Field Guide to Joint Patterns and Geomorphological Features of Northern Ohio[1]

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Abstract. **Bedrock in northern and northwestern Ohio consists of Middle Paleozoic carbonates and shales and is pervasively jointed. The regional joint pattern and chronology, established by the characteristics of joint traces, mineralization, and surfaces, reveal a complex history of fracture development. Joint studies along the north-south trending Bowling Green fault zone indicate that northwest-trending joints formed first in response to extensional stresses associated with differential dip-slip movement in this fault zone, or by left lateral movement along this zone.**

Depositional features associated with Pleistocene glaciation and geomorphological features related to differential erosion of carbonate rocks dominate the topography of northern and northwestern Ohio. The region around Toledo is best characterized as a glacial lake plain. Approximately 30-40 mi (48-64 km) to the east-southeast near Clyde, OH, several Pleistocene glacial lake beach ridges and associated features are first encountered on the field trip. The beach ridges merge toward the northeast with the Columbus Limestone cuesta, which dips gently southeastward off the Findlay Arch. Dissolution of the Columbus Limestone has led to numerous karst features, including large sinkholes and high volume flow springs that emerge around the famous "Blue Hole" near Castalia, OH.

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INTRODUCTION

The field trip will study bedrock fractures and a variety of geomorphological features of northwestern and northern Ohio. Main emphasis on fractures will be on joint development from a standpoint of chronology and propagation dynamics. Geomorphological emphasis will concentrate on features associated with glacial deposition and differential erosion of carbonate rocks.

The bedrock of northwest Ohio is composed of nearly horizontal Paleozoic sedimentary rocks, with an almost continuous cover of glacial and glacial-lacustrine sediments. The configuration of Precambrian basement rock (Fig. 1) indicates the gentle dip of Paleozoic sedimentary strata. Bedrock consists of Silurian dolomites and Devonian limestones and shales very gently arched upward into a low, north-northeast-plunging feature called the Findlay Arch. The axis of this northern extension of the Cincinnati Arch, with dips on its flanks of about 20 ft per mi (3.79 m/km), trends north-northeast and lies just east of Toledo. It will be crossed, though it will not be visible, between Stops 2 and 3 (Fig. 2) on this trip. Erosion of bedrock by preglacial streams (the Teays and Erigan river systems) throughout the Mesozoic and most of the Cenozoic, produced the broad banded outcrop pattern presently shown on the bedrock geology map of Ohio. These river systems ceased to exist after Pleistocene glaciation.

Joints are well developed in almost all bedrock units of northwest Ohio and will be a primary emphasis of this field trip. Joints will be examined in the Upper Silurian Tymochtee Dolomite at Stops 1 and 2, in the Middle Devonian Columbus Limestone at Stops 5 and 10, in the Middle Devonian Delaware Limestone at Stops 8 and 9, and in the Upper Devonian Huron (Ohio) Shale at Stops 6 and 7.

Glacial deposits in northwestern Ohio are mainly Wisconsinan ground moraine that is composed of clay-rich till. It is capped in much of the area to be visited on this trip by lacustrine deposits, which consist of lake-

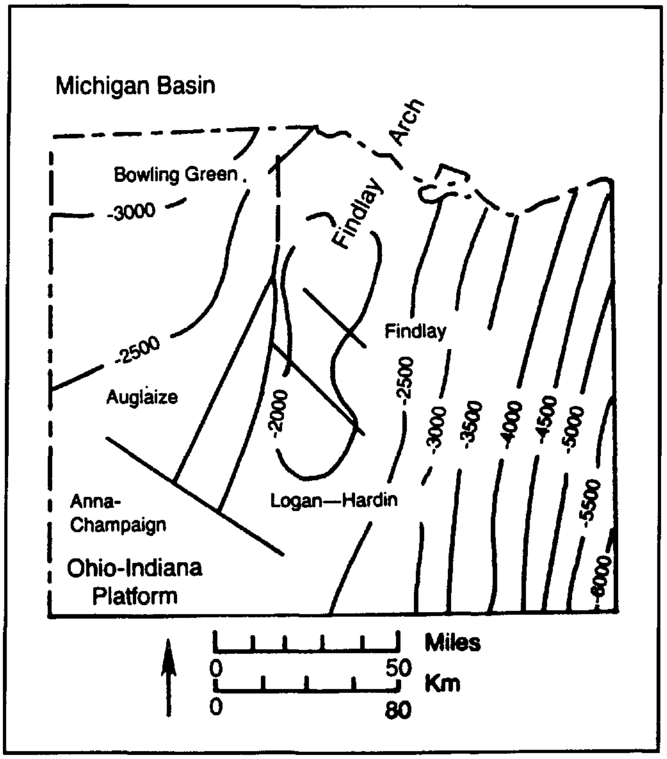

Figure 1. Map showing the principal tectonic features of northern and northwest Ohio, with structural contours on the Precambrian basement (Cole et al. 1987).

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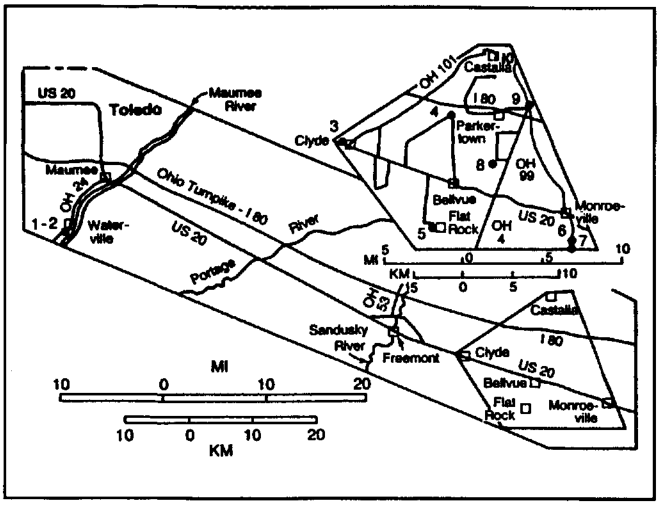


FIGURE 2. Map of the field trip route.

bottom clays and sand ridge beaches. The different beach deposits formed when the retreating glacier blocked the outlet for Lake Erie, causing it to take a higher level. As the margin of the ice alternately retreated and readvanced during its overall recession, the level of the lake varied, corresponding to the elevation of the lowest ice-free outlet available. Lake level variations resulted in about a dozen different levels of lake water and related beaches. Three of these levels produced especially well-developed beach ridges: the Maumee beach (oldest) at 238 m (780 ft), the Whittlesey beach at 224 m (735 ft), and two or three Warren beaches at 210-204 m (690-670 ft). These beaches will be observed northwest of Bellevue (Stops 3, 4), where a promontory created by the cuesta of the Middle Devonian Columbus Limestone (Stop 4) projected out into the ice-dammed lake and allowed the prevailing southwesterly winds to be most effective in beach-building.

Preglacial erosion of the Columbus Limestone created this cuesta. In addition, because of the unusual purity and solubility of this formation, the Columbus Limestone supports extensive karst development. Several sinkholes will be observed along the field-trip route, including what is probably the largest sinkhole in Ohio. In addition, several springs emerge from the base of the cuesta near Castalia, the most famous being the commercial "Blue Hole."

FIELD TRIP ROAD LOG

The field trip group will assemble at the front of the Sheraton-Westgate Hotel (3536 Secor Road) at 7:30 A.M. on Saturday, 20 April 1991. Transportation will be provided by Department of Geology, University of Toledo vans. The group will travel southwest via Secor Road, Dorr Street, Holland-Sylvania Road, Airport Highway, I-475, and the Anthony Wayne Trail (U.S. Route 24) to the France Stone Company quarry at the western city limits of Waterville, OH. The road log begins at this site. Before entering the quarry, release forms must be signed and hard hats and goggles obtained from France Stone Company if not provided by participants. Then the group will ride into the quarry and proceed to the eastern mined-out section.

Distance: km (mi)

cum.		inc.	
km	mi	km	mi
0.0	(0.0)	0.0	(0.0)

STOP 1. France Stone Waterville Quarry at western city limits of Waterville, OH. First site at eastern quarry floor. Geologic and tectonic overview of the field trip route.

The Waterville quarry lies in the Silurian Tymochtee Dolomite some 20 mi (32 km) northwest of the crest of the Findlay Arch (Fig. 3), the northeastern extension of the Cincinnati Arch. In this structural position, strata at the surface are progressively younger toward the Michigan Basin to the northwest and become older to the east and southeast toward the crest of the Findlay Arch. The Bowling Green fault-Lucas County monocline, a major structure in northwestern Ohio (Fig. 3), passes through the western part of the quarry. The fault juxtaposes strata from the Middle Silurian Lockport Group and the Greenfield and Tymochtee formations to the east with strata from the Upper Silurian Bass Island Group to the west, a west side down offset of more than 250 ft (76 m) (Fig. 4).

First examined will be strata exposed in the eastern section of the quarry, with a principal emphasis on the tectonics and the evolution of small scale structures (Fig. 4). A myriad of joints cut strata of the Tymochtee Formation that make up the quarry floor. Because these strata originated primarily as algal mounds, one possible origin for the joint pattern is early desiccation of these carbonate sediments. Close examination, however, shows no semblance of the typical irregular polygonal pattern of desiccated sediments. Instead, there are four principal joint sets, trending approximately N45W, N45-50E, N5E, and N80-90W. Several characteristics of joints in the quarry floor and quarry face indicate that the N45W set, although widely spaced, formed first. This conclusion is based on the following observations: 1) All other joints tend to abut

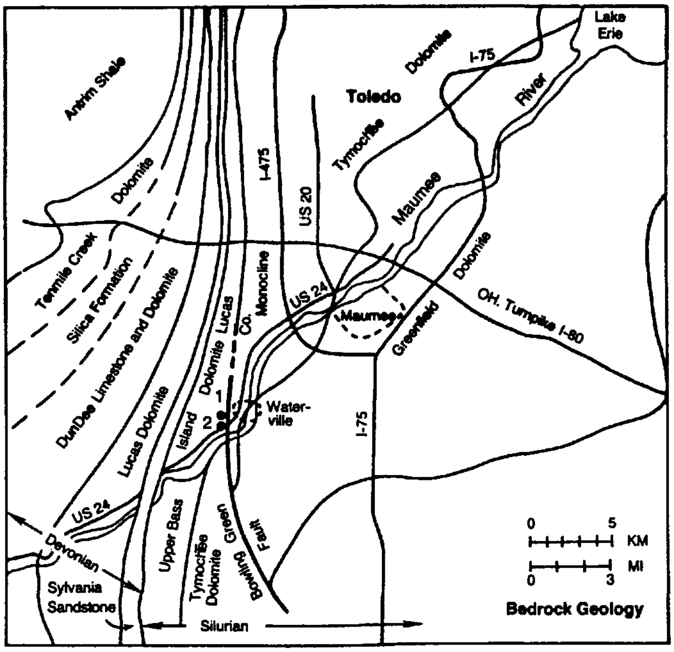


FIGURE 3. Bedrock geology and structure of the Toledo area showing the Waterville Quarry (STOP 1) and Farnsworth Park (STOP 2) (Forsyth 1968).

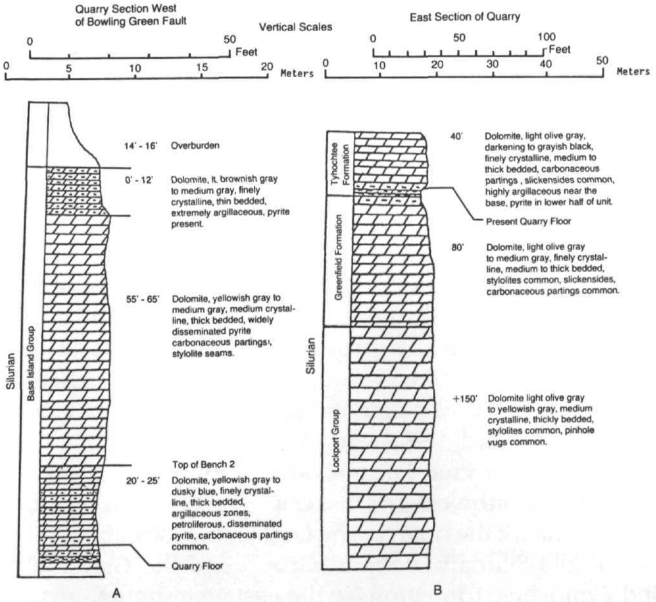


FIGURE 4. Stratigraphic section at Waterville Quarry.

against this set. Typically, later joints do not propagate across an earlier free surface (Kulander et al. 1979). The several blast holes in the quarry floor illustrate well the concept of abutting relations (Fig. 5). 2) This NW-trending set is the most pervasive and penetrative joint set in the quarry (Fig. 6). 3) At some locations other joints tend to hook (Kulander et al. 1979) (Fig. 7) into the NW-trending joint set, indicating that the northwest-trending set was a pre-existing free surface. The succeeding joint chronology is not entirely clear, but joint characteristics suggest that N45E trending joints formed orthogonal to the NW-trending joints, followed by the N5E joints and then the N80-90W joint set.

This simple chronology does not hold at all locations, however. For example, beyond the limits of the Bowling Green fault zone, abutting relationships indicate that the poorly developed N80-90W set was first formed, followed by the N45-50E set. In addition, interpretive problems commonly exist because joints exhibit conflicting relationships with regard to abutting and hooking characteristics. Local joint chronology must be established by the most consistent abutting relationships at any outcrop (Figs. 8A and 8B). Early joint formation occurred, with incomplete segmentation of the rock, perhaps because jointing occurred at depth. Later propagation of these early joints progressed as erosion, quarrying activity, or recession of glacial ice, removed overburden pressure and permitted renewed joint propagation. A similar process occurs in oil and gas well cores when a section of intact core that is raised to be examined breaks apart. Joints within cores may not break through to the core surface during the coring process, but stresses generated in lifting the core may be sufficient to cause the internal fractures (i.e., joints) to propagate to the core boundary, thereby causing complete core separation (Kulander et al. 1990).

These quarry floor outcrops present other commonly misinterpreted joint phenomena. First of all, numerous N5E to N45-50E trending joints that terminate against N45W joints appear to continue, slightly offset, on the other side of this NW joint set (Fig. 9). It is tempting to ascribe these apparent offsets to right lateral or left lateral displacement. However, this assumption is illusory and has no validity unless clear cut markers verify this sort of offset. With closely spaced joints that abut an earlier formed joint set, almost any desired lateral offset can be found along a joint trace. Some workers use slickenlines on laterally persistent joints in rocks with many joint sets to indicate that the laterally persistent joints are younger than, and offset, pre-existing joints. Slickenlines are valid

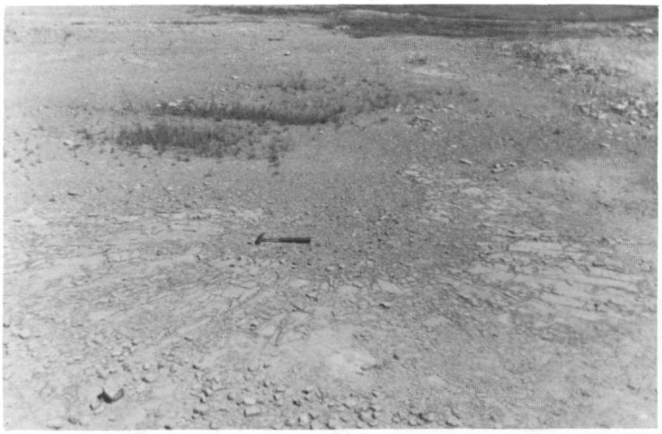


FIGURE 5. Blast hole in Waterville Quarry floor. Radial joints are first formed and are consistently abutted by concentric joints. Ellipticity of blast hole trends N15E, parallel to hammer.

FIGURE 6. North wall of Waterville Quarry showing first-formed N45-50W systematic joints.

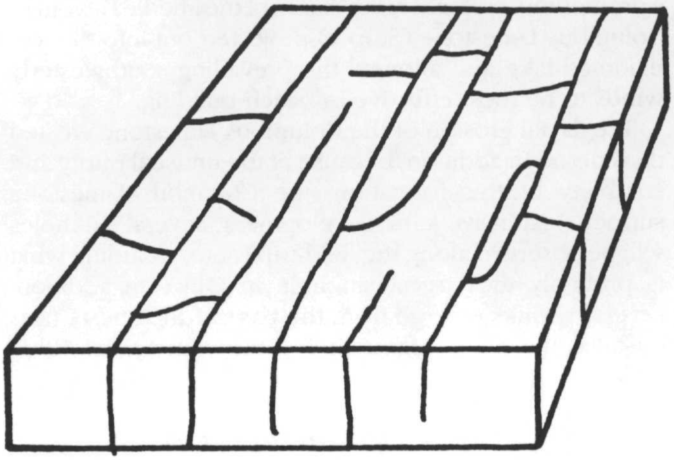


FIGURE 7. Diagram of tendential joint features showing hooking relationships (Kulander et al. 1979).

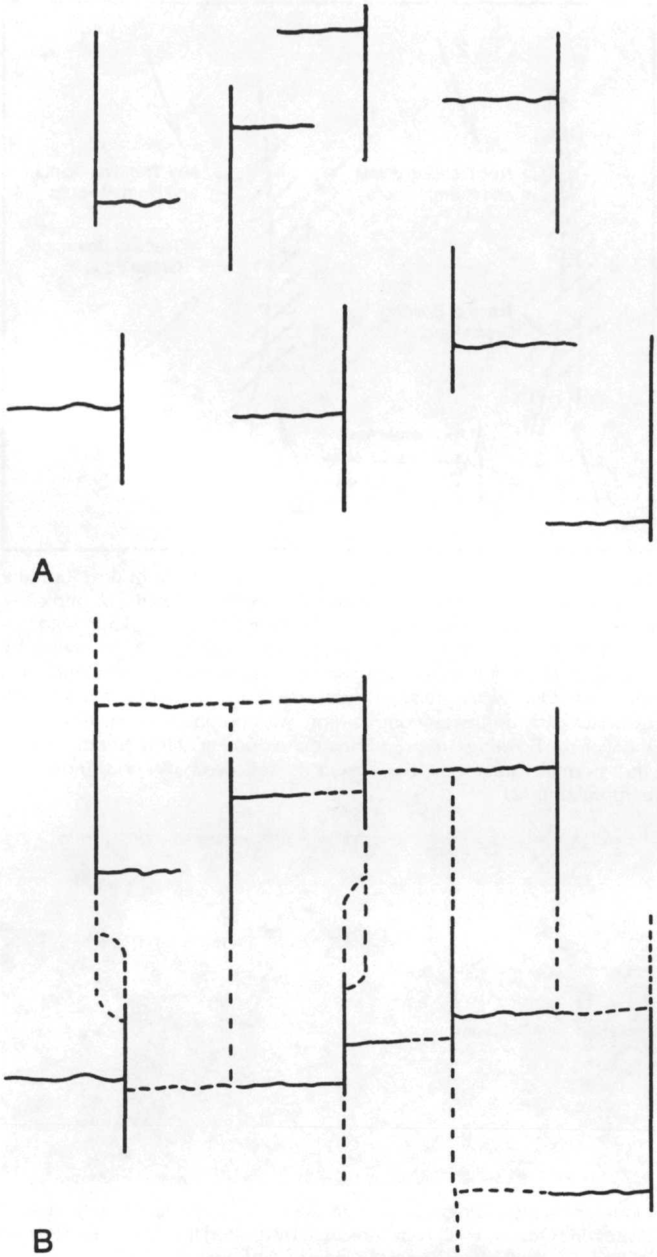


FIGURE 8. A. Diagram showing initial development of N-S systematic joints and E-W nonsystematic joints. B. Continuation of joint development from 8A, after removal of overburden. Rock is completely segmented, shows hooking and some conflicting abutting relationships.

criteria only where other offset markers indicate lateral displacement because slickenlines may indicate later movement along an earlier formed joint surface. The most realistic interpretation for joint chronology, unless otherwise consistently disproven, is that later formed joints abut earlier formed joints.

Mineralization is another criterion commonly used in the determination of joint chronology. Where a mineralized joint set cross-cuts other joints at a locale, then this mineralized set is commonly interpreted as last formed. This assumption is often ill-advised because the mineralization may have occurred at any time after the development of the joint, which may have formed early. For example, many traces of the dominant N45W joints here are mineralized. Close inspection with a hand lens reveals a crack-seal geometry (Ramsay 1980) in the mineralization, suggesting multiple opening events. These joints experienced a multiple and complex opening history after their early origin.

FIGURE 9. Waterville Quarry floor with apparent offset of N5E-trending joints against N45W systematic joints.

Criteria for establishing the chronology of joint formation require mechanistic, rather than geometric arguments. Any realistic tectonic interpretation requires a well-established joint chronology. The joint chronology must be established within a regional framework. This simply means that in virtually any area a regional joint background is present and must be determined. In the area of the quarry and east of the quarry, the dominant regional systematic joint set has a trend of approximately N45W (Armstrong 1976). However, west of the quarry, the N45-50E joint set is the dominant systematic set.

The southern quarry wall sheds light on the origin of this N45W joint set by pointing out the extensional nature of this set. Here, N45W joints in the quarry floor are seen as normal faults in the quarry face, with several centimeters (in) of offset (Fig. 10). (Please stay clear of the walls because of loose rock.) Several of these normal faults show multiple slickenlines, with dip slip slickenlines overprinted by right-lateral strike slip slickenlines. This chronology holds at several locations around the quarry in the vicinity of Waterville.

Two tectonic models appear feasible for joint formation associated with the Bowling Green fault complex. One model (Fig. 11A) necessitates early extensional tectonics, resulting in a steeply dipping normal fault, with the western side downthrown. In this case, differential displacement with greater displacement to the south, would result in a pervasive N45W extension joint set and related small scale normal faults with the same trend. Later compressive stress oriented N-NE, S-SW would cause right lateral slip on the early formed joint faces and small scale normal fault surfaces. The second tectonic model (Fig. 11B) involves early regional compression directed approximately N45W, causing the Bowling Green fault to be formed as a left lateral strike-slip fault, with sufficient oblique slip to give the 250+ ft (76+ m) of offset observed at the Waterville quarry. According to this model, the N45W joints and small scale normal faults would have formed as extensional joints and faults during left lateral shear in the Bowling Green fault zone. Later compressive stress directed N-NE, S-SW would then have caused right lateral slip along the fault and on the early formed joints

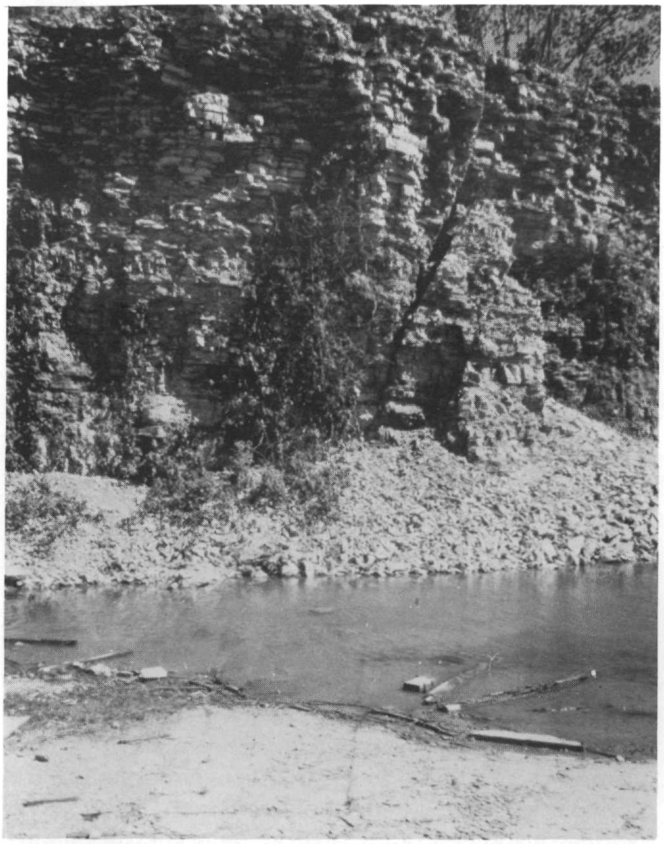


FIGURE 10. N45W-trending systematic joints trending into normal faults in the south wall of the Waterville Quarry.

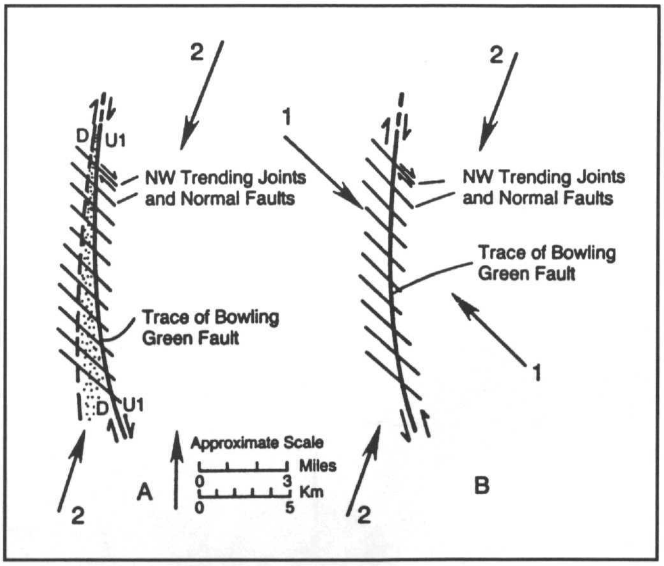


FIGURE 11. Different tectonic models for systematic joint development associated with the Bowling Green fault complex. Model 11A: Indicates early differential displacement on the Bowling Green fault with accompanying jointing and parallel normal faulting (1), followed by essentially north-northeast compression (2). The stippled pattern represents the fault zone, with greater displacement to the south. Model 11B: Indicates early northwest compression, with dominant strike-slip movement on the Bowling Green fault and development of NW-trending joints and normal faults (1). This event is followed by north-northeast compression (2).

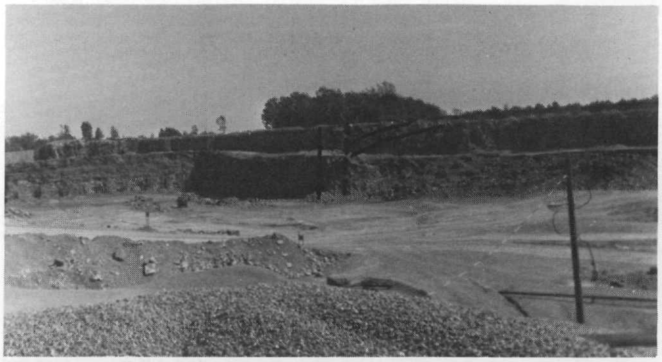


FIGURE 12. Bowling Green fault zone in southwest quarry face of Waterville Quarry. Fault zone indicated by dashed lines. Note eastern dip of bedding (solid lines) on west side of fault into the fault zone.

and faults, as with the other model. In both models, the late mean compressive stress direction, determined from joint and fault faces, was north-northeast, south-southwest.

The ellipticity of the blast holes may give some indication of the orientation of in situ compressive stress in the Waterville quarry (Fig. 5). The greatest propagation of blast-induced radial joints is north-northeast (i.e., N15-30E). This stress direction is consistent with late right lateral shear on the N45W systematic joint set, on the small scale normal faults, and on the Bowling Green fault. It is also close to the compressive stress orientation of north-northeast associated with lateral slickenlines measured on joint faces and small scale normal faults.

Reboard the vans at this time and travel to the northern quarry wall which shows the Bowling Green fault zone. Here, rock is intensely brecciated and shows calcite mineralization and numerous small scale faults, some with apparent reverse movement. One large joint face has horizontal slickenlines. Where the rim drops off to the lower level of the quarry, a view to the southwest (Fig. 12) shows the Bowling Green fault zone in the southwest quarry face. The bedding there shows apparent reverse drag, that is, the western beds dip eastward into the fault zone. It appears that this drag is caused primarily by strike-slip movement, rather than by dip slip.

Reboard the vans and proceed to the lower quarry level just viewed. Here, the Bowling Green fault and associated structural features can be examined at close range. An interesting phenomenon here is the occurrence of petroleum in calcite-filled vugs in the carbonate rock. Apparently, hydrocarbons migrated upward from the Trenton (Middle Ordovician) along the fault zone.

Board the vehicles and travel a short distance from the Waterville quarry to Farnsworth Park on the southeast side of U.S. Route 24 adjacent to the Maumee River. (This stop is dependent on maintaining the time schedule, and water conditions of the river.)

0.16 (0.1) 0.16 (0.1) **STOP 2. Farnsworth Park and the northwest bank of the Maumee River.**

This location reveals several small normal faults in the bedrock exposures above the river bank. The faults trend N45W like the major systematic joint set and minor normal faults in the Waterville quarry. Horizontal slickenlines showing right lateral displacement are also present on several of these fault faces. At the position of the small ravine, where quarry water is pumped into the Maumee River, the Bowling Green fault is exposed and shows deflected bedding, as well as horizontal slickenlines, to indicate right lateral displacement.

The Maumee River at this location and for some distance upstream, is shallow with abundant outcrops and rapids. A few miles (km) downstream, the river deepens, marking the farthest upstream extent of navigable water, hence the old location there of historic Fort Meigs. Interestingly, from that point downstream, the level of the river is dominantly controlled by the level of Lake Erie, into which the river flows some 12 mi (19 km) farther on. Accordingly, much of the lower Maumee River, downstream from this location, is actually an estuary of Lake Erie.

The group will now reboard the vans and proceed east toward the east flank of the Findlay Arch and the Flat Rock quarry of France Stone Company. Travel east from Farnsworth Park on U.S. Route 24.

2.30	(1.4)	2.1	(1.3)	Intersection of Ohio Route 64 and U.S. Route 24 in Waterville.
6.30	(3.9)	4.0	(2.5)	Proceeding east on U.S. Route 24, the Manville plant is located on the south side, separated from the highway by a low area that is an ancient abandoned channel of the Maumee.

The present Maumee is a young river that began only when ice-dammed Glacial Lake Maumee, which flooded as far west as Fort Wayne and drained westward down the Wabash River in Indiana, first dropped in elevation as its glacial dam retreated. This decrease in lake level opened up a lower outlet westward across central Michigan, resulted in Glacial Lake Whittlesey, and initiated drainage from Fort Wayne eastward across the old lake bottom. The present Maumee River utilizes a valley initiated at that time. Since then, the river has cut a significant valley, in the process abandoning several channel segments like this one, and has formed several sets of terraces related to the different levels of Glacial Lake Erie. The original land was very flat, so the gradient of this stream is also very gentle. The channel we see here represents one of the earlier segments of the river channel.

9.8	(6.1)	3.5	(2.2)	Cross under I-475.
12.9	(8.0)	3.1	(1.9)	Intersection of U.S. Route 24 and U.S. Route 20 (west) in Maumee, OH. Turn left and proceed north on U.S. 20.
15.8	(9.8)	2.9	(1.8)	Turn off U.S. 20 onto Ohio Turnpike and head east.
21.1	(13.1)	5.3	(3.3)	Cross Maumee River. Here, 1.5 mi (2.4 km) downstream from Ft. Meigs, the river is already a Lake Erie estuary. It is navigable here for small craft, but not for the freighters that enter the lower reaches of the river and make Toledo an important lake port.
25.3	(15.7)	4.2	(2.6)	Cross under I-75.
37.2	(23.1)	11.9	(7.4)	Pass Turnpike Exit 5.

The very flat land here is underlain by clay-rich till of a Wisconsinan ground moraine. However, it is much flatter than most ground moraine because of the smoothing effect of the ice-dammed lake that flooded this area and left its corresponding lake deposits. Because of the flat topography and the low permeability of the clay-rich till and lake deposits, rain water does not drain well or infiltrate. This problem is partly solved now by tile drains and drainage ditches. In pioneer days, after leveling of the forests, but before these drainage features were installed, swampy conditions, flooding, and corresponding pestilence were common problems of the early settlers. In fact, this area is still referred to as the Black Swamp.

41.7	(25.9)	4.5	(2.8)	Ottawa County line.
44.0	(27.3)	2.3	(1.4)	Sandusky County line.

Ahead 1 mi (0.6 km), just beyond the service area, a large quarry is visible 1 mi (0.6 km) to the right (south), just north of the town of Woodville. This quarry is excavated deeply into the Silurian (Niagaran) Lockport Dolomite. The Lockport Dolomite is believed to have an uneven contact with the overlying Silurian Greenfield Dolomite. J. E. Carman (personal communication) has suggested that highs on the surface of the Lockport are biohermal masses. The rises help to create topographic bedrock highs on the otherwise flat modern landscape because of the somewhat more resistant nature of the Niagaran biohermal dolomite. These bedrock highs are common in this part of northwest Ohio and, because the rock is so shallow, many have quarries located in them, although most of those quarries are now not active.

49.6	(30.8)	5.6	(3.5)	Ottawa County line.
52.5	(32.6)	2.9	(1.8)	Cross Portage River. Bedrock exposed in river bed to the north.

West of the Portage River, unconsolidated material at the surface is clay-rich glacial till, whereas east of the river lacustrine silty clay, generally only a few feet (m) thick, covers the underlying till in most places. The boundary between the clay-rich glacial till and lacustrine silty clay, which has no topographic expression, trends diagonally southeastward across our route. The ice-dammed lake actually covered both areas, but the fine lacustrine sediments remained in suspension and were transported into deeper water before settling to the bottom.

Differentiating such similar materials with the same topographic expression would be difficult without soils information, which is fortunately available in great detail. Soils maps show Hoytville soil on the glacial till and Lenowee soil on the lacustrine silty clays. Where bedrock is very shallow, especially on bedrock highs, the Millsdale soil is developed on this thin veneer of glacial till. Thus, in areas where no topographic relief exists to reveal the presence of shallow bedrock, soils can be used to locate these bedrock highs.

54.9	(34.1)	2.4	(1.5)	Sandusky County line.
55.7	(34.6)	0.8	(0.5)	Bedrock high on south side of Ohio Turnpike.

The bedrock high on the south side of the Turnpike probably represents a biohermal mass in the Lockport

Dolomite, causing positive topographic relief at the Greenfield/Lockport contact and a low rise on the landscape. Soil to the south is Hoytville (representing glacial till), with Millsdale soil (shallow bedrock) near the crest of the rise and Lenawee soil (lacustrine silty clay) along the Turnpike here. Where bedrock is shallowest, poor land use results because of limited soil cover and more droughty conditions due to fractures in the bedrock. Thus, wood lots in this area often identify bedrock highs. A few miles farther east, the Turnpike passes onto a different soil, the Toledo, which identifies lacustrine clay at the surface, though no change is apparent on the landscape there.

71.0	(44.1)	6.0	(0.5)	Exit 6 on Ohio Turnpike. Travel south on Route 53 on lacustrine sediments, marked first by Toledo (lake clay) soil, and farther southeast by Lenawee silty clay, lacustrine soil.
77.0	(47.8)	6.0	(3.7)	Junction of Ohio Route 53 and U.S. Route 20. Turn east on Route 20.
78.1	(48.5)	1.1	(0.7)	Cross Sandusky River, which here represents the upper reaches of another Lake Erie estuary. In another 9 km (5 mi), Route 20 goes back onto Hoytville glacial till soil.
89.2	(55.4)	11.1	(6.9)	Western city limits of Clyde, OH.
92.1	(57.2)	2.9	(1.8)	Begin gentle climb up first beach ridge (Glacial Lake Warren) in city of Clyde. Soils are mostly sandy Ottokee here.
92.4	(57.4)	0.3	(0.2)	Turn left at hilltop at McPherson Cemetery onto Ohio Route 101 (the cemetery lies on what is likely an old Lake Warren dune). This route follows the Lake Warren beach ridge (see Fig. 13).
93.4	(58.0)	1.0	(0.6)	**Stop 3. Lake Warren beach ridge.**

The prominent Lake Warren beach, at an elevation of 207 m (675-680 ft) here, has a clear-cut dropoff to the northwest that is both depositional and erosional in origin. This beach can be traced all the way east to the Buffalo, NY, area, so the position of the ice dam for this lake must have been located in that area. The drop from the highest level of Lake Warren, 210 m (690 ft), to the next lower level, 206 m (675 ft), probably occurred because erosion lowered the lake's outlet across central Michigan. Therefore, formation of this beach probably began with the lake at the higher level, and the beach was completed with the lake at the lower level. This beach is the lowest of the three best-developed glacial lake beaches in northern Ohio (Fig. 13), all three of which we will see and drive on, in the next 15 mi. All owe their strong development to a favorable orientation relative to the prevailing southwest winds; the same beaches, in areas protected from these winds, are much more poorly developed and sometimes barely visible. Continue east on Ohio Route 101.

96.4	(59.9)	4.0	(2.5)	Turn south on Vickery Road (Sandusky County Road 268) and proceed toward beach of Glacial Lake Whittlesey.
99.1	(61.6)	2.7	(1.7)	Intersection of Vickery Road and Sandusky County Road 175 on Lake Whittlesey Beach. Turn right on Road 175, following the beach.
99.4	(61.8)	0.3	(0.2)	Cross U.S. Route 20 on Whittlesey Beach.
99.8	(62.0)	0.3	(0.2)	Turn left off Road 175 onto Sandusky County Road 264. Head due south, crossing railroad tracks, and approach Lake Maumee Beach and related dunes visible ahead to the left. Note old sand pit to the left as the road rises onto the beach.
103.2	(64.1)	3.4	(2.1)	Maumee Beach Ridge. Turn left on Sandusky County Road 183 and travel east on Maumee Beach Ridge.
103.4	(64.2)	0.2	(0.1)	Bend left (northeast) onto Sandusky County Road 177 and follow Maumee Beach Ridge. Hills to the left at the farm are Maumee Beach dunes (Fig. 13).
104.6	(65.1)	1.2	(0.8)	Turn left onto Sandusky County Road 270 and proceed north down old beach front and in 0.6 km (0.4 mile), cross low sand ridge that may represent a lower Maumee level offshore bar.
107.2	(66.6)	2.6	(1.6)	Turn right on U.S. Route 20, Whittlesey Beach lies 2.4 km (1.5 mi) to the north, but the low hills along Route 20 here are Whittlesey-age dunes.
109.3	(67.9)	2.1	(1.3)	Turn left (north) off U.S. Route 20 onto Sandusky County Road 288 and travel north toward Lake Whittlesey Beach ridge.
112.3	(69.8)	3.0	(1.9)	Turn right onto Sandusky County Road 175 and proceed northeast along Lake Whittlesey Beach ridge, which in places is a shore-

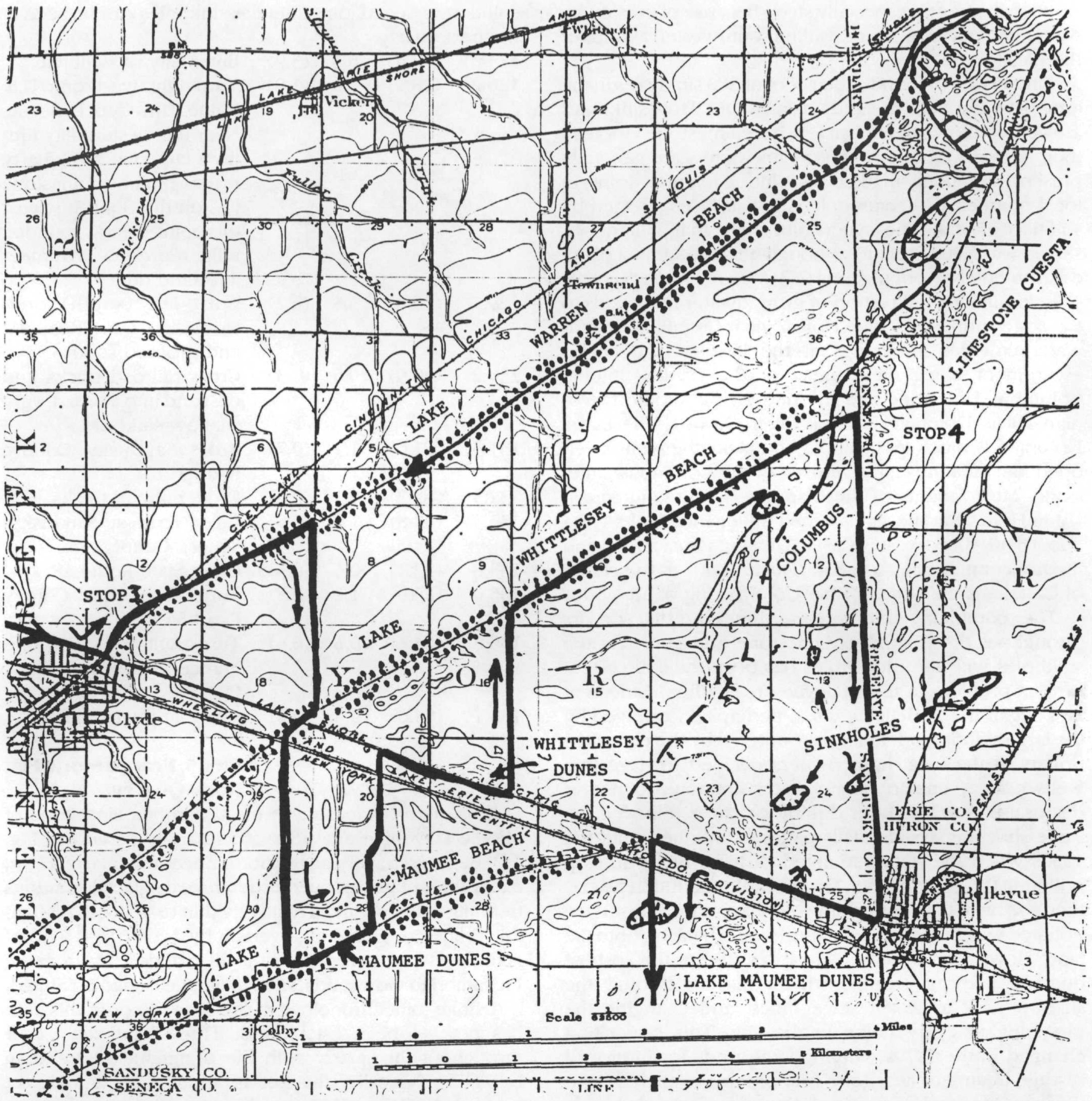


FIGURE 13. Lake Warren, Whittlesey, and Maumee beach ridges and associated features, with topography and solution features related to the Columbus Limestone.

line beach and elsewhere clearly had a bay behind it. The high ridge ahead is the cuesta of Columbus Limestone (Fig. 13).

118.3 (73.5) 6.0 (3.7) **STOP 4. Intersection of Whittlesey Beach Ridge and the Columbus Limestone cuesta at intersection of Sandusky County Road 175 and Southwest Road.**

This location on the crest of the Columbus Limestone cuesta gives a view to the northwest where the Whittlesey beach, impressively developed here, merges into the bedrock ridge (Fig. 13). At the time of the highest of the ice-dammed lakes, Glacial Lake Maumee, the crest of this ridge would have been just awash. Basal rosettes of the nodding thistle (*Carduus nutans*), a showy introduced thistle that does well only on shallow limestone and does not spread like most thistles (Stuckey and Forsyth 1971) may be present. The dip on the Columbus Limestone here is only about 20 ft per mi (3.7 m/km) to the southeast, but the eastern dip slope seems steeper than that because of preglacial erosion of the bedrock surface. The escarpment slope to the west is especially steep because of erosion by waves generated by the prevailing southwesterly winds of the Pleistocene.

Tintera (1980) found a total of over 200 sinkholes in the area between Bellevue and Castalia, OH. Most sinkholes are very shallow, and only a few have limestone visible in their bottoms. Where rock is visible, joints are generally present, commonly marked by solution features. Joints in local quarries also commonly show surfaces affected by solution. Overall, the major joint trend that Tintera observed was N50E to N70E, although near the summit of the escarpment, NW orientations (N35W) are more common. The dominant NE direction of groundwater flow leads to the large springs, or "Blue Holes," near Castalia. Groundwater emerges in springs at the base of the cuesta escarpment along the contact of the readily soluble Columbus Limestone and the underlying Middle Devonian Lucas Dolomite (Detroit River Group). The Lucas Dolomite is much less soluble and lacks the well-developed karst features characteristic of the Columbus Limestone. Most famous of these springs is the commercial "Blue Hole," but the state-owned Miller Blue Hole, lying about 5 mi (9 km) west of Castalia, is somewhat larger, and the noncommercial, so-called "Duck Pond" in the center of Castalia is the largest "Blue Hole" spring of all.

The complex subterranean plumbing that occurs throughout the Columbus Limestone and connects the sinkholes with the Blue Holes has been the source of a serious problem in the Bellevue area. When settlement first began in the Bellevue area, perhaps encouraged by the large solution openings encountered by the early well drillers in the area, homeowners decided to have two wells drilled; one to obtain water and one to use in disposal of sewage. Later drilling practices followed the same shocking system. This pattern continued until the 1930s when the state attempted to have Bellevue stop polluting the groundwater. Groundwater pollution was by then so severe that, during times of heavy rains, subsurface polluted water from the limestone would back up onto the land. However, opposition arose because of the costs of building a sewage-treatment plant, blasting through the shallow rock to install sewer lines, and changing the plumbing in every home in the city. This opposition changed in the 1970s when federal funds for improved sewage treatment near Lake Erie became available, and the city acquired a sewage-treatment plant. However, polluted water moving through openings in soluble limestone experiences almost no purification, and wells for new homes in the known arc of pollution sometimes clearly tap badly polluted water.

South toward Bellevue, Southwest Road is the Erie-Sandusky County line and the western boundary of the Connecticut Western Reserve lands. The land to the west is divided into one-mile sections, whereas the land to the east, within the Western Reserve, is not divided in this manner because reserve lands were set aside before sectioning of land began.

South 3 km (1.9 mi), along the side road to the right, a wood lot on the far side of the road hides a small sinking stream, and 0.5 km (0.3 mi) farther, woods to the right contain several sinkholes that expose limestone with solution-widened joints. Similar sinkholes can be seen at the next quarry.

124.6	(77.4)	6.3	(3.9)	Enter City of Bellevue.
126.2	(78.4)	1.6	(1.0)	Turn right (west) onto U.S. Route 20 in city of Bellevue. Near the western city limits, a large inactive quarry in the Columbus Limestone lies on the right. Just past this point, the low rounded hills represent Maumee-age sand dunes.
129.7	(80.6)	3.5	(2.2)	Turn left (south) onto Sandusky County Road 302 and proceed south.
130.2	(80.9)	0.5	(0.3)	Cross railroad tracks and descend into a broad, very shallow sinkhole.
131.3	(81.6)	1.1	(0.7)	Cross Sandusky County Road 191.
132.3	(82.2)	1.1	(0.6)	Cross railroad tracks.
133.3	(82.8)	1.0	(0.6)	Cross road at Sandusky-Seneca County line.
133.8	(83.1)	0.5	(0.3)	Cross State Route 18.
135.0	(83.9)	1.2	(0.8)	Turn left on Seneca County Road 34.
135.6	(84.3)	0.6	(0.4)	Turn right onto road into France Stone Flat Rock Quarry.
136.1	(84.6)	0.5	(0.3)	Arrive at quarry office.

STOP 5. France Stone Flat Rock Quarry.

This quarry is located in the Columbus Limestone of Middle Devonian age. (See stratigraphic section in Fig. 14). Begin by traversing the north rim of the quarry. Here, excavation of glacial overburden reveals glacial striations trending S40-45W and a relatively thin (8-10 ft-, 2.4-3.0 m-thick) layer of glacial till, overlain by 2-3 ft (0.6-0.9 m) of lake clay deposits. Erratics in the till include a few from the Precambrian Gowganda Tillite from the Canadian Shield. A definite joint chronology at this location or in this area has not yet been established. Three joint sets occur throughout the quarry with the dominant set trending N45-65E. Typically, this set is abutted by a joint set trending N15W to N15E, which in turn is abutted by a set trending N40-50W. Small folds in the bedrock appear to be "pop-ups" caused by contemporary compressional stresses, which in this area trend east to northeast (Engelder 1982). Notice that these pop-ups tend to follow N15W-N15E joints, trending nearly normal to the contemporary compressive stresses. Since glacial overburden is so thin here, it seems extremely unlikely that its removal in preparation for quarrying caused these pop-ups. More likely, their origin is related to elimination of overburden pressure by melting of the thick cover of glacial ice. A possibility does exist that these small folds may be related to differential subsidence caused by solution of gypsum beds below the quarry floor, as Verber and Stansberry (1953) proposed for the subsidence-produced caves on South Bass Island. Differential subsidence may be responsible for the linear swale in the

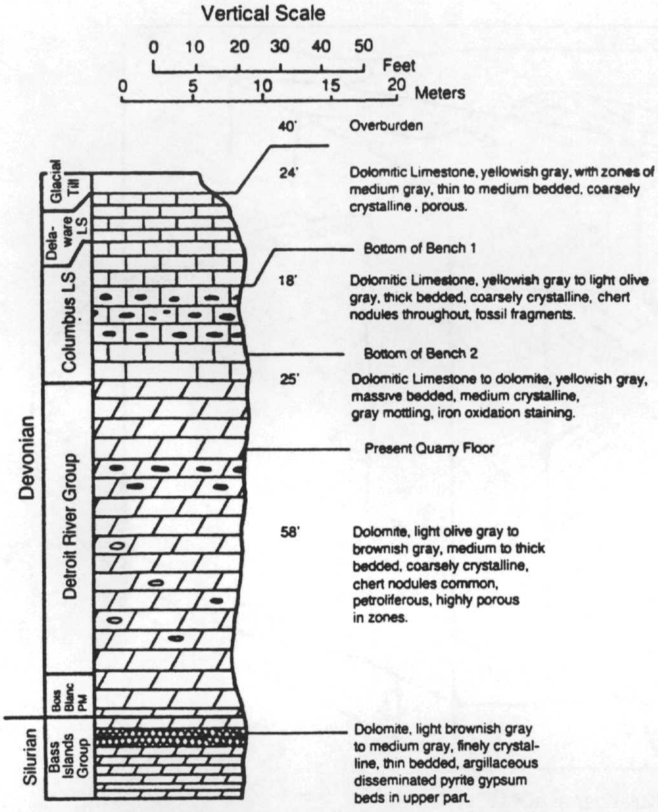


FIGURE 14. Stratigraphic section at the Flat Rock Quarry.

quarry that trends north into the grove of trees north of the quarry, but the sharp nature of the small folds and their consistent N5W to N5E trends do not support a differential subsidence origin.

This entire area shows extensive karstification, somewhat subdued by glacial deposits. Several small sinkholes in the grove of trees adjacent to the north rim of the quarry are apparently controlled by jointing since the exposed bedrock shows joint faces trending N-S to N15W, N50E to N55E, and E-W. Solution along joints is common throughout the region and is especially evident in the exposed bedrock floor of the north quarry rim. For example, a solution channel runs along a N60-65E-trending joint (Fig. 15) Such channels present problems in quarrying operations because they may "belly out" and be filled with large quantities of overburden material which must be separated from the bedrock before marketing the stone.

Proceed now to the southeast bench of the quarry; the exposed dolomitic limestone shows a variety of sedimentological and structural features. Excellent bedding stylolites are present, as well as cherty zones associated with silicification of rip-up clasts. Petroliferous beds are present, defined by thin, dark, organic-rich layers. Co-author Forsyth has found a few small fish fossils at this location. Well-exposed joint surfaces show excellent transient features that constitute the typical plumose structure commonly described in texts on structural geology (Fig. 16) (Kulander et al. 1979). Terminations and origins of fracture plumes, as well as abutting relations of joints, help determine joint chronology and fracture propagation characteristics. For example, a typical fracture plume is shown with a top origin and fracture propagation leading

FIGURE 15. Solution channel developed along a N60-65E-trending joint.

at the top of the bed, indicating that tensile stress peaked there, possibly because of a slight bending moment of the bed (Fig. 17). Excellent plumose features, such as well-defined twist hackle, are also associated with blast holes. Here, some of the blast-induced joints appear to follow the early N50-60E joint anisotropy.

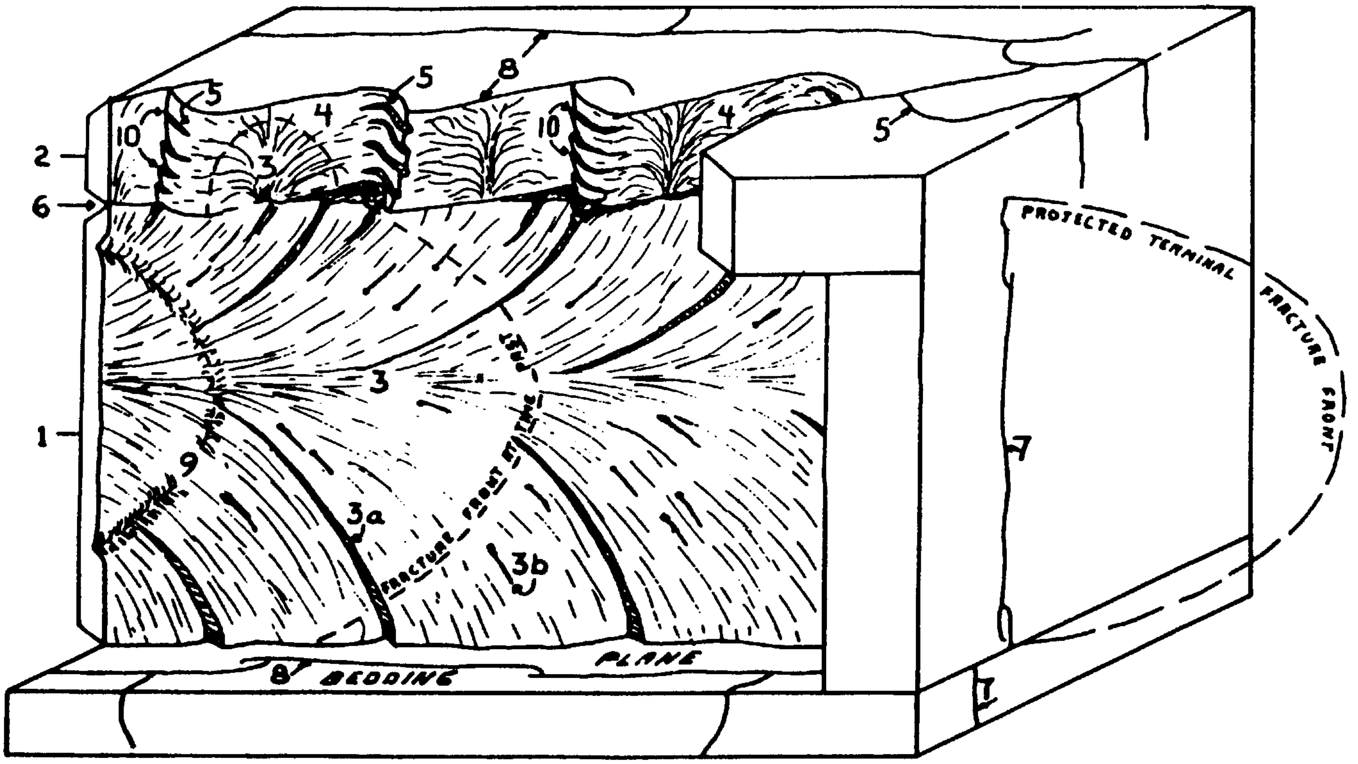
Viewed from this current position, the small synclinal swale in the north quarry face can easily be seen (Fig. 18). The origin of this feature, as previously stated, is likely the solution of underlying gypsum beds and subsequent collapse.

At this time, the group will travel back to Bellevue for lunch and then proceed eastward on U.S. Route 20 into the Devonian shale belt, where the shale shows a remarkable consistency in joint trends.

136.7	(85.0)	0.6	(0.4)	Turn left (west) onto Seneca County Road 34.
137.3	(85.4)	0.6	(0.4)	Turn right (north) onto Seneca County Township Road 82 and proceed north to U.S. Route 20.
142.9	(88.8)	5.6	(3.4)	Turn right onto U.S. Route 20 and proceed into Bellevue.
150.6	(93.6)	7.7	(4.8)	Junction of U.S. Route 20 and Ohio Route 4.
158.0	(98.2)	7.4	(4.6)	Monroeville city limits.
159.0	(98.8)	1.0	(0.6)	Turn right (south) onto Ohio Route 99.
161.9	(100.6)	2.9	(1.8)	**STOP 6. Devonian Shale outcrop at highway bridge over Frink Run.**

At this stop, the upper shale section of the Ohio Shale shows pervasive N60E-trending systematic joints and a less well developed orthogonal nonsystematic set. Notice that the mechanical properties of the shale were different from the upper to lower layers. The upper section was apparently more brittle and shows the best joint development. It is also interesting that extensional stresses were sufficient for continuous joint propagation from shale through the large carbonate nodule. From this location we will proceed south to examine one more Devonian shale outcrop.

162.5	(101.0)	0.6	(0.4)	Turn south onto Hettle Road.



Genetic classification after Kulander et al. (1979)

1. main fracture face
2. twist hackle fringe
3. fracture plume, 3a = twist hackle component; 3b = inclusion hackle component
4. twist hackle face
5. twist hackle step
6. plumose-coarse twist hackle boundary
7. tendential penetration — in vertical plane or perpendicular to bedding
8. tendential extent — in horizontal plane or parallel to bedding
9. arrest or Wallner line depending on morphology
10. second order twist hackle

FIGURE 16. Diagram of transient joint features (Kulander et al. 1979).

162.8	(101.2)	0.3	(0.2)	At road fork, take the right lane and cross Slate Run.

Stop 7. Devonian Shale exposures in the bed of Slate Run.

The Ohio Shale here shows an excellent orthogonal pattern of systematic and nonsystematic joints. As at the previous stop, systematic joints trend N60-65E, with nonsystematic joints approximately orthogonal to these. These last two locations emphasize the consistency of joint trends in the Ohio Shale throughout this area. This consistent orientation constitutes the regional background. Only after establishing the regional background can departure from this consistency be interpreted in the context of local structures. Now proceed back to U.S. Route 20 and northward back into the Devonian carbonate belt.

166.9	(103.7)	4.1	(2.5)	Return by same route to U.S. Route 20; turn left (west).
175.1	(108.8)	8.2	(5.1)	Turn right (north) onto Ohio Route 4.
177.3	(110.2)	2.2	(1.4)	Cross Ohio Route 113 in the small community of Strongs Ridge, which is located on the old Maumee beach.
177.9	(110.6)	0.6	(0.4)	Erie County line.
178.5	(111.0)	0.6	(0.4)	Railroad overpass. Low wooded rise, 0.8 km (0.5 mi) to the right is a bedrock high in what is believed to be the Devonian Prout Limestone.
179.0	(111.3)	0.5	(0.3)	Turn left onto Smith Road.
180.2	(112.0)	1.2	(0.7)	Turn left onto Billings Road and proceed to end of dead-end road.
180.5	(112.2)	0.3	(0.2)	Park at dead-end road adjacent to property of Mr. and Mrs. Larry Schindley.

Stop 8. Devonian Delaware Limestone exposures in old borrow pit.

At this stop, walk west approximately 1000 ft (300 m) to an old borrow pit where the bedrock floor is Delaware Limestone. The Delaware lies stratigraphically above the Columbus Limestone, whose cuesta lies 3 mi (4.8 km) to the west. The Delaware lies below the Prout Limestone, which crops out just to the east. Here, systematic joints trend E-W and are accentuated by vegetation growing in the fractures (Fig. 19). Nonsystematic joints most typically abut these E-W joints and range in trend from N-S to N35E. Engelder and Hancock (1989) implied that joints trending

FIGURE 17. Fracture plume on joint face with top origin and fracture propagation leading at the top of the bed. Note that later bedding movement has offset the fracture plume.

FIGURE 18. Synclinal downwarp in north wall of Flat Rock Quarry.

E-W and at high angles to the northeast throughout this part of eastern North America were caused by the contemporary compressive stress field as shown by Engelder (1982) and Zoback and Zoback (1982). However, systematic joints were not caused by contemporary compressive stress at this location because a pronounced pop-up (Fig. 20) trending N-S to N35E follows the local nonsystematic joints, which were rotated by the development of this feature. The structural chronology at this location involved development of E-W-trending systematic joints, followed by formation of N-S-to N35E-trending nonsystematic joints, followed by E-W compressive stress to develop the pop-up, which most likely occurred in response to melting back of glacial ice and removal of overburden pressure. At this time, the group will walk back to the vans and proceed north to another limestone exposure.

184.9 (114.9) 4.4 (2.7) Travel north on Billings Road to Strecker Road. Turn right onto Strecker Road. Parkertown Quarry on left, developed in the Columbus and Delaware limestones.

186.2	(115.7)	1.3	(0.8)	Turn left off Strecker Road onto Ohio Route 4 and proceed north.
188.0	(116.8)	1.8	(1.1)	Cross Ohio Turnpike.
189.1	(117.5)	1.1	(0.7)	Turn right onto Portland Road.
189.4	(117.7)	0.3	(0.2)	Turn left onto Ohio Route 99 (Skadden Road).

FIGURE 19. East-west trending joints accentuated by vegetation in Delaware Limestone in borrow pit floor.

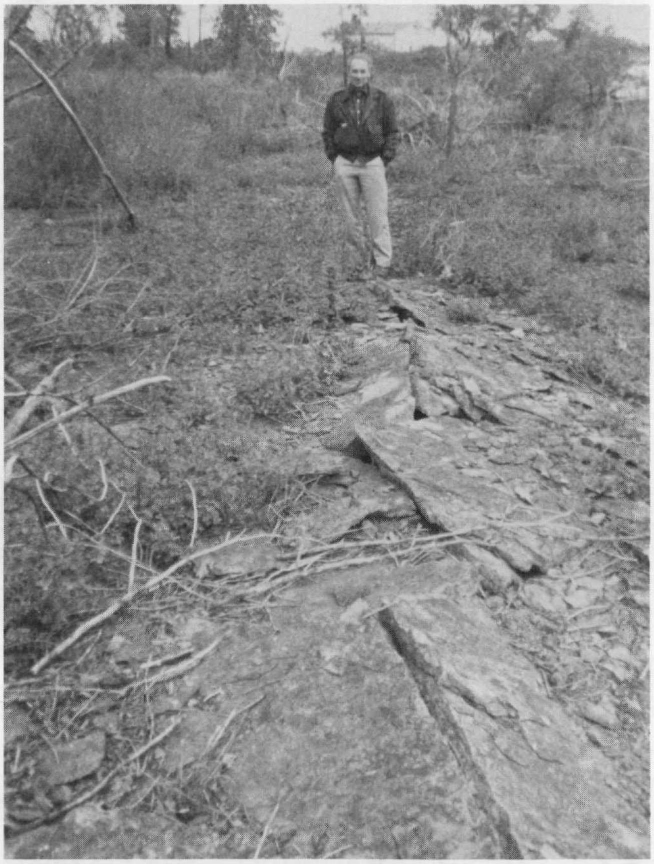


FIGURE 20. Contemporary compressive stress field "pop-up" in borrow pit floor. Note en echelon configuration of "pop-up" where N-S-N35E-trending nonsystematic joints terminate against the E-W systematics.

189.6	(117.8)	0.2	(0.1)	**STOP 9. Middle Devonian Delaware Limestone with joint traces accentuated by vegetation.**

The stop will be brief and is included to show excellent joint patterns accentuated by grass growing in the fractures. Traces of large scale joints such as seen here are visible on low altitude aerial photographs in much of the field trip area. They are especially evident where glacial overburden is thin. The systematic joints here trend N55-60E and are abutted by second-formed nonsystematic joints trending N55-60W. A large hook is outlined by the

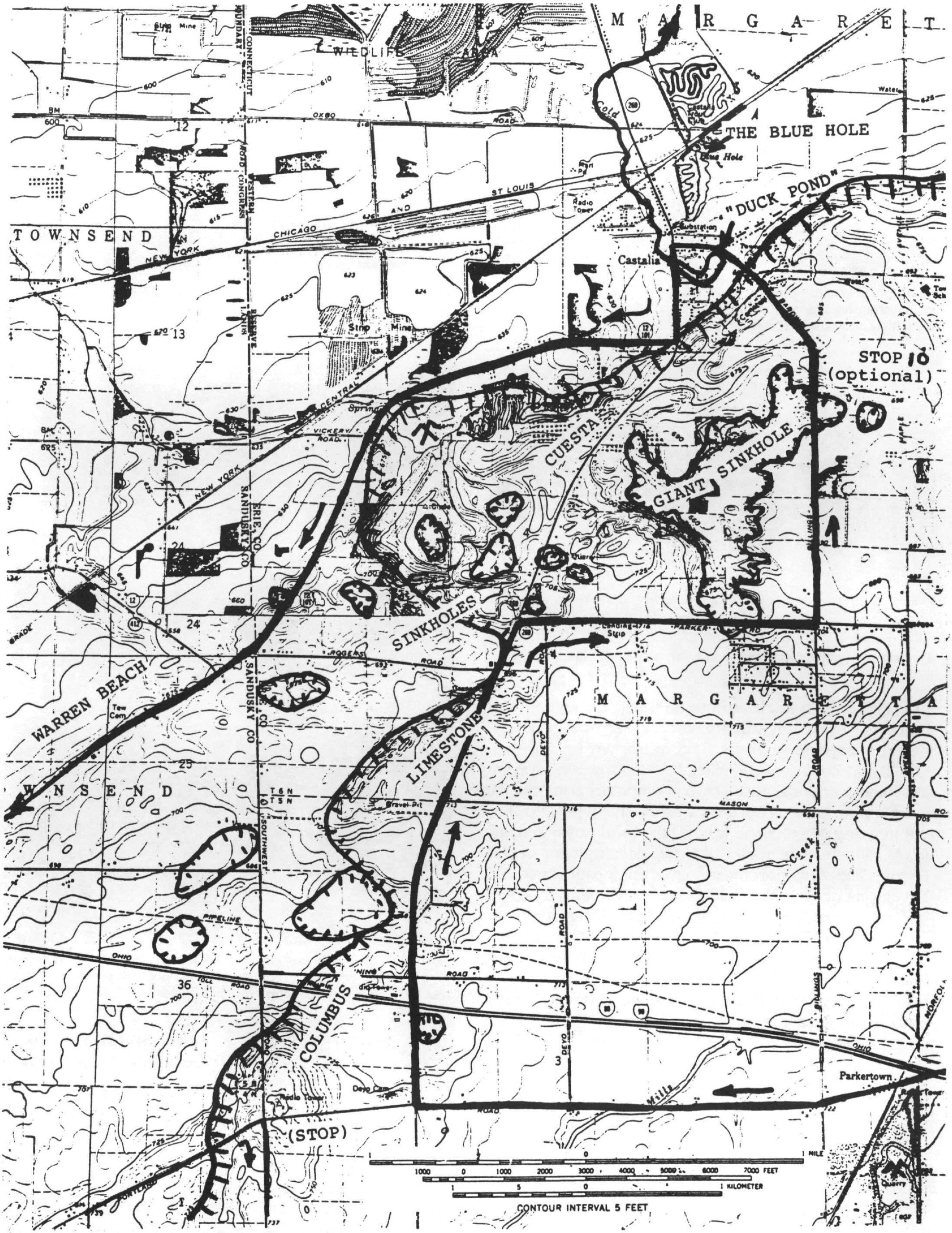


FIGURE 21. Solution features developed in the Columbus Limestone from Parkertown to Castalia, OH.

grass-filled joint in the middle of the field. This systematic fracture has propagated to meet the pre-existing systematic joint (i.e., free surface) orthogonally. Notice that consideration of only the area at the orthogonal junction would have resulted in the interpretation of two joint sets at right angles, instead of the correct interpretation of one systematic joint set. From this point, the field trip group will reboard the vans and proceed to the west and northwest.

189.9	(118.0)	0.3	(0.2)	Turn left (southwest) onto Ohio Route 4.
190.4	(118.3)	0.5	(0.3)	Turn right (west) onto Portland Road.
192.8	(119.8)	2.4	(1.5)	Cross under Ohio Turnpike. Parkertown Quarry in the Columbus and Delaware limestones on left. Ahead, the glacial till cover is 10-15 ft (3-5 m) thick, but limestone is very shallow again at the next turn, which lies 0.5 mi (0.8 km) east of the crest of the Columbus Limestone cuesta. Route is shown on Fig. 21.
197.0	(122.4)	4.2	(2.6)	Turn right (north) onto Ohio Route 269.

Columbus Limestone is visible in cuts east and west of the Turnpike overpass, representing the northern extension of the Columbus Limestone cuesta. Ahead 0.5 mi (0.8 km), Route 269 descends into a large sinkhole, and 0.25 mi (0.4 km) farther, the open pit on the ridge to the left, was excavated in coarse limestone gravel, piled up against the solid limestone of the cuesta by Lake Whittlesey waves.

197.8	(122.9)	0.8	(0.5)	Cross Ohio Turnpike.
201.0	(124.9)	3.2	(2.0)	Turn right (east) onto Parker Road past deep sinkholes to the left, in the woods behind houses.
203.6	(126.5)	1.6	(1.0)	Travel down slope into bottom of large sinkhole. This same feature will be crossed 2.0 mi (3.2 km) ahead at Optional Stop 10.
204.2	(126.9)	0.6	(0.4)	Turn left (north) onto Billings Road toward Castalia. Note extensive use of Columbus Limestone slabs in stone fences here where rock is shallow and plentiful.
206.0	(128.0)	1.8	(1.1)	Travel down slope into bottom of large sinkhole (Fig. 21).

Stop 10. (Optional)

Bottom of large sinkhole, 1 mi (1.6 km) or so long (this is the sinkhole observed 2 mi [3.2 km] back). It is about 50 ft (15 m) deep, possibly the biggest sinkhole in Ohio, and is developed at the crest of the Columbus Limestone cuesta. Note exposures of Columbus Limestone to the right and basal rosettes of the nodding thistle.

206.5	(128.3)	0.5	(0.3)	Continue north on Billings Road, turn left onto Bardwell Road and travel down the Columbus Limestone cuesta into Castalia.
207.6	(129.0)	1.1	(0.7)	Lake in Castalia on left is the so called "Duck Pond," the largest of three springs, or "Blue Holes." The L-shape of this bedrock lake indicates that its configuration is controlled by jointing. Turn left onto Ohio Route 101.
207.9	(129.2)	0.3	(0.2)	Turn left (south) and remain on Ohio Route 101.
208.7	(129.7)	0.8	(0.5)	Turn right (west) and remain on Ohio Route 101. Road follows the base of the Columbus Limestone cuesta and slowly climbs onto the Lake Warren Beach, which it follows all the way to Clyde, OH.
213.2	(132.5)	4.5	(2.8)	Enter Sandusky County.
216.9	(134.8)	3.7	(2.3)	Cross over Ohio Turnpike.
225.9	(140.4)	9.0	(5.6)	Clyde city limits.
226.9	(141.0)	1.0	(0.6)	Turn right onto U.S. Route 20 in Clyde and proceed back to Toledo. End of field trip. We hope you enjoyed it.

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