Field Conference

GUIDE BOOK

NIAGARAN REEF at Thornton, Illinois

Held in connection with the Annual Convention of the
AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS and the
SOCIETY OF ECONOMIC PALEONTOLOGISTS and MINERALOGISTS
at Chicago, Illinois, April 22, 1956.

Field Conference sponsored by
ILLINOIS STATE GEOLOGICAL SURVEY
Urbana, Illinois

Guidebook Series No 4

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THE NIAGARAN REEF AT THORNTON, ILLINOIS

Leader

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Urbana, Illinois

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GENERAL DIRECTIONS

The trip will start promptly at 12:30 P.M.

Buses will load at the 8th Street entrance of the Conrad Hilton Hotel. You will be assigned to a bus and will make the entire trip in that bus.

On the return trip the buses will reach the hotel at about 6:00 P.M.

We will visit the quarry at the village of Thornton, three miles north of Chicago Heights and 18 miles almost due south from the Conrad Hilton Hotel.

SOURCE OF DATA

This guidebook is based largely on the references listed below and on unpublished manuscripts by H. B. Willman, H. A. Lowenstam, and L. E. Workman in the files of the Illinois State Geological Survey. It is modified from the guidebook for the 1950 A.A.P.G. field conference by the same authors.

Descriptions of physiography and Pleistocene features are based on the Chicago Area Geologic Maps by J Harlen Bretz and his recent report "Geology of the Chicago Region - The Pleistocene," Illinois Geological Survey Bull. 65, Pt. II, 1955.

REFERENCES

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Lowenstam, H. A., 1949, Niagaran reefs in Illinois and their relation to oil accumulation: Illinois Geol. Survey Rept. Inv. 145.

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LOG

Leaving the Conrad Hilton Hotel, we will cross eastward over the Illinois Central Railroad tracks to the Outer Drive near the shore of Lake Michigan. We follow the Outer Drive south for about 6 miles, passing the Chicago Natural History Museum and Soldiers Field. The highway is on made land, but on the right (west) across the Illinois Central Railroad the city is built on the bottomland of Glacial Lake Chicago, 15 to 20 feet above the level of the present lake. The lake plain was marked by many low bars, spits, and beach ridges of sand and gravel, built during the lowest (Toleston) stage of Lake Chicago, but because of excavations and construction they are inconspicuous in the built-up part of the city.

Turn right (west) on U. S. Highway Alternate 30 on the north side of the Museum of Science and Industry. Follow Alternate 30 around the west side of the Museum and then south through Jackson Park to Stony Island Avenue. Jackson Park is the site of the 1893 World's Fair.

Continuing south on Alternate 30 (Stony Island Avenue), we reach the Stony Island klint at 92nd Street, about 3 miles south of Jackson Park. From 87th Street to 92nd Street, the klint may be seen on the left (east) extending as an east-west ridge a little more than a mile long, and less than a half mile wide, rising about 25 feet above the lake plain. The Stony Island klint is typical of several in the Chicago region. Because of the superior weather resistance of the reef-type dolomite, many of the reefs were prominent oval or nearly circular hills on the preglacial erosional surface. Before it was covered by glacial drift the Stony Island klint was a hill that rose about 50 feet above the general level of the deeply dissected bedrock surface. After it was buried by glacial deposits it was partially exhumed by erosion of the glacial lakes and was an island during the late stages of Lake Chicago. Bedrock lies immediately beneath a thin cover of soil throughout the hill. Several road cuts and quarries, now mostly filled, formerly showed the characteristic reef lithology and the radial dip of the beds on the flanks of the hill.

From Stony Island the route continues south on Alternate 30 for about 5 miles along the west side of Calumet Lake, a large shallow lake at nearly the same level as Lake Michigan, to which it is connected by the navigable channel of the Calumet River. On the left (east), across the lake, are the plants of the International Harvester and other large concerns at South Deering; on the right (west) are the plants of the Pullman Car Manufacturing Company at Pullman and other large industrial plants.

About 2 miles south of Calumet Lake the highway crosses the Toleston shoreline of Glacial Lake Chicago, marked by a sandy beach ridge that is accentuated by a cover of low dunes. The ridge rises 20 to 25 feet above the flat lake plain to the north.

A mile farther south the route turns right (west) on U. S. Highway 6, which is followed west for about 1½ miles to Indiana Avenue. Turn left (south) on Indiana Avenue (Illinois Highway 83).

About half a mile south on Indiana Avenue the highway passes under the Grand Trunk Railroad, and immediately beyond it the Thornton klint is visible about three-fourths of a mile ahead. The klint has a relief of 25 to 30 feet and the Calumet beach of Lake Chicago, which is 15 to 20 feet higher than the Toleston beach, is on the slope of the klint.

Rising on the klint the route joins Vincennes Avenue. The North quarry of the Material Service Corporation, which we are to visit, is visible on the right (west) of the road. The North quarry (fig. 1) is separated from the South quarry by a narrow ridge of rock occupied by Ridge Road. The North quarry is entirely in a reef in the upper part of the Niagaran of this region (fig. 2). At the north end of the North quarry, reef-flank beds dip steeply to the north. At the south end similar strata dip steeply to the south. Between the dipping beds is the massive core of the reef, about one-third of a mile across from north to south. All the rocks in the North quarry are pure reef-type dolomite. Relatively impure interreef-type dolomite occurs only in the South quarry. The general relations are shown in the cross section (fig. 3).

Continue south on Vincennes Avenue to the stop street (Ridge Road) in the center of Thornton. Continue one block south, turn right and park. The buses, if separated, will assemble here but the buses will not unload. However, we will drive directly to stop 1 at the west face of the North quarry.

THORNTON QUARRY

We are privileged to visit the Thornton quarry of the Material Service Corporation through the courtesy of Mr. Irving Crown, Vice-President, and with the helpful cooperation of the Superintendent, Mr. Edward Schwartz, and his staff. This is one of several quarries operated by the Material Service Corporation and is one of the largest operations in the country.

The primary gyrator crusher can crush blocks as large as 5 feet in diameter and has a capacity of about 1,500 tons per hour. The plant supplies stone for concrete aggregate, road stone, agricultural limestone, lime making and other uses. A large tonnage of the stone is used as a refractory material in the open-hearth steel furnaces of the Chicago region. Part of the stone for refractory material is made into dead-burned dolomite at a plant of the Marblehead Lime Company, just south of the quarry. Outstanding characteristics of the dolomite reef-rock are its high purity and exceptional weather resistance.

GENERAL RELATIONS OF THE THORNTON REEF

No Niagaran reefs are completely exposed. Hence, the concept of a Niagaran reef has been evolved from observations of many partial exposures of different reefs. The Thornton exposure represents only the late stage of a Niagaran reef that was characteristic of reefs in the low-clastic belt (Lowenstam, 1950), that is, in an area where the non-reef facies is a moderately pure carbonate, as compared to the very shaly Niagaran of southern Illinois and the very pure carbonates of northwestern Illinois. Thornton is a key exposure of this particular stage. To relate Thornton to the overall pattern of Niagaran reef growth, a brief summary of the pertinent characteristics of all reef-growth stages is necessary.

The Niagaran reefs in the low-clastic belt began to develop at depth in quiet, muddy water, on a substratum of unconsolidated argillaceous carbonates. Subsequent growth carried the reef surface upward, first through effective wave base, and finally into turbulent surface waters. Three consecutive though intergrading reef-growth stages can be distinguished: 1) quiet water, 2) semi-rough water, and 3) the rough-water, wave-resistant stage (Lowenstam, 1950, 1952, 1956). Their distinction is based on structural, lithologic, and biologic characteristics.

Fig. 1. - Surface extent of the Thornton klint, locations of the quarries and stops.

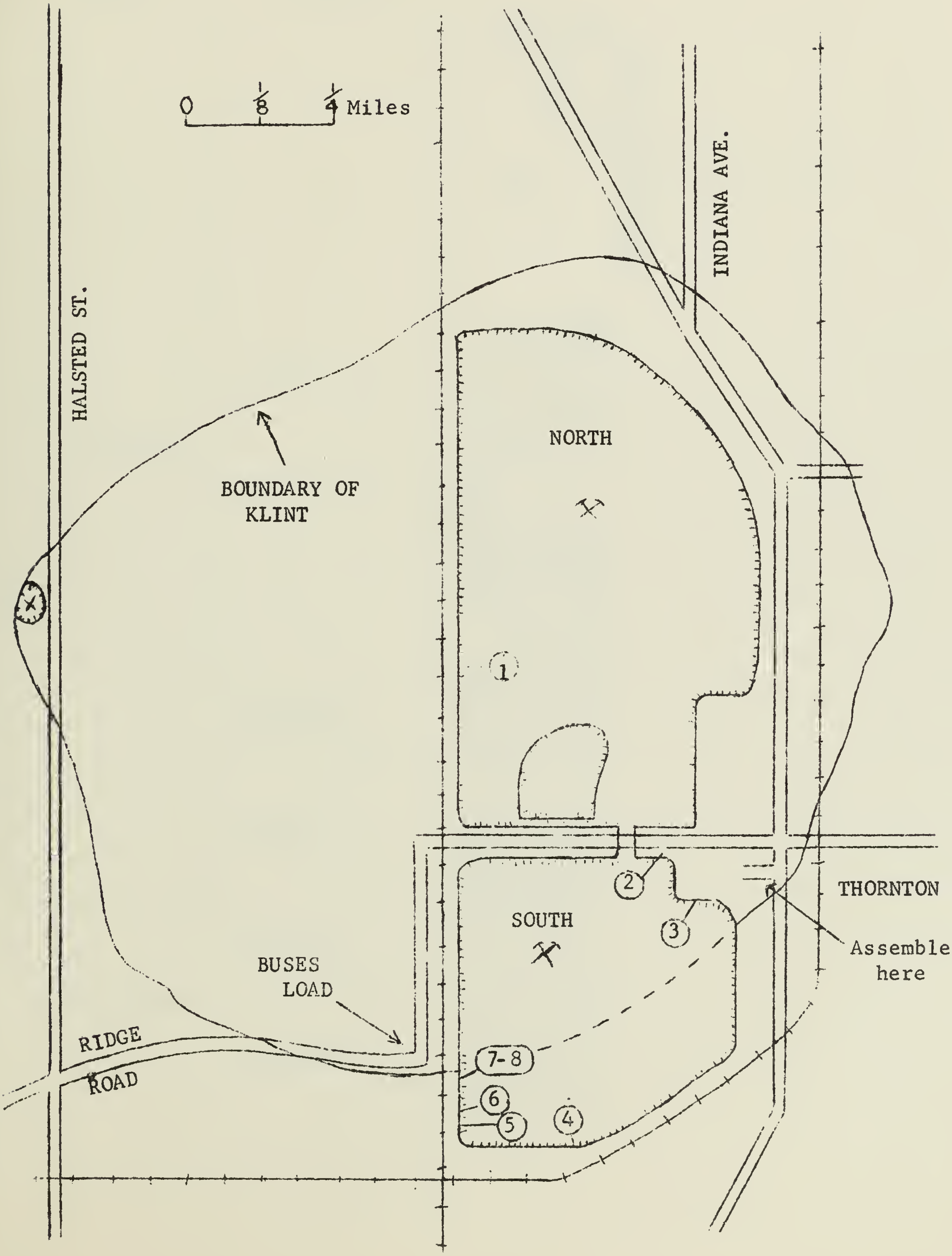
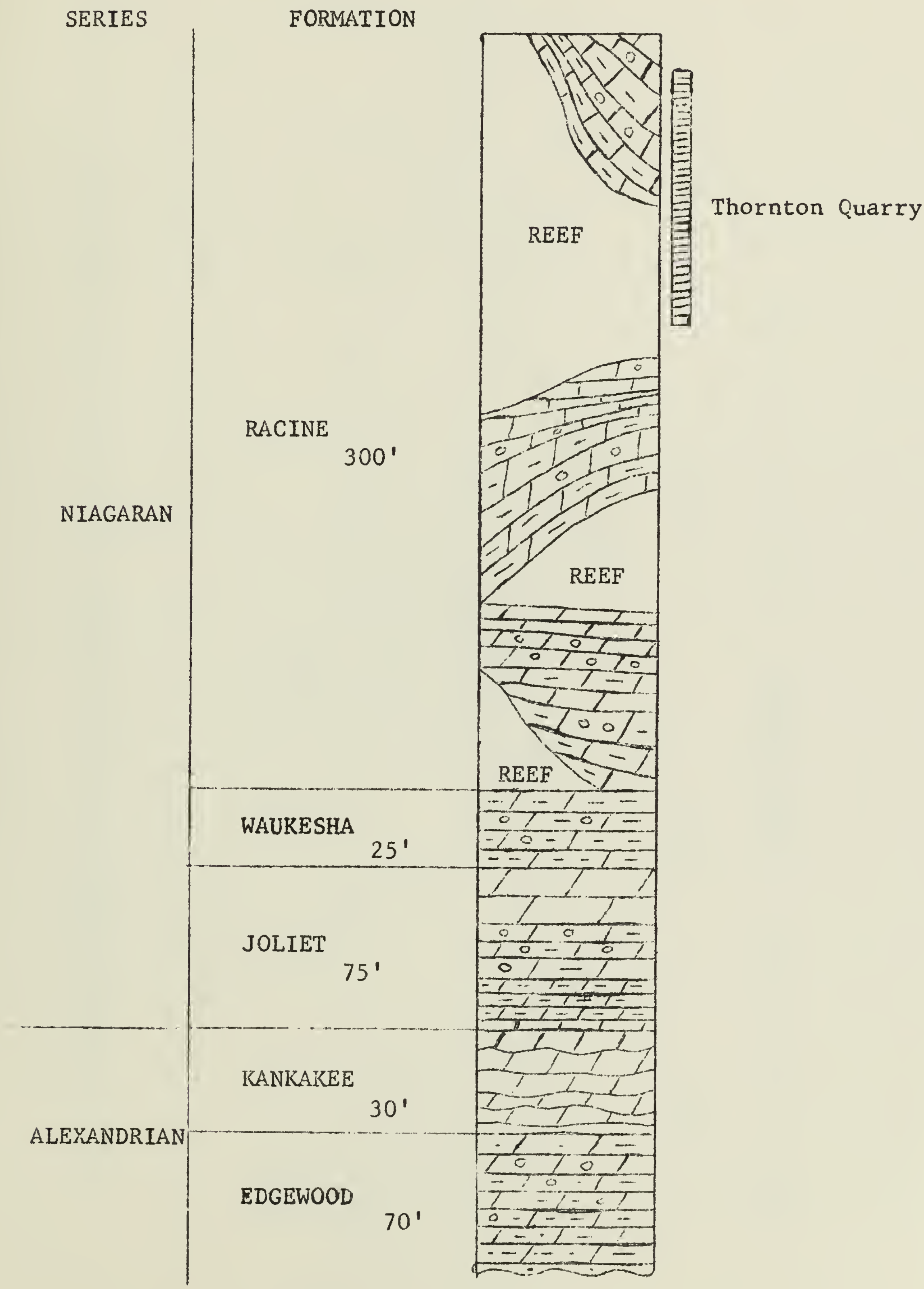


Fig. 2. - Generalized stratigraphic section of Silurian strata in northeastern Illinois, showing the approximate stratigraphic position of the Thornton reef.



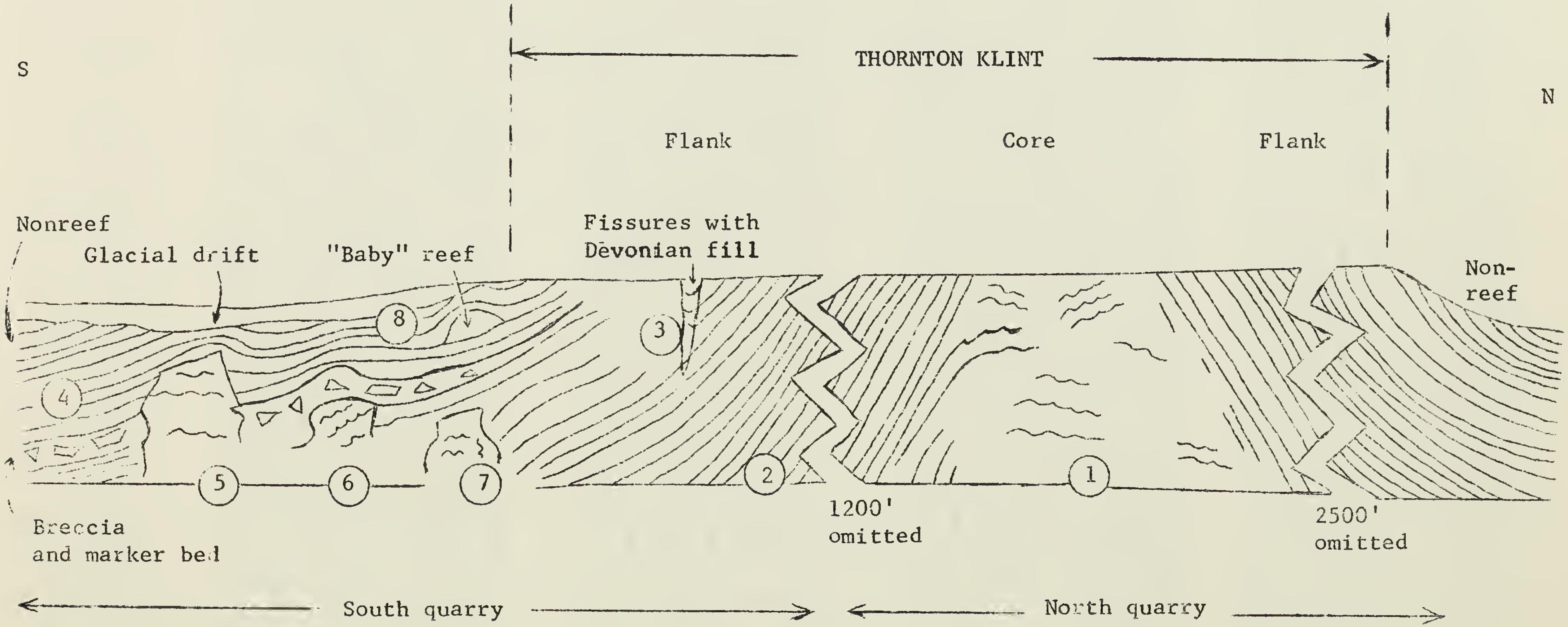


Fig. 3. - Diagrammatic cross section of the Thornton reef showing relations of stops projected onto west wall of the Material Service Corporation quarries.

The quiet-water stage involves structurally only the massive reef core of Cumings and Shrock (1928), that is the rigid open-mesh lacy framework formed of the skeletons of reef builders. This framework encloses moderately argillaceous carbonates with a low content of bioclastics. Reef builders and reef dwellers are confined to few species, and the dwellers, as opposed to the structural builders, are not abundant.

The semi-rough-water stage is structurally distinguished by the introduction of reef-flank deposits. The massive core is similar in construction to deposits of the first stage. The interstices of the skeletal framework, however, are filled with matrix rock that contains less argillaceous material, but more bioclastic carbonates. The reef flank is an apron of beds that dip more or less steeply radially away from the massive core. Bioclastic carbonate is the main constituent of the flank. Admixture with terrigenous clastics is conspicuous at the early phase of this stage and becomes minor toward the end. Tongues of reef core constitute another element of the flank beds. Biologically, there is a greater variety of reef-building and reef-dwelling organisms. The dwellers range over the flank and their population density is greater than during the previous stage.

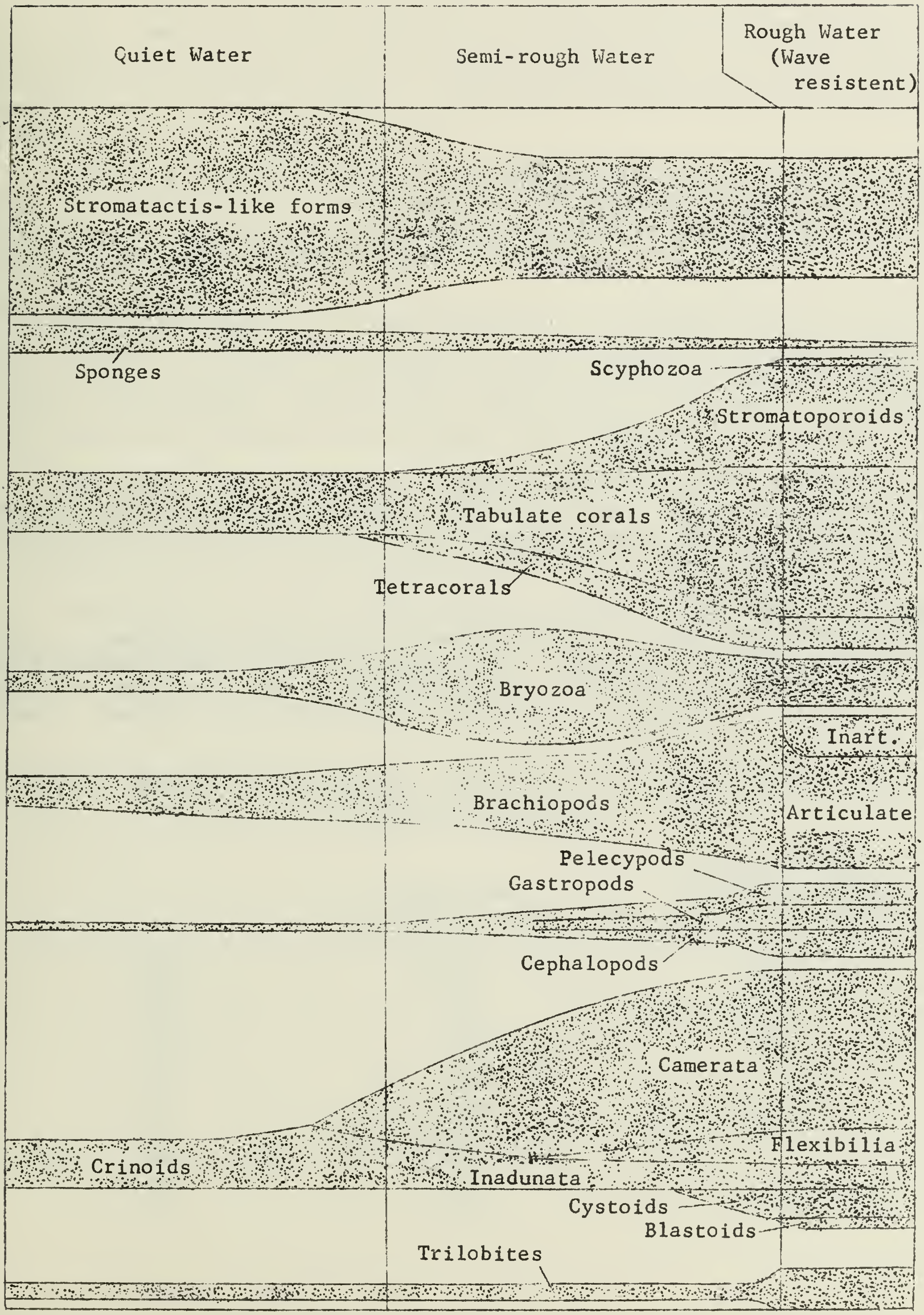
The third, or wave-resistant stage, the only stage seen at Thornton, marks the shift from vertical to lateral reef expansion. The reef core, initially the principal structural component, becomes subordinate in areal extent to the greatly enlarged reef flank. The flank developed as tongue-like expansions with successive compensational filling of the intervening depressions. At the mature stage the result was a broad terrace bounded at the top by the surf base. Lithologically, the core is entirely composed of high-purity carbonate which is skeletal in origin. The same is true for most of the flank element. The exceptions are 1) occasional streaks of low terrigenous clastic content, and 2) tongues of argillaceous interreef deposits in the lower reaches of the flank in the terminal phase.

Localization of terrigenous clastics is a criterion for differentiating reef-flank deposits outward from the core into three or rarely four successive components. The first consists of alternating layers of reef-core type, that is, reef-builder layers, with coarser bioclastic deposits; the second of coarse bioclastics alternating with dense structureless carbonate with few coarse bioclastic elements. The third, in addition, includes argillaceous components. Layers made up entirely of oolites form a fourth, rarely developed, member. Biologically, the wave-resistant stage forms the climax in abundances of species, with all carbonate-secreting groups represented. Also, it is the stage of maximum population densities. Faunal composition and relative abundance by classes and orders for all stages are shown schematically in figure 4 (modified after Lowenstam, 1956, fig. 4).

The reef exposures at Thornton, Illinois, are limited to the last or wave-resistant stage of reef upgrowth, and show the relations to succeeding younger nonreef deposits. The reef-flank exposures extend across all four members. The contrast in lithology and fossils between reef and interreef is extreme because we are comparing quiet-water interreef with extreme rough-water reef facies.

The Thornton reef, as indicated by its topographic expression as a klint, is roughly circular in outline and about one square mile in area (fig. 1). The North quarry and the northern half of the South quarry of the Material Service Corporation expose most of the eastern half of the reef.

Fig. 4. - Succession of Niagaran Reef Faunas (Lowenstam, 1956).



The southeastern half of the South quarry shows interreef deposits interbedded with small fore-reefs, and their physical relations to the main reef mass (fig. 3). The quarry faces are on the average about 50 feet in height, except in the southwestern part of the North quarry, where an additional 50 feet is exposed in a newly opened lower bench. They expose a topless and bottomless cross section of the reef. Reef core is exposed only in a limited area of the west wall of the North quarry, but when the face was near the central part of the quarry about one-third mile of reef core was exposed. The bulk of the exposures are of bedded reef-flank beds, which dip steeply radially away from the core to the north, east, and south.

The flank beds that we can see are younger than the core portion exposed, and in turn a large portion of the interreef deposits are younger than the reef flank. However, at least the lower part of the visible interreef deposits is contemporaneous with parts of the reef now eroded.

STOP 1. The reef core.

The core of the reef is distinguished by its massive structure and exceptional purity. In this part of the quarry, which is near the center of the reef (fig. 1), the entire face is reef core. The top of the reef core is eroded and the base is not exposed. It is not known how far the reef extends beneath the quarry floor, but the base of the Niagaran strata is about 300 feet below (fig. 2).

The rock in the reef core is a medium-grained dolomite, commonly medium gray but locally streaked or mottled with light gray. Some areas are dense but vesicular streaks and large vugs are common. The total porosity ranges from 6 or 7 percent in the dense areas to about 20 percent in the vesicular parts.

The high purity of the reef dolomite is shown by the chemical analysis in table 1. Insoluble residues are negligible except for occasional well-rounded grains of quartz sand, the local presence of a mere trace of clay, and variable amounts of asphaltum. The sand grains pose a problem not yet satisfactorily explained. Possibly they were dropped on the reef by animals.

Table 1. - Comparison of Chemical Composition of Reef and Interreef Dolomite

	Reef-rock from North quarry	Interreef rock from South quarry (bed at base of south face)
$CaCO_3$	54.57	36.47
$MgCO_3$	44.30	26.77
SiO_2	0.06	26.39
Al_2O_3	0.25	4.66
Fe_2O_3	0.02	1.12
FeO	0.07	
MgO	21.54	14.70
CaO	30.57	20.43
Na_2O	0.11	
K_2O	0.01	
CO_2	47.12	30.01

The asphaltum which impregnates many porous areas throughout the reef, as well as the bordering interreef rocks, is extremely viscous but on hot days it drips slowly from openings, especially those in fresh exposures. The occurrence of asphaltum in reefs is common in the Chicago region but is not universal. Some exceptionally good reef structures are entirely free from asphaltum and others have very little. It appears to be more common in the higher Niagaran reefs which have strongly developed flank beds than in the reefs lower in the Niagaran, which generally are smaller. The higher Niagaran reefs also were close to a cap of Devonian-Mississippian black shale.

The reef core and flank beds are characterized by abundant and diverse fossils, in contrast to the limited fauna of the interreef beds. Crystallization and dolomitization have destroyed the fossils in parts of the reefs, but in many places excellent casts and molds are preserved. The framework of the reef appears to have been a mesh of Stromatactis-like forms, colonial corals, and stromatoporoids. The reef assemblages are characterized by large heavy-shelled robust forms in contrast with the small fragile forms in the interreef deposits.

Among the most abundant fossils in the reef are the c rals Favosites, Halysites, Lyellia, Thecia, Heliolites, and Plasmopora; the crinoids Crotalocrinites and Eucalyptocrinites; the brachiopods Monomorella, Conchidium, Eospirifer, and Wilsonia; and the trilobites Bumastus and Calymene.

In some parts of the reef core the dolomite is almost structureless, but in other parts, as at this locality, poorly defined bedding is observed. It is usually inclined, the amount and direction varying irregularly within short distances. Much of the inclination of the bedding may be due to slumping during reef growth. At places the massive structure of the core is interrupted by a few prominent undulatory but nearly horizontal breaks or bedding-planes. Although weakly developed here, they can be seen in the fore-reef at stop 5. They appear to mark interruptions in the growth of the reef and are interpreted as growth lines. They show, therefore, that the core is the zone of vertical reef growth.

Follow the west face southward to observe the transition from the reef core to the reef-flank deposits. The transition zone is marked by an increase in degree of bedding, with a persistent dip to the south that steepens rapidly until it reaches a maximum angle of 30° to 40° which persists across the zone of reef-flank deposits.

Leaving stop 1 the buses will circle the North quarry so that you can see the radial dip of the flank beds around the reef core. A short distance north of stop 1 indistinct and somewhat irregular northward dipping beds are present but give way sharply to well-defined beds that dip sharply northward. The north face is along the strike of the northward dipping beds but near the northeast corner the change to an easterly dip is visible. Going southward along the east face the route again is along the strike but the eastward dip of the beds can be seen at small offsets in the face. The beds do not dip as steeply as in the typical flank beds, and this area has been described as a flank terrace (Lowenstam, 1949). When the quarry face was about 1,000 feet farther west, it exposed a long section of massive reef core. In the southeast part of the North quarry, the eastward dip of the flank beds is well shown on the north face of the offset on which the school is located. The buses will unload at the base of the incline on the south side of the tunnel (stop 2) and will pick us up again at the top of the abandoned incline (stop 3).

STOP 2. - Reef-flank deposits.

The reef-flank beds are typically developed and may be examined near the tunnel, especially on the south side.

The reef-flank beds are distinguished by high purity, excellent bedding, and a steep dip away from the reef core. Most of the beds are 2 to 6 inches thick. In parts of the sequence the beds have a remarkably uniform thickness and indivdual beds maintain a uniform thickness throughout their exposure. The four categories of flank-type differentiation, described above, can be seen in sequence by walking from the core area south and into the old quarry. In chemical and mineralogical composition the dolomite is similar to that in the reef core.

The total thickness of the individual beds exposed in the reef-flank zone is more than 1,000 feet. Before the reef origin was recognized, the steep dip was interpreted as a fold in the strata, and the formation was assumed to have very great thickness. However, a well in Thornton, on the outer margin of the dipping beds, penetrated only 465 feet of both Niagaran and Alexandrian strata overlying the Maquoketa shale, a normal figure for this part of the region (fig. 2).

As noted above, the reef-flank beds at the extreme north end of the North quarry dip northward and are identical in character with those observed at stop 2. The radial dip of the reef-flank beds is also shown by a small quarry on the west side of the reef (fig. 1) where similar beds dip steeply to the west.

The reef-flank beds represent reef detritus that was broken by waves from the core zone and deposited among flank-dwelling organisms on the steep sides of the reef. Dolomitization has destroyed the original granular character of the matrix material, but the presence of broken and irregularly oriented fossils and the local presence of lenticular beds and breccias supports the detrital origin for a considerable part of the material. However, many of the coral growths are oriented parallel to the sloping surface of the beds and appear to have grown in place.

Examine the section up the incline and then go southeast about 100 yards to the abandoned incline above the settling basin.

STOP 3. Transition to interreef deposits.

Along the incline you can see the gradual introduction of argillaceous beds into the sequence. The effect of the argillaceous material is to make the dolomite more dense, more fine grained, and lighter in color. The addition of 1 to 2 percent of argillaceous material makes a very appreciable change in the appearance of the dolomite, and beds with 5 percent or more argillaceous and silty insoluble residues are not vesicular, weather light gray, and turn brownish on long-weathered surfaces. These dense-appearing beds have a total porosity equal to or greater than that of most of the vesicular reef-rock.

The exposure at stop 3 marks the outer limit of the steeply dipping reef-flank deposits. You can see the rapid flattening of the dip when you look back toward this face from across the quarry. The beds appear to mark the final steges of growth of the major reef.

Devonian sharks' teeth are found above the incline in the clay-filled joints. Devonian strata were penetrated in a well a few miles to the southeast.

The party will load into the buses and ride down the south incline to the parking area at the base of the incline. Follow the abandoned track grade west from the southwest corner of the building near the parking area for about a quarter of a mile and then bear left (south) to the place where a remnant of a high bench can be seen.

STOP 4. Interreef strata.

The interreef sediments consist largely of still-water deposits that accumulated in relatively deep water surrounding the reefs. The rocks are characteristically dense, very fine grained, contain argillaceous and siliceous impurities, and are well bedded. The most common fossils are sponges and crinoids, less commonly bryozoa. Locally a gastropod-trilobite-cephalopod assemblage is found. The most common crinoids, all small, are Pisocrinus, Gisocrinus, and Lecanocrinus. The trilobites are mostly Encrinurus and Calymene.

Some rough-water sediments are found in the interreef habitat. They contain only a slight amount of siliceous clastics and are relatively coarse-grained and porous. In physical appearance they do not differ greatly from reef lithology. Crinoidal fragments are generally common with fewer colonial corals and stromatoporoids.

Lenticular bodies of reef-rock or "baby" reefs are common in the interreef strata.

The sequence of interreef beds exposed near the middle of the south face of the quarry consists of the following major units in ascending order:

Unit A. Argillaceous dolomite. - This argillaceous dolomite contains 20 to 45 percent insoluble residue. A chemical analysis is given in table 1. It is locally at least 12 feet thick but its base is not exposed.

Unit B. Reef-detritus bed. - Above the argillaceous dolomite is a distinctive massive breccia 4 to 10 feet thick, consisting of blocks of porous reef-type dolomite in a matrix of light-colored argillaceous dolomite similar to but not so impure as that in Unit A. This is a continuous massive unit, set off from adjacent units by well marked bedding-planes. It is easily traced because of the presence at the top of a distinctive 6-inch to 1-foot bed of brown finely porous relatively pure dolomite overlain by 1 to 4 inches of argillaceous dolomite. The unit is the breccia zone noted earlier, which denotes mass destruction of the reef by a storm. As will be seen in tracing it in the west face, the breccia rises to the north, up the slope of the reef. Some of the blocks torn from the reef are very large, up to 20 feet across and more than 10 feet thick.

Unit C. Nodular cherty dolomite. - Approximately 7 to 10 feet of nodular impure cherty dolomite with thin wavy lenticular argillaceous partings, overlies the reef detritus. In several places it grades laterally, within a foot or two, into a mixture of nodules in green shale. Even in the more dolomitic facies the unit contains about 20 percent insoluble residue consisting of micaceous silty clay. In general the nodular character increases toward the reef. At the contact with the fore-reef, to be examined at stop 5, it locally changes to shale that contains nodules. The origin of the nodular structure is not clear, but it may have resulted from deposition under the particular type of agitation characteristic of water near the edge of the reef. The nodular character is not well developed in many interreef sections which are presumed to be farther from the reefs, and it therefore may be an indication of reef proximity.

Unit D. Upper variable beds. - The uppermost unit consists of variable beds 15 to 30 feet thick, eroded at the top. At stop 4 the unit contains some beds of nodular dolomite similar to that in Unit C but mostly not as impure and with chert less common. Most of the strata are very slightly vesicular and have generally less than 10 percent of insoluble residue. Some beds are pure dolomite of the reef type; a distinctive lens of pure dolomite crowded with silicified horn corals is present near the top of the section. The unit becomes more impure westward toward the margin of the fore-reef and nearer to the main reef. Close to the fore-reef the unit is all nodular and in places is differentiated from Unit C below only by tracing the prominent bedding-plane between them.

Continue westward along the south face of the quarry noting the continuity of the reef-detritus bed to the exposure of the fore-reef in the west face just north of the southwest corner of the quarry.

STOP 5. The fore-reef.

The fore-reef exposed in the west face near the corner of the quarry is only one of several that were encountered when the quarry was expanded westward from the plant. Although the extent of this fore-reef is not known, it was apparently a linear feature parallel to the edge of the main reef. Many exposures of massive reef-rock in the quarry floor on a line slightly north of east from the exposure in the west face apparently show the continuation of the reef. Exposures of argillaceous dolomite in the floor south of the reef-rock indicate relations similar to those in the west face.

Examination of the fore-reef gives much information on the growth of the reef and its relation to interreef sedimentation. It emphasizes the complexity of conditions around the margin of a large reef and the abruptness of facies variations. Observations on the growth of the fore-reef and other "baby" reefs do not apply entirely to growth of the main reef. Surrounded as it is by interreef-type sediments, it is apparent that the fore-reef grew in relatively quiet water. There is no evidence that it contributed detrital material to the adjacent sediments. Its growth was essentially vertical and no reef-flank beds were formed.

A preliminary view of the fore-reef from a short distance out in the quarry will show the major relations: the sharpness of the margins of the reef, the overlapping interreef beds, the absence of reef-flank beds, and the massive structure of the reef core that is broken only by growth lines which are not conspicuous and are not easily traced through the reef.

A close examination of the south side of the fore-reef (fig. 5) shows that the stratigraphic units differentiated in the south face (stop 4) continue to stop 5. The reef-detritus breccia (Unit B) ends about 10 feet from the reef and is separated from it by a mass of very argillaceous dolomite like that in Unit A. Unit C laps onto the reef and Unit D overlaps it.

The sequence of events which produced these relations is interpreted tentatively as follows:

1. Deposition of part of the argillaceous dolomite (Unit A).

2. Vertical growth of the fore-reef.

3. Deposition of the reef detritus (Unit B) in the matrix of argillaceous dolomite. At this stage the fore-reef had an uneven top and stood only slightly above the bottom so that detritus moving down the slope from the main reef on the north overrode or by-passed the fore-reef.

Fig. 5. - Sketch showing contact of the fore-reef with interreef strata on the south side of the fore-reef (stop 5).

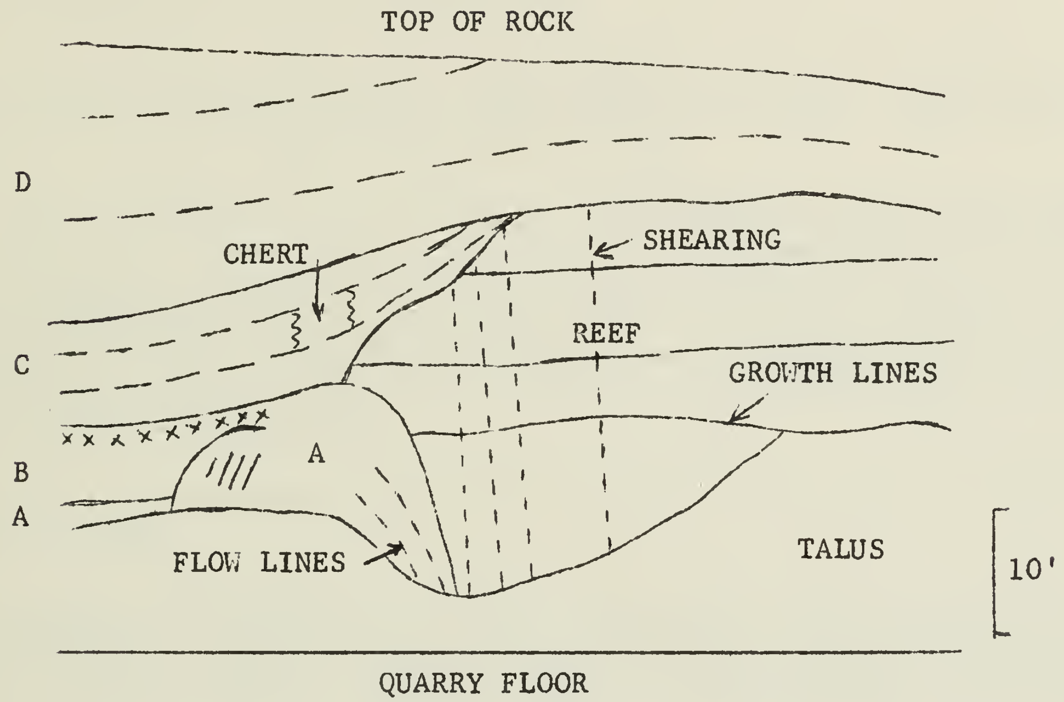
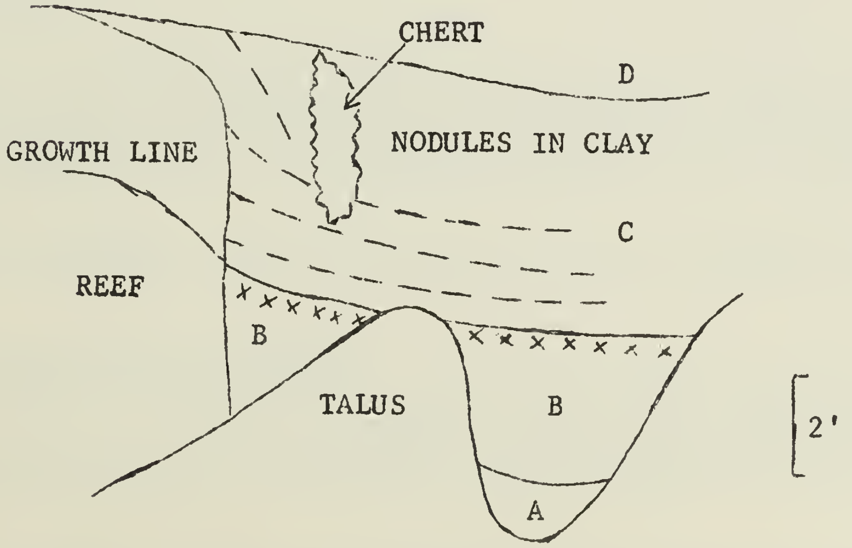


Fig. 6. - Sketch showing relations on the north side of the fore-reef (stop 5).



Letters mark the units described at stop 4. Unit B is the reef-detritus bed with its distinctive top.

4. The reef then attained such size that the argillaceous mud beneath could not support the weight of the reef. The reef settled and the mud flowed up along the side of the reef breaking through the detritus bed. Flaring flow lines may be observed in the argillaceous dolomite. Settling appears to have been almost entirely on the south side of the reef. The top of the vertical side of the reef is about 10 feet lower on the south side than on the north, which is more than can be accounted for by the normal dip.

5. The fore-reef continued to grow upward. All the reef above the tongue at about the middle of the south side grew during this stage. There was almost no deposition of interreef beds during this growth.

6. The argillaceous beds of Unit C were deposited after reef growth ended. Unit C beds built up the sea floor to the level of the top of the reef. The off-reef dip of the upper surface of the unit may have resulted entirely from compaction of the argillaceous muds by the weight of the overlying sediments. The rigid frame of the reef would prevent its compaction, but concentration of the load on the reef resulted in the development of vertical shears, particularly on the south side where settling had occurred.

7. Unit D was deposited after the reef had ceased to be a topographic feature on the sea floor.

The presence of dense chert in Unit C near the reef is an interesting problem. The presence of a similar zone in the same unit at the same position on the north side of the reef suggests that the chert is environmentally controlled. Bedding-planes pass through the chert so that the silicification apparently is diagenetic.

Continue northward to the north side of the fore-reef, where the relations are as shown in figure 6.

Note that there is no evidence of settling and flowing of mud on the north side of the reef. The reef-detritus bed (Unit B) was deposited against the reef. It may have settled slightly during compaction. The top of the fore-reef at the end of deposition of the reef-detritus bed is shown by the bedding-plane or growth line indicated in the sketch (fig. 6). The bedding-plane dips steeply into the face showing the undulatory surface at that stage of growth. The surface of the reef may well have been low enough on the west for detritus from the main reef to by-pass the fore-reef.

The extreme argillaceousness of Unit C close to the reef is well shown. As Unit C apparently was not deposited until the reef had reached full growth, the steep face of the reef may have provided a protected place favorable for settling of suspended clay.

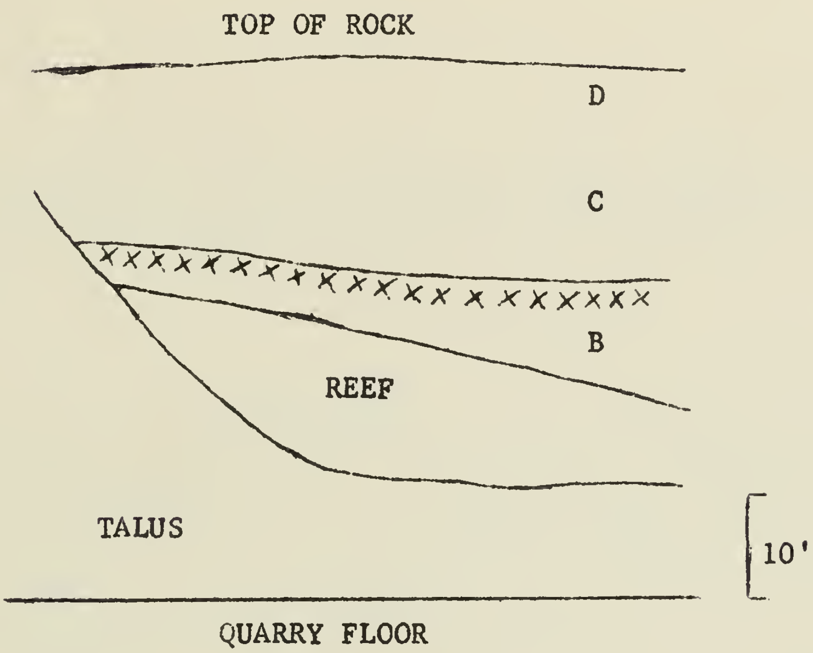
Continue northward to the next exposure, which is beyond the first waste pile.

STOP 6. Reef detritus on a fore-reef.

At stop 6 the exposure (fig. 7) shows the reef-detritus bed (Unit B) resting directly on a reef. Although not continuously exposed, the reef may be continuous with the fore-reef just described. If so, it confirms partial growth of the fore-reef before deposition of the reef-detritus bed.

Continue northward passing a long interval of face covered by waste material. Keep to the right and descend to the lowest quarry floor.

Fig. 7. - Sketch showing relations at stop 6.



STOP 7. Contact of reef-flank beds of the main reef with a block of reef-core type. The exposure at stop 7 is in the edge of the bench close to the water. It is directly east of and lower than an exposure in the main west face (stop 8), and the two sections are combined in figure 8 to show their relation.

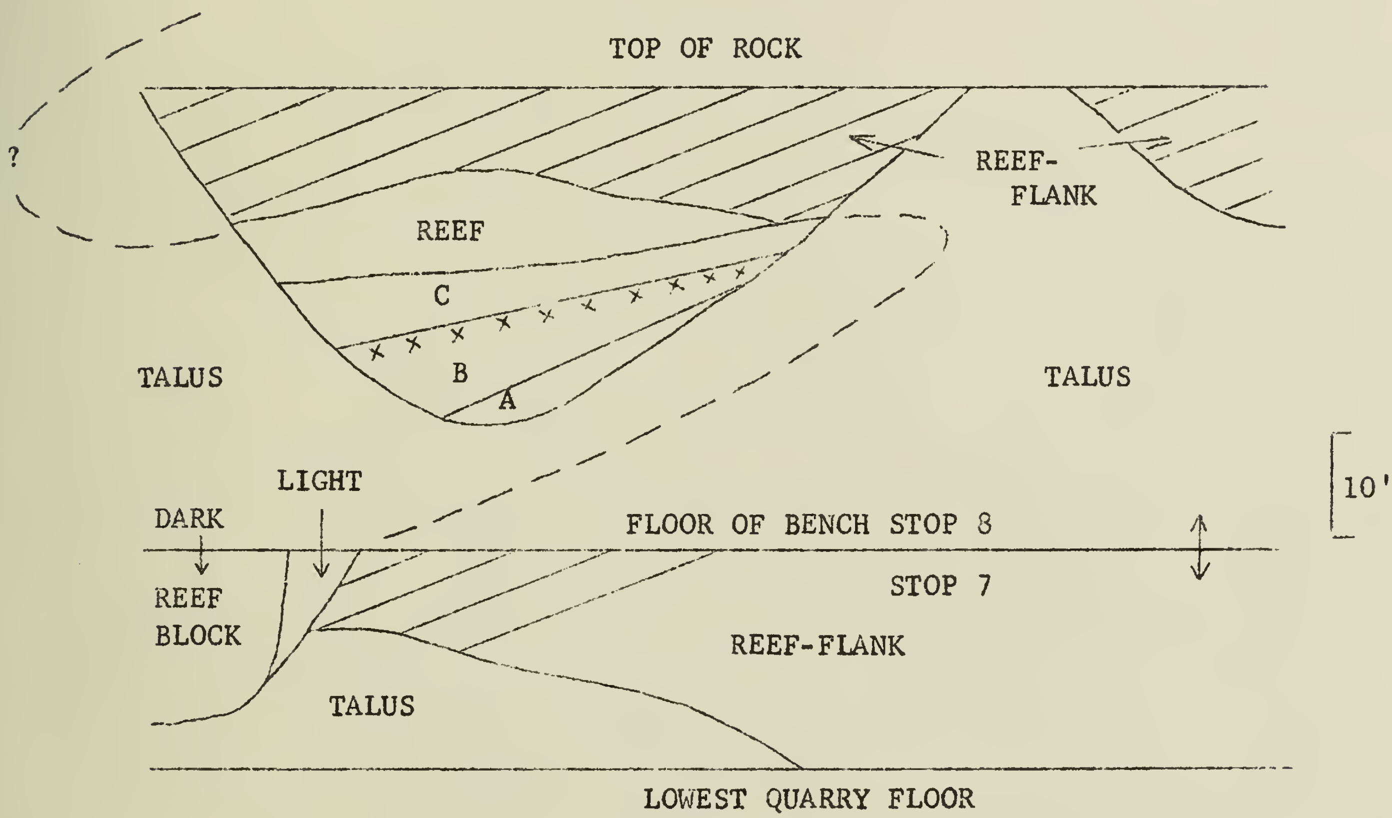
The face north of this locality shows that the steeply dipping reef-flank beds of the main reef continue from this point northward to the north face of the quarry. At stop 7 they end against a huge block of reef rock which appears to have slid from high on the reef. The unconformable contact and squeezing phenomena against the reef-flank beds are visible. Light-colored slightly argillaceous dolomite was deposited later on top of the reef-flank beds and between them and the upper part of the block of reef-rock.

Climb over this exposure or pass around it on the south in order to reach the main face directly west from stop 7.

STOP 8. Contact of reef flank of the main reef with interreef strata.
The exposure at stop 8 is shown in the upper part of figure 8. It is best studied along the steep trail on the south side, but for those who appreciate a more gentle slope the abandoned incline on the north side of the exposure also leads to the top of the quarry.

The continuity of the argillaceous dolomite (Unit A) and the reef-detritus bed (Unit B) up the slope of the reef is well shown. As suggested by the projection of the surface of the reef-flank beds from the lower bench (fig. 8), the interreef strata (Units A, B, and C) were deposited during a recession of the main reef face, and they appear to mark an interval which culminated in temporary mass destruction of the reef.

Fig. 8. - Sketch showing relations at stops 7 and 8. The dashed line shows the projected margin of the reef-flank beds and their interfingering with the interreef beds.



Later, under conditions more favorable for reef growth, the reef expanded laterally over the interreef beds and over a "baby" reef which had started on the surface of Unit C. Erosion of the overlying strata ends the record of succeeding events in the history of the Thornton reef.

The buses await at the top of the quarry.

The return trip will be over the same route as that followed coming to the quarry.