THE SILURIAN DOLOMITE AQUIFER OF THE DOOR PENINSULA: FACIES, SEQUENCE STRATIGRAPHY, POROSITY, AND HYDROGEOLOGY

FIELD TRIP GUIDEBOOK
(Revised Version)

1996 Fall Field Conference of the
Great Lakes Section of the SEPM
Green Bay, Wisconsin

and

Pre-meeting field trip for the 1997 Meeting of the
North-Central Section of the GSA
Madison, Wisconsin

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A WELCOME

The convenors welcome the participants of the 1996 Fall Field Conference of the Great Lakes Section of SEPM and the 1997 meeting of the North-Central Section of GSA. We are pleased to offer you a field trip that presents different perspectives on the Silurian dolostones of the Door Peninsula. This interval is both an excellent example of Midcontinental Silurian facies and (in the subsurface) a regional carbonate aquifer. Thus this guidebook include articles on facies and sequence stratigraphy, paleontology, environmental issues, and hydrogeology. We believe that these diverse studies reflect the multifaceted nature of sedimentary geology. We hope to stimulate an exchange of viewpoints and to encourage participants to broaden their own thinking about sedimentary facies.

This guidebook was orginally prepared for the SEPM Fall Field Conference. This version includes an additional stop (Wequiock Church Quarry, stop 2), a revised road log, and some text corrections.

We want to thank the landowners of the Door Peninsula who have allowed us to conduct our studies over many years. Their cooperation and patience have made this work possible. We also want to acknowledge the continued support of the Door County Soil and Water Conservation Department, the State of Wisconsin, and the University of Wisconsin for our work. Joyce Ohrmundt and the staff at the Midway Motel were very helpful at making the SEPM meeting a success. Mike Mudrey of the Wisconsin Geological and Natural History Survey provided assistance with the GSA trip.

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INTRODUCTION TO THE FIELD TRIP AND THE GEOLOGY OF THE DOOR PENINSULA

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The field trip will introduce the geology and hydrogeology of the Silurian aquifer of the Door Peninsula, northeastern Wisconsin. Our goal is to illustrate the important links between stratigraphy and hydrogeology for understanding and predicting groundwater flow patterns. To help demostrate these geologic connections, the guidebook includes articles summarizing Silurian stratigraphy, Pleistocene geology, and hydrogeology of the Door Peninsula. Our field trip stops also reflect these varied geological topics. The first four stops provide examples of the basic Silurian facies whereas the final two stops stress local and regional hydrologic patterns.

This article introduces some of the major geological features of the peninsula as a prelude to the contributions which follow.

Geological Setting

The Door Peninsula is located in northeastern Wisconsin between Lake Michigan and Green Bay (Figure 1). The peninsula is approximately 130 km long, including Washington Island, and tapers from 45 km wide in the south to less than 8 km wide in the north. General overviews of the natural history of the peninsula are provided by Palmquist (1989) and Hershbell (1990).

The Door Peninsula is one segment of the well-known Niagara Escarpment of the Great Lakes region. In eastern Wisconsin, the escarpment is the highest and most continuous of a series of cuestas fromed by Paleozoic units that dip gently (< 1°) from the Wisconsin Arch into the Michigan Basin (Shrock, 1940; Sherrill, 1978). Strike roughly parallels the Green Bay shoreline (Figure 2). The peninsula is underlain (from oldest to youngest) by: (1) Precambrian crystalline rock; (2) Cambrian and Ordovician sedimentary rocks; (3) Silurian dolostones; and (4) Quaternary glacial deposits (Stieglitz 1990; Kluessendorf and Mikulic, 1989). Less resistant Ordovician shales underlie Green Bay to the west of the peninsula and post-Silurian strata occur beneath Lake Michigan to the east.

Paleozic Stratigraphy

The Paleozoic stratigraphy of the Door Peninsula was first described by Chamberlin (1877) as part of his report on eastern Wisconsin (Figure 2 and 3). Until recently, there have been relatively few detailed stratigraphic studies but overviews are presented in Kluessendorf and Mickulic (1989) and Stieglitz (1990).

The oldest rocks on the peninsula are Upper Ordovician shales, dolostones and limestones of the Maquoketa Formation (Ostrom, 1967; Froming, 1971; Sivon, 1980). This formation crops out along the base of the Niagara Escarpment in southwest Door and northeast Brown Counties. The upper part of the formation is soft claystone that was eroded by ice of the Green Bay Lobe (Mason and Stieglitz, 1994; Waltman and Stieglitz, 1995). The Maquoketa is important

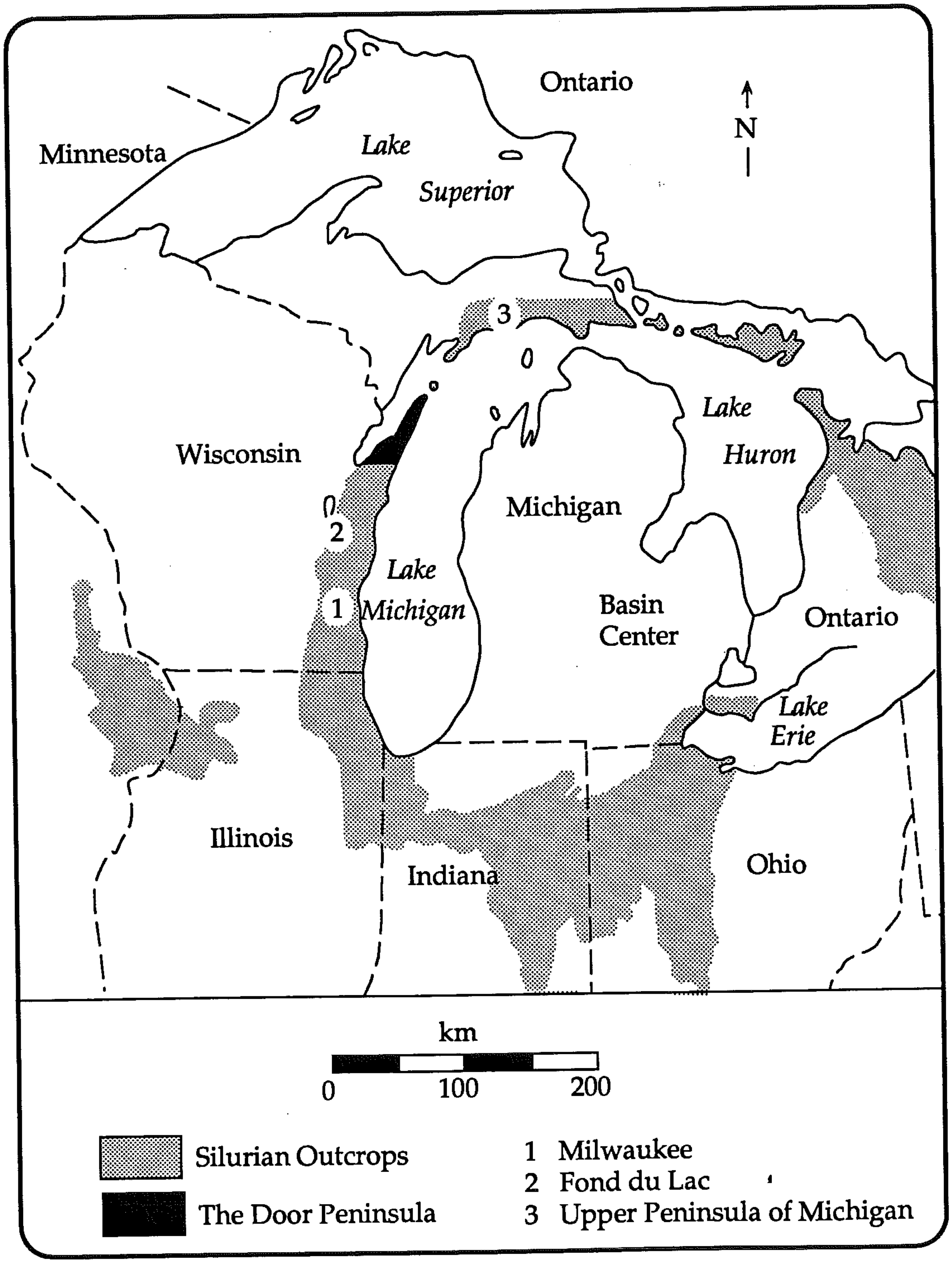

Figure 1: Location map of the Door Peninsula and other areas mentioned in the the articles superimposed on generalized Silurian outcrops of the Midcontinent (modified from Lowenstam, 1950)

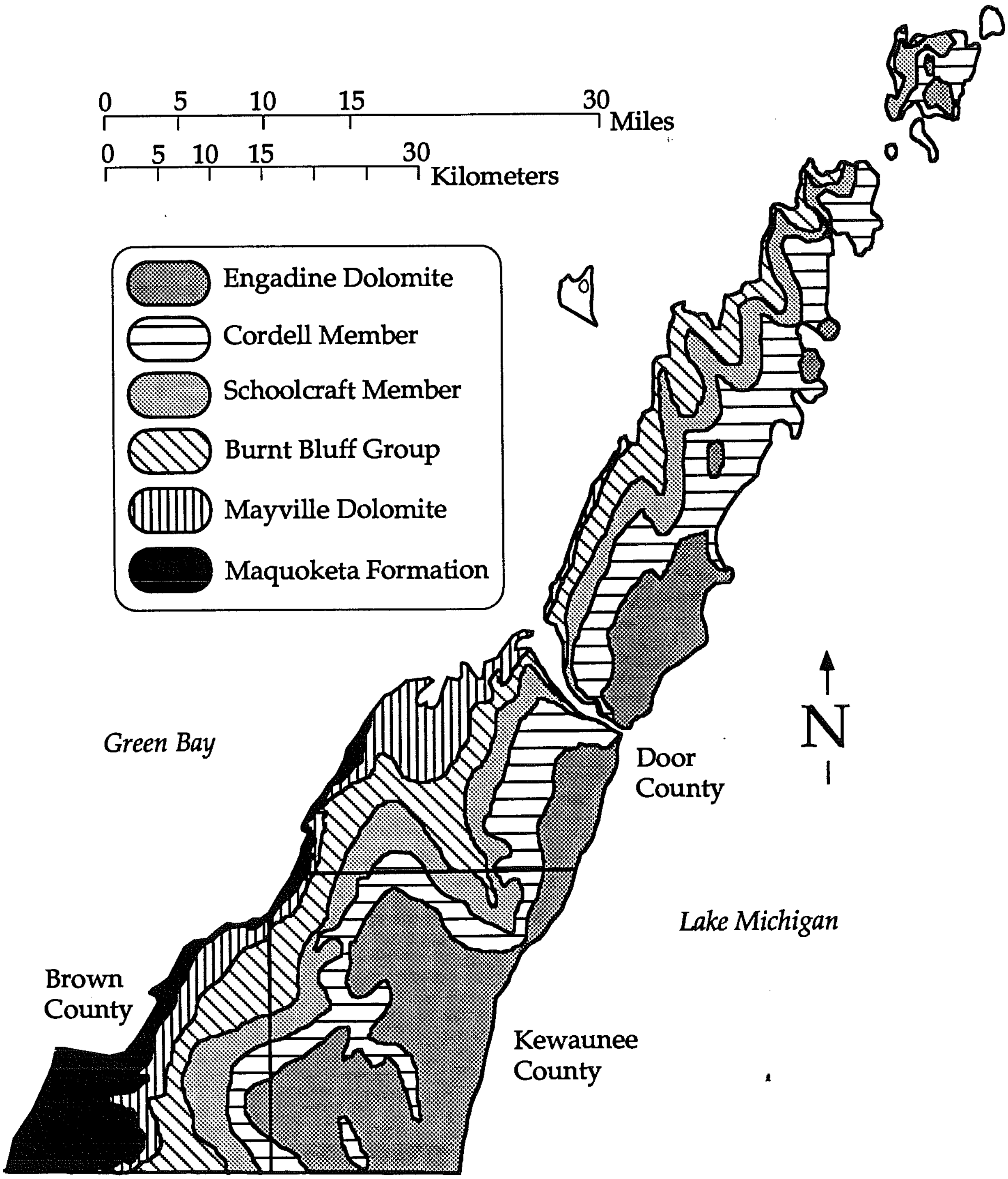

Figure 2: Geological map of the Door Peninsula with county boundaries. Map modified from S. Johnson (1987) and Chamberlin (1877).

System	N. Am. Series	Chamberlin (1877) Northeast Wisconsin	N. Am. Series	Europ. Series	Stiegltiz, 1990, 1991; Harris and Waldhuetter, (1996)	
Lower Silurian	Niagaran	Racine Beds	Niagaran	Llandoverian	Engadine Dolomite	
		Upper Coral Beds			Manistique Formation	Cordell Member
		Lower Coral Beds				Schoolcraft Member
		Transition Beds			Burnt Bluff Group	Hendricks Dolomite
		Byron Beds				Byron Dolomite
		Mayville Beds	Alexandrian		Mayville Dolomite	
Ordovician		Cincinnati Shales			Maquoketa Formation	

Figure 3: Comparison of the Silurian stratigraphic nomenclature of Chamberlin (1877) with the present nomenclature for the Door Peninsula (Harris and Waldhuetter, 1996).

hydrologically because it acts as a regional aquitard that seperates deeper sandstone aquifers from the Silurian dolostones and restricts karstification to these units.

The uppermost Ordovician unit is the Neda Formation, an oolitic ironstone that occurs locally in eastern Wisconsin above the Maquoketa. It crops out along the escarpment in Brown County and is reported in wells in Manitowoc County to the south (Rosezweig, 1951). The Neda varies in thickness but generally thins northward. The ironstone was mined in east-central Wisconsin until 1928 (Frederick, 1993).

Silurian dolostones underlie most of the peninsula and are the focus of the field trip. The units are, in ascending order, the Mayville Dolomite, Byron Dolomite, Hendricks Dolomite, Manistique Formation, and Engadine Dolomite. Past studies included detailed studies on bioherms (Shrock, 1939; Soderman and Carozzi, 1963), Washington Island (Shrock 1940), and paleoecology (Allen and Stieglitz, 1983; Allen, 1986). Waldhuetter (1994) and Harris and Waldhuetter (1996) provide more extensive stratigraphic and sedimentologic data.

In an important study, Sherrill (1978) placed the stratigraphy in a hydrogeological framework and laid the foundation for subsequent groundwater investigations.

Pleistocene deposits and karst features

Glaciation and deglaciation of the peninsula occurred numerous times during the Pleistocene. The Green Bay Lobe moved through northwest-southeast trending valleys in the escarpment to cover much of Door and Brown Counties (Schneider, 1993). However, south and east of Sturgeon Bay, ice from the Michigan Bay Lobe deposited younger tills (Mode, 1989). After withdrawal of the most recent ice, post-glacial lakes inundated most of the peninsula until isostatic uplift stablized drainages near their present levels. Remnants of old shoreline features indicate the extent of the former lake levels (Schneider, 1993).

The glacial and post-glacial sediments consist of a variable thickness of till, outwash, lake sediments, beach and dune sands, and organic wetland soils. Overburden thickness generally increases southward on the peninsula. The surface till (Figure 4) north of Sturgeon Bay ("Buff Till") is primarily the Liberty Grove Member of the Holy Hill Formation although the Glenmore and other tills occur locally (Schneider, 1993). To the south, younger tills ("Red Till") deposited by the Green Bay or Lake Michigan Lobes are at the surface (Acomb et al., 1982; McCartney and Mickelson, 1982).

Silurian dolostones are modfied by fracturing, groundwater dissolution and karst features that occur over several scales of investigation (Rosen, 1984; Johnson, 1987). Although no cave decorations have been dated, most of the karst features predate the last ice advance over the peninsula. Radiocarbon analyis of organic remains from the fills in the Brussels Hill Cave (southern Door County) yielded dates of 670 and 1820 BP, but postdate cave formation and decoration (Howe, 1987a, 1987b).

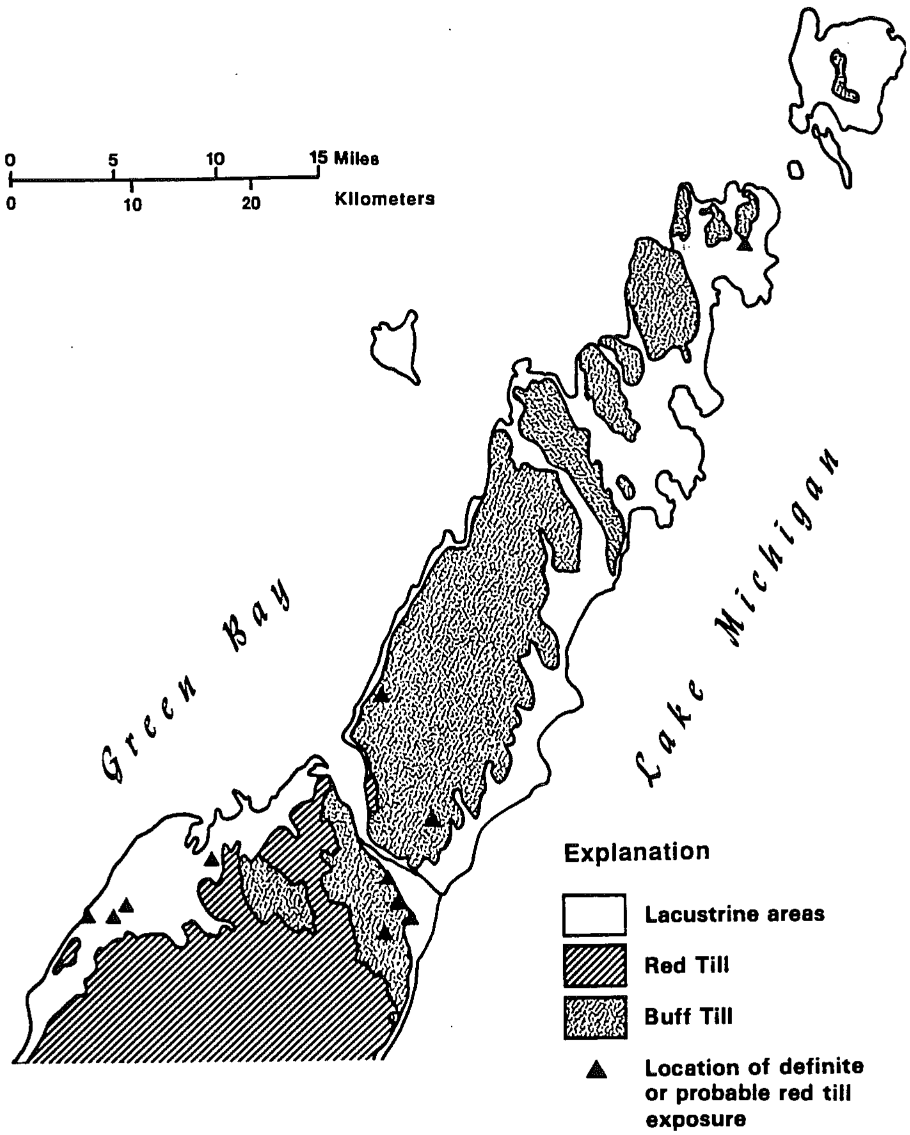

Figure 4: Glacial deposits of Door County (Schneider, 1989, modified from Thwaites and Bertrand, 1957). Used by permisssion of the Wisconsin Academy of Sciences, Arts and Letters.

LOWER SILURIAN (LLANDOVERY) FACIES, SEQUENCE STRATIGRAPHY, AND POROSITY PATTERNS IN THE DOOR PENINSULA, WISCONSIN: AN OUTCROP VIEW

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Introduction

The abundant outcrops and quarry exposures in the Door Peninsula provide the best opportunity to directly observe the Silurian dolostone section of eastern Wisconsin. All stratigraphic units are exposed with only parts of one formation unavailable in outcrop. Reflecting the field area's location on the flank of the Wisconsin Dome, the Lower Silurian (Llandovery) formations consist of three facies representing inner to middle shelf environments. The facies succession and exposure surfaces delineate five sequences that appear regionally correlatable from the Upper Peninsula of Michigan to east-central Wisconsin. This sequence-keyed facies interpretation provides a framework for facies and porosity prediction.

Stratigraphic Studies

The Door Peninsula and the Upper Peninsula of Michigan share the same stratigraphic nomenclature because Silurian formations appear continuous between the two areas (Shrock, 1940; Allen, 1986). The nomenclature is basically Chamberlin's (1877) with the addition of more precisely defined units (Figure 1). Most of the present stratigraphic names were proposed for the Upper Peninsula of Michigan (Smith, 1915; Ehlers and Kesling, 1957; Ehlers, 1973 although in use decades earlier) and introduced into Wisconsin by Shrock (1939) and Allen (1986). Harris and Waldhuetter (1996) provide details on the nomenclature of individual units.

Most detailed geological investigations of the Silurian rocks in eastern Wisconsin focused on biostratigraphy or paleontology. Shrock (1939) studied the Silurian "coral reefs" previously described by Chamberlin (1877) and recognized that most Niagaran coral reefs are bioherms without framebuilding organisms. Soderman and Carozzi (1963) studied the microfacies of Burnt Bluff Group bioherms in eastern Wisconsin. Brooks (1978) and Elger (1979) studied the facies of the Byron Dolomite and the Mayville Dolomite, respectively, near Fond du Lac, Wisconsin (southeast of the field trip area). Although well exposed, Silurian strata of the Door Peninsula have been the subject of few detailed studies (Shrock, 1940; Allen, 1986; Waldhuetter, 1994; Harris and Waldhuetter, 1996). Watkins and Kuglitsch (this volume) summarize recent paleontological studies.

Sedimentology and Depositonal Facies

Waldhuetter's (1994) study provided the framework for an improved understanding of the depositional facies of the Silurian section of the Door Peninsula. He recorded detailed sedimentology logs for twenty-seven sections located throughout the peninsula (Figure 2). We have adopted the approach of Demicco and Hardie (1995) in characterizing depositional facies. Subfacies are defined based upon diagnostic textures, grain types and sedimentary structures. Reoccurrent collections of subfacies define facies that correspond to depositional environments. This approach results in a two-level hierarchy of subfacies and facies units that are used in descriptions and interpretations.

System	N. Am. Series	Northeast Wisconsin (Chamberlin, 1877)	N. Am. Series	Door Peninsula, Wisconsin (Shrock, 1939, 1940)		N. Am. Series	Upper Peninsula of Michigan (Ehlers and Kesling, 1957; Ehlers, 1973)		N. Am. Series	Europ. Series	Door Peninsula, WI (Stieglitz. 1990, 1991; Harris and Waldhuetter, 1996)	
Lower Silurian	Niagaran	Racine Beds	Niagaran	Racine Formation		Niagaran	Engadine Dolomite		Niagaran	Llandoverian	Engadine Dolomite	
		Upper Coral Beds		Manistique Formation	Cordell Dolomite		Manistique Group	Cordell Dolomite			Manistique Formation	Cordell Member
		Lower Coral Beds			Schoolcraft Dolomite			Schoolcraft Dolomite				Schoolcraft Member
		Transition Beds		Burnt Bluff Formation	Hendricks Dolomite		Burnt Bluff Group	Hendricks Dolomite			Burnt Bluff Group	Hendricks Dolomite
		Byron Beds			Byron Dolomite			Byron Dolomite				Byron Dolomite
		Mayville Beds	Alexandrian	Mayville Dolomite		Alexandrian	Mayville Dolomite		Alexandrian		Mayville Dolomite	
Ordovician	Cincinnati Shales		Maquoketa Shale			(not studied)			Maquoketa Formation			

Figure 1: Silurian stratigraphic nomenclature for the Door Peninsula of Wisconsin and the Upper Peninsula of Michigan by various authors

The Silurian section in the Door Peninsula consists of three facies (Burrowed, Rippled, and Laminite Facies). Each facies (described below) contains multiple component subfacies that are summarized in Figure 3.

Burrowed Facies

The Burrowed Facies consists of Subfacies 1-3. The facies is characterized by abundant burrows and a normal marine fauna consisting of stromatoporoids, tabulate corals (*Halysites, Favosites*), rugose corals, brachiopods and echinoderms. *Thalassinoides* burrows are common and are usually filled with a fossil packstone to grainstone replaced by chert. This facies occurs in the Manistique Formation where a silicified fauna is present and in the Mayville Dolomite where Subfacies 3 is absent.

The Burrowed Facies represents a subtidal, marine shelf environment with normal salinity levels. Moderate to low energy conditions below fairweather wave base were interrupted by storm

Figure 2: Map of the Door Peninsula with locations of field trip stops and other measured sections.

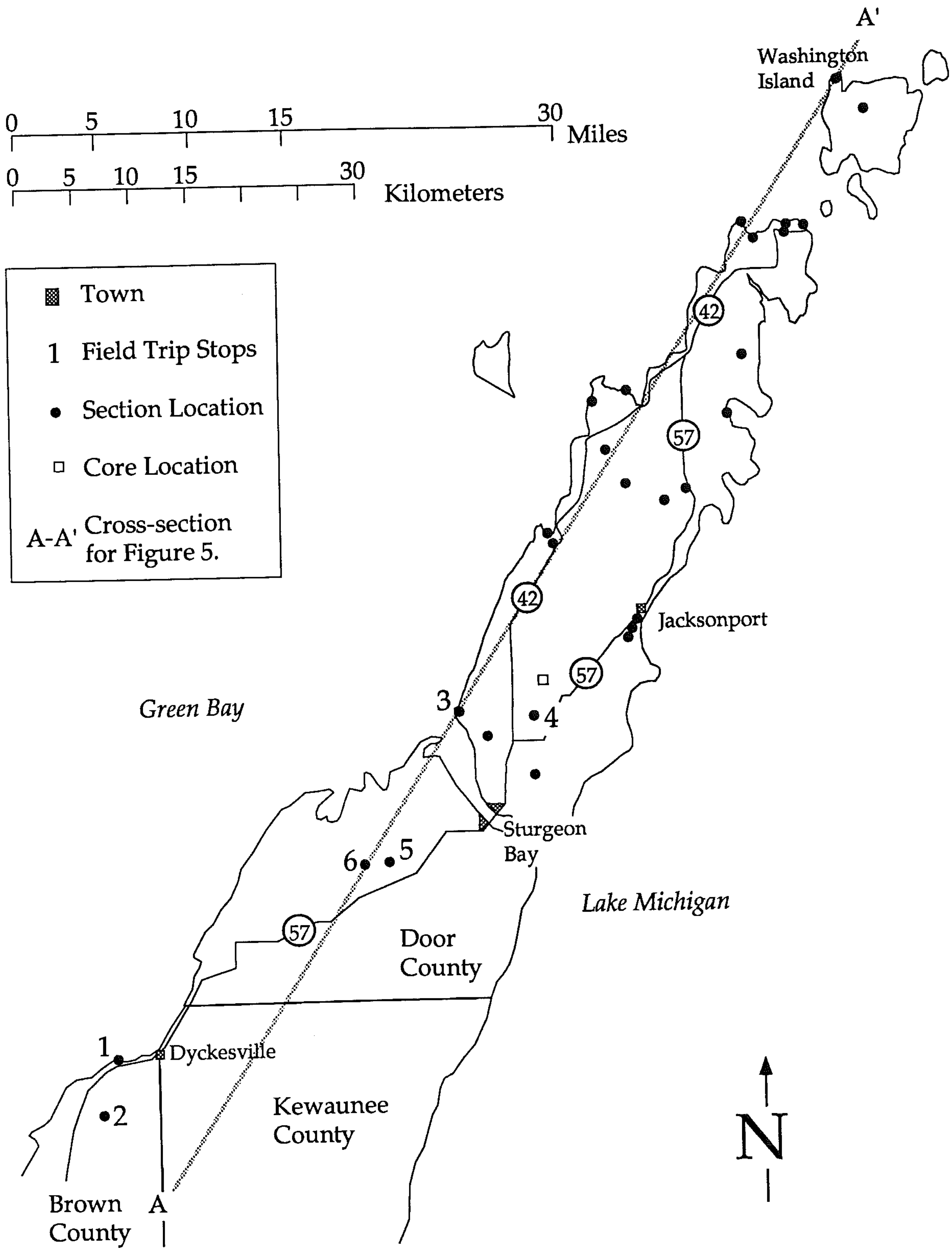


Figure 2: Map of the Door Peninsula with the locations of the field trip stops and the locations of the measured sections and the core hole (Harris, Hegrenes and Muldoon, this volume) used in constructing Figure 5.

Figure 3: Summary of subfacies

SUBFACIES	SED. STRUCTURES	FAUNA	POROSITY	PORE TYPES
1. Brachiopod Wackestone-Packstone		Brachiopods, sparse tabulate and rugose corals, stromatoporoids.	6-8%	Brachiopod moldic
2. *Thalassinoides* Mudstone-Wackestone	Burrows, carbonaceous laminations. Variable chert content.	In burrow fills	<1%	
3. Laminar Stromatoporoid-Coral Floatstone	Wavy thin beds. Most fauna silicified.	Stromatoporoids, brachiopods, tabulate and rugose corals, crinoids.	<1%	Fossil moldic and vug
4. Domal Stromatoporoid-Coral Floatstone	Wavy to rippled thin beds. Variable chert content.	Stromatoporoids, brachiopods, tabulate and rugose corals, crinoids.	<1%	Fossil moldic and vug
5. Rippled Coral Packstone	Wavy to rippled bedding. Variable chert content.	Fragmented brachiopods, tabulate and rugose corals, crinoids.	1-4%	Vug
6. Pellet Packstone-Wackestone	Thick wavy laminations, thin to medium wavy beds. Nodular chert.	Stromatoporoids, brachiopods, rugose corals.	1-5%	Vug and fossil moldic
7. Coral Floatstone	Wavy laminations, medium to thick beds.	Tabulate and rugose corals, stromatoporoids.	0-6%	Fossil moldic and vug
8. Coral-Stromatoporoid Boundstone		Tabulate corals and stromatoporoids.	2-6%	Vug
9. Pellet-Ostracode Wackestone	Planar thick laminations and very thin beds, cross lamination, cross bedding, ripples, fenestral fabrics.	Ostrocodes, rare trilobites.	< 1%	
10. Bioturbated Mudstone-Wackestone	Burrows, bioturbation index 3-6.	Ostracodes.	1-3%	Intercrystalline
11. Interbedded Mudstone and Intraclastic Jelly-Roll Wackestone	Very thin, wavy to crinkly laminations, rare mudcracks, deformed ("jelly-roll") beds.		<6%	Vug, fracture
12. Laminated Mudstone	Thin to thick, planar to wavy laminations, cross laminations, fenestral fabrics, rare mudcracks.		1-4%	Fenestral, mudcrack, and vug
13. Crinkly Laminated Mudcracked Mudstone	Thin to thick, parallel, flat, wavy to crinkly laminations, mudcracks, sheet cracks, fenestral fabrics.		3-4 %	Fenestral, mudcrack, mat shelter, and vug

events. The Brachiopod Wackestone-Packstone (Subfacies 1) and Laminar Stromatoporoid-Coral Floatstone (Subfacies 3) probably formed within storm wave base as indicated by the broken fauna and crude bedding and Benthic Assemblage (BA) 3 faunas (Brett et al., 1993; Watkins and Kuglitsch, this volume). *Thalassinoides* Mudstone-Wackestone (Subfacies 2) is also interpreted to form in subtidal conditions within effective storm wave base. Chert bands with irregular internal layering are replacements of coarse skeletal layers that formed during storm deposition.

Rippled Facies

The Rippled Facies consists of Subfacies 4-8. The abundant sedimentary structures include ripple marks, wavy bedding (probably representing migrating ripples), and fragmented skeletal detritus. Bioturbation is less extensive than in the Burrowed Facies. Different subfacies predominate in different stratigraphic units: Subfacies 5 and 6 in the Mayville Dolomite, Subfacies 4, 5 and 6 in the Schoolcraft Member of the Manistique Formation, and Subfacies 7 and 8 in the Engadine Dolomite.

The Rippled Facies represents a moderate to high energy, subtidal environment at or above fairweather wave base based upon the predominant physical structures, fragmented skeletal remains, and scarce bioturbation. The faunas represent BA 3 (Johnson and Campbell, 1980; Brett et al., 1993; Watkins and Kuglitsch, this volume). The Coral-Stromatoporoid Boundstone (Subfacies 8) is interpreted as a moderate to high-energy biostrome based upon its well-winnowed fabric.

Laminite Facies

The Laminite Facies consists of a series of shallowing-upward cycles typical of tidal flat deposition. Complete cycles ideally consist of four parts: (1) a thin, subtidal, wackestone to floatstone with corals, crinoids, and fossil moldic and vug porosity (Subfacies 4); (2) a shallow subtidal mudstone to wackestone with bioturbation, pellets, laminations, very thin beds and ostracodes (Subfacies 9 and 10); (3) an intertidal mudstone with mudcracks, fenestrae, microbial mat laminations, "jelly-rolls" (deformed laminations), and intraclastic storm deposits with scoured bases (Subfacies 11 and 12); and (4) a supratidal laminated, mudcracked mudstone (Subfacies 13). Subfacies 4 is absent in most Byron cycles although it is common in Hendricks cycles. Both the Byron and Hendricks Dolomites entirely consist of Laminite Facies. Thin intervals in the Mayville Dolomite and the Schoolcraft Member are assigned to this facies.

Subfacies 9 and 10 contain a restricted, ostracode-dominated fauna indicative of BA 1 as expected in a tidal flat setting (Johnson and Campbell, 1980; Brett et al., 1993; Watkins and Kuglitsch, this volume). Subfacies 4 horizons at the bases of some cycles indicate normal open marine conditions assigned to BA 2.

Regional Facies Model

The facies recognized in the Door Peninsula can be combined with previous work to develop a regional facies model for the Silurian strata of eastern Wisconsin (Figure 4). Harrison (1985) noted similar facies changes in subsurface data from the northern Michigan Basin.

The Silurian strata in the Door Peninsula represent three inner to middle shelf depositional settings of a carbonate platform. The Laminite Facies represents tidal flat conditions adjacent to the Wisconsin Arch. The Rippled Facies represents moderate energy subtidal conditions at or above fairweather wave base (10-20 meters). The Burrowed Facies represents lower energy subtidal conditions below fairweather wave base with a maximum depth of 20-40 meters for the

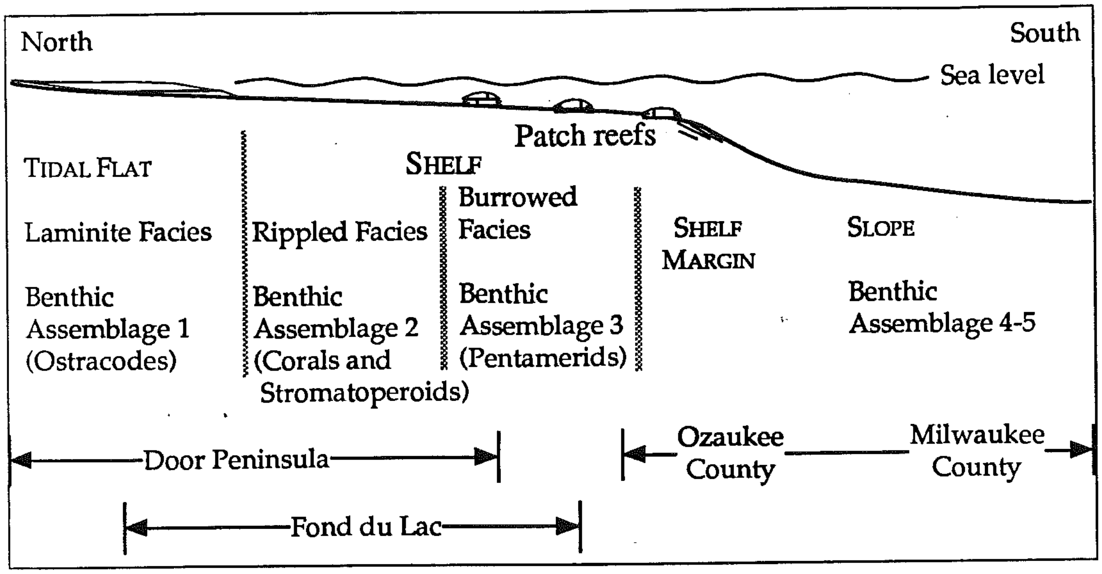


Figure 4: Lower Silurian facies model for eastern Wisconsin

pentamerid brachiopod zones (Johnson, 1987; Brett et al., 1993; Watkins and Kuglitsch, this volume).

East-central Wisconsin time-equivalent facies include slightly deeper water conditions than the Door Peninsula. Elger (1979) described biotic "reef-like" structures in the lower Mayville and Brooks (1978) described the Byron as intertidal to subtidal deposits.

To the south, obliquely along strike in Ozaukee County, the Llandovery shelf margin is not exposed. We infer that it was similar to the Wenlock margin which was a complex of migrating carbonate shoals and patch reefs (R. Watkins, pers. comm., 1993; our observations). In southern Ozaukee and Milwaukee Counties, Rovey (1990) described deeper-water clays, dark shales and argillaceous dolostones in Llandovery strata. Byron and lower Manistique equivalents contain a very high-diversity BA 4-5 fauna that includes abundant siliceous spicules (Watkins and Kuglitsch, 1995).

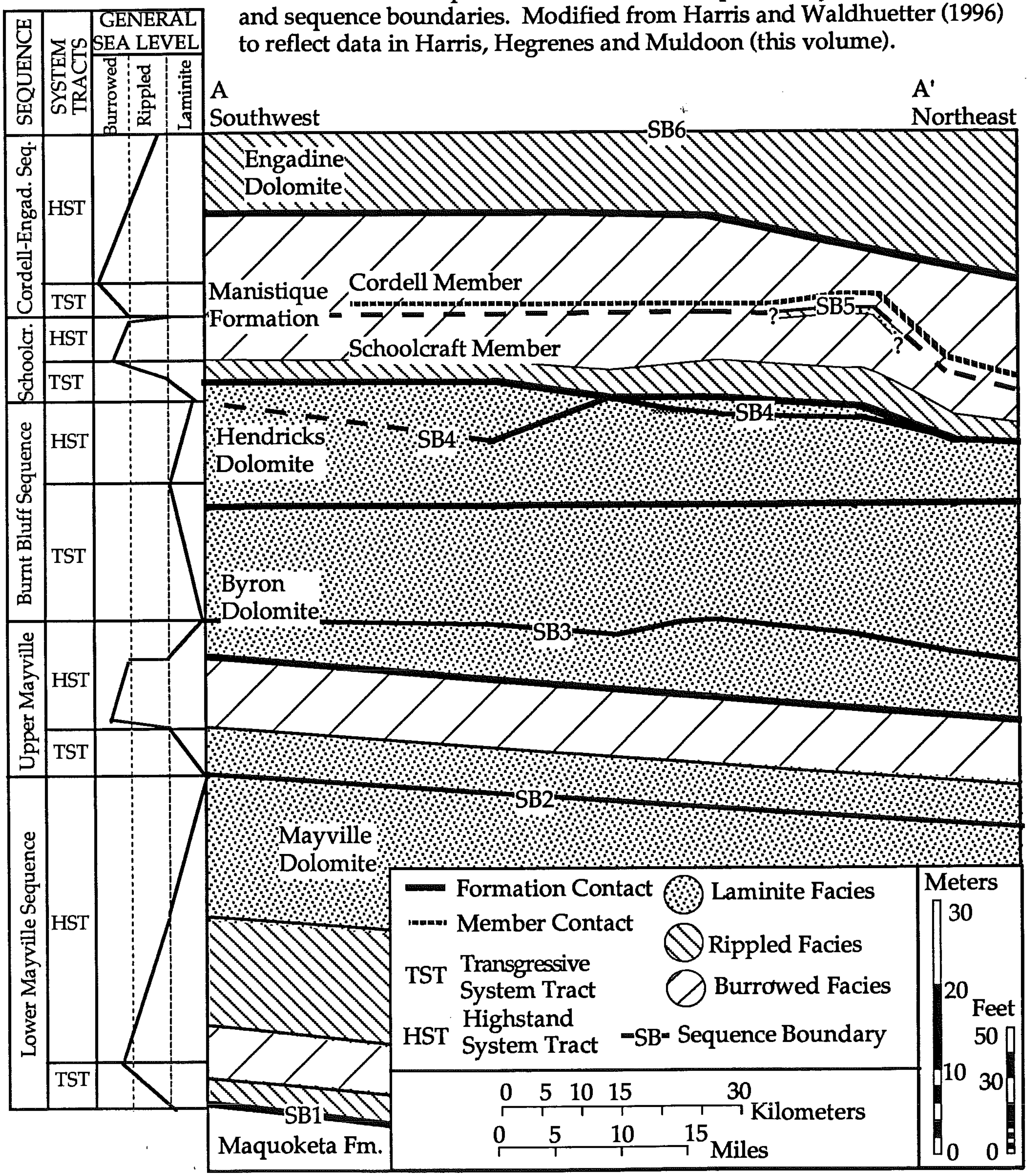
Facies of Stratigraphic Units

Each stratigraphic unit consists of one or more facies (Figure 5). The following brief descriptions focus on features observable at the field stops. Harris and Waldhuetter (1996) present additional details on specific localities.

Mayville Dolomite

The entire Mayville Dolomite is not exposed in the Door Peninsula. A section of lower Mayville is exposed at Bayshore County Park in northern Brown County (Stop 1). Quarries east of Route 57 in northern Brown County expose sections in the middle part of the unit. Small outcrops also occur at Wequiock Falls (Sivon, 1980) and along the Green Bay shoreline north of Sturgeon Bay (in Peninsula Park and near Stop 2). A recent core hole (Hegrenes, 1996) indicates a formation thickness of 62 m (203 ft) near Sturgeon Bay.

Figure 5: Facies cross section for the Silurian strata of the Door Peninsula with interpreted sea level curve, sequences, systems tracts, and sequence boundaries. Modified from Harris and Waldhuetter (1996) to reflect data in Harris, Hegrenes and Muldoon (this volume).



The Mayville section at Bayshore County Park (Stop 1) exposes the lower 14 meters of the formation. The outcrop consists of 2.2 meters of Rippled Facies overlain by a 5.5 m thick interval of Burrowed Facies dominated by *Thalassinoides*. The upper half of the section is Rippled Facies with unusually well displayed sedimentary structures at the top of the outcrop. A similar lower Mayville section occurs in cores near Sturgeon Bay (Gary Gianniny, pers. comm., 1995; Hegrenes, 1996). The Rippled Facies continues through the lower half of the Mayville Dolomite (stop 2).

In scattered outcrops and core (Harris, Hegrenes and Muldoon, this volume), the upper Mayville consists of Laminite Facies capped by a Burrowed Facies interval. Traditionally, the top of the Mayville is placed above the uppermost Burrowed Facies beds containing *Virgiana mayvillensis* (Subfacies 1) at the base of Byron laminite cycles.

Byron Dolomite

The escarpment along the Green Bay shoreline exposes numerous sections of the Byron Dolomite between Sturgeon Bay and Washington Island. The unit is 23-25 meters in thickness and consists entirely of Laminite Facies.

The Byron Dolomite is informally divided into upper and lower units based upon an exposure surface exposed in the "Big Quarry" (Stop 3) and other localities. The lower Byron consists of 4-6 laminite-capped cycles. In most sections (Egg Harbor, Peninsula Park, Washington Island, Death Door Bluff), the mid-Byron exposure surface is a mottled, brecciated argillaceous zone. In the Big Quarry, the surface occurs within a 2 meter interval with laminae-truncating scour surfaces and small channels.

Overlying upper Byron cycles lack diverse fauna except for an interval of 1-3 cycles with BA 2 faunas. This faunal zone within the upper Byron can be correlated regionally. Locally (as in the Big Quarry) cross-laminated pellet packstone units also occur in the Byron cycles.

Hendricks Dolomite

Hendricks strata were termed "Transition Beds" by Chamberlin (1877) because they contain alternations of Byron-style (laminite) and Manistique-style (faunal-rich) lithologies. The base of the Hendricks consists of Laminite Facies cycles with basal units containing diverse (BA 2) faunas that are commonly leached. In the Big Quarry (upper quarry face), faunal units decrease upward to a low-angle scour surface that we interpret as an exposure surface. The surface in onlapped by laminite units that pass upward into normal Laminite cycles. The total outcrop thickness of the unit is 15-17 meters, although it is 28 m in some cores (Harris, Hegrenes and Muldoon, this volume).

Manistique Formation

The Manistique Formation is divided into a lower Schoolcraft Member (14 meters thick) and an upper Cordell Member (13 meters thick). They are distinguished based upon the greater chert content (10-30%) in the Cordell. They are probably partially equivalent to each other based upon thickness variations (Hegrenes, 1996).

The Schoolcraft Member consists of a thin (few meters thick) basal Rippled Facies interval overlain by Burrowed Facies. Silicified faunas are common. At the northern end of Door County, a thin Laminite Facies interval (Subfacies 9) occurs in the upper Schoolcraft equivalent to the "upper laminated" bed in a similar position in the Upper Peninsula of Michigan (Johnson and Campbell, 1980).

The Cordell Member entirely consists of Subfacies 2 (*Thalassinoides* Mudstone-Wackestone) and 3 (Laminar Stromatoporoid-Coral Floatstone) of the Burrowed Facies.

Engadine Dolomite

The Engadine Dolomite is a white, thickly bedded dolostone with poorly preserved but silicified fauna. Typical Rippled Facies lithologies are Coral Floatstone (Subfacies 7) and Boundstone (Subfacies 8). The Cordell to Engadine transition is marked sedimentologically by a shallowing. The boundary is lithologically gradational and is primarily based upon color and fossil preservation. Kuglitsch (1994a) dated the Engadine Dolomite as late Llandovery based on conodonts.

Stratigraphic Sequences

The sedimentological and paleontological (Johnson and Campbell, 1980; Brett et al., 1993; Watkins and Kuglitsch, this volume features provide the basis for constructing a relative sea level curve for the Door Peninsula section (Figure 5). The curve is based on a scale of increasing water depths:

(1) exposure surface
(2) Laminite Facies and ostracode faunas
(3) Ripple Facies with domal coral faunas, boundstones
(4) Burrowed Facies with laminar coral/stromatoporoid faunas
(5) Burrowed Facies with brachiopod-rich units.

The resulting sea level curve can be combined with other studies in the Upper Peninsula of Michigan (Ehlers, 1973; Johnson and Campbell, 1980; Johnson, 1981) and east-central Wisconsin (Brooks, 1978; Elger, 1979) to construct a sequence stratigraphic interpretation of the Llandovery section (Figure 6). The five recognized sequences are named based upon their predominant constituent stratigraphic unit(s).

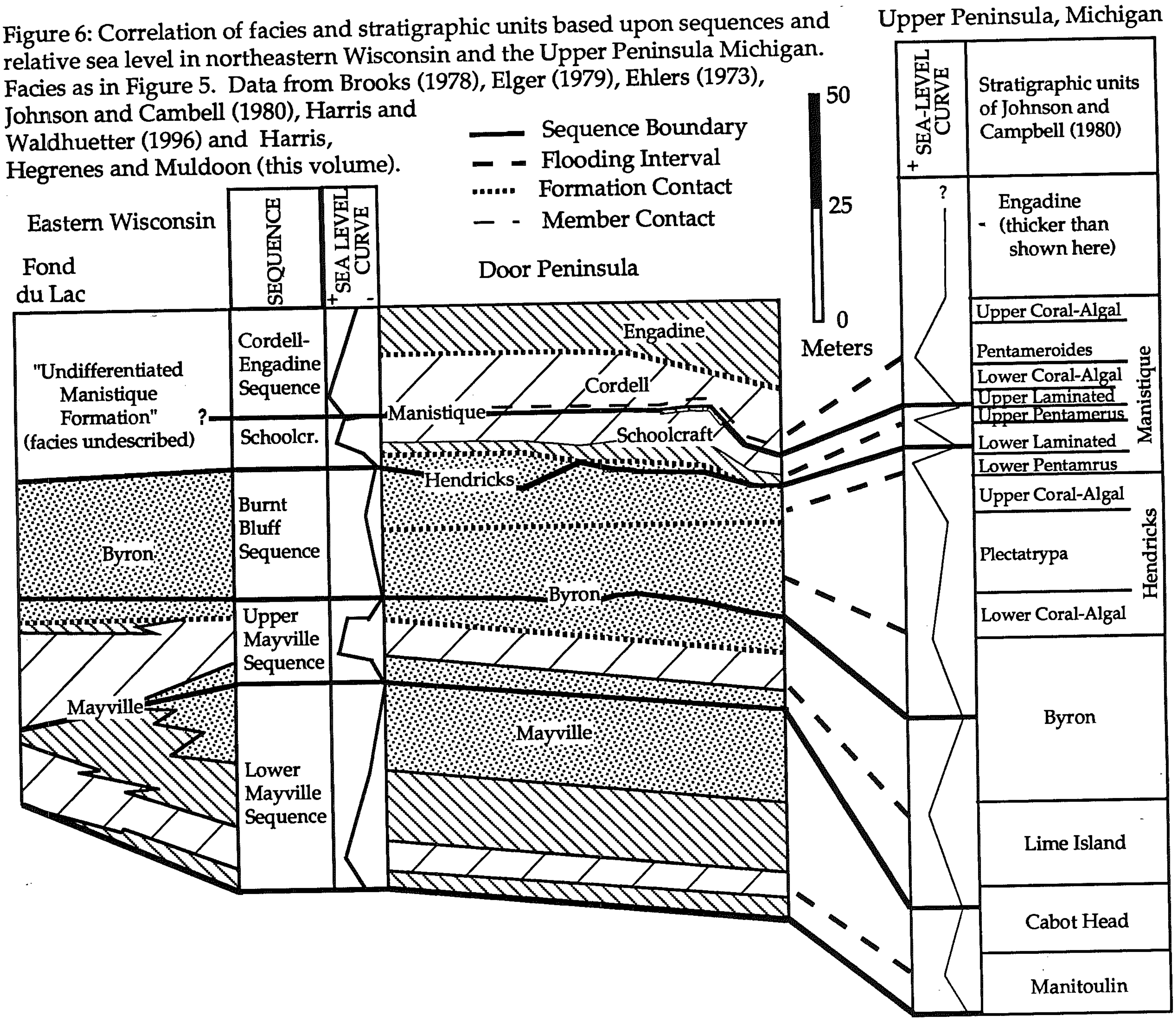
The base of the Lower Mayville Sequence is the Ordovician-Silurian boundary, a world-wide sea level low (McKerrow, 1979; Lenz, 1982; Hambrey, 1985; Brenchley et al., 1991; Ross and Ross, 1992, 1995). The sequence is asymmetrical: the thin transgressive systems tract (TST) extends upward to the lower Mayville Burrowed Facies interval (stop 1); the highstand systems tract (HST) is a thick shallowing-upward succession that includes Burrowed, Rippled, and Laminite Facies. The top of the sequence occurs within the Mayville Laminite Facies at a soil surface (Hegrenes, 1996).

The TST of the Upper Mayville Sequence is a mixture of Laminite and Burrowed Facies indicative of fluctuating water depths. The HST is lower Byron laminite cycles capped by the middle Byron exposure surface (stop 3).

The Burnt Bluff Sequence entirely consists of Laminite Facies. The subtidal, open marine cycle bases are more fully developed toward the top of the TST/base of the HST (lowermost Hendricks) but decrease toward the top of the sequence. The exposure surface occurs within or at the top of the Hendricks and is locally scoured (Big Quarry, stop 3) or marked by quartz sand (Peninsula Players Quarry).

In some sections, the Schoolcraft Sequence includes the uppermost Hendricks Dolomite (e.g. Big Quarry) as the TST. Maximum flooding occured in the lower Schoolcraft Member. The section shallows locally to Laminite Facies (near the top of the Schoolcraft Member) that marks the top of the sequence in the north end of study area and the Upper Peninsula of Michigan (Johnson and Campbell, 1980).

Figure 6: Correlation of facies and stratigraphic units based upon sequences and relative sea level in northeastern Wisconsin and the Upper Peninsula Michigan. Facies as in Figure 5. Data from Brooks (1978), Elger (1979), Ehlers (1973), Johnson and Cambell (1980), Harris and Waldhuetter (1996) and Harris, Hegrenes and Muldoon (this volume).



The uppermost Schoolcraft Member is the TST of the Cordell-Engadine Sequence. Maximum deepening occurs in the Burrowed Facies at the base of the Cordell Member. Most of the Cordell (Burrowed Facies) and Engadine (Rippled Facies) comprise the HST (stop 4) although the top of the sequence is not preserved in Door County.

Porosity Patterns and Hydrogeology

Groundwater flow in the Silurian aquifer is primarily through fractures; while both fractures and matrix porosity provide the storage capacity for the aquifer (Sherrill, 1978; Bradbury and Muldoon, 1992; Gianniny et al, 1996; Muldoon and Bradbury, this volume; Harris, Hegrenes and Muldoon, this volume). Dissolution along horizontal stratigraphic discontinuities such as depositional bedding planes, diagenetic surfaces, cycle and sequence boundaries, has led to the development of preferred horizontal flowpaths which carry the majority of groundwater in the Silurian Aquifer. Gianniny et al (1996) suggest that the high-conductivity zones are laterally continuous at regional scales and appear to follow and be controlled by the stratigraphy.

The Silurian facies interpretation provides a framework for predicting general flow pathways and storage capacity because these parameters are related to depositional facies (Harris, Hegrenes and Muldoon, this volume). Both flow and storage in the Laminite Facies is dominated by fractures because the matrix has negligible porosity. In the Burrowed and Rippled Facies, the large fractures still dominate flow, however, matrix porosity is significant and provides storage capacity. The matrix porosity in these facies also correlates with the lower- and middle-range hydraulic conductivity values (Harris, Hegrenes and Muldoon, this volume), suggesting groundwater moves slowly through these matrix blocks.

Porosity in the rock matrix largely follows facies patterns (Figure 3) so the sequence-keyed facies model provides a framework for porosity prediction. This can be used to construct a conceptual model of the matrix hydraulic conductivity distribution and the storage capacity of the stratigraphic units (Figure 7). In this perspective the stratigraphy consists of two types of hydrogeologic units: low matrix porosity units in which groundwater flow and storage is dominated by fractures, and high matrix porosity units in which groundwater storage is dominated by the matrix and groundwater flow is primarily through fractures, with a small matrix component.

Current research efforts are attempting to quantify the relative contributions of both fracture flow and matrix porosity to the "plumbing system" of the Silurian aquifer (Muldoon and Bradbury, this volume; Harris, Hegrenes and Muldoon, this volume; Bradbury et al, in prep.).

Acknowledgments

This study was funded by a grant from the University of Wisconsin System through the Wisconsin Groundwater Coordinating Council. We thank Ron Steiglitz (University of Wisconsin-Green Bay), Rodney Watkins (Milwaukee Public Museum), Maureen Muldoon (Wisconsin Geological and Natural History Survey) and Door County landowners for their assistance.

Hydrologic Layer		Stratigraphic Unit	Facies	Porosity	Primary Storage
Aquifer		Pleistocence and Holocene sediments			
Silurian Aquifer	L5	Engadine	Rippled	1-8%	Matrix
	L4	Manistique	Burrowed > Rippled	<1%	Fracture
	L3	Hendricks upper Byron	Laminite	1-4%	Fracture
	L2	lower Byron	Laminite	<1%	Fracture
	L1	Mayville	Rippled & Laminite > Burrowed	1-8%	Matrix
Aquitard		Maquoketa Formation			

Figure 7: Hydrogeological model for the Silurian aquifer based on Muldoon and Bradbury (this volume) and Harris, Hegrenes and Mulddon (this volume).

LOWER SILURIAN BENTHIC MEGAFAUNAL COMMUNITIES AND CONODONT FAUNAS OF THE DOOR PENINSULA, WISCONSIN

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Introduction

Lower Silurian carbonates of the Door Peninsula contain several megafaunal communties that occupied intertidal to shallow subtidal environments. These communties represent Benthic Assemblages (BA) 1 through 3 in the standard bathymetic classification of Silurian faunas (Brett et al., 1993), and they probably occupied water depths of about 40 m or less. Conodonts occur at several levels in the section, and the presence of *Aulacognathus bullatus* in the Engadine Formation indicates that Silurian outcrop of the Door Peninsula is no younger than earliest Wenlockian in age (Kuglitsch, 1994a). The sedimentary occurrence of these faunas is described in terms of the facies and subfacies of Harris and Waldhuetter (1996).

Mayville Dolomite

The *Virgiana* Community (BA3) consists predominately of the large brachiopod *Virgiana mayvillensis* Savage, and it occurs in the upper part of the Mayville at Peninsula State Park (Facies 1B, Brachiopod Wackestone-Packstone). Articulated shells of *V. mayvillensis* are rare, depositional breakage is common, and pedicle valves greatly outnumber brachial valves. Other taxa, which form less than 4% of the fauna, include a favositid, solitary rugose coral, gastropod, and small crinozoan ossicles. Watkins (1994) described other occurrences of the *Virgiana* Community in southeastern Wisconsin.

A more diverse, but as yet unstudied BA3 community occurs in the Mayville Formation at Bay Shore County Park, where large, branching burrow systems of *Thalassinoides* are associated with stromatoporoids, tabulates, rugose corals, brachiopods, molluscs, and crinozoans. Conodonts recovered from the Mayville are not diagnostic of age and include only *Panderodus* sp. and non- coniform fragments. *Virgiana mayvillensis* indicates a Late Rhuddanian age for the upper part of the formation.

Burnt Bluff Group (Byron and Hendricks Dolomites)

A leperditiid ostracod communty (BA1) occurs in both the Byron and Hendricks within Subfacies 9, Pellet-Ostracode Packstone- Mudstone, but this fauna has yet to receive detailed study on the Door Peninsula. The same community is much better preserved in limestones of the Hendricks Dolomite at Hendricks and Fiborn Quarries, Mackinac County, Michigan (Ehlers, 1973). Here the community consists (by point count of skeletal material in section) of 81% ostracods, 9% brachiopods (*Alispira lowi* (Whiteaves) and *Hercotrema winiskensis* (Whiteaves)), 6% gastropods, 3% stromatoporoids, <1% favositids, <1% bivalves, and <1% crinozoans. The community is most common in bioturbated beds of fenestral mudstone, where skeletal material is dispersed, matrix-supported, and variably oriented. It also occurs as thin packstone layers that represent tempestites (storm beds), and it is rarely present in finely-laminated mudstone with mudcracks, where it lacks stromatoporoids, corals and crinozoans. All of these occurrences are interpreted as restricted subtidal to intertidal.

A well-preserved, silicified stromatoporoid-coral community (BA2) occurs in the upper part of the Byron Dolomite at The Big Quarry (Stop 3, this volume) and at Boyer Bluff, Washington Island (unit 12 of Shrock, 1940). Silicified material of this community also occurs in several beds in the Hendricks Dolomite, where it is present at the base of small-scale shallowing-upwards sequences. All of these occurrences are in Subfacies 4, Domal Stromatoporoid-Coral Floatstone. Stromatoporoids dominate the biofacies and form 51% of skeletal material. Corals include favositids (26%), solitary and colonial rugosans (15%), and halysitids, auloporids and alveolitids (<1%). Brachiopods (4%) include *Hesperorthis davidsoni* (de Verneuil), *Platystrophia* sp., *Salopina* sp., *Dalejina* cf. *D. striata* Jin et al., *Eomegastrophia* sp., *Morinorhynchus* n.sp., *Gypidula* n.sp., *Hercotrema winiskensis, Alispira lowi, "Whitfieldella"* n.sp., and *Howellella* sp. Leperditiid ostracods are present as 3% of skeletal material. Taxa with an abundance of <1% include heteractinid sponges (represented by isolated sexiradiate spicules), bryozoans, gastropods, cephalopods, spirorbids, cornulitids, conularids, trilobites and crinozoans.

Conodonts of the Byron and Hendricks at The Big Quarry, Peninsula Players Quarry and Boyer Bluff include *Panderodus* sp., *Kockelella manitoulinensis* (Pollack, Rexroad & Nicoll), *Spathognathodus* sp. A s.f. Over & Chatterton, *Ozarkodina* n.sp. A and n.sp. B of Pollack, Rexroad & Nicoll, *Ozarkodina excavata puskuensis* Männik, *Ozarkodina oldhamensis* Rexroad, *Icriodella deflecta* Aldridge, *Icriodella discreta* Pollack & Rexroad, *Oulodus* sp., and *Aspelundia* sp. The presence of *I. deflecta* indicates the upper part of the *Icriodella discreta-Icriodella deflecta* zone, which is correlative with the lower part of the *Distomodus kentuckyensis* zone. This indicates an Aeronian age.

Manistique Formation

The *Pentamerus* Community (BA3) occurs in thick beds of Subfacies 1 (Brachiopod Wackestone-Packstone) and was described by Watkins (1994). The large brachiopod *Pentamerus oblongus* Sowerby forms 64% of skeletal material by point count. Other taxa in silicified collections include crinozoans (26%), stromatoporoids (7%), tabulates (2%, including favositids, heliolitids, alveolitids, halysitids and syringoporids), solitary rugosans (1%), bryozoans (<1%) and cephalopods (<1%). The *Pentamerus* Community also occurs in the Manistique Formation in Upper Michigan (Johnson & Campbell, 1980) and in Upper Llandovery strata in southeastern Wisconsin (Watkins, 1994).

The Manistique Formation at Baileys Harbor also contains a *Pentameroides* Community (BA3) preserved in thin, normally-graded packstones that represent storm deposits (Watkins, 1994). The community is dominated by the brachiopod *Pentameroides bisinuatus* (McChesney) and also contains atrypids, solitary rugosans, bryozoans and crinozoans.

A coral-stromatoporoid-crinozoan community is intergradational with the *Pentamerus* and *Pentameroides* communities and also represents BA3, occurring in Subfacies 3 (Laminar Stromatoporoid-Coral Floatstone) and 4 (Domal Stromatoporoid-Coral Floatstone). Tabulate corals form 26% of skeletal material by point count and are dominated by favositids, with fewer alveolitids, heliolitids, pachyporids, syringoporids, auloporids, and halysitids (including both *Halysites* and *Catenipora*). Rugose corals (7%) are dominated by several types of solitary forms and also include colonial arachnophyllids. Stromatoporoids form 32% of skeletal material, and crinozoan ossicles form 29%. Brachiopods (6%) are dominated by pentamerids and also include dolerorthids, stropheodontids, stricklandids, rhynchonellides, and atrypids. Groups forming <1% of skeletal material include bryozoans and molluscs. Preliminary work on silicified collections indicates a high species diversity and a variety of growth interaction among encrusting forms. Allen (1986) made a detailed study of sedimentologic relations and small-scale distributional patterns within this community.

Preliminary sampling of conodonts has yielded only a non- diagnostic assemblage of *Panderodus* sp. and non-coniform fragments. Conodont age assignments from the underlying Burnt Bluff Group and overlying Engadine date the Manistique Formation as Upper Llandovery (Telychian) in age.

Engadine Dolomite

The Engadine Dolomite contains a very poorly preserved BA3 megafauna that is similar to the coral-stromatoporoid-crinozoan community of the Manistique. An 18 kg sample from the highest exposures of the Engadine at the Mountain, Washington Island yeilded a small number of *Panderodus* sp. and two Pa elements of *Aulocognathus bullatus* Nicoll & Rexroad. Most reports of *A. bullatus* cite its range as just below and throughout the *Pterospathodus celloni* zone, which indicates a Telychian age. A small number of reports record *A. bullatus* from the lower part of the *Pterospathodus amorphognathoides* zone, of Telychian to earliest Sheinwoodian age. The Engadine Formation is thus no younger than earliest Wenlock in age.

Discussion

The succession of Silurian benthic megafaunal communities on the Door Peninsula records several changes in water depth along the northwest margin of the Michigan Basin. Harris and Waldheutter (1996) divided the section into five stratigraphic sequences. The Lower Mayville and Upper Mayville Sequences, of Rhuddanian age, each shallow upward from subtidal BA3 communities to intertidal laminites. The Burnt Bluff Sequence, of Aeronian age, contains a cyclic alternation of BA1 and BA2 communities, representing eustatic shifts between intertidal and very shallow subtidal environments. The Schoolcraft Sequence (Telychian) and Cordell-Engadine Sequence (Telychian to possibly earliest Wenlock) are each dominated by BA 3 communities, representing a deeper subtidal environment.

Conodonts of the *I. discreta-I. deflecta* zone permit correlation of the Burnt Bluff Group into offshore deposits of the Michigan Basin (Kuglitsch, 1994b), revealing a lateral transect of Aeronian shallow to deep-water megafaunal communities. Outcrop of the Burnt Bluff in northern Michigan and the Door Peninsula, representing intertidal and very shallow subtidal conditions, contain BA1 and BA2 communities described above. To the southeast, in the H.L. Brown Snowplow cores of Alpena County, Michigan (Harrison, 1985), the upper part of the Burnt Bluff contains packstone beds with the *Pentamerus* Community (BA3) and floatstone with a coral-stromatoporoid-crinozoan community (BA3). Further south in outcrop in Waukesha County, cores in Ozaukee County, and a core in Newago County, Michigan, Aeronian beds of the Burnt Bluff consist of a few meters of bioturbated mudstone representing offshore ramp deposits. These beds contain a very diverse BA4/5 community dominated by small crinozoans and siliceous sponges. The community also includes brachiopods and trilobites of deep-water aspect, as well as corals, bryozoans, spirorbids, cornulitids, molluscs, machaeridians and echinoids (Watkins and Kuglitsch, 1995).

EFFECTS OF GEOLOGICAL PROCESSES ON ENVIRONMENTAL QUALITY, DOOR PENINSULA, WISCONSIN

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A pleasant mix of natural amenities continues to attract a growing number of tourists and retirees to the Door Peninsula. This is certainly true of the peninsula north of Sturgeon Bay, although bay and lake shore areas south of the city are also experiencing development. New resort or condominium complexes have been proposed or started throughout the region. For example, the Little Sweden ski complex on Highway 57 just south of Fish Creek, the Horse Shoe Bay development along the bay shore south of Egg Harbor, and the Edgewater Bluff Villas condominiums in northern Brown County, have caused environmental concerns and met opposition. Concerns have also been raised by the trend toward larger farm operations with more cows and the resulting problems associated with manure storage and spreading.

Many general and technical articles that deal with the history, culture, and the physical environment of the region are available. Good introductions and overviews can be found in Palmquist (1989) and Hershbell (1990).

Karstification and Glaciation

Karstic features have been described and their distribution mapped in some detail in the region as part of Wisconsin Fund Priority Watershed Projects (Johnson, 1987; Johnson and Stieglitz, 1990; Stieglitz and Dueppen, 1994; 1995). A summary of the glacial history and lake phase sequence can be found in Schneider (1993). Mode (1989) provides an overview of the glaciation of the southern part of the area. It appears that much of the karstification preceeded at least the last several ice advances and that the Greatlakean ice had relatively little affect on most of the peninsula.

The orientation of fracture traces, joints, and sinkholes (dolines) was mapped during the inventory phase of several Priority Watershed Projects (e.g., Johnson and Stieglitz, 1990). The vertical development of dissolution is limited and the region displays a rather immature stage of karstification, probably because of moderate local relief, dolostone rather than limestone bedrock, and recent age of glaciation (Johnson and Stieglitz, 1990). The same authors noted a lower density of karst features in the northern part of Door County than in the central part and suggested differential ice scour as the explanation. Directional indicators, such as striations and a small drumlin field near Ellison Bay, indicate that Green Bay Lobe ice passed through re-entrants in the escarpment front and advanced southeastward across the peninsula. Additional work by Stieglitz and Dueppen (1994, 1995) also revealed lower densities of karst features in southern Door, Brown, Kewaunee, and Manitowoc Counties apparently because of the thicker and less permeable glacial drift in those areas.

Rosen (1984) and Rosen et al. (1987) studied several locations on the peninsula and described them as glaciokarstic. Ford (1983; 1987) lists a series of effects of glaciation of karst landscapes that range from slight modification through plugging to truncation. Ice-wedge glide blocks, frost-shattered talus, and solifluction aprons suggest that the west and northwest faces of the escarpment experienced periglacial conditions at some point during the last retreat of the Green Bay Lobe (Stieglitz, Moran and Harris, 1980).

Over much of the peninsula, the surface of the bedrock has a step-like configuration. Rosen (1984) studied a stepped surface in southern Door County and considered it an example of schichttreppen, or glacially scoured steps similar to those described from Europe. Where the stepped surface is buried by drift, such as within and along the sides of northwest-southeast trending valleys, soil depths can vary markedly over short horizontal distances.

In places, large areas of the bedrock surface are exposed as dolostone pavements (kamenitzas). The pavements have either been striped of overburden by glaciers or unmantled post-glacially by water erosion. Extensive pavements are located on the upland divides between valleys or in low topographic positions on the eastern dip slope of the cuesta. Smaller pavements occur on the treads of the stepped surfaces. Pavements are usually divided into blocks by solution-widened joints and also display other evidence of dissolution, such as pans, runnels and other karren of a variety of scales. In other locations, similar surfaces lie buried beneath a cover of soil and drift. In either instance, such porous and permeable epikarst zones appear to be important in the storage and lateral transmission of water to a surface outlet or to a master joint through which recharge occurs. It is unclear whether well developed epikarst zones indicate that considerable dissolution has taken place since deglaciation or that such areas have escaped significant glacial scouring. Exposure of fresh striations and glacially polished rock surfaces preserved beneath thin drift in shallow excavations indicate that infiltrating water reaches carbonate staturation before it reaches the bedrock. On the other hand, where bedrock is at the surface or run-in is concentrated, dissolution is more effective. Williams (1966) and Rose and Vincent (1986) have studied similar features in Great Britain.

Other examples of karst features include caves, of which Tecumseh Cave in Egg Harbor Township is the longest known; dry valleys; abandoned channels; and sinkholes. Dry valleys are located in the western and central parts of the peninsula. They may carry stream flow during the spring snow melt season and usually extend down stream to where permanent flow occurs or until they join a larger drainage. Many streams loose part of their flow through bed infiltration or swallets, and a least one discharges into the subsurface and disappears. Several abandoned channels exist that appear unrelated to present surface drainage feature and may date from preglacial or deglacial flow.

Hundreds of sinkholes have been mapped for the watershed projects. The most abundant are the subsidence or suffosion type (Figure 1). This type of sinkhole is small in diameter, shallow in depth and formed as soil is piped into fractures or openings in the bedrock. They are often ephemeral, forming during the snow melt or a heavy rain only to be filled by material washed or slumped into the depression or during tillage of farm fields. Sinkholes are closely related to fractures in the dolostone and often occur in groups because the first depressions to form focus and integrate drainage into the subsurface. Many of the joints and preglacial karst features are masked or plugged by drift. They continue to open or enlarge as the fill is removed and they are reoccupied as elements of the present drainage system.

Ground Water Resources and Environmental Concerns

Karstic or fractured rock aquifers are particularly susceptible to pollution. In such areas, human activities and land-uses take place in close proximity to various kinds of interface features that provide relatively direct point source input routes for aquifer recharge. Dissolved and suspended contaminants can be moved rapidly across the land

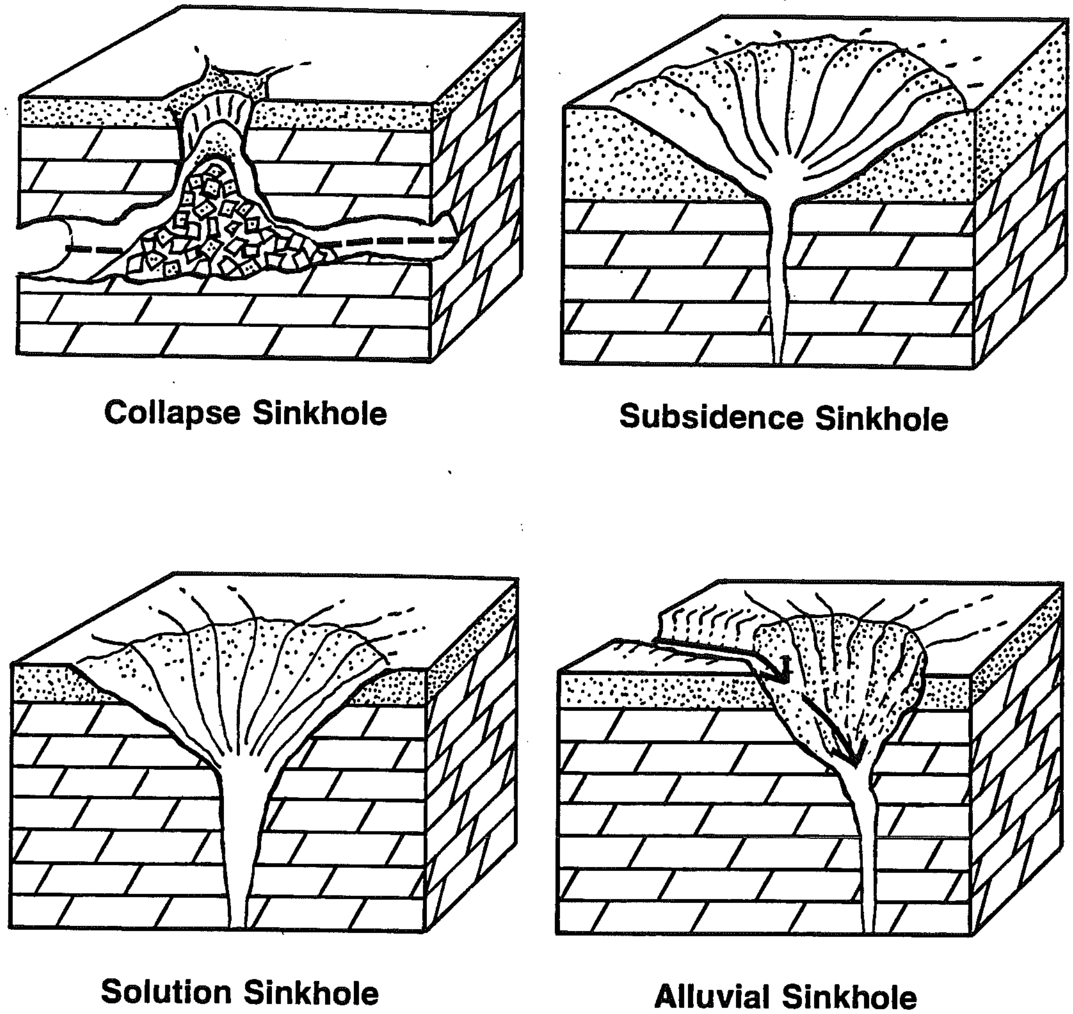

Figure 1: Sinkhole types (Stiegltiz, 1989). Used by permission of Perin Press.

and into the subsurface with little or no attenuation. Examples of affected water supply wells, springs, and surface water bodies are common in such geologic settings.

The basic characteristics of the Silurian dolostone aquifer of northern Door County are described by Sherrell (1978) and Bradbury (1982). Bachhuber and Schuster (1987) describe the groundwater quality in the Nonpoint Source Control Plan for the Upper Door Priority Watershed Project. Modern and historical examples of groundwater contamination by bacteria, nitrates, lead, arsenic, other toxic metals, organic pesticides and volatile organic compounds are all well documented in the Watershed Plan. Pollution sources such as barnyards and environmental features such as soils and sinkholes were mapped and inventoried for the Northern Door Watershed Project. That information was used to develop pollution potential maps and to allocate state cost share funds to landowners for installation of pollution abatement practices. Similar watershed projects are in progress for other parts of the peninsula (Sturgeon Bay/Red River and Branch River Watershed Plans) and karst feature mapping has been completed (Stieglitz and Dueppen, 1994; 1995). Additional groundwater studies have been carried out by the Wisconsin

Geological and Natural History Survey and the University of Wisconsin in order to better understand flow systems, determine water quality and to assess the effectiveness of best management practices or alternative technologies. Several of these projects will be discussed during this conference.

The Door Peninsula differs from many karst regions because of the extensive areas of shallow soil cover overlying the solution altered bedrock. The Door County Soil Survey (Link et al.,1978) illustrates that approximately 22% of the land area of the county has soils which are 0.5 meters or less to bedrock. Furthermore, an additional 17% of the land area has soils which are 0.5 to one meter to bedrock. Considering the important role the soils perform in the attenuation of contaminants in surface water as it move downward to the groundwater aquifer, the greater susceptibility of Door County's drinking water supply to surface derived pollution is apparent. Hallberg and Hoyer (1982) in their studies of groundwater quality in northeastern Iowa, an area of karst features, noted that contamination is controlled by the depth of the soil material overlying the bedrock. They defined thin soils as those less than 15 meters in depth and very thin soils as those less than 7.5 meters to bedrock and noted an increased occurrence of groundwater contamination in the areas of very thin soils. In contrast in Door County, approximately 39% of the land area is mapped as less than one meter to bedrock and field investigations indicate that is a conservative total. Brown, Kewaunee and Manitowoc Counties also have significant areas of shallow soils. To further complicate the situation, valuable soil is lost into the subsurface each year. Vertical soil erosion is a difficult process to measure but undoubtedly significant.

Because many of the land-use problems of the region are exacerbated by the shallow soils and the glaciated and karstified dolostone bedrock, continued care and attention is necessary. Door County for example, has been very proactive in its efforts to regulate on-site waste disposal systems, land spreading of effluent, and the storage and spreading of manure. Local and state governmental agencies have cooperated in the past on projects and programs designed to understand and protect the natural environment. A case in point is the project to evaluate advanced alternative on-site waste disposal systems on Washington Island that brought together the Town of Washington, Door County, the Department of Natural Resources, the Department of Industry, Labor and Human Relations, and the University of Wisconsin-Green Bay (Van Huizen, 1994). They must continue to do so in the future. Both political and scientific efforts with public and private support are necessary to ensure that environmental quality is maintained and not sacrificed.

HYDROGEOLOGY OF THE FRACTURED SILURIAN DOLOMITE AQUIFER, DOOR COUNTY, WISCONSIN

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Introduction

Groundwater is the source of drinking water for most Door County residents and past studies reported frequent occurrences of elevated nitrate, coliform bacteria, turbidity, and other constituents in water samples from drinking water supply wells (Sherrill, 1978; Blanchard, 1988; Bradbury, 1989; Bradbury and Muldoon, 1992). The aquifer is vulnerable to contamination because the fractured, highly-permeable dolomite is covered by thin soils which have little attenuation capability. Contaminants at or near the land surface have the potential to move rapidly, through fractures, to the water table. Once contaminants have entered the aquifer they move rapidly through near-horizontal, dissolution-enlarged bedding planes.

Current work on the Silurian dolomite in northeastern Wisconsin suggests that detailed stratigraphic analysis coupled with geophysical and hydrogeologic data may provide a tool for predicting the frequency and occurrence of high-permeability discontinuities. This research (Muldoon and Bradbury, 1994; Rovey and Cherkauer, 1994; and Gianniny and others, 1996; Hegrenes, 1996) has indicated that lithologies and horizontal stratigraphic discontinuities control both the distribution of preferred flowpaths and storage capacity. Dissolution along horizontal stratigraphic discontinuities such as depositional bedding planes, diagenetic surfaces, cycle and sequence boundaries, and stylolites has led to the development of preferred flowpaths. From this work, it is apparent that high-conductivity zones in carbonate aquifers are laterally continuous at regional scales and appear to follow and be controlled by the stratigraphy. Matrix porosity, which varies following depositional environments and diagenesis, provides the majority of storage for the aquifer.

Hydrogeologic Setting

The Silurian dolomite forms an important regional aquifer along the western flank of the Michigan Basin from Canada to northeastern Illinois (see Figure 1, Steiglitz and Harris, this volume). In Door County (Figure 1), the dolomite lies beneath a thin cover of unlithified Pleistocene sediment and forms a prominent escarpment along the western edge of the county, adjacent to Green Bay. The Silurian strata dip gently into the Michigan basin to the east-southeast at approximately 0.5 degrees or 40-50 ft per mile. Erosion has beveled the dolomite aquifer into an eastward thickening wedge that thickens from 25 ft along the shore of Green Bay near Little Sturgeon Bay to more than 550 ft near Whitefish Dunes State Park on the eastern shore of the peninsula.

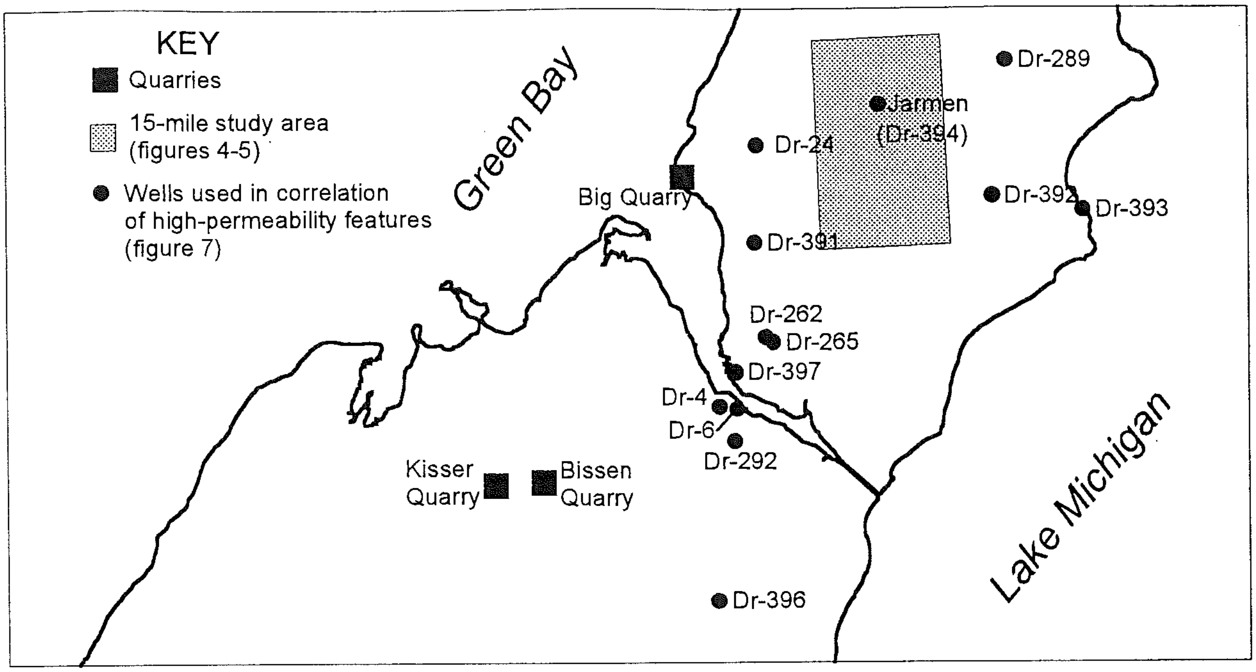

Figure 1. Map showing location of Bissen and Kisser quarries (stops 5 and 6), the northern Door study area including the Jarmen Road research site, and wells used in regional correlation of high-permeability features.

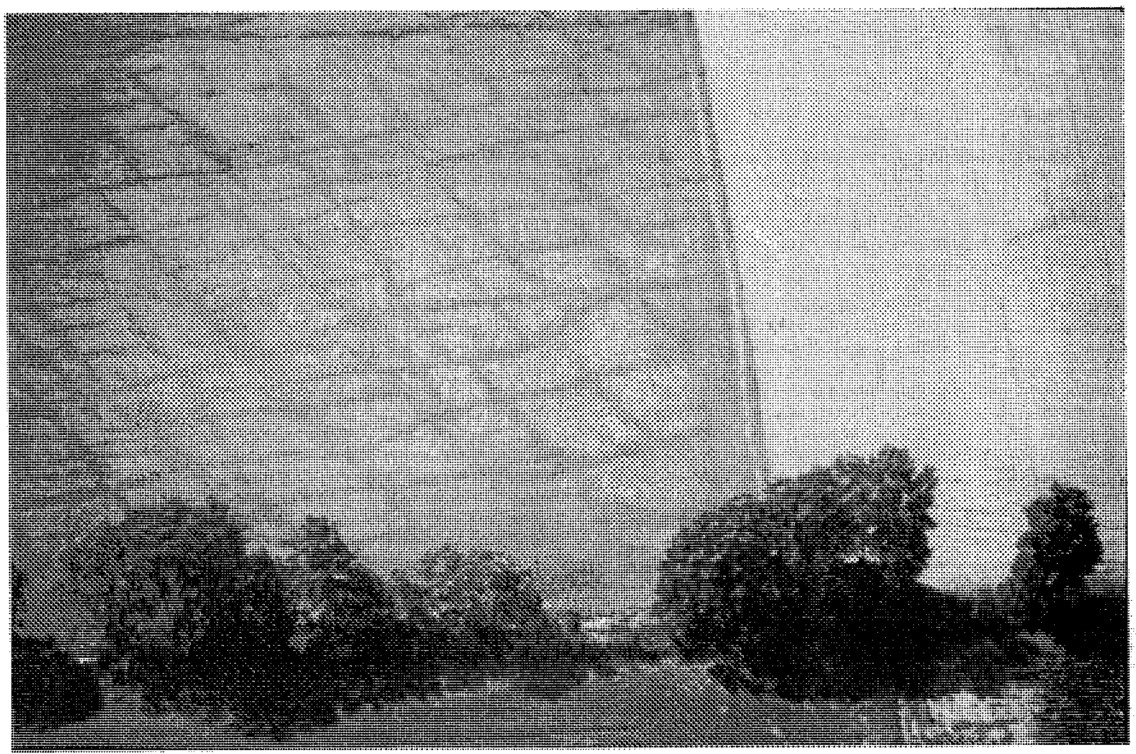

Figure 2. Oblique airphoto of fracture traces in an alfalfa field in the northern Door study area (photo by Bradbury).

Distribution of Vertical Fractures

Previous work in Door County suggest that vertical fractures as well as horizontal bedding planes and dissolution zones provide the primary pathways for groundwater flow in the Silurian dolomite (Sherrill, 1978; Bradbury and Muldoon, 1992). Figure 2 shows near-vertical fracture expression in an alfalfa field in the northern Door study area. The photo shows two predominant joint sets with fractures spaced approximately 10 to 20 ft apart. The major joint sets are oriented approximately N45°W (azimuth 135°) and N70°E. Each fracture, if open, can provide a direct route for infiltrating water to recharge the groundwater system; however, most fractures are at least partially filled with clayey or silty sediment near the land surface.

Fracture trace and lineament analysis at multiple scales (Roffers, 1996) suggest that orientation of fractures are generally similar across the different Silurian formations. Dominant fracture sets have orientations of approximately 45°, 70°, 135°, and 155°. Observed joint spacing in outcrop averages 1.5 to 5 ft, while the spacing between major joints interpreted from low-altitude aerial photographs ranges from approximately 30 to 115 ft. The spacing of larger fracture traces visible on 1:20,000 scale airphotos is typically 115-250 ft. Orientations are similar for fracture features ranging in size from outcrop joints to landscape-scale lineaments.

Water Budget

In the northern Door Peninsula, the Silurian aquifer is a self-contained unconfined aquifer system; bounded on all sides by surface water and beneath by the Ordovician Maquoketa Shale, a regional confining unit. All groundwater in the northern Door Peninsula originates as precipitation that falls within the county boundaries. The area receives about 30.1 in/yr of precipitation; including both rain and snow. Most of this water (about 20.6 in/yr) is lost to evapotranspiration. Due to the thin soils and permeable bedrock of the area, runoff is negligible, leaving about 9.5 in/yr for groundwater recharge (Bradbury, 1989).

Groundwater Flow Systems

There are two flow systems in the fractured dolomite aquifer. At the Jarmen Road site (location shown in Figure 2), there is a shallow water table, 20 to 40 ft below the land surface and a deep potentiometric surface at approximately 150 ft below the land surface. Previous "water-table" maps of the area, based on measurements in deeply cased domestic wells, delineated only the deeper potentiometric surface.

Distribution of Hydraulic Head at Jarmen Road Site

Figure 3 shows long-term water-level data collected from wells and piezometers at the Jarmen Road site. Well MW1 and piezometer MW2A represent the deep flow system, while piezometers MW2D, MW6A and well MW3 represent the shallow system. These wells and piezometers continually contained water, while the intermediate piezometer, MW7C, was frequently dry. Water-table measurements in shallow wells, combined with observed surface

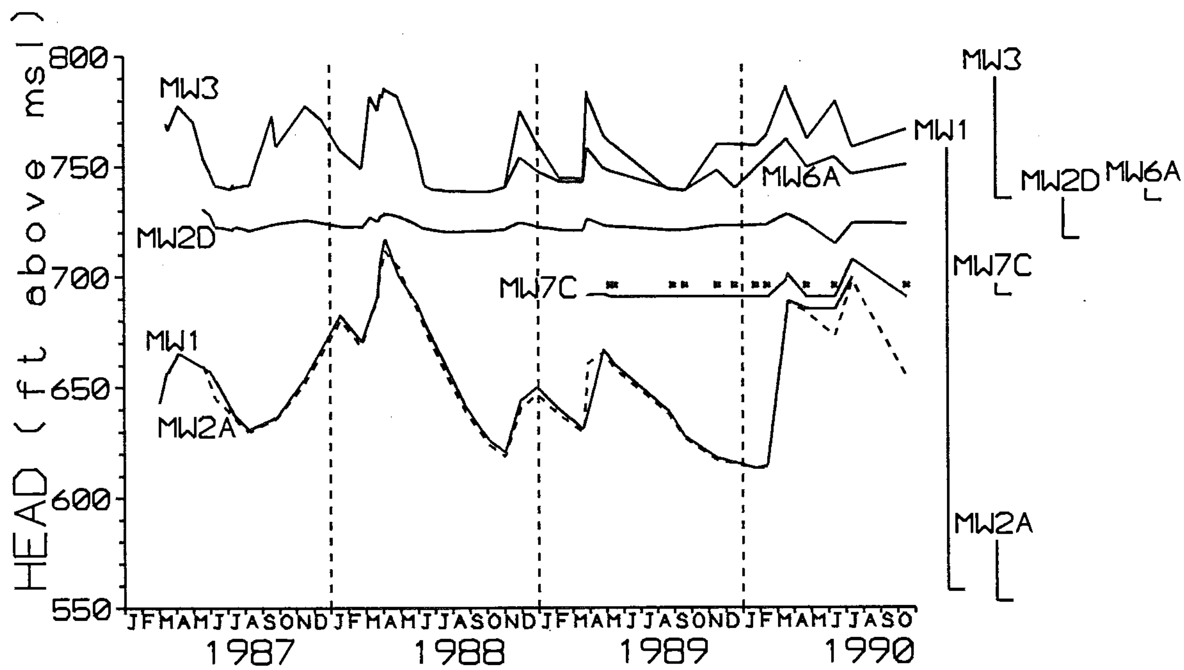

Figure 3. Hydraulic head of wells and piezometers at the Jarmen Road site. Lines on the right side of the figure indicate the open interval of the well or piezometer; small x's (MW7C) indicate that the well was dry (from Bradbury and Muldoon, 1992).

features such as wetlands and ponded water, show that a relatively shallow groundwater flow system occurs at the site, in addition to the deeper system. Water-table and potentiometric-surface maps were constructed for September of 1989 and March of 1990 using field-measured groundwater levels from approximately 50 domestic and irrigation wells in the area surrounding the site. The March data represent the maximum water-levels in the aquifer while the September data, represent low-flow conditions in the aquifer.

Deep Flow System

Significant temporal fluctuations occur in the deep flow-system; these variations lead to reversals in groundwater flow directions in the central portion of the county. Figure 4 shows the configuration of the potentiometric surface for the 15-mi^2 study area near the Jarmen Road site (see Figure 1 for location). Comparison of the September and March figures reveals that the deep flow system fluctuated by over 90 ft in response to the spring snowmelt event. The September figure represents the usual configuration of the flow system for this part of the county; groundwater tends to flow from northeast to the west/southwest. In spring, however, a large groundwater mound forms under the central portion of the county and in the eastern half of the study area, groundwater flows from west to east.

Shallow Flow System

The shallow flow system does not fluctuate as much as the deep system and no significant reversals in flow direction occur. Figure 5 shows the configuration of the water table for the

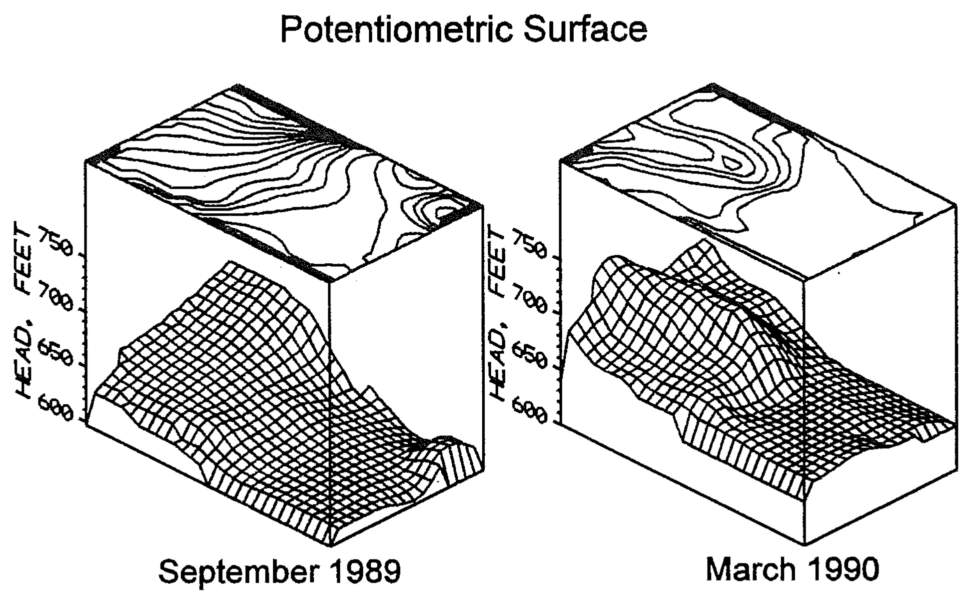

Figure 4. Configuration of the potentiometric surface in the 15 mi^2 study area of central Door County in September 1989 and March 1990. Contour interval is 20 ft. (from Bradbury and Muldoon, 1992)

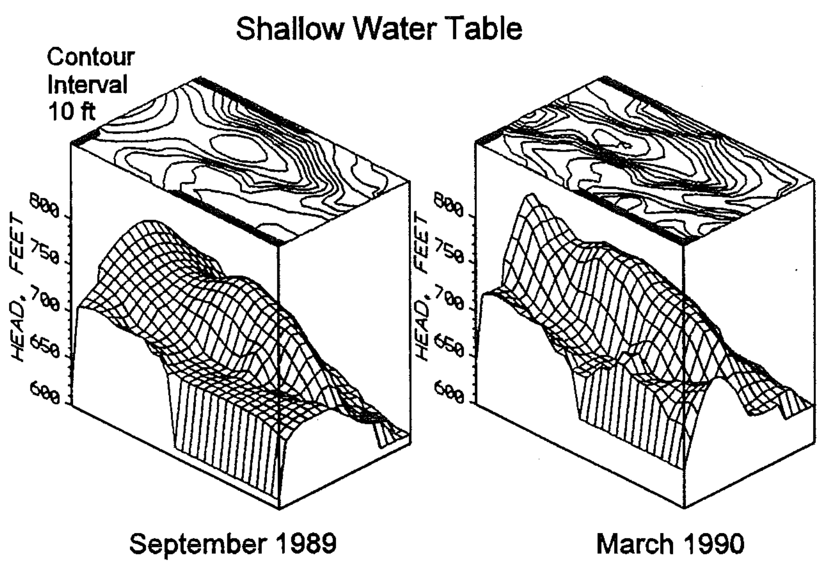

Figure 5. Configuration of the water table in the 15 mi^2 study area of central Door County in September 1989 and March 1990. (from Bradbury and Muldoon, 1992)

study area near the Jarmen Road site (see Figure 1). The water-table essentially mimics the topography of the land surface and no major changes in the configuration of the water table occur between fall and spring. Comparison of the two figures reveals that the water table fluctuated over 40 ft in response to spring snowmelt.

Flow Rates

Planned tracer tests and accidental releases of contaminants both demonstrate that groundwater flow rates can be very rapid in the dolomite aquifer. Bradbury and Muldoon (1992) reported a flow rate of 55 ft/day from a bromide tracer test conducted at the Jarmen Road research site and flow rates of 210 and 380 ft/day calculated from an accidental nitrate release in the northern portion of their study area.

The Wisconsin Geological and Natural History Survey (WGNHS) is currently conducting detailed tracer tests at the Bissen Quarry research site (see site description for stop 6). During the summer of 1995, five tracer experiments were conducted at the site. Most tests consisted of injection of a bromide tracer at a single port, with simultaneous sampling at up to 70 surrounding ports. Tracer velocities in fractures were rapid, with center-of-mass velocities of approximately 100 ft/day. Tracer velocities in the rock matrix were slower--approximately 4 ft/day.

Groundwater Quality

Groundwater in Door County is generally "hard" and contains moderate concentrations of calcium, magnesium, and bicarbonate naturally derived from the dolomite aquifer. Deep wells that are finished near the top of the Maquoketa shale or in the underlying sandstone sometimes produce water having objectionably high levels of sulfate, chloride, and total dissolved solids.

Commonly reported contaminants in Door County include bacteria, nitrate, and turbidity. Other contaminants less frequently detected include lead (primarily from the use of lead arsenate pesticides on fruit orchards prior to 1960), pesticides, and volatile organic compounds (Bachhuber and Schuster, 1987).

In 1986, the WGNHS initiated a small basin monitoring project in order to 1) determine background concentrations of water-quality parameters and 2) quantify spatial and temporal variations in groundwater quality in a portion of northern Door County. The project was part of the Northern Door Priority Water shed Project as was conducted in cooperation with the Wisconsin Department of Natural Resources (DNR), the Door County Soil and Water Conservation Department, and UW-Green Bay.

Domestic wells in central Door County were sampled for common water-quality parameters including nitrate, chloride, turbidity, conductivity, and bacteria. Coliform bacteria was the most common contaminant found in the WGNHS small basin monitoring project. The percentage of positive detections at a single well or spring ranged from 0.0 to 91.3%, and the average well contained coliform bacteria in 35% of the samples. Table 1 presents a statistical summary of nitrate, conductivity, turbidity and chloride results. These parameters were quite variable with time. Figure 6 illustrates the variability in nitrate concentrations at four domestic wells over a five-year period. All the wells show a significant increase in nitrate-N concentrations in December 1987, followed by a gradual decrease in concentrations during the spring of 1988.

Table 1. Summary of groundwater sampling results for WGNHS small basin monitoring project (from Bradbury and Muldoon, 1992)

Parameter	Number of samples	Mean	Range	Standard Deviation	Drinking Water std
NO_3-N (mg/l)	2064	7.4	0.0-267.0	8.2	10*
Chloride (mg/l)	2071	19.5	0.4-204.0	17.4	250**
Cond (μmho/cm)	2043	632	296-23800	558	none
Turbidity (NTU)	1839	0.4	0.1-98.0	3.0	1**

*Primary drinking water standard (NR 109.11, Wisc. Admin. Code)
**Secondary drinking water standard (NR 109.60, Wisc. Admin. Code)
***as determined from a monthly average

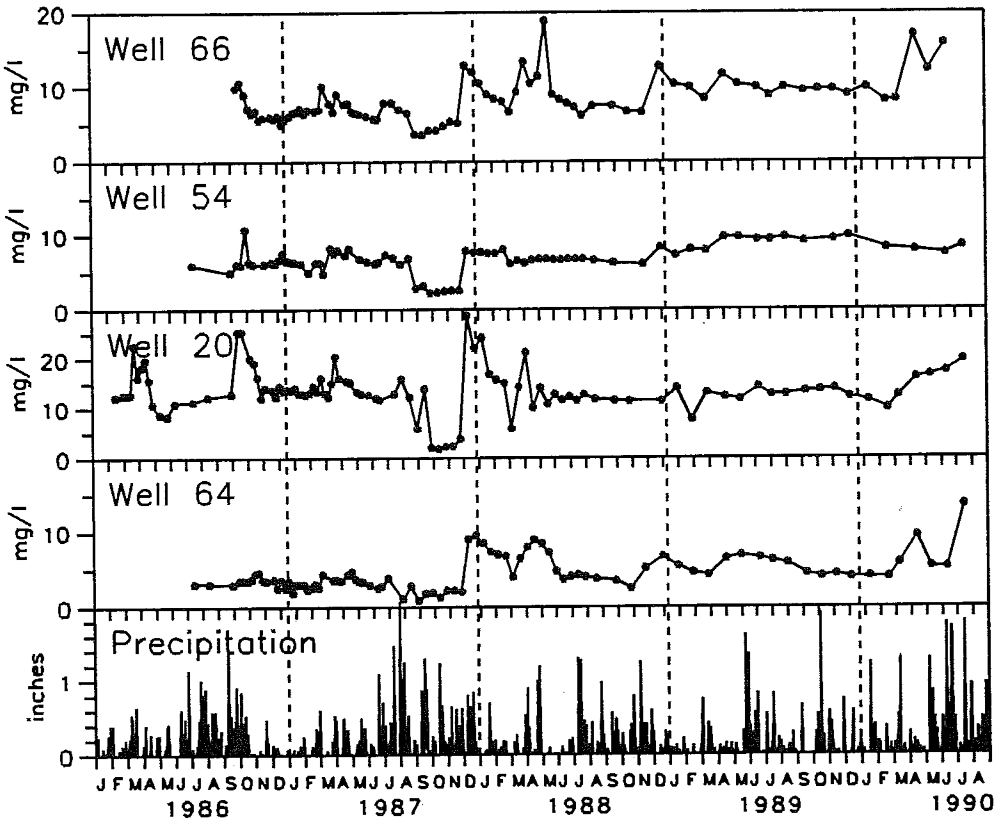

Figure 6. Plots of nitrate-N values versus time for four domestic wells in northern Door County. Dashed vertical lines mark the beginning of calendar years.

Other simultaneous changes in concentration include increases in October 1986, December 1988, and April 1990. The four domestic wells plotted in Figure 6 are located within five miles of the Jarmen Road research site. The fact that such widely spaced wells show similar trends in groundwater-quality parameters suggests that the contamination sources are diffuse, nonpoint sources that cover a broad area of the landscape.

Distribution of Hydraulic Conductivity

The WGNHS recently completed a project to identify high-permeability zones within the Silurian dolomite in the vicinity of Sturgeon Bay and determine if these zones could be correlated on a regional scale (Gianniny and others, 1996). By combining stratigraphic, geophysical, and hydrogeologic data they were able to delineate and correlate fourteen high-permeability features within the Silurian aquifer in the vicinity of Sturgeon Bay (Figure 7). At least three of these zones (C, I, J) are regional in extent and can be correlated in wells over 10 miles apart. These zones parallel bedding and appear most pronounced at contacts between contrasting lithologies and are most abundant in lithologies deposited in shallow to supratidal environments with indications of intermittent subaerial exposure (e.g. mud cracks or fenestral porosity).

Methods used to locate and characterize high-permeability features include fluid temperature and resistivity (or conductivity) logs, flow-meter logs, and discrete-interval permeability tests in available coreholes. Over 210 hydraulic conductivity measurements have been completed at 1.5-ft increments in corehole Dr-394 (Jarmen Road corehole). The hydraulic conductivity profile from this hole (Figure 8) provides data on matrix permeabilities as well as high-permeability features for portions of the Mayville, Byron and Hendricks Dolomites and the Schoolcraft Member of the Manistique Formation. Measured hydraulic conductivity values range over five orders of magnitude from $1.5\text{x}10^{-1}$ to $2.0\text{x}10^{-6}$ cm/sec. The downhole profile (Figure 8) and histograms of hydraulic conductivity values (Figure 9) indicate that there are several distinct populations of measured hydraulic conductivity values, thus the profile has been divided into six segments.

Lower Mayville Dolomite

The basal 85 ft of the Mayville is composed primarily of bioturbated mudstone-wackestones. Throughout this discussion we will also note the Facies associations defined by Harris, Hegrenes, and Muldoon (this volume). The lower Mayville Dolomite contains the Burrowed and Packstone Facies. We were not able to collect discrete-interval packer test data for this section of the aquifer (Figure 8). Flow zones A and B occur within this portion of the Mayville and appear to be controlled by contacts between contrasting lithologies.

Upper Mayville Dolomite -Segment 1 in Hydraulic Conductivity Profile

The upper 100 ft of the Mayville is Laminite Facies. Slug test data suggest matrix permeabilities are generally low in this bioturbated, mud-rich facies (segment 1, Figures 8 and 9). Flow zones C and D (Figure 7) occur within the upper Mayville and they also appear to be controlled by contacts between contrasting lithologies.

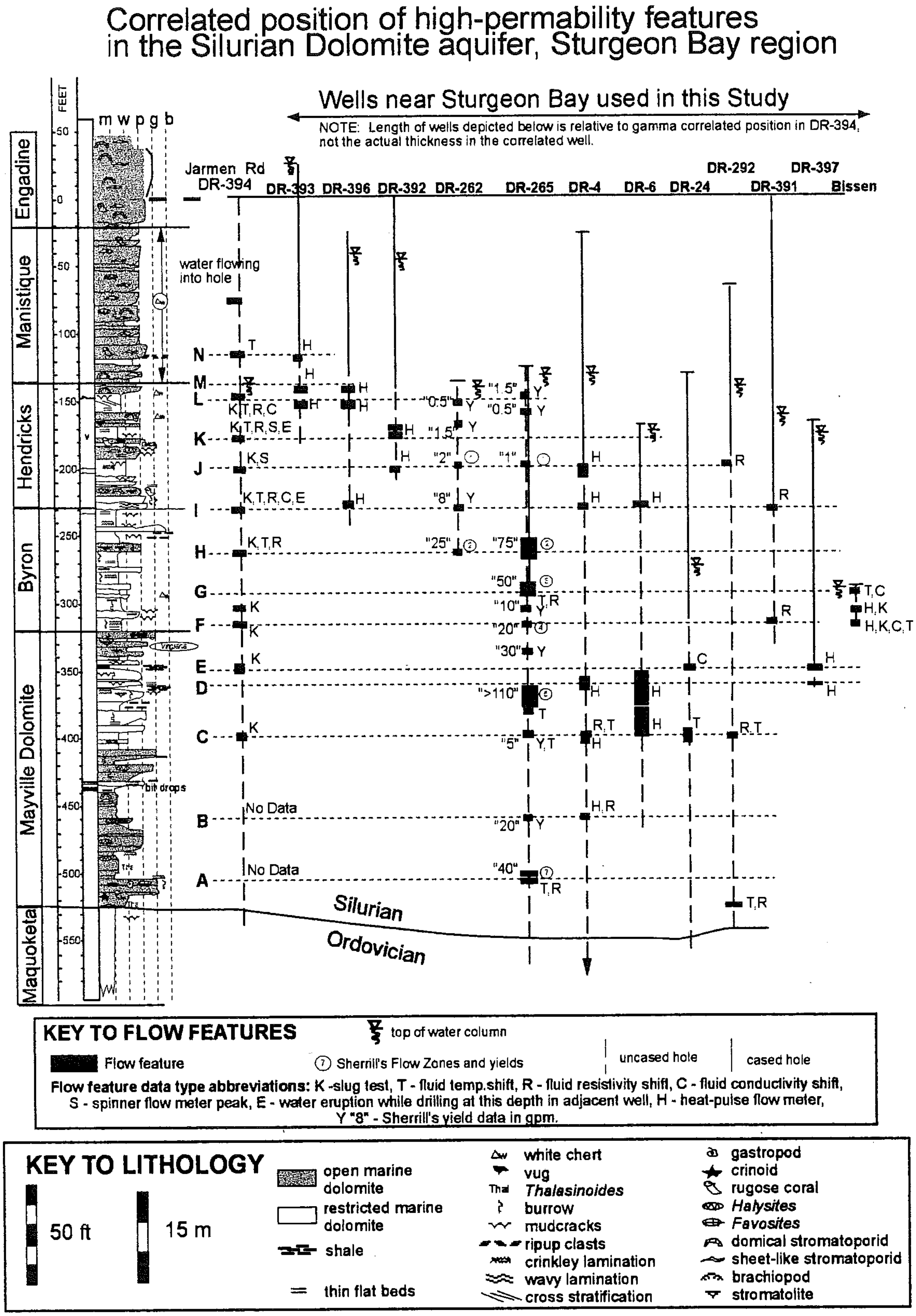

Figure 7. Correlation of high permeability features from 13 wells in the Sturgeon Bay region. Stratigraphic position of flow features has been correlated using natural gamma logs and all features were then projected onto hole Dr-394 to allow for comparison with core description (Figure modified from Gianniny and others, 1996; see Hegrenes, 1996 for core description).

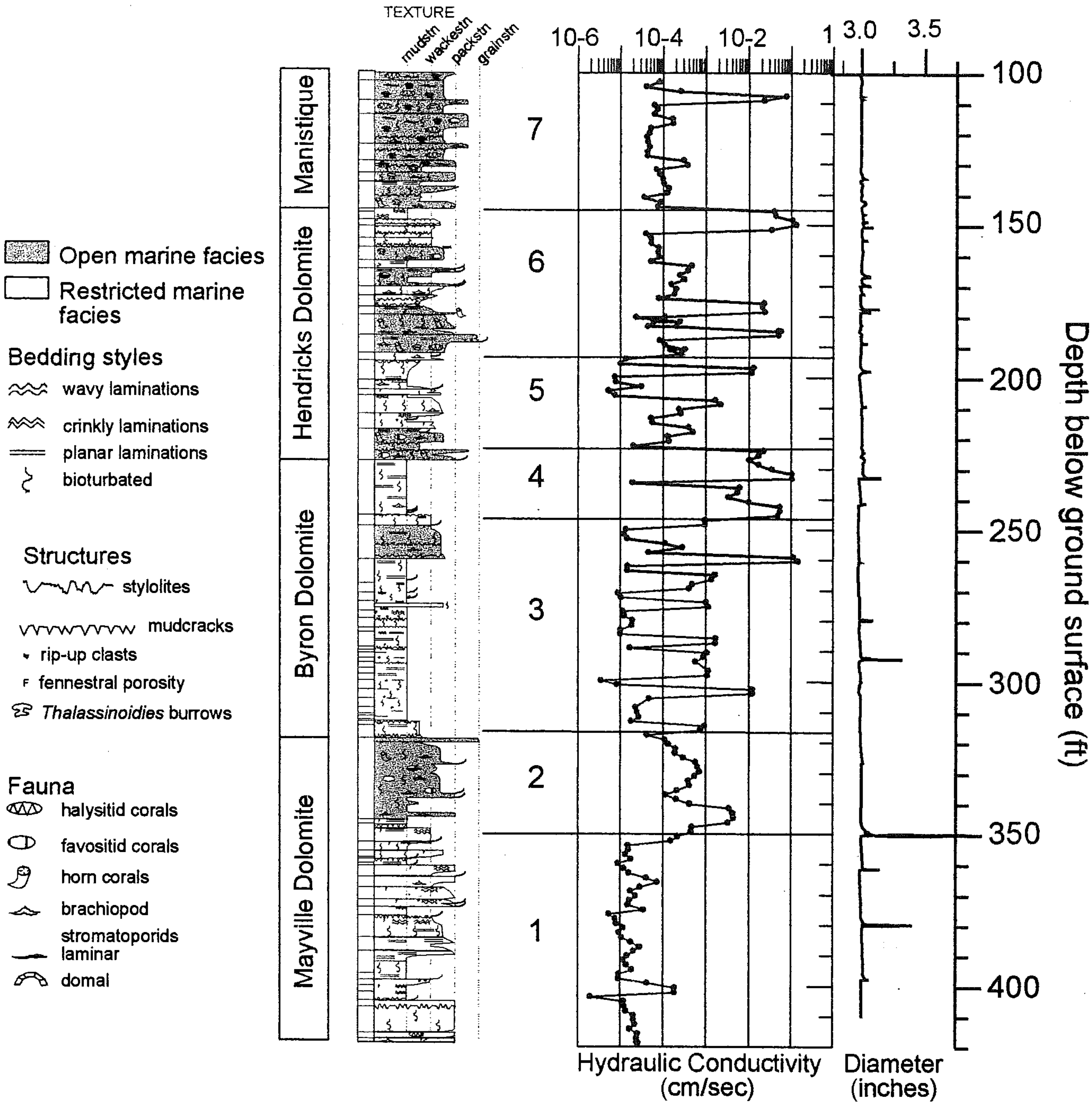

Figure 8. Hydraulic conductivity profile for Jarmen Rd. corehole (DR-394, location shown in Figure 1). Slug tests were conducted at 1.5-ft intervals using straddle-packers. The profile has been divided into seven segments based on variations in hydraulic conductivity. The stratigraphic column, based on descriptions from Hegrenes, (1996) is shown to the left of the hydraulic conductivity profile; the caliper log is shown to the right.

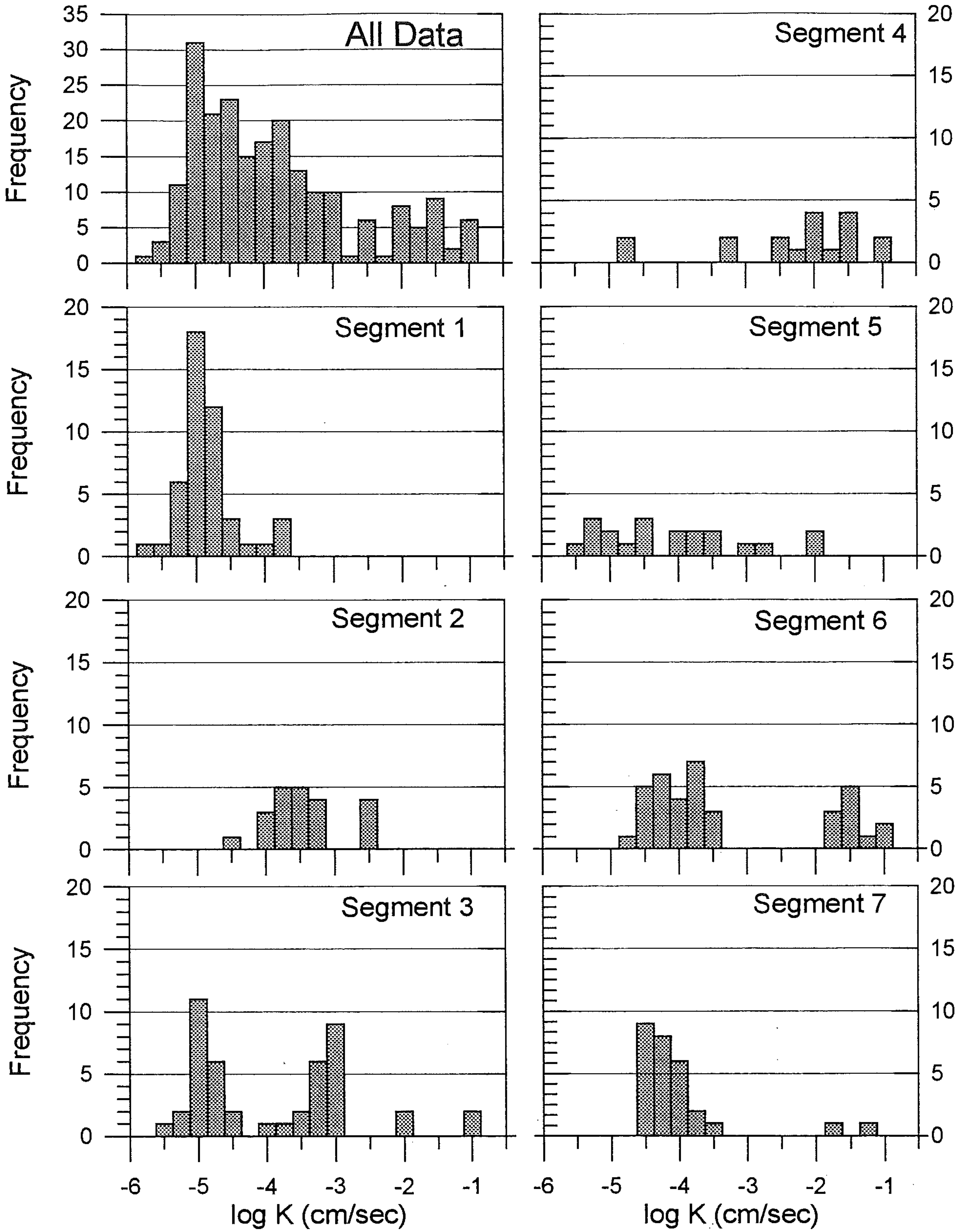

Figure 9. Histograms of hydraulic conductivity values measured with short-interval packer tests in the Jarmen Rd. corehole (Figure 8).

Upper Mayville Dolomite - Segment 2 in Hydraulic Conductivity Profile

Segment 2 in the hydraulic conductivity profile (Figures 8 and 9) is within the upper Mayville and is characterized by a transition from the underlying laminites to a brachiopod-rich zone that exhibits high moldic porosity and contains abundant fossils and small fractures (Burrowed Facies). The hydraulic conductivity profile suggests that this zone has a higher average matrix permeability than the underlying dolomite. Flow zone E (Figure 7) occurs within this portion of the Mayville and appears to be controlled by both the contact between contrasting lithologies (sharp contact between laminites and fossiliferous zone at 347 ft) and the overall higher matrix porosity. Like flow zone D, this feature overlies a 1" thick green shale in the DR-394 core and displays the crumbly, leached fenestral porosity seen in flow zone D.

Byron Dolomite - Segment 3 in Hydraulic Conductivity Profile

The Byron Dolomite, similar to the upper Mayville, is composed of cyclic alternations of bioturbated mudstones and very fine-grained, laminitic mudstones (Laminite Facies). One to two fossiliferous zones occur in the middle Byron. Mudcracks and interclastic lenses suggest repeated instances of intermittent sub-aerial exposure. The hydraulic conductivity profile (Figure 8) indicates that most measurements alternate between a low of 10^{-5} cm/sec which probably represents a matrix permeability of these finer-grained sediments and a high of 10^{-3} cm/sec which may be due to bedding-plane partings located at cycle boundaries. There are also a few values greater than 10^{-2} cm/sec which are probably large, open bedding plane fractures. Flow zones F, G, and H occur within this portion of the Byron and appear to correlate with the lithologic contrasts at cycle boundaries.

The Byron Dolomite, including flow zones F and G, is well-exposed in Bissen and Kisser quarries. The section exposed in Kisser Quarry is stratigraphically equivalent to the saturated section where tracer tests are being performed in Bissen Quarry. We will visit these two sites in stops 5 and 6 of the fieldtrip.

Upper Byron to Lower Hendricks Dolomite - Segment 4 in Hydraulic Conductivity Profile

All but one measurement in segment 4 (Figure 8) was greater than 10^{-3} cm/sec. These high hydraulic conductivities are associated with two very different facies. The portion from 231-246 ft corresponds to the "Blue Beds" of Thwaites and Lentz (1922). These bioturbated mudstones show evidence of tepee and other restricted sedimentary structures (Big Quarry, Stop 3; Bissen Quarry, Stop 6). In outcrop, this unit exhibits numerous cycle boundaries and appears quite well-cemented and brittle. This combination of abundant bedding-plane partings at cycle boundaries and numerous vertical fractures may account for the high permeability of the Blue Beds.

The upper portion of segment 4 consists of coarse-grained, open marine facies with abundant stylolites. Flow zone I, one of the most regionally extensive flow zones, occurs near the contact of the Byron and Hendricks Dolomites.

Hendricks Dolomite - Segments 5 and 6 in Hydraulic Conductivity Profile

The Hendricks Dolomite represents a transition in lithology from the dominantly fine-grained mudstones of the Byron Dolomite (Laminite Facies) to the coarser, more fossiliferous Manistique Formation (Packstone Facies) and is composed of cyclic alternations of those lithologies. Segment 5 correlates with the Lower portion of the Hendricks (Figures 8 and 9). Hydraulic conductivity values are quite variable which is consistent with the variable lithologies and depositional cycles of the Hendricks. Flow zone J is associated with enlarged borehole diameter and has developed within a shallowing upward cycle containing numerous stylolites.

Segment 6 correlates with the upper portion of the Hendricks Dolomite (Figure 8). Hydraulic conductivity values are bimodally distributed (Figure 9). Matrix hydraulic conductivities appear log-normally distributed with a mean of approximately 10^{-4} cm/sec. Flow zones K and L appear to be associated with finer-grained lithologies containing abundant stylolites and exposure surfaces. Flow zone M occurs at the base of the Manistique Formation and it coincides with the transition from fine-grained mudstones with thin flat beds at the top of the Hendricks Dolomite to fossiliferous, coarse-grained rock types.

Manistique Formation - Segment 7 in Hydraulic Conductivity Profile

Segment 7 correlates with the Manistique Formation which is characterized by fossiliferous, grain-supported packstones (Packstone Facies). This segment is characterized by a relatively high matrix hydraulic conductivity, on the order of 10^{-4} cm/sec. The histogram for this segment (Figure 9) suggests a log-normal distribution of the matrix measurements. Flow zone N coincides with an interval of rip-up clasts in a fossiliferous packstone matrix

Summary

Groundwater is an important resource in Door County; over 99% of the water used by the residents of the county for domestic water supply, agriculture, industry, and commercial uses is supplied by groundwater (Bradbury, 1989). The Silurian dolomite aquifer is quite productive and water quantity is not a concern in the county. Water-quality is a concern and long-term monitoring of private wells suggests that much of the observed contamination is a direct result of agricultural and other land-use practices in areas where thin soils overlie the fractured dolomite. The majority of the groundwater used in Door County originates as precipitation within the county and so groundwater protection strategies, such as wellhead protection and agricultural best management practices, may help protect the aquifer in the future. Any groundwater protection plan needs to be based on a thorough understanding of the dynamics of the groundwater flow system.

Groundwater flow in the Silurian aquifer is characterized by recharge through vertical fractures and rapid lateral movement along horizontal high-permeability zones that appear to be laterally continuous on the scale of miles. While the fractures carry the majority of the flow, both fractures and matrix porosity provide the storage capacity for the aquifer. Detailed stratigraphic analysis, coupled with geophysical and hydrogeologic data, provide a method for characterizing the hydraulic properties of the Silurian aquifer and similar fractured-carbonate aquifers elsewhere.

JARMEN ROAD CORE STUDY

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Introduction

A complete core through the Silurian aquifer was recovered at the Jarmen Road (Door County) site in spring 1995 (Figure 1). The 541-ft (165 m) core provided an opportunity to study sedimentologic, geophysical and hydrogeologic information as a single integrated dataset. Including information obtained by the Wisconsin Geological and Natural History Survey (Gianniny et al., 1996; Muldoon and Bradbury, this volume), the data include a core description, geophysical logs (Gianniny et al., 1996), 10-ft (3 m) packer tests, and 1.7-ft (0.5 m) packer tests (Muldoon and Bradbury, this volume).

Stratigraphy and Facies

The core includes all Silurian units and the top of the Upper Ordovician Maquoketa Formation (Figure 2). The upper 10 ft (3 m) of the Engadine Dolomite are probably missing at this site based on comparison to local outcrop sections (Harris and Waldhuetter, 1996).

Facies are similar to those in outcrop (Harris and Waldhuetter, 1996, this volume) and the same subfacies/facies approach was used in the core study (Figures 3 and 4). Some modifications were necessary because of the nature of the core sample. Ripple bedforms were hard to discern so the outcrop Ripple Facies is represented in the core by the Packstone Facies. Some laminated subfacies of the Laminite Facies could not be differentiated. However the core had two major advantages over the outcrop exposures. First, the complete section was recovered. This provided a detailed description of the entire Mayville section including (for the first time) the facies in the upper part of the unit. Second, exposure surfaces are more clearly expressed in the core, improving the recognition of sequence boundaries.

Figure 2 summarizes the lithostratigraphy, facies and sequence stratigraphy of the core. The core description is presented at the end of this article (Figure 8).

Hydrogeological Aspects

The Jarmen Road corehole provided the opportunity to collect an integrated set of stratigraphic data (Hegrenes, in prep); geophysical data - natural gamma, spontaneous potential, single-point resistivity, caliper (Gianniny and others, 1996); hydraulic data - fluid temperature, fluid resistivity, and heat-pulse flowmeter (Gianniny and others, 1996); and hydraulic conductivity data collected at varying scales. Hydraulic conductivity values determined from injection packer tests conducted at 10-ft intervals (Hegrenes, in prep.) and from slug tests conducted with a 1.7-ft packer interval (Muldoon and Bradbury, this volume) could be directly compared to core features such as facies, porosity and fracture density.

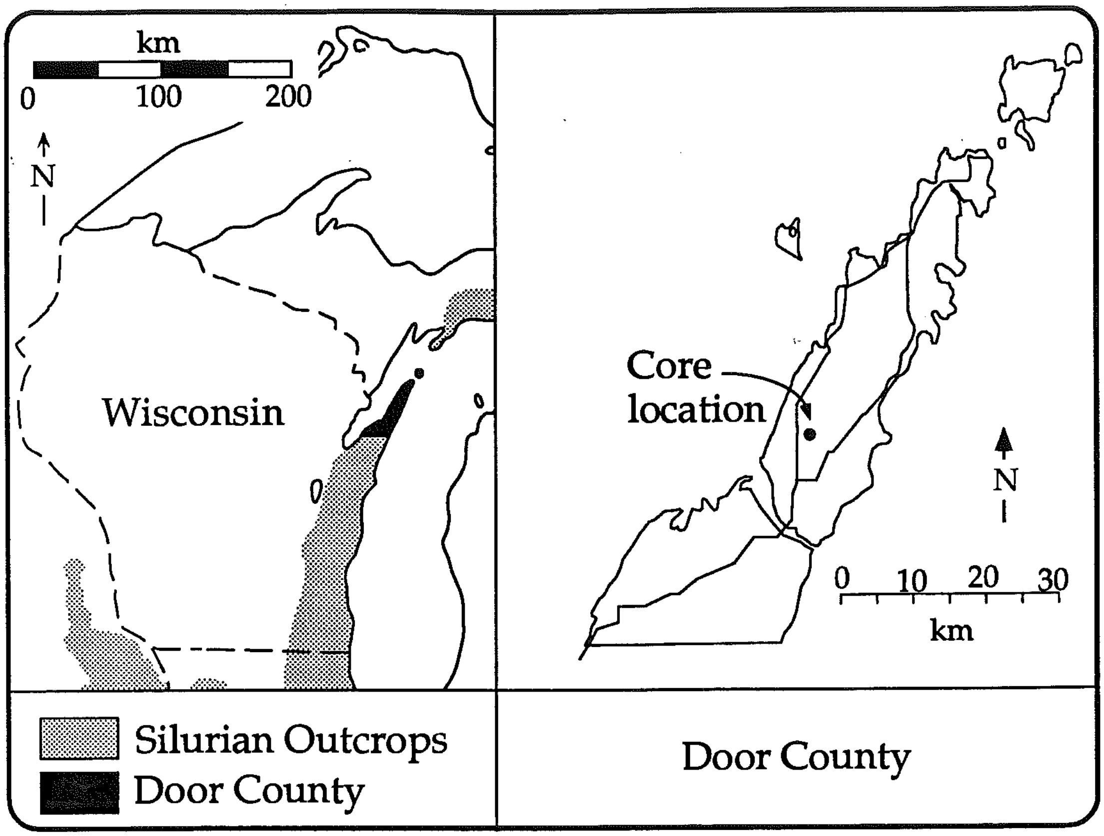


Figure 1: Map showing the location of the Jarmen Road core. Silurian outcrop modified from Lowensam (1950).

Comparison of measured hydraulic conductivity values from injection tests (10-ft packer interval) and from slug tests (1.7-ft packer interval) illustrates several relevant points. Figure 5 shows that the hydraulic conductivities calculated from the 10-ft packer tests range from 10^{-3} to $5x10^{-4}$ cm/sec and show significantly less variability than the hydraulic conductivities measured with a packer interval of 1.7 ft. Geometric mean hydraulic conductivities, calculated for each 10-ft interval using the hydraulic conductivites measured at 1.5-ft intervals, are generally within one order of magnitude of the hydraulic conductivity measured in the 10-ft packer tests. Comparison of hydraulic conductivity values from the two types of packer tests shows that long-interval packer tests provide "average" measures of hydraulic conductivity and they are therefore of limited use in differentiating the detailed hydraulic conductivity distributions of either the fractures or the matrix blocks (see stop 5 description for further discussion of hydraulic conductivity testing methods).

The hydraulic conductivity calculated from the 1.7-ft tests can be compared with the number of core breaks (Figure 6) and visually estimated porosity (Figure 7) in the core. The hydraulic conductivity data shown include the interval from 180 ft to 419 ft because shallower data were note available when the plot was made. The plots are divided at the 320 ft horizon because the section above this depth is entirely Laminite Facies (Burnt Bluff Group) whereas all three facies occur in the underlying Mayville section. The Laminite Facies contains more core breaks.

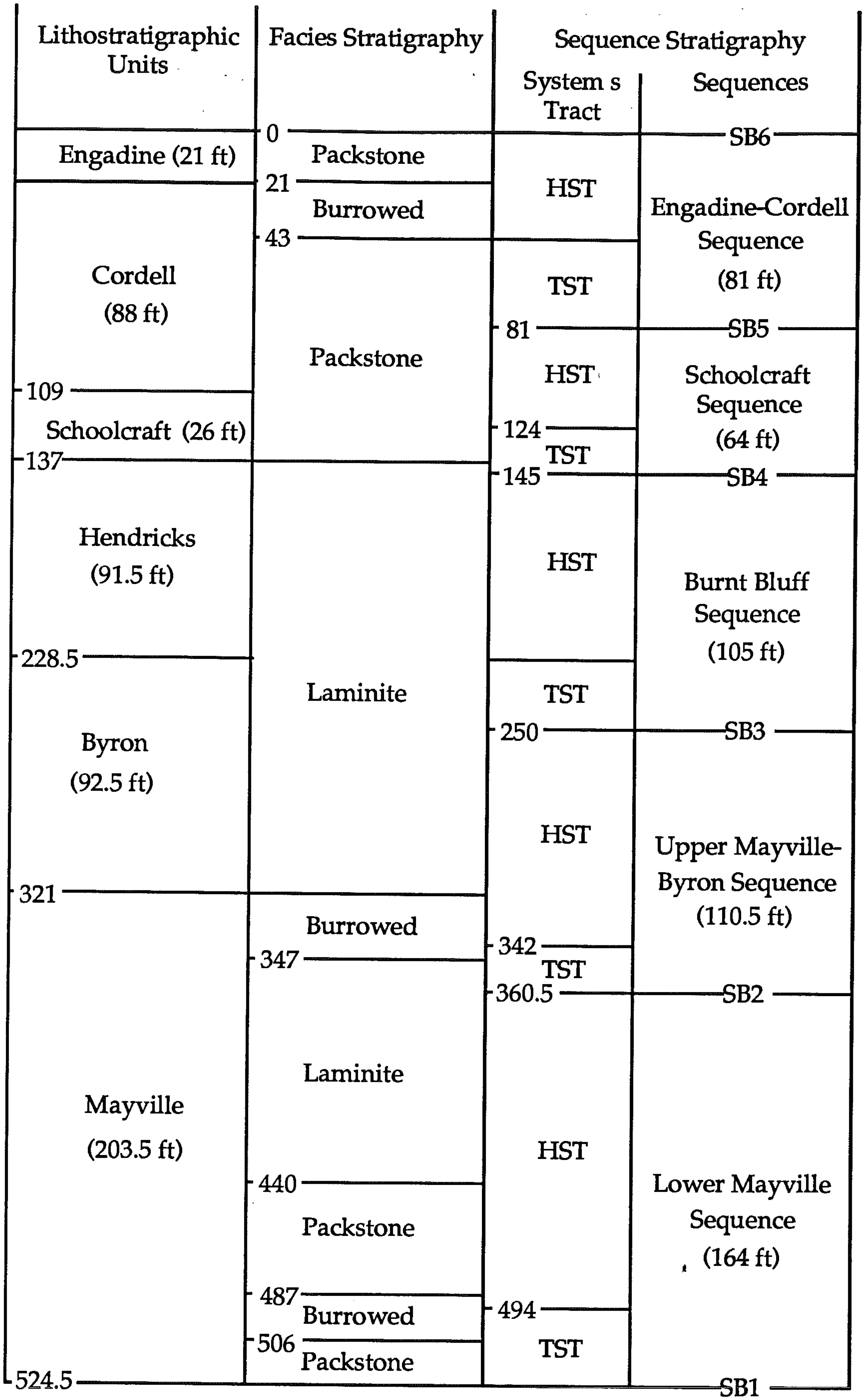


Figure 2: Summary of the lithostratigraphy, facies and sequence stratigraphy of the Jarmen Road core. All depths in feet, matching core boxes.

Figure 3: Subfacies summary

SUBFACIES	SED. STRUCTURES	FAUNA	POROSITY TYPE	%
1. Brachiopod wackestone-packstone	Burrows, bioturbation. Ichnofabric = 5-6.	Brachiopods, sparse tabulate and rugose corals.	Brachiopod moldic and vug, minor interparticle.	<12%
2. Bioturbated peloid mudstone-wackestone	Burrows, bioturbation, laminations. Ichnofabric = 3-6.	Fragments in burrow fills includes brachiopods, tabulate and rugose corals.	Interparticle or vug	<1%
3. Bioturbated skeletal wackestone-packstone	Burrows, bioturbation, minor chert. Ichnofabric = 3-6.	Brachiopods, stromatoporoids, tabulate and rugose corals, crinoids.	Fossil moldic and vug, minor interparticle.	1-4%
4. Bioturbated cherty mudstone-wackestone	Burrows (probably *Thalassinoides*) with abundant (5-25%) chert, bioturbation. Ichnofabric = 5-6.	Fragments of brachiopods, rugose corals.	Interparticle, intercrystal.	<1%
5. Bioturbated skeletal wackestone	Burrows, bioturbation. Ichnofabric = 3-6.	Brachiopods, crinoids, tabulate and rugose corals. Most fossils are fragmented (i.e. <2 cm).	Interparticle, brachiopod moldic, vugs.	1-4%
6. Laminar stromatoporoid-coral floatstone with mudstone-wackestone matrix.	Bioturbation, silicified fauna and chert nodules (0-10%). Ichnofabric = 5-6.	Laminar stromatoporoids, tabulate and rugose corals.	Vugs	1-4%
7. Stromatoporoid-mixed coral floastone with skeletal-peloid packstone matrix	Bioturbation, silicified fauna, and chert nodules (10-20%). Ichnofabric = 4-6.	Laminar and domal stromatoporoids, tabulate and rugose corals, brachiopods, crinoids.	Interparticle, intraparticle.	1-5%
8. Skeletal pellet packstone-wackestone	Burrows, bioturbation, Chert (0-10%). Ichnofabric = 4-6. Preservation poorer than subfacies 7.	Brachiopods, tabulate and rugose corals, crinoids.	Interparticle, intraparticle.	1-4%
9. Coral floatstone with skeletal wackstone matrix.	Burrows, bioturbation. Ichnofabric = 5-6.	Laminar stromatoporoids, tabulate and rugose corals, brachiopods.	Vug.	1-4%
10. Coral-stromatoporoid boundstone	Growth framework. Ichnofabric = 1.	Poorly preserved stromatoporoids and tabulate corals.	Growth framework, shelter.	7%
11. Crinoid packstone	Horizontal, flat, thin laminations, some graded. Ichnofabric = 1.	Crinoids, brachiopods, tabulate and rugose corals.	Interparticle.	0-7%
12. Recrystallized peloid packstone	Thin to thick, flat laminations, fenestra, bioturbation. Ichnofabric = 1-5.		Interparticle, intercrystal.	<1%
13. Flat to wavy laminated mudstone	Thin to thick, flat to wavy laminations, mudcracks, fenestrae, rip-up clasts. Ichnofabric = 1-4.			<1%
14. Wavy to crinkly laminated mudstone-wackestone	Thin to thick, wavy to crinkly laminations, fenestrae. Ichnofabric = 1-3.		Fenestral, vug.	0-6%

Figure 4: Facies components and environmental interpretation

Facies	*Subfacies*	*Depositional Environment*
Burrowed Facies	Brachiopod wackestone-packstone Bioturbated peloid mudstone-wackestone Bioturbated skeletal wackestone-packstone Bioturbated cherty mudstone-wackestone Bioturbated skeletal wackestone Laminar stromatoporoid-coral floatstone with mudstone-wackestone matrix	Open marine below normal wave base but above storm wave base.
Packstone Facies	Bioturbated skeletal wackestone-packstone Stromatoporoid-mixed coral floatstone with skeletal-peloid packstone matrix Skeletal peloid packstone-wackestone Coral floatstone with skeletal wackestone matrix Coral-stromatoporoid boundstone Crinoid packstone Recrystallized peloid packstone	Open marine above normal wave base.
Laminite Facies	Bioturbated peloid mudstone-wackestone Bioturbated skeletal wackestone Flat to wavy laminated mudstone Wavy to crinkly laminated mudstone-wackstone	Tidal flat.

There is no relation between number of core breaks and hydraulic conductivity suggesting that only a subset of the fractures is hydrologically important. Similarly, the comparison with porosity shows no relation between porosity and hydraulic conductivity for the Laminite Facies section (above 320 ft). However where all three facies occur, there is a linear relation suggesting that about half of the variability in conductivity is related to porosity.

Hydraulic testing of boreholes throughout Door County suggests that the majority of groundwater entering wells is contributed from horizontal bedding plane fractures (Sherrill, 1978; Bradbury and Muldoon, 1992; Gianniny and others, 1996). By using natural gamma logs to correlate subsurface stratigraphy between boreholes, Gianniny and others (1996) were able to show that some of these high-permeability features are laterally continuous on the scale of miles. The Jarmen Road core provided the opportunity to compare the location of the high-permeability features with detailed stratigraphic descriptions (Hegrenes, in prep) in order to explore possible controls on the location of these high-permeability features. Regionally important high-permeability features seem to be located at contacts between units with sharp contrast in lithology.

The corehole also provided an opportunity to obtain detailed hydraulic conductivity distributions for both the matrix and fracture portions of the aquifer. Comparison of short-interval packer tests (Muldoon and Bradbury, this volume) with core descriptions (Hegrenes, in prep) suggests that variations in matrix hydraulic conductivity appear to be controlled by lithologic texture. The distribution of fracture hydraulic conductivity appears to be controlled by 1) frequency of depositional cycle boundaries, 2) lithologic contrasts, and 3) presence of thin shale layers. The Silurian facies interpretation (Harris and

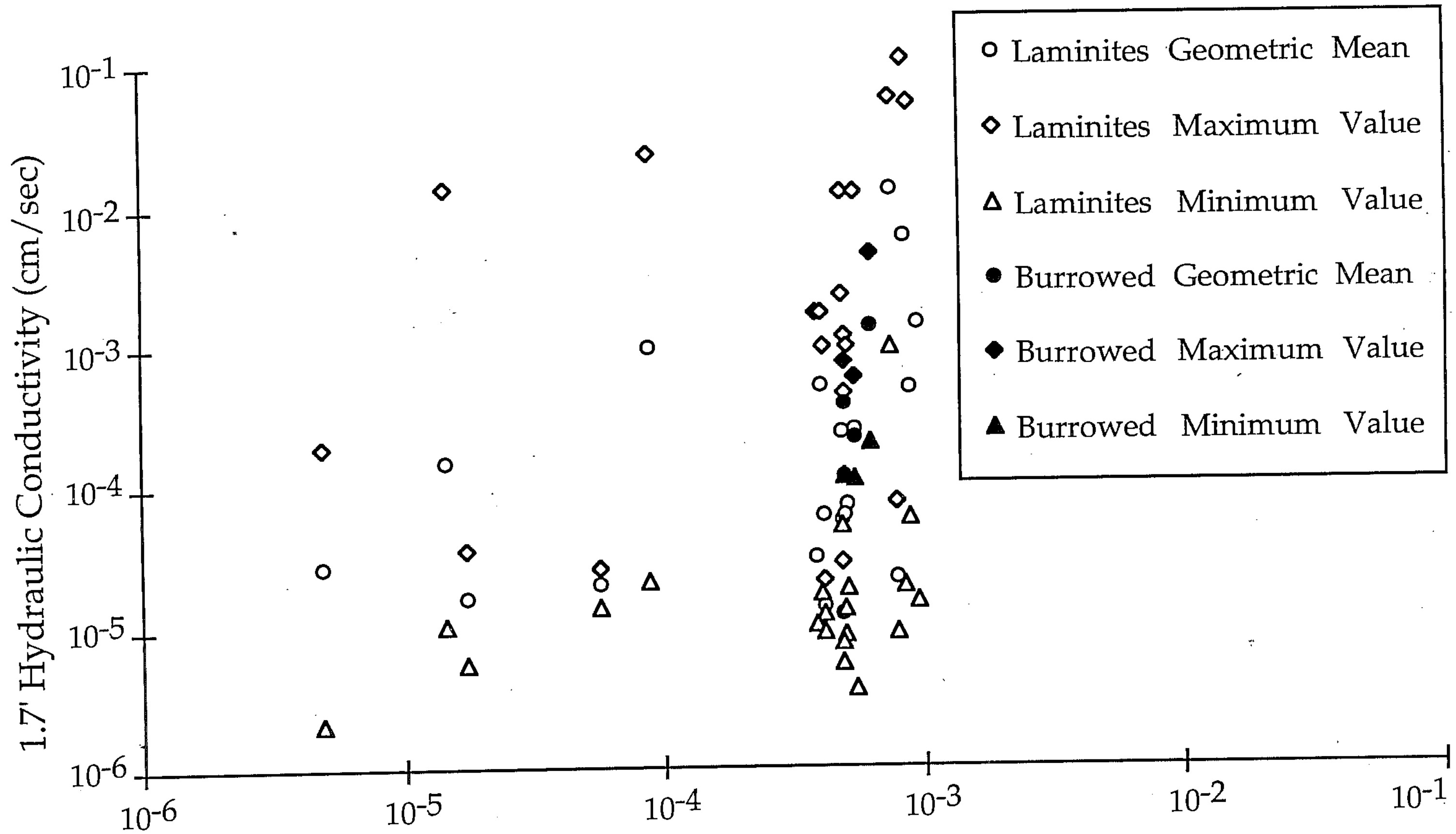


Figure 5: Cross plot of hydraulic conductivity calculated from 10-ft and 1.7-ft packer tests

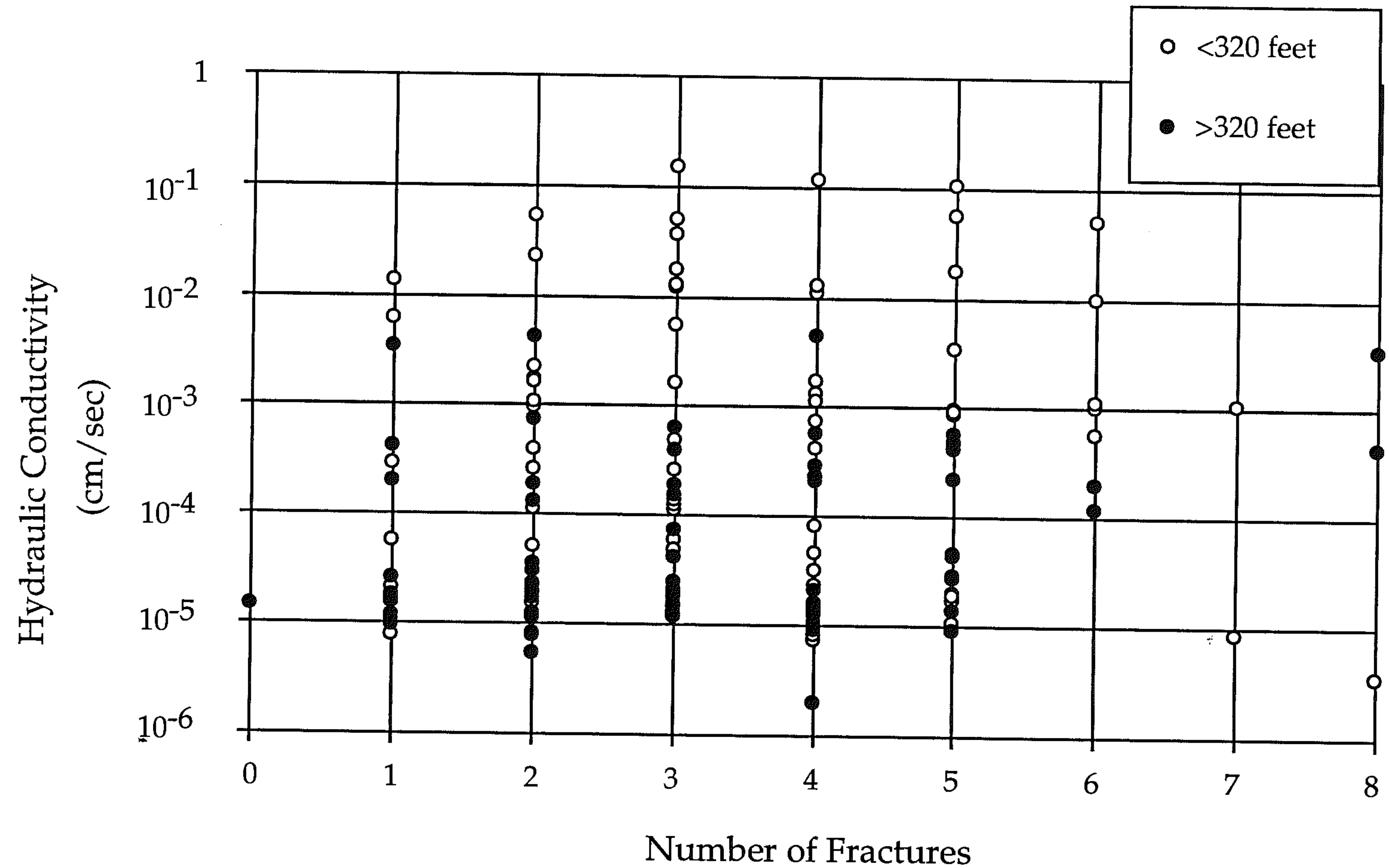
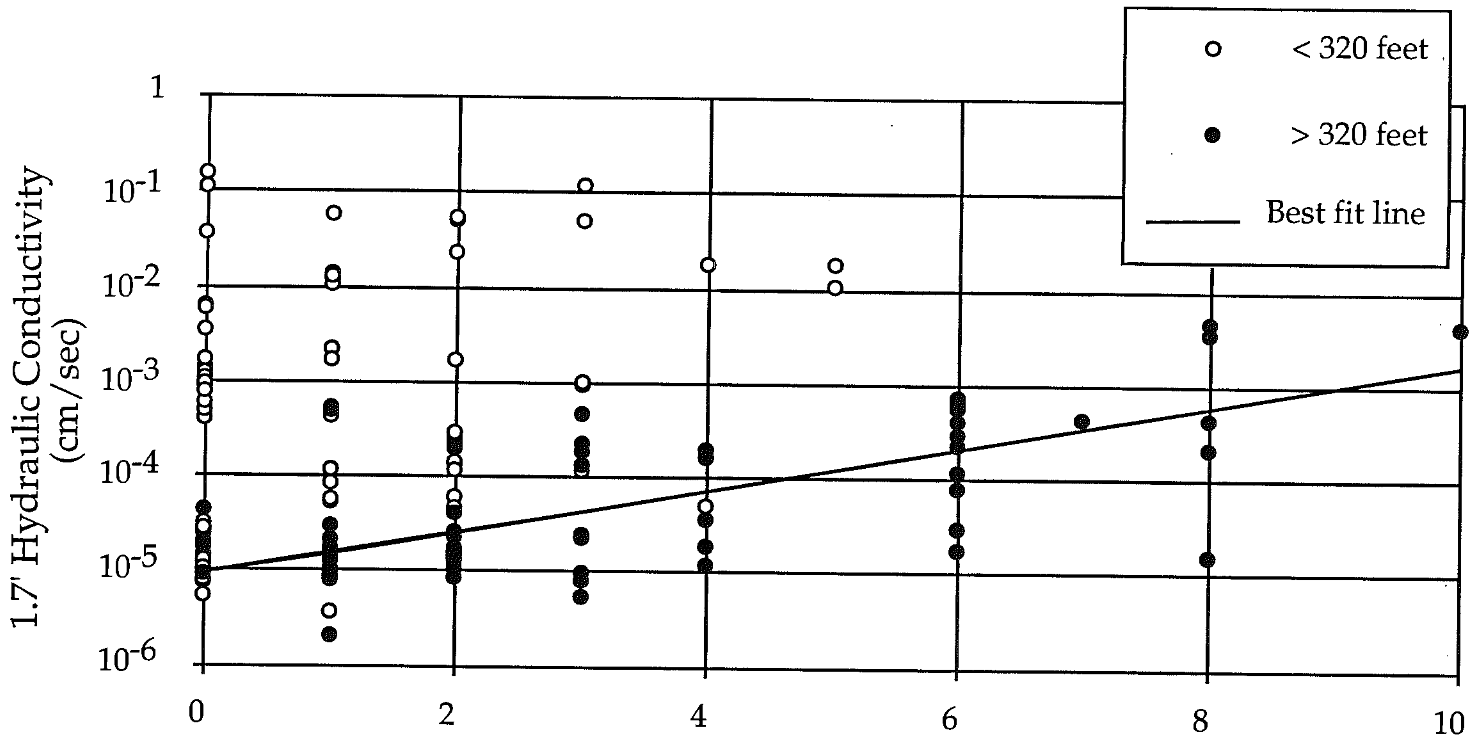


Figure 6: Cross plot of number of core break versus hydraulic conductivity in 1.7-ft packer tests



y=0.225367*(porosity)+-5.03126

$r^2 = 0.51$

Figure 7: Cross plot of visually estimated porosity versus hydraulic conductivity in 1.7-ft packer tests

Waldhuetter, this volume) provides a framework for predicting general flow pathways and storage capacity because these parameters are related to depositional facies. Both flow and storage in the Laminite Facies is dominated by fractures because the matrix has negligible porosity. In the Burrowed and Rippled Facies, the large fractures still dominate flow, however, matrix porosity is significant and provides storage capacity. The matrix porosity in these facies also correlates with the lower- and middle-range hydraulic conductivity values suggesting groundwater moves slowly through these matrix blocks.

Core Description

The core description is presented as Figure 8. The columns to the left of the graphic column present lithostratigraphic, sequence stratigraphic and facies information. Subfacies are numbered as in Figure 3 and facies coded by letter (B=Burrowed, L=Laminite, and P=Packstone). The width of the graphic column represents the Dunham (1962) texture and the symbols are explained in Figure 3 of the Road Log. To the right of the graphic column are porosity (Choquette and Pray, 1970), ichnofabric index (Droser and Bottjer, 1986), chert and fracture logs. Fracture types are keyed as follows:

C	Clay seam.
Ch	A break along chert or silicified coral boundaries.
D	Dish surface due to grinding along the core fracture.
Dm	Drilling mud on the fracture surface is present.
Ef	Exact fit
M	Mineralization or Rerystallization.
Nf	No fit between fractures.
O	Open and distance between fractures.
St	Stylolite fractures.

Finally, core and box number and results of the 10-ft hydraulic conductivity tests are shown on the right.

Acknowledgments

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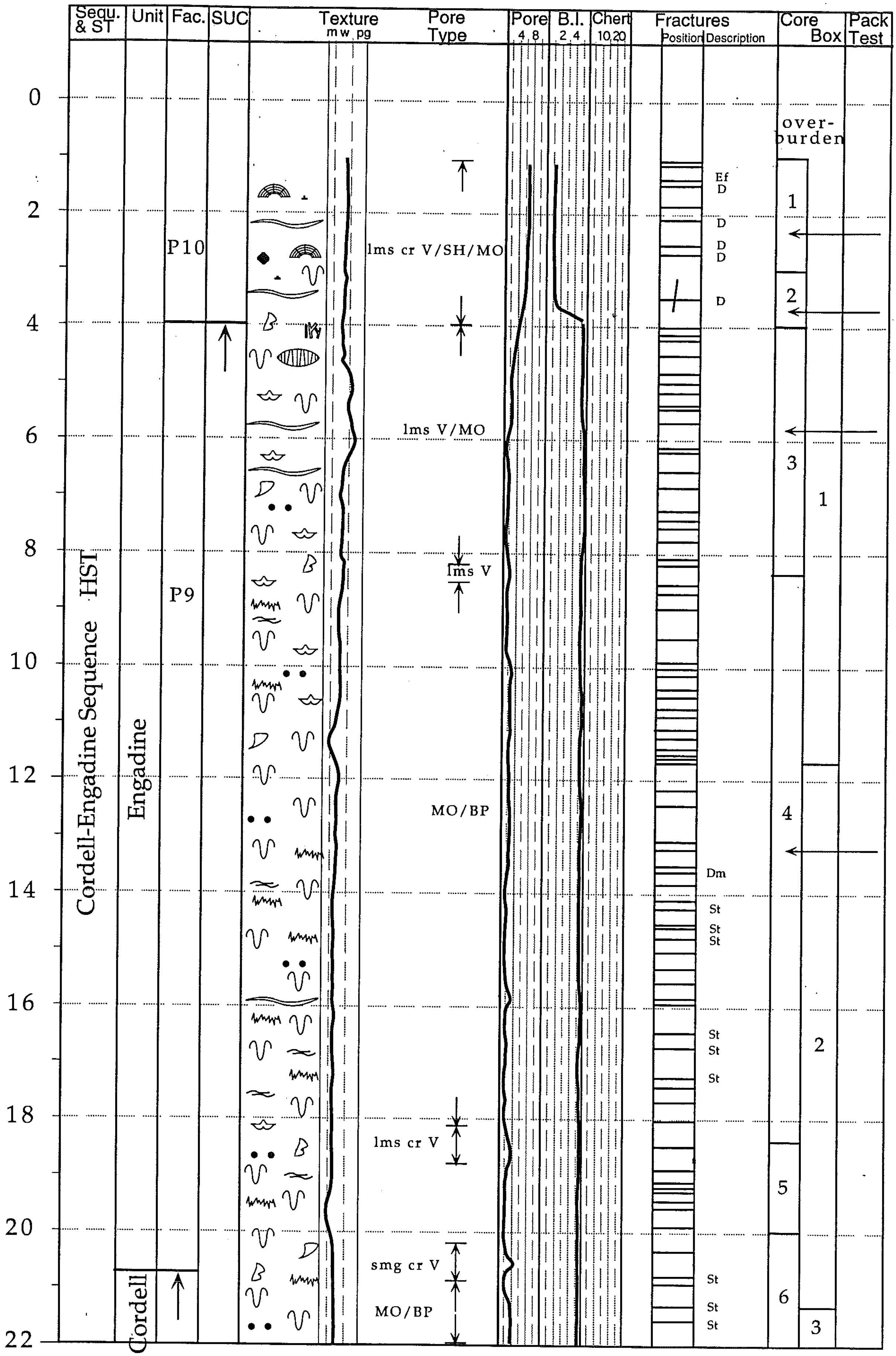
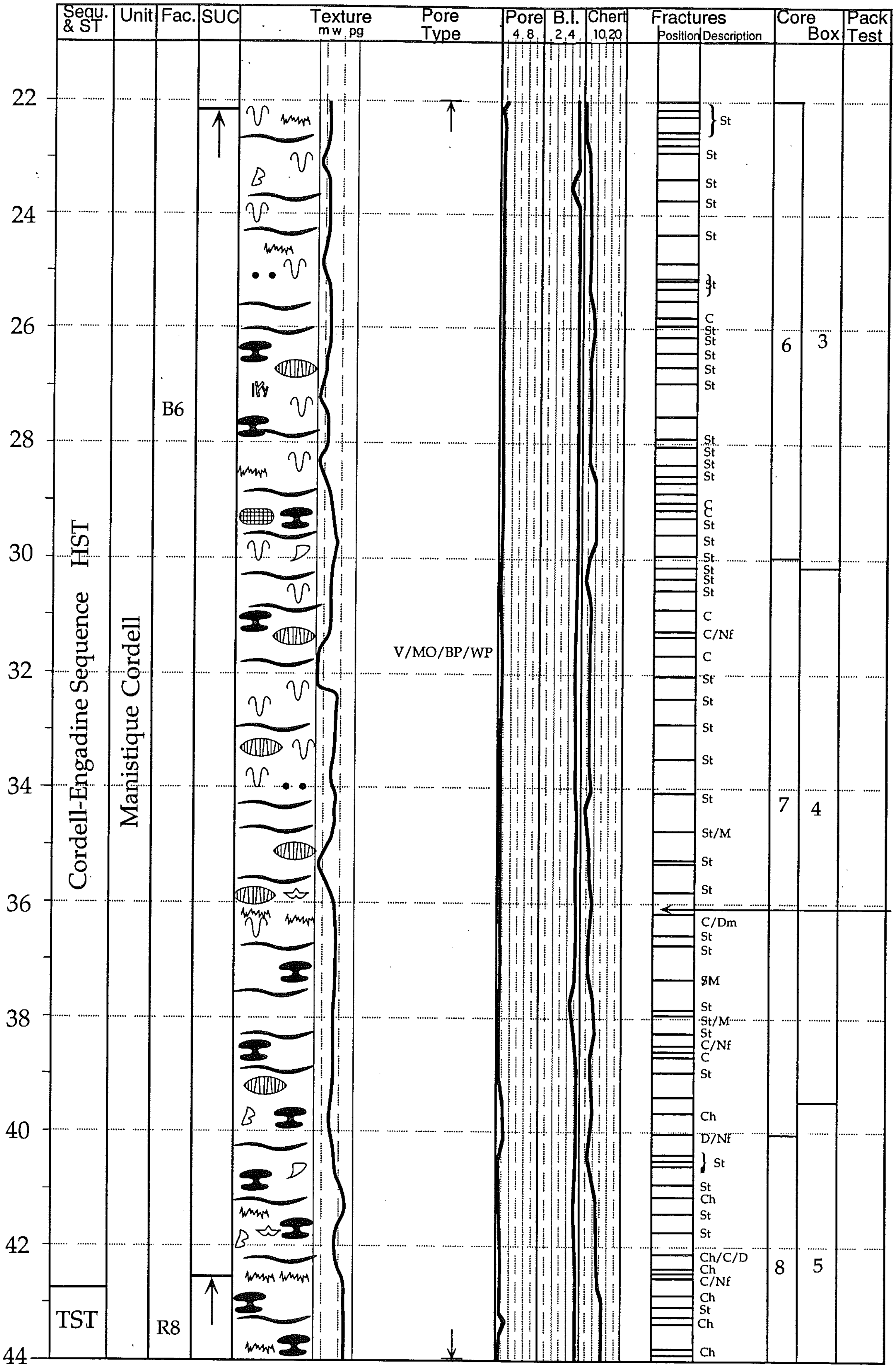


Figure 8: Jarmen Road Core Description, p. 1



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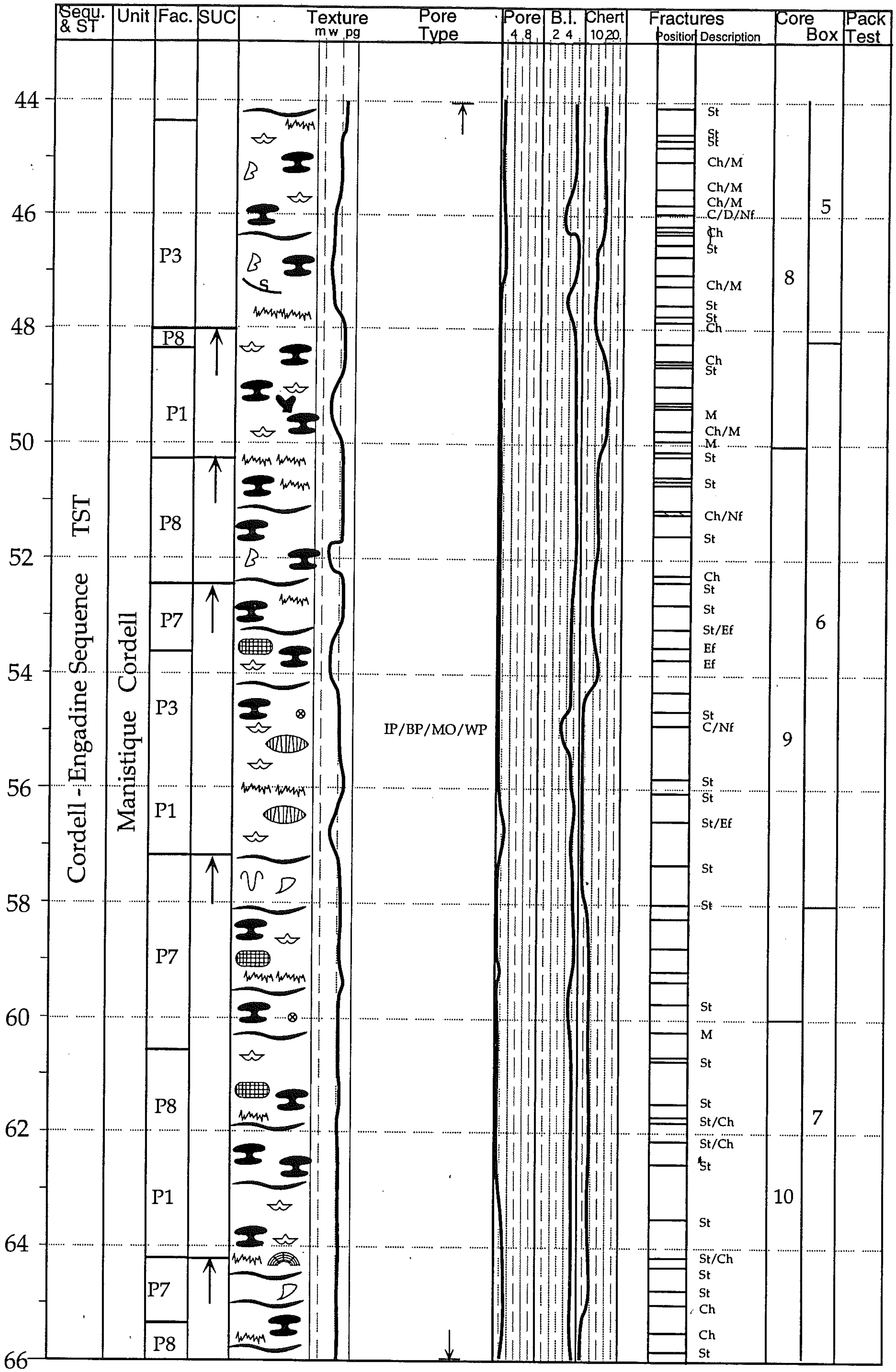

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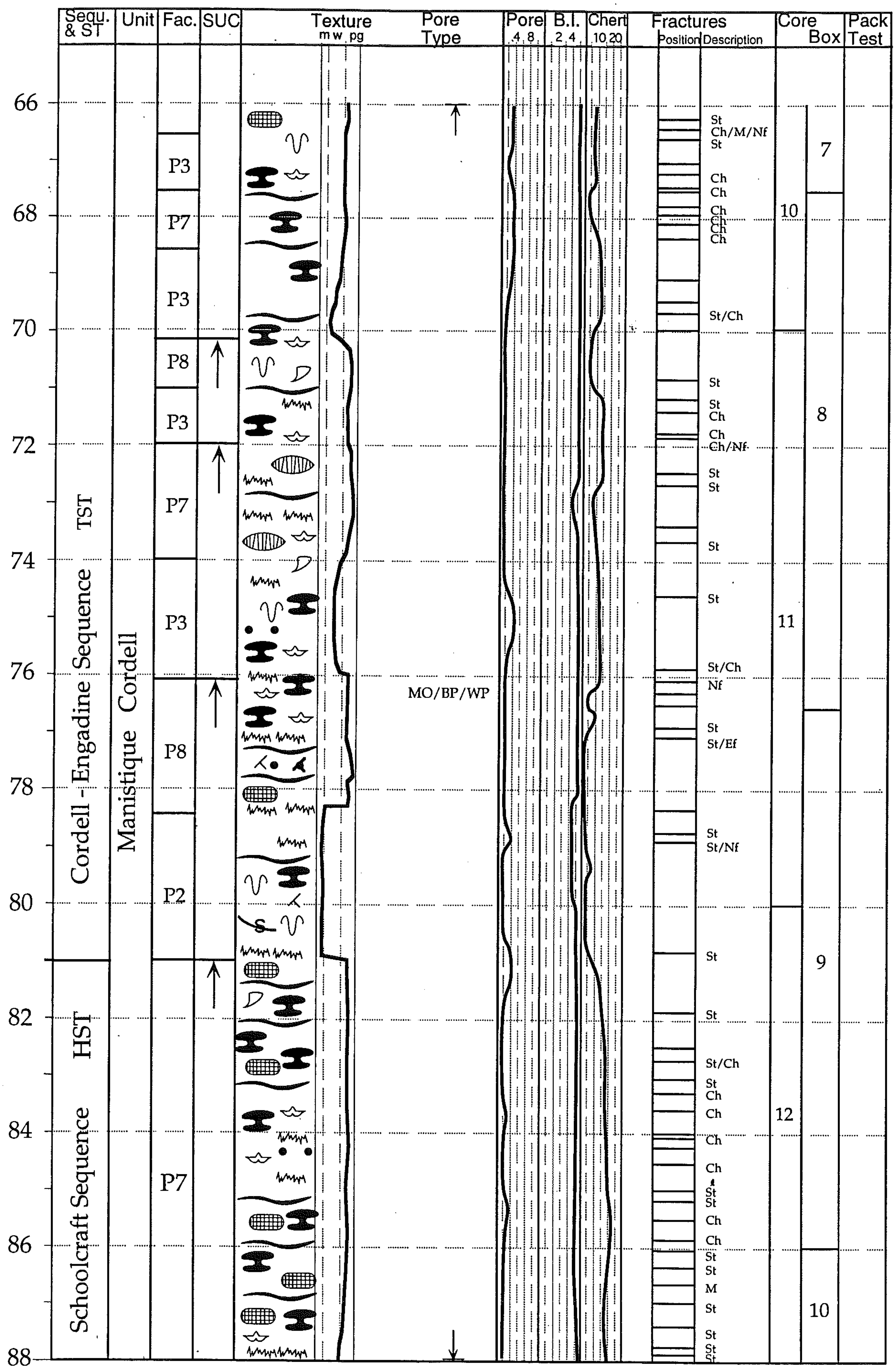

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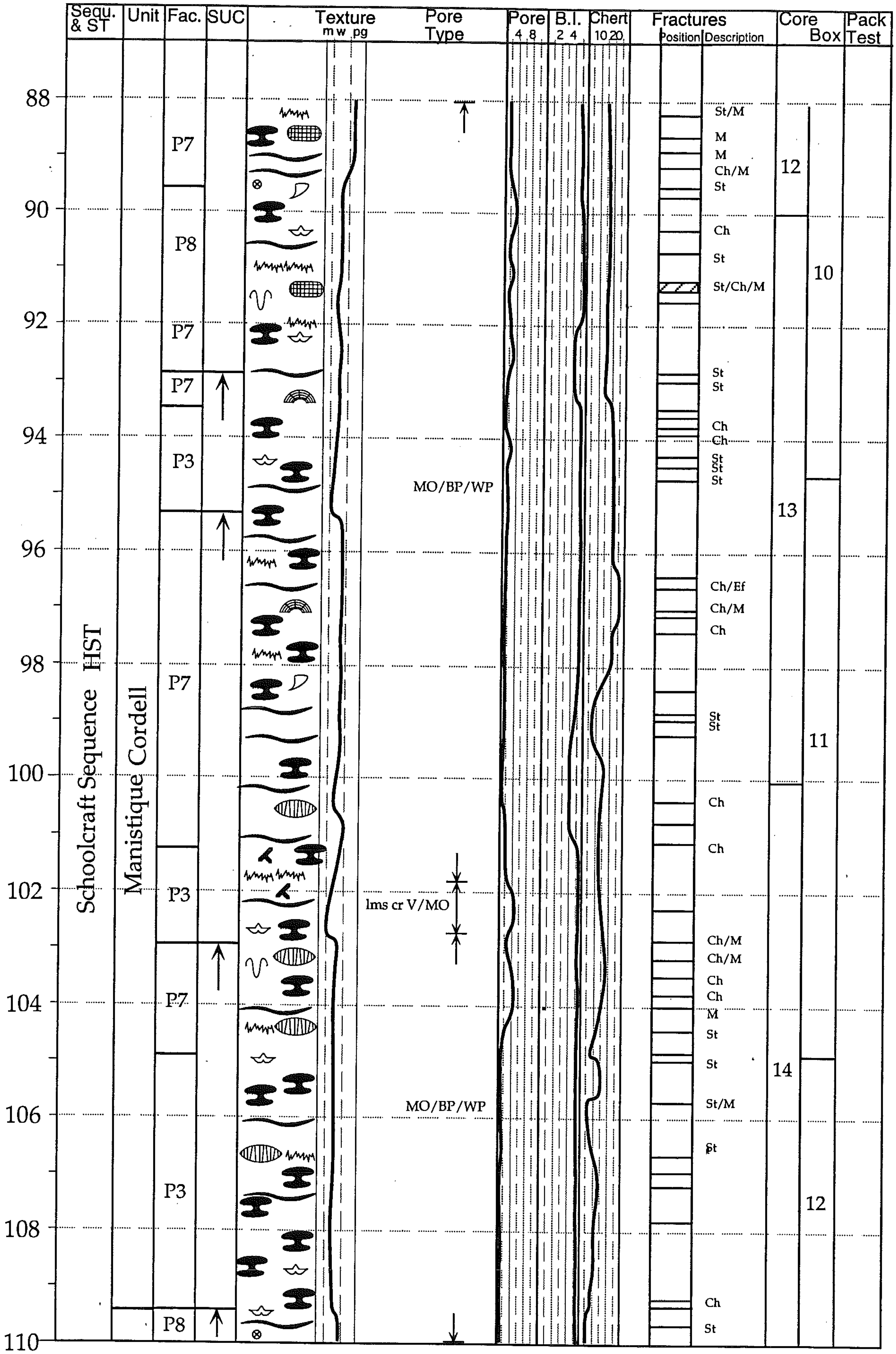

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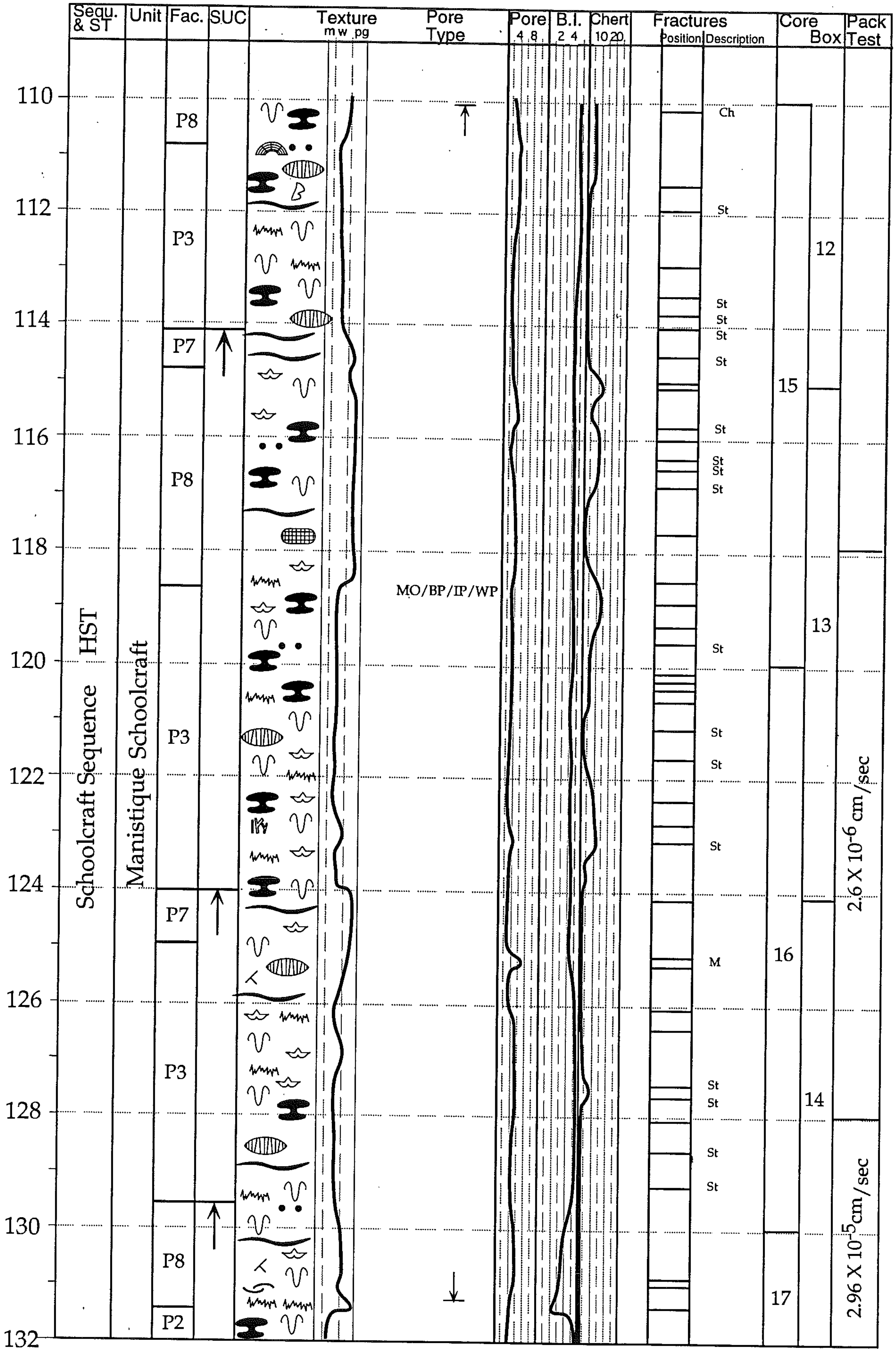

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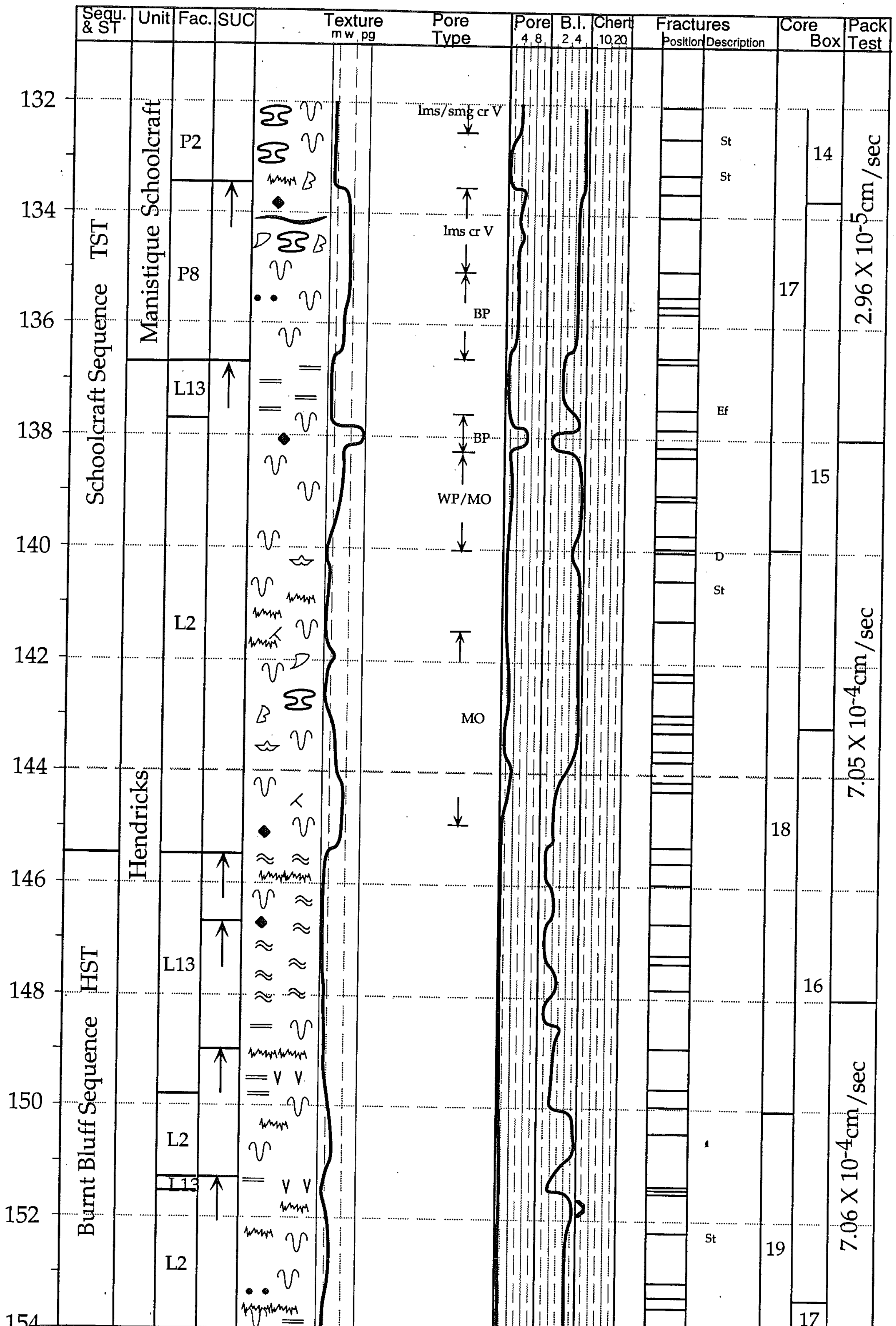

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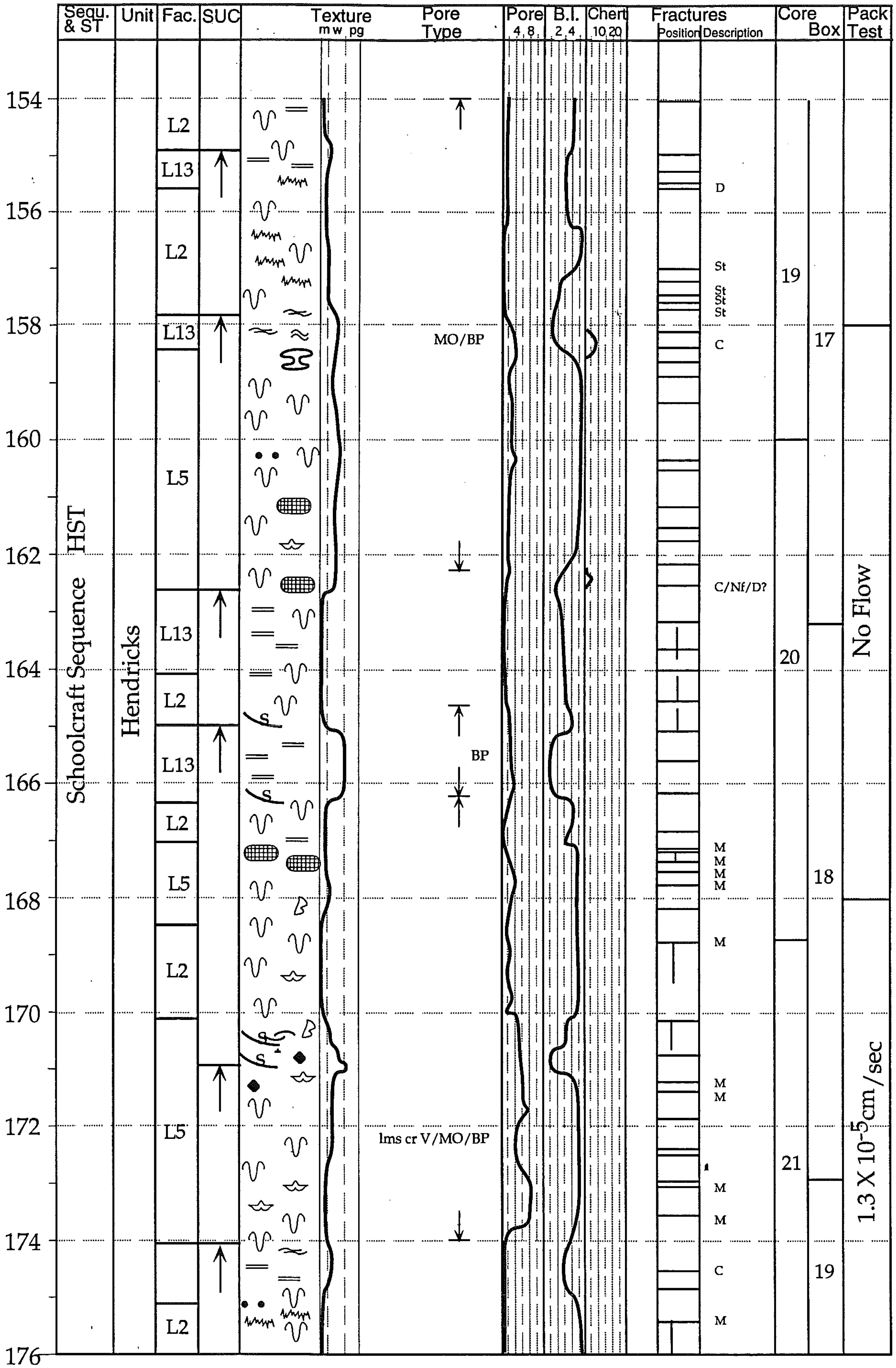

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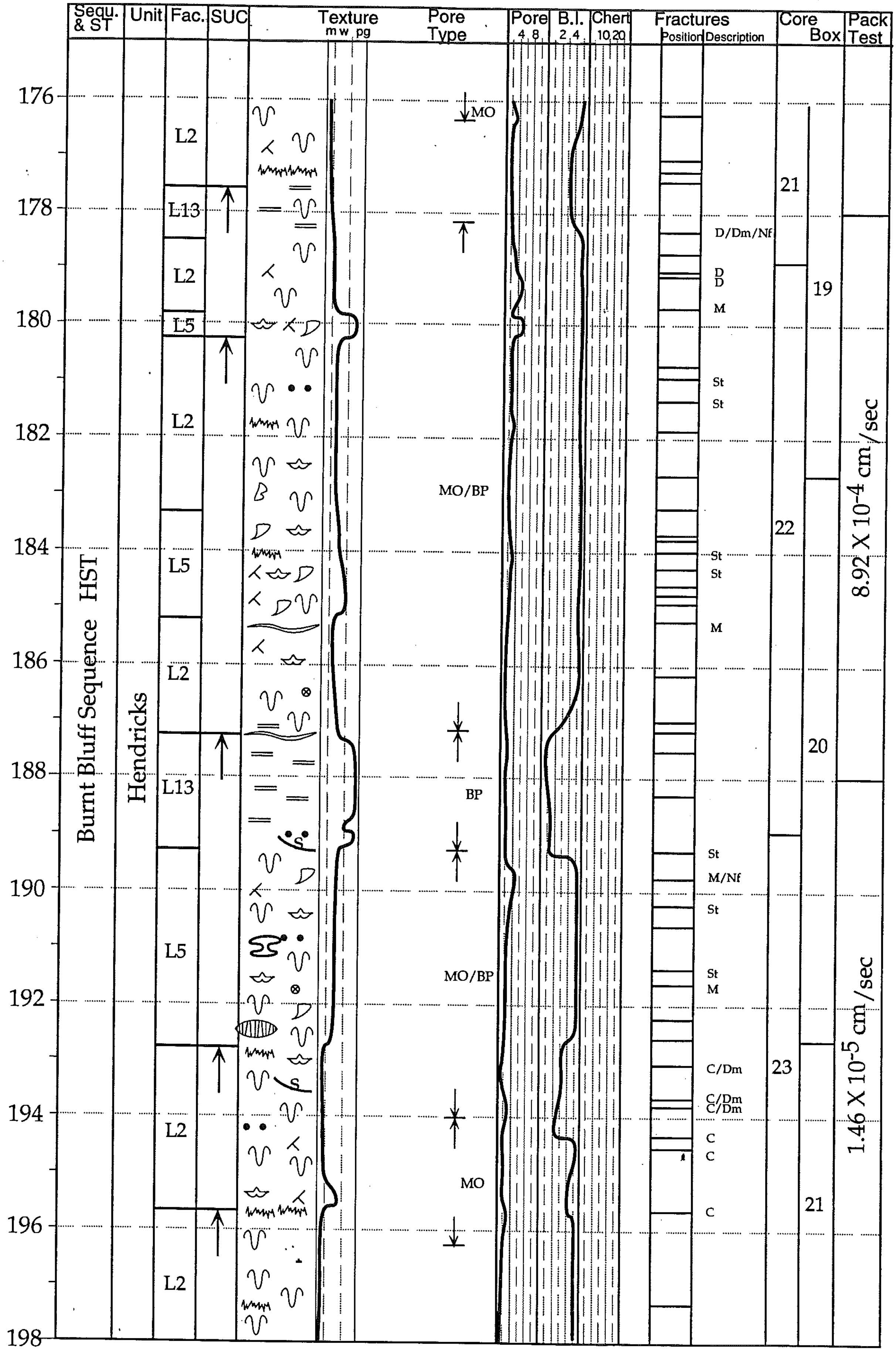

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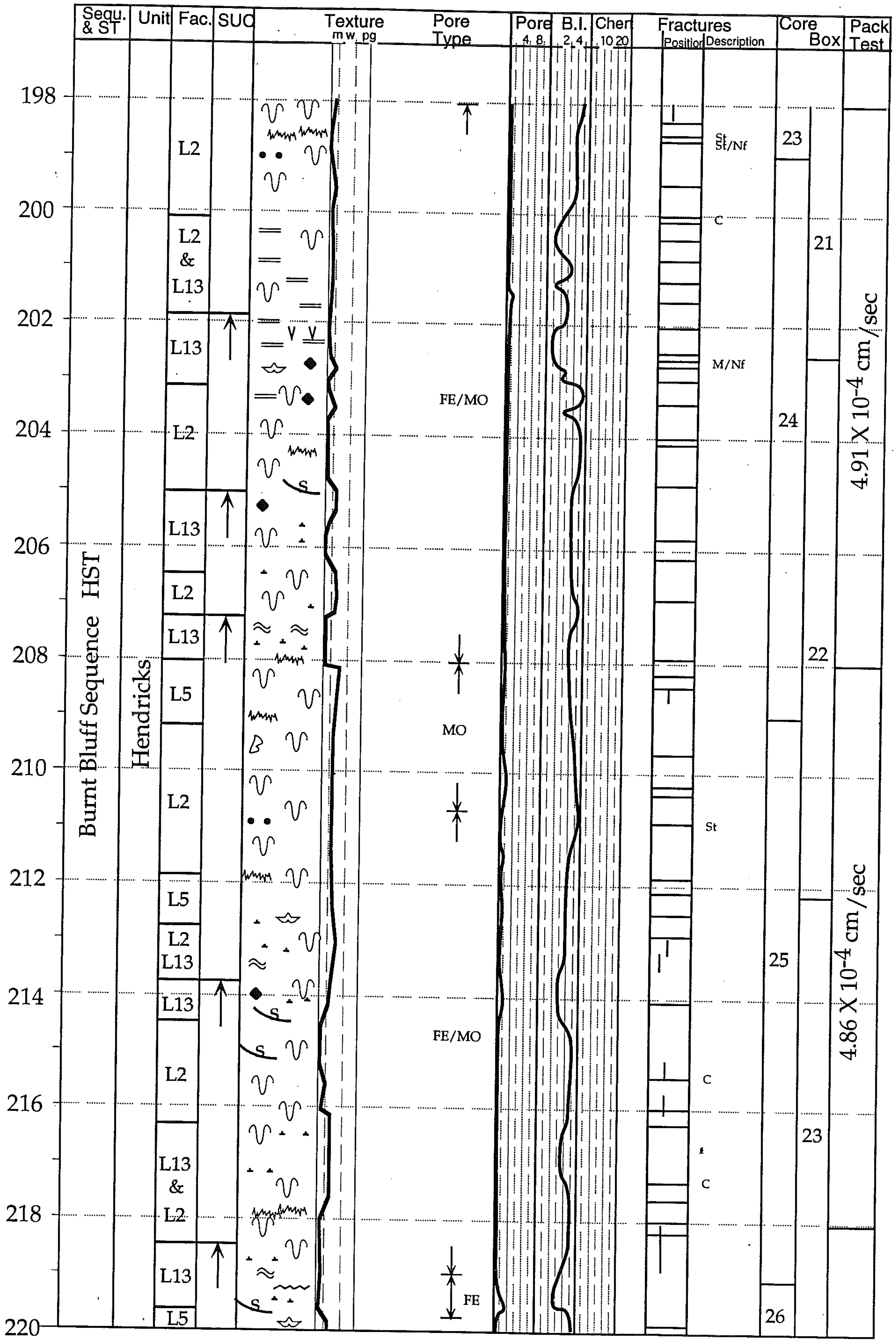

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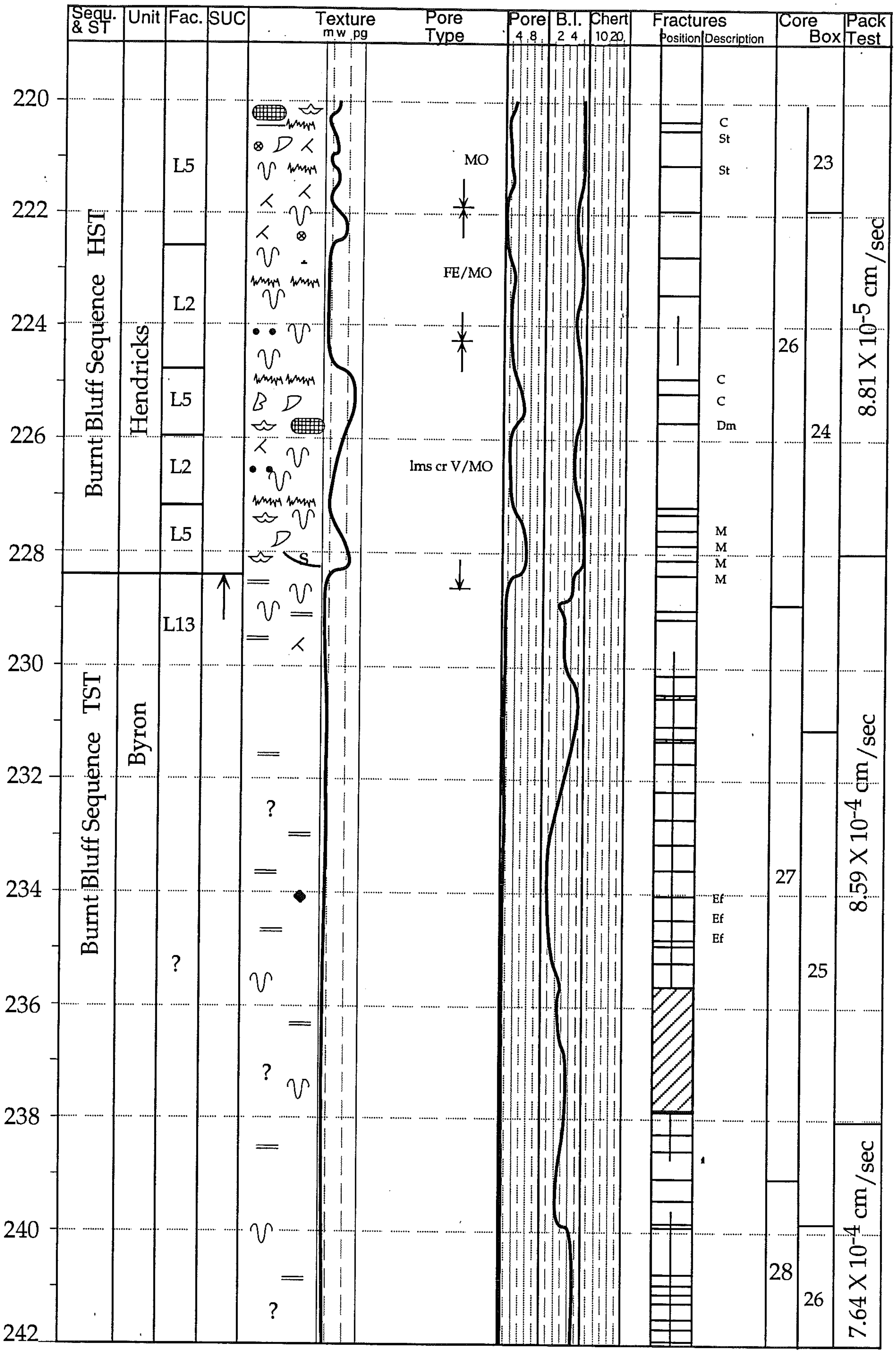

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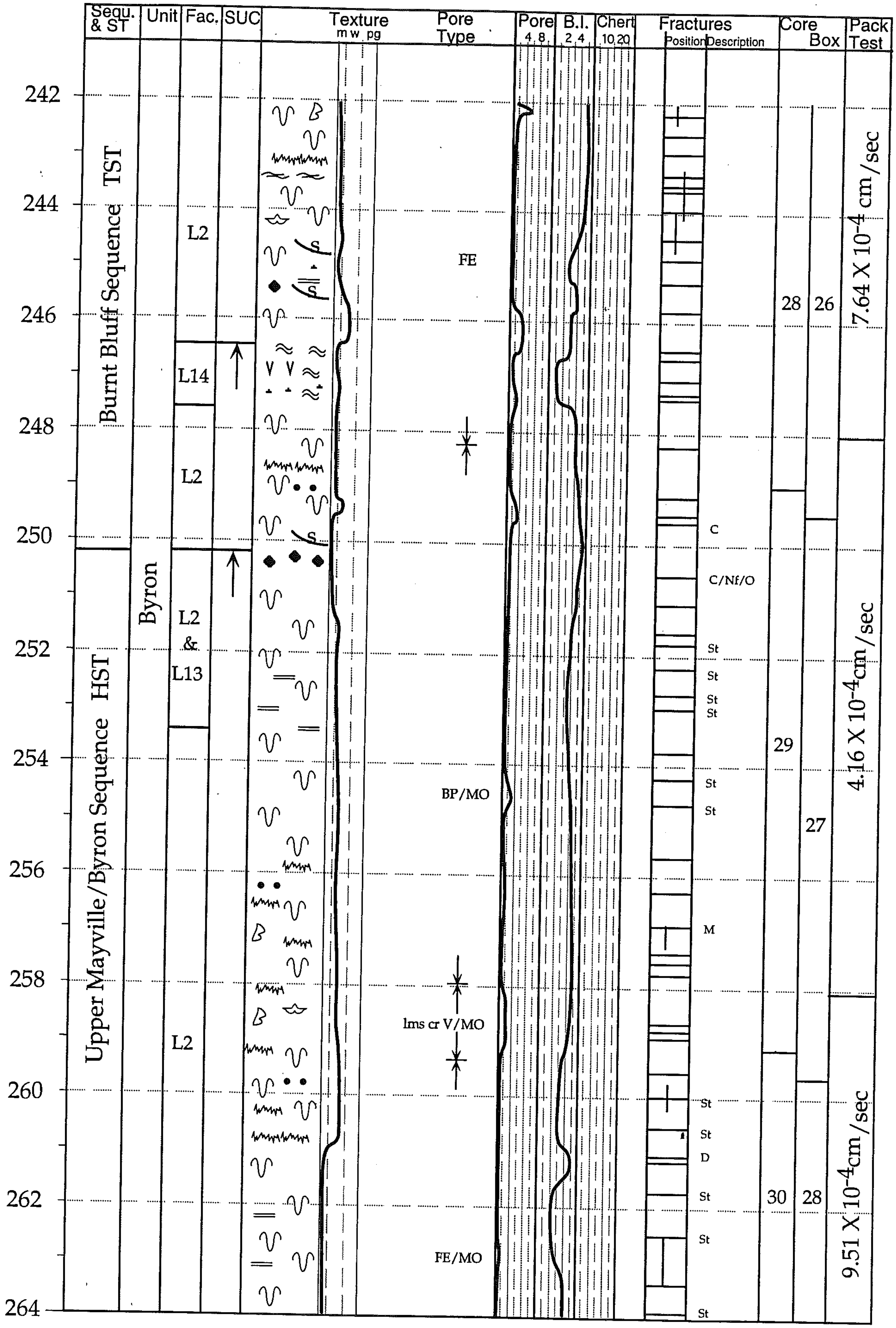

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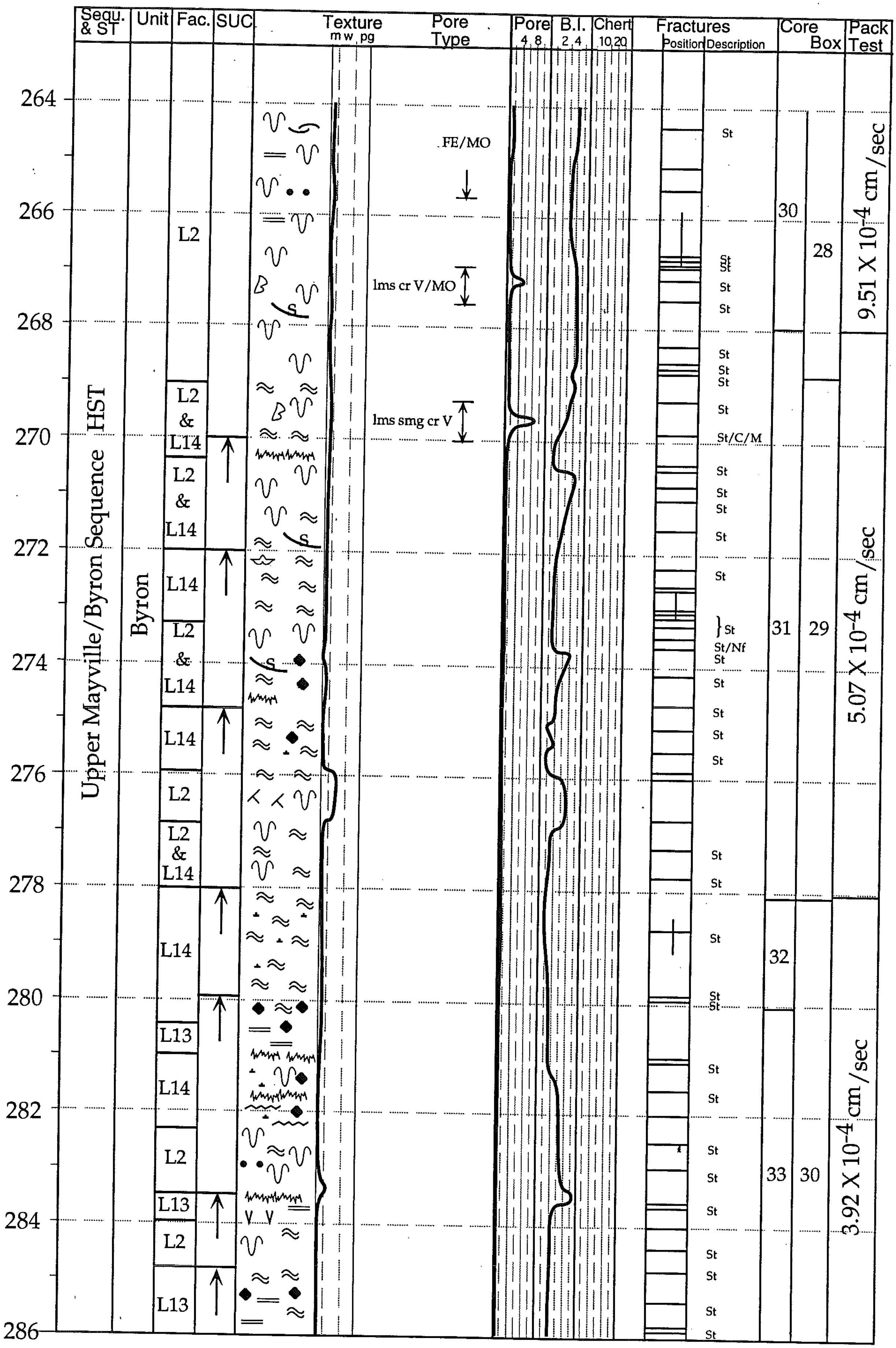

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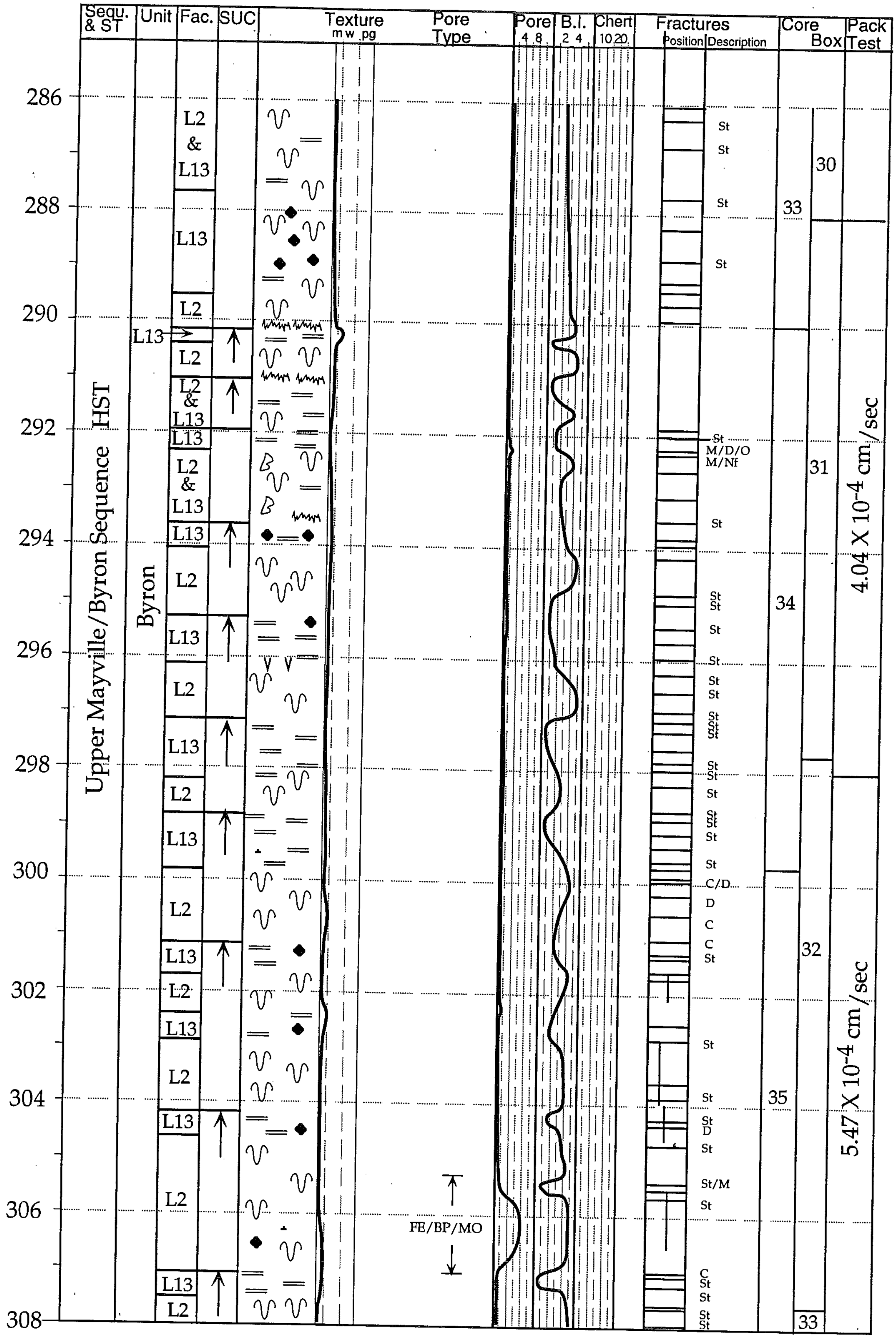

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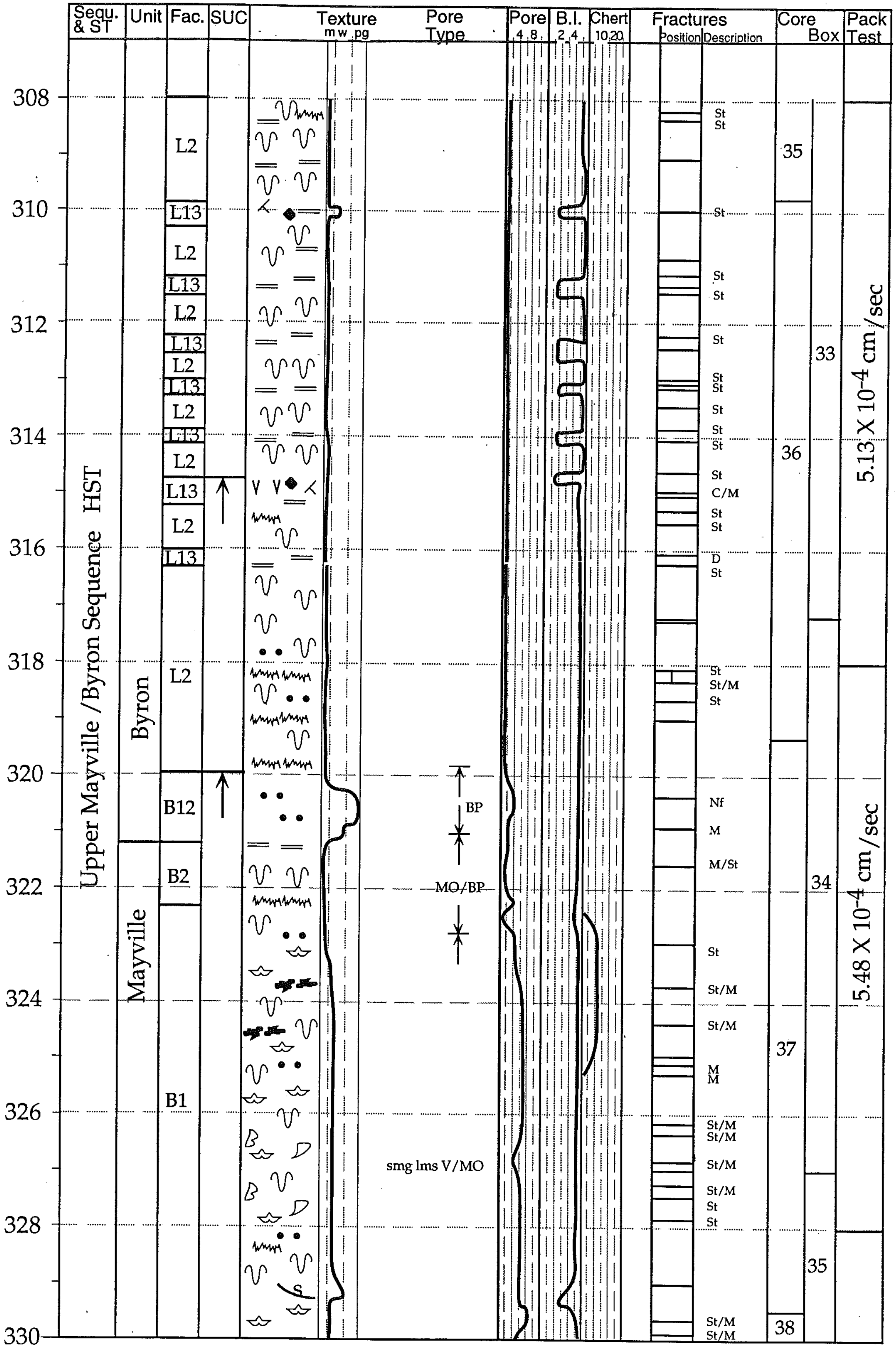

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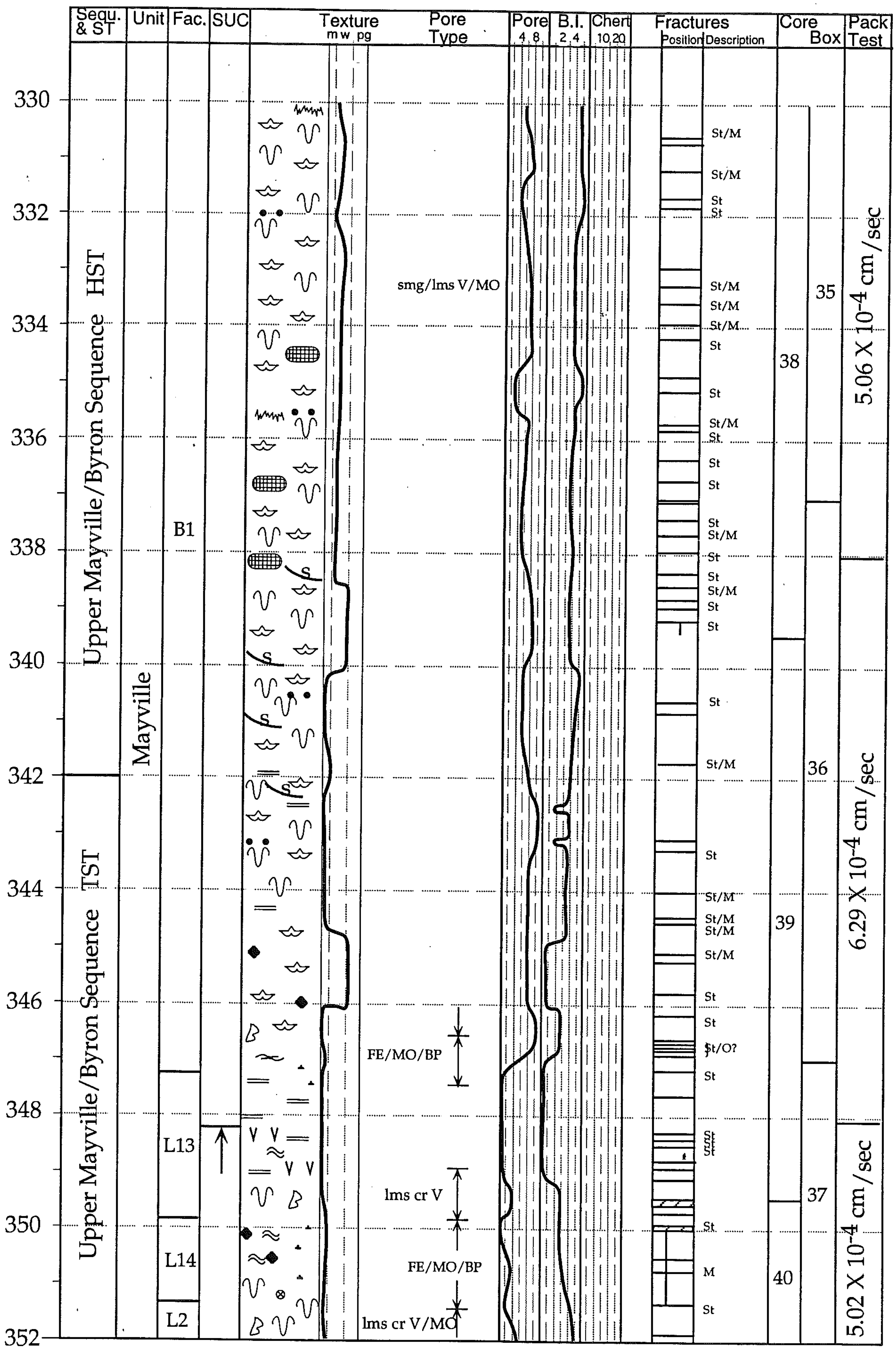

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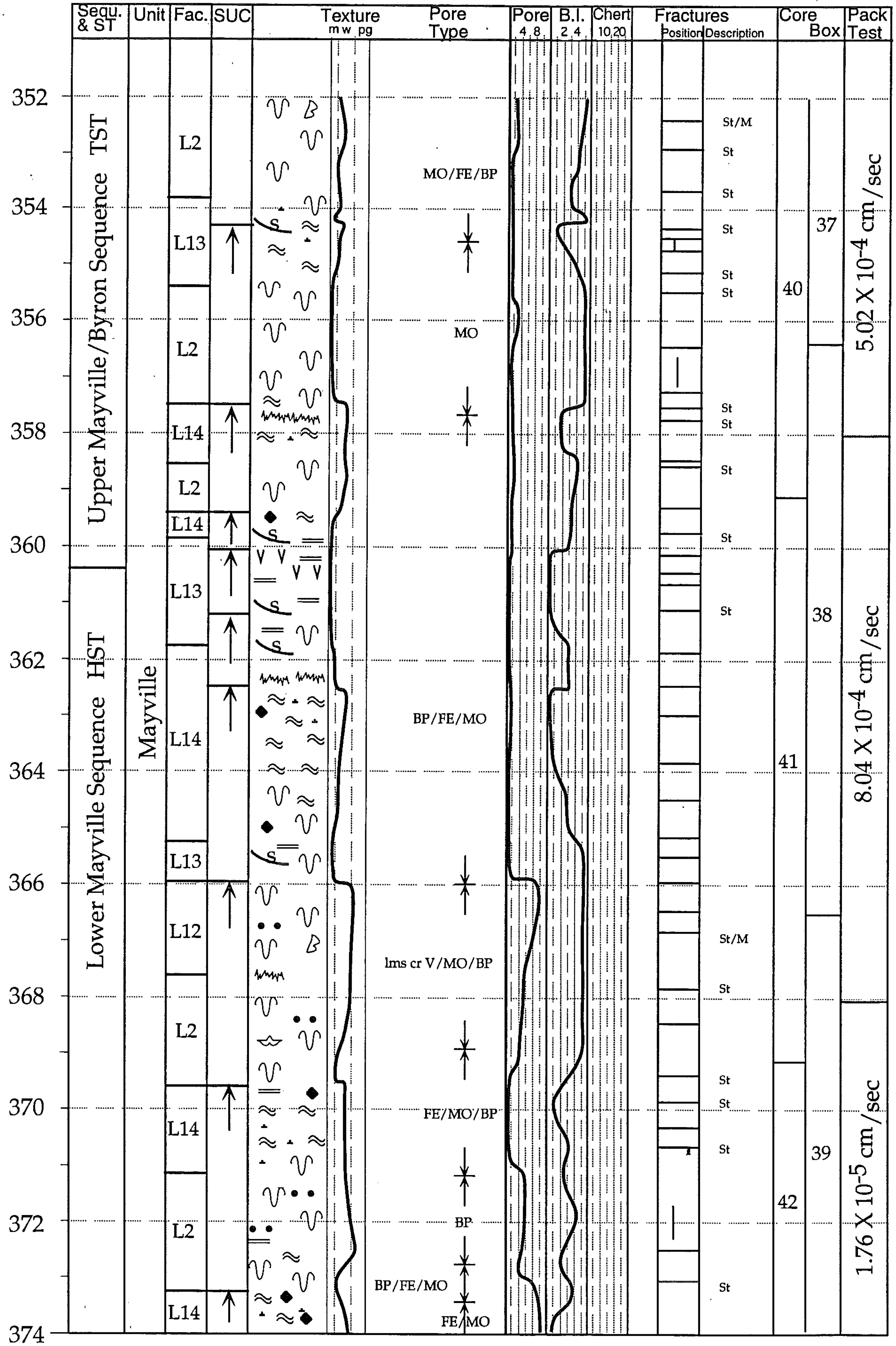

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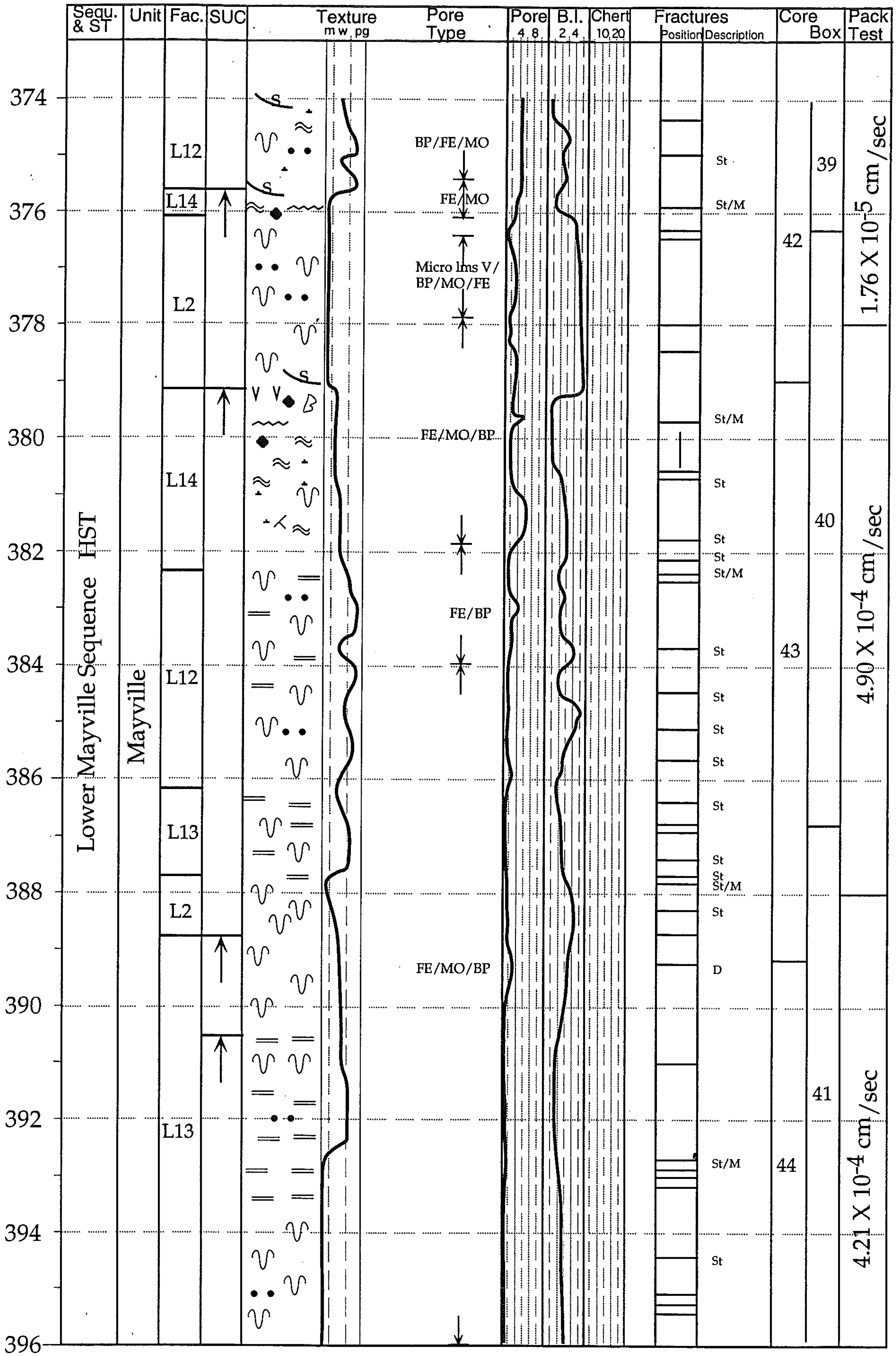

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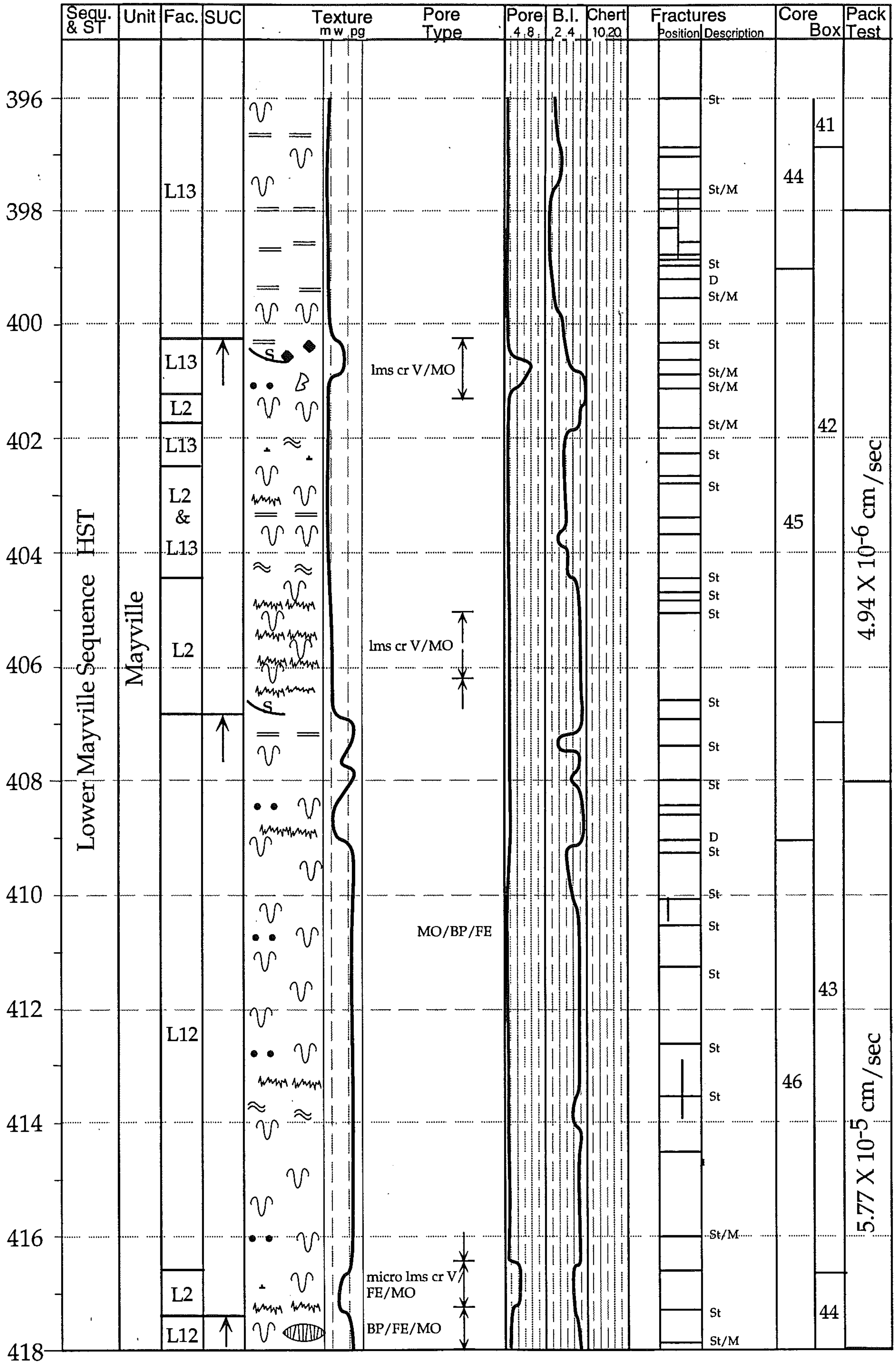

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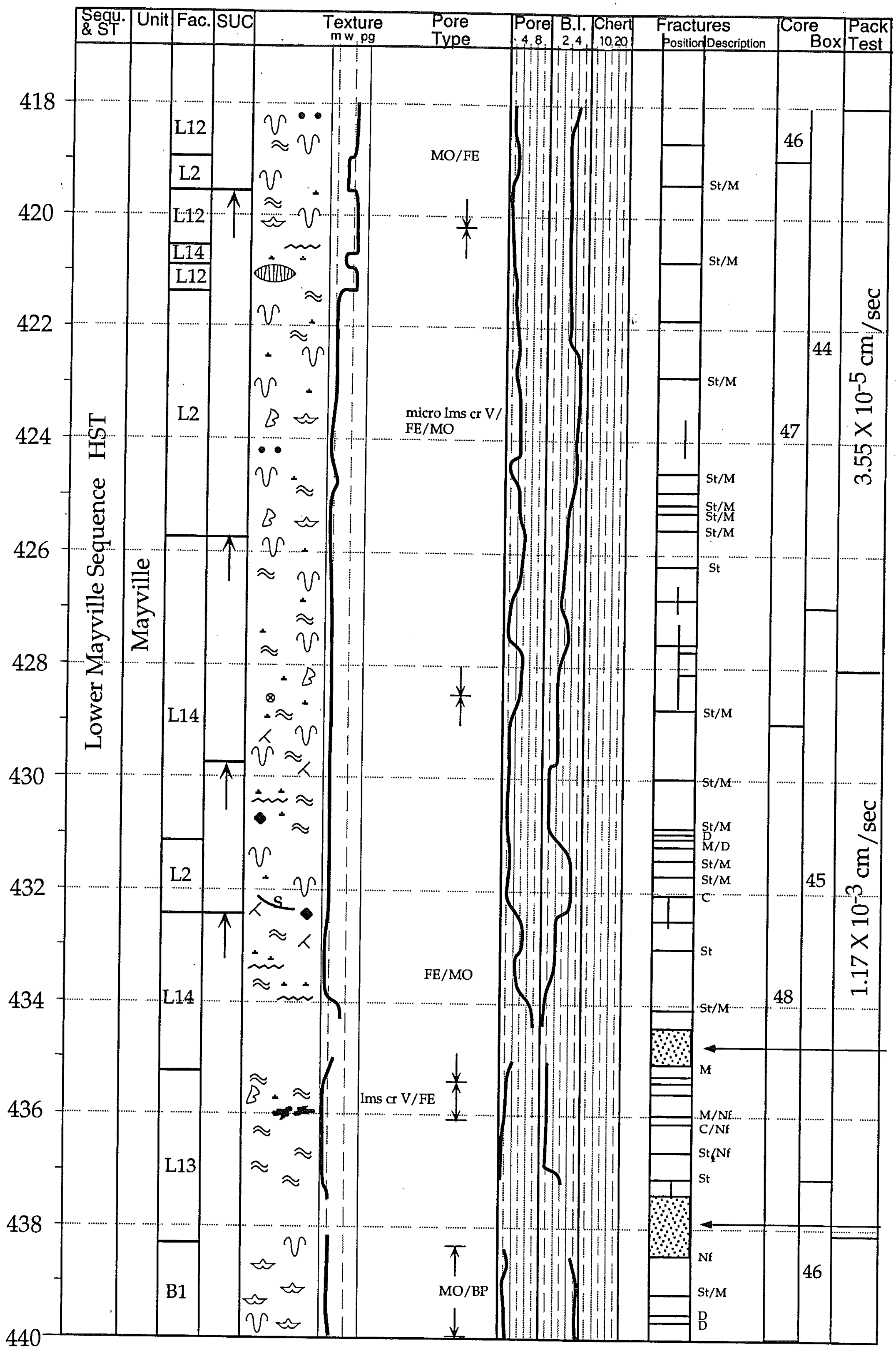

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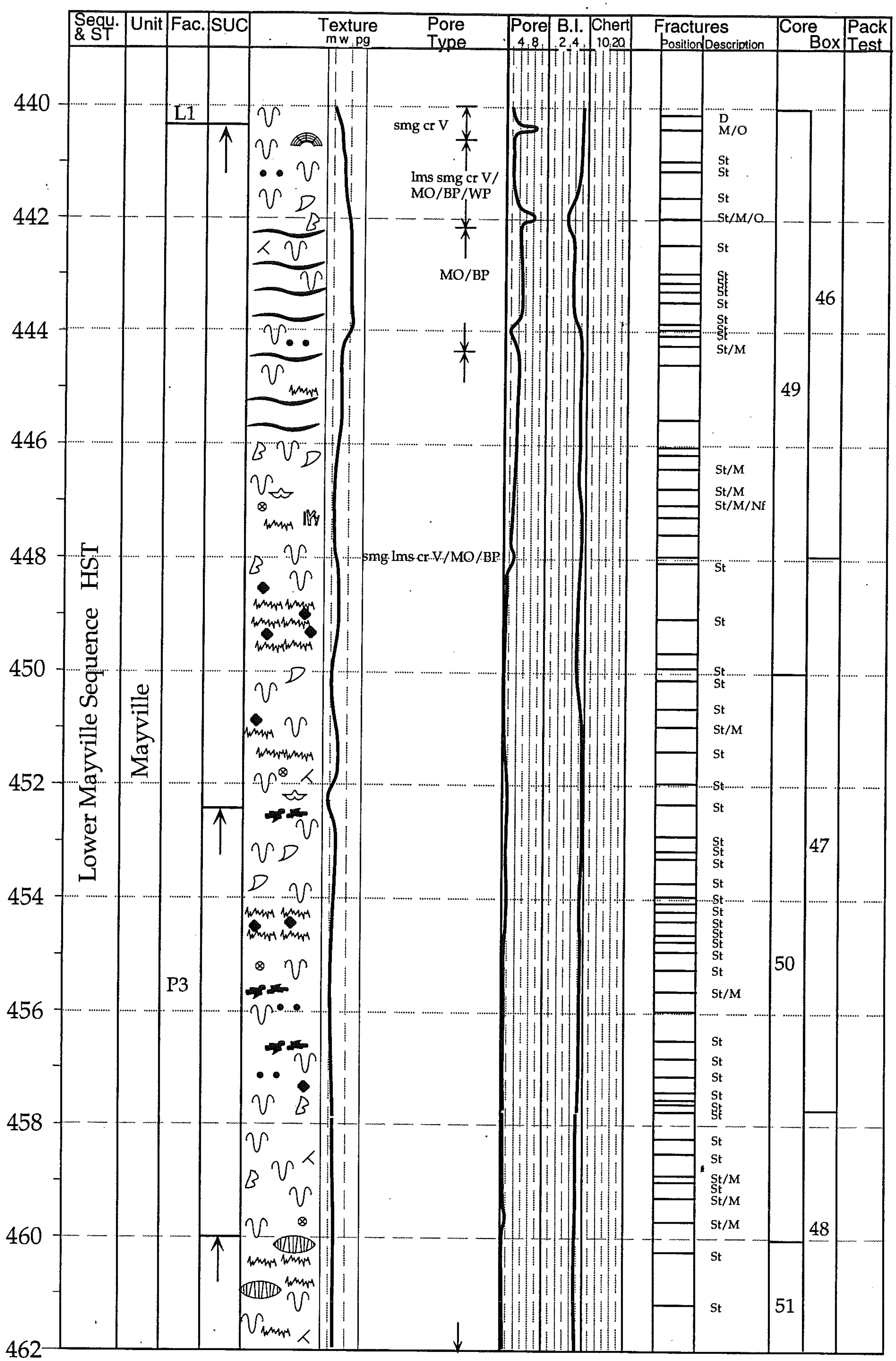

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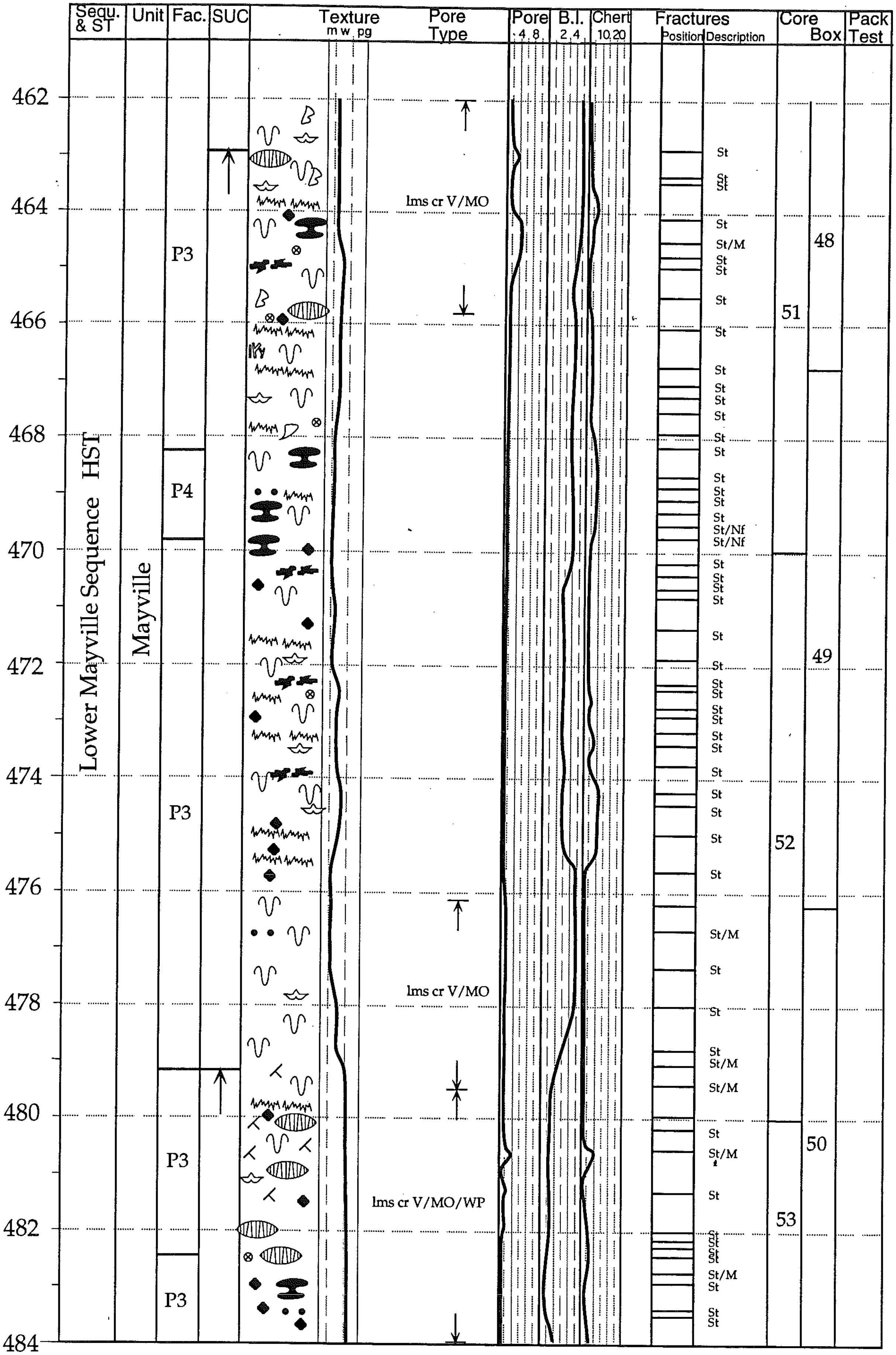

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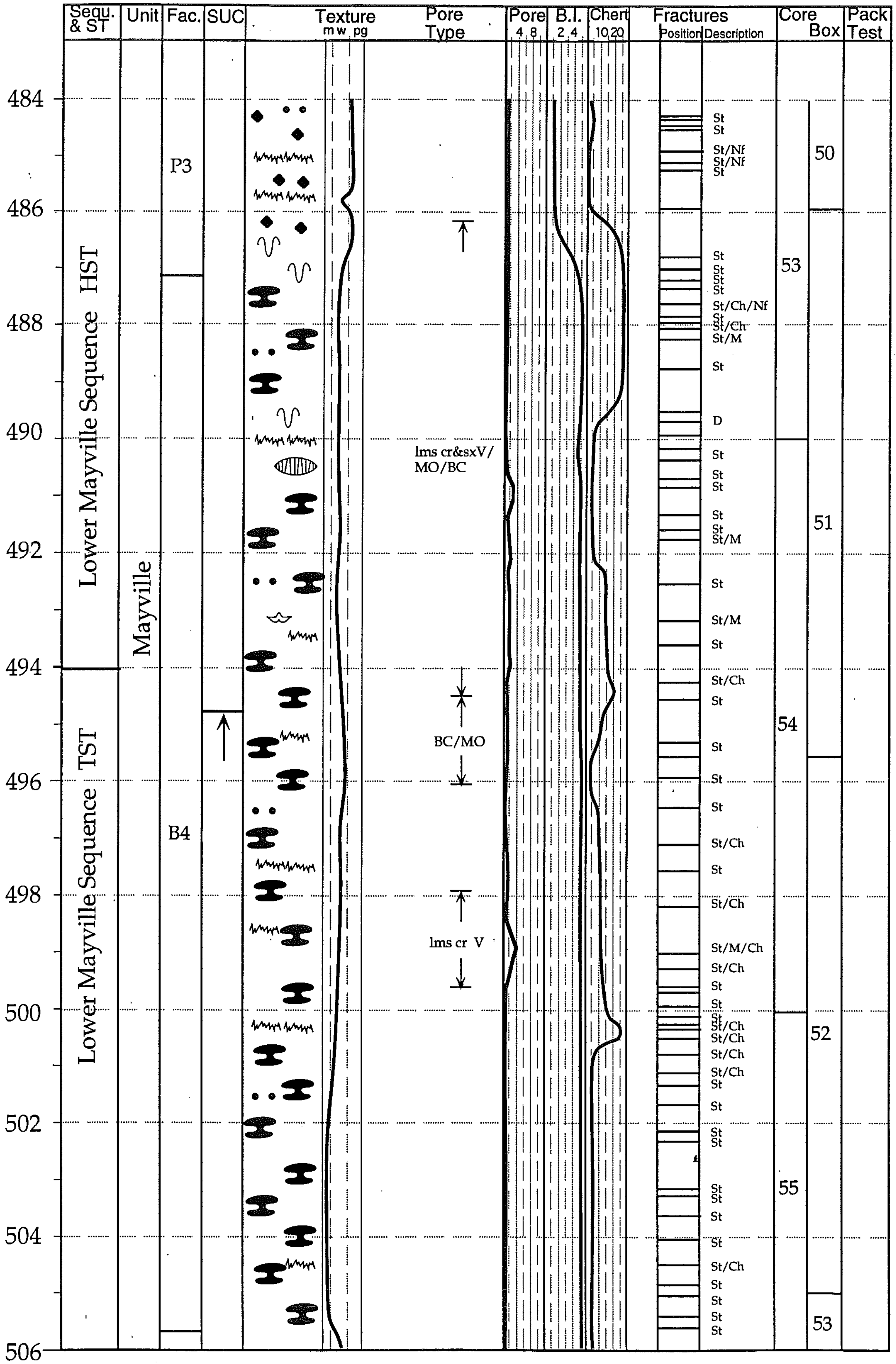

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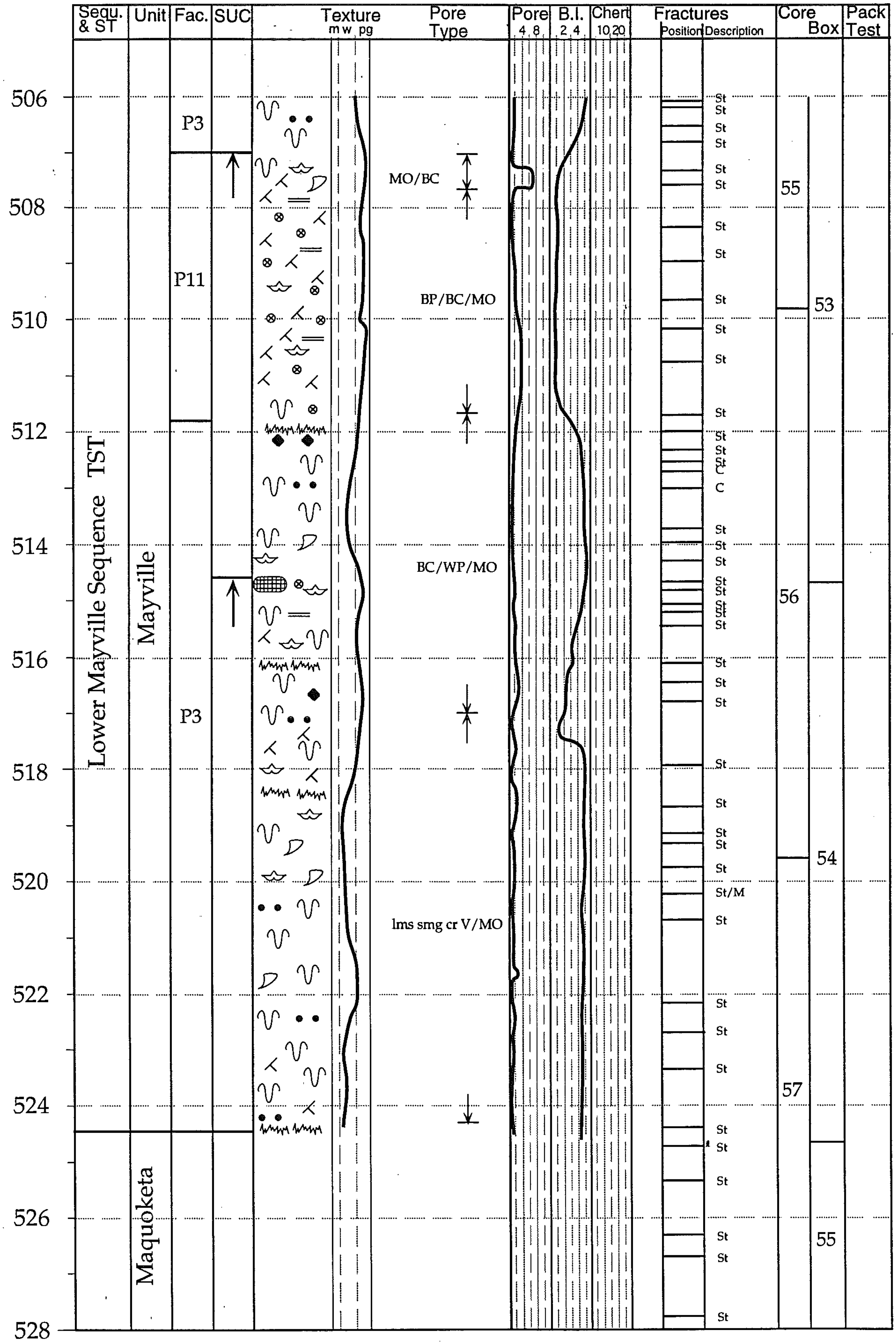

Figure 8 (cont.): Jarmen Road Core Description, p. 24

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PART II: FIELD STOPS

The following pages present the road log and stop descriptions for the field trip. The stops have been selected to illustrate our central argument that the distribution of hydraulic conductivity is tied to the sedimentologic framework. Therefore the stops include sedimentologic (depositional facies), stratigraphic (stratigraphic sequences) and hyrdrologic features (regional ground water flow horizons).

The location map (Figure 1), road log, and generalized stratigraphic column (Figure 2) will help keep you oriented as the trip proceeds.

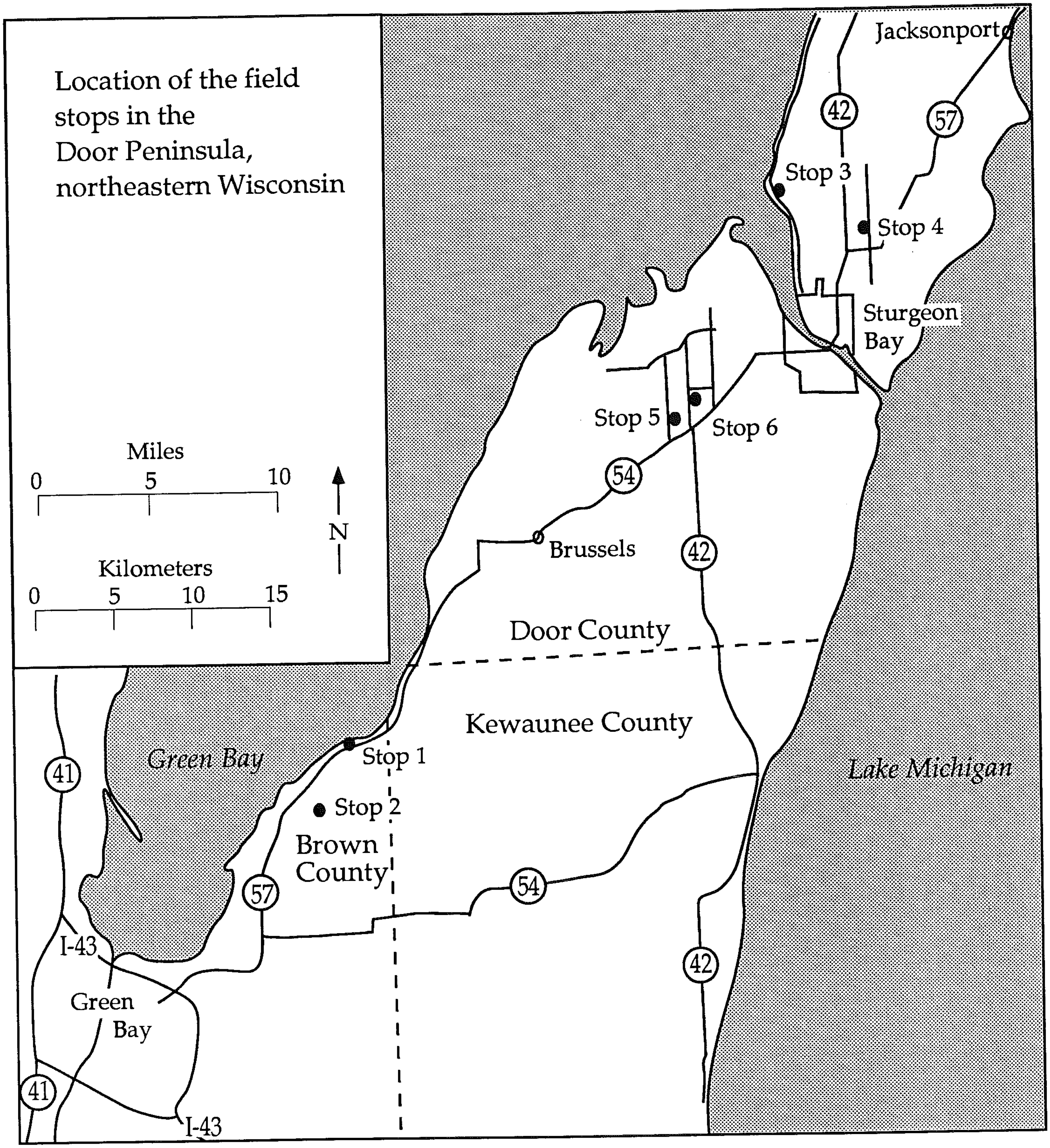


Figure 1: Location map for the field stops.

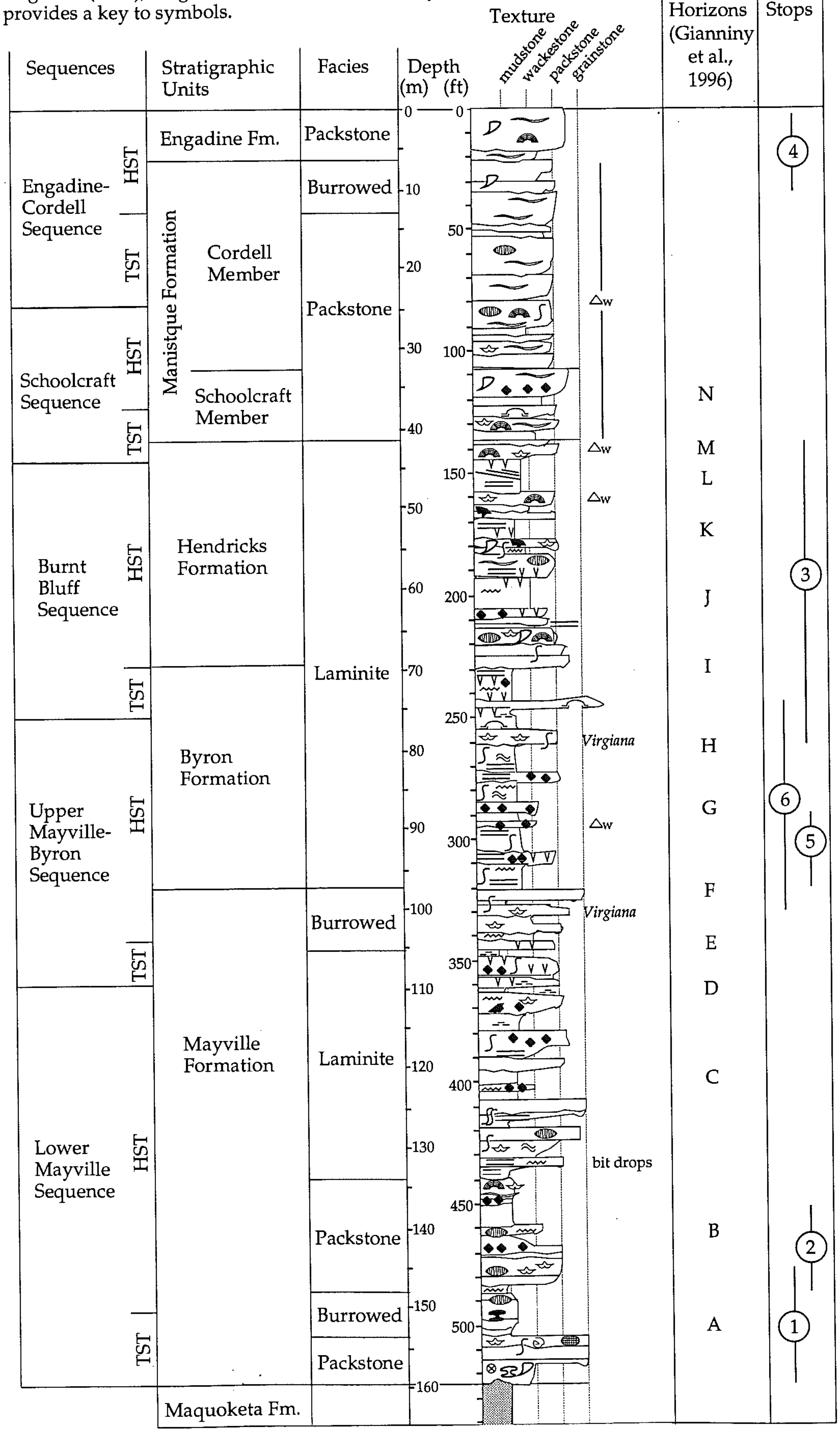
ROAD LOG

Road log begins at the intersection of Routes 54 and 57, approximately 5 miles northeast of the intersection of merged Routs 54/57 with Interstate 43 on the northeast side of Green Bay.

Mileage		Notes and directions
Total	Interval	
0.0	0.0	Proceed north on Route 57. Route 54 runs east to Luxemburg and Algoma.
2.1	2.1	Wequiock Falls (to left): Systemic boundary between the Maquoketa (Ordovician) Formation and Mayville (Silurian) Dolmite (Sivon, 1980; Allen (1980; Stieglitz, McCartney and Allen, 1980; Mikulic and Kluessendorf, 1983).
3.0	0.9	The escarpment on the Green Bay side of the peninsula is well expressed. Here resistant Mayville makes the escarpement with soft Makoqueta along the shoreline. The escarpment shifts upsection as we travel north so that near Sturgeon Bay the overlying Burnt Bluff Group is the dominant cliff-forming unit.
5.3	2.3	Red Bank Historical Marker (left) commemorating the nearby meeting between Jean Nicolet and the Winnebago Indians in 1634.
8.4	3.1	Turn left into Bay Shore County Park
8.5	0.1	Turn right into the parking lot.
8.55	0.05	Park and disembark for STOP 1.
8.6	0.05	Turn left out of parking lot.
8.7	0.1	Turn right onto Route 57 (south).
13.4	4.7	Turn left (east) on unnamed road.
13.7	0.3	Park at quarry entrance. STOP 2. Turn around and return to Route 57.
14.0	0.3	Turn right (north) on Route 57.
18.7	4.7	Turnoff for Bay Shore County Park. Continue on Route 57.
21.1	2.4	Junction with County Route S in Dyckesville. Continue on Route 57.
23.9	2.8	Door County Line. Door County is known for both its agricultural products (especially cherries) and its senic beauty. Tourists and retirees have been steadily increasing over several decades leading to increased demand on water supplies and increased concerns on water quality.
29.5	5.6	Namur: Historical Marker commemorating Belgian settlement in Wisconsin in the 1850s. This area is the largest Belgian-American community in the country and the heritage is reflected in the place names.
31.8	2.3	Junction with County Route C in Brussels. Continue on Route 57.
33.2	1.4	Start up Brussels Hill. This hill has numerous karst features including caves (Howe 1987a, 1987b).
36.5	3.3	Wayside (left) with marker commemorating the fires that raged throughout the area on October 8, 1871, killing an estimated 2500 people. After an extremely dry summer, tornado-like fires swept north along both sides of Green Bay burning 1.3 million acres (Moran and Stiegltiz, 1983). Pestigo (north side of the bay) was the largest town destroyed. The community of Williamsonville was located at this site - only 17 people survived of its 77 inhabitants.
40.0	3.5	Junction with Route 42. Continue north on Route 42/57
45.1	5.1	Exit for Business 42/57 to Sturgeon Bay. Continue straight (north).
47.3	2.2	Crest of bridge over Sturgeon Bay. The canal to the east (right) was completed in the 1890s, eliminated the need for the dangerous voyage around the north end of the peninsula through the straight named "Porte des Morts" (Death's

		Door). The City of Sturgeon Bay is known for its long history of ship building. A couple companies are still active in this business.
48.7	1.4	Outcrop of Engadine Dolomite (left).
51.1	2.4	Go straight on Route 42. Route 57 turns right at intersection, toward Jacksonport.
51.8	0.7	State Experimental Station (right) works on growing cherries and potatoes.
52.7	0.9	Turn left on Dunn Road (at intersection with County Route P).
53.7	1.0	Road turns left. This is Big Creek Valley a dry valley with numerous sinkholes.
53.9	0.2	Road turns right, passing through the Cherry Hills Golf Course.
54.4	0.5	Stop sign at Walker Road. Continue straight on Dunn Road.
54.6	0.2	Former cherry processing plant (right). Cherry orchards were sprayed with lead-arsnic compounds. The old mixing sites are significant point sources for ground water contamination.
54.7	0.1	Cross Martin Road and continue straight on Dunn Road.
55.3	0.6	Turn right on County Route B (Bay Shore Drive). Small abandoned quarries to the right are in the Burnt Bluff Group.
56.9	1.6	Turn left into parking at the second drive into the small park by Sturgeon Bay. STOP 3 is the quarry across the road. After stop, exit parking area and turn right on County Route B (toward the City of Sturgeon Bay).
60.6	3.7	Turn left on County Route BB.
61.1	0.5	Stop sign at juction with County Route HH. Go straight on BB.
62.5	1.4	Turn left on Route 42/57.
63.3	0.8	Turn right on Route 57 toward Jacksonport.
64.4	1.1	Turn left on Mathey Road.
65.3	0.9	Turn left into Mathey Road Quarry. Park at entrance. STOP 4. After stop, Exit quarry and turn right on Mathey Road.
66.2	0.9	Turn right on Route 57.
67.1	0.9	Stop sign at juction with Route 42. Turn left on Route 42/57.
78.3	11.2	Go straight on Route 57. Route 42 turns left at intersection toward Algoma.
79.4	1.1	Turn right on Stone Road.
80.9	1.5	Turn right at entrance with Kisser Quarry
81.1	0.2	Drive to the upper level of the quarry and park. STOP 5. After stop, exit quarry by same road.
81.3	0.2	Turn right on Stone Road
83.0	1.7	Stop sign with County Route C. Turn right on C.
84.1	1.1	Turn right on County Route MM.
86.3	2.2	Turn left into Bissen Quarry.
86.45	0.15	Park in quarry. STOP 6 is at the collection of pipes in the northwest part of the quarry. Exit quarry by same road.
86.6	0.15	Turn left on County Route MM.
87.8	1.2	Turn right on Route 57.
117.3	29.5	Intersection with Route 54. Continue on Route 57 to return to Green Bay.

Figure 2: Stratigraphic summary of the Jarmen Road core (Gianniny et al., 1996; Harris, Hegrenes and Muldoon, this volume). Core description by Hegrenes (1996), diagram modified from Gianniny et al. (1996). Figure 3 provides a key to symbols.



FIELD STOP DESCRIPTIONS

The field stop descriptions include notes on the stratigraphy, sedimentology, paleontology and hydrogeology of the exposed sections. Stop 6 also includes a discussion of subsurface hydrogeology.

The measured stratigraphic columns provided for stops 1-4 are modified from Harris and Waldhuetter (1996). The sections for stops 5 and 6 are by Toni Simo (University of Wisconsin-Madison). The sections from Harris and Waldhuetter are presented in a standard graphical format that contains the following items (from left to right)

- Sequence and Systems Tract
- Stratigraphic Unit
- Facies and Subfacies keyed as follows:
  - Number represents Subfacies
    - 1 = Brachiopod Wackestone-Packstone
    - 2 = *Thalassinoides* Mudstone-Wackestone
    - 3 = Laminar Stromatoporoid-Coral Floatstone
    - 4 = Domal Stromatoporoid-Coral Floatstone
    - 5 = Rippled Coral Packstone
    - 6 = Pellet Packstone-Wackestone
    - 7 = Coral Floatstone
    - 8 = Coral-Stromatoporoid Boundstone
    - 9 = Pellet-Ostracode Wackestone
    - 10 = Bioturbated Mudstone-Wackestone
    - 11 = Interbedded Mudstone and Intraclastic Jelly-Roll Wackestone
    - 12 = Laminated Mudstone
    - 13 = Crinkly Laminated Mudcracked Mudstone
  - Letter represents Facies
    - B = Burrowed Facies
    - L = Laminite Facies
    - R = Rippled Facies
- Shallow Upward Cycles (tops marked in column)
- Graphic Column
  - Width represents Dunham (1962) texture
  - Symbols represent sedimentological features (Fig. 3)
- Flow horizons (Gianniny et al., 1996)
- Pore Type (Choquette and Pray, 1970)
- Pore abundance expressed as a percentage
- Ichnofabric Index (Droser and Bottjer, 1986)
- Chert abundance expressed as a percentage (not including silicified fauna)
- Notes

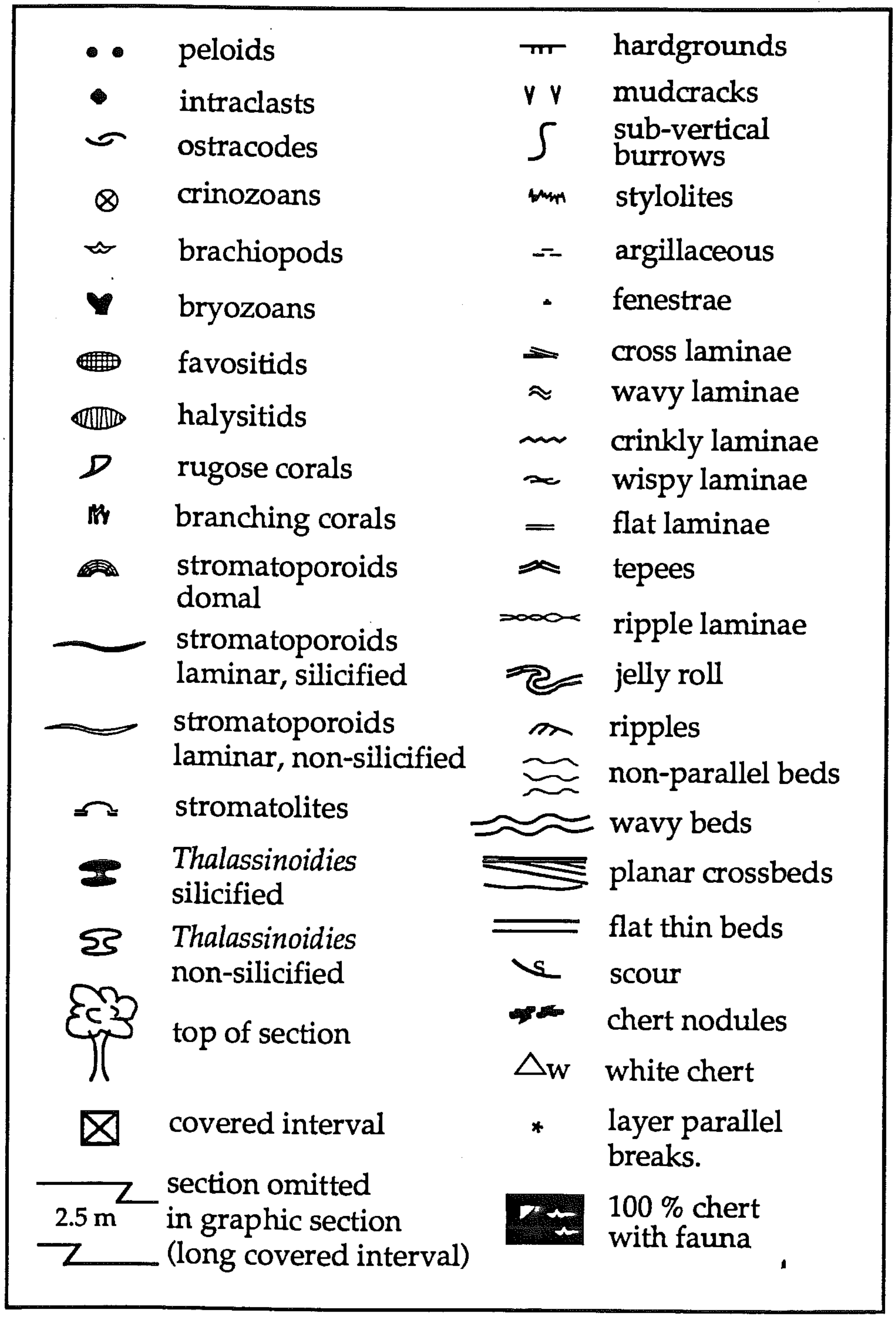


Figure 3: Symbols used in stratigraphic sections for stops 1-4.

STOP 1: BAYSHORE COUNTY PARK, STATE HIGHWAY 57, BROWN COUNTY

The road to the boat ramp in Bayshore County Park provides the best outcrop exposure of the lower Mayville Dolomite in the Door Peninsula. At times, the contact with the underlying Maquoketa Formation (Ordovician) is also exposed although usually it is covered by slumped Mayville blocks.

There are three main points of interest at this stop. First, the sedimentological contrasts between the Rippled and Burrowed Facies of the Mayville are well displayed, reflecting deposition above and below fairweather wave base. Second, the relative depth changes recorded in the facies are used to define the Transgresive Systems Tract (TST) and Highstand Systems Tract (HST) of the Lower Mayville Sequence. Finally, this section includes the stratigraphic position of the lowest Mayville flow zone recognized in wells in the Sturgeon Bay area (Gianniny et al., 1996).

The lower 14 meters of the Mayville Dolomite is exposed here and can be divided into a three-part succession (Figure 4). The lower 2 meters are Rippled Facies (peloidal wackestone-packstone). The overlying 10.5 meters consist of Burrowed Facies with large burrows assigned to *Thalassinoides*. The central part of this facies is marked by abundant chert replacements of burrows. The upper part of the outcrop is Rippled Facies, as illustrated by the spectacularly weathered south wall of the roadcut. Thin cycles of alternating burrowed and rippled subfacies pass upward into two meters of rippled packstone.

This section is the TST and lower HST of the Lower Mayville Sequence. The maximum deepening is in the middle of the Burrowed Facies at about 4-6 m. Core data (Harris and Hegrenes, this volume) and a few quarry exposures (Harris and Waldhuetter, 1996) indicate the remainder of the HST consists of Burrowed and Rippled Facies with a thin Laminite Facies cap.

The lowest Mayville flow zone (Zone A of Gianniny et al., 1996) appears to straddles the boundary between the lower interval of the Rippled Facies and the Burrowed Facies. Porosity up to 4% occurs in this interval, compared to about 1% above and below (Waldhuetter, 1996). Zone B of Gianniny et al. (1996) is just above the section in a similar position (at the transition from Rippled Facies upward into Burrowed Facies). Both flow zones occur at contacts between contrasting lithologies where a bedding plane fracture develops.

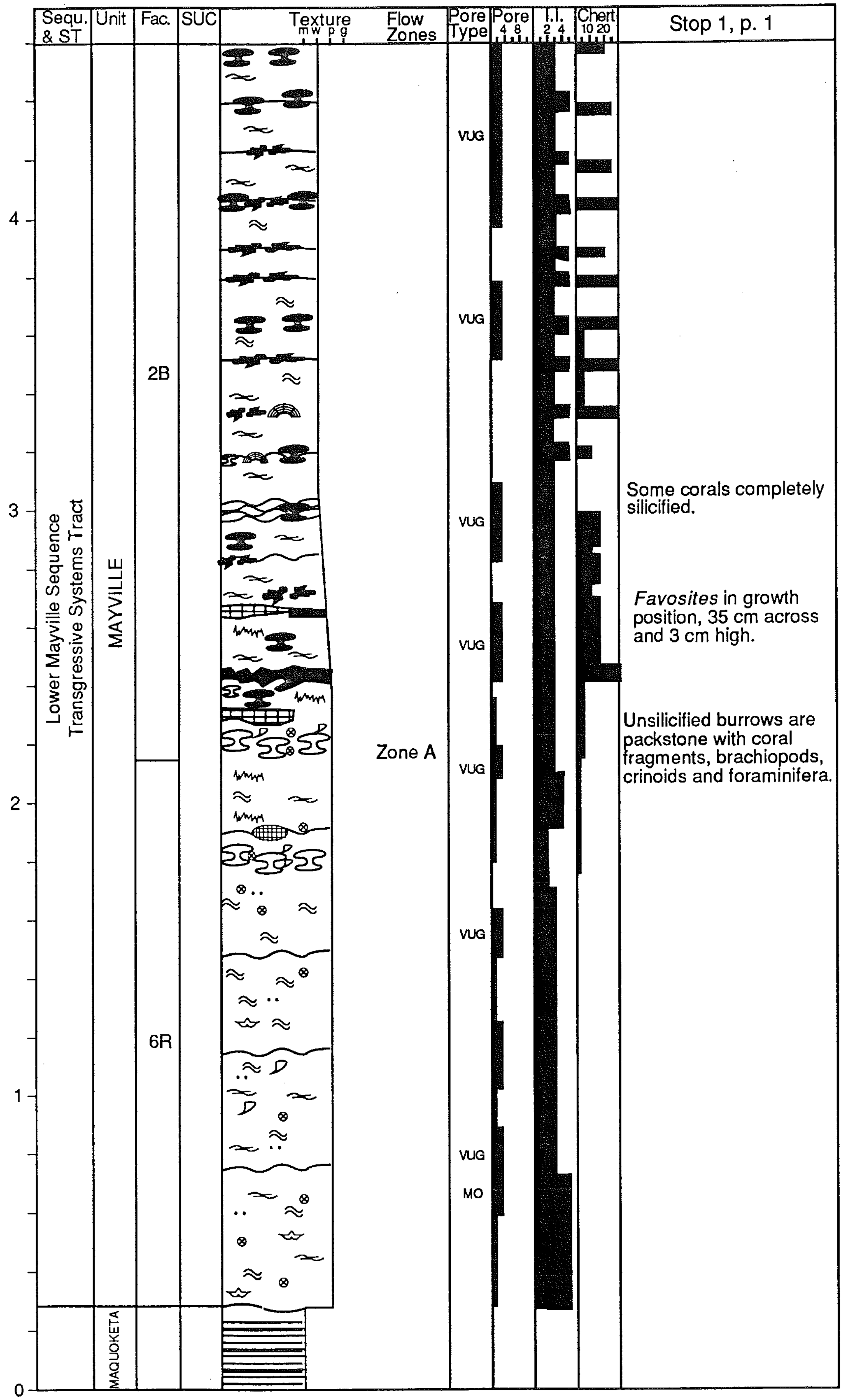


Figure 4: Stratigraphic section for Bayshore County Park boat ramp, stop 1, page 1.

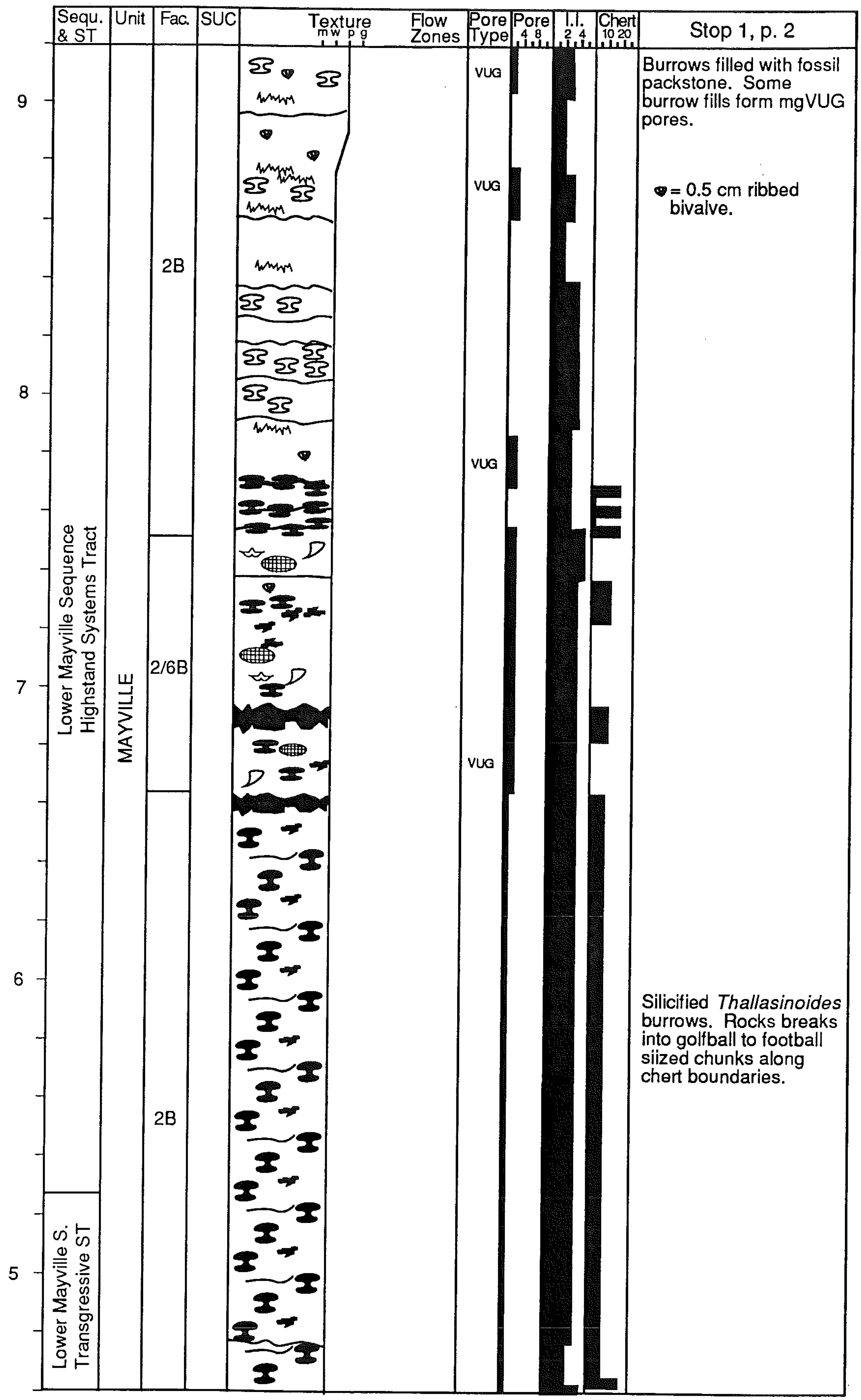


Figure 4 (cont.): Stratigraphic section for Bayshore County Park boat ramp, stop 1, page 2.

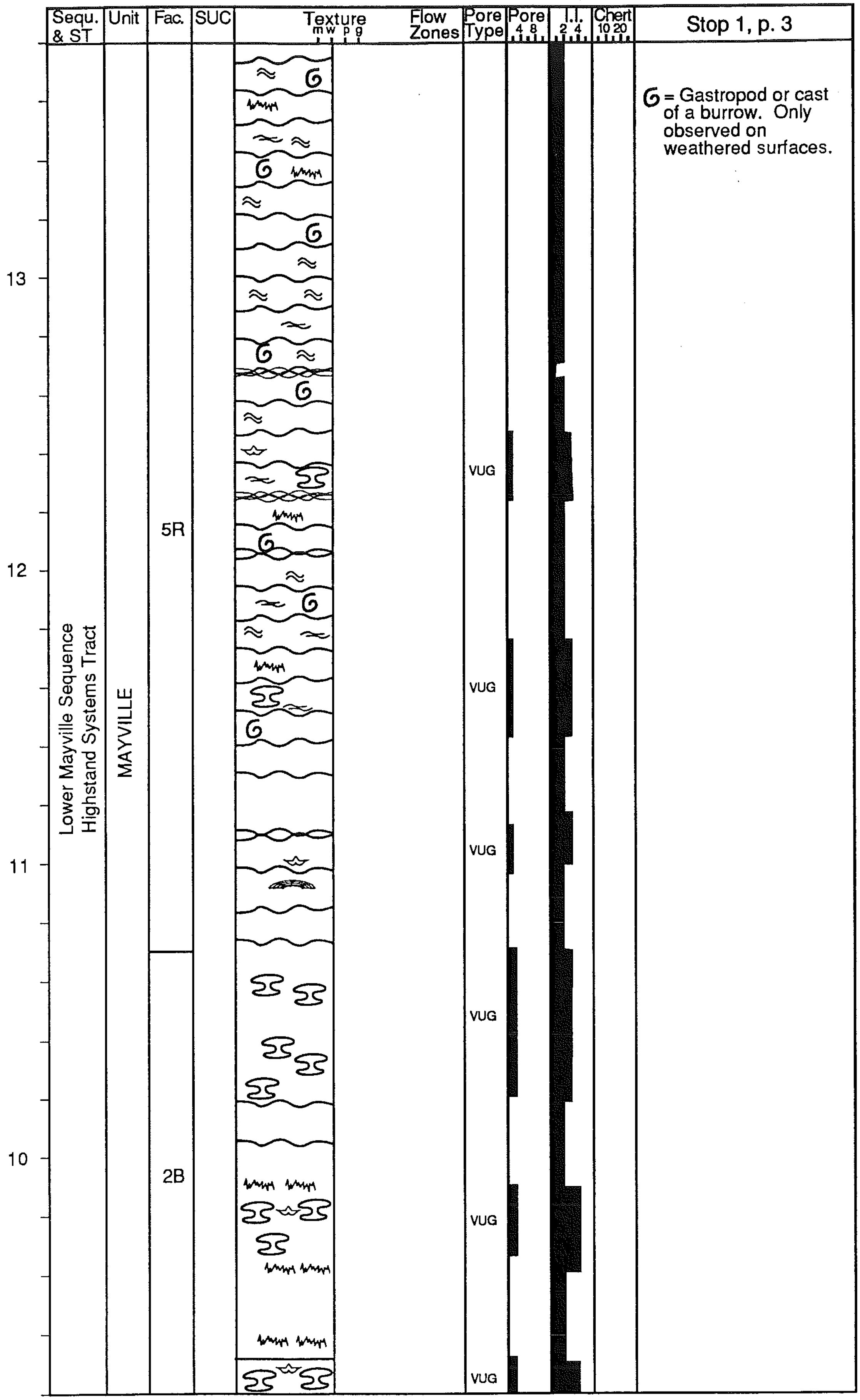


Figure 4 (cont.): Stratigraphic section for Bayshore County Park boat ramp, stop 1, page 3.

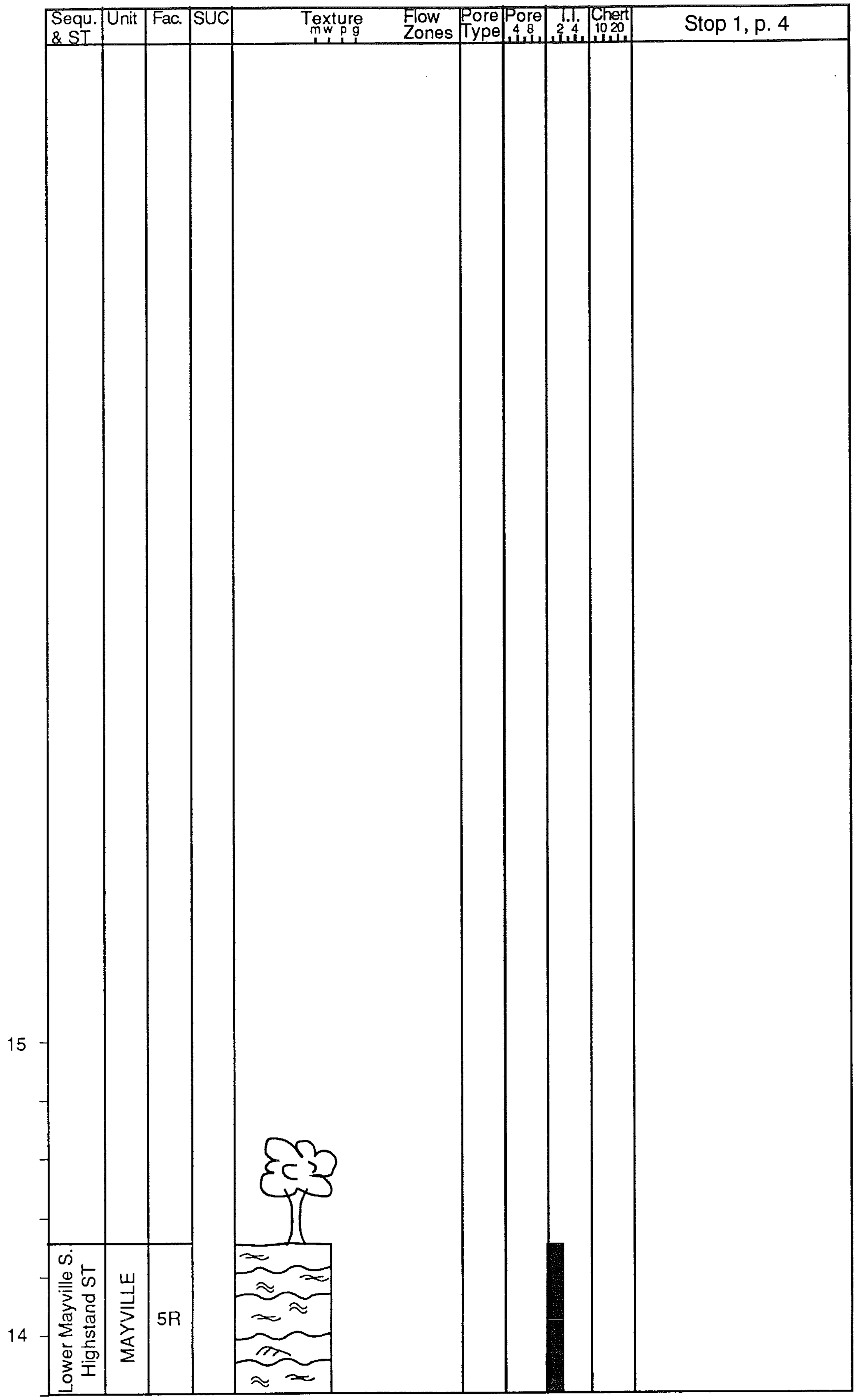


Figure 4 (cont.): Stratigraphic section for Bayshore County Park boat ramp, stop 1, page 4.

STOP 2: WEQUIOCK CHURCH QUARRY, EAST OF STATE HIGHWAY 57, BROWN COUNTY

The walls of the "Wequiock Church" Quarry exposes a partial section of the Mayville Dolomite. The section consists of packstones and wackestones of the Packstone Facies and is marked by ripples, wavy bedding planes, and scattered corals. Probable *Thalassinoides* burrows at the base of the section are replaced by chert. We interpret this section as equivalent to the Packstone Facies interval in the HST of the Lower Mayville Sequence in the core (Harris et al., this volume).

Hydrologically, the most notable feature is the prominent seepage horizon located about two-thirds of the way up the wall. This may be flow zone B of Gianniny et al., (1996).

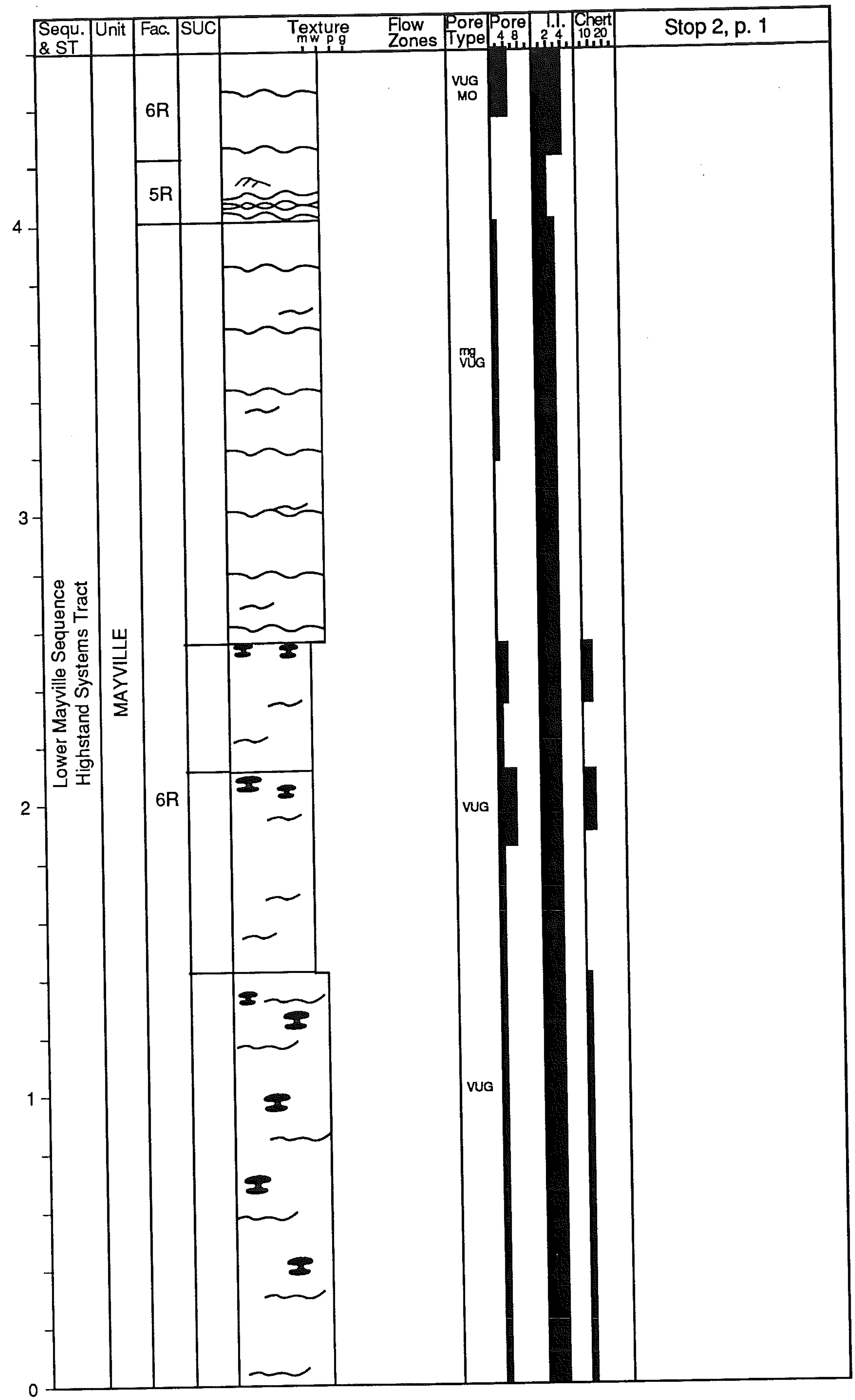


Figure 5: Stratigraphic section for the Wequiock Church Quarry, stop 2, page 1.

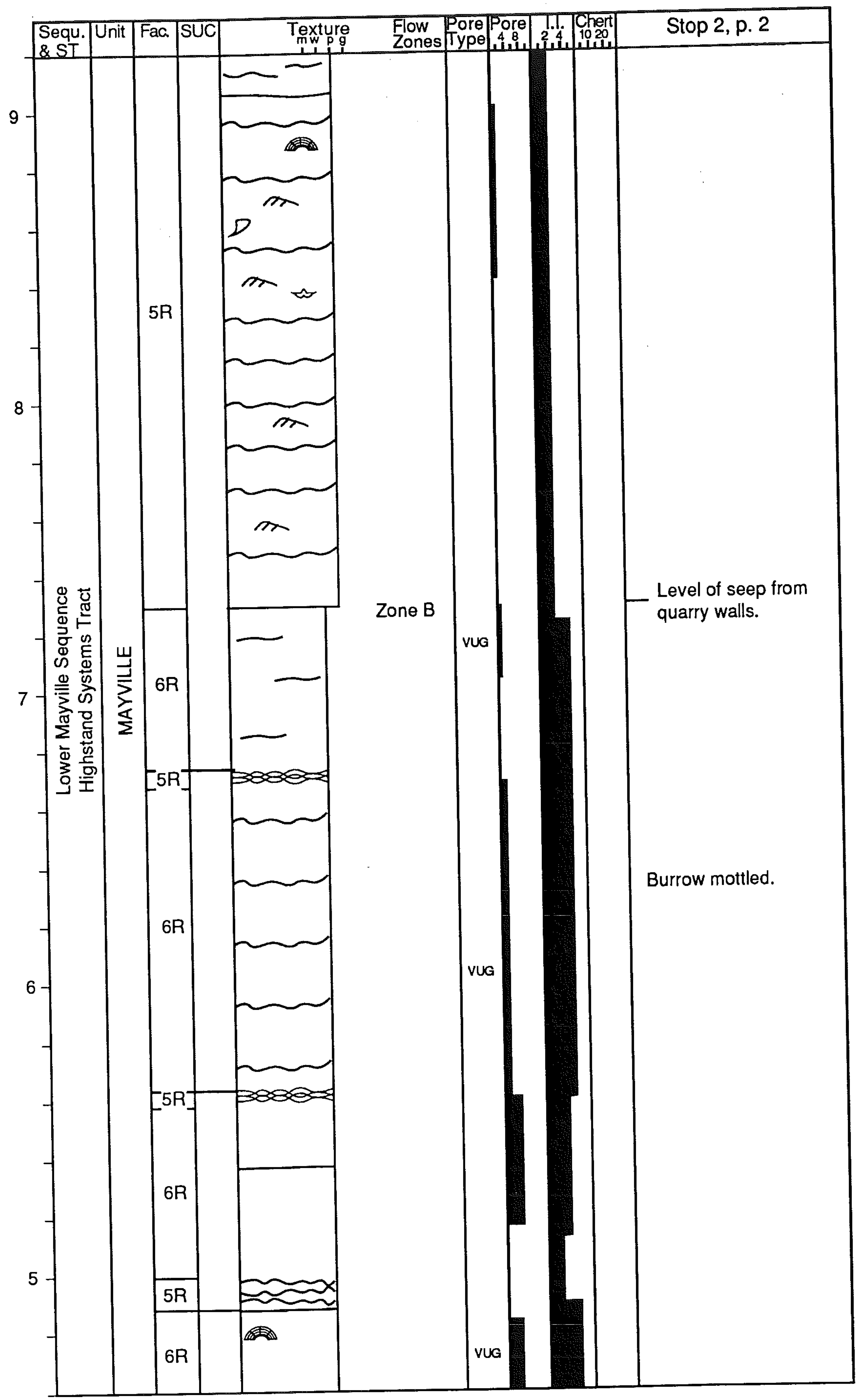


Figure 5 (cont.): Stratigraphic section for the Wequiock Church Quarry, stop 2, page 2.

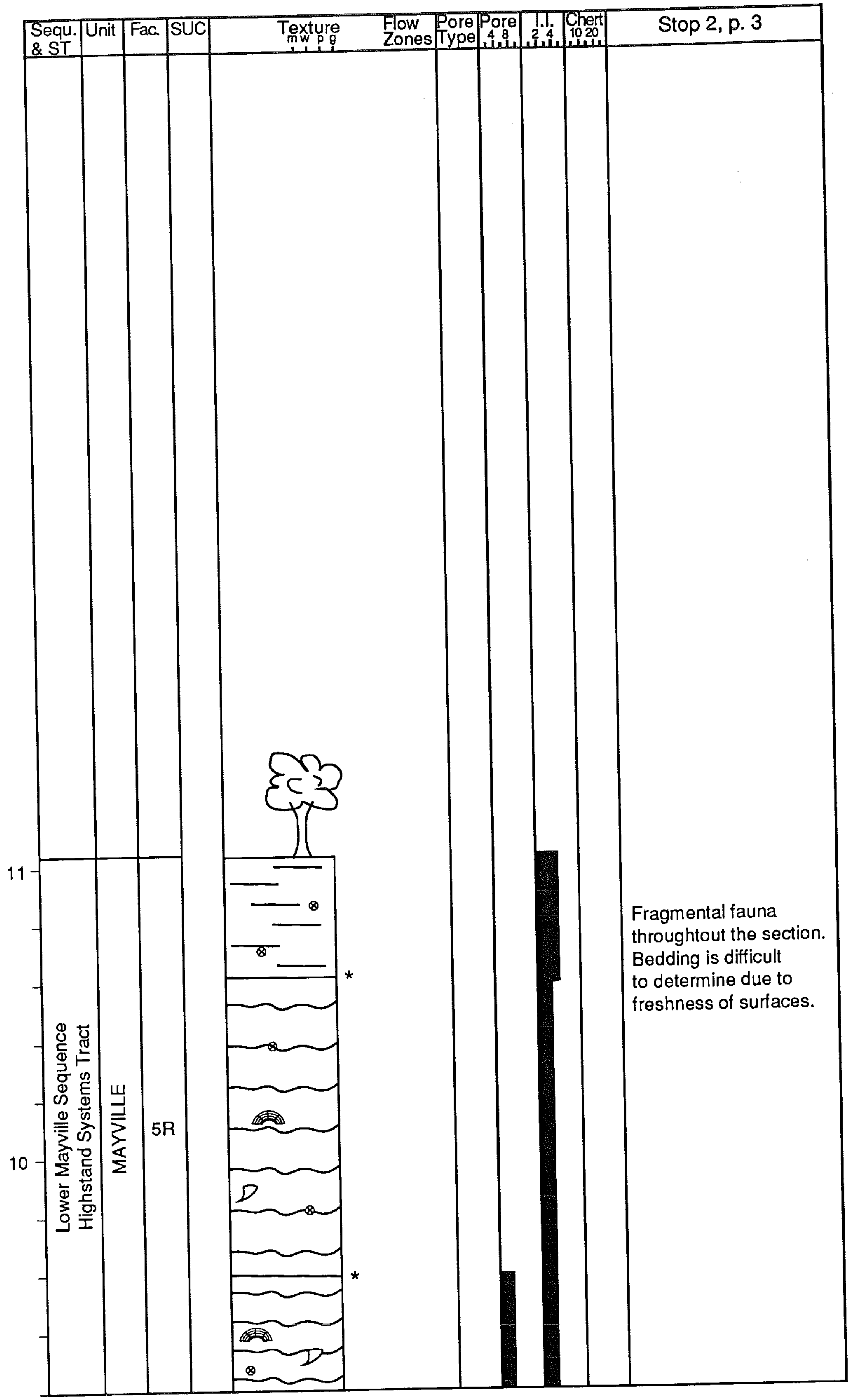


Figure 5 (cont.): Stratigraphic section for the Wequiock Church Quarry, stop 2, page 3.

STOP 3: THE "BIG QUARRY", COUNTY ROAD B, 8 KM NORTH OF STURGEON BAY, DOOR COUNTY

The Big Quarry is one of the thickest exposures in the peninsula and includes the uppermost Mayville, Byron, and most of the Hendricks. The quarry was opened by Leatham & Smith in 1893 and operated until 1944 (Kluessendorf and Mikulic, 1989). This exposure provides an excellent opportunity to examine the Laminite Facies that make up the Byron and Hendricks. The section also can be viewed as including the top of the Upper Mayville Sequence, the complete Burnt Bluff Sequence, and the base of the Schoolcraft Sequence. Five of the regional flow zones recognized in the vicinity of Sturgeon Bay occur in the section. Included in this stop description are the measured stratigraphic section (Figure 6), paleontological data (Watkins and Kuglitsch, this volume), and the gamma ray log correlation to the Jarmen Road core (Figure 7; Harris, Hegrenes and Muldoon, this volume).

The uppermost beds of the Mayville Dolomite outcrop along the shoreline north and west of the quarry. They consist of brachiopod wackestone-packstone with domal stromatoporoids. The Byron Dolomite is exposed from the base of the quarry through the lower 7.2 meters of the upper quarry face. The overlying Hendricks Formation continues into the slope above the quarry wall. These two units consist entirely of numerous meter-scale cycles of the Laminite Facies with well displayed sedimentary structures. We will also point out variations in the subtidal bases of the cycles and the laterally extensive erosional surfaces (sequence boundaries).

The sequence boundary between Upper Mayville ("lower Byron") and Burnt Bluff ("upper Byron") Sequences occurs in the section at 8.8 m, located toward the top of the lower quarry wall. The boundary occurs within a two-meter inveral marked by erosional surfaces, thin channel fills, and deformed bedding. The surface is marked by a soil horizon in sections to the north. Here we place the boundary below the channel scours. Cycles in this quarry wall contain ostracode (BA1) faunas.

The cycles exposed in the upper half of the middle quarry wall differ from those below. Laminated peloid packstone and overlying coral wackestone occur at approximately 3.5 m above the base of this quarry wall (best viewed along the north end of the blast pile). Faunal collections from an intraclast bed below the laminated bed (collection #1) and the coral wackestone bed (collection #2) contain BA2 faunas. One to three faunal beds occur in the Byron Formation at this level throughout the peninsula (e.g. Peninsula Park, Boyers Bluff).

Only the lower part of the high (21.4 m) upper quarry wall will be accessable to the field party. The Byron extends through the "gray band" near the base of this exposure. The uppermost Byron cycles are marked by a return to laminite-capped cycles without diverse faunas. The basal cycles of the overlying Hendricks contain subtidal marine faunas which are largely preserved as molds. In the middle Hendricks, the faunal content decreases (collection #3 is from this interval) and physical structures predominate up to the sequence boundary between the Burnt Bluff and Schoolcraft Sequences. The boundary occurs high on the quarry wall but can be traced as a low-angle erosional surface below a light-colored bed. The light-colored bed consists of onlapping tidal laminites. The overlying Hendricks cycles are marked by thicker subtidal units with a diverse BA 2 fauna (collection #4).

The Burnt Bluff Sequence here consists entirely of Laminite Facies. The upper Byron comprises the TST. The stack of multiple fauna-rich cycles in the Hendricks marks the maximum flooding interval, so that the HST consists of most of the Hendricks. Here the uppermost Hendricks is the TST of the overlying Schoolcraft Sequence. However, in other sections the sequence boundary is closer to or at the formation boundary.

Several of the flow zones recognized by Gianniny et al. (1996) occur in this section and their approximate located is marked in the section. Zone F is near the base of the Byron Dolomite.

An unnamed flow horizon occurs at the mid-Byron sequence boundary. At this location, this horizon is associated with numerous fractures and/or dissolution features that enhance flow. Zone H occurs in the upper part of the second bench in the quarry wall, in a vuggy interval. Zone K is positioned near the floor of the upper quarry bench. Zone I is at the top of the Byron. The highest flow zone visible in the quarry wall is Zone J, positioned just below the top of the quarry wall.

Faunal collections
(Watkins and Kuglitsch, this volume)

Faunal collection #1: Intraclast bed in the Byron Dolomite at 14.5 meters.

Kockelella manitoulinensis, Spathognathodus sp. A, *Ozarkodina* n. sp. A, and n. sp. B, *Okarkodina excavata puskuensis, Ozarkodina oldhamensis, Icriodella deflecta, and Icriodella discreta.*

Faunal collection #2: Stromatoporoid-coral community (BA2) in the Byron Dolomite at 16-17 meters.

Silicified fauna includes heteractinid sponge spicules, stromatoporoids, corals (favositids, halysitids, auloporids, solitary rugose corals, open-branching colonial rugose coral), brachiopods (*Hesperorthis davidsoni, Platystrophia* sp., *Dalejina* cf. *D. striata, Salopina* sp., *Gypidula* n. sp., *Hercotrema winiskensis, Alispira lowi, "Whitfieldella"* n. sp., *Howella* sp.), and crinozoan ossicles.

Faunal collection #3: Hendricks Dolomite at 34.5 meters.

Denticles of thelodont fish.

Faunal collection #4: Stromatoporoid-coral community (BA2) in the Hendricks Dolomite at 37.4-38.9 meters.

Silicified fauna includes stromatoporoids, corals (favositids, halysitids, auloporids, solitary rugose corals), brachiopods (*Eomegastrophia* sp., *Gypidula* n. sp., *Alispira lowi, "Whitfieldella"* n. sp.), gastropods, and crinozoan ossicles.

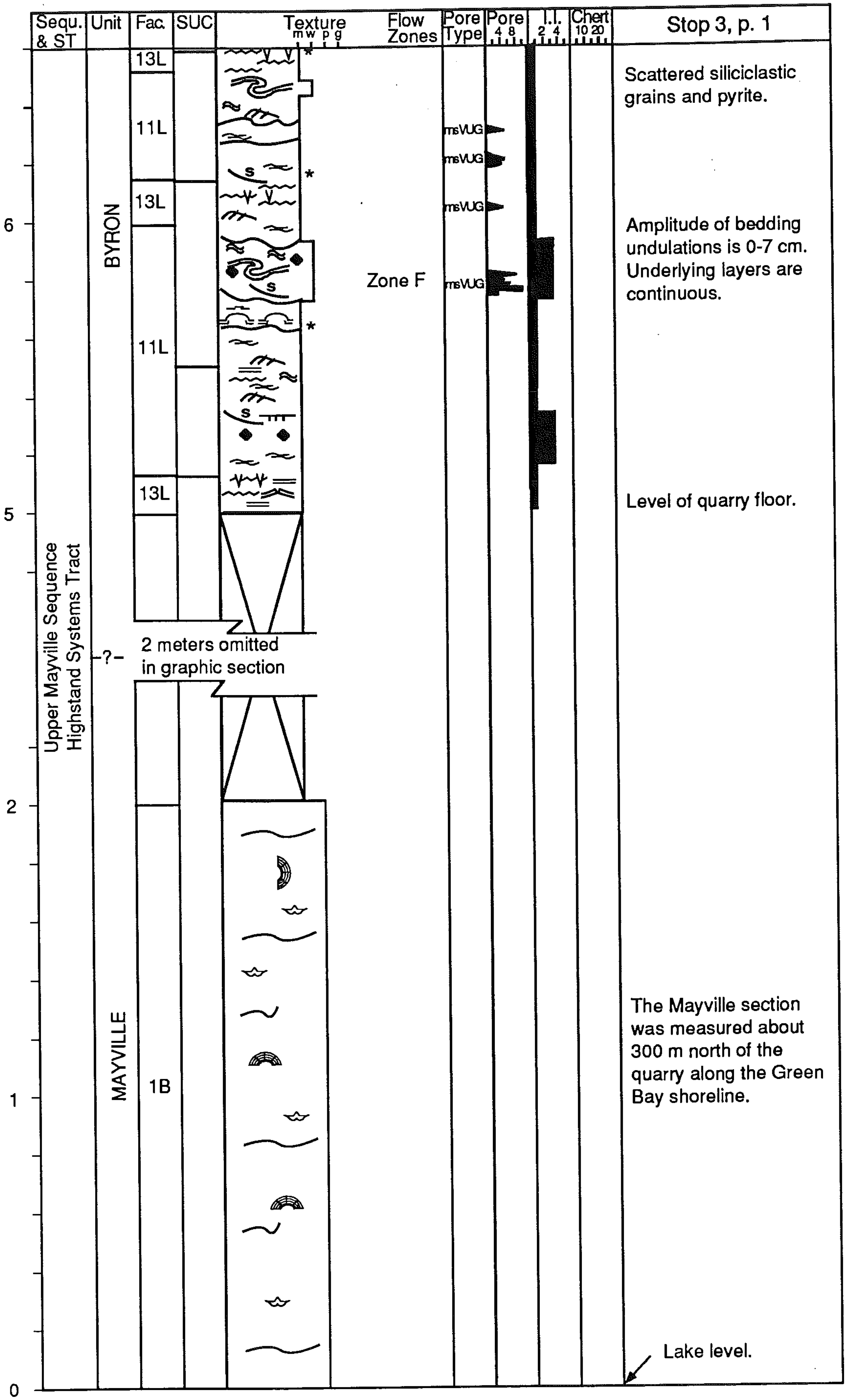


Figure 6: Stratigraphic section for the Big Quarry, stop 3, page 1.

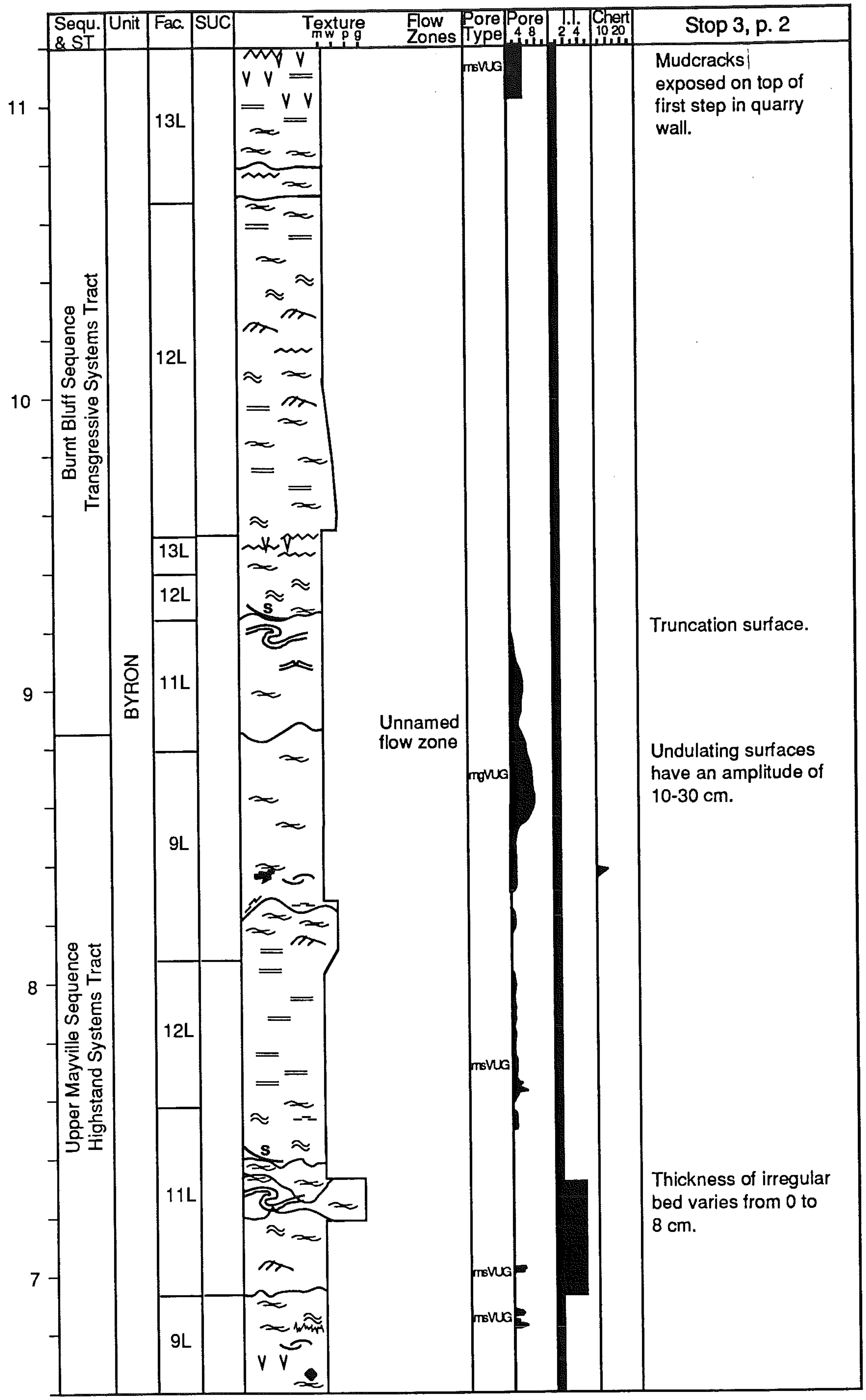


Figure 6 (cont.): Stratigraphic section for the Big Quarry, stop 3, page 2.

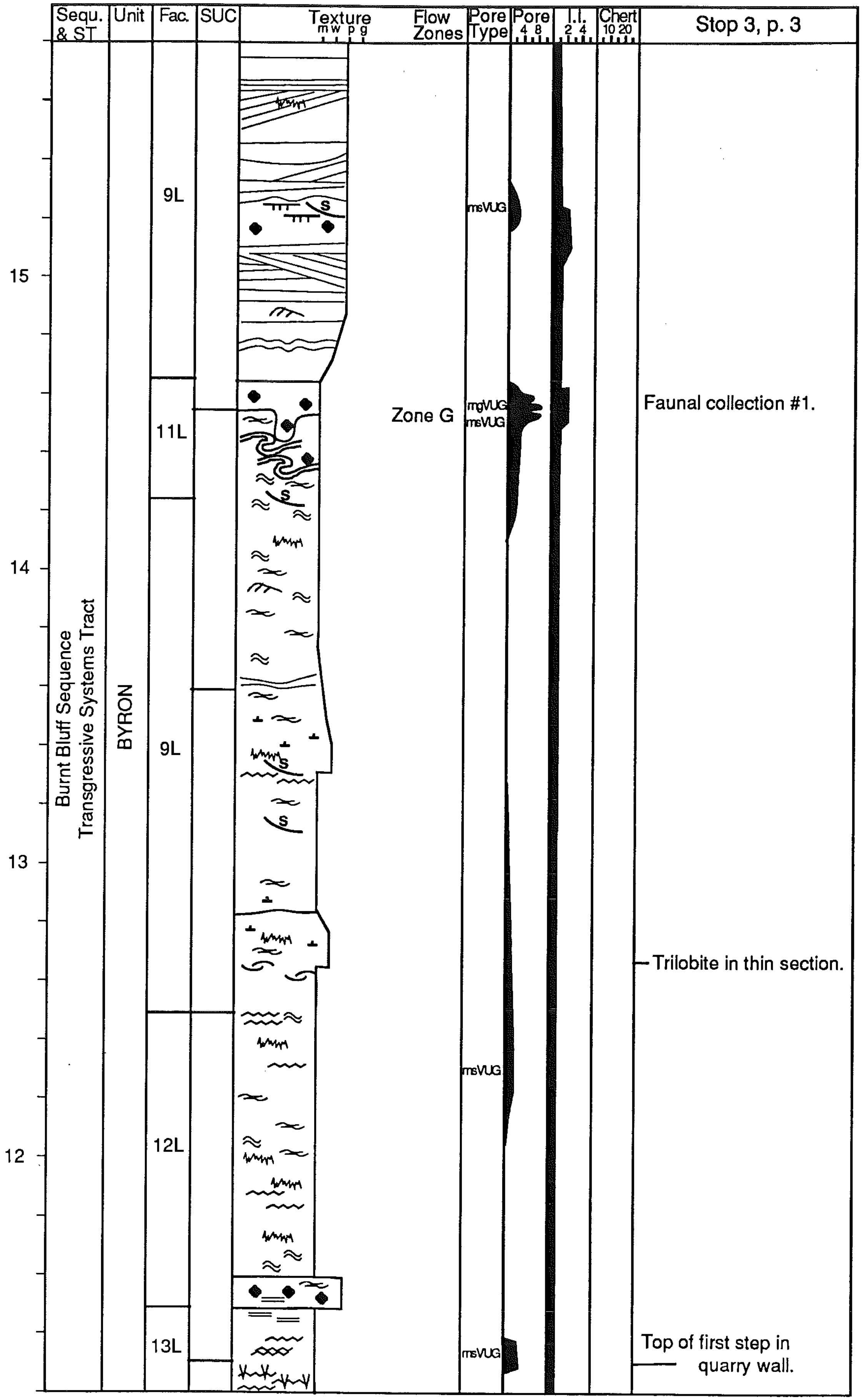


Figure 6 (cont.): Stratigraphic section for the Big Quarry, stop 3, page 3.

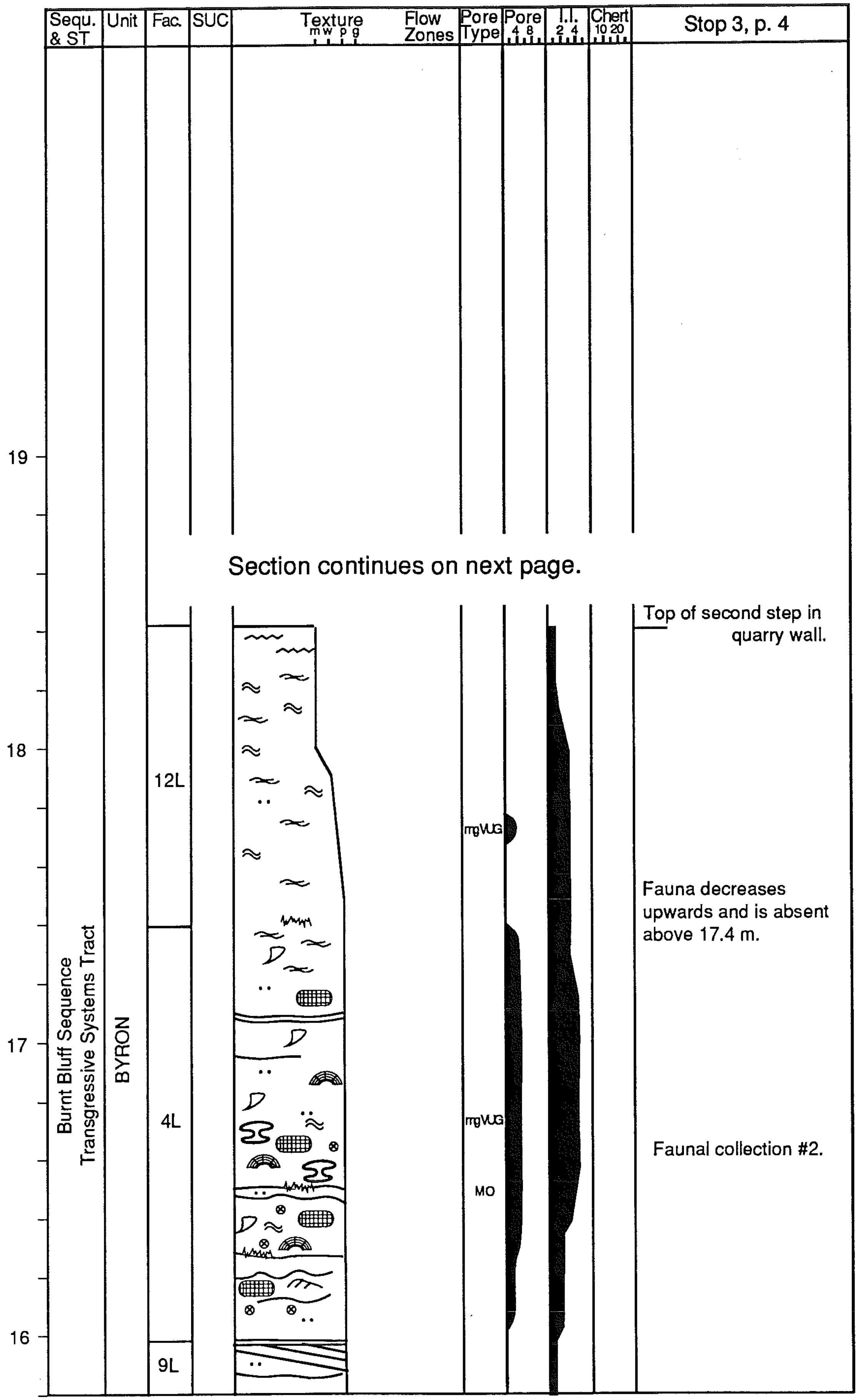


Figure 6 (cont.): Stratigraphic section for the Big Quarry, stop 3, page 4.

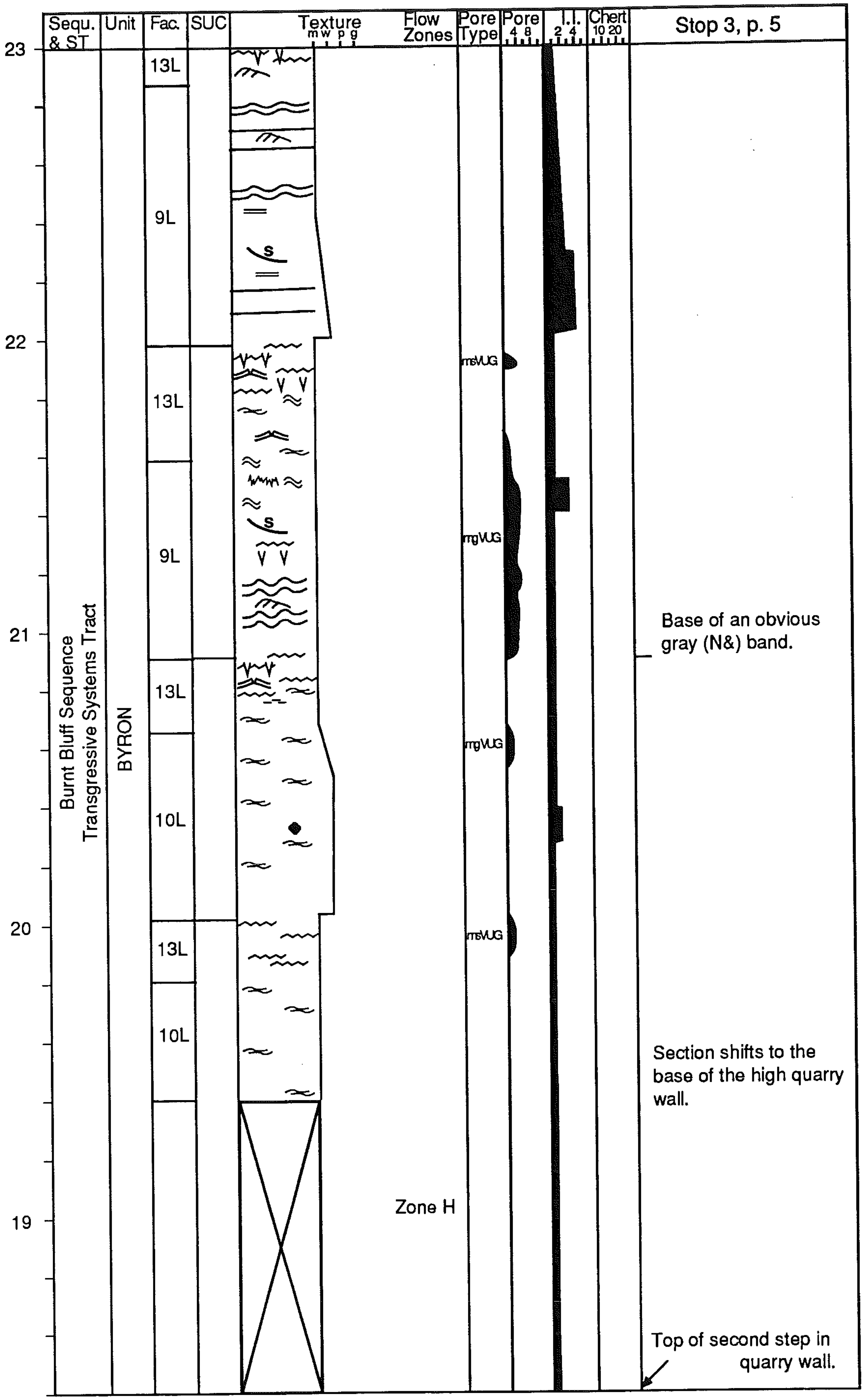


Figure 6 (cont.): Stratigraphic section for the Big Quarry, stop 3, page 5.

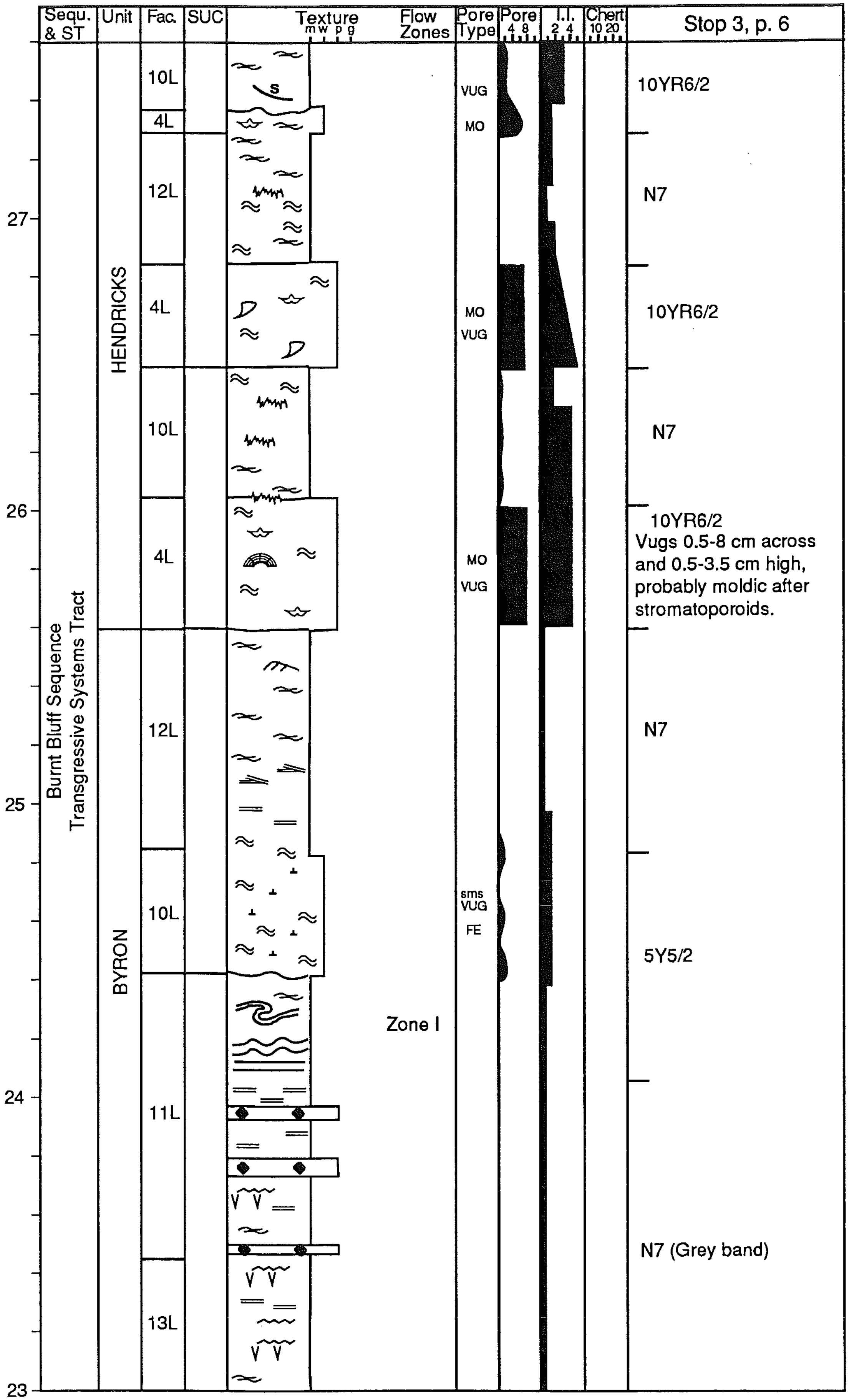


Figure 6 (cont.): Stratigraphic section for the Big Quarry, stop 3, page 6.

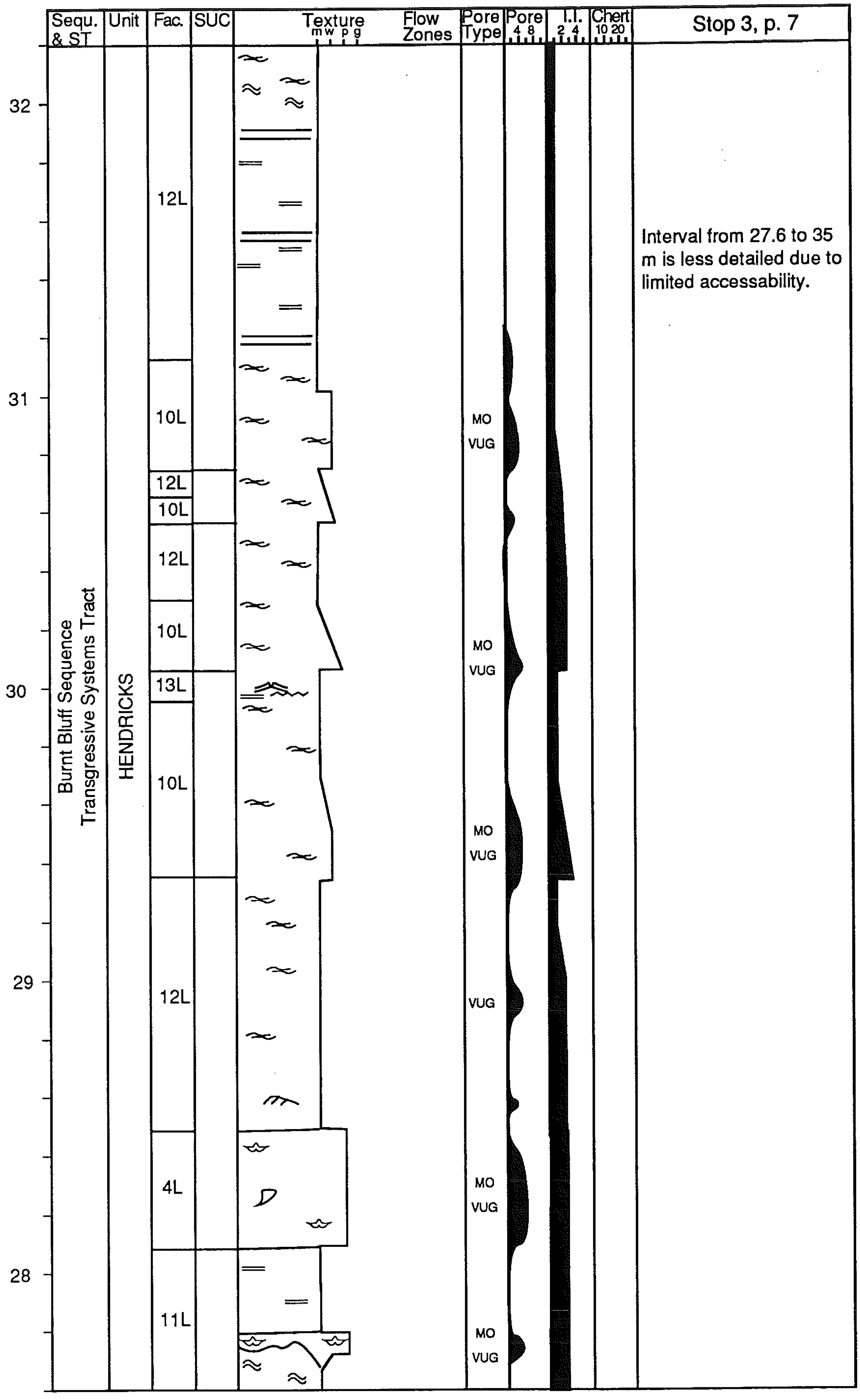


Figure 6 (cont.): Stratigraphic section for the Big Quarry, stop 3, page 7.

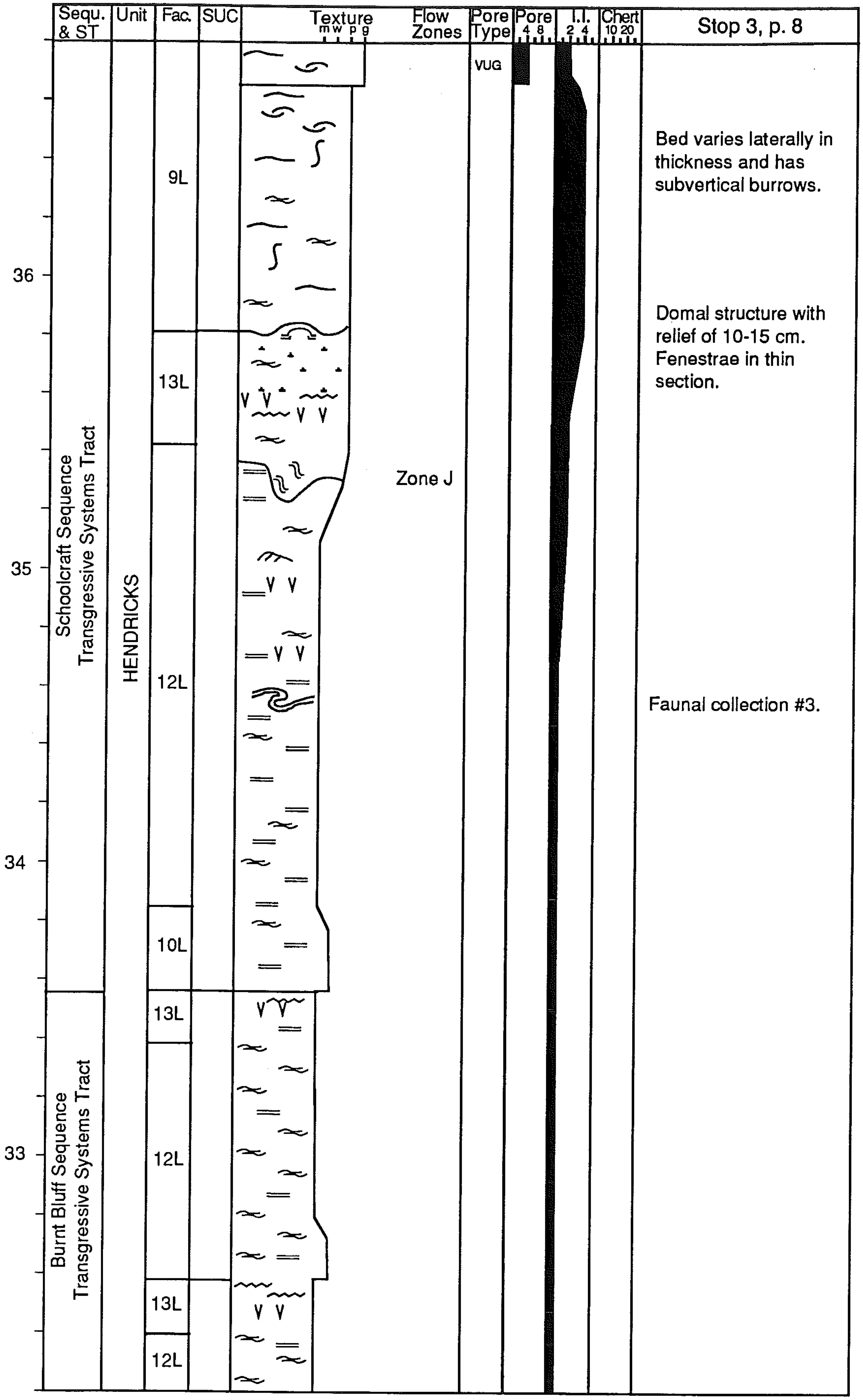


Figure 6 (cont.): Stratigraphic section for the Big Quarry, stop 3, page 8.

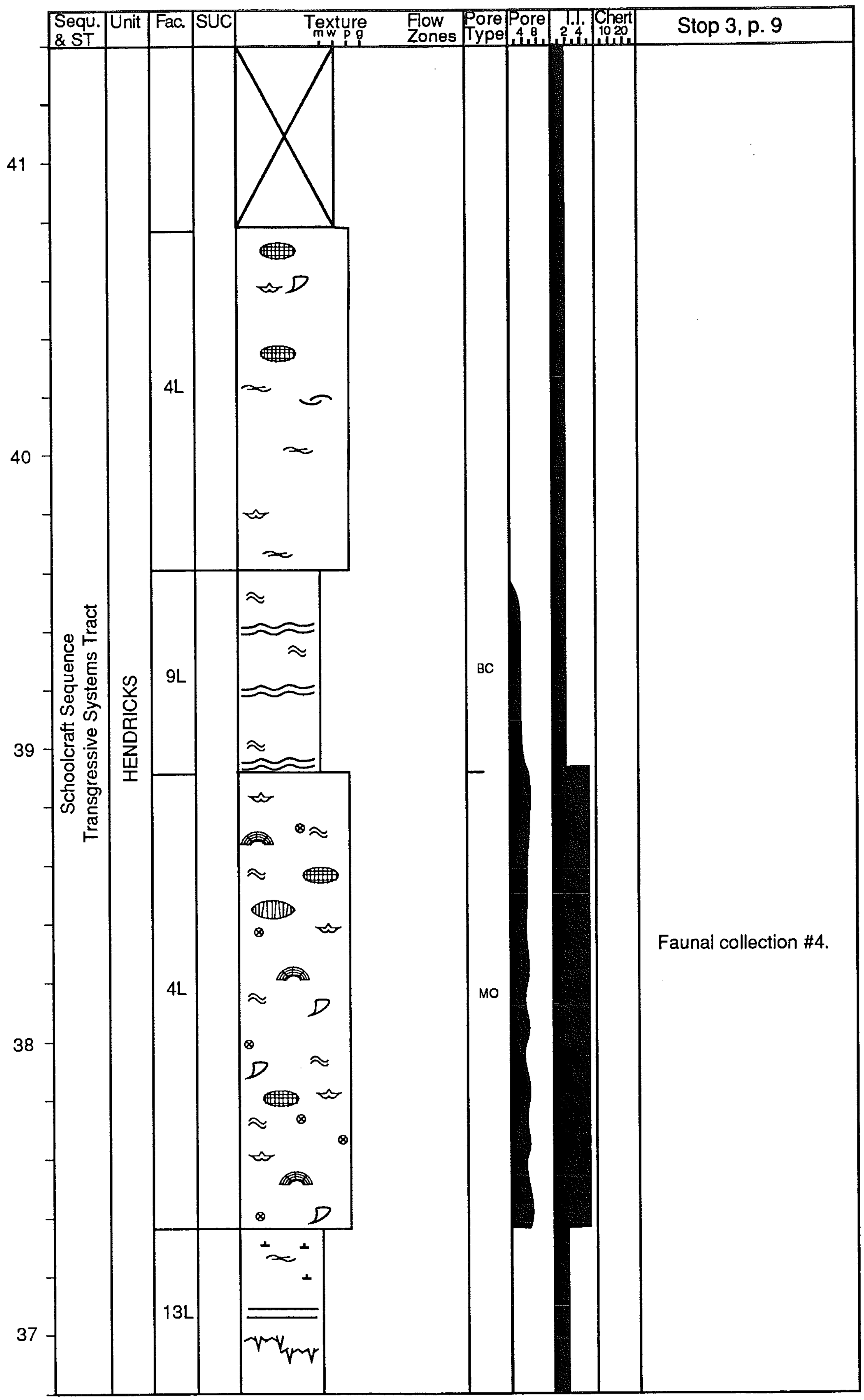


Figure 6 (cont.): Stratigraphic section for the Big Quarry, stop 3, page 9.

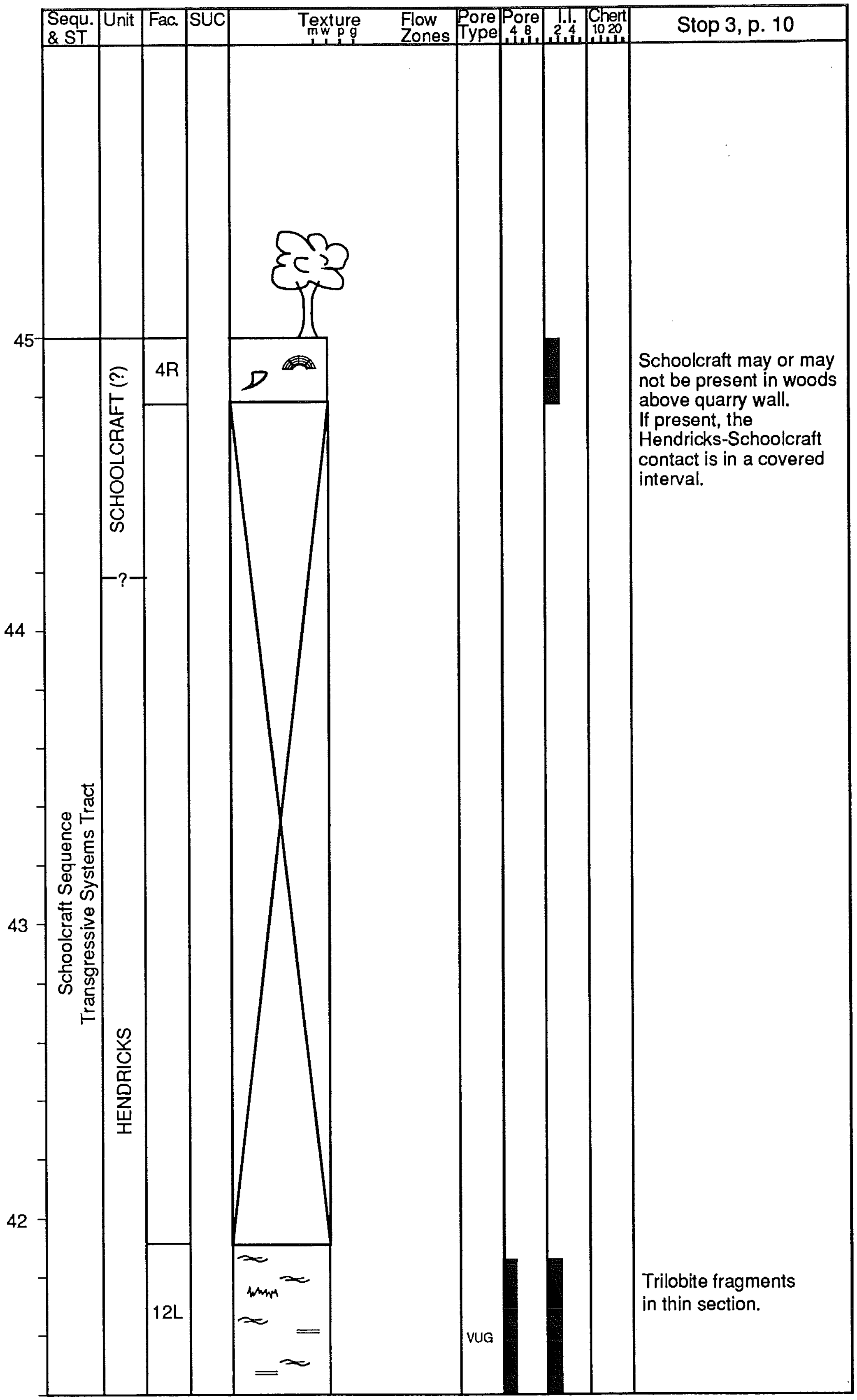
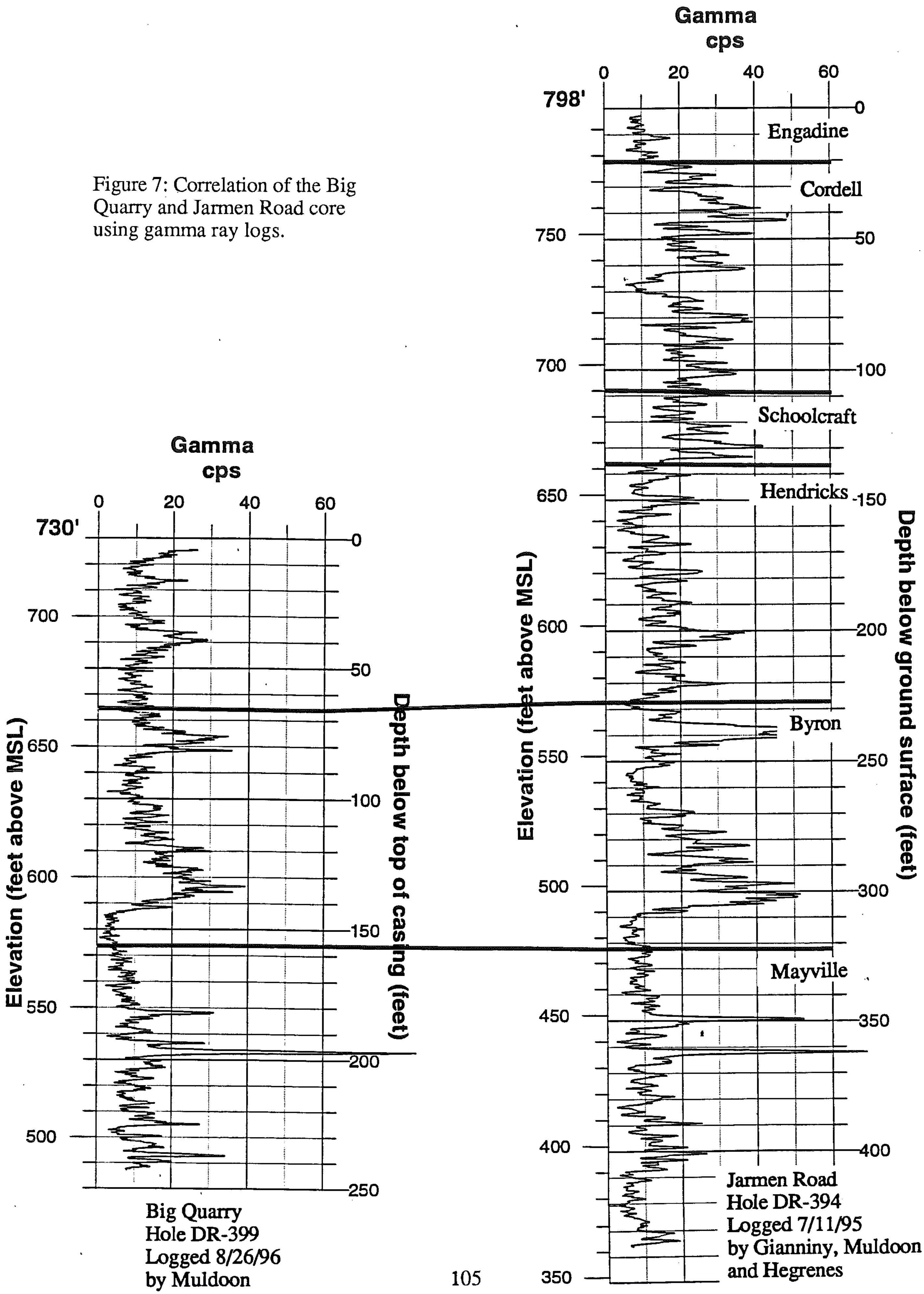


Figure 6 (cont.): Stratigraphic section for the Big Quarry, stop 3, page 10.

Figure 7: Correlation of the Big Quarry and Jarmen Road core using gamma ray logs.



STOP 4: MATHEY ROAD QUARRY, MATHEY ROAD, 5 KM NORTH OF STURGEON BAY, DOOR COUNTY

The Mathey Road Quarry is typical of the many small quarries scattered throughout the Door Peninsula. Most quarries expose incomplete Manistique and, in some cases, Engadine sections. This stop provides an opportunity to inspect the vertical transition from the Cordell Member (Chamberlin's "Upper Coral Beds") to the Engadine Dolomite ("Racine" of the older literature).

The section consists of one shallowing succession. The Cordell is medium gray in color, non-porous, laminar stromatoporoid-coral floatstone. The overlying Engadine strata is light gray to white in color, porous, coral floatstone and coral boundstone (top of quarry wall). Unfortunately, diagenesis prevents precise faunal identifications.

Hydrologically, the lower Cordell (below the level of this quarry) acts as a aquitard and maintains a perched water table during the dryer parts of the year at the Jarmaan Road site (Bradbury et al., 1991; Bradbury and Muldoon, 1992). The Cordell also influences the distribution of surface-water (karst) features in the peninsula (Bradbury and Muldoon, 1992). These features are more abundant where the Cordell is present (i.e., beneath the eastern half of the peninsula) to maintain water levels close to the surface.

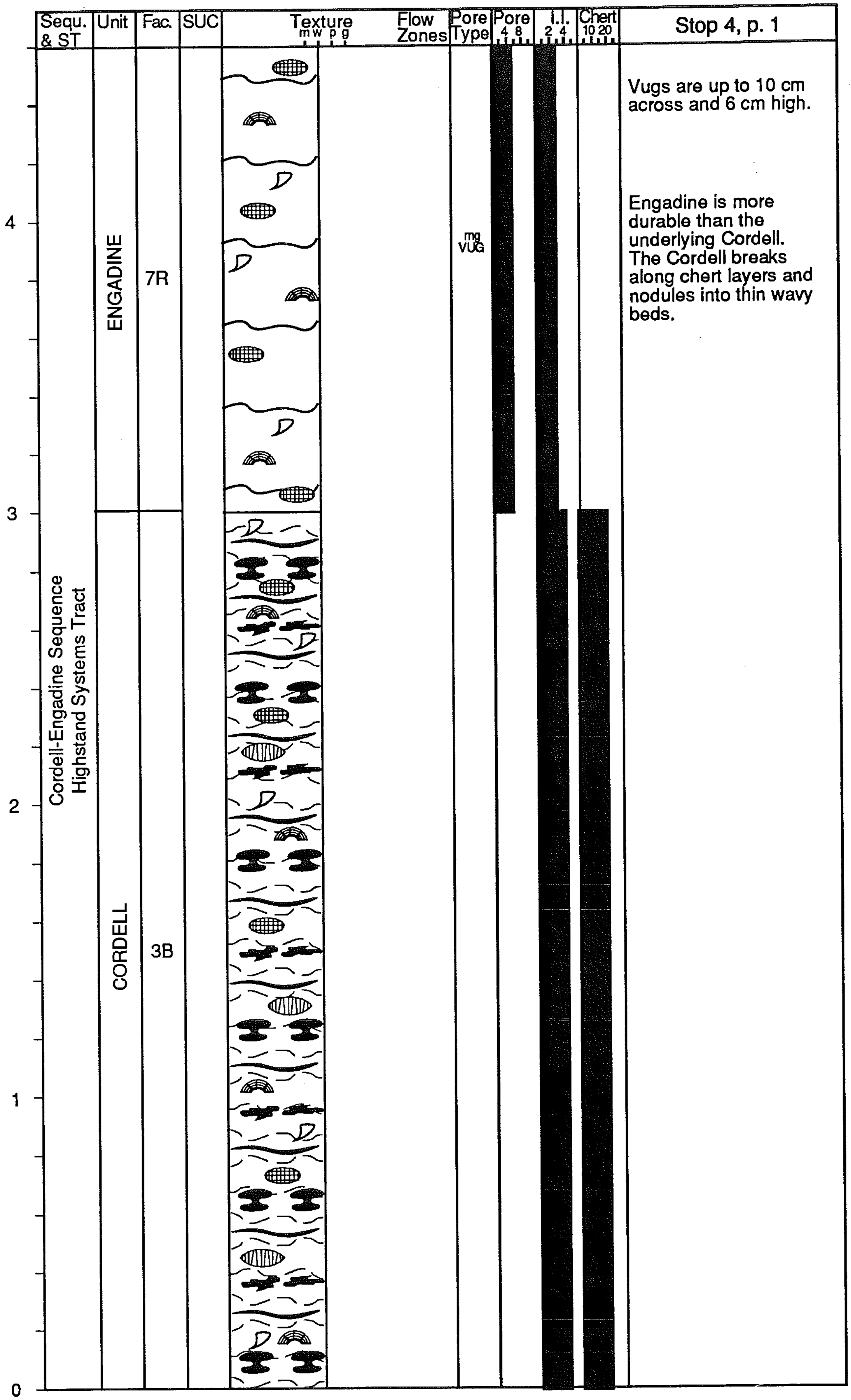


Figure 8: Stratigraphic section for the Mathey Road Quarry, p. 1.

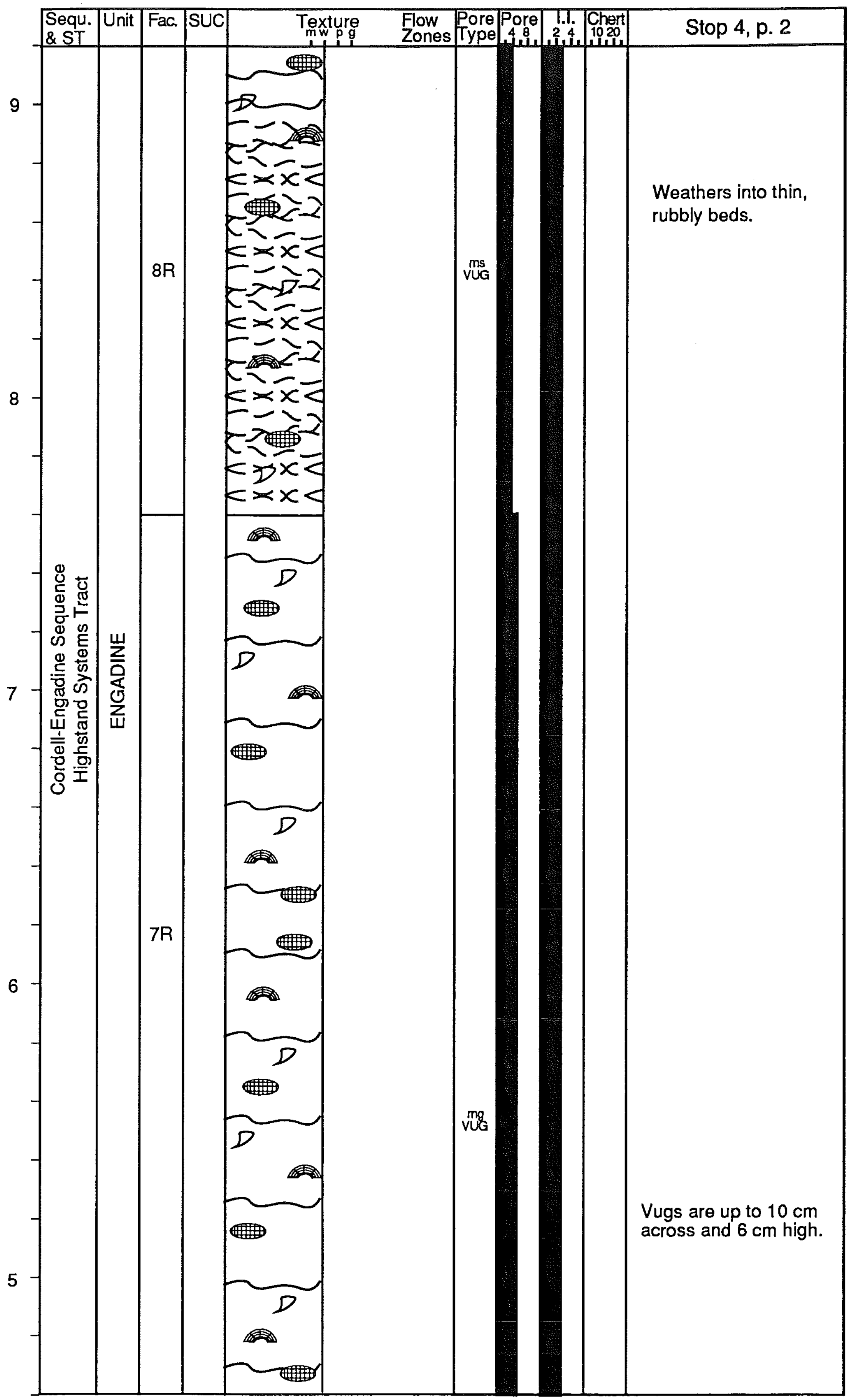


Figure 8 (cont.): Stratigraphic section for the Mathey Road Quarry, p. 2.

STOP 5: KISSER QUARRY, STONE ROAD, 9 KM WEST OF STURGEON BAY, DOOR COUNTY

The section of the Byron Dolomite outcropping in Kisser Quarry is present in the subsurface in Bissen Quarry, the site of WGNHS's tracer study research site (Stop 6), and corresponds to the stratigraphic interval with flow zones F and G (Figure 7, Muldoon and Bradbury, this volume). The objective of this stop is to describe the sedimentology and vertical/horizontal discontinuities on the quarry walls that are analogous to the subsurface in Bissen Quarry. The observations at Kisser Quarry enhance our understanding of the complexities of the groundwater flowpaths delineated at Bissen Quarry (see Stop 6, and Muldoon, in prep.).

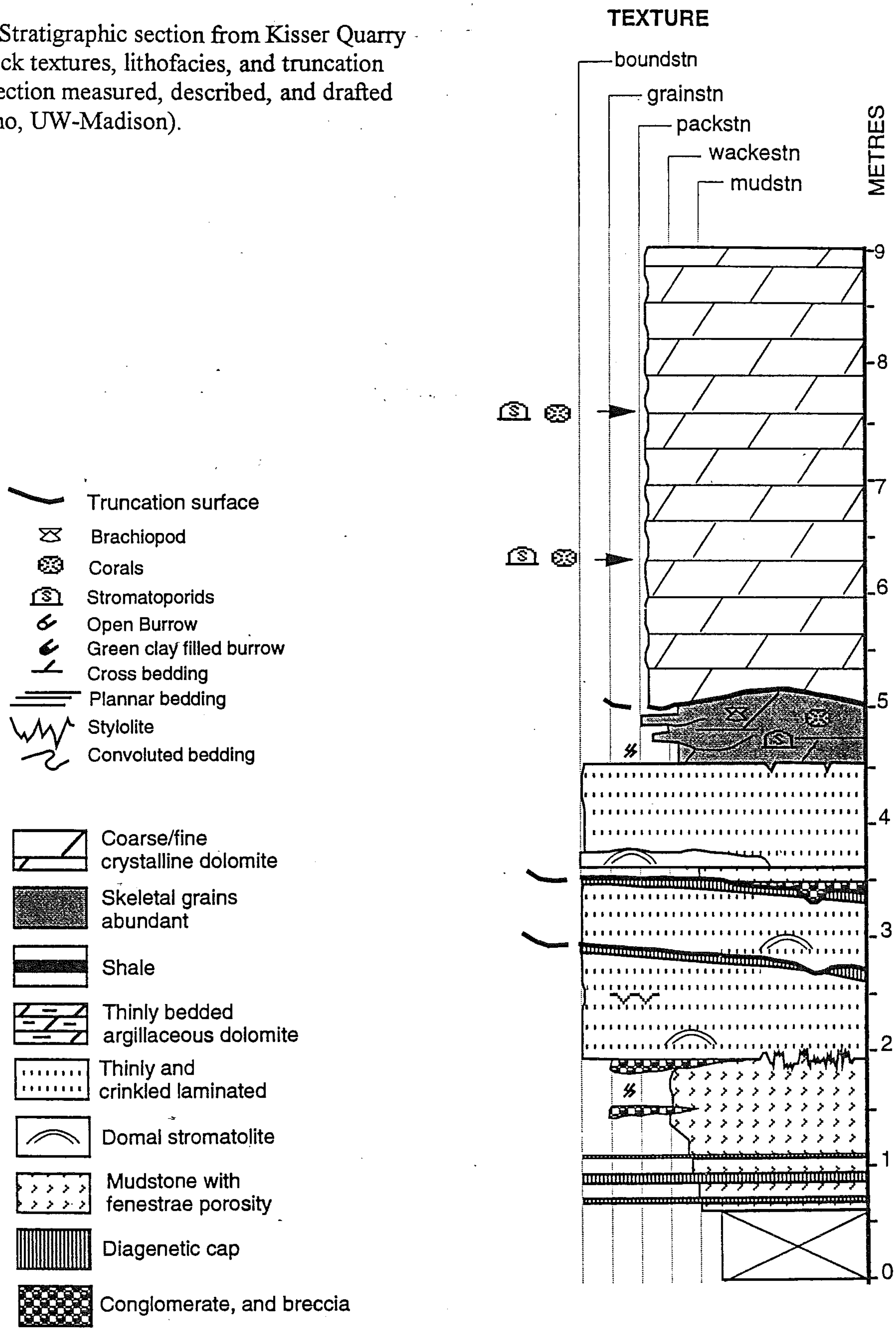
Recent work in southeastern Wisconsin (Rovey and Cherkauer, 1994) and in Door County (Muldoon and Bradbury, 1990, 1994; Harris and Waldhueter, 1996; Gianniny and others, 1996; Harris, Hegrenes, and Muldoon, this volume) suggests that lithologies and horizontal discontinuities in the Silurian Dolomite play an important role in determining the distribution of hydraulic conductivity within the aquifer. While at Kisser Quarry, we shall pay special attention to 1) variations in lithologies, 2) discontinuities developed at lithologic contrasts, and 3) the lateral extent of those discontinuities.

Lithostratigraphy

Figure 9 is a graphic representation of the lithologies and truncation surfaces in Kisser Quarry. The lower part of the section (0-4.5 m) corresponds to a restricted marine cyclic facies characterized by shallowing upward cycles which exhibit pronounced vertical lithologic variations. Complete cycles contain a lower part with mudstones, and an upper part characterized by algal lamination; most of the cycles are capped by a diagenetic cap and overlain by a surface with depositional relief. The basal mudstones may be bioturbated, and often contain fenestral porosity. Discontinuous brecciated horizons may occur within the mudstones. The upper part of the cycles consist of laminated facies, which may contain domal stromatolites at the base, and thinly and crinkly laminites at the top. These laminated lithologies are typically very well-cemented and may have a brownish color. The diagenetic cap varies in thickness and occasionally is truncated by the overlying surface. Cemented sheet-cracks, and vertical cracks are very common and occasional micro-karst affects the diagenetic cap. Cycle boundaries separate the very well cemented laminite/diagenetic cap and the overlying less cemented mudstones. At these contacts, thin and discontinuous organic-rich mudstones may occur and often represent a horizontal discontinuity on the quarry walls (Figure 10).

The upper part of the quarry (4.5-9 m) consists of medium bedded coarse dolomite with open marine fauna (corals, stromatoporids, brachiopods and gastropods) that appear to be concentrated along bedding planes. The contact between the restricted cyclic facies and open marine coarse dolomite is sharp. The base contains a bed with bioturbated wackestones with discontinuous thin beds with abundant skeletal fragments. A truncation surface with relief, locally enhanced by a centimeter- thick organic-rich mudstone, separates this bed from the coarser dolomite.

Figure 9. Stratigraphic section from Kisser Quarry showing rock textures, lithofacies, and truncation surfaces (section measured, described, and drafted by J.A. Simo, UW-Madison).



Vertical and Horizontal Discontinuities

A sketch of the quarry wall (Figure 10) highlights some of the more prominent vertical and horizontal discontinuities observed in the southwest corner of Kisser Quarry. While many vertical fractures are present in the quarry wall, only a few are noted in the sketch. Many of these fractures may be due to blasting and stress relief at the quarry face, however, several exhibit Fe-staining, weathered fracture faces, green clay coatings, and/or appear enlarged by dissolution suggesting that they have been pathways for fluid flow.

Several horizontal discontinuities can be traced on the quarry walls. It is important to notice that these horizontal discontinuities follow depositional facies and may show up to 1 ft of relief. Gamma correlation (Gianniny and others, 1996) suggests that some of these discontinuities are continuous at a regional scale, however, comparison with nearby Bissen Quarry (Stop 6) suggests that the specific discontinuities may amalgamate or disappear.

The lowest of the horizontal discontinuities, approximately 2.5 m from the quarry floor, develops at the contact between fenestral mudstone and thinly and crinkled laminated boundstone. This discontinuity is more prominent on the south, rather than the west wall. In mid-August (1996), some seepage was observed along the south wall, suggesting that this discontinuity provides a pathway for water.

The most prominent discontinuity is approximately 3.5 m from the quarry floor at an especially well-developed cycle boundary. The fracture does not always follow the truncation surface or a specific bedding plane, but rather appears to be contained within the organic-rich mudstones that overlie the cycle boundary. This prominent discontinuity is believed to be equivalent to Flow Zone F (Figure 7, Muldoon and Bradbury, this volume) and is the major horizontal flowpath at Bissen Quarry (Stop 6).

The contact between the restricted marine facies and the overlying coarser dolomite (approximately 4.5 m from quarry floor) is marked by a color change and a bedding-plane discontinuity best seen in the northern end of the quarry. The coarser dolomite in the upper wall is generally massive in appearance; one weakly-developed bedding-plane discontinuity can be noted about 6.5 m from quarry floor.

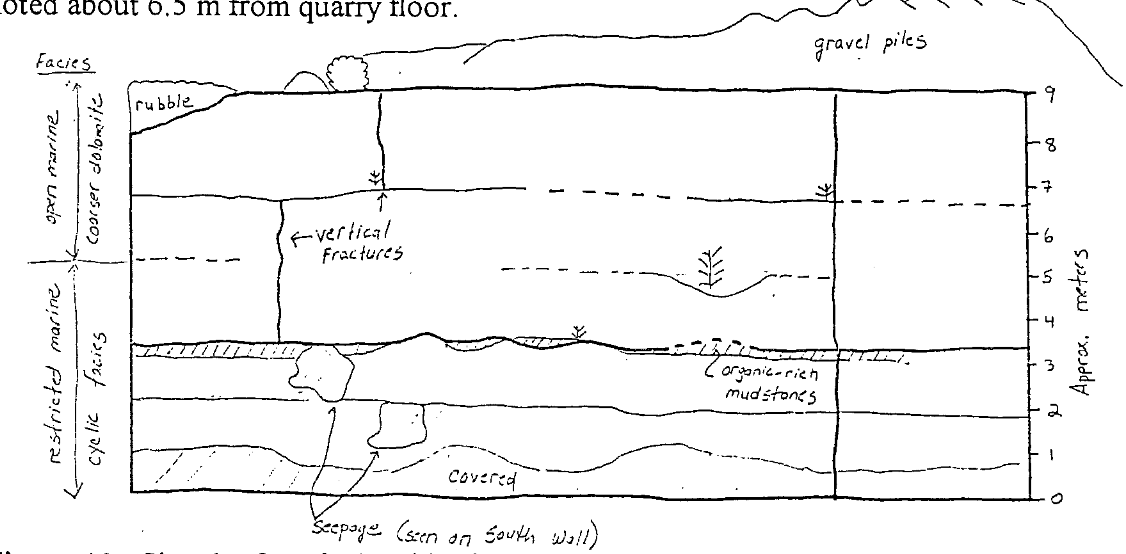


Figure 10. Sketch of vertical and horizontal discontinuities in walls of Kisser Quarry.

STOP 6: BISSEN QUARRY, CORNER OF COUNTY ROAD MM AND ROCK RIDGE ROAD, 7 KM WEST OF STURGEON BAY, DOOR COUNTY

Background

Bissen Quarry is the site of a WGNHS groundwater tracer study. The objectives of the study are 1) to develop a better understanding of the movement of groundwater and contaminants in a shallow, unconfined, fractured-carbonate aquifer by completing a detailed hydrogeologic characterization of a site and performing a series of tracer tests and 2) to use data from the tracer tests, coupled with modelling studies, to test the predictive capabilities of discrete fracture-flow and transport models.

The quarry is approximately 4.5 miles southwest of Sturgeon Bay. Our stop at the tracer study site in Bissen Quarry will include an overview of the hydrogeologic characterization of the site with a focus on methods of determining hydraulic conductivity, presentation of data which help identify the primary flowpaths at the site, and a discussion of the relationship between stratigraphic features observed at Kisser Quarry and the flowpaths delineated at Bissen Quarry.

Stratigraphy

The rocks in the walls of Bissen Quarry and cores (depth of 35 ft below ground surface) belong to the Byron Dolomite. The subsurface stratigraphy is approximately equivalent to the rocks exposed at the base of Big Quarry (Stop 3) and in Kisser Quarry (Stop 5, Figure 9). A description of a 35-ft core recovered from Bissen Quarry (hole 5) is summarized in Figure 11; the measured section of the rocks exposed in the quarry is shown in Figure 12.

The lower part of the core (25.5 - 36.5 ft depth) belongs to the open marine facies. The middle portion of the core (14-25.5 ft depth) belongs to the restricted marine cyclic facies (seen in the basal 4.5 meters in Kisser Quarry) and the upper 14 ft of core belong to the open marine facies (seen in the upper 4.5 meters at Kisser Quarry) with a minor laminite at 5-6 ft depth.

Rocks exposed in the walls of Bissen Quarry (Figure 12) are of the open marine facies. This facies generally becomes more restricted as you move upsection (0-8 meters); a similar trend can be see in the rocks exposed in the lower section of Big Quarry (see Stop 3). The quarry walls are topped by a bioturbated mudstone, which we believe to be equivalent to the "Blue Beds" described by Thwaites and Lentz (1922). This unit tends to fracture conchoidally and evidence of tepee and other restricted sedimentary structures can be seen. These sedimentary features are easily observed in Big Quarry (Stop 3) but difficult to see in Bissen. A zone of large vugs, interpreted as differentially dissolved burrows, occurs at the base of the "Blue Beds".

Site Characterization and Monitoring System

A small site, on the northern edge of the quarry was chosen as the tracer study site. The site (Figure 13) measures approximately 125x75 ft; in this area the quarry floor was cleared of

Figure 11. Stratigraphic log from hole 5 showing rock textures and lithofacies (log measured, described, and drafted by J.A. Simo, UW-Madison). Legend is shown in Figure 9. On the right side of the diagram, multiple axes show depth in both feet and meters below ground surface and elevation (relative to an arbitrary datum).

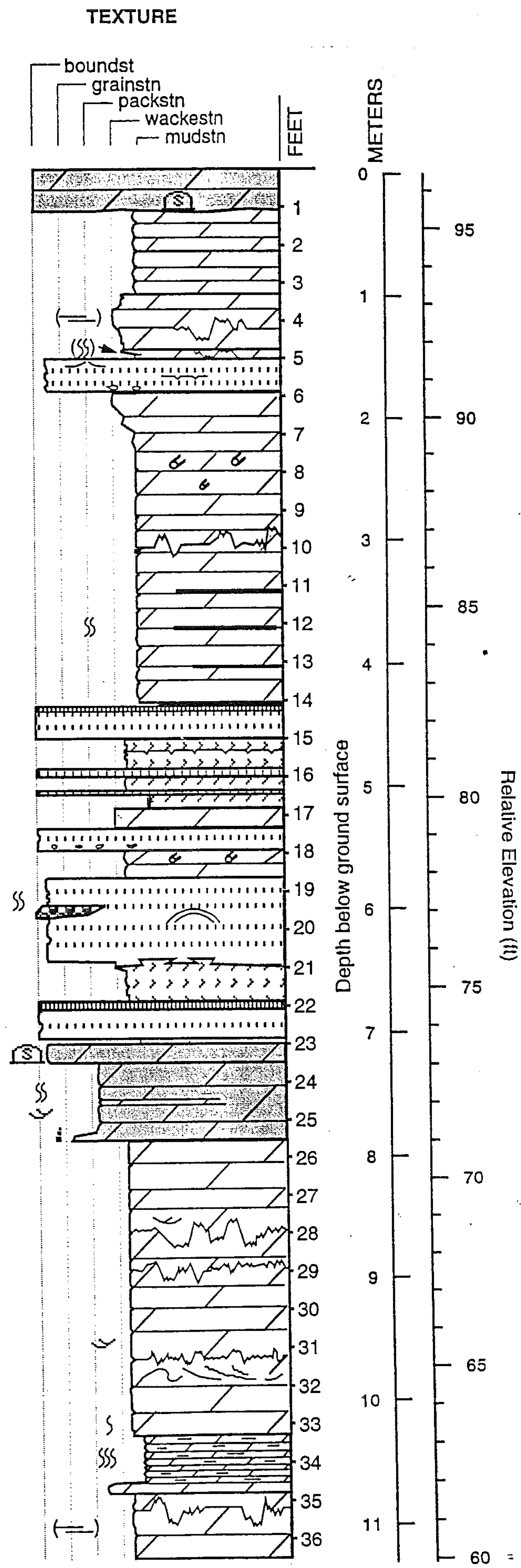
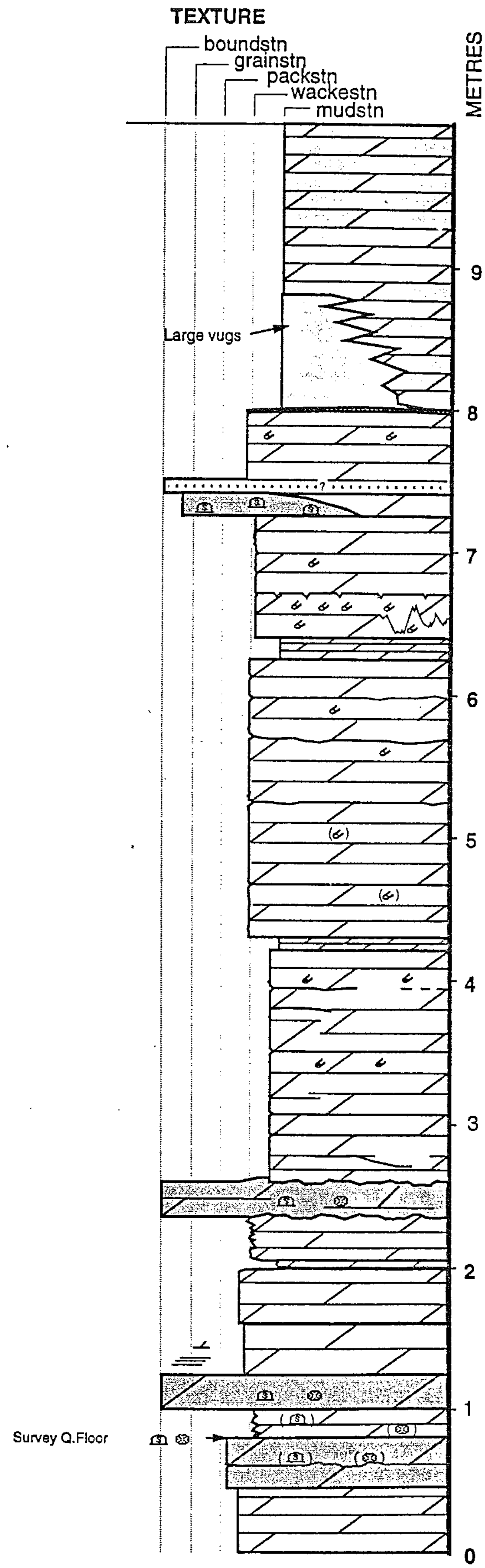


Figure 12. Stratigraphic section of rocks exposed in the walls of Bissen Quarry (section measured, described, and drafted by J.A. Simo, UW-Madison). Legend is shown in Figure 9.



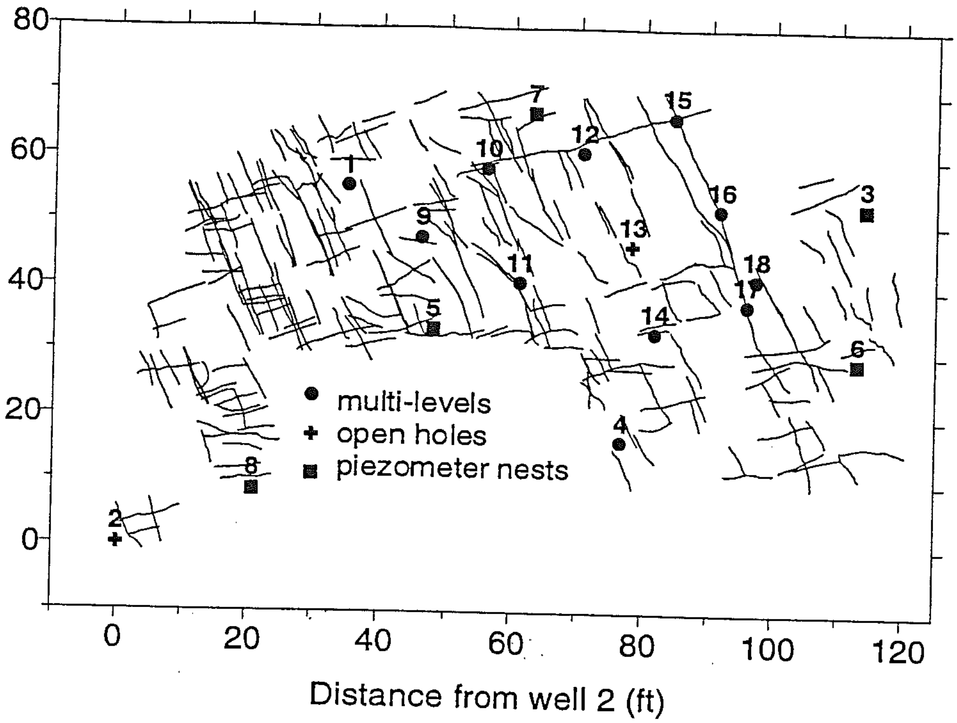


Figure 13. Map-view diagram of study site showing location of multi-level samplers, piezometers, and open boreholes. Fractures > 5 ft length are also shown.

sediment and visible vertical fractures were mapped and digitized.

Eighteen boreholes (including five coreholes) were drilled to a depth of 35 ft. All holes were cased to approximately 2 ft depth prior to installation of the monitoring system. Well elevations, determined by-rod-and-level surveying, are relative to the top of well 5 which was arbitrarily set at 100 ft.

Geophysical Logs

Geophysical logs run on all holes prior to installation of the multi-level samplers include caliper, natural gamma, single-point resistivity, spontaneous potential, fluid temperature, and downhole video. Additional logs run on selected holes include neutron, and electrical conductivity. Figure 14 summarizes logs for hole 5, as well as the neutron log from hole 11 (approximately 15 feet away). Horizontal fractures (relative elevations 92, 82, 77.5, and 75 ft) are shown as dotted lines. The temperature, single-point resistivity, caliper, and electrical conductivity logs all provide indications of one or more of these fractures. The dominant fracture, reflected in all of the above logs, occurs at an elevation of 75 ft. The neutron log (right-most graph) provides a qualitative estimate of porosity.

Monitoring System

Multi-level samplers, each with five to six ports, were installed in 11 of the 3-inch holes. Borehole logs revealed laterally extensive horizontal fractures and dissolution zones. Hydraulic tests, including borehole flow-meter and short-interval packer tests (described below),

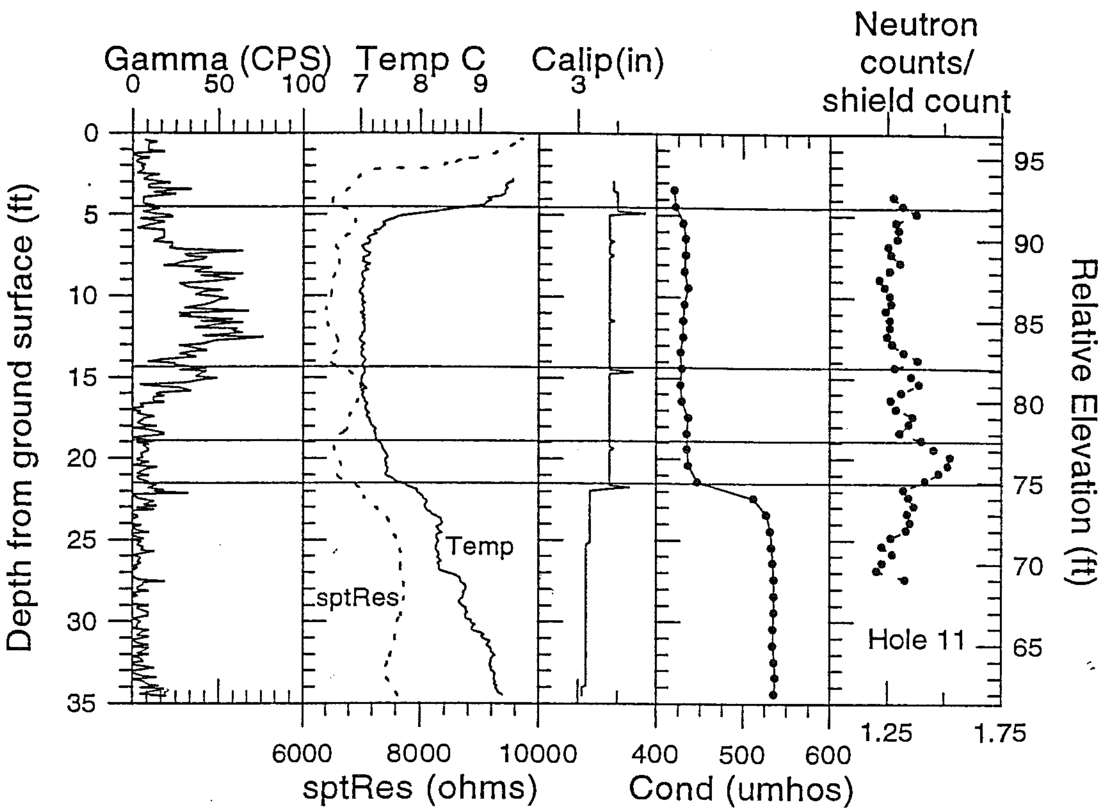


Figure 14. Geophysical logs for hole 5 with neutron log for hole 11. Horizontal lines indicate horizontal fractures.

identified the hydraulically important fractures and dissolution zones. The system of multi-level samplers was designed to monitor four horizontal fractures (approximate relative elevation 92, 82.5, 79, and 75.5 ft) and two dissolution zones (relative elevations 87.5 and 72 ft); some ports were also placed within matrix blocks. Figure 15 is a schematic diagram of the site illustrating which zones are monitored by the multi-levels.

Hydraulic Conductivity Distribution

Data on the hydraulic characteristics of the fracture network at Bissen Quarry have been obtained from a variety of hydraulic tests including a multi-well pumping test conducted with eight 35-ft open boreholes, a second pumping test conducted with multi-level samplers containing ports open in discrete 0.5- to 1-ft intervals, and packer tests conducted with a 0.75-ft straddle intervals.

The results of 372 short-interval packer tests indicate a bimodal distribution of fracture and matrix hydraulic conductivities. Measured hydraulic conductivities range from 7.0×10^{-7} to 4.2×10^{-1} cm/s; the geometric mean of all tests is 3.0×10^{-4} cm/s (Figure 16). The bimodal distribution of packer-test hydraulic conductivity values is expected in fractured-carbonate settings as some packer intervals test matrix conductivity while other intervals are intersected by high-conductivity fractures or dissolution zones.

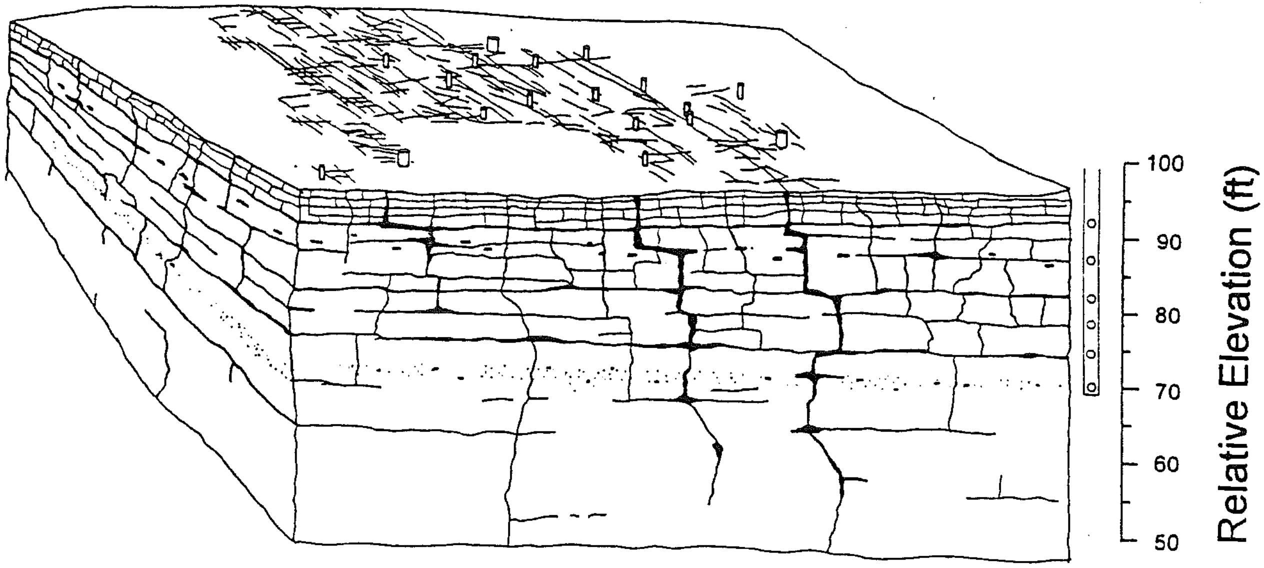


Figure 15. Schematic block diagram of site. Relative elevations are shown on the right along with a schematic multi-port sampler. Ports have been installed in four horizontal fractures (92 ft, 82.5 ft, 79 ft, and 75.5 ft elevation) and two dissolution zones (87.5 and 72 ft elevation). The horizontal fractures appear to be laterally continuous across the site. The upper dissolution zones is characterized by sparse but large vugs; the lower zone is characterized by abundant small vugs.

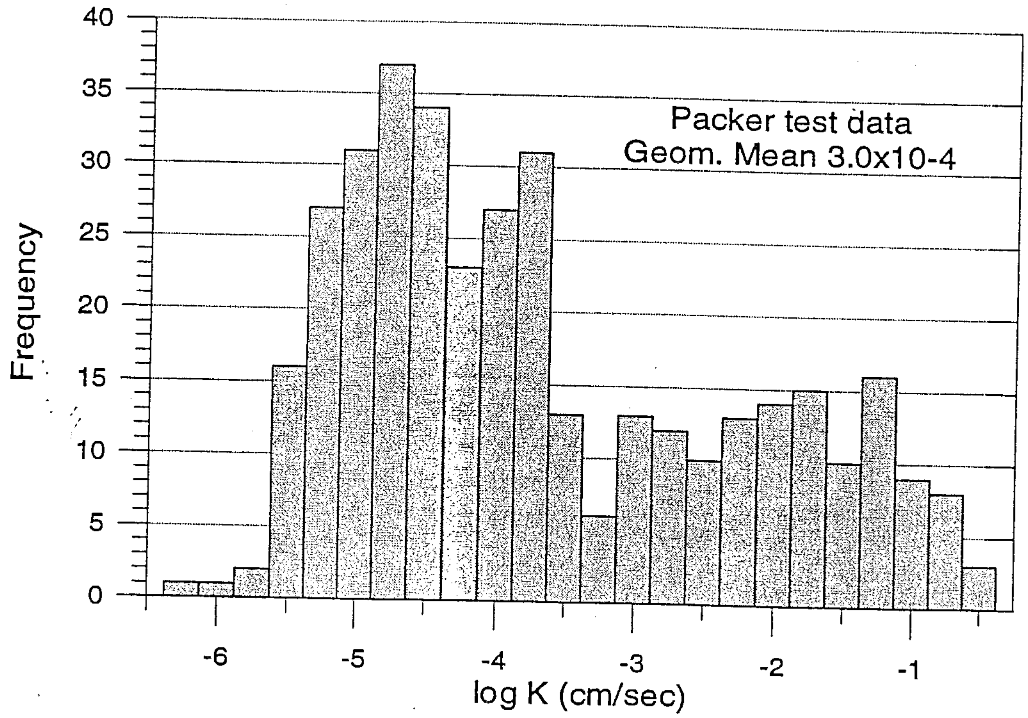


Figure 16. Histogram of 372 hydraulic conductivity values measured with short-interval packer tests. The bimodal distribution clearly shows the distribution of both low-conductivity matrix blocks and high-conductivity fracture and dissolution zones.

Comparison of hydraulic conductivity values from tests conducted at several scales shows that traditional pumping tests (or long-interval packer tests) provide "average" measures of hydraulic conductivity and they are therefore of limited use in providing information on the flow characteristics of fractures.

To illustrate this point, groundwater travel times for an 80-ft long flow path were calculated using the hydraulic conductivities measured at the various scales. The calculations used the head distribution measured in the open boreholes and an estimated effective porosity of 1%. Figure 17 shows the hydraulic gradient and flow-line for which travel times were calculated; table 1 summarizes the results. The variation in calculated travel times is a graphic illustration of the difference in the "continuum" versus the "discrete" approach to aquifer characterization. Tracer test results (described below) indicate that hydraulic conductivity values determined by standard monitoring techniques such as the open-hole pumping test or the geometric mean value of packer test results provide unrealistic estimates of travel time. Only the short-interval tests (multi-level pumping test and the maximum hydraulic conductivity measured by short-interval packer tests) provide realistic estimates of travel time through fractures.

Identification of Flowpaths

Methods used to locate hydraulically important fractures include fluid temperature and resistivity (or conductivity) logs, flow-meter logs, discrete-interval permeability tests (discussed above) and tracer tests. Fluid temperature and resistivity logs, completed for all boreholes, provide a qualitative methods for locating high-permeability flowpaths. Figure 14 suggests that flowpaths are present at 92, 82, 77.5, and 75 ft elevation. The exceedingly sharp contrast in temperature at 75 ft elevation suggests a very significant flowpath. These profiles cannot provide quantitative measures of flow.

Heat-pulse Flowmeter Logs

Flowmeter logging is a useful tool for determining which fractures are significant in terms of flow. Figure 18 shows the flowmeter logs for hole 13 under both static (left side) and pumping conditions (right side); negative flow rates indicate downward flow, positive flow rates indicate upward flow. Changes in flow rate indicate water entering or leaving the borehole. Under static conditions, water moves down and exits the hole through the fracture at a depth of approximately 21.5 ft. The second log was run while pumping 1.5 gpm from the top of the borehole; under these conditions, all flow was upward (note difference in horizontal scale). Comparing both figures helps identify the important flowpaths. Below an elevation of approximately 74.5 ft (21.5 ft depth) , the flow rate is essentially zero indicating that flow into or out of the hole is negligible. Going up the hole, there is a sharp increase in flow rate between 74 and 75 ft, a significant change between 80 and 81 ft elevation, and a small change between 86 and 87 ft elevation; these changes indicate the relative contributions of fractures in those intervals. The fracture at approximately 74.5 ft contributes more than half the water being pumped from the hole.

Table 1. **Comparison of measured hydraulic conductivity values and calculated travel times**

Test Method		**Hydraulic Conductivity (cm/s)**	**Calculated Travel Time* (units vary)**
Pumping tests			
Open Holes	Maximum	$5.1x10^{-3}$	109 days
	Minimum	$1.5x10^{-3}$	378 days
	Geometric Mean	$2.4x10^{-3}$	240 days
Multi-levels	Maximum	$1.2x10^{1}$	67 minutes
	Minimum	$5.6x10^{-1}$	23.4 hours
	Geometric Mean	$1.4x10^{0}$	9.5 hours
Packer Tests			
	Maximum	$4.2x10^{-1}$	1.3 days
	Minimum	$7.0x10^{-7}$	2206 years
	Geometric Mean	$3.0x10^{-4}$	5.3 years

* Calculations use a horizontal hydraulic gradient of .04/80 and assume an effective porosity of 1%

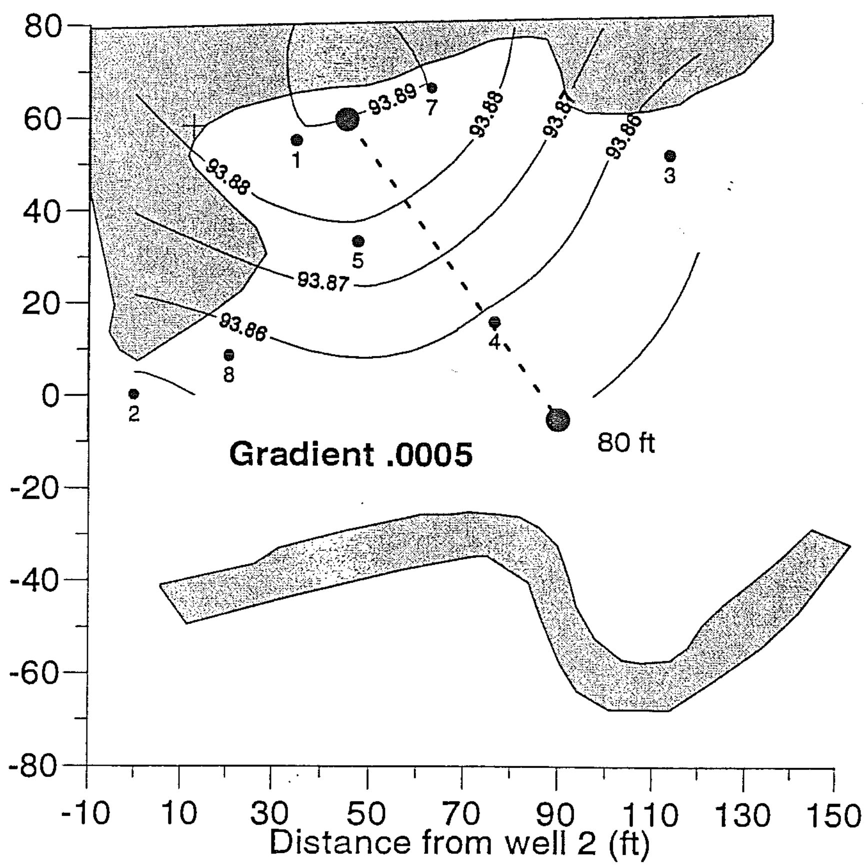


Figure 17. Head distribution, hydraulic gradient, and flow path used in calculating travel times.

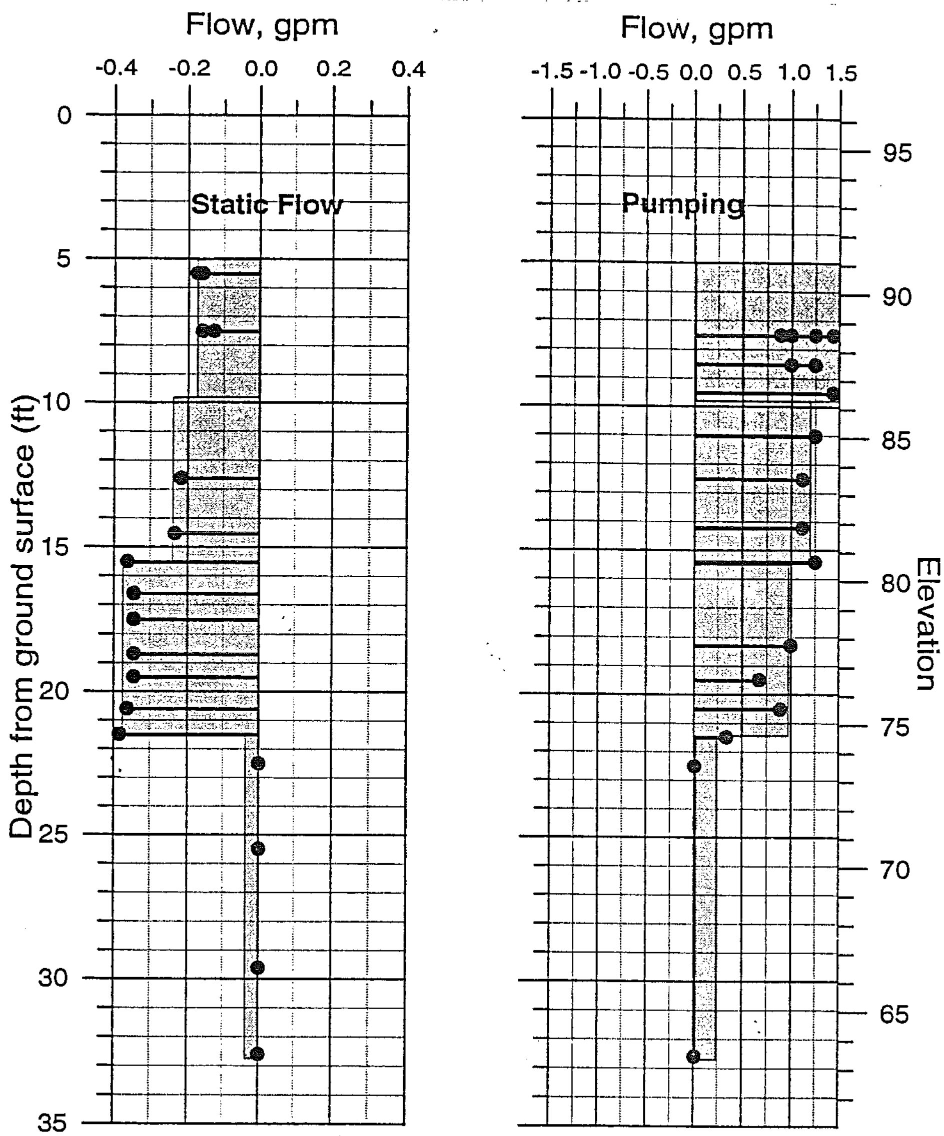


Figure 18. Heat-pulse flowmeter logs from hole 13 run under static (left log) and pumping (right log) conditions. Negative flows are downward and positive flows are upward; note difference in flow scale for the two logs.

Tracer Tests

During the summer of 1995, five tracer experiments were conducted at the site. Most tests consisted of injection of 1000 mg/l bromide tracer at a single port, with simultaneous sampling at up to 70 surrounding ports. The goal of the tests was to monitor tracer movement in three dimensions.

A natural gradient test, where tracer was injected at well 12 into the zone at 87 ft elevation, illustrates a variety of flow paths at the site. Hydraulic and geophysical data suggest that this is primarily a dissolution zone with a possible discontinuous horizontal fracture. Tracer movement is controlled by the head distribution as well as by the fracture network. Frequent and rapid fluctuations in hydraulic heads at the site indicate a dynamic flow system that

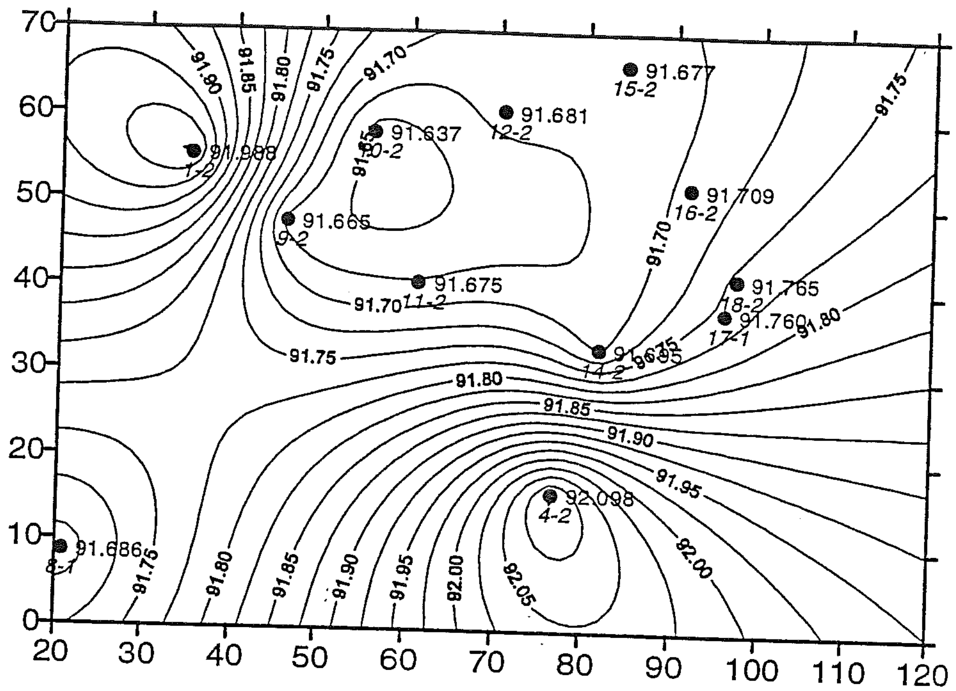


Figure 19. Head distribution in the tracer injection zone (approximately 87 ft elevation).

responds rapidly to recharge events. Horizontal gradients are quite low within individual horizontal fractures because the high transmissivities allow head to dissipate; vertical gradients are relatively high because the fracture network appears less integrated in the vertical direction. Figure 19 illustrates the head distribution in the zone at 87 ft elevation. Note that the low point in the head field is just left of center in the top portion of the diagram (port 10-2); the injection port for the tracer test is 12-2 (top center of diagram).

Figure 20, a cross section through wells 10, 12, and 15 (see Figure 13 for locations), and Figure 21, the tracer breakthrough curves for wells 10 and 12, illustrate the results of the tracer test. Starting with the top port, we see that tracer moved very slowly in the injection zone; the peak tracer pulse did not reached port 10-2 (elevation 87 ft) even after one week. In contrast, the tracer moved rapidly downward to port 12-3 (82 ft elevation), and very rapidly to the west to ports 10-3 (elevation 82 ft) and 10-4 (elevation 78 to 79 ft). The ports at approximately 75 ft elevation (12-4 and 10-5) both exhibit very low concentrations, and travel times to these ports are relatively rapid. Site characterization suggests that the fracture at 75 ft is the primary horizontal flowpath at the site and I believe that the tracer is greatly diluted upon reaching this elevation. Ports 12-5 and 10-6 both exhibit higher concentrations than the ports directly above them suggesting that some concentrated tracer manages to move through the vertical fractures and penetrate past the large fracture at 75 ft. Once the tracer penetrates below this fracture, it appears to spread laterally as several of the deepest ports received had trace detections of tracer (< 1 mg/l); including port 15-6.

Correlation Between Flowpaths and Stratigraphy

The tracer test data suggest that vertical and horizontal fractures are important pathways for groundwater movement. Numerous vertical fractures allow the tracer to quickly penetrate to the

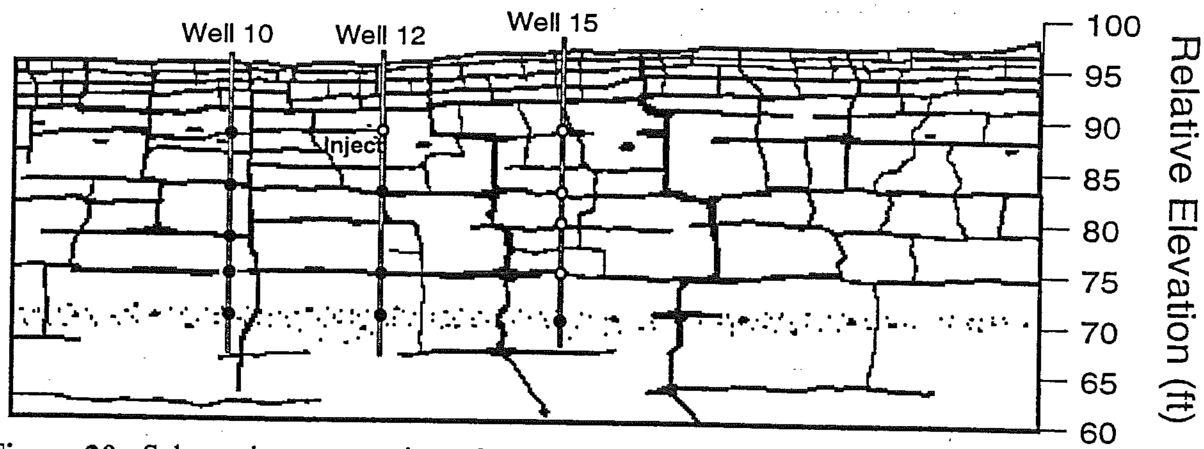


Figure 20. Schematic cross section of tracer pathways. Closed circles indicate ports where tracer was detected; open circles indicate ports where tracer was not detected.

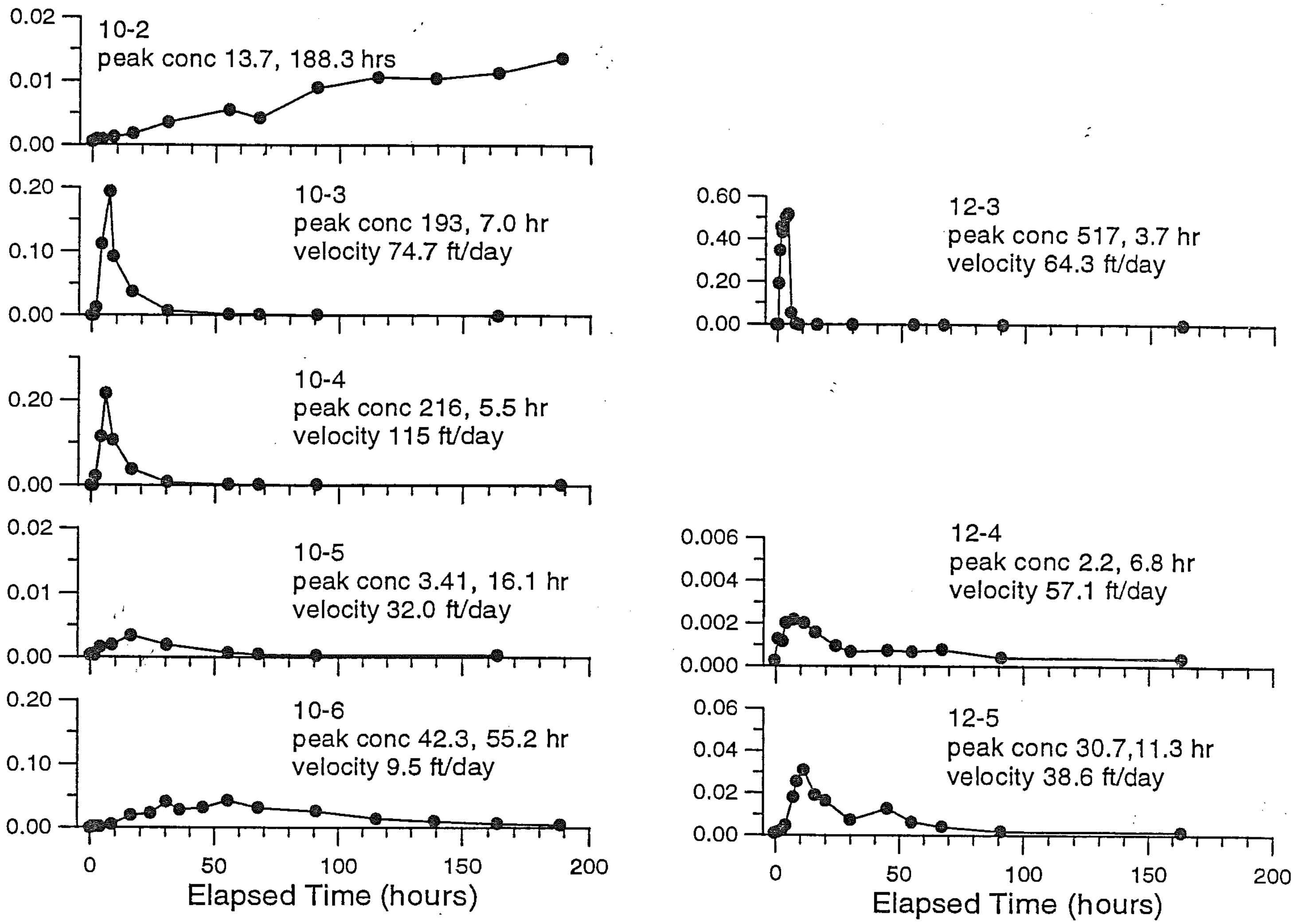


Figure 21. Breakthrough curves for holes 10 and 12; peak tracer concentration, peak arrival time, and a calculated velocity are shown for each port. The vertical axes are tracer concentration/injection concentration (C/1000 mg/l). Note that tracer concentrations vary greatly.

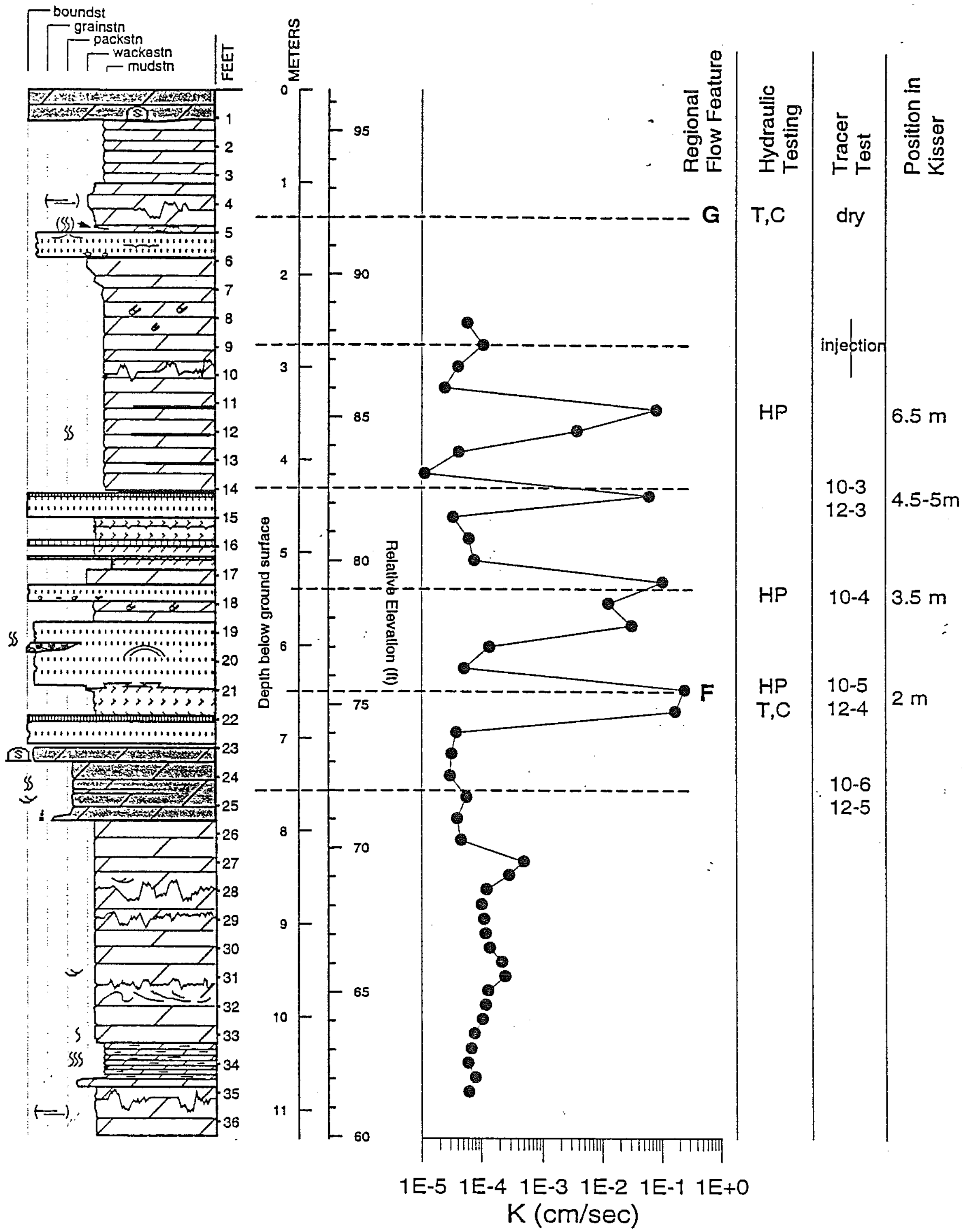


Figure 22. Comparison of subsurface stratigraphy and hydrogeologic data at Bissen Quarry. Core log (hole 5) is on left side of diagram (see Figure 9 for legend). The position of specific discontinuities in the walls at Kisser Quarry (Stop 5, Figure 10) is noted on the right side of the figure. Dashed horizontal lines indicate locations of multi-level sampling ports. The "Regional Flow Feature", "Hydraulic Testing" and "Tracer Test" columns summarize data that indicate a specific stratigraphic discontinuity is a significant flowpath. Abbreviations for hydraulic testing data are: T=fluid temperature, C=fluid conductivity, HP=heat pulse flowmeter. Refer to figure 21 for the breakthrough curves for the specific ports listed in tracer test column.

base of the monitoring system (approximately 25-30 ft). Monitoring ports placed in "dissolution zones" (i.e. port 10-2 at 87 ft elevation and port 15-6 at 70 ft elevation) indicate that groundwater flow in these zones is much slower and less significant that the fracture pathways. Comparison of the core log and hydrogeologic data (Figure 22) illustrates the relationships between stratigraphy and horizontal flowpaths at Bissen Quarry. Multiple lines of evidence suggest that the primary flowpath at the site is the fracture at approximately 75 ft elevation. This regional flow feature was seen in the walls at Kisser Quarry (Stop 5, Figure 10) and appears to develop at an especially well-developed cycle boundary. In outcrop the fracture does not always follow the truncation surface or a specific bedding plane, but rather appears to be contained within the organic-rich mudstones that overlie a cycle boundary. Several other discontinuities noted at Kisser Quarry also appear to be significant flowpaths at Bissen; these include the horizontal discontinuities/fractures at 79, 82.5, and 85 ft elevation.