite at the center of fossil. Sample S-354, DDH 54, 126 feet, in Lower Limestone. Celestite followed fracture and filled center of fossil.

b. Photomicrograph of celestite-calcite vein in fossiliferous Lower Limestone. Sample S-79, DDH 57, 242.2 feet as Plate III-e. Sr; celestite; remainder of vein; calcite.
Texture of celestite; subhedral to anhedral, interlocking, partly interstitial.

c. Photomicrograph of celestite-calcite vein filling cavity. Sample S-78, DDH 57, 242.2 feet, in Lower Limestone. Celestite: narrow lath form or acicular form, euhedral to subhedral.
Below: fragmentation of host limestone by celestite-calcite vein is shown.

d. Photomicrograph of calcite vein containing pyrite and sphalerite. Sample S-276, DDH 73, 3017 feet, in Lower Limestone. Py - pyrite, Sph - sphalerite, Ca - calcite.

Plate 23


Sr
Ca
ca
Sr
Sr
Sr
a
0.5 mm
b
Py
Ca
Sph
c
d

Some have been replaced by celestite, and some others are mainly celestite with minor amounts of calcite or aragonite. The amount of such celestite is very minute, and all is found with open-space-filling celestite in fossiliferous limestone. (See Plate 23-a).

(4) CELESTITE-CALCITE VEINS

Veins containing calcite and celestite are found in bedded celestite, open-space-filling celestite, barren limestone, and igneous basement. Some of the veins appear to cut bedding planes in limestone. The proportion of celestite in such veins varies from a trace to 85 per cent. Iron minerals are associated with the veins in many places. (See Plate 23-b, c and d.)

The amount of celestite in veins is less even than the celestite that replaces fossils.

(5) CELESTITE IN CALCIUM SULPHATE

Celestite is generally known as a common minor constituent in calcium sulphate along with magnesite, hematite, carbonaceous pigment, pyrite and barite. Celestite occurs as isolated grains and as patches or nodules in calcium sulphate of this area. These always contain disseminations of calcite or silty calcite. Nodules and isolated grains are broken and traversed by calcium sulphate. Isolated grains range up to 0.5 mm and nodules up to 50 mm in length.

CHAPTER VI

GEOCHEMISTRY OF CELESTITE

INTRODUCTION

The structural, stratigraphical, and mineralogical character of the Enon Lake deposits have been described. To establish an hypothesis regarding the origin of these deposits, the geochemistry of strontium must be considered, and the literature on celestite deposits is therefore reviewed. There is apparently very little information on geochemistry of celestite in English literature, and the following is drawn mainly from the Russian literature available in translation.

Strontium, symbol Sr, atomic number 38, atomic weight 87. 62 is a typical alkaline earth element situated in group IIA in D. Mendeleev's periodic table between calcium and barium. The chemistry of strontium closely parallels that of calcium. Sr^{++} has a radius for 6-coordination of 1.12 angstrom which is slightly larger than 0.99 angstrom, the radius of Ca^{++}.

Celestite is a member of the barite group of minerals and celestite has the same crystal structure as orthorhombic barite. The principal substituent for strontium in the structure of celestite is barium, which produces the complete solid solution series between celestite and barite. At ordinary temperatures only limited solid solution of $CaSO_4$ in $SrSO_4$ appears to be possible (approximately 12 per cent, $CaSO_4$).

STRONTIUM CONCENTRATION IN CHLORIDE WATERS

A. N. Kozin (1968) pointed out that the Sr concentration in water depends on a combination of several factors, including the content of the sulphate ion, the calcium content in chloride waters and their salinity, etc. His conclusions are as follows:

EFFECT OF SULPHATE ION CONTENT

In Fig. 2, the points showing the dependence of strontium content in waters on the content of the sulphate ion are bounded by a curve, which represents the inverse relationship between the concentration of strontium in waters and their sulphate content when the solubility produce is exceeded. When the ion products are less than the solubility product, the concentration of strontium in waters does not depend on their sulphate ion content.

EFFECT OF CALCIUM ION CONTENT

The content of strontium in the chloride waters depends directly on their calcium content (Fig. 3). The contents of strontium and calcium increase simultaneously in all ground and surface chloride waters, but Ca/Sr ratio is different in the ground waters from different stratigraphic zones.

EFFECT OF SALINITY

The effect of salinity (117-340 g/liter) on the concentration of

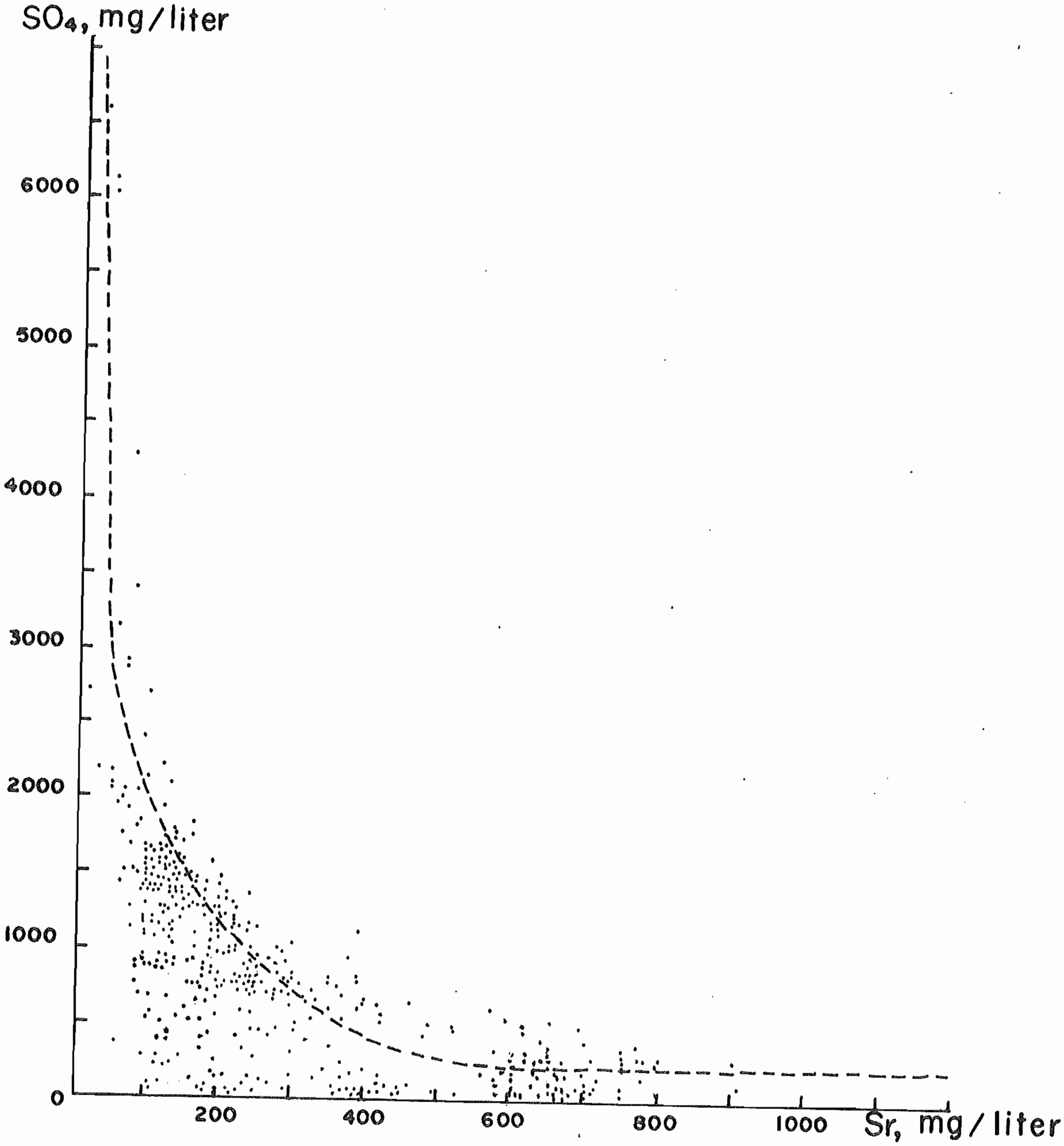


Fig. 2. Strontium content in chloride ground water as a function of sulphate ion content (after Kozin, 1968)

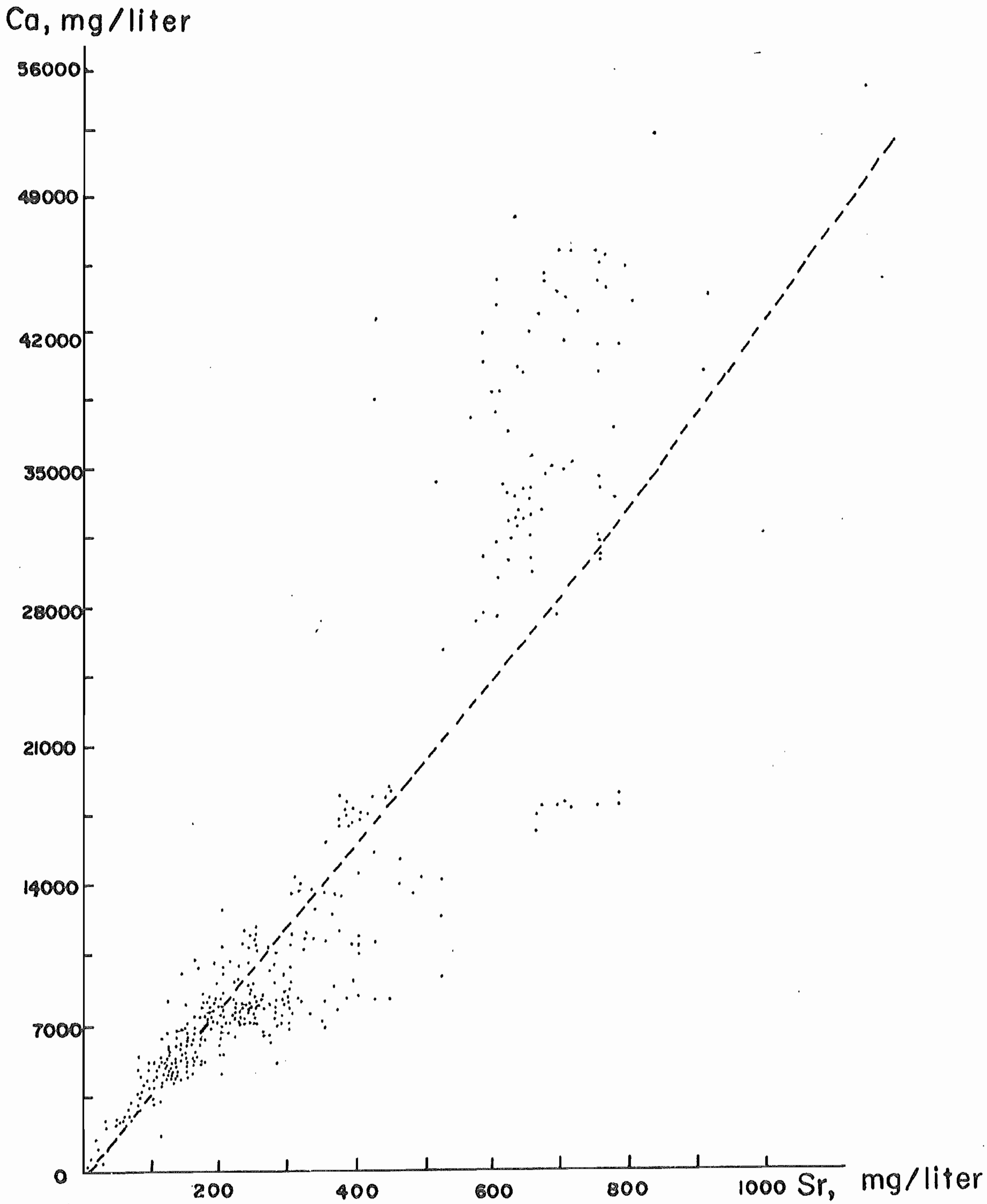


Fig.3. Strontium content in chloride ground waters as a function of their calcium content (after Kozin, 1968)

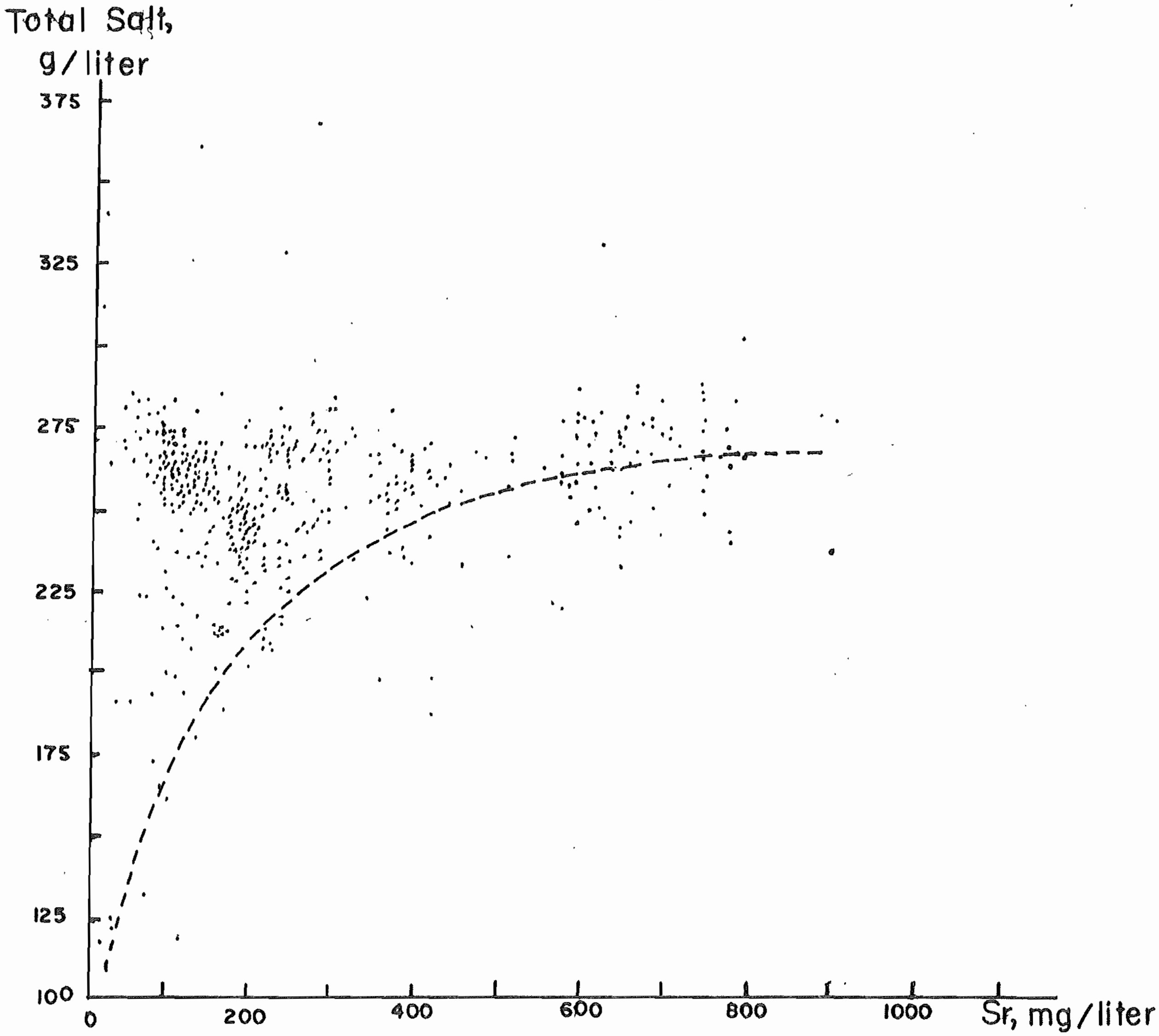


Fig. 4. Strontium content in chloride ground waters as a function of salinity

(after Kozin, 1968)

strontium is very limited, irregular, and impossible to evaluate (Fig. 4). The curve of Fig. 4 merely suggests a relation between strontium content of water and salinity. It shows that in the early stages of concentration of waters the content of strontium increases slowly with increasing salinity, and that, in the later stages, the effect of salinity on strontium content becomes indefinite.

Also, according to Kozin, the highest concentration of strontium in sea water (35.5 mg/liter) corresponds to the beginning of precipitation of gypsum; it decreases to 25.2 mg/liter by the time halite begins to crystallize.

SOLUBILITY OF CELESTITE

According to Strübel: "The hydrothermal reaction of solubility of celestite shows a strong retrograde trend along the boundary of the three-phase region in the temperature-solubility diagram from 114.1 mg $SrSO_4$/Kg H_2O at 22°C to 2.6 mg $SrSO_4$/Kg H_2O at 350°C. (Table 4 and Fig. 5). (His curves, however, (Fig. 5) show a wide range of values as determined by various investigators.) The same trend is shown by the curves of solubility in the ternary system $SrSO_4$-NaCl-H_2O, which were experimentally investigated for 0.1n, 0.5n, 1.0n and 2.0n NaCl solutions in the temperature range of the aqueous mixed phases from 20°C to the boiling point at intervals of 10°C. They were represented as isotherms of solubility. (Fig. 6). It was shown that minor amounts of halite in the solution increased the solubility by 100 per cent or more."

Table. 4. Experimentally determined Solubility of $SrSO_4$ in Water along the Equilibrium Curve of Liquid Water-Water Vapor between 22°C and 350°C.

T (°C)	P (Bar)	D (g cm⁻³)	S (mg $SrSO_4$/kg H_2O)
22.0		0.9977	114.09 ± 0.81
30.5		0.9955	113.31 ± 0.44
50.0		0.9881	109,45 ± 0.93
75.5		0.9740	90.33 ± 0.57
89.5		0.9657	74,24 ± 0.91
100.5		0.9579	66.30 ± 0,41
150.5	4.8	0.917	47.1
200.0	15.6	0.865	23.8
250.0	39.8	0.799	11.3
300.0	85.9	0.712	6.2
350.0	165.4	0.572	2.6

(from Strübel, 1966)

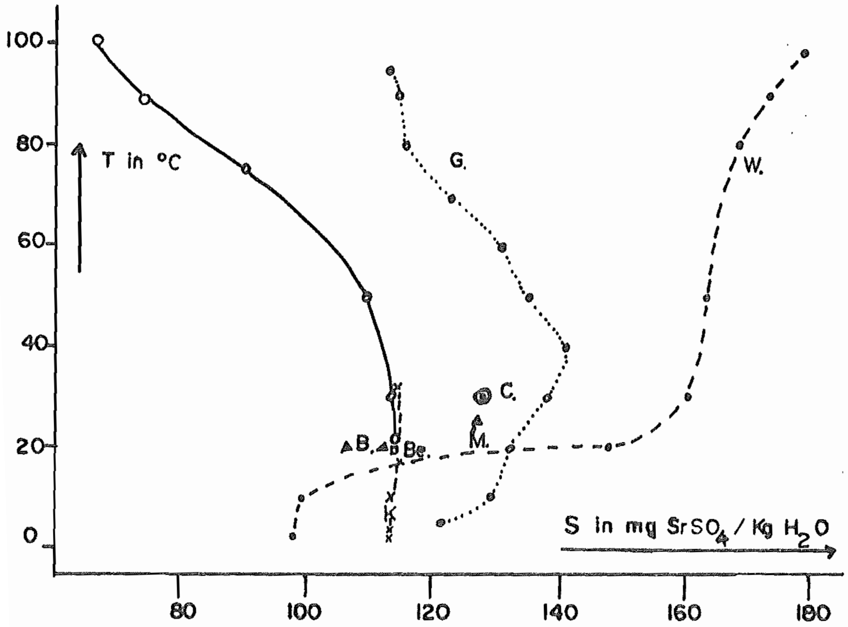


Fig. 5. Solubility of $SrSO_4$ (in mg) in 1 kg H_2O. THE VALUES OF BOOTH & POLLARD (B), BELFIORI (Be), CAMPBELL & COOK (C), GALLO (G), KOHLRAUSCH (K), MÜLLER (M) & WOLFMANN (W) ARE SHOWN FOR COMPARISON. (from Strübel, 1966)

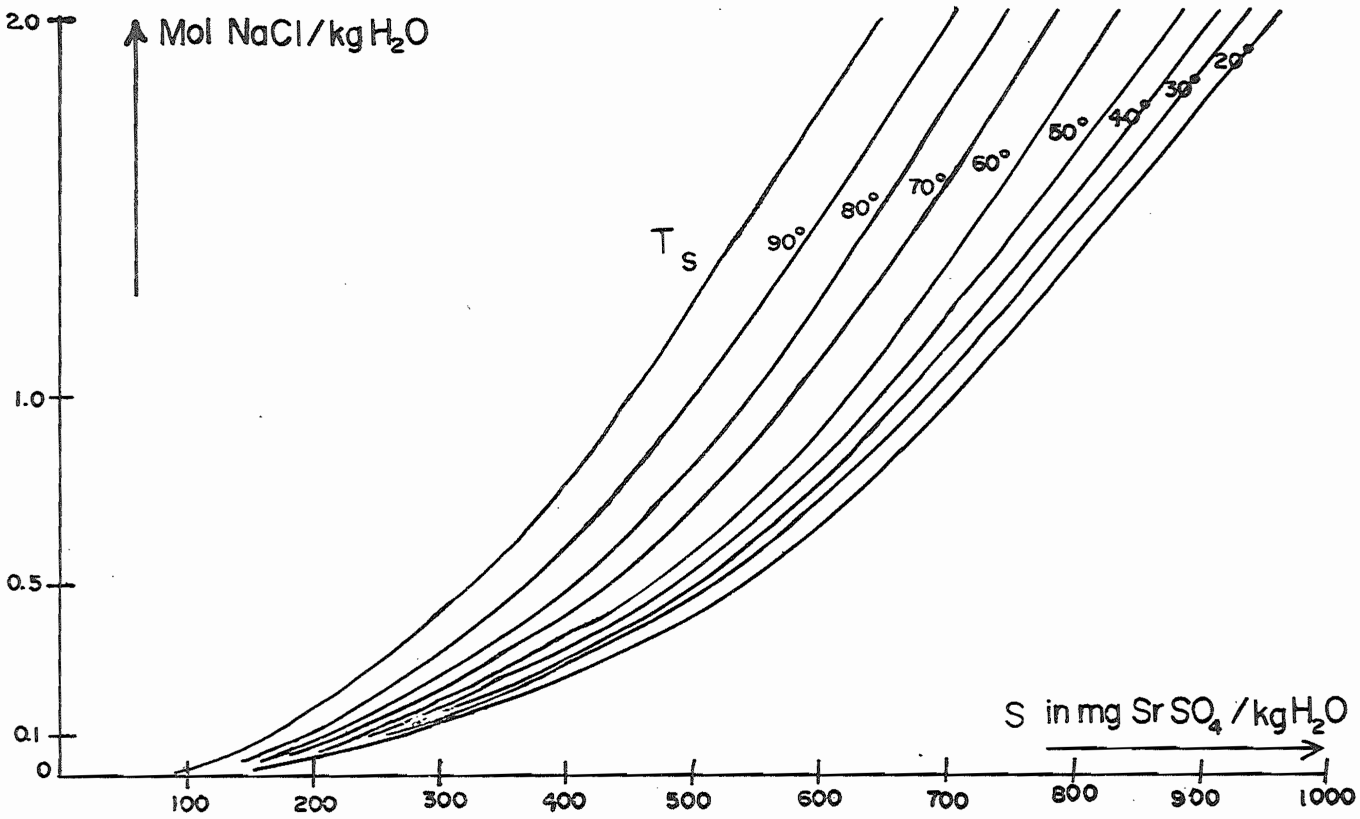


Fig. 6. Isotherms of solubility of celestite in NaCl-Concentration-Solubility Diagram (from Strübel, 1966)

DISTRIBUTION OF STRONTIUM IN ROCKS

Strontium is present in igneous rocks in amounts between 0.003 and 0.1 per cent, and in sedimentary rocks (other than evaporite) in amounts between 0.002 and 0.06 per cent. In gypsum and anhydrite, the average content of strontium is 0.2 per cent. In natural waters, the average content of strontium is as follows: (Vlasov, ed., 1964).

River Waters ---------	0.00000n	- 0.0000n per cent
Fresh Waters ---------	0.000n	- 0.00n per cent (SrO)
Sea Water ------------	0.0007	- 0.0014 per cent (SrO)

The strontium content in rocks of each clan is highly variable.

In sedimentary rocks, generally, the highest strontium content is characteristic of the sulfatolites and carbonate rocks.

"In the sulfatolites, the strontium content is fairly constant and apparently independent of the age of the rock and its geographical location. The average strontium content in gypsums and anhydrites is 0.2%. Primary gypsums invariably contain less strontium than primary anhydrites, since the anhydrite lattice is more amenable to strontium than the gypsum lattice. During the dehydration of gypsum we should therefore expect an increase in the strontium content in the anhydrites formed, and during anhydrite hydration - a decrease in the strontium content in the gypsums formed.

Among all the carbonate rocks, the highest degree of strontium concentration occurs in dolomites and dolomitized limestones because of the presence of syngenetic celestite in these rocks. Sometimes the strontium content in these rocks may amount to several per cent." (Vlasov, ed., 1964).

S. M. Katchenkov (1959) observed that argillaceous carbonate rocks generally contain more strontium than "pure" carbonates.

STRONTIUM CONCENTRATION IN SEDIMENTARY ROCKS

The process of strontium concentration in sedimentary rocks can be subdivided into four stages; preliminary, sedimentary, diagenetic, and epigenetic. (Vlasov, ed., 1964).

"The preliminary stage is characterized by the leaching of strontium from igneous and sedimentary rocks, its transport by surface waters, and accumulation in sea and lake basin, the final stages of the drainage cycle.

Although the strontium content of sea water is much higher than that of river water, the amount of strontium present in the seas is still well below the saturation level, so that direct chemical precipitation of this element is possible only in special conditions, namely in evaporite basins of arid climatic zones. The principal features of this process were understood following study of the conditions of celestite formation in sulphate-carbonate Permian strata of the eastern part of the Russian platform. (Miropol'skii, 1927; Vinogradov and Borovik Romanova, 1945; Strakhov and Boreneman Starynkevich, 1946). It was established that an increase of salinity in the sea basin, as a result of the evaporation of water, led to increase in the basic salt content in the brines and to a gradual increase in the concentration of fluorine, boron, bromine, and strontium, which finally attained saturation point and started to precipitate. Strontium precipitation attains a maximum when the brine becomes saturated in gypsum and celestite commences to precipitate (at the end of the carbonate and at the very beginning of the sulfate stage of halogenesis). The average density of the brine at this point is 1.22, and its salinity 8-15 per cent NaCl. With further salinity increases in the basin during the sulfate stage of sedimentation, an extended precipitation of celestite, together with gypsum and anhydrite, occurs, but quantitatively this precipitation distinctly decreases ....

The Kara-Bogaz-Gol Gulf is a recent analog of the strontium-accumulating evaporite basins of the geological past. In this gulf, which communicates with the Caspian by a narrow strait replenishing its sea-water reserve, strontium-rich carbonate-sulfate and saline sediments are formed ....

In humid climatic zones, strontium mostly concentrates during biogenic processes. Strontium is concentrated in the tissues of various marine and river invertebrata. It is also assimilated by algae. The strontium content of shells and tissues of invertebrates depends directly on the concentration of strontium in the water in which these organisms live ......

Considerable accumulations of strontium minerals in sedimentary rocks (concretions, concretionary intercalations, etc.) are formed during diagenesis and epigenesis. Unfortunately, the physiochemical features of the diagenetic redistribution of strontium in sediments have not been studied adequately, and at this stage can only be outlined ......

Epigenetic concentrations of strontium minerals are formed after sediment lithification, when strontium has been leached by ground waters from primary concentrators of strontium and subsequently transported and reprecipitated from the mineralized waters either in the parent horizon or in overlying and underlying strata.....

Strontium is precipitated from mineralized ground waters when certain changes occur in their hydrochemical regime ......

Epigenetic celestite strata are frequently formed as a result of metasomatic reactions between mineralized ground waters and carbonate or sulfate rocks."

Sherlock (1938, 3rd ed.) gives a probable explanation of the Yate celestite deposits, Gloucestershire, England. The celestite is found in masses or lenticles at a definite horizon in marl and dolomitic conglomerate, formed, as it would seem, by precipitation from the waters. Gypsum occurs not far below the base of the marls or even in them.

"At the time of their deposition a river containing traces of strontium salts in solution entered, near Yate, a land-locked inland sea. These salts were precipitated as sulphate by sea water saturated with calcium sulphate. $SrSO_4$ is highly insoluble and very readily precipitated by sulphates. The effect of the dilution of the sea water by river water, and also to some extent the lowering of the concentration of calcium sulphate by interaction with soluble strontium salts, would cause the amount of $CaSO_4$ in solution to sink below saturated point locally and prevent gypsum being deposited. This may be confirmed by the fact that although celestite occurs on the gypsum horizon and although gypsum is found nearby, the two minerals are never mixed."

CLASSIFICATION OF STRONTIUM DEPOSITS

Strontium in the Earth's crust is present in both the dispersed state and in the form of independent minerals. Celestite and strontianite are the most common strontium minerals and celestite alone is the principal

TABLE 5

Formation and genetic classification of strontium deposits

Type of deposit			Climate	Tectonic setting	Facies of ore formations	Paragenesis of surrounding strontium-bearing rocks	Nature of mineralization	Associated minerals and ores	Degree of mineralization	Examples of deposits
ore-forming stage	principal type of ore-forming process	strontium-bearing formations								
	Chemogenic (source of strontium — waters of the hydrosphere)	Sulfate-carbonate	Arid	Syneclises of old and epi-Paleozoic platforms; foredeeps; occasionally — geosynclines in their final development stages	Evaporite basins of varied facies (lagoons, epicontinental seas and their gulfs)	Dolomitic limestones, dolomites, gypsums and anhydrites	Celestite impregnations in rocks, occasionally celestite concretions and geodes	Gypsum, fluorite, halite	Mineralization occurs over large areas but never attains economic concentrations	Ore shows in Permian rocks of the Russian Platform
		Red gypsiferous marl		Syneclises of old and epi-Paleozoic platforms	Alluvial plains with lacustrine and relic lagoon-evaporite basins	Red marls with gypsum concretions and lenses	Celestite concretions and concretionary intercalations	Gypsum, fluorite, barite, cuprous compounds	Economic deposits occur	Yate, England (Triassic), Vikhtovo, USSR (Permian); Valyn River, USSR (Ordovician)
		Mottled sulfate — terrigenous		Syneclises in activated zones of epi-Paleozoic platforms	Intracontinental evaporite basins in regions with dissected topography	Variegated clays, siltstones, and sandstones with gypsum and dolomite interlayers	Beds of stratified concretions of cryptocrystalline celestite (in terrigenous rocks), celestite inclusions (in dolomites and gypsums)	Gypsum, barite	Large economic deposits	Fergana (Upper Cretaceous, Paleogene)
	Volcanic chemogenic (source of strontium — volcanic solutions)	Continental effusive-sedimentary		Inner troughs of geosynclines in their final development stages	Continental lacustrine basins in regions of active volcanism	Tuffs, tuffogenic sandstones, and clays with effusive interlayers	Beds of celestite and strontianite intercalations and concretions	Borates, iron and manganese oxides, chalcedony	Rare; very large economic deposits	California, USA (Miocene)
	Biochemogenic	Carbonate-glauconitic	Humid	Platform syneclises and troughs	Shallow-water epicontinental seas of normal salinity	Limestones (frequently zoogenic), marls, calcarous sandstones	Celestite concretions, zoo- and phyto-morphs	Barite, glauconite, phosphorites, limonites	Small-scale deposits (only in Mesozoic formations)	Mangyshlak, USSR (Upper Cretaceous)
	Crystallization from strontium-bearing solutions in veins, geodes, etc. (filling bodies)	No clear genetic relationship to definite formations	Varied climatic conditions	Mainly folded zones, and in the crests of anticlinical structures	No genetic relationship with definite facies	Limestones, dolomites, marls	Celestite geodes	Gypsum, calcite, chalcedony	Uneconomic ore-shows	Ore-shows in the Valanginian limestones, Northern Caucasus
						Clays	Parallel-columnar celestite veins	Calcite	Small-scale uneconomic deposits	Kok-Tav Mountains, Turkmen SSR (Oligocene)
						Limestones, dolomites, marls	Celestite and strontianite veins	Calcite, barite	Relatively large deposits	Westphalia, West Germany (Upper Cretaceous)
	Metasomatic replacement of celestite for sulfate and carbonate rocks (replacement bodies)					Gypsums, anhydrites with clay and sandstone horizons	Celestite lenses and lenticular beds of irregular form	Calcite, gypsum, barite, native sulfur crush zones, etc.	Large deposits	Soviet Central Asia, USSR (Neogene)
						Limestones, dolomites, marls	Irregular bodies, composed of celestite and confined to crush zones, etc.			Soviet Central Asia, USSR (Neogene)

Vlasov, ed. 1964

mineral source of strontium in commerical quantity. The other strontium minerals are rare.

Strontium is distributed in rocks during the magmatic, pegmatitic, hydrothermal, or metamorphic processes, besides sedimentary processes. In most igneous rocks, no independent strontium minerals or deposits are formed; strontium is more commonly dispersed in rocking-forming calcium and potassium minerals. The content of strontium minerals in pegmatite is very low, and they are thus without economic value. Metamorphic rocks are occasionally known to contain celestite segregations along fissures, and very rarely, small-scale epigenetic ore "showings" of this mineral. From the economic standpoint, some consideration should be given to the low-temperature hydrothermal celestite and strontianite deposits. These deposits, however, are quite rare and the ore reserves of known deposits of this type are inferior to those of sedimentary deposits which at present serve as the principal source of strontium raw material.

Vlasov (1964, ed.) divided strontium deposits into two large groups, namely sedimentary-diagenetic and epigenetic (redeposited) deposits. The deposits of the first group were classified in more detail into several types based upon their relationships to formations of definite sedimentary origin such as the nature of mineralization, conditions of ore occurrence, extent of deposits, etc. The classification of epigenetic deposits lacking clearcut association with definite formations was based on the morphology of the ore bodies and the nature of the surrounding rocks. (Table 5).

General character of the celestite deposits at Enon Lake is similar to those of chemogenic type (source of strontium - waters of the hydrosphere) of this classification. Within this group, however, the Enon Lake deposits do not fit exactly into any of the three subdivisions shown in Table 5. This is because the mineralization here appears as layers of celestite, rather than as concretions or disseminations of celestite within carbonate or sulphate beds. This probably reflects only an unusually high concentration of celestite, rather than a unique process of formation.

CHAPTER VII

DISCUSSION

SUMMARY OF OBSERVATIONS

The major problem involved in the study of celestite deposits at Enon Lake is to determine the history of celestite mineralization in an attempt to analyse structural and mineralogical factors which controlled ore localization.

The celestite deposits occur as layer or lenses at the base of the Windsor group which unconformably overlies the Devonian igneous basement complex. Are the celestite deposits of epigenetic origin and restricted to certain horizons by the physical and chemical properties of the horizons? Are the celestite deposits confined to certain stratigraphic horizons in the sense that they represent an initial precipitate in these layers? Are they the products of diagenetic migration or modification? Field and laboratory work has been carried out to find answers to these questions.

The basement complex at the mine site consists of granitic and dioritic rocks which have been intensely altered. Rocks of the basement were invaded by some thin diabase dikes. The granitic rocks range in composition from granite to granodiorite. There is also a rock type which closely resembles rhyolite. Diorite, gabbro, and their fine-grained equivalents, are less widely distributed.

The bulk of the Windsor group is limestone, conglomerate, siltstone, gypsum and anhydrite. The stratigraphic section of the mine area has been subdivided into several lithologic units: Silstone and Limestone, Upper Conglomerate, Middle Limestone, Calcium Sulphate, Middle Conglomerate, Lower Limestone, Basal Conglomerate and Basement. The lithologic facies change very rapidly laterally as well as vertically. These facies changes reflect the paleotopography of the basin in which each rock unit was deposited. The thickness of the Windsor group at the mine site ranges up to 510 feet.

Celestite mineralization is confined lithologically within limestone or calcareous beds. Most of the celestite occurs as a few layers or lenses in the Lower Limestone underlying the Calcium Sulphate. Some of the high grade celestite mineralization, however, is found in the Middle Limestone and in the limestone interbedded in the Calcium Sulphate sequence. In each unit, the thickness and tenor of the ore zones are irregular and variable.

Structural analysis of ore localization reveals control of ore in two directions: the major ore zones are parallel to the direction of dip of the Windsorian sedimentary bedding and the subsidiary ore band are parallel to the direction of the strike of the bedding. Generally, ore in a rock unit occurs more extensively along the flank of its paleotopographic ridge where the unit has the same dip as the ridge upon which it was deposited, and it pinches out against the ridge where the dips are contrary, and towards valley or bottom of the paleobasin.

Celestite, limestone, limy siltstone, conglomerate, gypsum and anhydrite are interrelated in their occurrence in the Windsor group.

The relationships may be summarized as follows:

(1) Bedded Celestite, up to 95 per cent $SrSO_4$ by weight and containing disseminations of calcite, silt, and iron minerals, occurs as interbeds in Lower Limestone, the Calcium Sulphate sequence and Middle Limestone. It varies from half an inch to 9 feet in thickness and the thickness is irregular. In places the bands are not continuous, but break off suddenly, and commence again further on, at or near the same level.

(2) Celestite as open-space-fillings is frequently observed in cavernous limestone, silty limestone, calcareous siltstone and conglomerate. This type of mineralization is also confined within well defined stratigraphic zones in the Lower Limestone and the Middle Limestone. This type of celestite, however, forms detached bodies and does not form continuous beds in the strict sense. Such celestite occurs as fillings of the interstices in biopelsparite, particularly in that which is fractured and fragmented, and as vug fillings in dismicrite.

(3) Celestite replacing fossils is found only with celestite that fills open spaces in fossiliferous limestone. The amount of celestite replacing fossils is very minute.

(4) Thin veins containing calcite and celestite are found in limestone and in the igneous basement.

(5) In calcium sulphate, trace amounts of celestite occur as isolated grains and as patches or nodules, which always contain disseminations of calcite or silty calcite.

PREVIOUS HYPOTHESES

The first mention concerning origin of celestite deposits at Enon Lake is by A. D. Hudgins (1969). It is as follows:

> "It is believed that the celestite mineralization is partly related to hydrothermal (telethermal) solutions of magmatic origin that were derived from late Post-Carboniferous dioritic intrusions in the region. These solutions moved upward along a major northeasterly-trending fault, co-mingled with deep circulating chloride-rich brines and leached strontium salts from the strontium-rich evaporite beds in the center of the basin. The solutions moved laterally along the unconformity and migrated upward through permeable zones in lower members of Windsor-age rocks. Impounding of the solutions took place below impervious shales and limestones; precipitation and replacement by $SrSO_4$ occurred in favourable sulphur-rich petroliferous limestones and calcareous arenaceous rocks."

In this work, no post-depositional effect, which might be attributed to hydrothermal solution, was observed. Neither alteration of wall rocks nor metamorphic halo of alteration was observed around celestite mineralization. The only noticeable post-depositional effect is celestite replacement by calcite.

Hydrothermal deposition of celestite appears to be unacceptable due to its retrograde solubility. The solubility of celestite shows a strong retrograde trend along the boundary of the three-phase region in the temperature-solubility diagram; by two orders of magnitude from 350°C to 22°C, as seen in Table 4. This implies that, as the temperature of a hydrothermal solution decreased, solubility of celestite would increase. Although such a solution would leach celestite from the evaporite beds, as Hudgins proposes, deposition of celestite would be impossible if the temperature of the solution is reduced, as the theory implies it must be.

It is, of course, theoretically possible that a solution could leach Sr from carbonates or other rocks in the basin, and that celestite could be deposited in the presence of a very high concentration of $SO_4^=$ ion, despite the effects of increasing solubility with decreasing temperature. It is, of course, necessary only to exceed the solubility constant for $SrSO_4$. This implies, however, that the celestite should be formed in the sulphate horizons, and not in the carbonate zones where it is, in fact, formed. Furthermore, there has been found no sign of the alteration minerals one would expect to find in the siltstones and carbonates, if a low temperature hydrothermal solution had been acting.

Some subsidiary faults were observed during the core logging, but celestite mineralization was not observed along them.

Most of the celestite mineralization took place in limestone, silty limestone below calcium sulphate or conglomerate, but not always below impervious shales or limestones. Several high grade ore bodies are actually isolated lens forms, which do not show any evidence that they were transported laterally or upwardly.

Two more theories, not incorporating the use of hydrothermal solutions, were suggested recently by G. D. Crowell (1971):

A. Co-precipitation of $SrSO_4$ and $CaSO_4$ during early diagenesis, whereby both sulphates would be deposited as both void fillers and as displacement phenomena. The occurrence of shell cavities and primary fabric porosity in addition to what seem to be $SrSO_4$ and $CaSO_4$ displacement nodules would lend support to that idea.

B. Replacement of the Ca^{++} ion in the $CaSO_4$ with the Sr^{++} ion to give $SrSO_4$ during the late diagenesis. A possible reaction would be $SrCl_2 + H_2O \rightarrow SrSO_4 \downarrow + CaCl_2 + H_2O$. The textural observations and the intimate association of $SrSO_4$ with $CaSO_4$ would lend support to this idea.

These theories were based on the information which had been gathered to date. Some of the data here reported were not available to Crowell, and his conclusions are significantly different from the writer's opinion. His main data are as follows:

> Four significant ore horizons have been developed to date. Each of these is in a different stratigraphic position. Two of the ore zones are in limestone and two are in ferruginous siltstone.
>
> He also pointed out several facts pertinent to the origin:
>
> 1. Significant celestite has been noted only on the eastern side of the Loch Lomond Basin - barite has been noted on the west side.
>
> 2. The celestite mantos occur around the flanks of igneous basement highs.
>
> 3. The celestite always changes facies laterally to gypsum in at least one direction, generally away from the basement high.
>
> 4. The textural appearance of the celestite in a siltstone or limestone host is almost identical to the appearance of gypsum in a similar host sediment.
>
> 5. The highest grade of celestite is always immediately adjacent to the laterally equivalent gypsum facies; the lowest grade occurs adjacent to the basement high.
>
> 6. In a few drill-hole intersections, part of the potential ore zone is gypsum and part is high grade celestite. This represents the actual transition zone.

As described previously, celestite mineralization is confined lithologically within limestone or calcareous beds. Some ferruginous host rocks may be easily misidentified as siltstone. Microscopic observation, however, has revealed them as mostly ferruginous silty micrite and a little of ferruginous calcareous siltstone. All the significant ores are in limestone or silty limestone host rocks only.

The writer interprets these facts in a somewhat different way than Crowell, as follows: (same numbers will be used for discussion).

2. Generally, celestite mineralization occurs around flanks of paleotopographic highs of each lithounit, but not around the flanks of igneous basement highs. The abrupt lateral changes of lithofacies and thickness continuously altered the paleotopography and provided a different paleotopography for each lithounit. The paleotopography of igneous basement is reflected chiefly by the Basal Conglomerate.

3. Lateral changes of lithofacies and thickness are a characteristic feature of the sedimentation of the area. Calcium sulphate facies changes laterally into Middle Conglomerate, which is believed to occupy similar time stratigraphy to Calcium Sulphate where calcium sulphate is absent. Celestite mineralization in Lower Limestone occurs below the Calcium Sulphate sequence or Middle Conglomerate.

4. The highest grade of celestite is in limestone or silty limestone below calcium sulphate or below conglomerate which occupies similar stratigraphic level where calcium sulphate is absent; the lowest grade occurs adjacent to the paleotopographic high or low.

One might comment:

A. As mentioned previously on page 86, "....... strontium precipitation attains a maxiumum when the brine becomes saturated in gypsum and celestite commences to precipitate (at the end of the carbonate and the very beginning of the sulphate stage of halogenesis) ...... With further salinity increases in the basin during the sulphate stage of sedimentation, an extended precipitation of celestite, together with gypsum and anhydrite, occurs, but quantitatively this precipitation distinctly decreases."

This is confirmed by the occurrence of celestite mineralization in limestone or silty limestone generally below calcium sulphate or conglomerate, which occupies similar stratigraphic level where calcium sulphate is absent. Co-precipitation of $SrSO_4$ and $CaSO_4$ was attained only at the latest period of $SrSO_4$ precipitation. And it is insignificant quantitatively.

B. Replacement of Ca^{++} ion in the $CaSO_4$ with the Sr^{++} ion might explain the origin of the trace amounts of celestite in calcium sulphate. Celestite in the Calcium Sulphate sequence, however, occurs in the limestone interbedded in it. Only minor amounts of celestite occur as patches or isolated grains in calcium sulphate.

CONCLUSIONS

In this study, the facts pertinent to the origin of celestite deposits at Enon Lake might be summarized as follows:

1. The celestite deposits occur at the base of Windsor group situated on the extreme eastern margin of the Bras d'Or sub-basin of the Windsorian Fundy Basin.

2. Celestite mineralization is confined lithologically within limestone or calcareous beds.

3. Most of the high grade ore occurs as layers. Celestite mineralization filling open spaces and replacing fossils is also common, and confined within well-defined stratigraphic zones.

4. In each rock unit, Lower Limestone, Middle Limestone or limestone interbedded in Calcium Sulphate, the thickness and tenor of the ore zones are irregular. Rapid lateral changes of lithofacies and thickness is also a characteristic feature of sedimentation at the whole mine site.

5. In many places, tenor of ore gradually decreases in both directions, downward and upward from a centre of higher grade until finally the rock becomes barren.

6. It is believed that some of the ore zones at different stratigraphic levels in each unit may be interconnected with each other.

7. Generally ore in a rock unit occurs more extensively along the flank of its paleotopographic ridge where the unit has same dip as the ridge upon which it was deposited, and it pinches out against the ridge where the dips are contrary and towards valley or bottom of the paleobasin.

8. The highest grade of celestite occurs in limestone or a calcareous bed below calcium sulphate, or below conglomerate which occupies similar stratigraphic level to calcium sulphate where it is absent.

9. In the Calcium Sulphate sequence, celestite is also found but mostly in limestone interbedded in it. Only a minute amount of celestite occurs as calcareous celestite patches or as isolated grains in calcium sulphate.

10. In places trace amounts of celestite are observed throughout the sedimentary sequence, while a few ore zones are confined to certain stratigraphic positions, as described previously, within restricted ranges.

11. Under the microscope, some solution channels are observed between thin celestite bands.

12. Thin ferruginous celestite bands cut the bedding planes of host limestone.

13. A few ferruginous calcite-celestite veins are observed along the fractures in igneous basement.

14. Neither alteration of wall rock nor metamorphic halo of alteration was observed around celestite mineralization. The only noticeable post-depositional effect is celestite replacement by calcite.

Some geochemical data pertinent to the origin of celestite deposits are as follows:

15. The contents of strontium and calcium increase simultaneously in all ground and surface waters.

16. The concentration of strontium in waters and their sulphate content show inverse relationships when the solubility product for strontium sulphate is exceeded.

17. An increase of salinity in the sea basin led to a gradual increase in the concentration of strontium, which finally attained the saturation point for strontium sulphate and started to precipitate. The highest concentration of strontium in sea water (35.5 mg/liter) corresponds to the beginning of precipitation of gypsum; it decreases to 25.2 mg/liter by the time halite begins to crystallize. With further salinity increases in the basin, an extended precipitation of celestite, together with gypsum and anhydrite, occurs, but quantitatively this precipitation distinctly decreases.

18. The hydrothermal reaction of solubility of celestite shows a strong retrograde trend from 114.1 mg $SrSO_4$/Kg H_2O at 22°C to 2.6 mg $SrSO_4$/Kg H_2O at 350°C.

Based on the facts described above, it is concluded that:

During the sedimentation of Windsorian, an arid climate zone was formed along the eastern margin of the Bras d'Or sub-basin. The Windsorian sea contained high amounts of Sr^{++} with Ca^{++}, Na^{+}, K^{+}, CO_3^{--}, SO_4^{--}, HCO_3^{-} and Cl^{-}, etc. but the amount of strontium present in the sea was very well below the saturation level. In some isolated bodies of sea water, salinity and temperature increased as a result of the evaporation of water. The increase of salinity led to gradual increase in the concentration of strontium and calcium simultaneously along with some other elements.

The increase of sulphate ion content and temperature, however, decreased solubility of strontium in the isolated bodies of sea water and finally led to strontium precipitation in the form of strontium sulphate, together with calcium carbonate as allochemical limestone or orthochemical limestone. These gave rise to bedded celestite and celestite as open-space-fillings. Strontium precipitation attained a maximum at the beginning of precipitation of gypsum, and most of the celestite was deposited before calcium sulphate. As salinity further increased, a minor amount of an extended precipitation of celestite occurred, together with gypsum.

During the early period of deposition, paleotopography showed a considerable range of relief and different sediments were derived from different source areas. These were reflected by rapid lateral changes in lithofacies deposited in the basin. Precipitation of strontium was also affected by these physical conditions, as well as by its chemical conditions. It resulted in irregular and variable thickness and tenor of the ore zones. In places, the site of deposition of the primary celestite might have moved from place to place at different times during the deposition. Celestite was more extensively precipitated along the flanks of paleotopographic highs, due to the more extensive evaporation of water along them because they were the margins of basins of evaporation, (possibly also because these very small sub-basins had very restricted water transfer within them?)

The deposition of these was repeated, and cyclic deposition of celestite deposits occurred.

During the diagenesis, there was replacement of fossils by celestite, some open-space-filling took place, and the brines were expelled from the sediments by compaction. The brine migrated through the permeable zones. The brines replaced Sr^{++} with Ca^{++} and leached iron from the sediments and weathered basement. With further circulation of brines, celestite was precipitated with iron minerals along certain zones which had favourable physicochemical conditions for decrease of solubility of strontium in brines. During this stage, thin solution channels were formed between thin celestite bands and secondary thin ferruginous celestite bands were formed cutting the bedding planes of the host limestone.

Circulation of diagenetic solutions, which took place also through anhydrite, leached strontium and altered anhydrite partly into gypsum.

GUIDE FOR EXPLORATION

From the foregoing investigations, discussions and conclusions, it is advised to concentrate exploration for celestite deposits on the following:

1. Along the margin of the Windsorian Fundy basin where evaporites formed in isolated bodies of sea water are expected to be found.
2. At the base of Windsor group (?)
3. In limestone or calcareous beds, especially below calcium sulphate or below any bed which occupies similar stratigraphic horizon where calcium sulphate is absent.
4. Along the flanks of paleotopographic ridge where the unit has same dip as the ridge upon which it was deposited.

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TOTAL ORE DISTRIBUTION MAP

PLATE 3

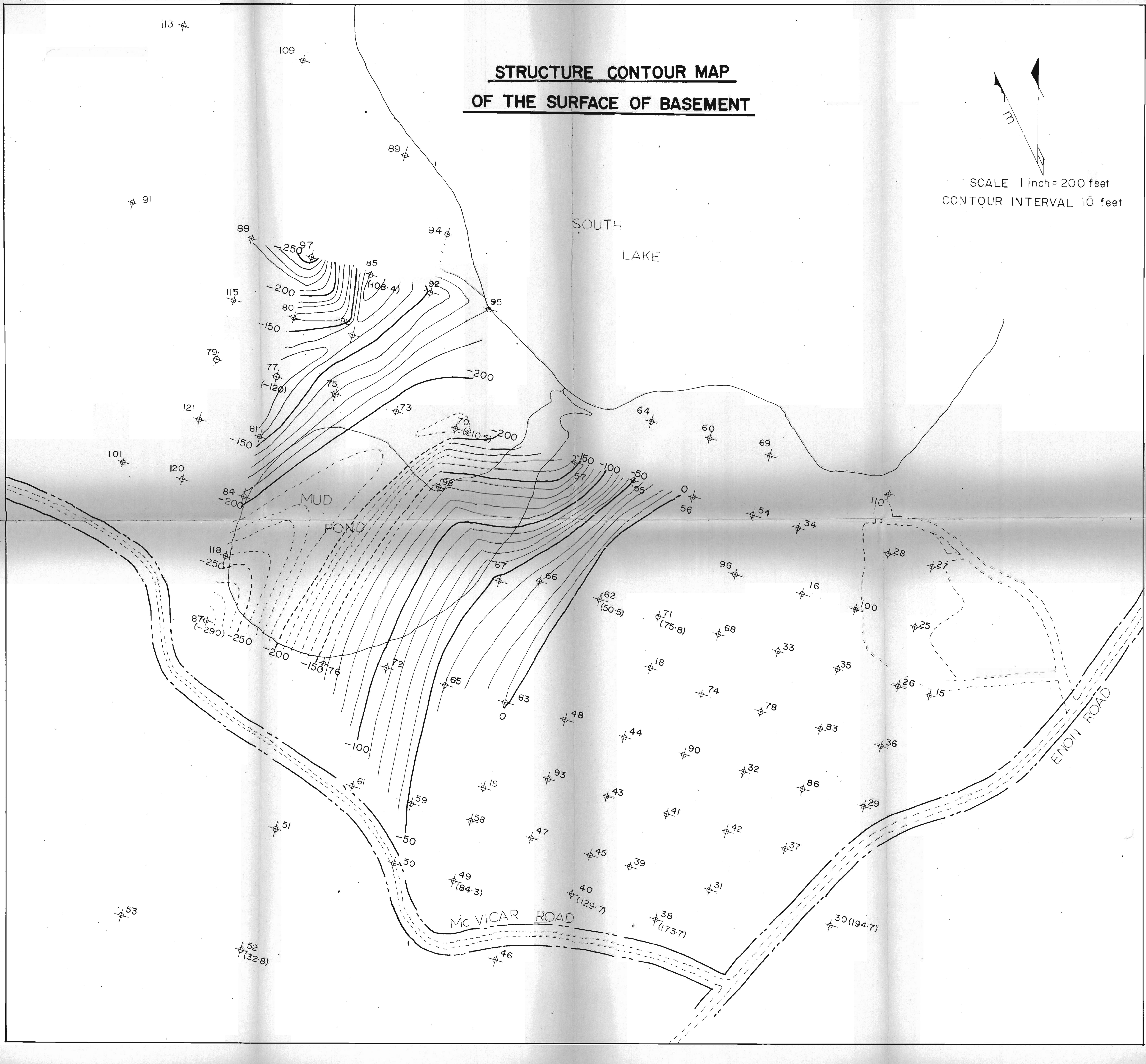

STRUCTURE CONTOUR MAP
OF THE SURFACE OF BASEMENT
SCALE 1 inch = 200 feet
CONTOUR INTERVAL 10 feet
m
SOUTH
LAKE
MUD
POND
Mc VICAR ROAD
ENON ROAD
-250
-200
-150
-100
-50
0
(108·4)
(-120)
(210·5)
(50·5)
(75·8)
(-290)
(84·3)
(129·7)
(173·7)
(194·7)
(32·8)

PLATE 4

CROSS SECTION I

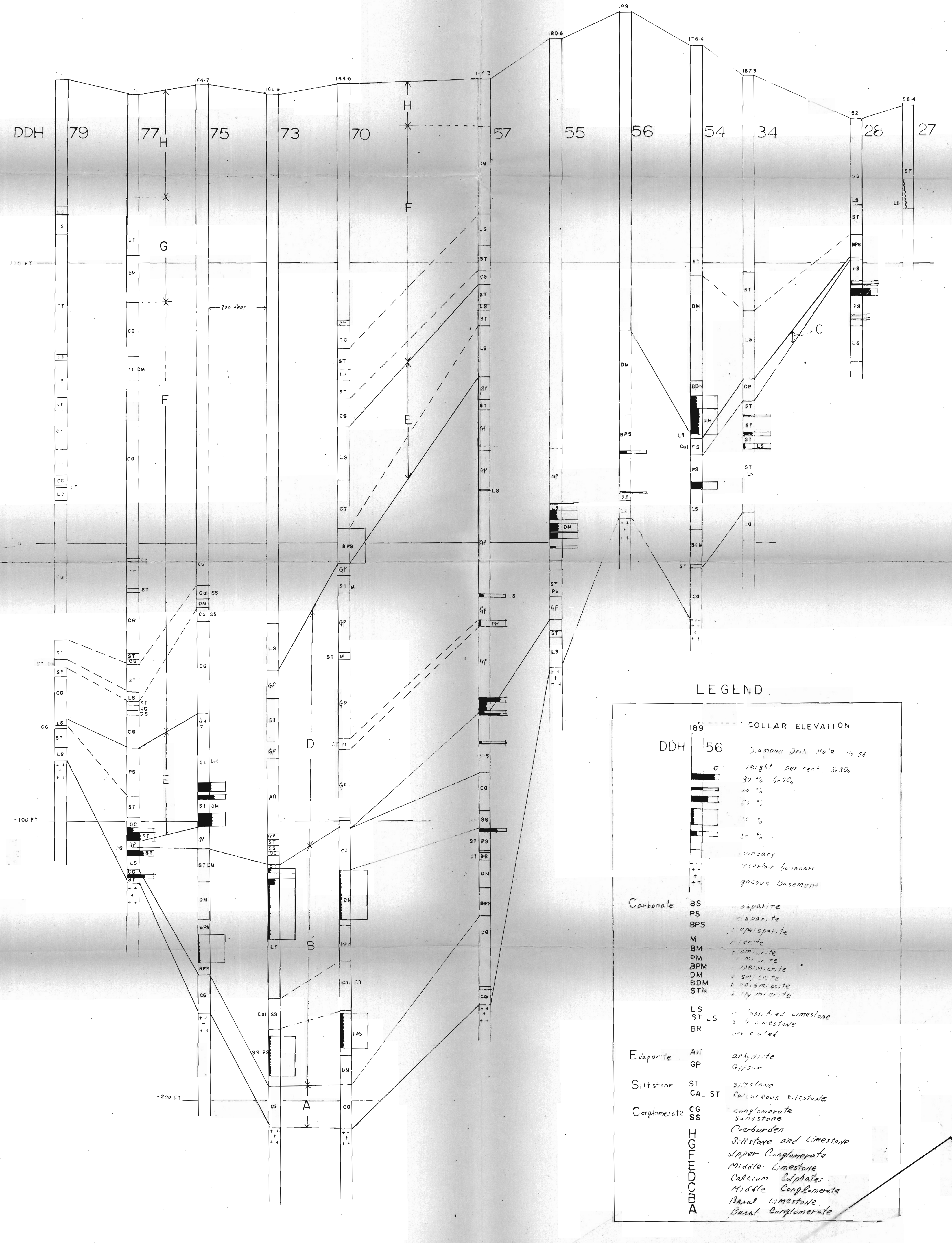
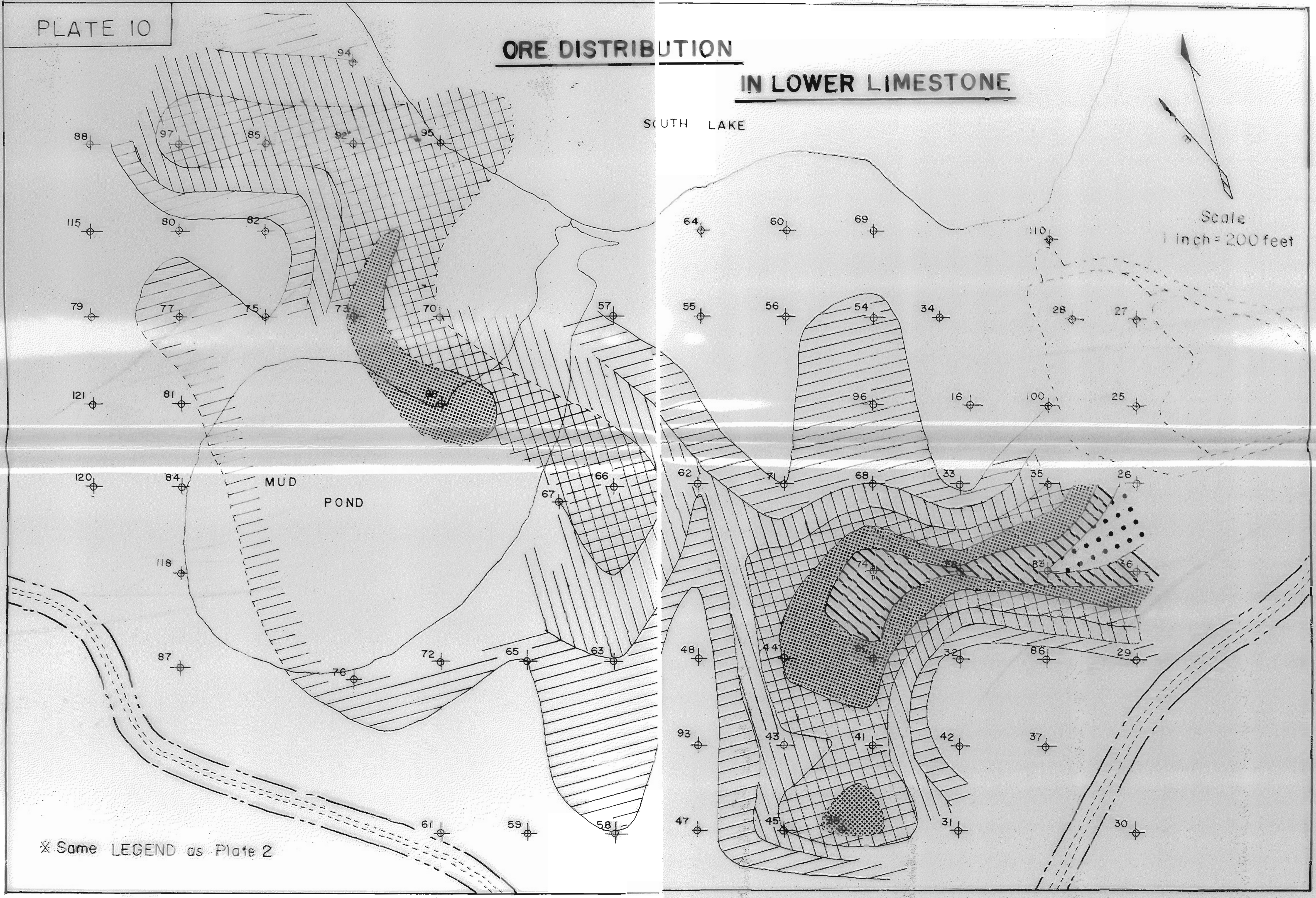


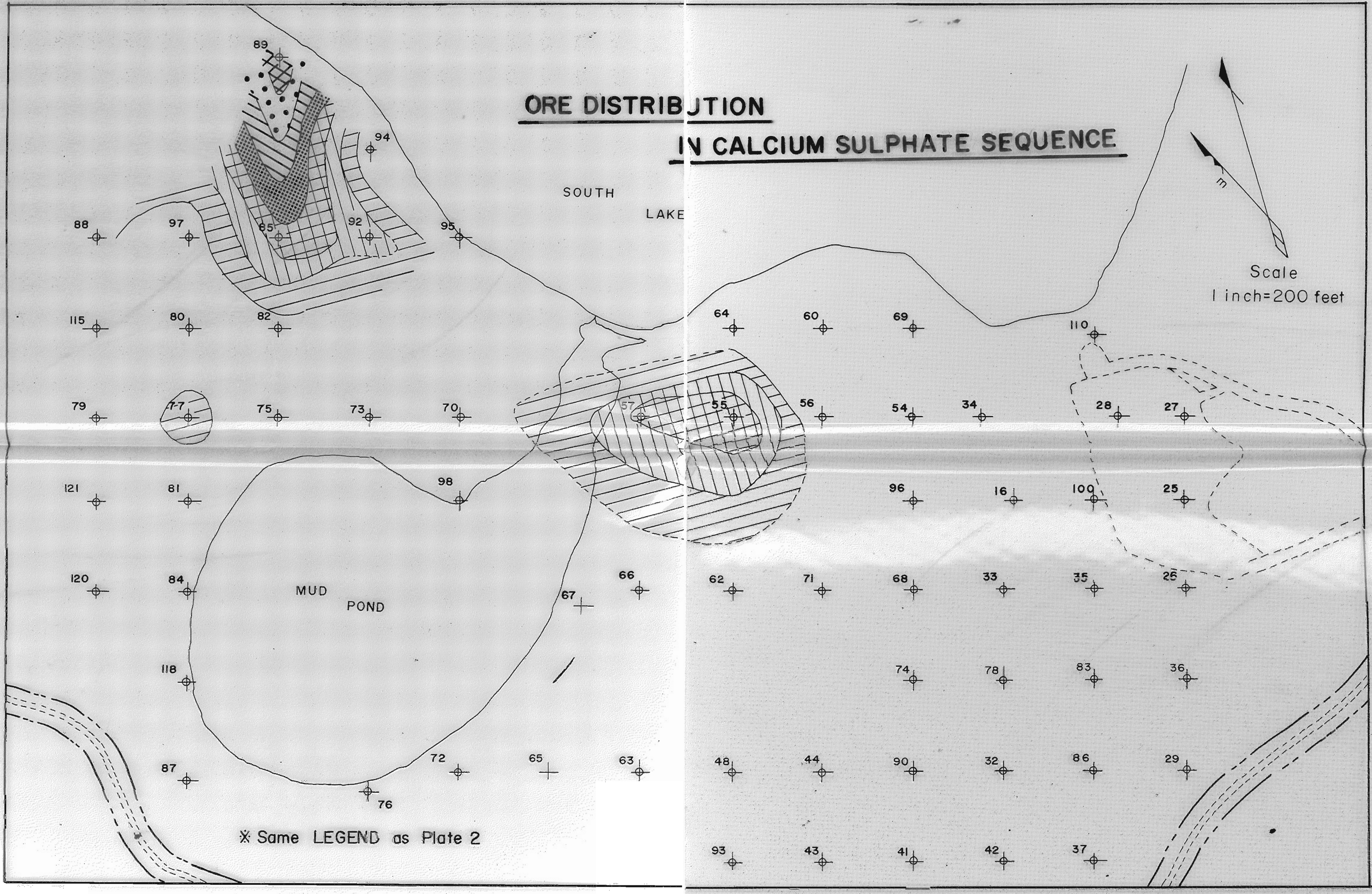
PLATE 10

ORE DISTRIBUTION IN LOWER LIMESTONE



※ Same LEGEND as Plate 2

PLATE II



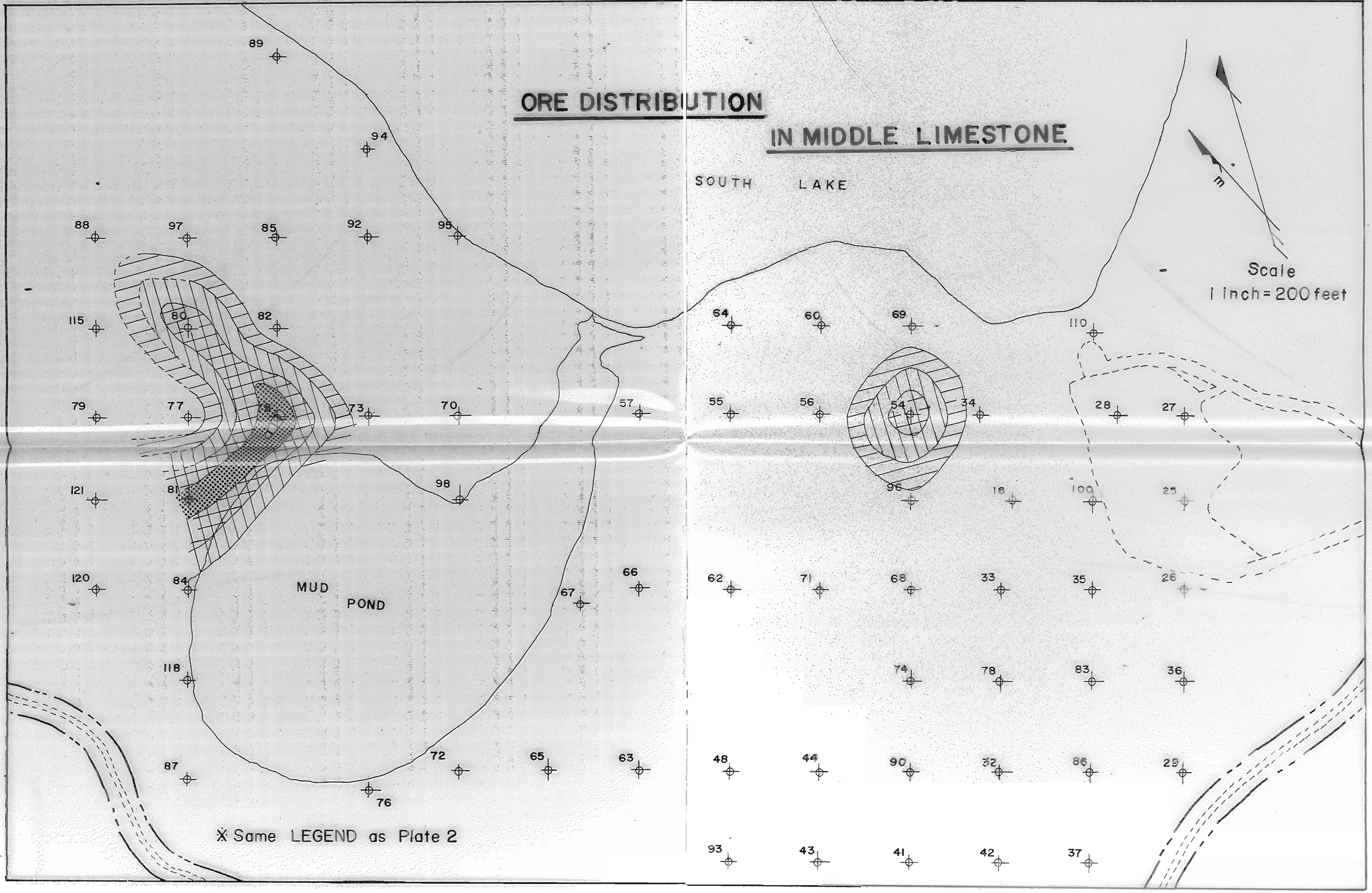
ORE DISTRIBUTION IN CALCIUM SULPHATE SEQUENCE

Scale
1 inch=200 feet

※ Same LEGEND as Plate 2

PLATE 12

ORE DISTRIBUTION IN MIDDLE LIMESTONE

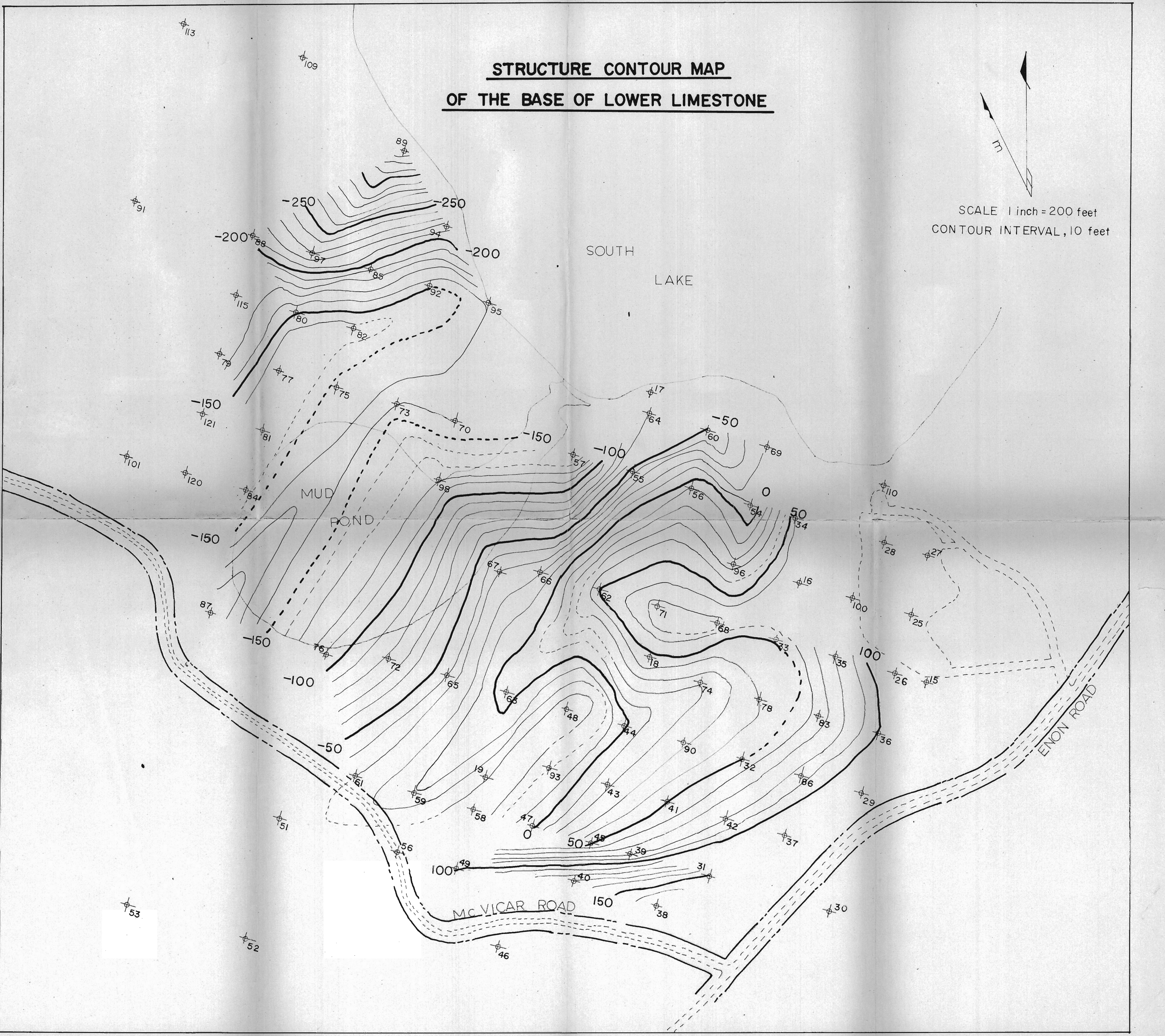


Scale
1 inch = 200 feet

X Same LEGEND as Plate 2

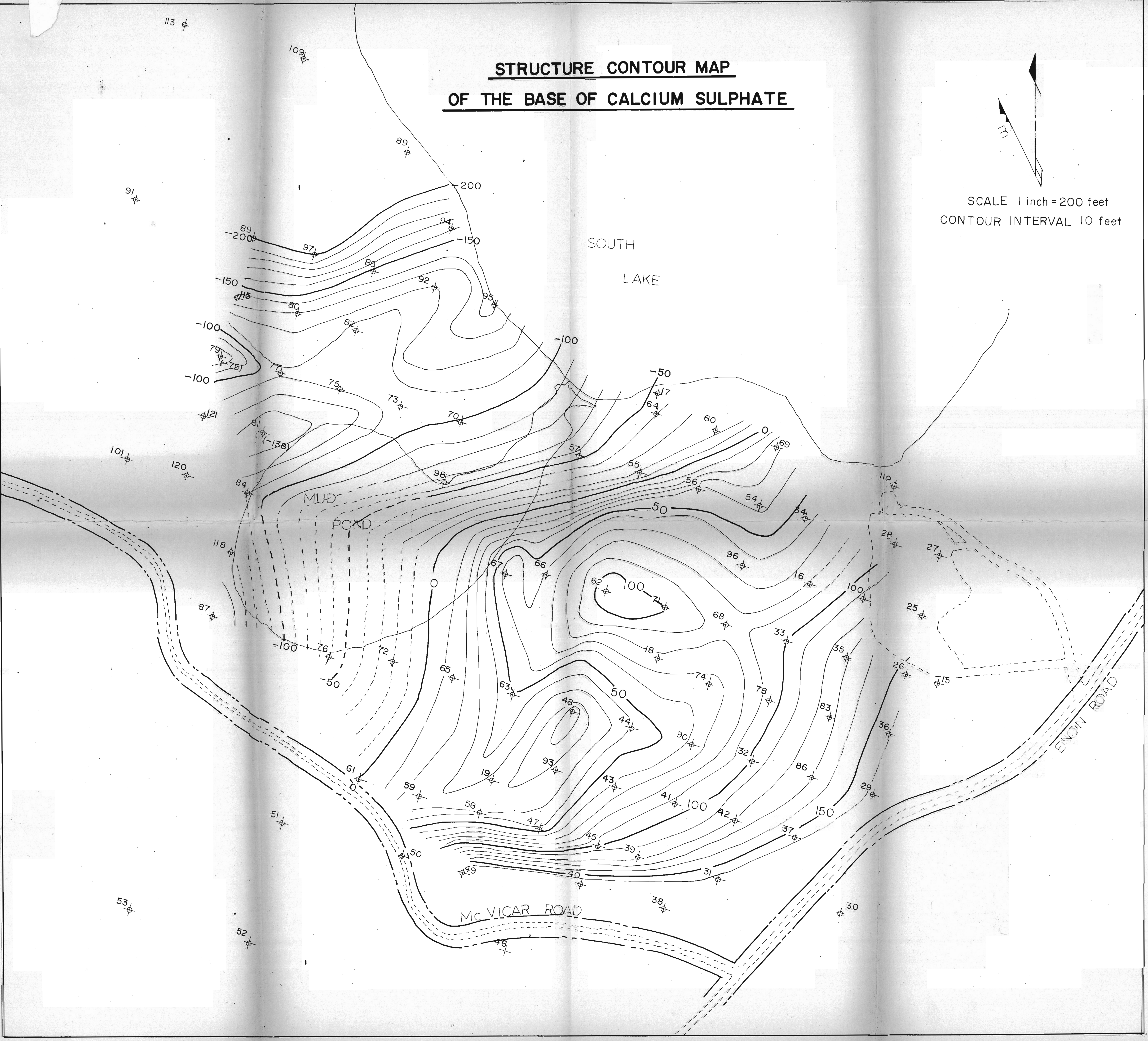
PLATE 13

STRUCTURE CONTOUR MAP OF THE BASE OF LOWER LIMESTONE



ATE 14

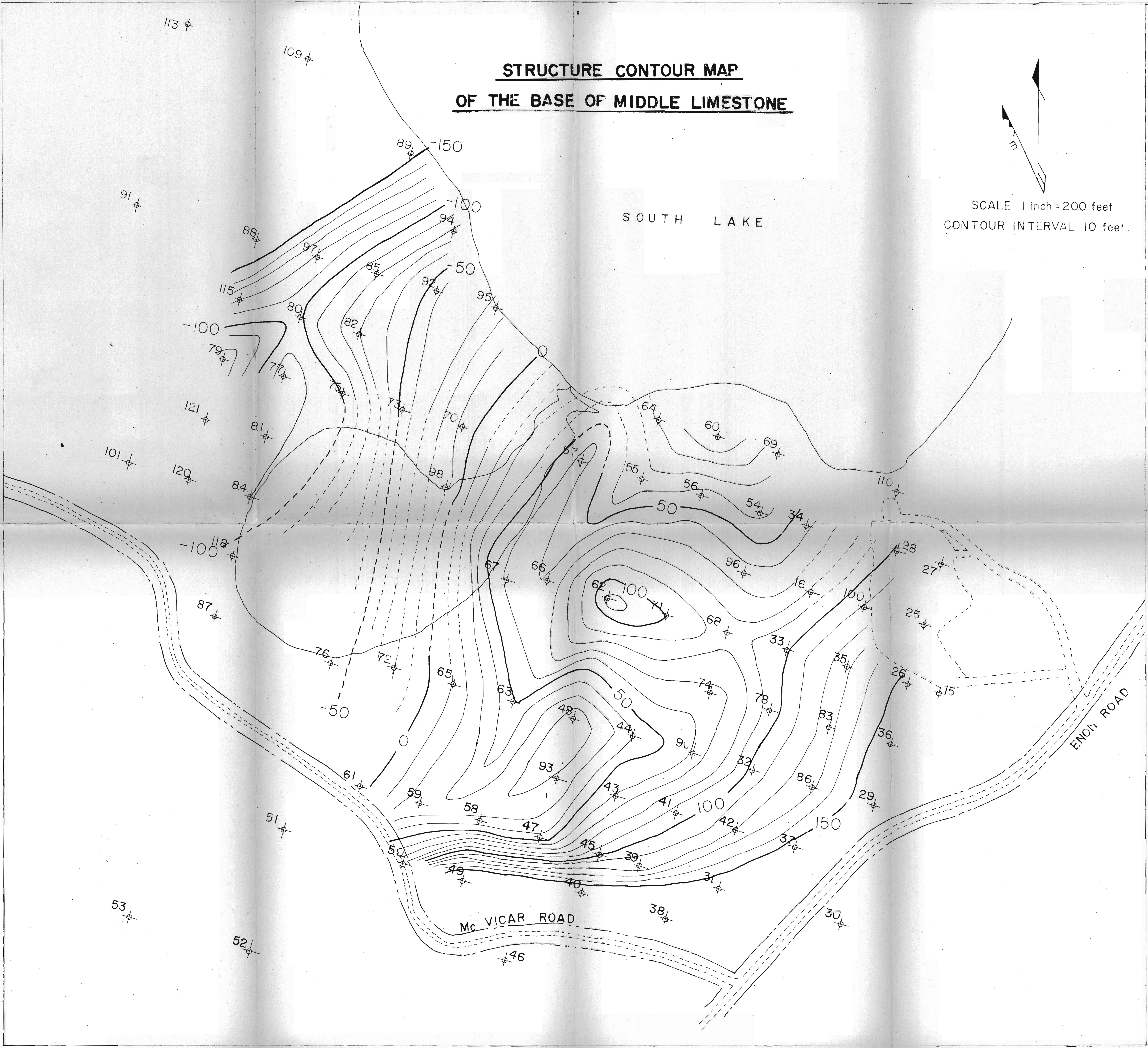
STRUCTURE CONTOUR MAP OF THE BASE OF CALCIUM SULPHATE



SCALE 1 inch = 200 feet
CONTOUR INTERVAL 10 feet

PLATE 16

STRUCTURE CONTOUR MAP OF THE BASE OF MIDDLE LIMESTONE



SCALE 1 inch = 200 feet
CONTOUR INTERVAL 10 feet.