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GEOLOGICAL AND NATURAL HISTORY SURVEY
3817 Mineral Point Road
Madison, Wisconsin 53705

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CORRELATION OF HIGH-PERMEABILITY ZONES WITH STRATIGRAPHIC FEATURES IN THE SILURIAN DOLOMITE, STURGEON BAY, WISCONSIN

by

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Open-file Report 1996-07
102 p. + 1 plate

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1996

CORRELATION OF HIGH-PERMEABILITY ZONES WITH STRATIGRAPHIC FEATURES IN THE SILURIAN DOLOMITE, STURGEON BAY, WISCONSIN

Final Report to Door County Soil and Water Conservation Department

by

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July, 1996

ACKNOWLEDGEMENTS

Many people have contributed to this project. We thank the Door County Soil and Water Conservation Department for their long support of hydrogeologic research in Door County and specifically for providing the funding for this project. Most research projects are collaborative efforts and we thank Prof. Mark Harris of the University of Wisconsin-Milwaukee and his student Dan Hegrenes for sharing core descriptions and for providing access for us to perform additional geophysical logging and hydraulic testing.

This project has been quite field-work intensive and many people have assisted with various aspects of the fieldwork. We thank the many quarry operators who granted us access to measure stratigraphic sections on their property and the homeowners who allowed us to log their wells. Several drilling companies, specifically Jorns Well Drilling, Euclide Drilling, Charlie's Pumps and Well Drilling, and Bill Van De Yacht Well Drilling provided valuable information on the location of open holes. Sturgeon Bay Utilities provided invaluable logistic support throughout the project. Several people assisted with the geophysical logging including Wylie Linquist, Jodi VanderVelden, Bill Raatz, and Dan Hegrenes. The discrete-interval packer testing of the Jarmen Road corehole was quite intensive both in terms of equipment preparation and actual test procedures and we thank Ron Hennings, Jodi VanderVelden, Scott Isberner, Marc Goodhue, Eric Oelkers, and Wylie Linquist for all of their efforts. Robert H. Dott Jr. provided valuable consultation in the field on stratigraphy. Many members of the staff at the Wisconsin Geological and Natural History Survey have assisted with data reduction and report preparation, especially Marcia Jesperson, Rilla Hinkes, Pete Roffers, and Jodi VanderVelden.

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INTRODUCTION

Project Background

The city of Sturgeon Bay (population 9,100) is located in Door County, northeastern Wisconsin, and lies partially within the Red River/Sturgeon Bay Priority Watershed. Drinking water for the city is provided entirely by wells completed in dolomite of Silurian age, known locally as the dolomite aquifer. The city has had difficulty in siting wells that remain free of bacteriological contamination. In 1991, five of the city's eight wells were considered "unsafe" because of the presence of detectable levels of bacteria (McMahon Associates, 1991). In order to provide a safe water supply, the city has installed ozone treatment systems on two wells. Contamination threats, however, are not limited to bacteria. The fractured, highly-permeable dolomite is covered by thin soils which have little attenuation capability. As a results, contaminants at or near the land surface have the potential to move rapidly, through fractures, to the water table.

The goal of the federal wellhead protection program is to protect groundwater used for public water supply by managing potential sources of contamination within the land area that supplies water to a given well or wellfield. The first step in any wellhead protection program is to identify the land area supplying water to the well (also called the zone of contribution of the well). Once this has been determined, a well head protection area can be defined that aims to protect some or all of the zone of contribution. As part of the ongoing Red River/Sturgeon Bay Priority Watershed (Door County Soil and Water Conservation Dept., 1995), the Wisconsin Geological and Natural History Survey (WGNHS) will be delineating zones of contribution for the City of Sturgeon Bay's wells using a variety of groundwater flow models.

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). The groundwater flow models for the Sturgeon Bay area require characterization of vertical fractures, horizontal high-permeability zones, and matrix permeabilities at a regional scale. As part of the on-going Sturgeon Bay wellhead protection project, air photos were used to map the distribution of vertical fractures in the study area (Bradbury and others, in preparation). This report integrates surface and subsurface stratigraphic, geophysical, and hydrogeological data in order to characterize both the horizontal high-permeability zones and matrix permeabilities in the Silurian aquifer.

Goals and Approach

The primary objective of this project was to identify high-permeability zones within the Silurian dolomite in the vicinity of the Red River/Sturgeon Bay Priority Watershed and determine if these zones could be correlated on a regional scale. In order to meet this objective, we 1) refined the geologic framework by combining detailed stratigraphic description of cores and outcrops with geophysical data (especially natural gamma) and then correlated the defined stratigraphic units in three dimensions, 2) located and characterized high-permeability features in selected boreholes using a variety of methods, 3) completed detailed hydraulic testing of available coreholes to quantify the hydraulic conductivity of both the matrix and the high-permeability features, and 4) compared the location of the high-permeability features with the core description in order to explore the possible stratigraphic controls on the position of these high-permeability features.

Methods

Stratigraphic Characterization

Surface stratigraphic data collected for this study include nine measured sections and 24 field checks on lithologies in smaller outcrops near Sturgeon Bay (see figure 1 for locations). Field notebooks containing data from the measured sections and locality notes are on file at the WGNHS. Subsurface lithologic data include a core from DR-394 and series of short cores from Bissen Quarry. Core descriptions for DR-394 (see figure 2) were provided by D. Hegrenes and Dr. M. Harris of the University of Wisconsin Milwaukee (Hegrenes, in prep.); a description of one of the Bissen cores is included in Appendix 1.

Geophysical Logging

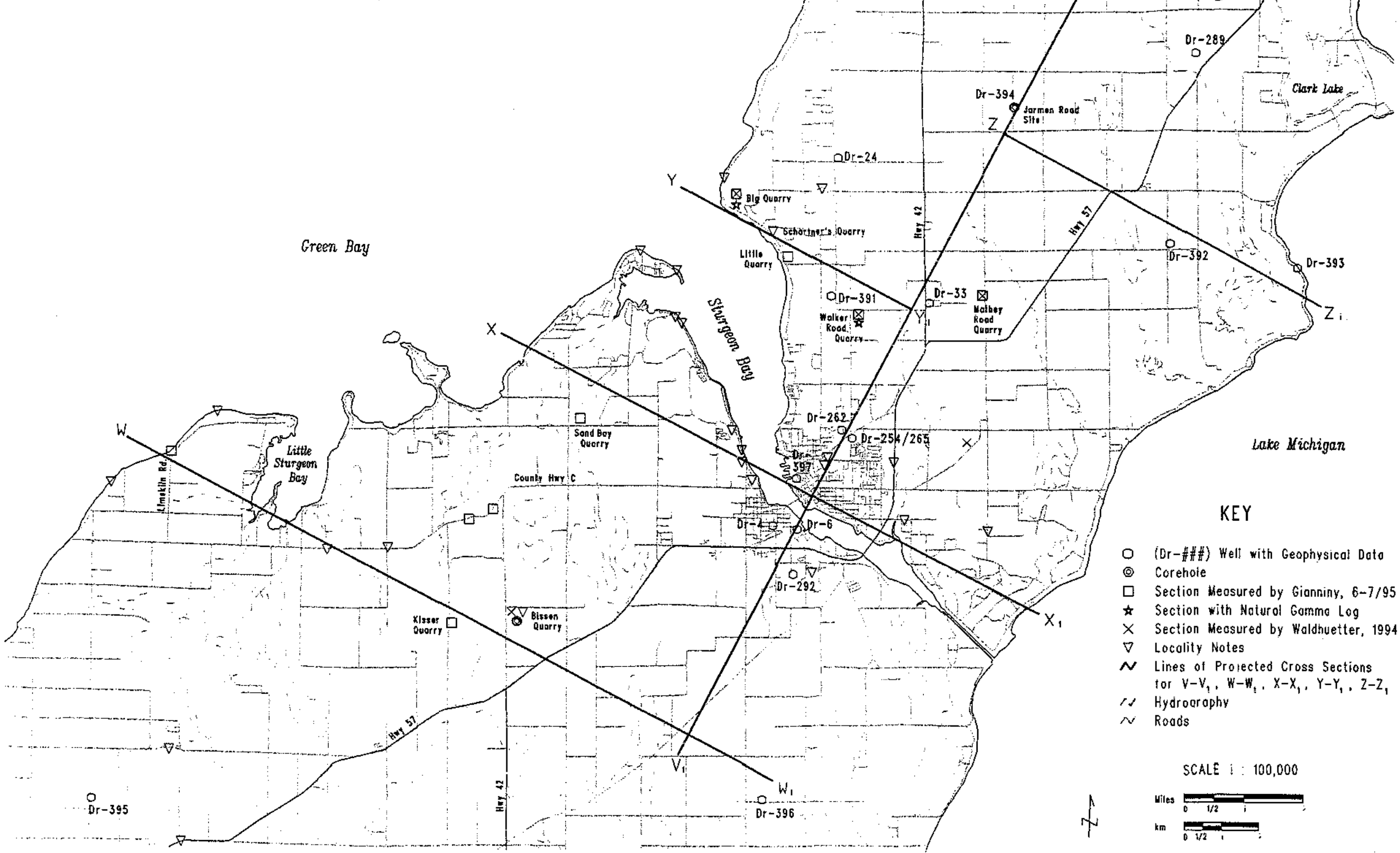
Geophysical logs are used to correlate stratigraphic units with similar geophysical characteristics, identify fracture zones and other horizontal discontinuities, and provide information on high-permeability features. We have compiled existing geophysical data for several previously-logged wells from Sherrill (1978; holes DR-24, DR-33, DR-262, and DR-289), Bradbury and Muldoon (1992; several holes at Jarmen Road site), Muldoon and Bradbury (in prep.; Bissen quarry site), and Bradbury and others (in prep.; DR-265, DR-292). We also logged nine new or previously unlogged wells (DR-4, DR-6, DR-391, DR-392, DR-393, DR-394, DR-395, DR-396, and DR-397) using a Mt. Sopris MGX digital borehole logger. All geophysical data were recorded relative to the depth from the top of the casing or depth from ground surface (Appendix 4). The elevation of each well (relative to feet above mean sea level) was estimated from U.S.G.S. 7.5 minute topographic maps. Locations of all wells with geophysical data are shown on figure 1. In addition to the borehole geophysical data, we completed natural gamma logs of two outcrop localities; these data are included in Appendix 1.

Geophysical logs provide information both on the lithologic and hydrogeologic characteristics of the stratigraphic units. Logs completed as part of stratigraphic portion of this study include caliper, which measures borehole diameter and can help identify fractures and dissolution zones; natural gamma, which measures natural radiation and can be used for stratigraphic correlation as well as to identify zones with shale or clay; and single-point resistivity and spontaneous potential, which are useful for stratigraphic correlation. Logs used to locate and characterize high-permeability zones include fluid temperature/resistivity and heat-pulse flowmeter. Appendix 4 contains caliper, gamma, single-point resistivity and spontaneous potential logs. Fluid temperature and resistivity, and heat-pulse flow logs are explained more fully below; these logs are included in Appendix 5.

Hydrogeologic Characterization

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. Some of these methods are qualitative and can be used to locate high-permeability features, while others provide a quantitative measure of the hydraulic conductivity of the feature. Fluid temperature and

Figure 1. Map showing location of measured geologic sections, locality notes, wells, coreholes and cross-section lines (see Plate 1 and Appendix 3).



resistivity/conductivity data can be acquired easily and rapidly in any open borehole. Sharp changes in these profiles, within a given borehole, provide a qualitative method of locating discrete high-permeability features where water of differing chemistry or temperature is flowing into or out of the borehole. Flowmeter logging can be used to quantify the amount of water entering a borehole at various depths. Data from spinner flowmeter logs (Bradbury and Muldoon, 1992; Jarmen Road site) and from heat-pulse flowmeter logs (Appendix 5) are incorporated in this study.

Permeability tests conducted on discrete sections of a borehole provide a quantitative method of characterizing high-permeability features. Discrete intervals can be isolated by installing piezometers screened over short intervals or by using inflatable packers. These zones can then be tested either by pumping tests or slug tests in order to quantify hydraulic properties. Sherrill (1978) reports yield data for portions of several wells obtained by pumping discrete zones isolated using inflatable packers. Hydraulic conductivity values for discrete interval tests have been reported by Bradbury and Muldoon (1992) who performed slug tests in piezometers at the Jarmen Road research site and by Muldoon and Bradbury (in prep.) who have conducted over 370 slug tests as part of the detailed hydrogeologic characterization of the Bissen site. Bradbury and others (in prep.) provided hydraulic conductivity values for DR-265 (included in Appendix 5) which were measured during straddle-packer pumping tests. In this study, we conducted slug tests in well DR-394 using a straddle packer.

Not all logs or hydraulic tests were completed on all holes, and we repeated some logs for holes that had been logged in previous studies. Fluid temperature and resistivity data were not collected for two wells (DR-393 and DR-396) due to partial obstruction or turbid water from recent well construction. Caliper and fluid temperature/resistivity were repeated in well DR-24. Table 1 summarizes the types of data available for the wells used in this study.

Table 1. Data types compiled from previous studies and collected as part of this study*

Well ID	Gamma	SP/ resistivity	Caliper	Fluid Temp/Res	Flowmeter	Hydraulic Testing
Sherrill (1978)						
DR-24	X	X				
DR-33	X	X				
DR-262	X					yield data
DR-263						yield data
DR-264						yield data
DR-265						yield data
DR-289	X					
Bissen (Muldoon and Bradbury, in prep.)						
	X	X	X	X	X	hydraulic cond
Jarmen Rd (Bradbury and Muldoon, 1992)						
	X	X	X	X	X	hydraulic cond
Sturgeon Bay WHP (Bradbury and others, in prep)						
DR-265	X	X	X	X	X	hydraulic cond
DR-292	X	X	X	X		
This Study						
DR-4	X	X	X	X	X	
DR-6	X	X	X	X	X	
DR-24			X	X		
DR-391	X		X	X		
DR-392	X	X	X	X	X	
DR-393	X	X	X		X	
DR-394	X	X	X	X	X	hydraulic cond
DR-395	X	X	X	X	X	
DR-396	X	X	X		X	
DR-397	X	X	X	X	X	

*see figure 1 for well locations

STRATIGRAPHY OF THE SILURIAN DOLOMITE

The Silurian Dolomite Aquifer

The Silurian dolomite forms an important regional aquifer along the western flank of the Michigan Basin from Canada to northeastern Illinois. In Door County, 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 feet per mile. Erosion has beveled the dolomite aquifer into an eastward thickening wedge that thickens from 25 ft (8-9m) along the shore of Green Bay near Little Sturgeon Bay to more than 550 ft (176 m) near Whitefish Dunes State Park on the eastern shore of the peninsula (see cross-sections, Appendix 3). Dolomite thickness within the city of Sturgeon Bay ranges from 360 to 420 feet.

The Silurian aquifer provides the primary source of groundwater for Door County residents. 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).

Previous hydrogeology studies in Door County have generally divided the dolomite into the Upper Niagaran and Lower Alexandrian Series and included all the Silurian carbonate rocks in the "Dolomite Aquifer System" (Sherrill, 1978; Bradbury, 1982; Nauta, 1987). Finer scale divisions of stratigraphic formations within these series have been long recognized (Chamberlin, 1877; Shrock, 1940; Sherrill, 1978). Because the stratigraphic units are somewhat difficult to distinguish and because it was assumed that fracture zones (Sherrill, 1978) rather than lithologies controlled groundwater movement, stratigraphy has not been incorporated into many groundwater investigations. Recent work in southeastern Wisconsin (Rovey and Cherkauer, 1994) and in Door County (Muldoon and Bradbury; 1990, 1994) suggests that lithologies and horizontal stratigraphic discontinuities in the Silurian dolomite play a more important role in groundwater movement than was previously assumed.

Stratigraphy

Previous Work

The Silurian strata of the Door peninsula were first described and mapped by Chamberlin (1877). Subsequent workers (Shrock, 1940; Ehlers and Kesling, 1957; Ehlers, 1973; and Allen, 1986) have modified the nomenclature and age estimates but not the original lithologic subdivisions. Additional overviews of Door County stratigraphy are provided by Steiglitz (1991) and Kluessendorf and Mikulic (1989). Detailed local studies on the Silurian stratigraphy include Shrock (1940), Brooks (1978), Elger (1979), and Johnson and Campbell (1980). A series of studies directed by Dr. Mark Harris at the University of Wisconsin Milwaukee are providing detailed sequence stratigraphic analysis of the entire Door County Silurian section (Waldhuetter, 1994; Harris and Waldhuetter, in press; Hegrenes, in prep.). Ongoing research at the University of Wisconsin-Milwaukee includes the description and interpretation of a continuous core from the lower Engadine Formation through the entire Silurian section and into the Ordovician Maqouketa shale in hole DR-394 (Hegrenes, in prep). The core and geophysical data from DR-394 form the critical linkage of lithostratigraphic data, sequence stratigraphic data, and geophysical data for this project and future studies in this portion of the Michigan basin.

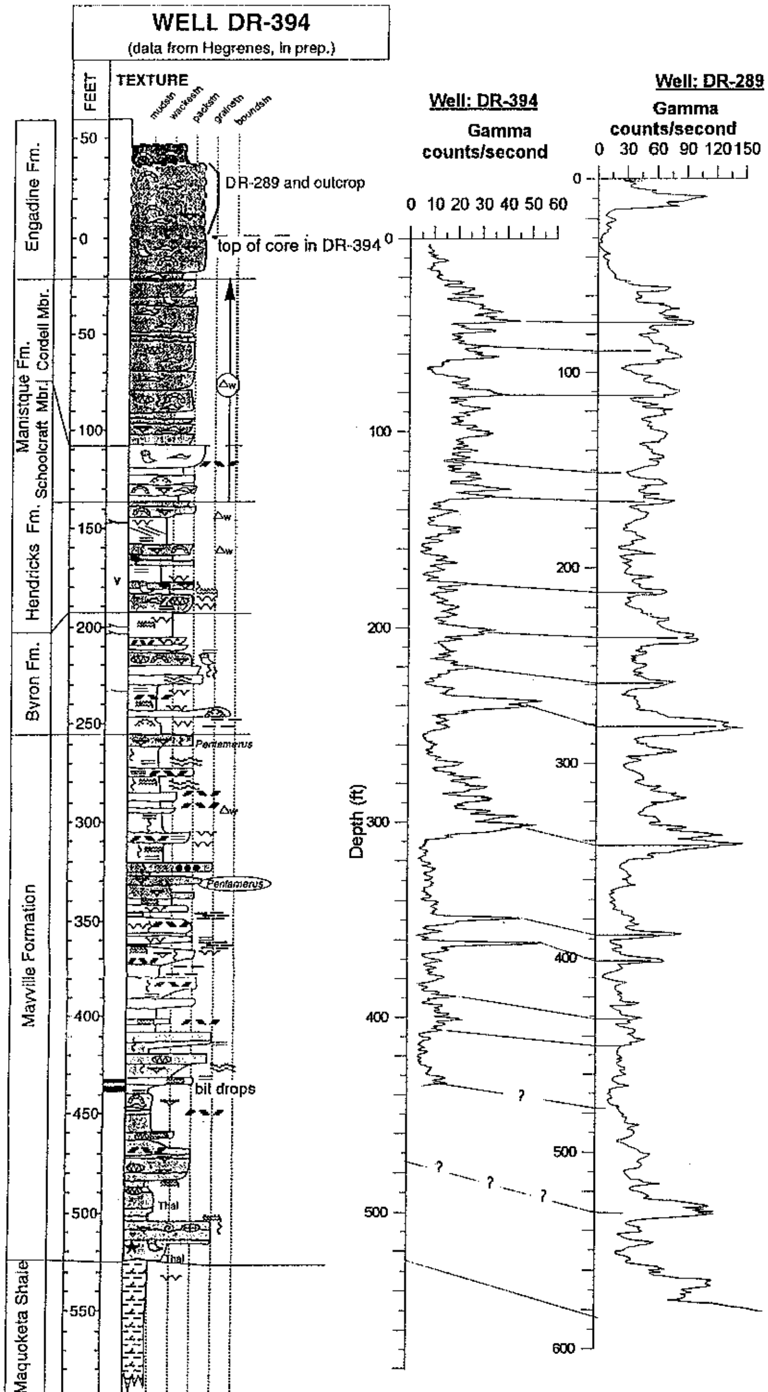
Compilation and Correlation of Stratigraphic Data

Figure 2 shows a generalized stratigraphic column for Door County, along with description of each of the formations and natural gamma logs for corehole DR-394 and well DR-289. The stratigraphic data comes from core and outcrop descriptions (locations shown in Fig. 1); unit thicknesses vary throughout the county and the thicknesses noted in the formation descriptions are from core DR-394. The lithologic units, vertical succession of units, and natural gamma signatures are similar throughout the study area making possible regional correlations and three dimensional stratigraphic reconstructions (Plate 1, and Appendix 3, described below)

Natural Gamma Correlation-- Natural gamma logs provided the primary tool for correlating lithostratigraphic units and flow features throughout the study area. The natural gamma logs for corehole DR-394 and well DR-289 are plotted in figure 2 adjacent to the lithologic column, illustrating the natural gamma signature of the stratigraphic section. Correlation of the gamma signature from these two holes (figure 2) illustrates that the thickness of the stratigraphic units varies somewhat throughout the study area. Natural gamma logs compiled for this project (see Table 1) form a database of 17 wells (Appendix 4) which have been used to correlate stratigraphic units and flow features throughout the study area (Plate 1). Plate 1 was constructed by projecting the gamma data from all wells onto a NE-SW line (line W-W' on figure 1); noting the position of observed flow features, and then correlating the gamma signatures between wells.

Structure Contour Maps-- Appendix 2 contains contour maps of the elevations of three distinct horizons: 1) the contact between the Maquoketa shale and the overlying Silurian dolomite, 2) flow zone D which occurs near a green shale layer (peak in gamma signature), and 3) flow zone I which is located just above a distinctive natural gamma peak. These maps illustrate the general and local strike and dip of these specific horizons and they were constructed to help constrain the stratigraphic correlations illustrated in the cross-sections (Appendix 3). Variations in strike and dip are illustrated by the differences in orientation and spacing of the lines. In general, these maps show a regional dip of the strata to the ESE and minor thickness variations. The exceptions are the Maquoketa shale/Mayville contact which exhibits some topographic relief and a small structure to the northwest of the city of Sturgeon Bay (Appendix, Y-Y' section) which appears to be a slight upwarping of the strata. This structure was noted by Thwaites and Lentz (1922), who interpreted it as the surface expression of an anticline that extends to the Precambrian basement.

Cross Sections--Five cross sections (Appendix 3) illustrate the three-dimensional distribution of stratigraphic units and high-permeability features. Cross sections were constructed by projecting outcrop, core, geophysical and flow data onto the five lines of cross section shown in Figure 1. The projected cross sections are constrained by structural contouring on three horizons (Appendix 2). Due to slight changes in the orientation (strike and dip) of the Silurian strata, the linear cross sections illustrate changing elevations of the stratigraphic horizons.



Engadine Formation: (21 ft in core; up to 50-60 ft in DR-289 and DR-393 which are downdip from corehole) Medium to fine crystalline dolomite composed of fossiliferous wackestones and packstones with domal and sheet-like stromatoporids, brachiopods, and corals *(Favosities, Halysities)*; chert is typically absent. Subtidal deposition is inferred.

Manistique Formation: (116 ft) Dolomite with textures dominated by fossiliferous grain-supported packstones (coarse-grained dolomite) with minor fine-crystalline mudstones. White chert is abundant. The basal 29 ft comprise the Schoolcraft Member which is dominated by fossiliferous, bioturbated packstones alternating with thin, flat-bedded mudstones. Deposition is inferred to have shifted from shallow to subtidal fossiliferous facies. This Member is conformably overlain by the Cordell Member (79 ft) which contains domal and sheet-like stromatoporids, brachiopods, corals *(Favosities, Halysities)*, and brachiopod packstones inferred to have been deposited in subtidal environments.

Hendricks Formation: (56 ft) Dolomite with textures that alternate between fossiliferous packstones (coarse-grained dolomite) and mudstones (fine-grained dolomite) with mudcracks, crinkly laminations and thin flat beds. Chert is common in packstones. Deposition is inferred to have shifted, at least four times, from shallow supratidal facies to subtidal fossiliferous facies. The upper 20 ft of the formation at Big Quarry (figure 1) contains inclined bedsets of crinkly and wavy laminated mudstones and packstones. Bed truncation occurs above and below this bedset and significant dissolution appears to be focused along these truncation surfaces.

Byron Formation: (62 ft) Dolomite dominated by mudstones with mudcracks, fenestral porosity, crinkly laminations, and thin flat beds; texture is medium to fine crystalline. The bottom half of the formation is typically medium to coarsely crystalline with green shaly partings and minor bioturbation. One (to two) 1-3 ft thick fossiliferous intervals occur within the middle portion of the Byron (214-222' in DR-394). At some locations, the upper 10-15 ft of this formation shows significant dissolution.

Mayville Formation: (269 ft) Dolomite with textures ranging from fossiliferous grain-supported packstones (coarse-grained) to mudstones with crinkly laminations (fine-grained). The basal 110 ft are dominated by fossiliferous, bioturbated wackestones and packstones alternating with minor and thin crinkly laminated mudstones (grey shading). The middle 90 ft (no shading) includes peloidal wackestones, mudstones, and is capped by a thick (27 ft) unit of pentamerid brachiopod packstones (grey shading). The upper 70 feet of the Mayville Formation (no shading) is dominated by very fine-grained, laminitic and bioturbated mudstones with thin, flat beds, abundant rip-up clasts, and white chert; it is capped by a 4-5 ft thick bed of pentamerid brachiopod packstone (grey shading).

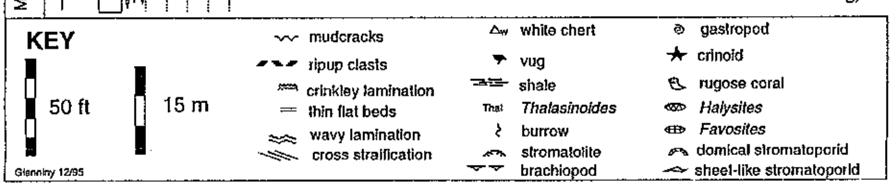


Figure 2. Composite stratigraphic section for Door County illustrating general lithologic textures, bedding characteristics, unit thicknesses, and significant fossil occurrences. The stratigraphic data come from core and outcrop descriptions (locations shown in Fig. 1). The natural gamma logs for holes DR-394 and DR-289 illustrate the natural gamma signature of the lithologic units. Brief descriptions of each stratigraphic formation are included on the right side of the figure. Unit thicknesses vary somewhat throughout the county and the thicknesses noted in the formation descriptions are from core DR-394.

HYDROGEOLOGIC CHARACTERIZATION

The hydrogeologic characterization of the Silurian dolomite included 1) discrete-interval slug tests of the saturated portion of corehole DR-394 in order to characterize the hydraulic conductivity distribution of both the matrix blocks and high-permeability features, 2) a compilation of existing data on high-permeability features, and 3) borehole logging of flow-meter data along with fluid temperature and resistivity data in order to locate and characterize high-permeability features in numerous boreholes

Discrete-Interval Permeability Tests

We conducted detailed discrete hydraulic conductivity measurements in the cored hole, DR-394, which penetrates almost the entire Silurian section. In this hole, over 150 hydraulic conductivity measurements have been completed at 1.5-ft increments between the depths of 419 and 180 ft. Measured hydraulic conductivity values range over five orders of magnitude from 1.5x10^{-1} to 2.0x10^{-6} cm/sec. Both the downhole profile (figure 3) and the histograms (figure 4) indicate that there are several distinct populations of measured hydraulic conductivity values, thus the profile has been divided into three segments.

Segment one occurs between depths of 418.8 to 352.3 ft (figure 3) and generally exhibits low matrix hydraulic conductivity values on the order of 10^{-5} cm/sec (figure 4b). A few significantly higher hydraulic conductivity values (on the order of 2x10^{-4} cm/sec) were measured at depths of 398 to 401 ft. Segment two occurs at depths from 352.3 to 317.6 ft (figure 3) and exhibits significant higher hydraulic conductivity values than segment one (compare histograms 4b and 4c). The majority of this segment is dominated by values on the order of 10^{-4} cm/sec with a notable exception of a 9-ft thick peak between depths of 342 and 349 ft. Hydraulic conductivity values in this peak measure 6x10^{-3} cm/sec. Segment 3 occurs at depths from 180 to 316.1 ft (figure 3) and is characterized by a trimodal hydraulic conductivity distribution (see histogram 4d) with a few high values on the order of 10^{-1} cm/sec, a second group of moderate hydraulic conductivity values that cluster around 10^{-3} cm/sec, and a group of low values clustered around 10^{-5} cm/sec.

Compilation of High-Permeability Data

High-permeability features from 13 holes are compiled in figure 5; this figure incorporates existing data from Sherrill (1978), Bradbury and Muldoon (1992), Muldoon and Bradbury, (Bissen quarry, in prep.), and Bradbury and others, (Sturgeon Bay wellhead protection project, in prep.) as well as heat-pulse flowmeter and fluid temperature/resistivity data (Appendix 5) collected as part of this study. A brief description of each of these data sources is outlined below

Gamma logs (Appendix 4) were used to identify the stratigraphic position of flow features in each well. The flow features from each well are projected onto the core lithology and gamma signature from hole DR-394 (figure 5). This was necessary since the thickness of lithologic units varies across the study area. By projecting data onto hole DR-394 we could account for this variable thickness and directly compare flow features with lithologic data; flow features across the region

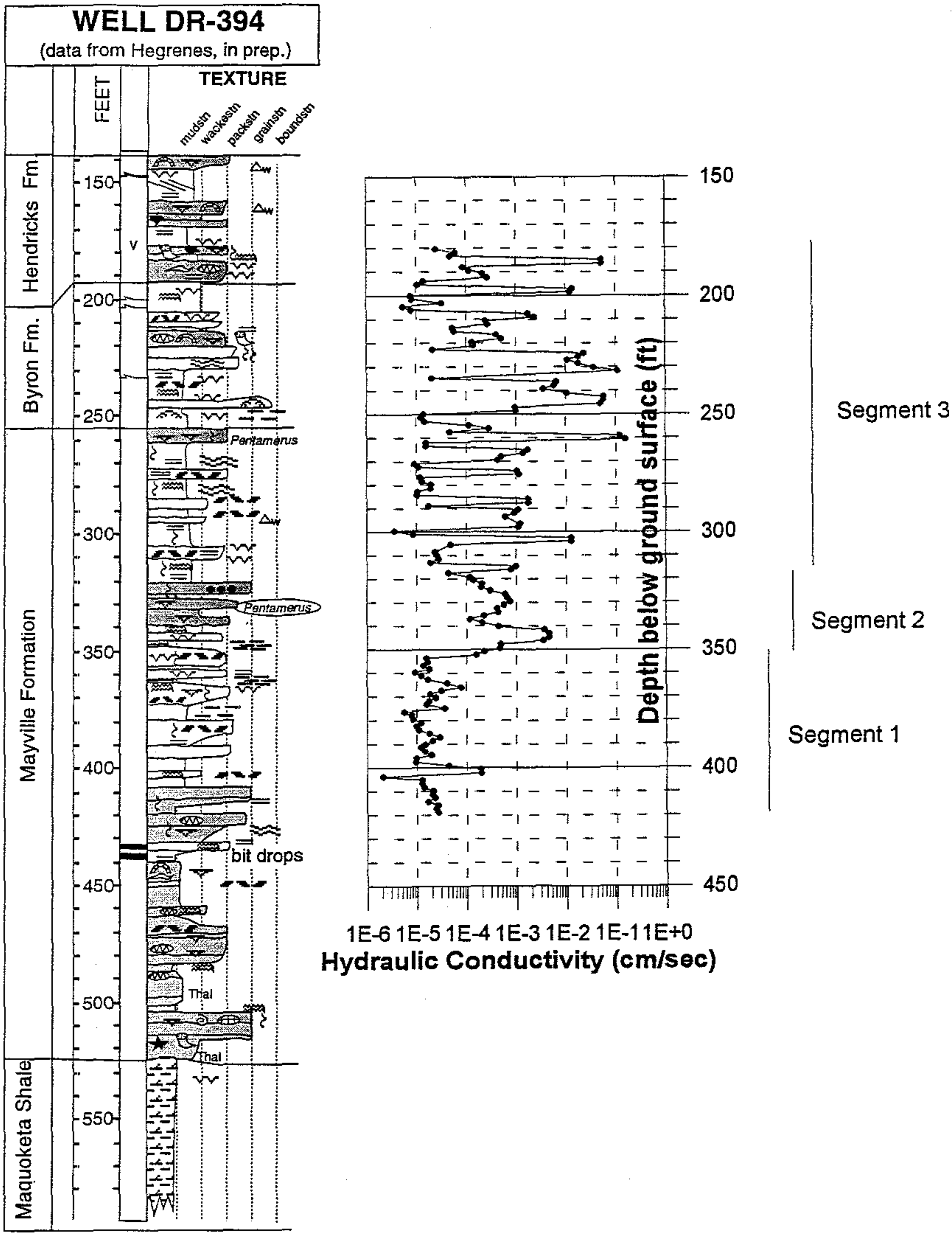


Figure 3. Hydraulic conductivity profile for Jarmen Rd. corehole (DR-394, location shown in figure 1) Slug tests were conducted at 1.5-ft intervals using straddle-packers. The profile has been divided into three segments based on variations in hydraulic conductivity. The stratigraphic column, based on descriptions from Hegrenes, (in prep.) is shown to the left of the hydraulic conductivity profile; legend is shown in figure 2.

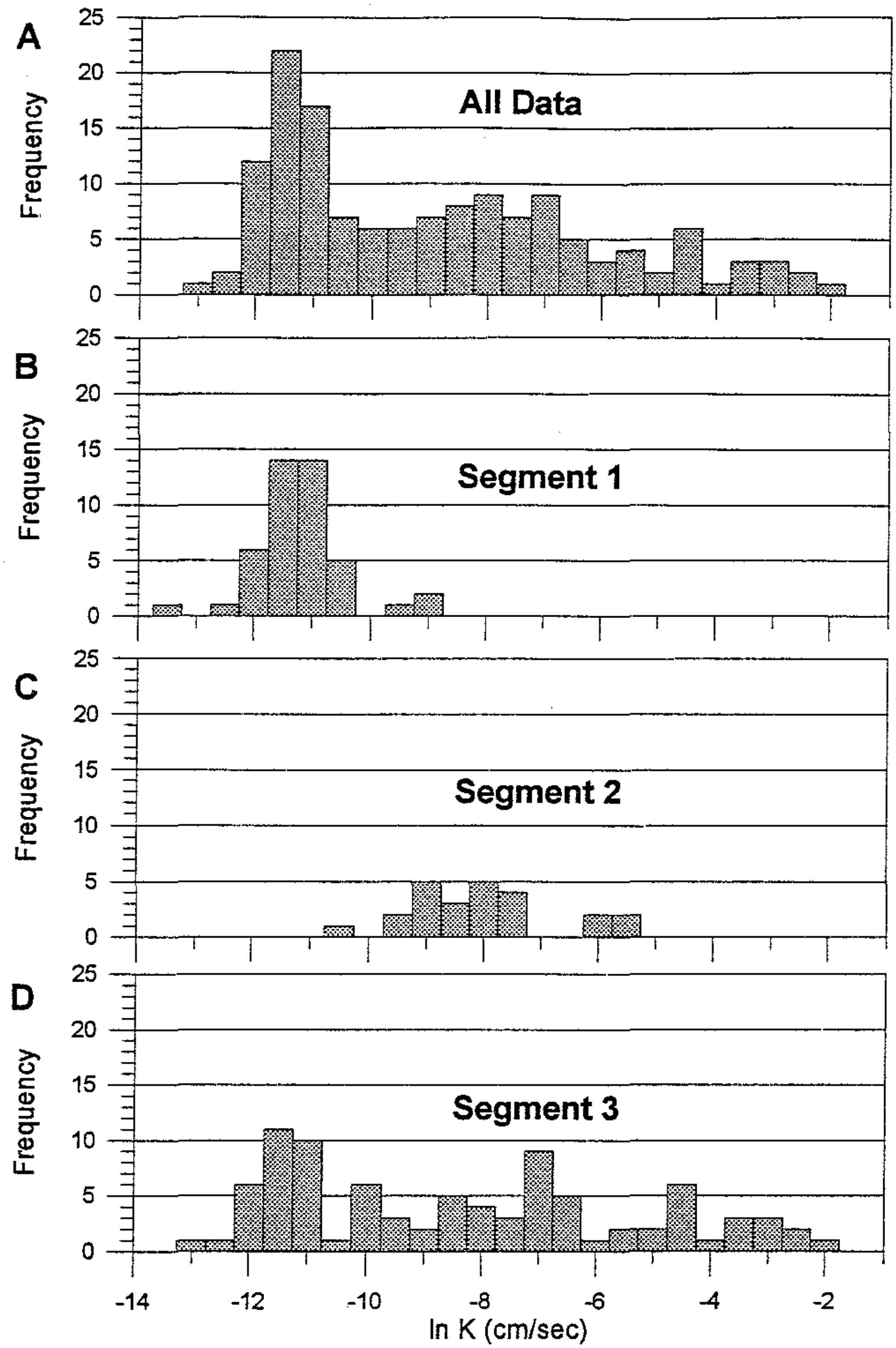


Figure 4. Histograms of hydraulic conductivity values measured with short-interval packer tests in the Jarmen Rd. corehole (figure 3). **A)** Histogram of all data. **B)** Histogram of data from 352.3 to 418.8 ft, hydraulic conductivity is generally low and appears to be dominated by matrix porosity. **C)** Histogram of data from 317.6 to 352.3 ft depth, matrix conductivity is higher than segment 1. **D)** Histogram of data from 180 to 316.1 ft depth, the trimodal distribution of hydraulic conductivity values suggests that matrix porosity, numerous small bedding-plane fractures and a few large bedding-plane discontinuities control hydraulic conductivity in this segment.

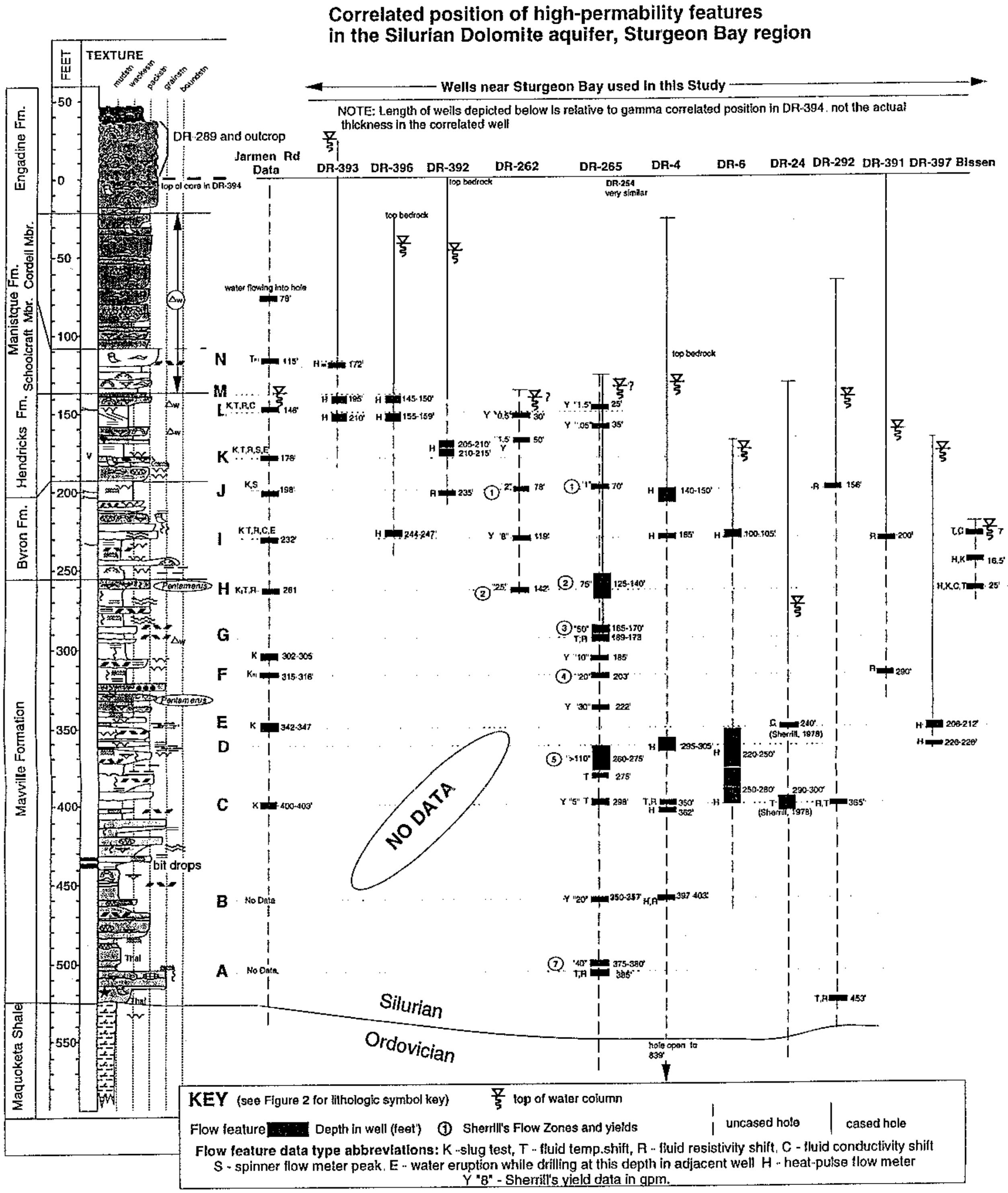


Figure 5. Flow features projected onto well DR-394 using gamma signatures from twelve wells in the Sturgeon Bay region (see Figure 1) Note: DR-262 abandoned in 1978 after testing, DR-4 (Sturgeon Bay municipal well #1) to be abandoned 12/95, DR-265 cased to 171' after testing in 1978. Flow features shown for Jarmen Rd site include data from DR-394 and seven nearby wells. Well DR-394 collapsed below a depth of 440 ft prior to geophysical and flow logging.

may now be viewed in terms of their stratigraphic setting. Since the flow features have been compiled relative to the gamma signature of DR-394, the length of the wells shown in figure 5 is a "correlated gamma length" rather than the true length. The true depth of each flow feature is noted to the right of flow-feature symbol.

Figure 5 presents all of the data used to locate high-permeability features; abbreviations for the different data types are summarized in the Key and plotted to the left of the flow-feature symbol. Most wells are open to only a small portion of the Silurian aquifer; flow features can only be detected in the uncased, saturated portion of a given well. Figure 5 indicates the cased and uncased portion of each hole and also illustrates the depth of water in each hole

Figure 6 presents the geographic distribution of each flow feature. The open circles indicate holes where it was possible to detect the flow feature (i.e saturated and uncased conditions) while the closed circles indicate that the flow feature was detected in a given hole. It is possible that a flow feature may be present in a given hole, but that we did not detect it in our current study. This is particularly likely for holes where only fluid temperature/resistivity data, but not flowmeter data, are available (DR-292, DR-24, DR-391). As explained in Appendix 5, changes in fluid temperature/resistivity are most pronounced in the spring and this study was conducted in the summer, thus some flow features may not have been detected. In addition, the accuracy of locating a flow feature with heat-pulse flowmeter measurements is determined by the spacing of the measurements. For holes with widely-spaced measurements, some flow features may not have been detected

Existing Data

Sherrill (1978)-- Sherrill performed packers test to determine the well yields for five wells in the Sturgeon Bay area (DR-254, DR-262, DR-263, DR-264, and DR-265) as well as additional tests in the vicinity of Fish Creek and Bailey's Harbor. We have compiled all of Sherrill's yield data for DR-262 and DR-265. Wells DR-254, DR-263, and DR-264 are located close enough to the other two wells that they provided no additional data. Sherrill's yield data are noted with a Y in figure 5 with the yields, in gpm, noted to the left of the feature. Sherrill used these data to define seven "high-flow" zones that were laterally continuous throughout the dolomite aquifer. Some of these zones appear to be discrete bedding plane discontinuities while other zones are several feet in length and appear to be composed of a clustering of bedding planes partings or perhaps zones of enhanced dissolution. It is not always clear from the yield data in the report why Sherrill places a high-flow zone in some wells (for example zone 1 in well DR-265), however, rather than reinterpret Sherrill's data, we have incorporated all the flow zones he identified as "high-permeability" features in our summary. These are noted on figure 5 as open circles with numbers inside. In addition to the packer-test yield data, we have compiled Sherrill's fluid temperature and conductivity logs for hole DR-24.

Bradbury and Muldoon (1992)--The Jarmen Road research site (figure 1) was initially established as part of the project on hydrogeology and groundwater monitoring in the Upper Door Priority Watershed. The original monitoring network consisted of seven boreholes in which several piezometers were installed. Flow data include several temperature and conductivity logs, a

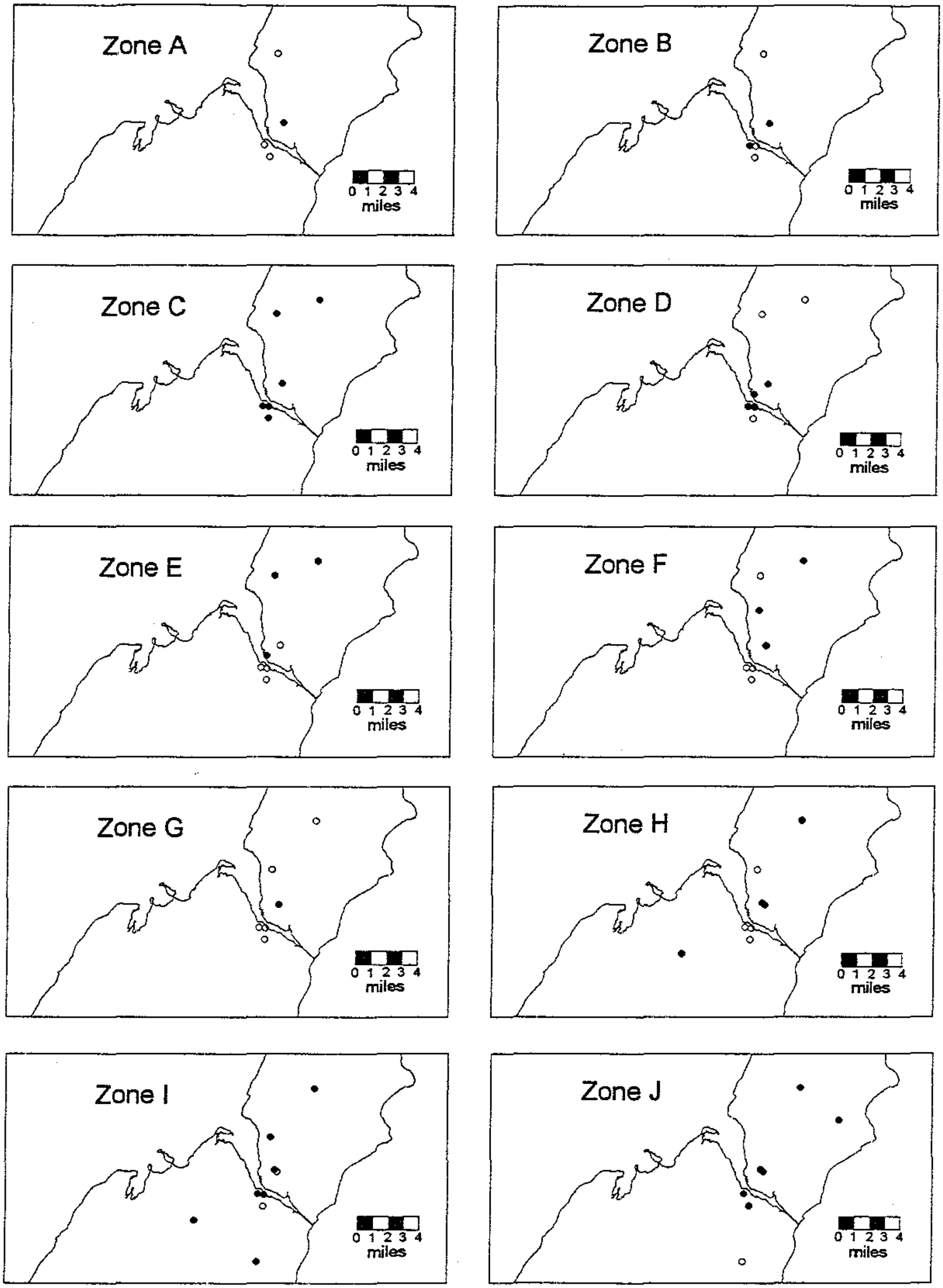


Figure 6. Geographic distribution of flow features A to J. Closed circles indicate that the flow feature was detected in a given hole while open circles indicate holes where it was possible to detect the flow feature (i.e. saturated and uncased conditions) yet the feature was not detected.

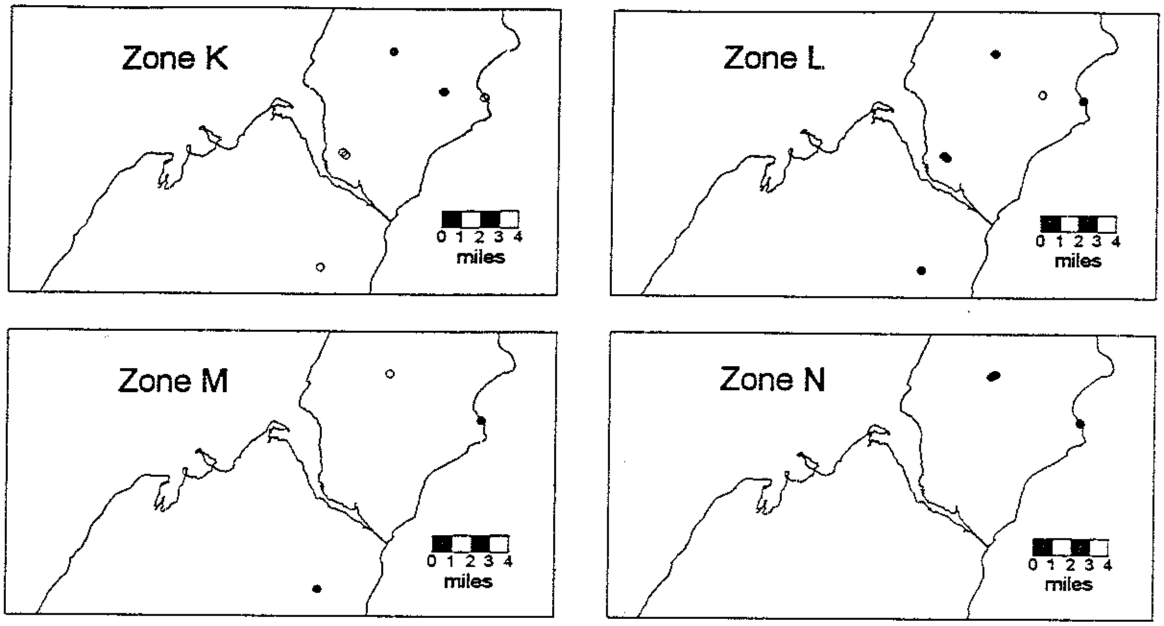


Figure 6 (cont). Geographic distribution of flow features K to N. Closed circles indicate that the flow feature was detected in a given hole while open circles indicate holes where it was possible to detect the flow feature (i.e. saturated and uncased conditions) yet the feature was not detected.

spinner flowmeter log of DR-339, a television borehole log of DR-339 showing water flowing into the hole at specific fractures in the upper portion of the hole, and hydraulic conductivity values from slug tests completed on the piezometers. In addition, Bradbury and Muldoon (1992) noted direct evidence for horizontal hydraulic connection while installing the original monitoring wells at the site. At two depths, water erupted from an existing well during construction of a second well nearby. The air-rotary drilling method uses air circulation to lift the cuttings from the hole during drilling; with both "erupting wells", the air moved through a high-permeability feature and out the second well rather than returning up the hole being drilled. In order to simplify compilations, all the data from the Jarmen Road site have been recorded on DR-394 (see figure 5), the corehole that was drilled at the site in May 1995 by Prof. Mark Harris.

Bissen Quarry (Muldoon and Bradbury, in prep.)--The WGNHS is currently conducting detailed tracer tests at Bissen Quarry on County Highway MM (figure 1). As part of that study, 18 boreholes have been installed and a detailed hydrogeologic characterization has been completed. All holes were televised. Hydraulic tests include fluid temperature/conductivity logging, heat-pulse flowmeter logging of two holes, and discrete-interval permeability testing of 11 of the 18 boreholes.

Detailed data suggest that there are several high-permeability features that are significant at the scale of the tracer study research site, however, it is not clear whether these features are regionally important. Since we do not have as much data from other sites, we have only recorded the "primary" flow features noted in heat-pulse flowmeter logs, fluid temperature/resistivity logs, and selected permeability tests. For simplicity, all data from the site have been compiled onto "Bissen hole 5" in figure 5.

Sturgeon Bay Wellhead Protection Project (Bradbury and others, in prep.)--As part of the ongoing wellhead protection project for the city of Sturgeon Bay, the WGNHS has conducted fluid temperature and resistivity logging for some of the high-capacity wells (DR-265 and DR-292) in the Sturgeon Bay area (see Table 1 and Appendix 5). Heat-pulse flowmeter logs were performed on wells DR-265 and DR-397, and detailed discrete-interval pumping tests were conducted on DR-265. These data were used in figure 5 and are included in Appendix 5.

Current Study

In order to locate high-permeability features, we collected heat-pulse flowmeter data from eight holes (DR-4, DR-6, DR-392, DR-393, DR-394, DR-395, DR-396, and DR-397) and fluid temperature/resistivity data from eight holes (DR-4, DR-6, DR-24, DR-391, DR-392, DR-394, DR-395, and DR-397). These data are included in Appendix 5 and compiled in figures 5 and 6.

Description of High-Permeability Features

Fourteen high-permeability zones have been identified (figure 5, lettered A-N from bottom to top) within the Silurian aquifer in the Sturgeon Bay area. Zones A (Sherrill's zone 7) and G (Sherrill's zone 3) appear in only one well, however, nine zones were detected in at least 50% of the wells that intersect that zone in uncased, saturated conditions.

Flow Zone *"A"* is equivalent to flow zone 7 of Sherrill (1978) in well DR-265 Fluid temperature and resistivity shifts in well DR-265 at depths of 385 ft (Appendix 5) and high well yield (Sherrill, 1978) at 375-380 ft suggest potentially significant flow. However, the extent of this zone appears limited as there are no indications of high flow in the other three wells which penetrate this stratigraphic horizon (DR-4, DR-24, and DR-292).

Flow Zone *"B"* occurs in two out of five possible wells and is very significant in the City of Sturgeon Bay (figure 6). A yield of 20 gpm was obtained by Sherrill (1978) during packer tests in well DR-265. Heat-pulse flow data collected in well DR-4 during controlled pumping of City well #8 (see Appendix 5) indicate that this zone (397-403 ft) contributed most of the flow to DR-4. Additional data from DR-4 suggesting a high-permeability feature at this depth include caliper (Appendix 4), fluid resistivity (collected 11/16/95), and heat-pulse flow data (collected 10/17/95). No indications of flow were found at this interval in wells DR-6, DR-24, and DR-292.

Flow Zone *"C"* is very widespread, occurring in six out of six possible wells (DR-4, DR-6, DR-24, DR-265, DR-292 and DR-394) and is easily correlated with gamma logs. Flow data include temperature and resistivity shifts, heat-pulse flow peaks, and hydraulic conductivity measurements (see Appendix 5).

Flow Zone *"D"*, equivalent to zone 5 of Sherrill (1978), appears to be locally important in the Sturgeon Bay area. It occurs in four out of seven possible wells and is very easily correlated via gamma logs (see Plate 1 and Appendix 2) The flow zone is defined by heat-pulse flow data (DR-4, DR-6, and DR-397) and yield measurements (DR-265) by Sherrill (1978). Flow zone D was not detected in wells DR-394, DR-24, or DR-292. The structure contour map of this horizon (Appendix 2) shows a minor divergence of contour lines to the N and NW, and some convergence to the NE.

Flow zone *"E"* occurs three out of seven possible wells; all occurrences are in the northern portion of the study area. High hydraulic conductivity values in DR-394 (depth 342-347 ft), a fluid conductivity shift in DR-24 (depth 240 ft; Sherrill, 1978), and heat-pulse flow data in DR-397 (depth 206-212) all indicate flow at this horizon. Zone E was not detected in DR-265, DR-4, DR-6, or DR-292.

Flow zone *"F"* is equivalent to flow zone 4 of Sherrill (1978) and occurs in three out of seven wells; all located on the north side of Sturgeon Bay (figure 6). Flow is indicated at this horizon in DR-394 (314.5-316 ft) by a weak (one order of magnitude) hydraulic conductivity peak, in DR-265 by increased well yield associated with enlarged borehole diameter (Sherrill, 1978), and by a fluid resistivity shift near the base of DR-391(290 ft). This feature was not detected in DR-4, DR-6, DR-24, and DR-292.

Flow zone *"G"* is very localized; occurring only in DR-265, at depth of approximately 165-170 ft. It was not detected in the other five available wells (DR-4, DR-6, DR-292, DR-391 and DR-394). This is flow zone 3 of Sherrill (1978) He concluded that a fracture zone, identified by caliper data, contributed significant flow to this well and other nearby wells; a yield of 50 gallons per minute was measured in this interval in DR-265.

Flow zone *"H"* has widespread, but sporadic, geographic distribution; occurring in two of Sherrill's wells (DR-262 and DR-265), the Jarmen Road site (DR-394), and Bissen Quarry. This flow feature was not detected in the other four possible wells (DR-4, DR-6, DR-292, and DR-391).

Flow Zone *"I"* is significant over the entire Sturgeon Bay region occurring in seven out of nine possible wells. Flow at this horizon is clearly indicated by the following data:

a) hydraulic conductivity peak in hole DR-394;

b) high yield in well DR-262 (Sherrill, 1978);

c) heat-pulse flow data in wells DR-4, DR-6, and DR-396;

d) changes in fluid temperature and/or resistivity in DR-394, DR-391 and Bissen 5;

e) water erupted from a well at the Jarmen Road Site when a second well, 150 ft to the southwest, reached this depth (Bradbury and Muldoon, 1992).

The structure contour map of Zone I shows variations in strike near the outcrop of the Byron Formation (Appendix 2).

Flow Zone *"J"*, correlative with Sherrill's zone 1, is also very widespread. It occurs in five out of seven possible locations. This zone is a major contributor in wells DR-4 (heat-pulse flow meter data, Appendix 5) and at the Jarmen Road site (spinner flow meter data in Bradbury and Muldoon, 1992). Shifts in the fluid resistivity profiles of wells DR-392 and DR-292 (Appendix 5) suggest high-permeability zones as do packer tests conducted by Sherrill (1978) in DR-262. The only well in which a flow feature is not detected at this stratigraphic position is DR-396 in the southeastern portion of the study area.

Flow Zone *"K"* is significant in two wells in the northeastern portion of the study area (DR-392 and Jarmen Road site) and not present in DR-262, DR-393, or DR-396. At the Jarmen Road site, high-permeability is indicated by hydraulic conductivity measurements, shifts in fluid temperature and resistivity/conductivity profiles, and eruptions while drilling in adjacent wells at this depth (Bradbury and Muldoon, 1992). Heat-pulse flow data suggest that this zone is the dominant contributor of water to well DR-392 (Appendix 5).

Flow Zone *"L"* only occurs under saturated, uncased conditions in the central and eastern portions of the peninsula due to the southeasterly dip of the Silurian strata. Although this horizon is visible in surface outcrops on the western side of the peninsula, it does not typically contribute to well yields as it is frequently above the water table or is cased. Flow at this horizon was found in five out of six possible wells. Heat-pulse flow data indicate significant flow in wells DR-393 and DR-396 (Appendix 5). At the Jarmen Road site, a significant flow feature is clearly indicated at a depth of 146 ft by high hydraulic conductivity values (Bradbury and Muldoon, 1992) and shifts in profiles of fluid temperature, resistivity and conductivity (Appendix 5). Sherrill's (1978) yield data suggest slight increases in yield in DR-262 and DR-265; significant flow was not detected at this horizon in DR-392.

The distribution of flow zone *"M"* is limited to the eastern half of the peninsula due the southeasterly dip of the Silurian strata. This zone was detected in DR-393 and DR-396 by heat-pulse flow meter data (Appendix 5); and not observed at the Jarmen Road site.

Only two wells in the Sturgeon Bay region sample Flow zone *"N"*. This zone is identified by increased inflow to a well at the Jarmen Road site as observed in a television log (Bradbury and Muldoon, 1992) and by heat-pulse flow data in DR-393 (Appendix 5).

STRATIGRAPHY OF HIGH-PERMEABILITY FEATURES

This portion of the report explores the correlation between stratigraphy and the high-permeability features and matrix permeabilities in the Silurian aquifer near Sturgeon Bay region The hydraulic conductivity profile from DR-394 (figure 3) provides data on matrix permeabilities as well as high-permeability features for portions of the Mayville, Byron and Hendricks Formations The stratigraphic positions of the 14 flow features have been correlated to core descriptions (from Hegrenes, in prep) from hole DR-394 (figure 5), and we examine the possible controls on permeability distribution

Stratigraphic Controls on Permeability Distribution

Lower Mayville Formation -Segment 1 in Hydraulic Conductivity Profile

The basal 175 feet of the Mayville is composed primarily of repetitive alterations of fossiliferous, bioturbated mudstone-wackestones and laminated mudstones (this includes both the more fossiliferous lower Mayville and part of the middle Mayville, see figure 2). Cycle thickness varies from 1 to 16 ft and bioturbated facies are thickest. Few hydrogeologic data are available for this portion of the aquifer and we were only able to collect discrete-interval packer test data for the upper 10 feet of this section of the aquifer (figure 3). The slug test data suggest low matrix permeabilities in the bioturbated, mud-rich facies (segment 1, figure 3).

Flow zones A, B, C and D occur within this portion of the Mayville and appear to be controlled by contacts between contrasting lithologies. Flow zone A occurs at the contact between the fossil-rich, coarsely crystalline dolomite and more shaly interbeds. However, the correlation of the lower most portions of the gamma record for the Silurian dolomite is the most difficult due to variability in thickness and lithologies above the erosional Silurian-Ordovician contact. The correlation of this portion of the gamma record to the core in well DR-394 is the least well-constrained of all of the fourteen flow features. Flow zone B occurs within very fossiliferous, bioturbated grainstones with selective dissolution of the burrow filling and fossils. Examination of the core suggests that bedding plane partings and possible fractures may have localized flow and dissolution. Flow zone C is seen in hole DR-394 (depth 400-403) and widely throughout the study area. Examination of the core suggests that sharp lithologic contrast at a cycle boundary and Silurian-age subaerial exposure play a significant role at this horizon. A shift from medium to coarsely crystalline bioturbated packstones to finely laminated mudstones is compounded by the presence of a porous, crinkly laminated, mud-cracked bed just above this shift. Supratidal deposition with intermittent exposure is indicated by the laminitic mudstones with fenestral porosity and by possible mudcracks. Dissolution and differential cementation during subaerial exposure may have enhanced porosity at this horizon. Flow Zone D was not detected in DR-394, however, it occurs in four out of seven possible wells, is easily correlated with the gamma logs, and is commonly associated with enlarged hole diameters suggesting bedding plane fractures or dissolution of poorly cemented rock types. Examination of the core suggests that this feature occurs near a major sequence boundary; sedimentary features suggest a period of subaerial exposure. A 1-2" thick green shale occurs at this horizon which is underlain by coarser-grained sediments associated with crinkly lamination and rip-up clasts. Above the shale sugary, friable, crinkly laminated dolomites with leached fenestral porosity are overlain by thin flat beds with 5-6 inch deep prism cracks. The dissolution within the laminites maybe related to increased aggressiveness of groundwater after contact with the green shale (Ford and Williams, 1989).

Middle Mayville Formation -Segment 2 in Hydraulic Conductivity Profile
Segment 2 in the hydraulic conductivity profile (figure 3) is characterized by a transition from the underlying laminites to a brachiopod *(Pentamerus)* zone that exhibits high moldic porosity and contains abundant fossils and small fractures. The hydraulic conductivity profile suggests that this zone has a higher average matrix permeability than the underlying dolomite

Flow zone E 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 at 1" thick green shale in the DR-394 core and displays the crumbly, leached fenestral porosity seen in "D".

Upper Mayville
The upper 70 ft of the Mayville is dominated by cyclic alternations of bioturbated mudstones and very fine-grained, laminitic mudstones (figure 2) Cycles vary in thickness from 0.5 to 3 feet and are capped by thick algal laminites. Mudcracks and interclastic lenses suggest repeated instances of intermittent sub-aerial exposure. The hydraulic conductivity profile (figure 3) 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. Alternatively, variations in hydraulic conductivity may be due to lithologic differences with higher values in crinkly laminated mudstones with fenestral porosity and possible subaerial exposure, and lower values in bioturbated, inferred deeper water sediments

Flow zones F, G, and H occur within this portion of the Mayville and appear to correlate with the lithologic contrasts at cycle boundaries Zone F occurs near the contact of medium to coarse crystalline bioturbated peloidal packstones with shaley partings and overlying medium crystalline mudstones to wackestones with thin flat beds, crinkly lamination and minor bioturbation. This zone also coincides with a dissolution-enhanced horizontal fracture in the laminitic mudstones at a depth of 315-316 ft in the DR-394 core. Flow zone G was not detected in DR-394. Correlation from DR-265 suggests that this zone occurs within the beds of coarsely crystalline dolomite. It is not clear whether the flow documented in this interval comes from this matrix porosity, or very localized fractures which correspond with the lithologic differences. Flow zone H correlated to a lithologic contrast between mudstones with thin flat beds and wavy lamination and overlying brachiopod (*Pentamerus*) packstones and grainstones. Similar to the brachiopod beds below flow zone F, these are coarsely crystalline dolomite with high biomoldic, intercrystaline, and shelter porosity.

Byron Formation (192-255)
The Byron Formation, similar to the upper Mayville, is composed of cyclic alternations of bioturbated mudstones and very fine-grained, laminitic mudstones (figure 2). In the lower Byron,

cycles are typically thin, varying from 0.5 to 3 feet in thickness; while in the upper Byron, cycles are typically thicker varying from 1 to 16 feet in thickness. One to two fossiliferous zones occur in the Byron. Mudcracks and interclastic lenses suggest repeated instances of intermittent sub-aerial exposure throughout this formation. The hydraulic conductivity profile (figure 3) indicates that hydraulic conductivity is quite variable. The lower Byron generally exhibits hydraulic conductivity greater than $3x10^{-3}$ cm/sec with a few values in the range of 10^{-5} cm/sec. The upper Byron exhibits generally lower hydraulic conductivity values with less variability than the lower Byron. Measurements are more evenly divided between high (10^{-5} cm/sec) and low values (between 10^{-4} and 10^{-3} cm/sec). The frequency of cycle boundaries within the lower Byron leads to numerous bedding plane partings and fractures.

Flow zones I and J are regionally significant flow features that occur within the Byron. Examination of the core combined with television logs from nearby wells suggest that zone I has developed at a bedding fracture associated with mudcracks in a intraclastic crinkly laminated mudstone. Outcrop study (Kisser Quarry) suggests that these beds are inclined and appear to prograde to the north east with basal truncation and possible top-set truncation surfaces which produce significant bedding plane parallel surfaces of dissolution enhanced porosity. Zone J occurs approximately 3 ft below the top of the Byron Formation in massive blue-grey crinkly laminated and mud-cracked mudstones. Television logs in DR-339 (30 feet from DR-394) show multiple small fractures near this zone. As described for flow horizon I, in the lower Byron Formation, these mudstones also form low angle inclined beds with numerous inclined partings and sub-horizontal truncation surfaces at some localities.

Hendricks Formation

The Hendricks Formation represents a transition in lithology from the dominantly fine-grained mudstones of the Byron Formation to the coarser, more fossiliferous Manistique Formation and is composed of cyclic alternations of those lithologies (figure 2). The hydraulic conductivity profile (figure 3) just extends into the base of the Manistique. The limited values suggest that matrix permeabilities range from 10^{-5} to 10^{-6} cm/sec, with occasional high-permeability features on the order of 10^{-2} to 10^{-1} cm/sec. Both of the high-permeability features appear to occur at a contact between contrasting lithologies.

Flow Zones K and L

Flow zone K occurs at a shift from underlying fossiliferous packstones and wackestones to non-fossiliferous mud-cracked thin flat bedded dolomitic mudstones. Vuggy porosity (biomoldic) is visible in core and in television logs of wells adjacent to the DR-394 core. The flow feature at 178' appears to coincide with a three- inch thick fossil rich packstone to coquina with large vuggy and biomoldic porosity. This bed is immediately overlain by a small horizontal fracture. The presence of abundant biomoldic porosity may have localized fracturing or the flow may be through the well-developed matrix porosity. Flow zone L is a 4-5 inch thick horizontal bedding plane fractures that is evident in both core and television logs of nearby wells. Sediment textures beneath this surface suggest that it marks the top of a shallowing upward depositional package that experienced sub-aerial exposure shortly after deposition. Harris and Waldhuetter (in press) suggest that this is an exposure surface of regional extent that forms a major sequence boundary.

Enhanced dissolution of bedding plane fractures and early diagenetic cementation of this contact are attributed to the period of sub-aerial exposure. This feature appears to correlate to the truncation surface at the top of the inclined crinkly laminated mudstones and peloidal packstones visible in Big Quarry, Schartner's Quarry and Little Quarry (Figure 1). In Little Quarry, dissolution has locally produced 1 to 3 foot high, semi continuous cavernous porosity

Manistique Formation

The Manistique Formation is generally coarser textured and more fossiliferous than the underlying units. The hydraulic conductivity profile does not extend into this unit.

<u>Flow Zones M and N</u>

<u>Flow zone M</u> 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 Formation to fossiliferous, coarse-grained rock types. <u>Flow zone N</u> coincides with an interval of rip-up clasts in a fossiliferous packstone matrix

The highest stratigraphic information on groundwater flow in this portion in the Sturgeon Bay region comes from well DR-394 where water cascades (or drips depending upon recharge) down the borehole wall from depths of 77 and 78 ft. This corresponds with the bedding plane breaks above and below a fossiliferous grain-rich bed with abundant skeletal molds.

CONCLUSIONS

By combining stratigraphic, geophysical, and hydrogeologic data we have been able to delineate and correlate fourteen high-permeability features within the Silurian aquifer in the vicinity of Sturgeon Bay. These data provide critical constraints for the groundwater flow models being developed as part of the Sturgeon Bay Wellhead Protection effort.

At least three of these zones (C, I, J) are regional in extent and can be correlated in wells over 10 miles apart. Zones K and L may also be regional, but are only saturated in central and eastern Door County. Two other zones (B, D) are correlated throughout the Sturgeon Bay municipal area. The other zones were not detected as extensively but may be locally important.

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). High permeability is also associated with bedding plane fractures within inclined supratidal mudstones, high biomoldic porosity in coquina-like packstones and grainstones, and in lithologies adjacent to thin green calcareous shales.

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APPENDIX 1- STRATIGRAPHIC DATA

This appendix contains the natural gamma logs collected for two outcrop locations and a description of one of the cores from Bissen quarry (see Figure 1 for locations).

Natural Gamma Logs

We collected natural gamma logs from Big Quarry and Walker Road Quarry. Natural gamma data collected from outcrops can be affected by solar radiation as well as distance of the detector from the outcrop wall. While collecting these logs, we attempted to keep the probe a uniform distance from the quarry wall and several runs were completed at each location. Data from all runs are plotted for each quarry.

Bissen Core

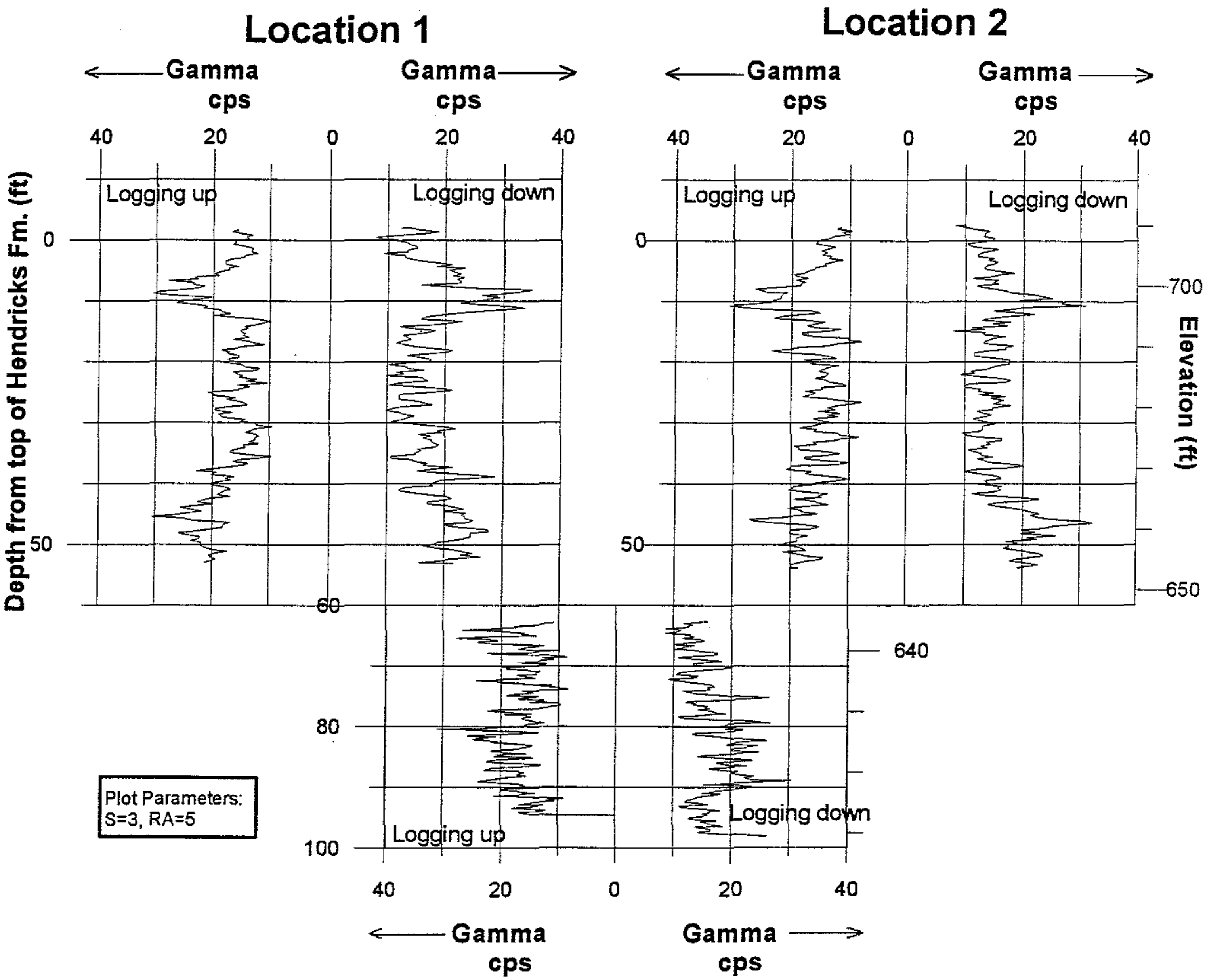
Five cores, approximately 35-ft in length, were collected from Bissen Quarry in Fall 1992 (Muldoon and Bradbury, in prep.) A description of the core recovered from hole 5, completed by Dr. J.A. Simo, is summarized in this appendix. Six distinct lithofacies are recognized (described in figure) and rock textures range from mudstones to boundstones. Dolomite crystal size (also summarized in figure) controls the amount of matrix or intercrystalline porosity. Crystal size varies from 500 microns (very coarse) to 60 microns (very fine) and visible porosity is estimated to be 8-15%. Secondary minerals are calcite (crystals 1-5 mm) partially filling molds and vugs, and pyrite (crystals <1mm) that predates the calcite, concentrates along stylolites, and coats vugs. Five shallowing-upward depositional cycles are recognized. Cycles 1 and 5 are incomplete. An ideal complete cycle shows the following succession: a lower unit with black shale or thin-bedded bioturbated mudstone (lithofacies 6 and 3 respectively); an intermediate unit with skeletal packstone, stromatoporid/skeletal-rich wackestone to packstone, and peloidal packstone-grainstone (lithofacies 5,4, and 2); and an upper unit with algal laminates. The cycles are interpreted as shallowing-upward successions with an initial marine flooding followed by sediment filling.

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 6/5/95 by M Muldoon, G Gianniny, and T Simo

Elevation: est 710 ft
(top of upper quarry wall)

Outcrop: Big Quarry

T28N, R25E, section 13, NE1/4, NE1/4, NE1/4

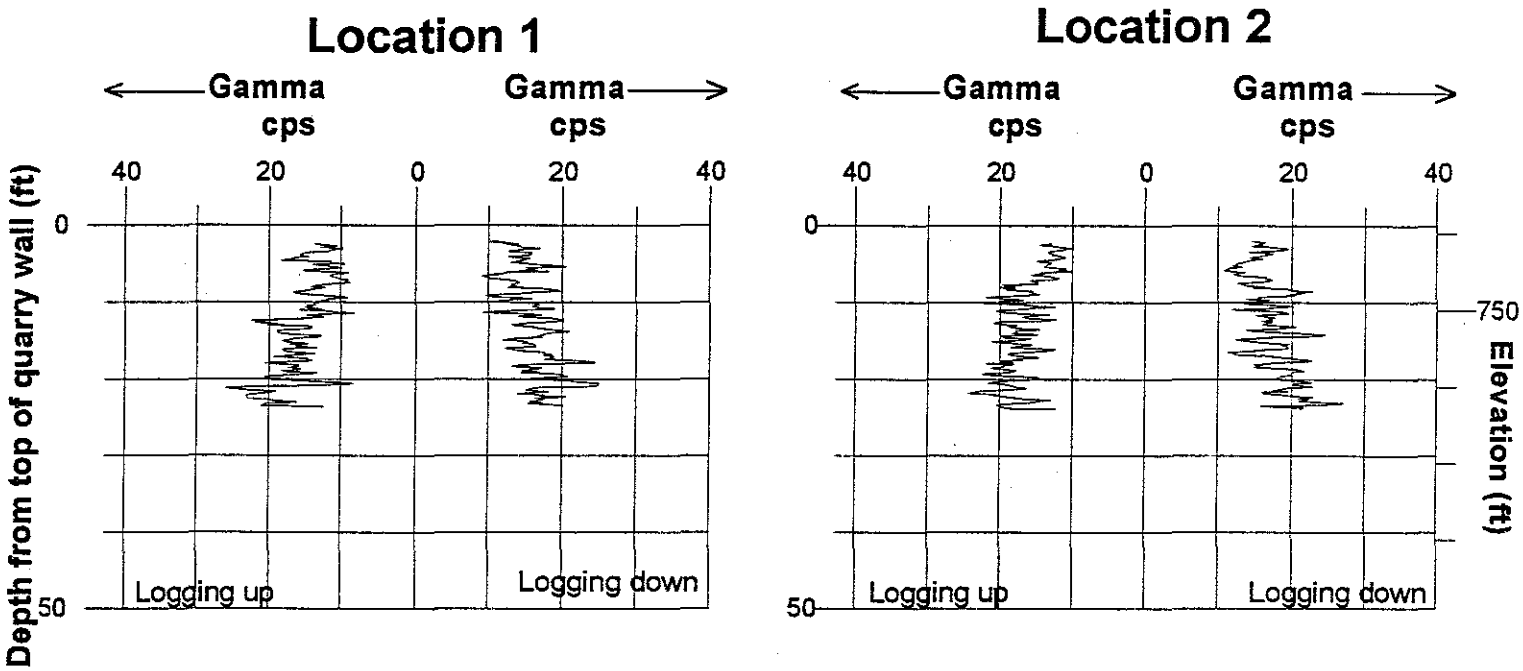


Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 6/8/95 by G Gianniny

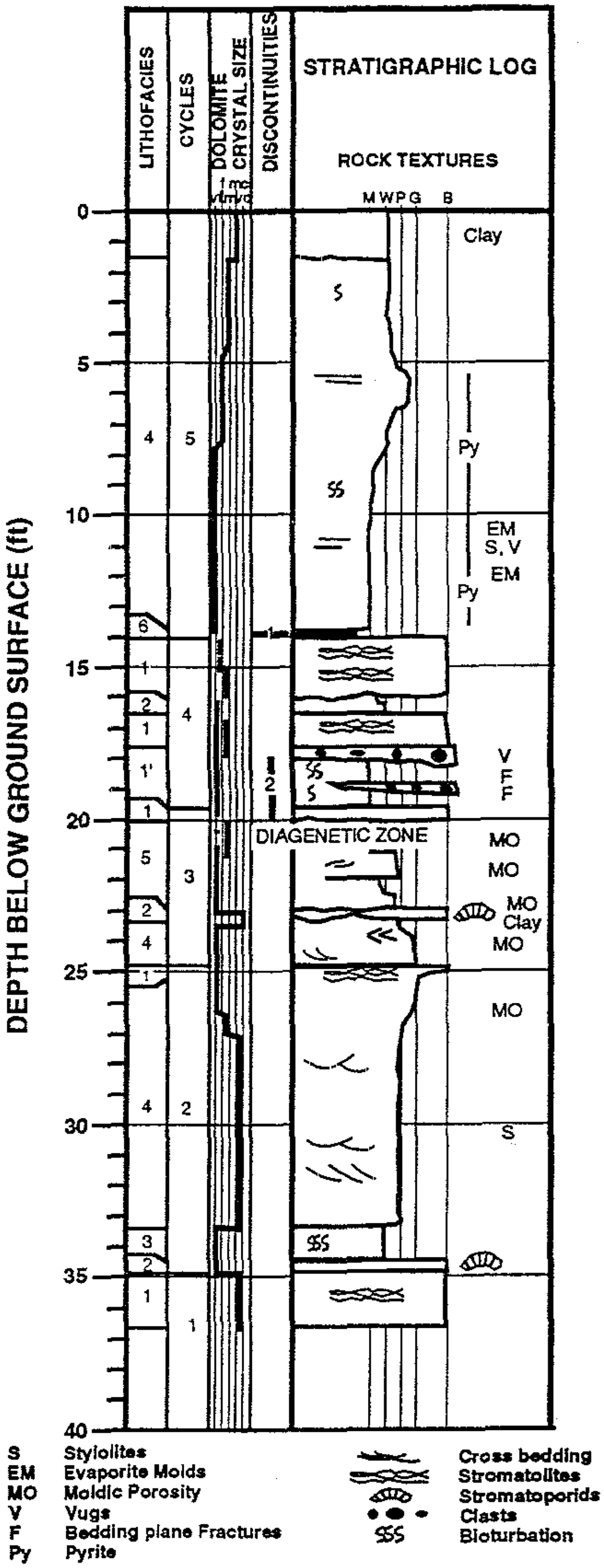
Elevation: 761 (top of quarry wall)

Outcrop: Walker Rd Quarry

T28N, R26E, section 29, NE1/4, NE1/4



Plot Parameters:
S=3, RA=5



Stratigraphic log from Bissen quarry (hole 5) showing rock textures, the six lithofacies recognized, interpreted cycles, and estimated dolomite crystal size. Lithofacies include:

1) algal laminite--millimeter-scale algal laminite with small and rare tepee structures and vugs,

1') algal laminate with intraformational conglomerates,

2) stromatoporid/skeletal-rich wackestone to packstone--stromatoporid and skeletal grains are commonly dissolved and partially replaced by sparry calcite and green clay,

3) thin-bedded, bioturbated mudstones,

4) peloidal packstone-grainstone with local sedimentary structures and bioturbation,

5) skeletal (bryozoan) packstone--skeletal grains are partially dissolved,

6) black, laminated shale

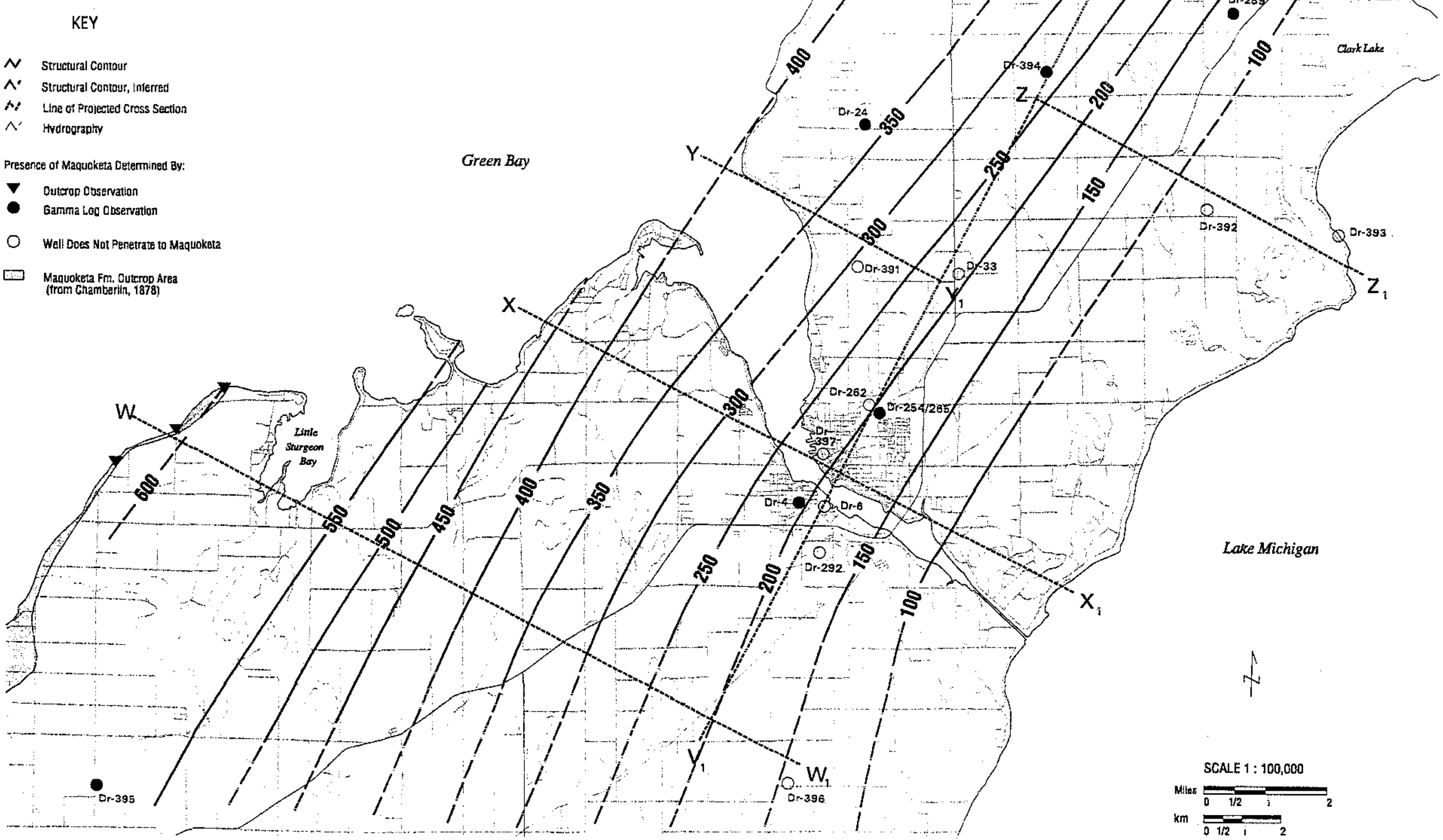
APPENDIX 2- STRUCTURE CONTOUR MAPS

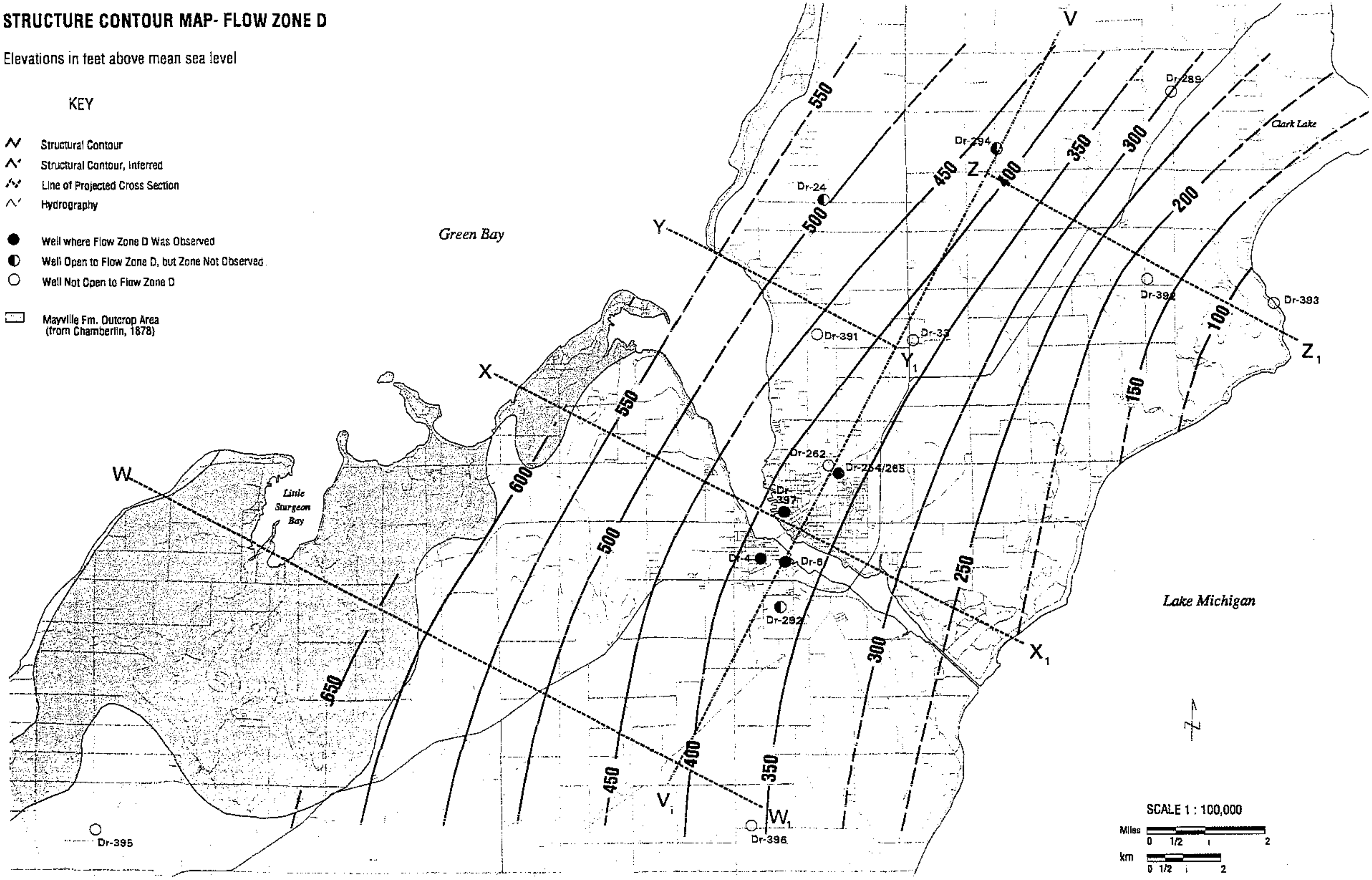
This appendix contains contour maps of the elevations of three distinct horizons: 1) the contact between the Maquoketa shale and the overlying Silurian dolomite, 2) flow zone D which occurs near a green shale layer (peak in gamma signature), and 3) flow zone I which is located just above a distinctive natural gamma peak. These maps illustrating the general and local strike and dip of these horizons and predict the elevation where the Maquoketa and flow zones can be found. Variations in the strike direction and amount of dip is illustrated by the differences in orientation and spacing of the lines.

These maps were constructed to help constrain the stratigraphic correlations illustrated in the cross-sections (Appendix 3). Data used in the structure contour maps include outcrop observations and the natural gamma signature of wells that penetrate the specific horizon. The natural gamma signature was used to determine the elevation of the specific horizon in the wells and these elevations were then contoured to produce the maps in this appendix.

STRUCTURE CONTOUR MAP- TOP SURFACE OF MAQUOKETA FORMATION

Elevations in feet above mean sea level



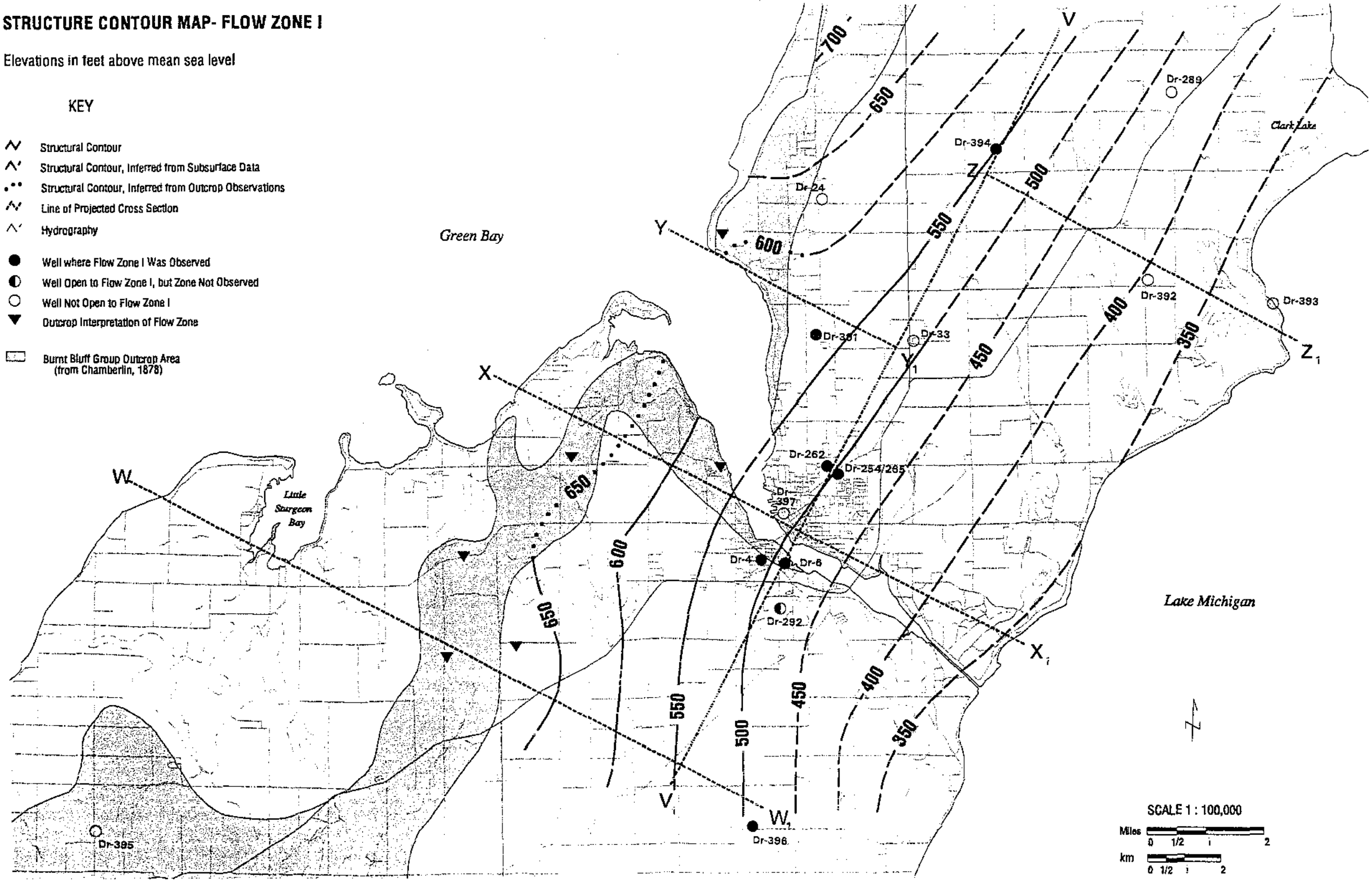

STRUCTURE CONTOUR MAP- FLOW ZONE D
Elevations in feet above mean sea level
KEY
Structural Contour
Structural Contour, Inferred
Line of Projected Cross Section
Hydrography
Well where Flow Zone D Was Observed
Well Open to Flow Zone D, but Zone Not Observed
Well Not Open to Flow Zone D
Mayville Fm. Outcrop Area
(from Chamberlin, 1878)
Green Bay
Lake Michigan
Little Sturgeon Bay
Clark Lake
Dr-289
Dr-294
Dr-24
Dr-393
Dr-391
Dr-262
Dr-264/265
Dr-397
Dr-4
Dr-6
Dr-292
Dr-395
Dr-396
V
V1
W
W1
X
X1
Y
Y1
Z
Z1
650
600
550
500
450
400
350
300
250
200
150
100
SCALE 1 : 100,000
Miles
0 1/2 1 2
km
0 1/2 1 2

STRUCTURE CONTOUR MAP- FLOW ZONE I

Elevations in feet above mean sea level

KEY

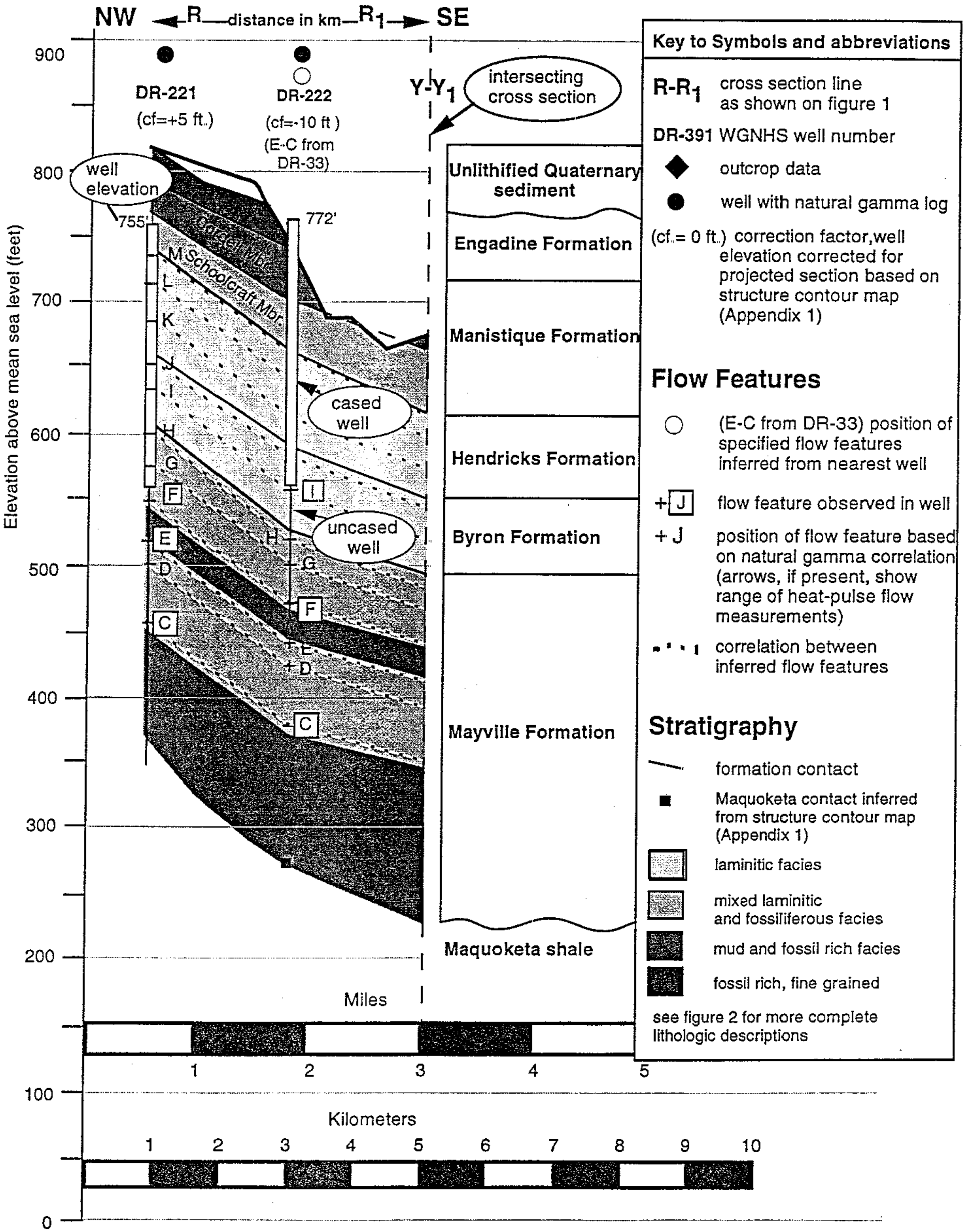
- Structural Contour
- Structural Contour, Inferred from Subsurface Data
- Structural Contour, Inferred from Outcrop Observations
- Line of Projected Cross Section
- Hydrography
- Well where Flow Zone I Was Observed
- Well Open to Flow Zone I, but Zone Not Observed
- Well Not Open to Flow Zone I
- Outcrop Interpretation of Flow Zone
- Burnt Bluff Group Outcrop Area (from Chamberlin, 1878)

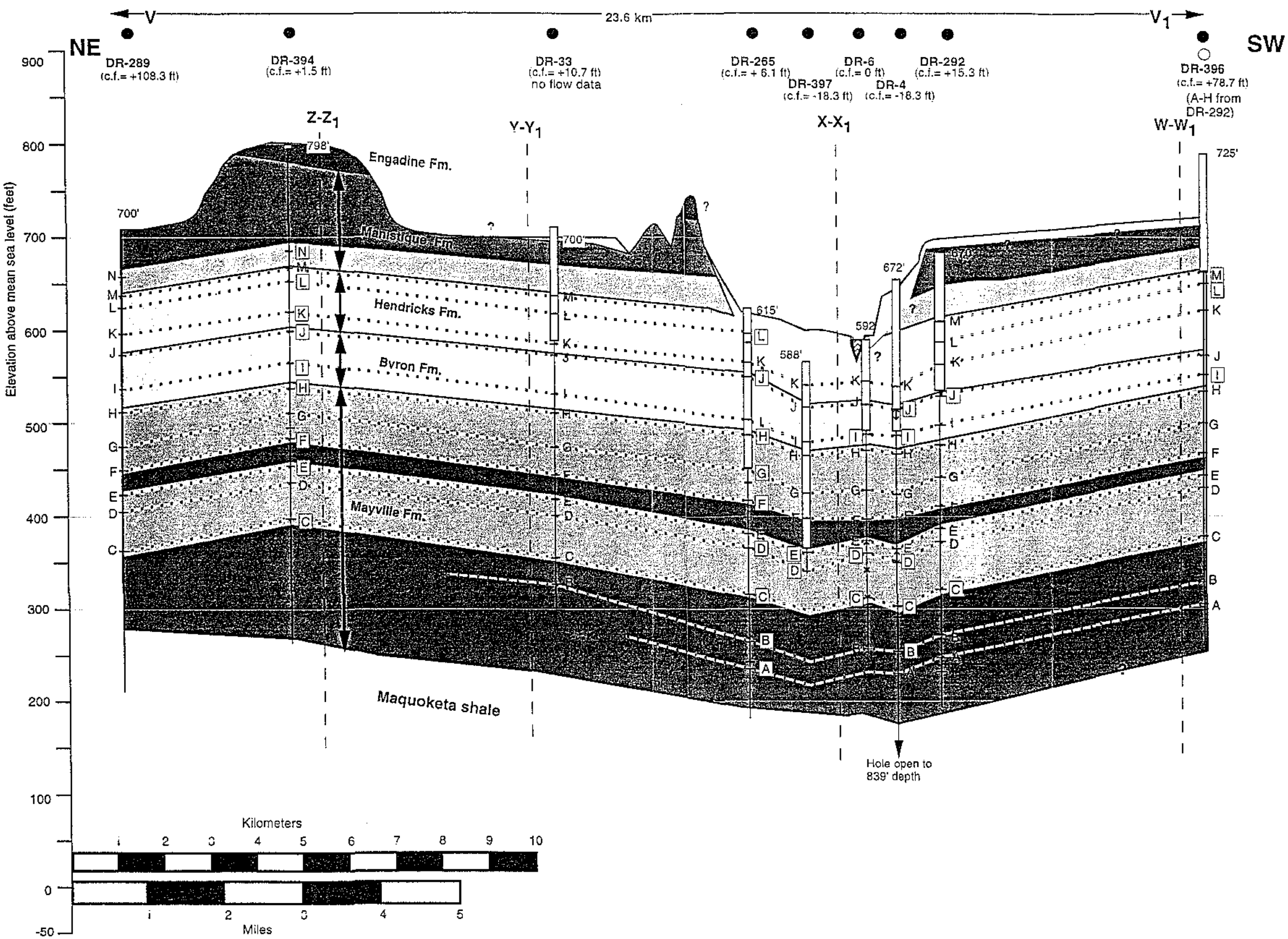


APPENDIX 3 - CROSS SECTIONS

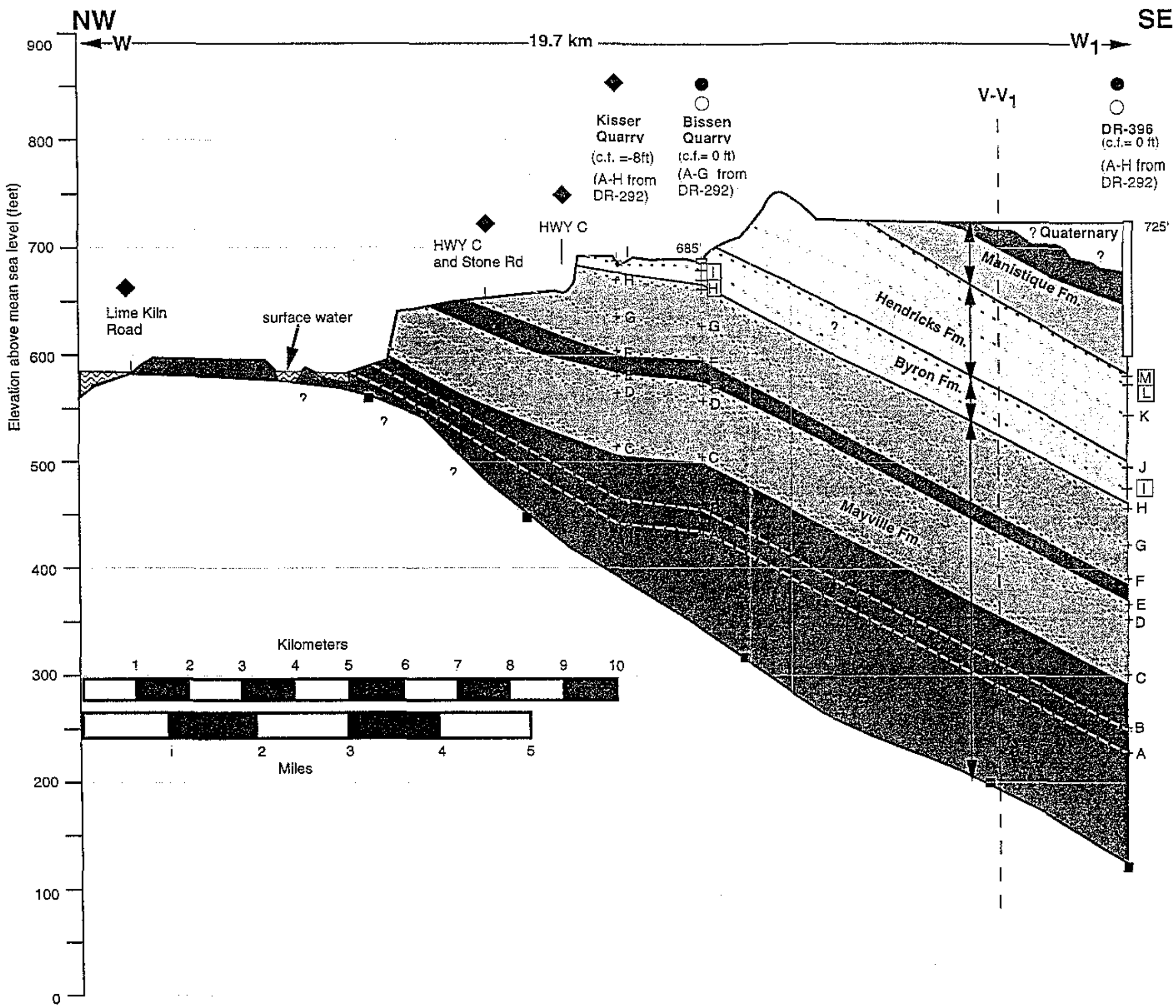
This appendix contains five cross sections which illustrate the three-dimensional distribution of stratigraphic units and high-permeability features in the Sturgeon Bay area. Cross sections were constructed by projecting outcrop, core, geophysical and flow data onto the five lines of cross section shown in Figure 1. Thickness of the formations, and relative elevations of flow zones (A-M) are projected from the closest well/outcrop. c.f. (correction factor) is the difference in elevation (calculated from the structure contour map, Appendix 2) between the location of the well and its projection onto the line of cross section.

Key and Example of Cross Sections

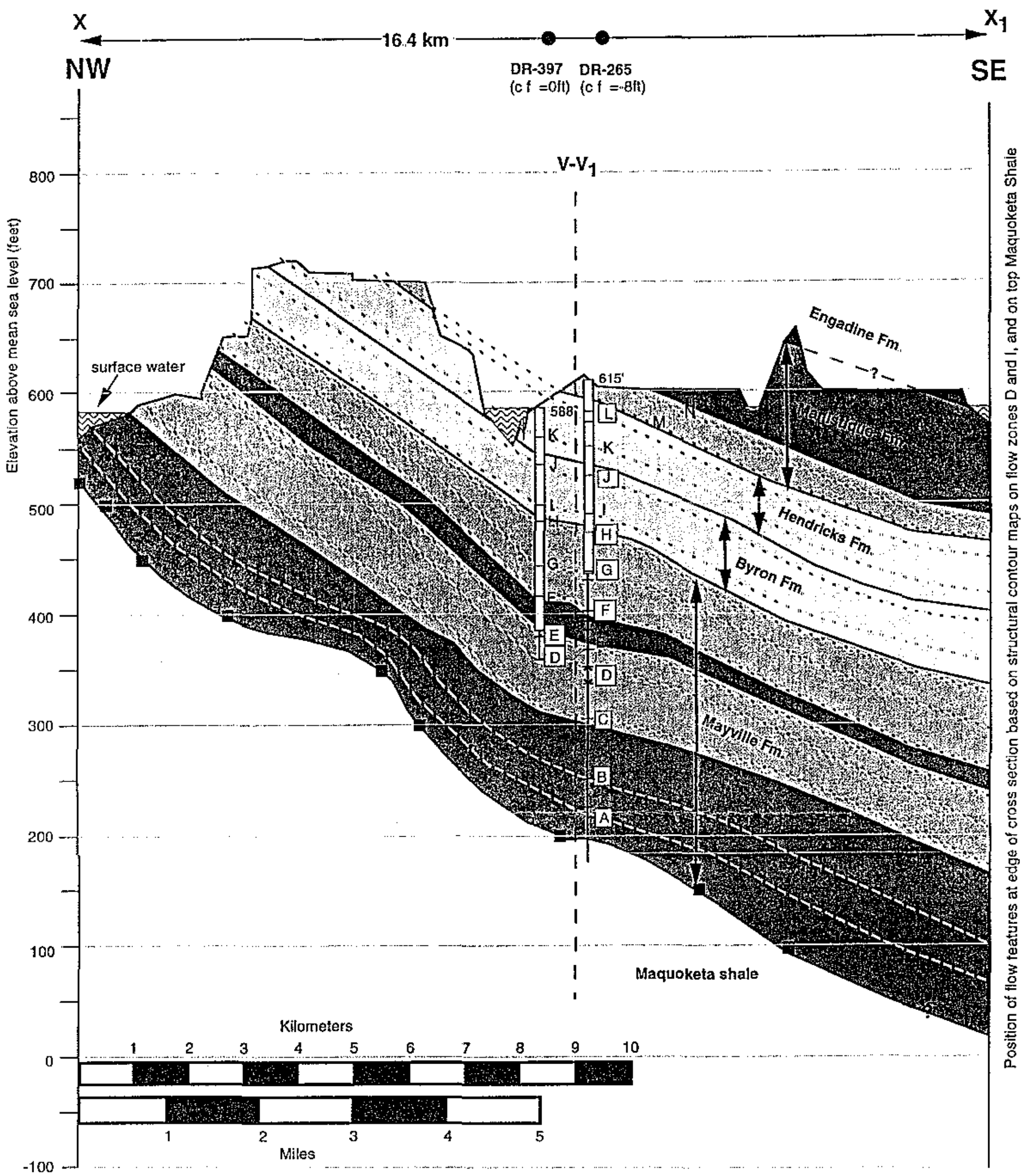


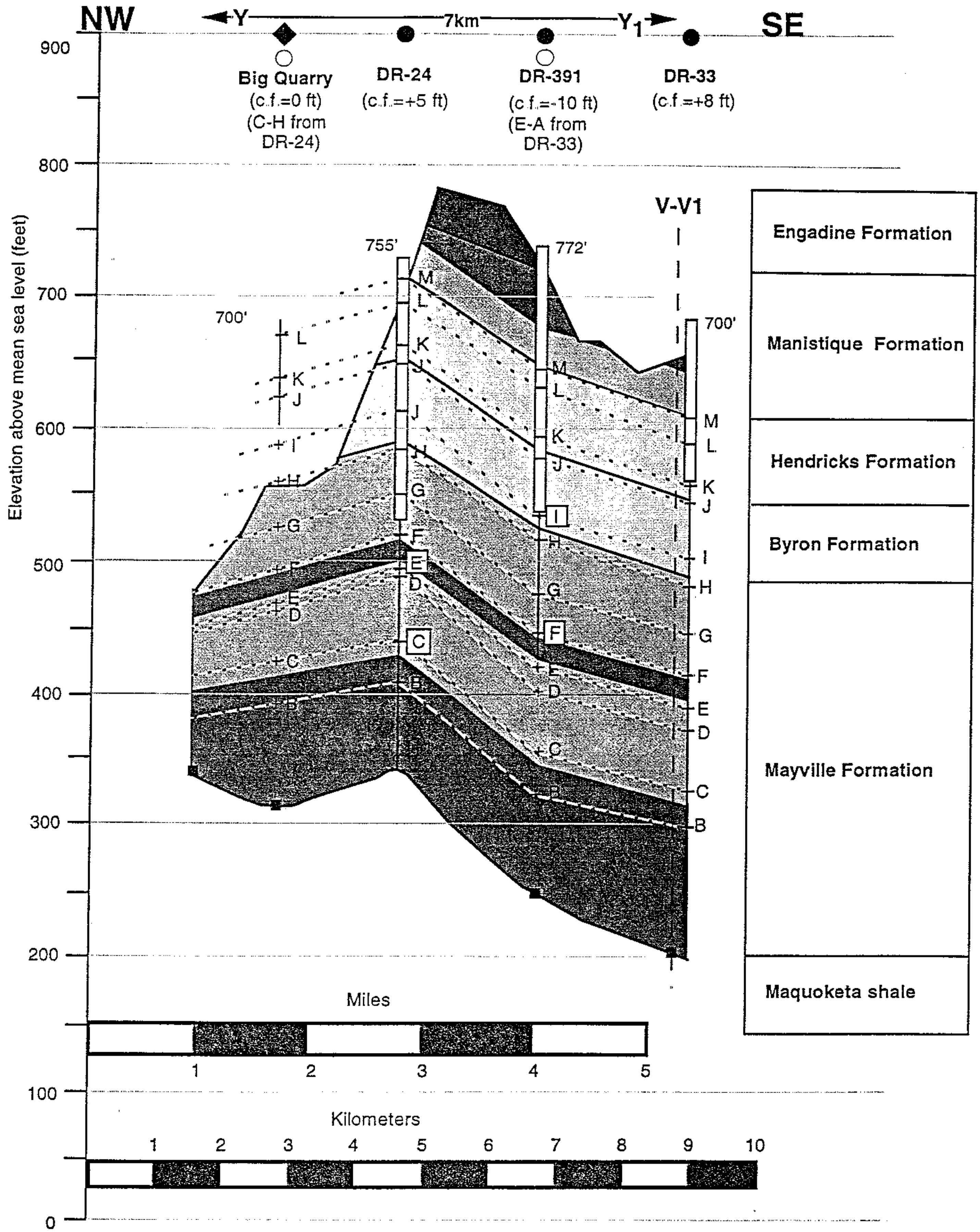


V
23.6 km
V1
NE
SW
DR-289 (c.f.= +108.3 ft)
DR-394 (c.f.= +1.5 ft)
DR-33 (c.f.= +10.7 ft) no flow data
DR-265 (c.f.= + 6.1 ft)
DR-397 (c.f.= -18.3 ft)
DR-6 (c.f.= 0 ft)
DR-4 (c.f.= -18.3 ft)
DR-292 (c.f.= +15.3 ft)
DR-396 (c.f.= +78.7 ft) (A-H from DR-292)
Z-Z1
Y-Y1
X-X1
W-W1
Elevation above mean sea level (feet)
Engadine Fm.
Manistique Fm.
Hendricks Fm.
Byron Fm.
Mayville Fm.
Maquoketa shale
798'
700'
615'
588'
592
672'
670
725'
Hole open to 839' depth
Kilometers
Miles

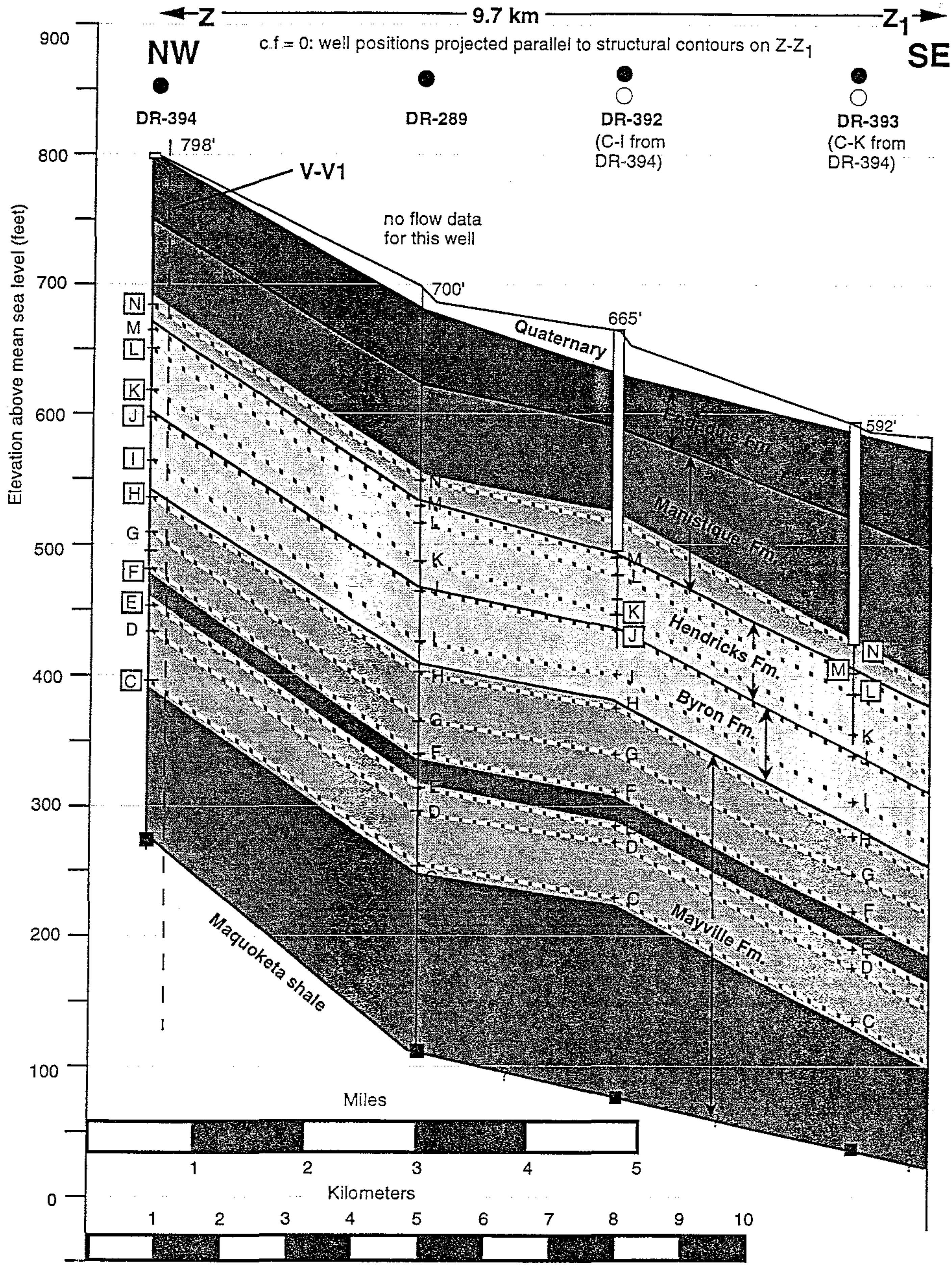


NW
SE
W
19.7 km
W_1
Elevation above mean sea level (feet)
900
800
700
600
500
400
300
200
100
0
Kisser Quarry
(c.f. =-8ft)
(A-H from DR-292)
Bissen Quarry
(c.f.= 0 ft)
(A-G from DR-292)
V-V_1
DR-396
(c.f.= 0 ft)
(A-H from DR-292)
HWY C
HWY C and Stone Rd
Lime Kiln Road
surface water
685'
725'
? Quaternary
Manistique Fm.
Hendricks Fm.
Byron Fm.
Mayville Fm.
Kilometers
Miles


X
X1
16.4 km
NW
SE
DR-397
(c f =0ft)
DR-265
(c f =-8ft)
V-V1
Elevation above mean sea level (feet)
800
700
600
500
400
300
200
100
0
-100
surface water
Engadine Fm.
Manistique Fm.
Hendricks Fm.
Byron Fm.
Mayville Fm.
Maquoketa shale
615'
588'
Kilometers
Miles
Position of flow features at edge of cross section based on structural contour maps on flow zones D and I, and on top Maquoketa Shale



NW
Y
7km
Y1
SE
Big Quarry
(c.f.=0 ft)
(C-H from DR-24)
DR-24
(c.f.=+5 ft)
DR-391
(c.f.=-10 ft)
(E-A from DR-33)
DR-33
(c.f.=+8 ft)
V-V1
755'
772'
700'
700'
Elevation above mean sea level (feet)
900
800
700
600
500
400
300
200
100
0
Engadine Formation
Manistique Formation
Hendricks Formation
Byron Formation
Mayville Formation
Maquoketa shale
Miles
1
2
3
4
5
Kilometers
1
2
3
4
5
6
7
8
9
10



Z
9.7 km
Z1
NW
SE
c.f.= 0: well positions projected parallel to structural contours on Z-Z1
DR-394
DR-289
DR-392
(C-I from DR-394)
DR-393
(C-K from DR-394)
798'
V-V1
no flow data for this well
700'
665'
592'
Quaternary
Engadine Fm.
Manistique Fm.
Hendricks Fm.
Byron Fm.
Mayville Fm.
Maquoketa shale
Elevation above mean sea level (feet)
900
800
700
600
500
400
300
200
100
0
N
M
L
K
J
I
H
G
F
E
D
C
Miles
1
2
3
4
5
Kilometers
1
2
3
4
5
6
7
8
9
10

APPENDIX 4- GEOPHYSICAL LOGS

Geophysical logs, including natural gamma, spontaneous potential, single-point resistivity, and caliper, were collected from nine holes as part of this project In addition, data from previous studies were also complied This appendix contains both the old logs as well as the new data; all logs have been plotted at the scale of 50 ft to the inch

Previous Logged Holes

Sherrill (1978) logged several holes (DR-24, DR-33, DR-59, DR-262, DR-265, DR-289, and DR-292) as part of his investigation of the groundwater resources of Door County The original data were collected using a pen-recording geophysical logger and the original logs are on file at WGNHS We have digitized selected logs and include those data in this appendix

Logs Acquired During This Project

Nine holes (DR-4, DR-6, DR-391, DR-392, DR-393, DR-394, DR-395, DR-396, and DR-397) were logged using the WGNHS digital logger (Mt Sopris, model 305, serial number 0169). Three holes (DR-4, DR-6, and DR-397) are high-capacity holes that are no longer in use; DR-394 is the corehole at the Jarmen Road site; and the other five holes are recently constructed domestic wells that were logged prior to installation of the pump In addition, we repeated selected logs for holes DR-24 and Dr-265 that had originally been logged by Sherrill (1978) and those data are included in this appendix Details of logging procedures and well locations are included on data sheets that accompany each log The original data and copies of each log are on file at WGNHS

Plotting Parameters for Gamma Logs

The natural gamma data have been smoothed for plotting purposes Natural gamma data reflect the number of gamma particles naturally emitted by the rock formation; as a result, the recorded gamma signature is somewhat dependant on logging speed The gamma logs collected as part of this study were typically collected at a logging speed of 15 ft/min resulting in detailed, if somewhat "spiky" gamma signatures The plotting program provides two methods of smoothing the data The first is a skip factor (noted as a S in the plot parameters box) If S=3, then every third data point was used in the plot The second plotting parameter is a running average (RA in the plot parameters box); if RA=5 then 5 values were averaged to produce the resulting data point shown in the plot

Geophysics Logging Documentation

Well or Hole Name: Sturgeon Bay City Well #1

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 10/5/95

WGNHS Geologic Log Number: DR-4

Estimated Elevation: 672 ft **County:** Door

Personnel: Gary Gianniny

Location: SE1/4, NW1/4, SW1/4 section 7 ,T27N, R26 E/W
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: ______Top of Casing ______Ground Surface
X Other (include in sketch on back)
Distance from top of casing to ground surface: ______

Measured Static Water Level: 91.6 ft

Hole Depth (reported by driller) 1178 **Casing Depth** (reported by driller) 99?

Hole Depth (from logging) 839 **Casing Depth** (from logging) 140

Casing Diameter (reported by driller) 12-inch

Open-hole Diameter(s) (reported by driller) 12" (99-150),10"(150-480) 9"(480-1178)

Caliper Calibration: Rings used to calibrate 7" and 10"

Readings at end of logging run ______

SP/resistivity Calibration: ______Yes X No

Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma	up	4.6-837.8	15 ft/min	Dr4gmaup.ga0
SP/resistivity	down	3.5-841.3	15 ft/min	Dr4SpRes.Ra0
Caliper	up	200-839 120-200	15 ft/min	Dr4cal.ca0 Dr4cal5.ca2
Fluid* temp/resistivity		5.5-835.91		Dr4frt.wa0
Other				

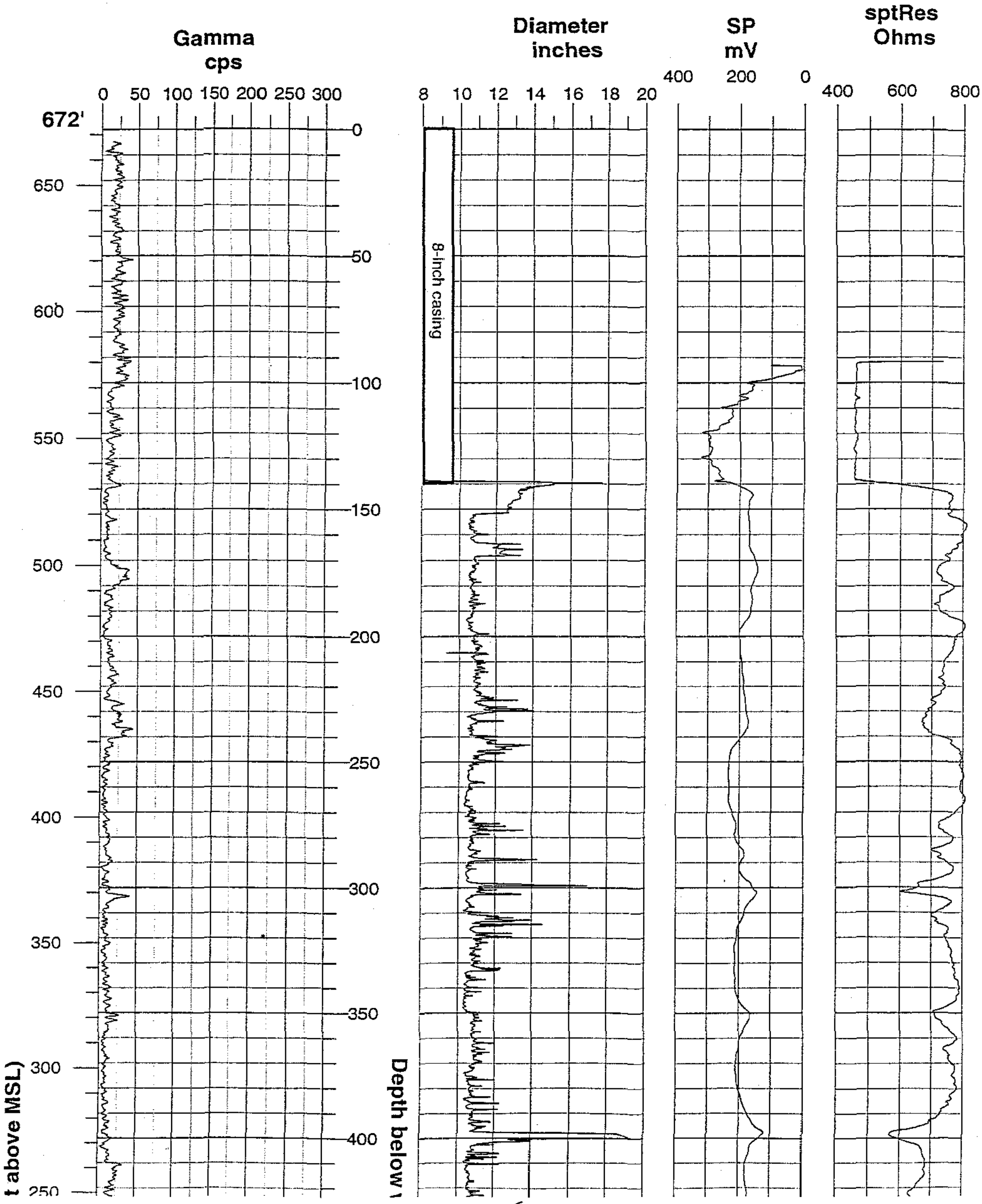
* logged 11/16/95 by K.Bradbury

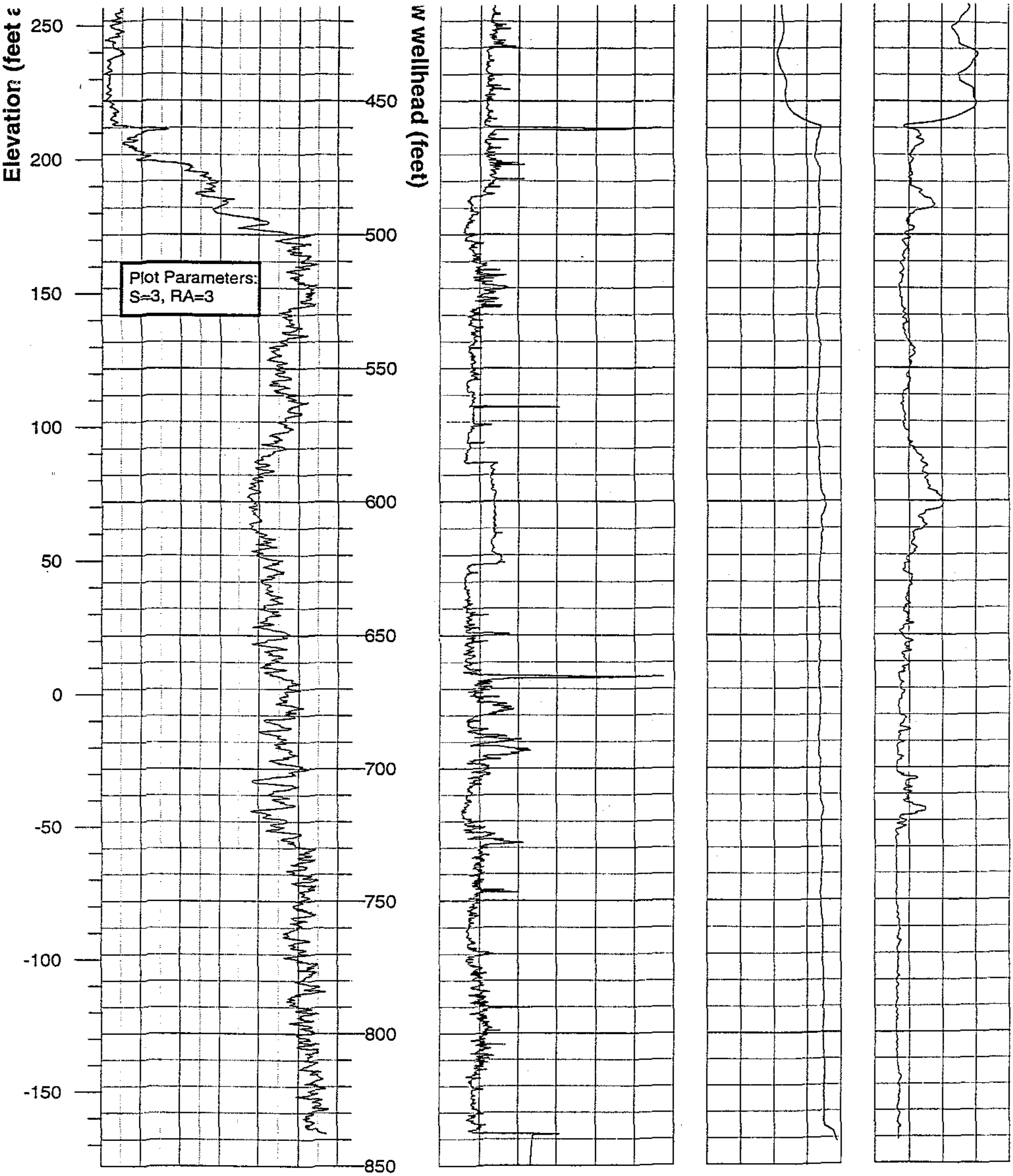
Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 10/5/95 by G. Gianniny

Elevation: est 672 ft
Depth to water: 91.6 ft
Casing
(determined by geophysics): 140 ft

Well: DR-4
Sturgeon Bay city well #1

T27N, R26E, section 7, SE1/4, NW1/4 of the SW1/4





Elevation (feet
250
200
150
100
50
0
-50
-100
-150
Plot Parameters:
S=3, RA=3
wellhead (feet)
450
500
550
600
650
700
750
800
850

Geophysics Logging Documentation

Well or Hole Name: Roen Salvage (formerly Evangaline Dairy)

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 8/25/95

WGNHS Geologic Log Number: DR-6

Estimated Elevation: 592 ft **County:** Door

Personnel: Gary Gianniny

Location: NE1/4, SE1/4 section 7 ,T27N, R26 E/W
(include sketch location map on back); 180 E. Redwood Ave, Sturgeon Bay, WI

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: 32 inches

Measured Static Water Level: 7.6 ft

Hole Depth (reported by driller) 350 **Casing Depth** (reported by driller) 100

Hole Depth (from logging) 339 **Casing Depth** (from logging) 100

Casing Diameter (reported by driller) 10-inch

Open-hole Diameter(s) (reported by driller) 10-inch

Caliper Calibration: Rings used to calibrate 4 1/2" and 7"

Readings at end of logging run ______

SP/resistivity Calibration: ______Yes X No

Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)	
Gamma	up			Dr6gmaup.ga0	
	down	3.5-338.9	20 ft/min	Dr6gmadn.ga0	*
SP/resistivity	down			Dr6SpRes.ra0	
	up	3.5-338.4	40-45 ft/min	Dr6SpRup.ra0	*
Caliper	up	4.7-337	15-17 ft/min	Dr6calip.ca0	*
Fluid temp/resistivity	down	10.2-338.2		Dr6tpres.wa0	*
Other					

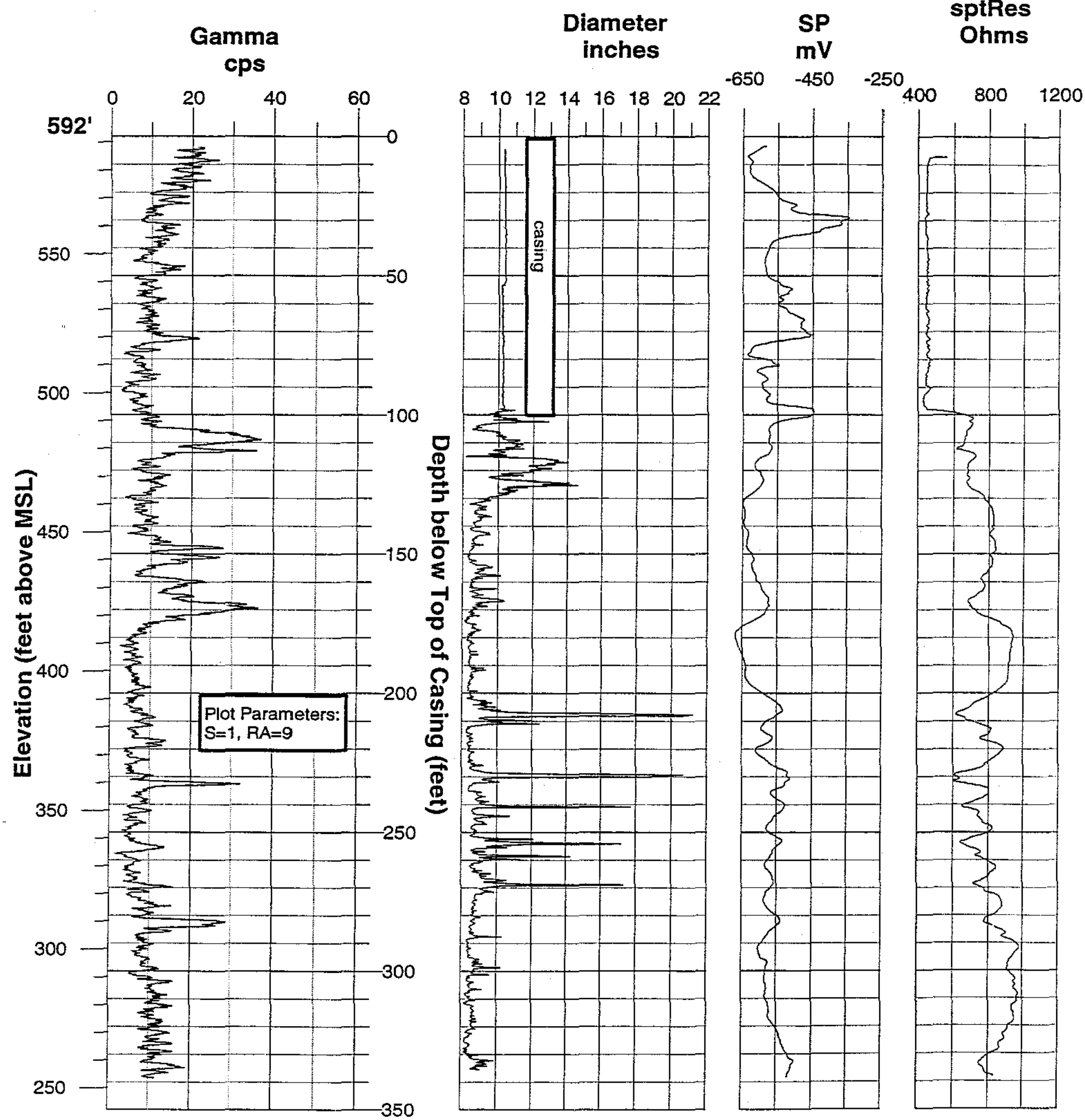
* used in plot

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 8/25/95 by G. Gianniny

Elevation: est 592 ft
Depth to water: 7.6 ft
Casing:
(determined by geophysics): 100 ft

Well: DR-6

T27N, R26E, section 7, NE1/4, SE1/4
180 E. Redwood Rd, Sturgeon Bay



Geophysics Logging Documentation

Well or Hole Name: Reynolds Preserving Company

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 8/30/95

WGNHS Geologic Log Number: DR-24

Estimated Elevation: 755 ft **County:** Door

Personnel: Gary Gianniny and Wylie Linquist

Location: NW1/4, SW1/4, NE1/4 section 8 ,T28N, R26 E/W
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: 4 ft below grade

Measured Static Water Level: 149 ft from ground surface

Hole Depth (reported by driller) 385 **Casing Depth** (reported by driller) 204

Hole Depth (from logging) 346.5 **Casing Depth** (from logging) 203

Casing Diameter (reported by driller) 8-inch

Open-hole Diameter(s) (reported by driller) 8-inch

Caliper Calibration: Rings used to calibrate 4 1/2" and 7"

Readings at end of logging run ______

SP/resistivity Calibration: ______Yes X No

Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma				
SP/resistivity				
Caliper	up	5.3 - 347.5	15 ft/min	caliper.ca0
Fluid temp/resistivity	down	5.5 346.5	21 ft/min	restemp.wa0
Other				

corrected so that it's relative to grd surface

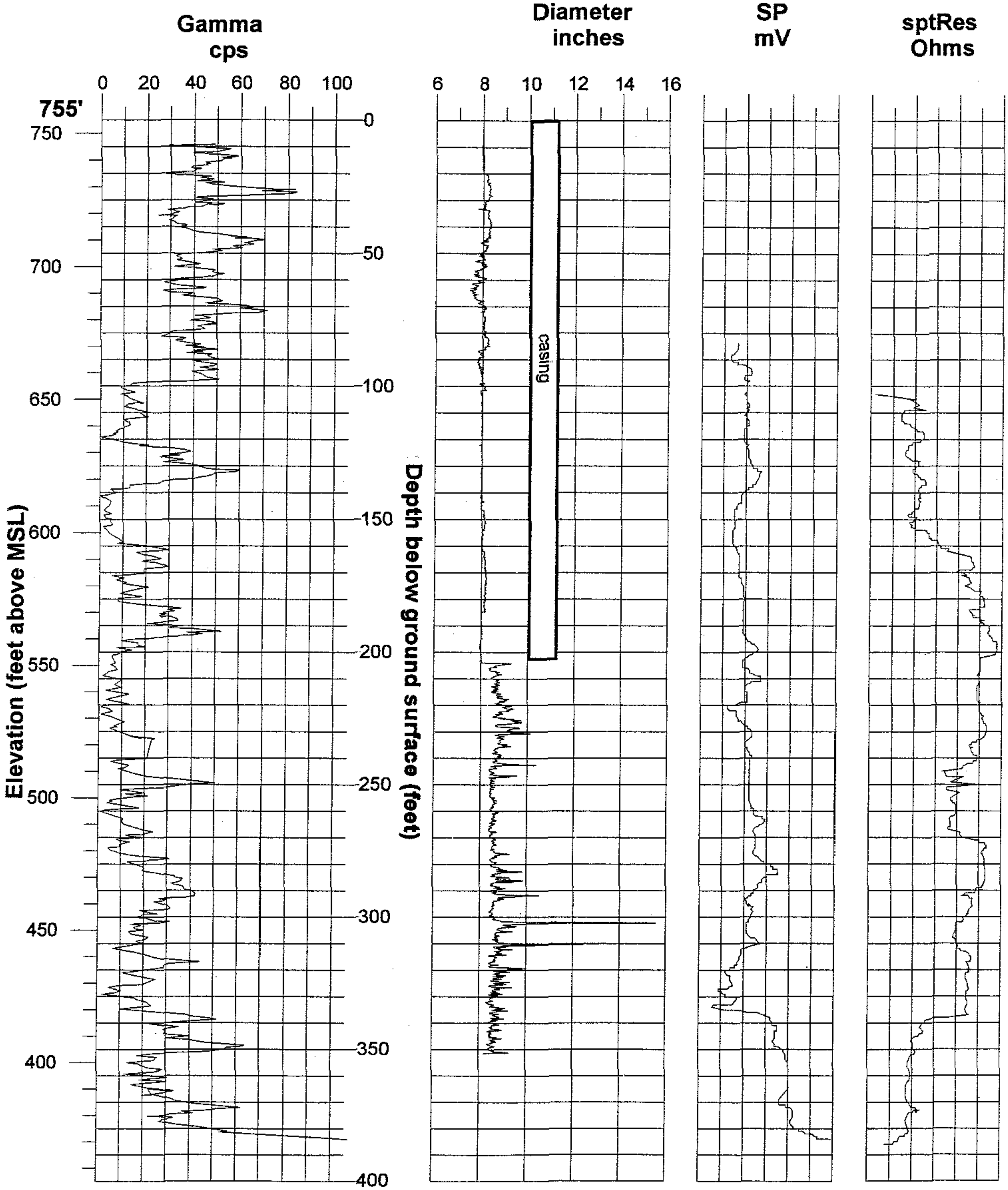
logged relative to ground surf

Wisconsin Geological and Natural History Survey
Geophysical Log
Digitized from electric logs on file at WGNHS
Caliper logged 8/30/95 by G. Gianniny and W. Linquist

Elevation: est. 755
Depth to water:
Casing:
(determined by geophysics): 204 ft

Well: DR-24
Reynolds

T28N, R26E, section 8, NW1/4, SW1/4, NE1/4

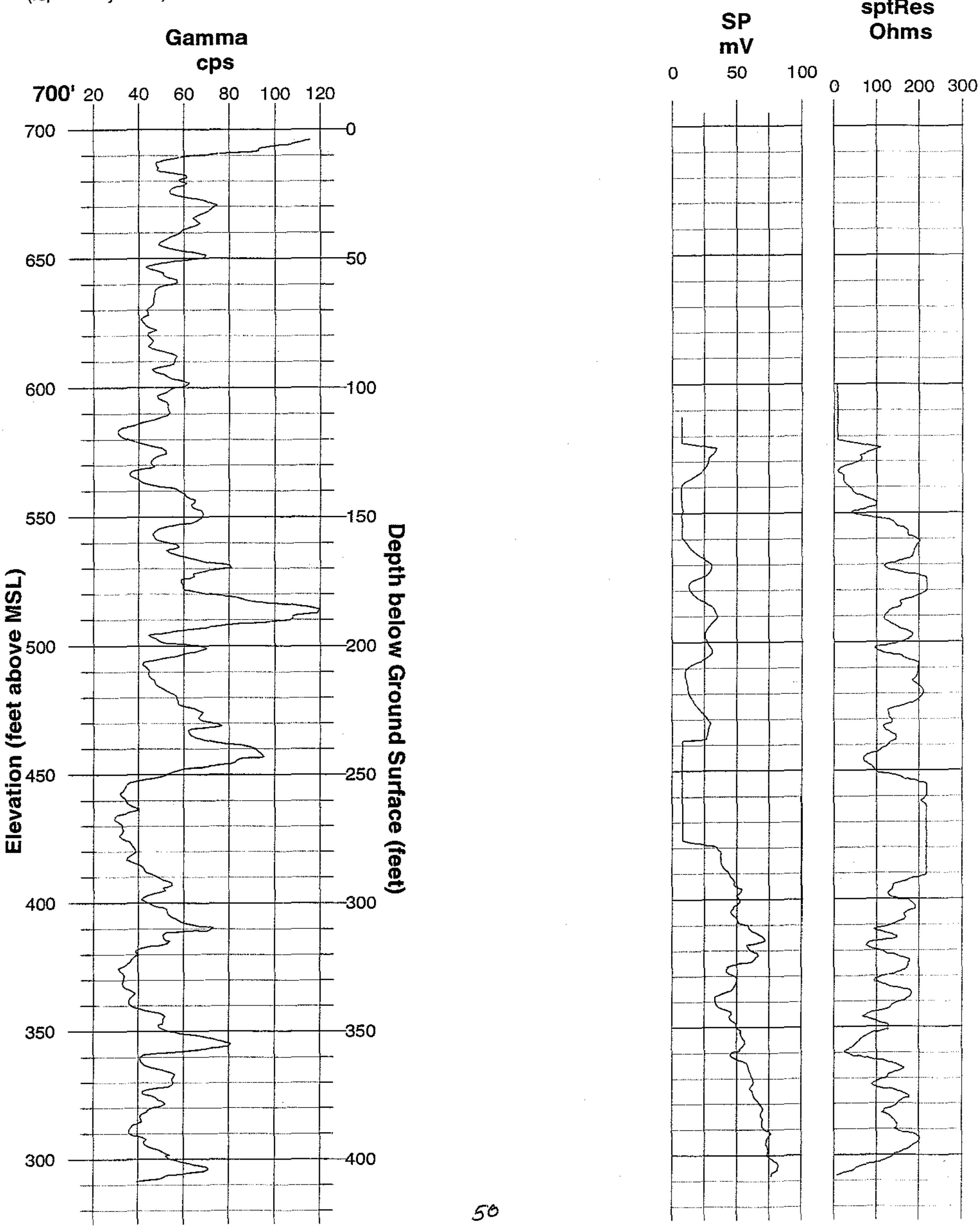


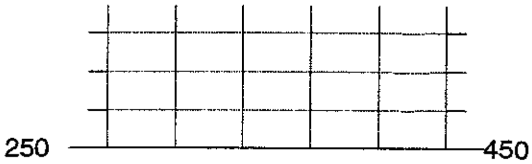
Wisconsin Geological and Natural History Survey
Geophysical Log
Digitized from electric logs on file at WGNHS

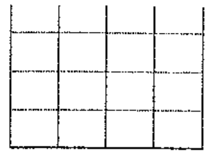
Elevation: est 700 ft
Depth to water:
Casing:
(reported by driller): 122 ft

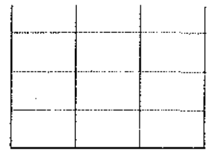
Well: DR-33
Peninsula Experiment Station

T28N, R26E, section 22, SW1/4, SW1/4, SW1/4




250
450



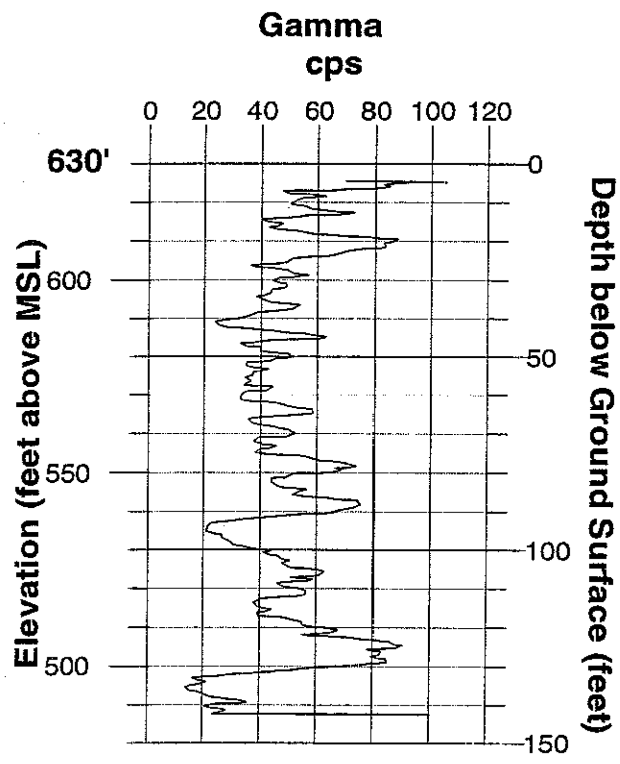


Wisconsin Geological and Natural History Survey
Geophysical Log
Digitized from electric logs on file at WGNHS

Elevation: est 630 ft
Depth to water:
Casing:
(reported by driller): 142 ft

Well: DR-262
USGS Piezometer Test Hole

T27N, R26E, section 5, NE1/4, NW1/4, NE1/4



Geophysics Logging Documentation

Well or Hole Name: U.S.G.S. Water-level monitoring well, Highway Garage

Project: Sturgeon Bay Wellhead Protection **Date Logged:** 8/21/94

WGNHS Geologic Log Number: DR-265

Estimated Elevation: 615 ft **County:** Door

Personnel: Ken Bradbury and Maureen Muldoon

Location: NE1/4, NE1/4 section 5 ,T27N, R26 E/W
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole Other (explain) USGS WATER LEVEL MONITORING WELL

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: ______

Measured Static Water Level: ______

Hole Depth (reported by driller)______ **Casing Depth** (reported by driller) ___

Hole Depth (from logging) 439 **Casing Depth** (from logging) 170

Casing Diameter (reported by driller) ______

Open-hole Diameter(s) (reported by driller) ______

Caliper Calibration: Rings used to calibrate 4 1/2" and 7"

Readings at end of logging run ______

SP/resistivity Calibration: ______Yes X No

Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma	down	3.5 - 439.2	20 ft/min	265gamma.ga0
SP/resistivity	up	3.7 - 439.2	15-20 ft/min	265rsp.ra0
Caliper	up	4.1 - 439.3	15 ft/min	265cal.ca0
Fluid temp/resistivity	down up	5.5 - 439.8 5.5 - 439.8	20 ft/min 20-25 ft/min	265tres.wa0 265tres.wa1 tempres.wa0*
Other				

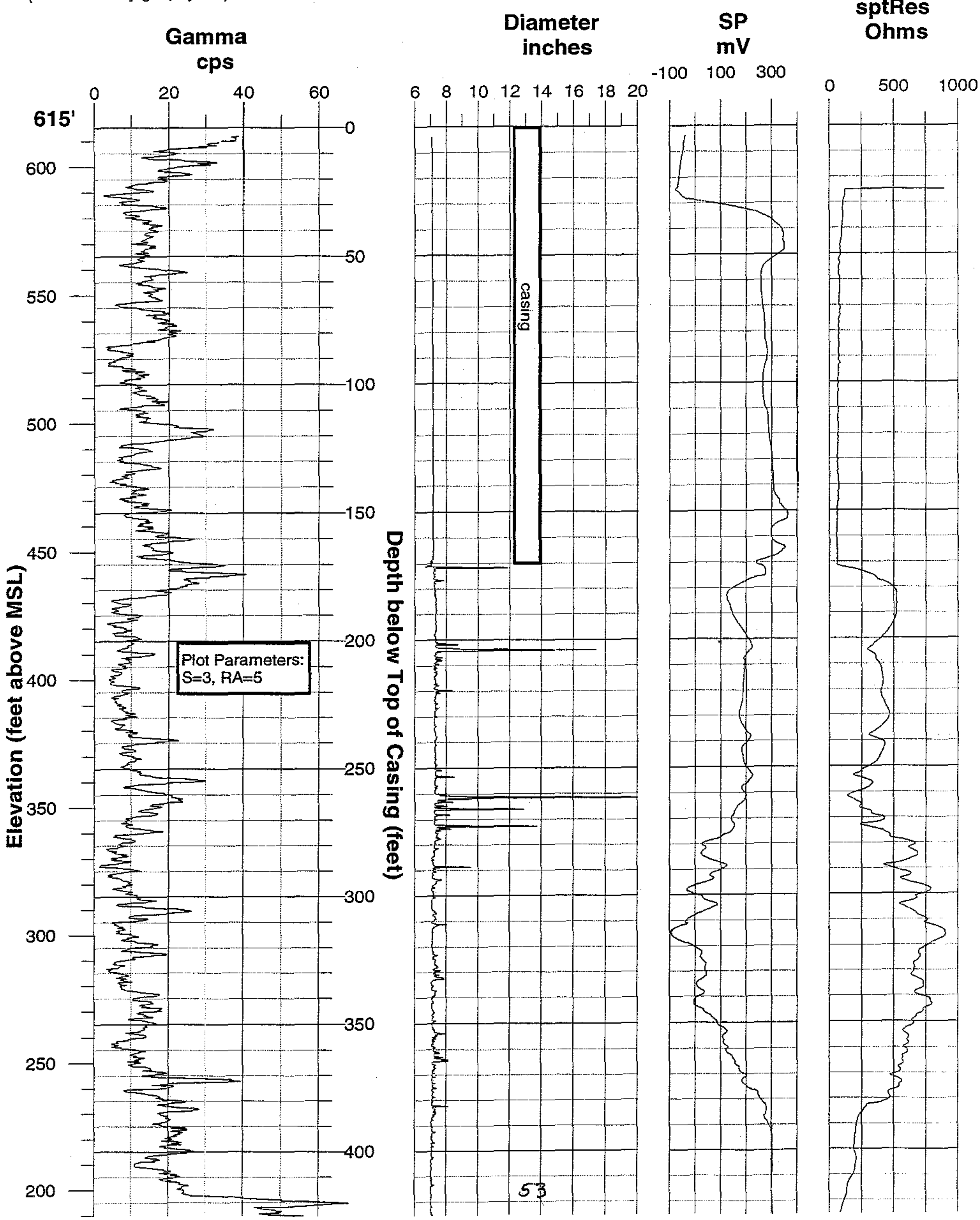
*Fluid temperature/resistivity also logged 9/27/94 by Bradbury and Muldoon

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 8/21/94 by K. Bradbury and M. Muldoon

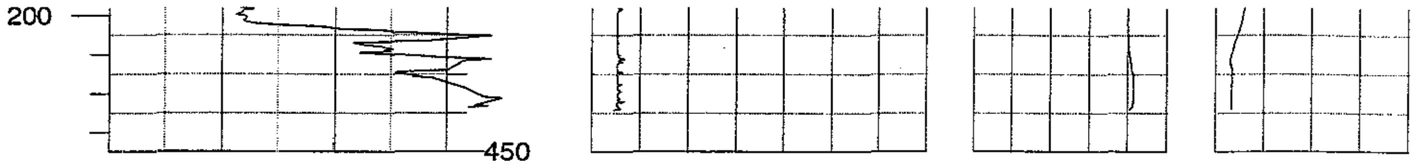
Elevation: est 615 ft
Depth to water:
Casing:
(determined by geophysics): 170 ft

Well: DR-265
U.S.G.S. well at highway garage

T27N, R26E, section 5, NE1/4, NE1/4



53

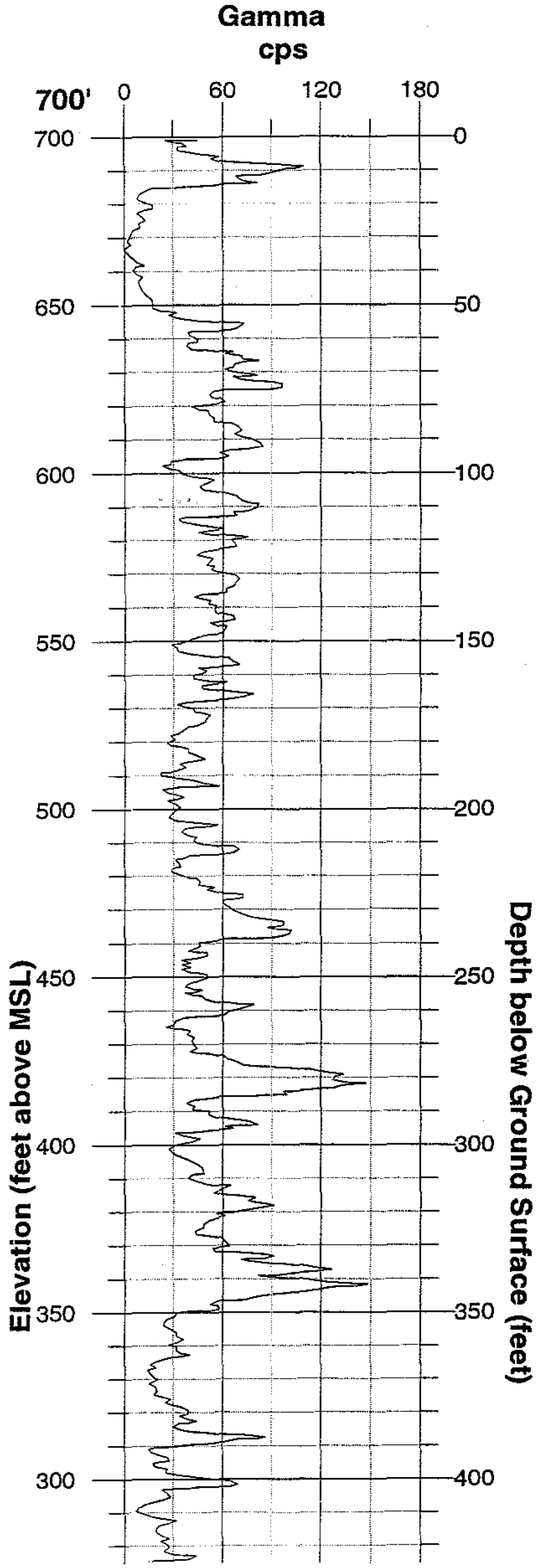

200
450

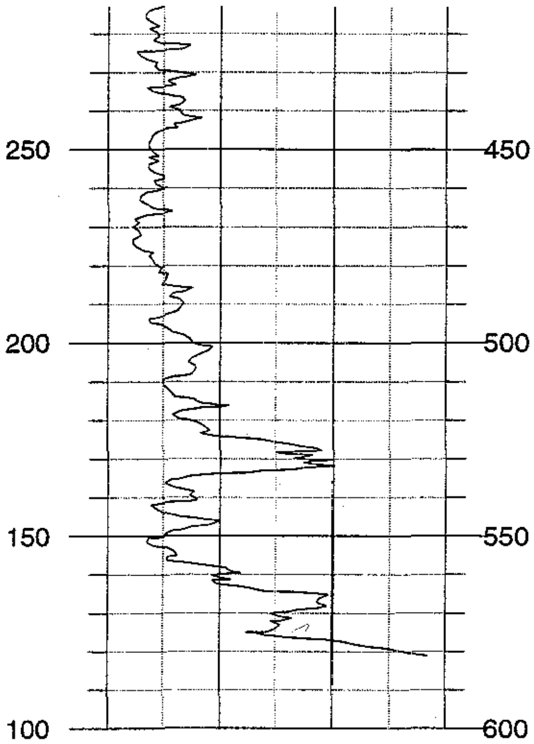
Wisconsin Geological and Natural History Survey
Geophysical Log
Digitized from electric logs on file at WGNHS

Elevation: est 700 ft
Depth to water:
Casing:
(reported by driller): 595 ft

Well: DR-289 (just Silurian portion)
USGS Test Hole

T29N, R27E, section 32, NW1/4, SE1/4





Note: Gamma log continues to a depth of 1711 ft

Geophysics Logging Documentation

Well or Hole Name: Sturgeon Bay City Well #9

Project: Sturgeon Bay Wellhead Protection **Date Logged:** 8/23/94

WGNHS Geologic Log Number: DR-292

Estimated Elevation: 670 ft **County:** Door

Personnel: Pete Roffers

Location: SW1/4, SE1/4, NE1/4 section 18 ,T27N, R26 E/W
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: ______

Measured Static Water Level: 82.78 ft from TOC

Hole Depth (reported by driller) 505 **Casing Depth** (reported by driller) 150

Hole Depth (from logging) 505 **Casing Depth** (from logging) 150

Casing Diameter (reported by driller) 18-inch

Open-hole Diameter(s) (reported by driller) 26"(0-37), 24"(37-150), 17"(150-507)

Caliper Calibration: Rings used to calibrate 4 1/2" and 7"

Readings at end of logging run ______

SP/resistivity Calibration: ______Yes X No

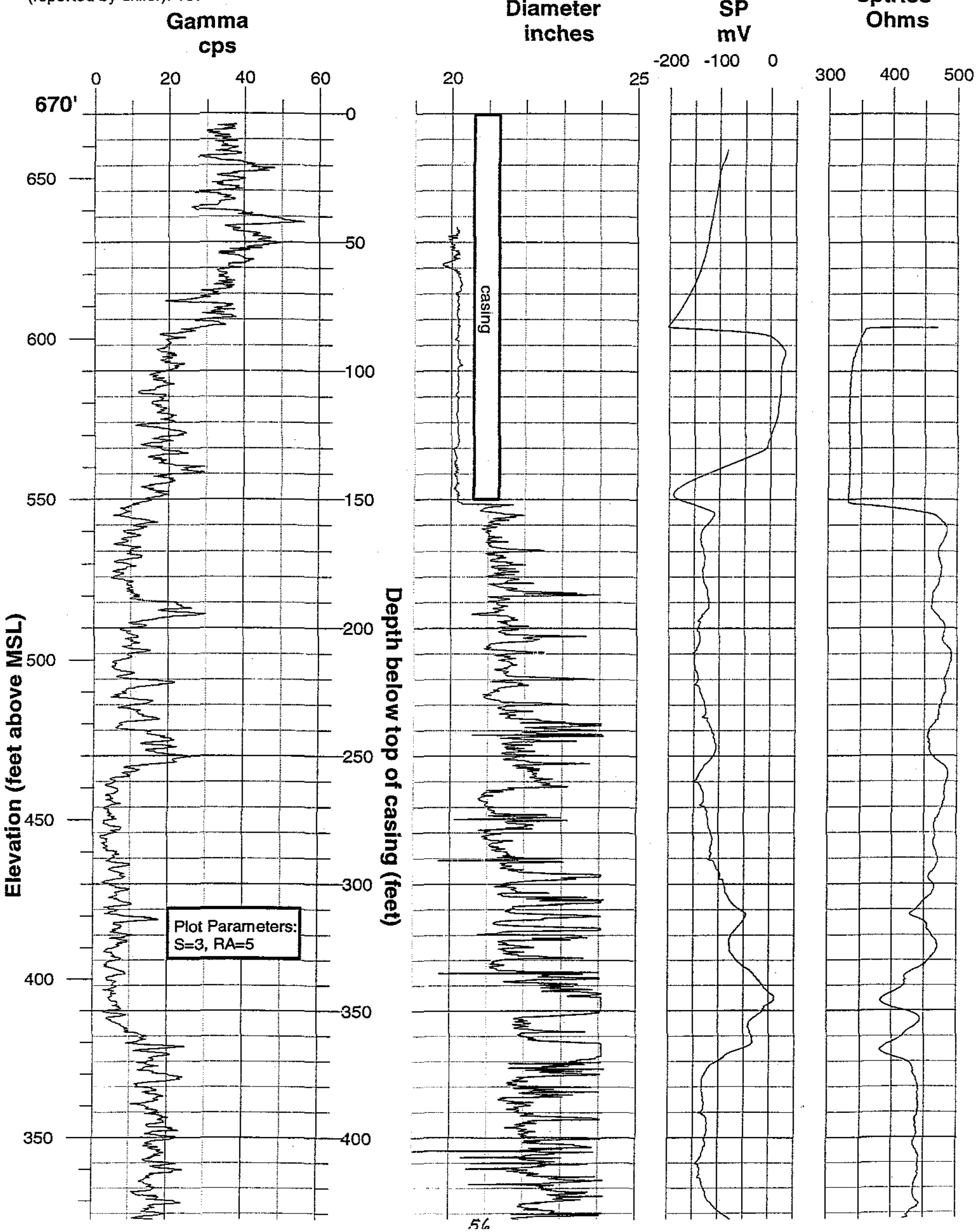
Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma	down	3.5 - 477.6	15 ft/min	292gam.ga0
SP/resistivity	up	3.5 - 476.7	15 ft/min	292rsp.ra0
Caliper	up	44.3 - 477	15 ft/min	292cal.ca4
Fluid temp/resistivity	down	5.5 - 504.7	15 ft/min	292tres.wa0
Other				

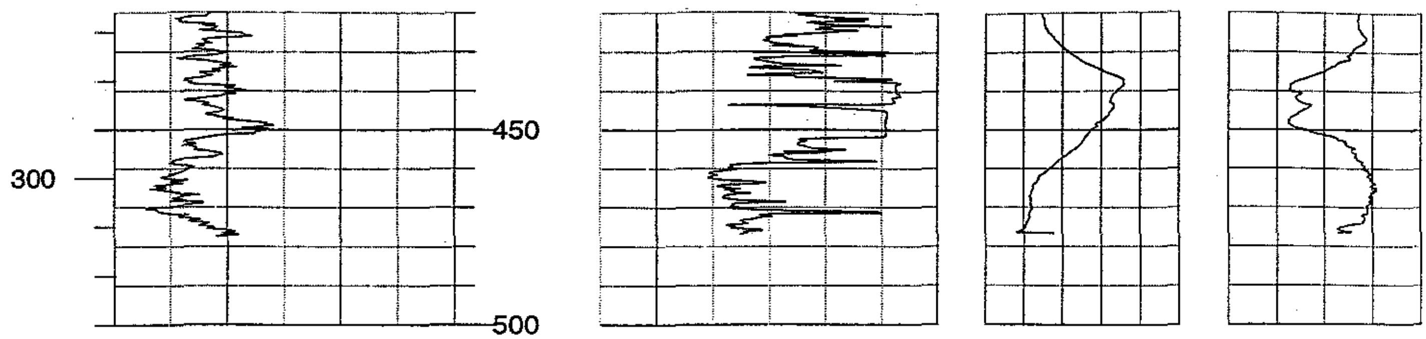
Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 8/23/94 by P. Roffers

Elevation: est 670 ft
Depth to water: 82.8 ft
Casing:
(reported by driller): 150 ft

Well: DR-292
Sturgeon Bay City Well #9

T27N, R26E, section 18, SW1/4, SE1/4, NE1/4




300
450
500

Geophysics Logging Documentation

Well or Hole Name: ______________________

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 8/23/95

WGNHS Geologic Log Number: DR-391

Estimated Elevation: 772 ft **County:** Door

Personnel: Gary Gianniny and Jodi VanderVelden

Location: NW1/4, SE1/4, SW1/4 section 20 ,T28N, R26 E/W
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______________________

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: 2 ft above grade

Measured Static Water Level: 169.3 ft

Hole Depth (reported by driller) 305 **Casing Depth** (reported by driller) 203

Hole Depth (from logging) 304 **Casing Depth** (from logging) 202

Casing Diameter (reported by driller) 6-inch

Open-hole Diameter(s) (reported by driller) 6-inch

Caliper Calibration: Rings used to calibrate 4 1/2" and 7"

Readings at end of logging run ______________________

SP/resistivity Calibration: ______Yes X No

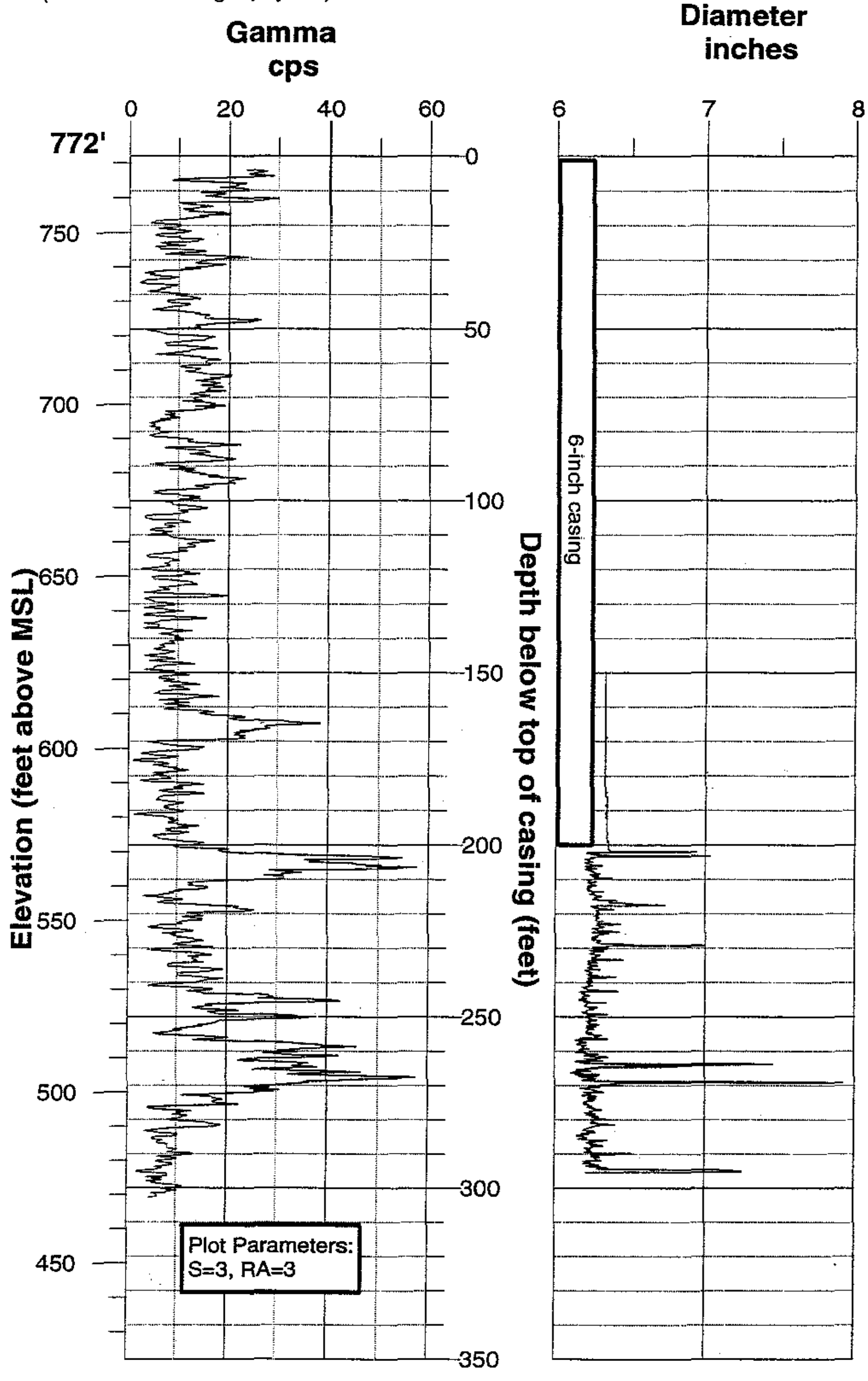
Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma	up down	3.8 - 303 3.6 - 303	 20 ft/min	391gamup.ga0 391gamdn.ga0
SP/resistivity				
Caliper	up	149.9 - 303.2	15 ft/min	Dr391cal.ca0
Fluid temp/resistivity	down	155.4 - 304	10 ft/min	391tmprs.wa0
Other				

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 8/23/95 by G. Gianniny and J. VanderVelden

Elevation: est 772 ft
Depth to water: 167.3 ft below TOC
Casing:
(determined from geophysics): 202 ft from TOC

Well: DR-391

T28N, R26E, section 20, NW1/4, SE1/4, SW1/4



Geophysics Logging Documentation

Well or Hole Name: VanderHoof (owner)

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 8/31/95

WGNHS Geologic Log Number: DR-392

Estimated Elevation: 665 ft **County:** Door

Personnel: Gary Gianniny and Wylie Linquist

Location: SW1/4, SW1/4, SW1/4 section 17 ,T28N, R27 E
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______ Ground Surface
______ Other (include in sketch on back)
Distance from top of casing to ground surface: 2.5 ft above grade

Measured Static Water Level: 60.5 ft

Hole Depth (reported by driller) 241 **Casing Depth** (reported by driller) 170

Hole Depth (from logging) 249.5 **Casing Depth** (from logging) 172

Casing Diameter (reported by driller) 6-inch

Open-hole Diameter(s) (reported by driller) 6-inch

Caliper Calibration: Rings used to calibrate 4 1/2" and 7"

Readings at end of logging run ______

SP/resistivity Calibration: ______ Yes X No

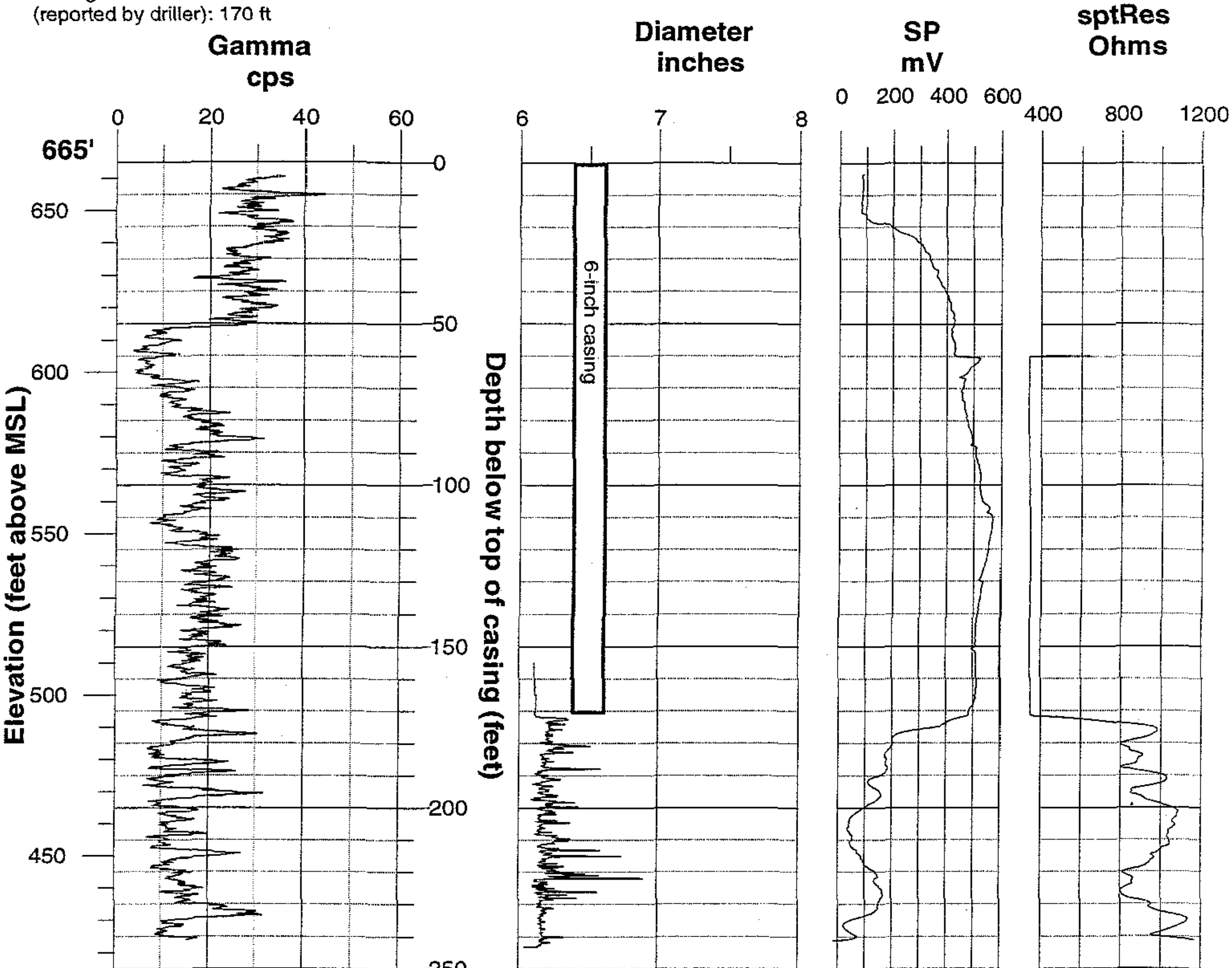
Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma	up	3.8 - 241.2	20 ft/min	392gamup.ga0
SP/resistivity	down	3.5 - 241.2	20 ft/min	392spres.ra0
Caliper	up	155 - 243.15	15 ft/min	dr392cal.dat
Fluid temp/resistivity	down	5.3 - 242.7	12.2 ft/min	392tmprs.wa0
Other				

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 8/31/95 by G. Gianniny and W. Linquist

Well: DR-392

T28N, R27E, section 17, SW1/4, SW1/4, SW1/4

Elevation: est 665 ft
Depth to water: 60.5 ft
Casing:
(reported by driller): 170 ft



Plot Parameters:
S=1, RA=9

Geophysics Logging Documentation

Well or Hole Name: ______________________

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 9/1/95

WGNHS Geologic Log Number: DR-393

Estimated Elevation: 592 ft **County:** Door

Personnel: Gary Gianniny

Location: SW1/4, NW1/4, NW1/4 section 22, T28N, R27 E; 4386 Glidden Rd.
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______________________

Reference Point for logging: X Top of Casing ____ Ground Surface
____ Other (include in sketch on back)
Distance from top of casing to ground surface: 18-24" above grade

Measured Static Water Level: artesian (1-2 gpm)

Hole Depth (reported by driller) 241 **Casing Depth** (reported by driller) 170

Hole Depth (from logging) 243.5 **Casing Depth** (from logging) 170

Casing Diameter (reported by driller) 6-inch

Open-hole Diameter(s) (reported by driller) 6-inch

Caliper Calibration: Rings used to calibrate 4 1/2" and 7"

Readings at end of logging run ______________________

SP/resistivity Calibration: ____ Yes X No

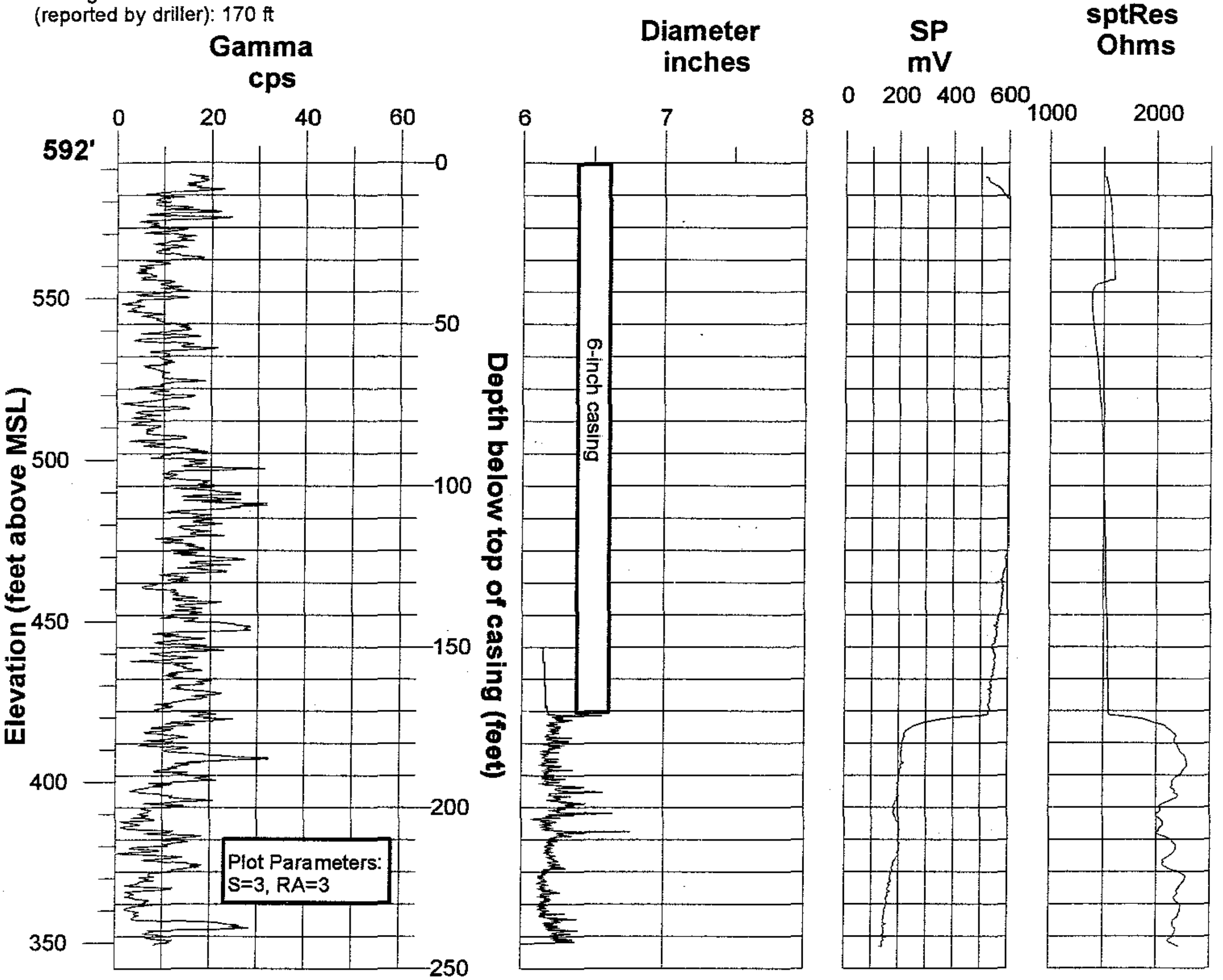
Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma	down up	3.5 - 24.3	20 ft/min	393gamdn.ga0 393gamup.ga0
SP/resistivity	down	4.3 - 243.3	20 ft/min	393spres.ra0
Caliper	up	150 - 242.4	15 ft/min	393calip.ca0
Fluid temp/resistivity				

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 9/1/95 by G. Gianniny

Elevation: est 592 ft
Depth to water: flowing (1-2 gpm)
Casing:
(reported by driller): 170 ft

Well: DR-393

T28N, R27E, section 22, SW1/4, NW1/4, NW1/4
4386 Glidden Road



Geophysics Logging Documentation

Well or Hole Name: Jarmen Road Corehole (drilled by Mark Harris, UWM)

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 7/11/95

WGNHS Geologic Log Number: DR-394

Estimated Elevation: 798 ft **County:** Door

Personnel: Gary Gianniny, Dan Hegrenes, Maureen Muldoon

Location: SW1/4, NW1/4, SE1/4 section 2, T28N, R26E; Jarman Road Site
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: ______Top of Casing X Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: 1.4 ft above grade

Measured Static Water Level: 138 ft

Hole Depth (reported by driller) 540 **Casing Depth** (reported by driller) 2

Hole Depth (from logging) 435 **Casing Depth** (from logging)______

Casing Diameter (reported by driller) 3-inch

Open-hole Diameter(s) (reported by driller) 3-inch

Caliper Calibration: Rings used to calibrate 41/2" and 7" (after logging)

Readings at end of logging run: 7" reads 8.21" 4.5" reads 5.24
(Correction factor: 0.8588)

SP/resistivity Calibration: ______Yes X No

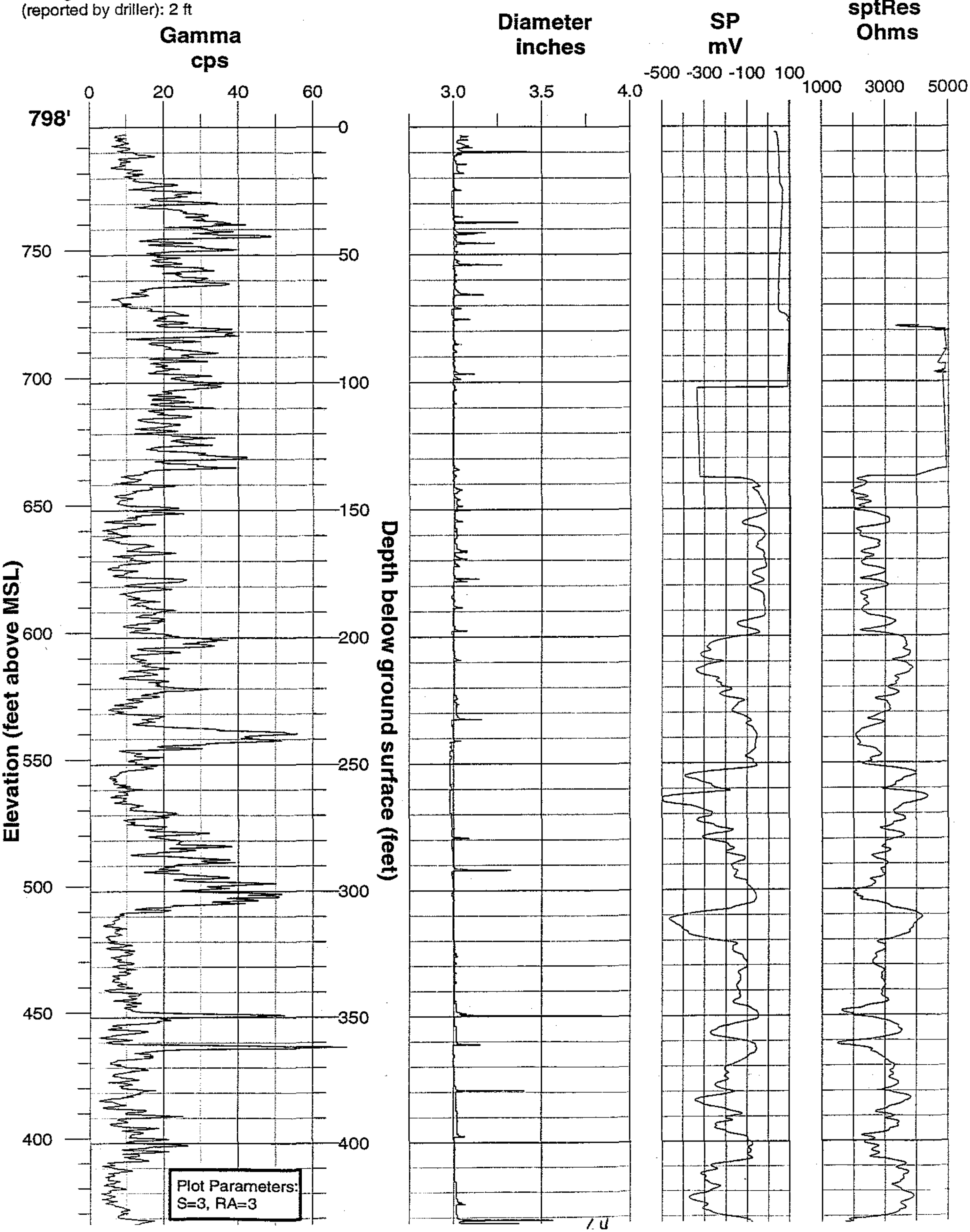
Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma	up	2.5 - 436.3	10-12 ft/min	394gma.ga0
	up	2.9 - 436.4	40 ft/min	394 gma2.ga0
SP/resistivity	down	2.1 - 436.4	20 ft/min	394sprs2.ra0
	down	2.1 - 436.3		394sprs.ra0
Caliper	up	3.3 - 436	5-15 ft/min	394calp.wk1
Fluid temp/resistivity	down	125.5 - 435.1	15 - 20 ft/min	394tmpre.wa0
	up	122.7 - 435.1	20 - 25 ft/min	tmpresup.wa1
Other				

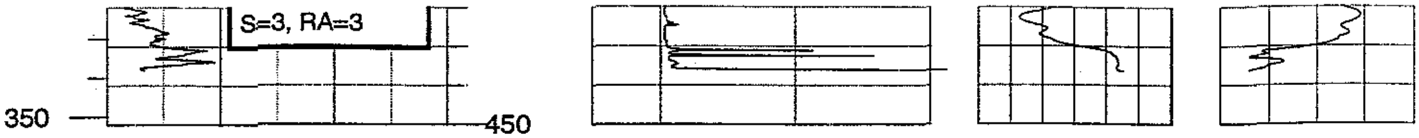
Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 7/11/95 by G. Gianniny, D. Hegrenes, M. Muldoon

Elevation: est 798 ft
Depth to water: 138
Casing:
(reported by driller): 2 ft

Well: DR-394
Jarmen Road Corehole

T28N, R26E, section 2, SW1/4, NW1/4, SE1/4




S=3, RA=3
350
450

Geophysics Logging Documentation

Well or Hole Name: ______________________

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 9/12/95

WGNHS Geologic Log Number: DR-395

Estimated Elevation: 770 ft **County:** Door

Personnel: Gary Gianniny and Bill Raatz

Location: SW1/4, SW1/4, NW1/4 section 5, T26N, R24E
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______________________

Reference Point for logging: _______Top of Casing __X__Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: 2 ft above grade

Measured Static Water Level: 198.42 ft

Hole Depth (reported by driller)_______ **Casing Depth** (reported by driller)____

Hole Depth (from logging) 805 **Casing Depth** (from logging) 170

Casing Diameter (reported by driller) 6-inch

Open-hole Diameter(s) (reported by driller) 6-inch

Caliper Calibration: Rings used to calibrate 4 1/2" and 7"

Readings at end of logging run: ______________________

SP/resistivity Calibration: _____Yes __X__No

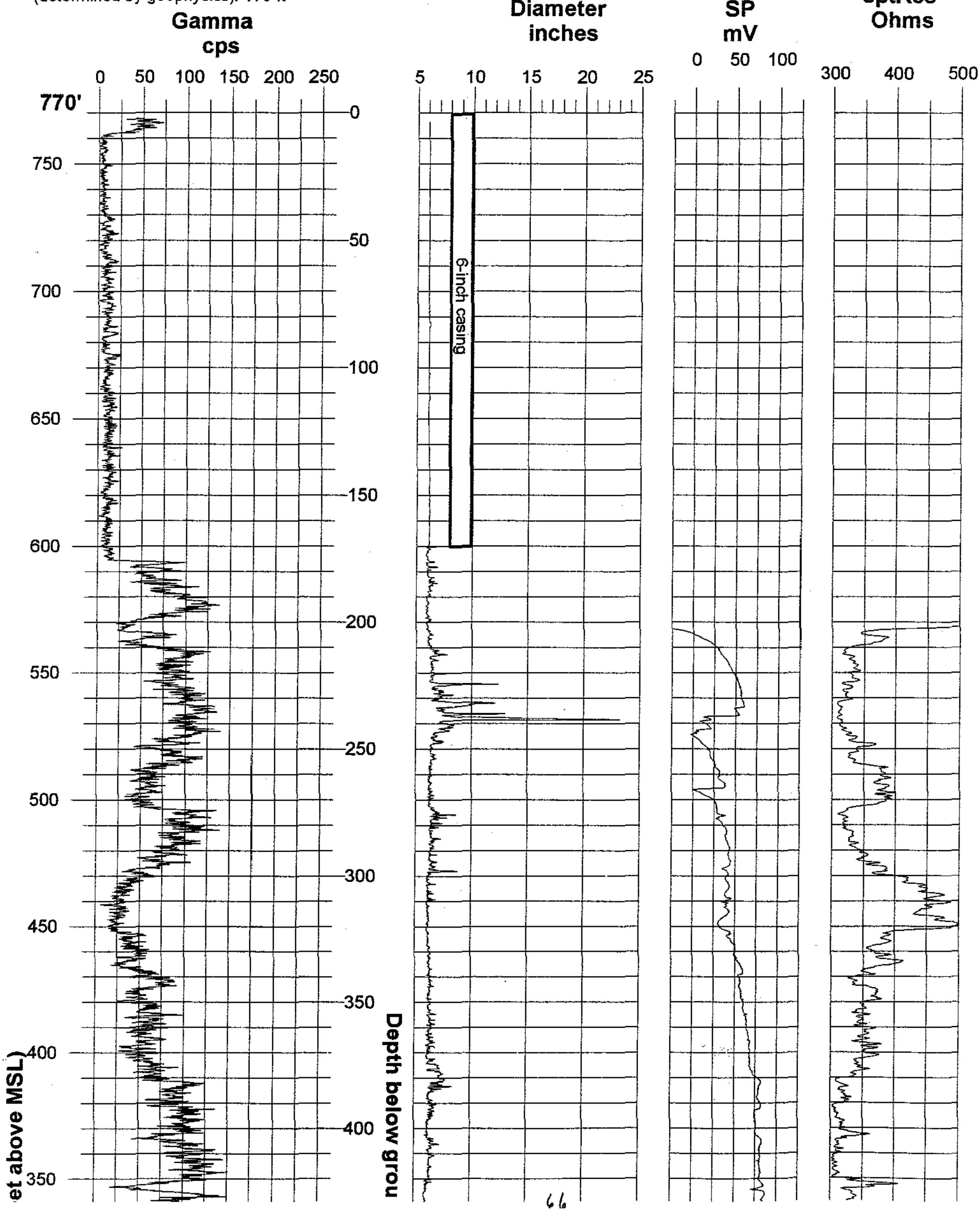
Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma	up	2.3 - 804.8	19-25 ft/min	395gamu.ga0
SP/resistivity	down	2 - 804.8	20 ft/min	395spres.ra0
Caliper	up	3 - 804.1	15 ft/min	395calp.ca0
Fluid temp/resistivity	down	4 - 805.6	5-7 ft/min	395tpres.ra0
Other				

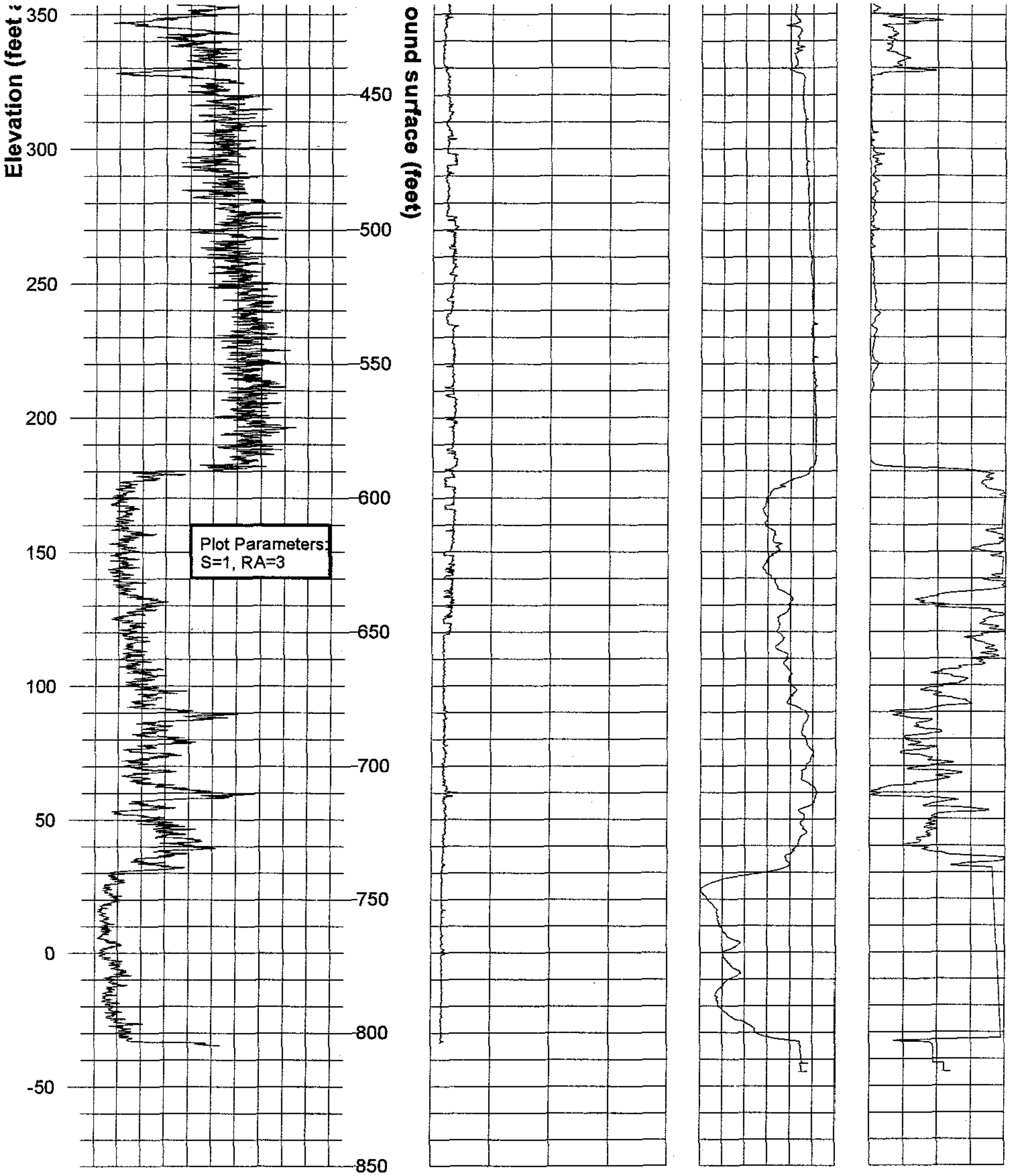
Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 9/12/95 by G. Gianniny and W. Raatz

Well: DR-395

T26N, R24E, section 5, SW1/4, SW1/4, NW1/4

Elevation: est 770 ft
Depth to water: 198.42
Casing:
(determined by geophysics): 170 ft




Elevation (feet
350
300
250
200
150
100
50
0
-50
ound surface (feet)
450
500
550
600
650
700
750
800
850
Plot Parameters:
S=1, RA=3

Geophysics Logging Documentation

Well or Hole Name: William Ruff (owner)

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 9/27/95

WGNHS Geologic Log Number: DR-396

Estimated Elevation: 725 ft **County:** Door

Personnel: Gary Gianniny

Location: SE1/4, NW1/4, NW1/4 section 6, T26N, R26E (Hornspier Rd)
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: ______

Measured Static Water Level: 27.7 ft

Hole Depth (reported by driller) 260 **Casing Depth** (reported by driller) 125

Hole Depth (from logging) 259 **Casing Depth** (from logging) 126

Casing Diameter (reported by driller) 6-inch

Open-hole Diameter(s) (reported by driller) 6-inch

Caliper Calibration: Rings used to calibrate 4.5" and 7"

Readings at end of logging run ______

SP/resistivity Calibration: ______Yes X No

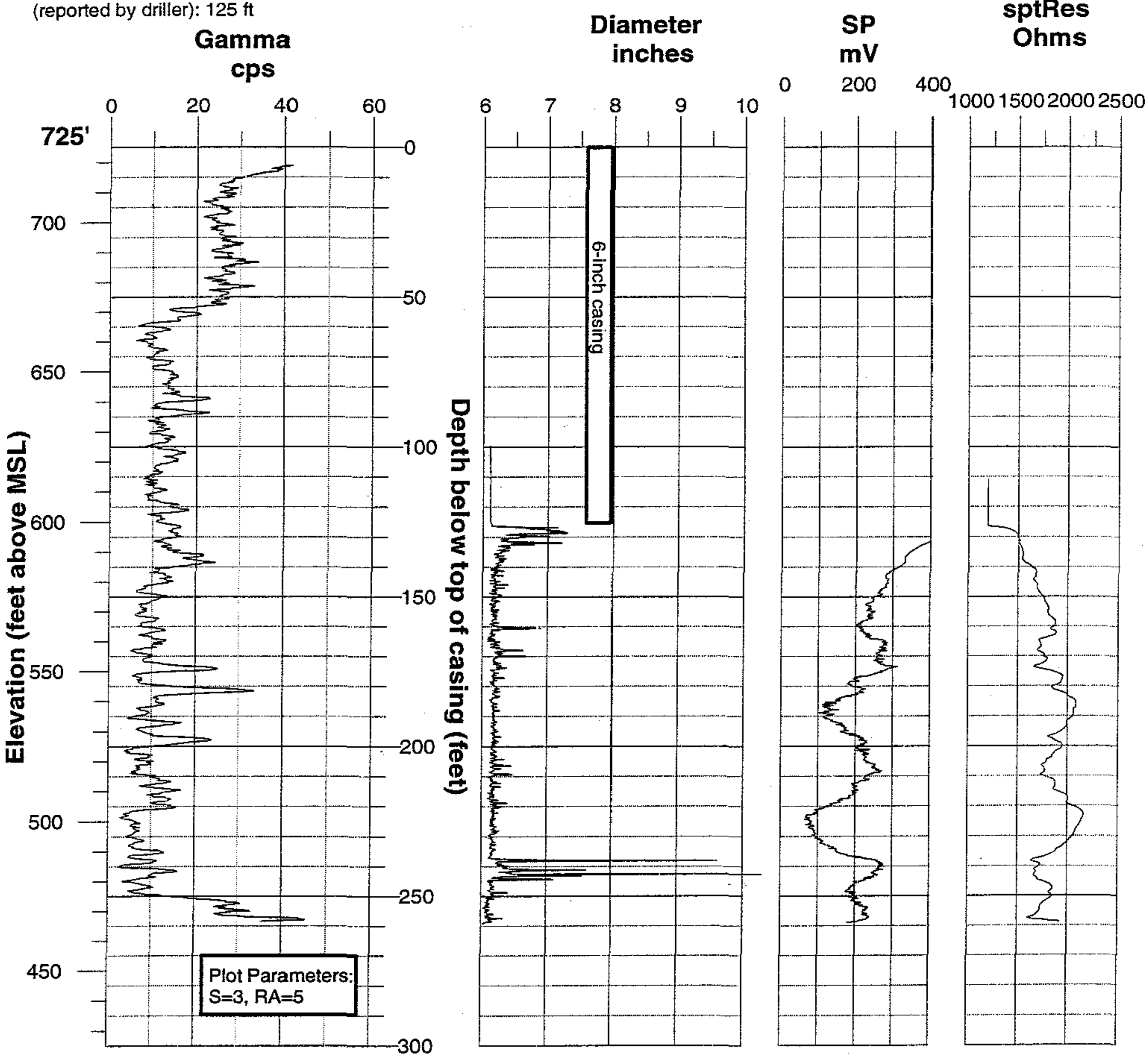
Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma	up	5.8 - 258.9	10-12 ft/min	396gmaup.ga0
SP/resistivity	down	110.8 - 258.9	11 ft/min	396spres.ra0
Caliper	up	99.8 - 259.2	15-17 ft/min	396cal.ca0
Fluid temp/resistivity				
Other				

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 9/27-28/95 by G. Gianniny

Elevation: est 725 ft
Depth to water: 27.7
Casing:
(reported by driller): 125 ft

Well: DR-396

T26N, R26E, section 6, SE1/4, NW1/4, NW1/4



Geophysics Logging Documentation

Well or Hole Name: Sturgeon Bay City Well #11

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 10/4/95

WGNHS Geologic Log Number: DR-397

Estimated Elevation: 588 ft **County:** Door

Personnel: Gary Gianniny and Pete Roffers

Location: NW1/4, SE1/4, SE1/4 section 6, T27N, R26E
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: ______Top of Casing ______Ground Surface
X Other (include in sketch on back)
Distance from top of casing to ground surface: ______

Measured Static Water Level: 10.1 ft

Hole Depth (reported by driller)______ **Casing Depth** (reported by driller)______

Hole Depth (from logging) 229 **Casing Depth** (from logging) 203

Casing Diameter (reported by driller) ______

Open-hole Diameter(s) (reported by driller) 8-inch

Caliper Calibration: Rings used to calibrate 4.5" and 7"

Readings at end of logging run 7.25 casing reads 8.1'

SP/resistivity Calibration: ______Yes X No

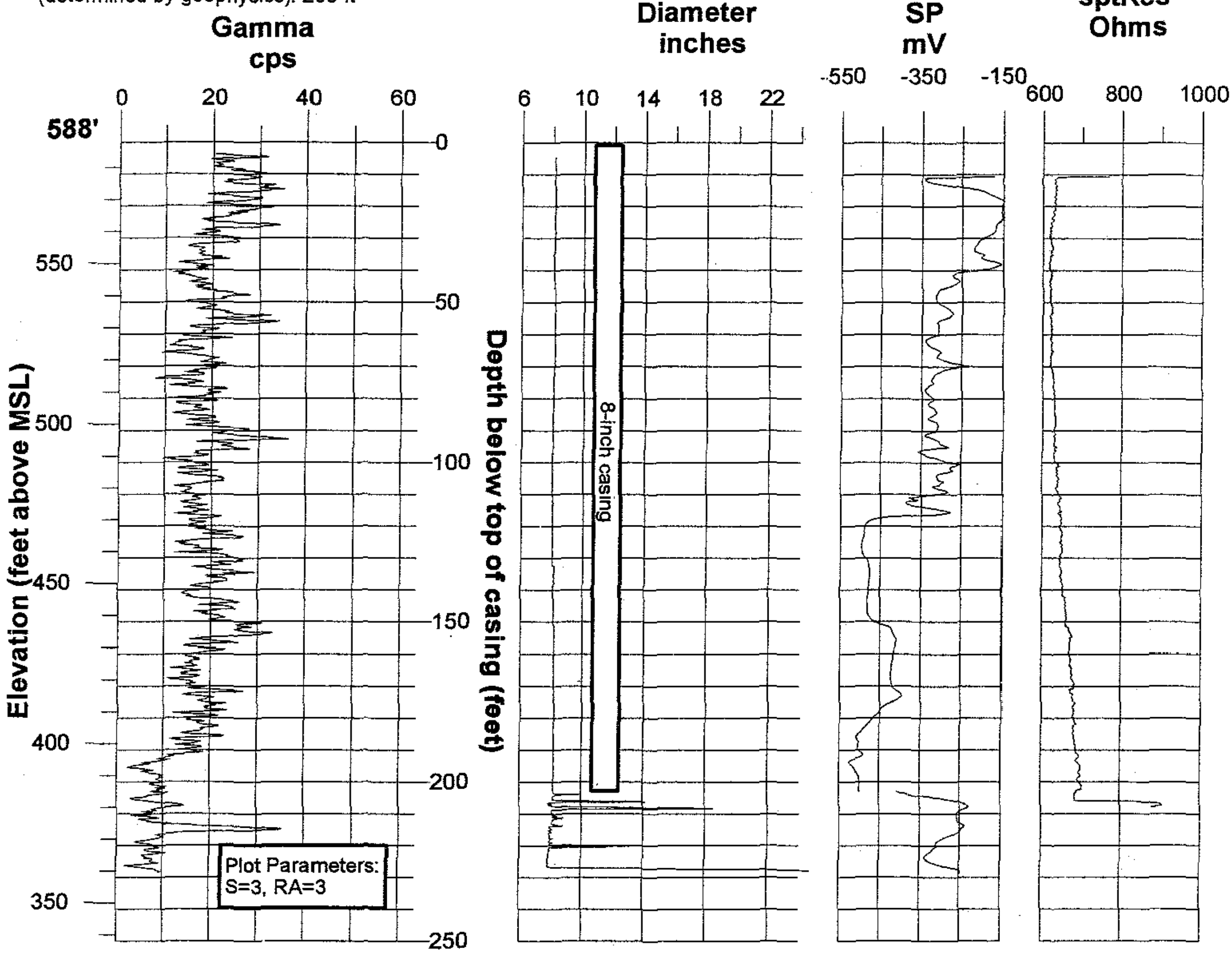
Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma	up	3.6 - 229	10 ft/min	39gmaup.ga0
SP/resistivity		3.6 - 207.9		397spres.ra0
	down	190 - 229	15 ft/min	397spre.ra0
Caliper	up	4.6 - 228.1	10 - 12 ft/min	397calip.ca0
Fluid temp/resistivity	down	5.5 - 229	5 -12 ft/min	397tempr.wa0
Other				

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 10/4/95 by G. Gianniny and P. Roffers

Elevation: est 588 ft
Depth to water: 10.1
Casing:
(determined by geophysics): 203 ft

Well: DR-397
Sturgeon Bay city well #11

T27N, R26E, section 6, NW1/4, SE1/4, SE1/4



Geophysics Logging Documentation

Well or Hole Name: Bissen corehole #5

Project: Tracer Study for characterization of groundwater movement and contaminant transport in fractured dolomite **Date Logged:** 4/21/94

WGNHS Geologic Log Number: ______

Estimated Elevation: 685 ft **County:** Door

Personnel: Maureen Muldoon, Ken Bradbury

Location: NE1/4, NW1/4, NW1/4 section 21 ,T27N, R25 E
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger (rented from Colog)

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: 3.57 ft

Measured Static Water Level: 6.03 ft

Hole Depth (reported by driller) 35 **Casing Depth** (reported by driller) 1.43

Hole Depth (from logging) 38 **Casing Depth** (from logging)______

Casing Diameter (reported by driller) 3-inch

Open-hole Diameter(s) (reported by driller) 3"

Caliper Calibration: Rings used to calibrate ______

Readings at end of logging run ______

SP/resistivity Calibration: ______Yes X No

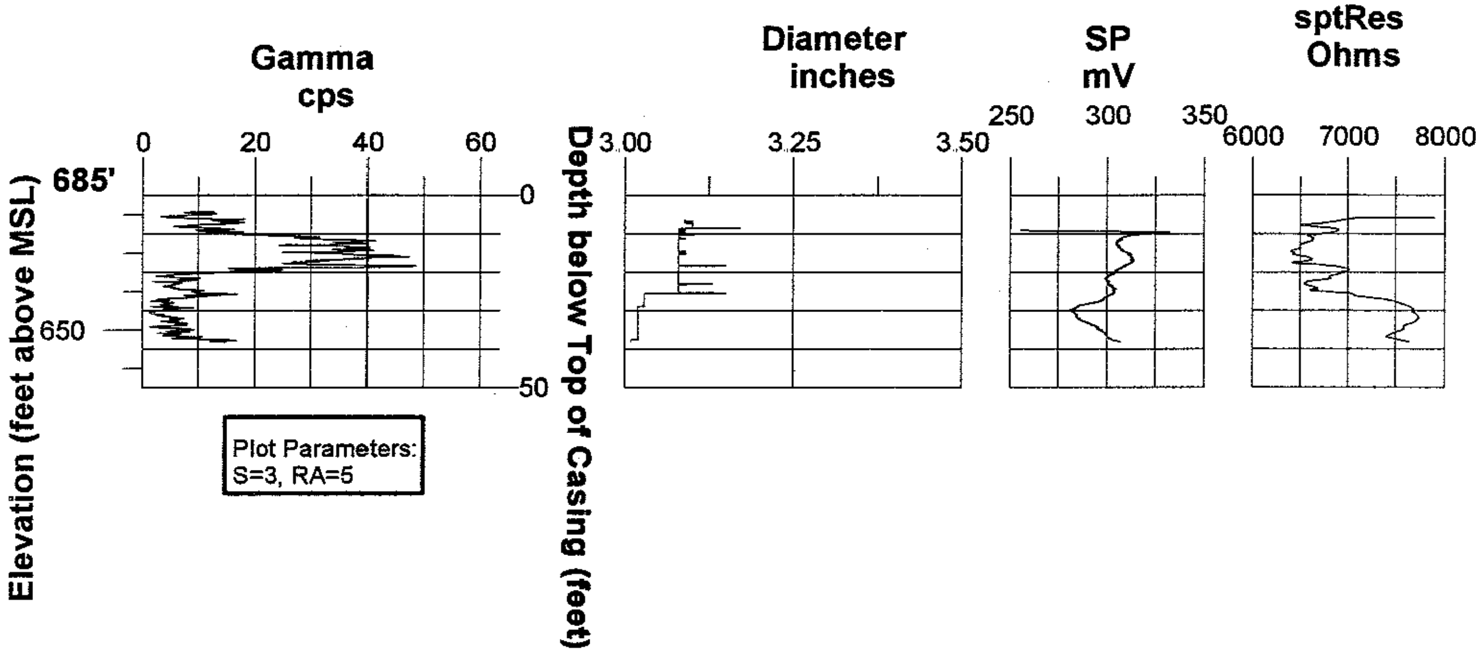
Logs Run	Direction (up/down)	Depths Logged	Logging Speed	Data Filename(s)
Gamma	down	4.0 - 38.2	5 ft/min	5gamma.ga0
SP/resistivity	up	3.9 - 38.1	10 ft/min	5res-sp.ra0
Caliper	up	6.48 - 38.06	3.5 - 4 ft/min	5caliper.3a0
Fluid temp	down	6.37 - 38.06	5-10 ft/min	5temp.pa0
Other				

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 4/21/94 by M. Muldoon

Elevation: est 685 ft
Depth to water: 6.03 ft (from TOC)
Casing: 2 ft

Well: Bissen 5
corehole at tracer study site

T27N, R25E, section 21, NE1/4, NW1/4, NW1/4



APPENDIX 5 - FLUID LOGS

This appendix contains data from fluid temperature and resistivity (or conductivity) logs and flow-meter logs. Fluid temperature and resistivity/conductivity data can be acquired easily and rapidly in any open borehole. Sharp changes in these profiles, within a given borehole, provide a qualitative method of locating discrete high-permeability features where water of differing chemistry or temperature is flowing into or out of the borehole. Not all logs were completed on all holes and we repeated some logs for holes that had been logged in previous studies. Details of logging procedures and well locations are included on data sheets that accompany each log. The original data and copies of each log are on file at WGNHS. Plotting scale varies for the different logs. If only fluid temperature and resistivity data were available, the log was plotted at a scale of 50 ft/inch so that it could be easily compared to the geophysical logs in Appendix 4. Holes with heat-pulse flowmeter data were typically plotted at a scale of 25 ft/inch so that individual measurements could be resolved.

Fluid Temperature and Resistivity

The temperature of groundwater is a function of both the time of year that precipitation recharged the groundwater system and the residence time of water in the aquifer. In Wisconsin, most groundwater recharge takes place in the spring, during snowmelt, or in autumn, after vegetation goes dormant. In the spring of the year, cold infiltrating water can be easily differentiated from warmer water that has been in the aquifer for a longer time; these temperature contrasts are frequently preserved well into the summer.

Fluid resistivity, or its inverse, fluid conductivity, are both controlled by the total amount of dissolved solids in the water. The amount of minerals dissolved in the water is largely a function of the time that the water has been in the aquifer and the type of pathway along which it flows. Water with high conductivity (low resistivity) is often indicative of longer residence times and transport through small pores, whereas low conductivity water is often an indication of more recent recharge that has moved rapidly through the aquifer.

Flowmeter Logging

Flowmeter logging can be used to quantify the amount of water entering a borehole at various depths. Data from spinner flowmeter logs (Bradbury and Muldoon, 1992; Jarmen Road site) and from heat-pulse flowmeter logs (Appendix 5) are incorporated in this study. These two logging methods are different both in terms of logging method and in terms of the effective flow rates that they measure.

Spinner logging is most effective at detecting larger flow rates and is frequently performed in a pumping well. The tool is lowered to the bottom of the well, a pump is placed near the top of the water column and the tool is gradually brought to the surface. The impeller in the tool spins faster at higher flow rates and the number of revolutions per minute is recorded and can be used to quantify flow rates. Sharp jumps in flow rates indicate discrete high-permeability zones that contribute the majority of water being pumped from the hole. These logs are sometimes effective in wells that are not being pumped if there is significant vertical movement of water in the boreholes, such as in flowing artisan wells. Previous studies in Door County have reported spinner flow data (Sherrill, 1978; Bradbury and Muldoon, 1992) We attempted to use a spinner tool in several holes and found that we were not able to generate measurable flow rates using pump rated at 30 gpm

The heat-pulse flowmeter was designed to measure the extremely low flow rates that are typical of fractured low-permeability rocks and the tool is only effective at flow rates less than 1 gpm. The method of measurement is quite different than the spinner tool. The heat-pulse meter consists of a heating element with two thermistors; one located above the heating element and one below it. A flexible rubber centralizer, located near the heating element, serves to center the tool in the borehole and focus flow through the meter. A heat pulse is generated and as the water flows either up or down the borehole, it is detected by one of the thermistors. The time from generation of pulse until it is recorded by one of the two thermistors is then used to calculate a flow rate. Measurements are taken at specific depths and any change in flow rate or flow direction from one measurement point to the next indicates water either entering or leaving the borehole over that distance.

In general, the ambient vertical flowrates were below the detection of the meter, however, pumping at rates varying from 1 to 20 gpm, induced measurable flow in the borehole. Typically we would start at one pumping rate (1-2 gpm) and proceed with measurements down the hole until we encountered a high-permeability feature that contributed the majority of the water that we were withdrawing. Once we moved below that feature, the flow would again be below the level of detection. We would then need to increase the pumping rate (2-20 gpm) to induce flow in the lower portion of the hole. This was less effective in high yield wells which appeared to be more strongly influenced by the pumping of near by city wells. Data interpretation is difficult if the pumping rate is not constant and the actual flow rate measured by the heat-pulse flowmeter must be evaluated in relation to the overall pumping rate. Data interpretation is more straight forward for those holes where we were able to maintain a relatively constant flow rate or where artisan conditions provided measurable ambient flowrates. In general, we felt that we could qualitatively identify high-permeability features by noting 1) sharp changes in measured flow rates while under a constant pumping regime and 2) locations at which we needed to increase the pumping rate

Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: Sturgeon Bay City Well #1

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 10/17/95

WGNHS Geologic Log Number: DR-4

Estimated Elevation: 672 ft **County:** Door

Personnel: Gary Gianniny

Location: SE1/4, NW1/4, SW1/4 section 7 ,T27N, R26 E/W
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169
Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: ______Top of Casing ______Ground Surface
X Other (include in sketch on back)
Distance from top of casing to ground surface: ______

Measured Static Water Level: 91.6 ft

Hole Depth (reported by driller) 1178 **Casing Depth** (reported by driller) 99?

Hole Depth (from logging) 839 **Casing Depth** (from logging) 140

Casing Diameter 8" (circle one) by driller from logging

Open-hole Diameters 9-11" (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 12 inch

Pumping Information:

Pump used: 4 inch submersible

Depth of pump in hole: ______ (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) Dr4data3.wk1

Heat-pulse File Information:

Filename(s): Dr4pulse.pa0, Dr4puls2.pa0, Dr4puls3.pa0

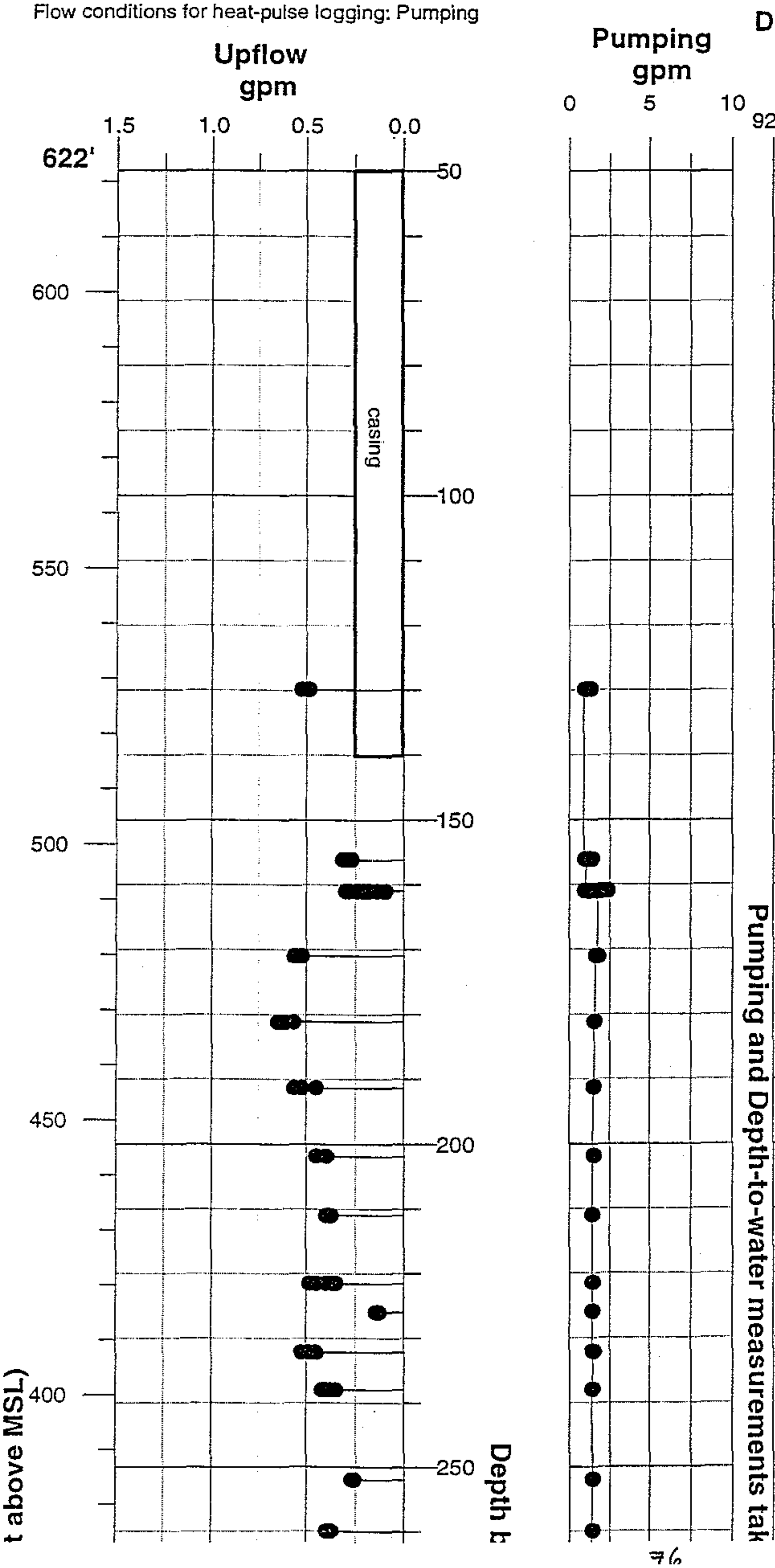
File Format: (circle one): summary record expanded

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Heat-pulse flowmeter logged 10/17/95 by G. Gianniny

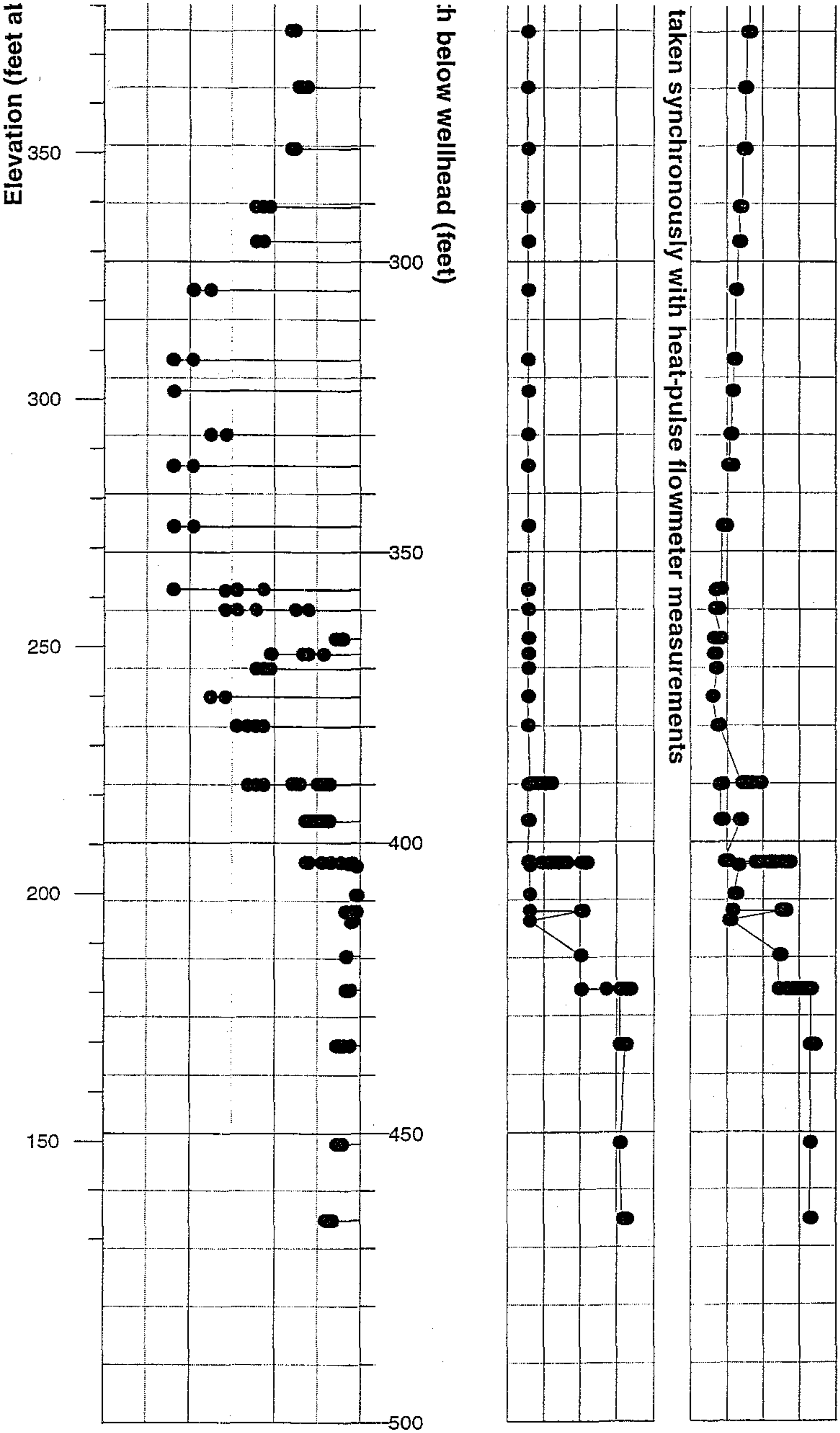
Elevation: est 672 ft
Depth to water: 91.6 ft
Flow conditions for heat-pulse logging: Pumping

Well: DR-4
Sturgeon Bay city well #1
(dolomite portion only)

T27N, R26E, section 7, SE1/4, NW1/4 of the SW1/4



76



Note: Well was open to a depth of 838 ft when logged

76a

Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: Sturgeon Bay City Well #1

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 11/16/95

WGNHS Geologic Log Number: DR-4

Estimated Elevation: 672 ft **County:** Door

Personnel: Ken Bradbury

Location: SE1/4, NW1/4, SW1/4 section 7 ,T27N, R26 E/W
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ____________

Reference Point for logging: ______Top of Casing ______Ground Surface
X Other (include in sketch on back)
Distance from top of casing to ground surface: ________

Measured Static Water Level: 91.6 ft

Hole Depth (reported by driller) 1178 **Casing Depth** (reported by driller) 99?

Hole Depth (from logging) 839 **Casing Depth** (from logging) 140

Casing Diameter 8" (circle one) by driller from logging

Open-hole Diameters 9-11" (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 12-inch

Pumping Information:

Pump used: city well # 8 pumping

Depth of pump in hole: ____________ (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) ____________

Heat-pulse File Information:

Filename(s): dr4flow.pa1, drflo3.pa0

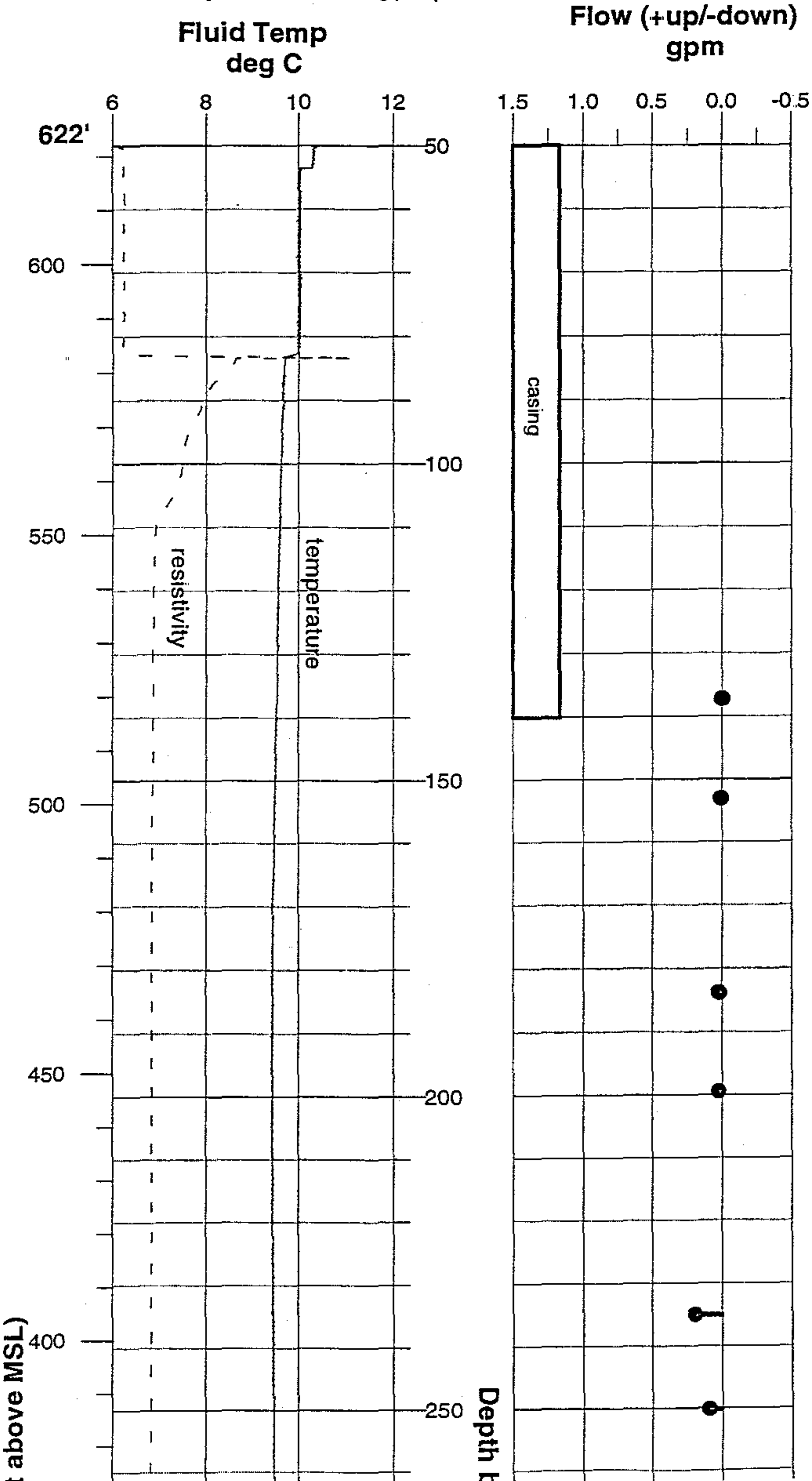
File Format: (circle one): summary record expanded

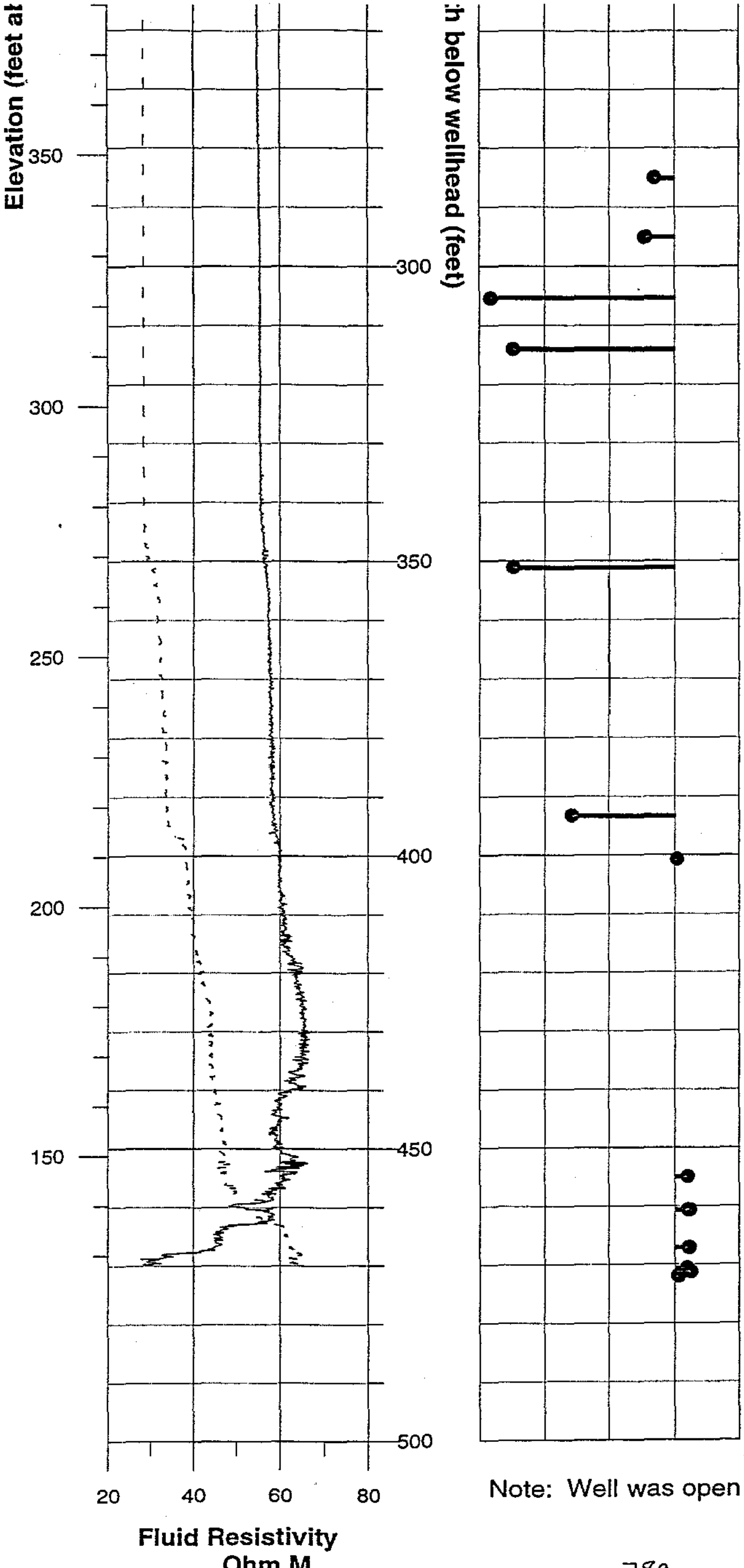
Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 11/16/95 by K. Bradbury

Well: DR-4
Sturgeon Bay city well #1
(dolomite portion only)

T27N, R26E, section 7, SE1/4, NW1/4 of the SW1/4

Elevation: est 672 ft
Depth to water: 91.6 ft
Flow conditions: City Well #8 was being pumped





Note: Well was open to a depth of 838 ft when logged

78a

Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: Roen Salvage (formerly Evangaline Dairy)

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 9/13/95

WGNHS Geologic Log Number: DR-6

Estimated Elevation: 592 ft **County:** Door

Personnel: Gary Gianniny and Bill Raatz

Location: NE1/4, SE1/4 section 7 ,T27N, R26 E W
(include sketch location map on back); 180 E. Redwood Ave, Sturgeon Bay, WI

Equipment: Mount Sopris Digital Logger, serial number - 0169

Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: 32 inches

Measured Static Water Level: 9.51 ft

Hole Depth (reported by driller) 350 **Casing Depth** (reported by driller) 100

Hole Depth (from logging) 339 **Casing Depth** (from logging) 100

Casing Diameter 10" (circle one) by driller from logging

Open-hole Diameters 10" (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 12 inch

Pumping Information:

Pump used: 4 inch submersible

Depth of pump in hole: 35 ft (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) ______

Heat-pulse File Information:

Filename(s): Dr6flow.pa0, Dr6flowb.pa0

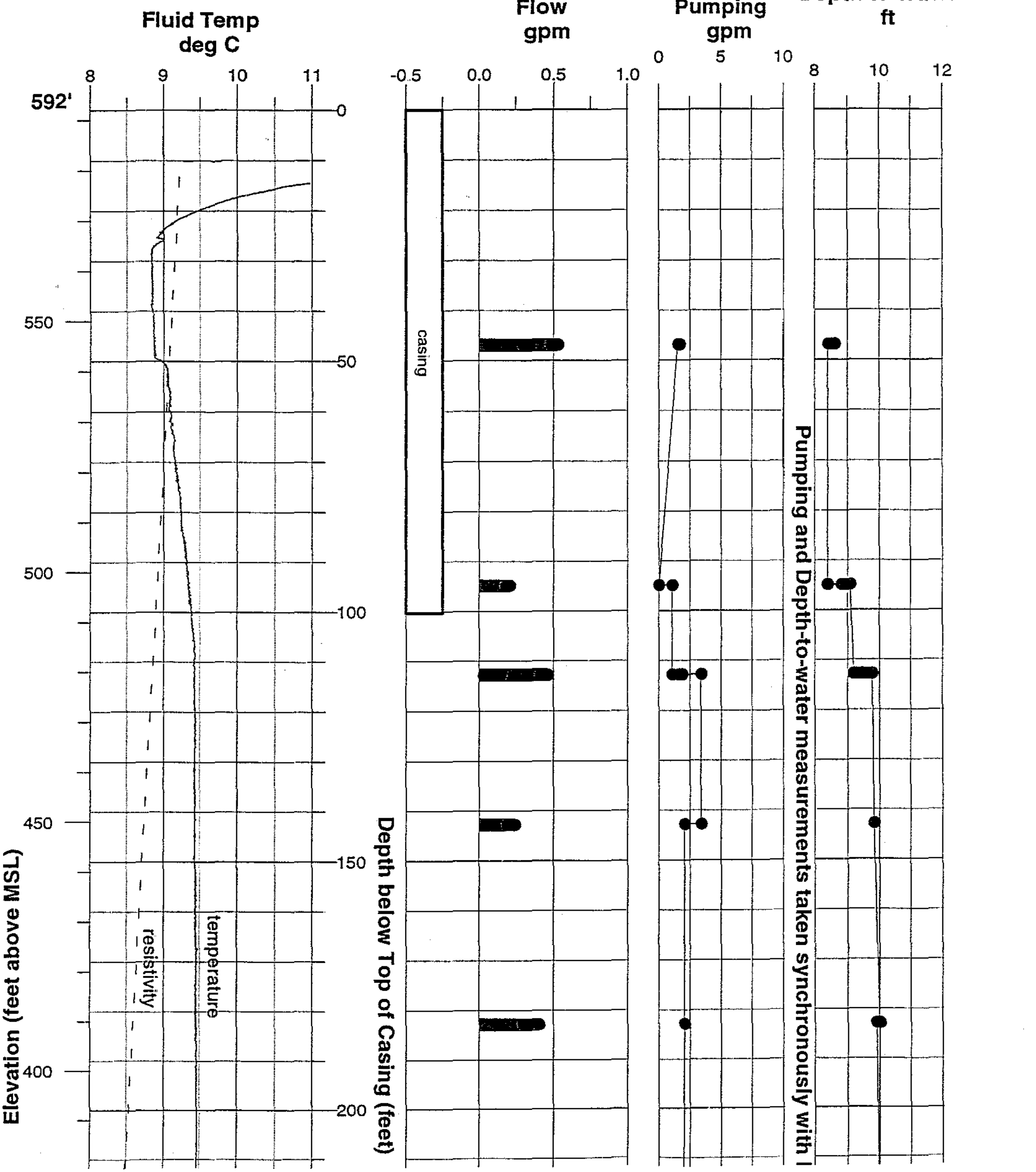
File Format: (circle one): summary record expanded

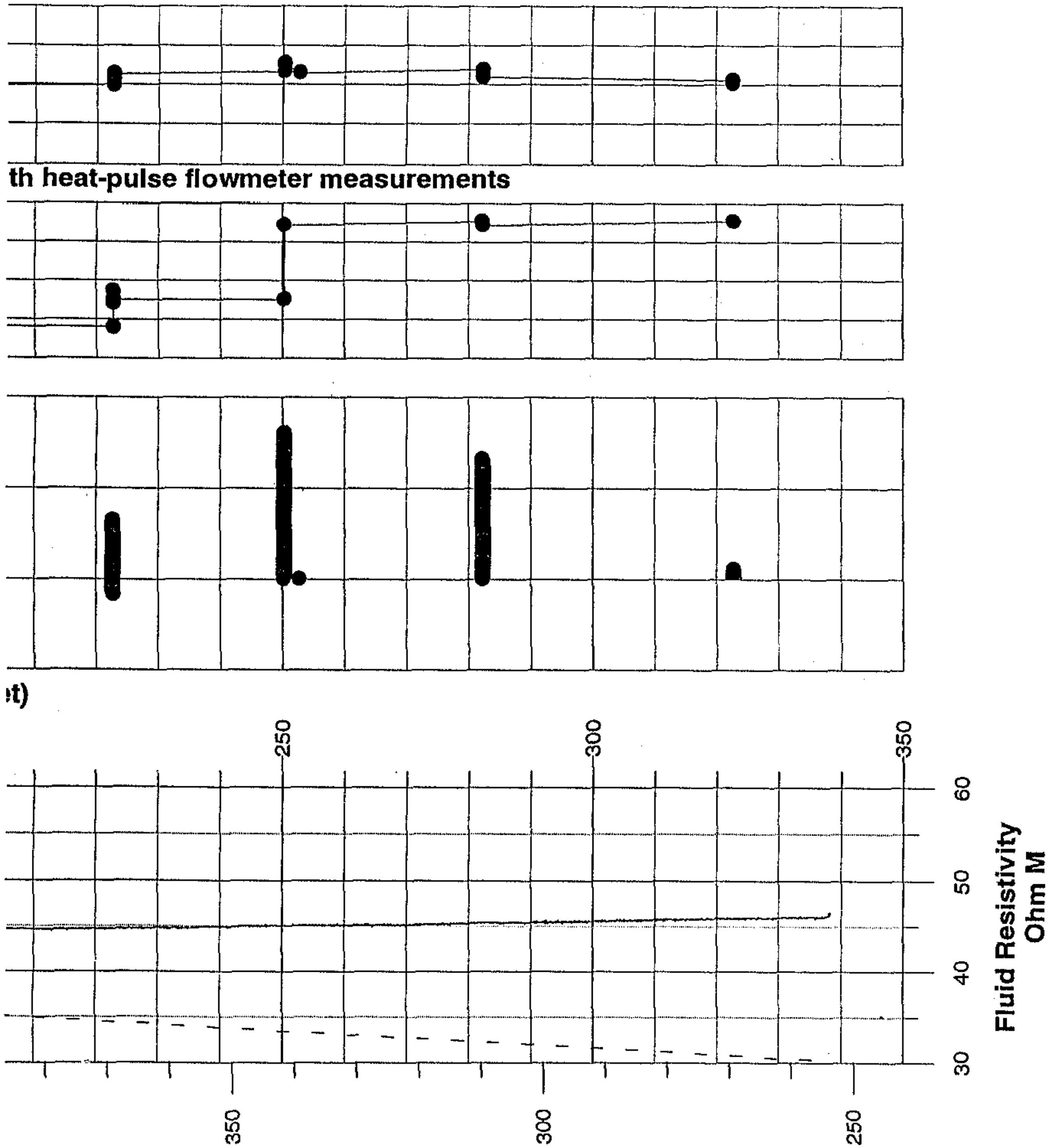
Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 9/13/95 by G. Gianniny and W. Raatz

Well: DR-6

T27N, R26E, section 7, NE1/4, SE1/4
180 E. Redwood Rd., Sturgeon Bay

Elevation: est 592 ft
Depth to water: 9.51 ft
Flow conditions for heat-pulse logging: Pumping




th heat-pulse flowmeter measurements
:t)
250
300
350
60
50
40
30
Fluid Resistivity
Ohm M
350
300
250

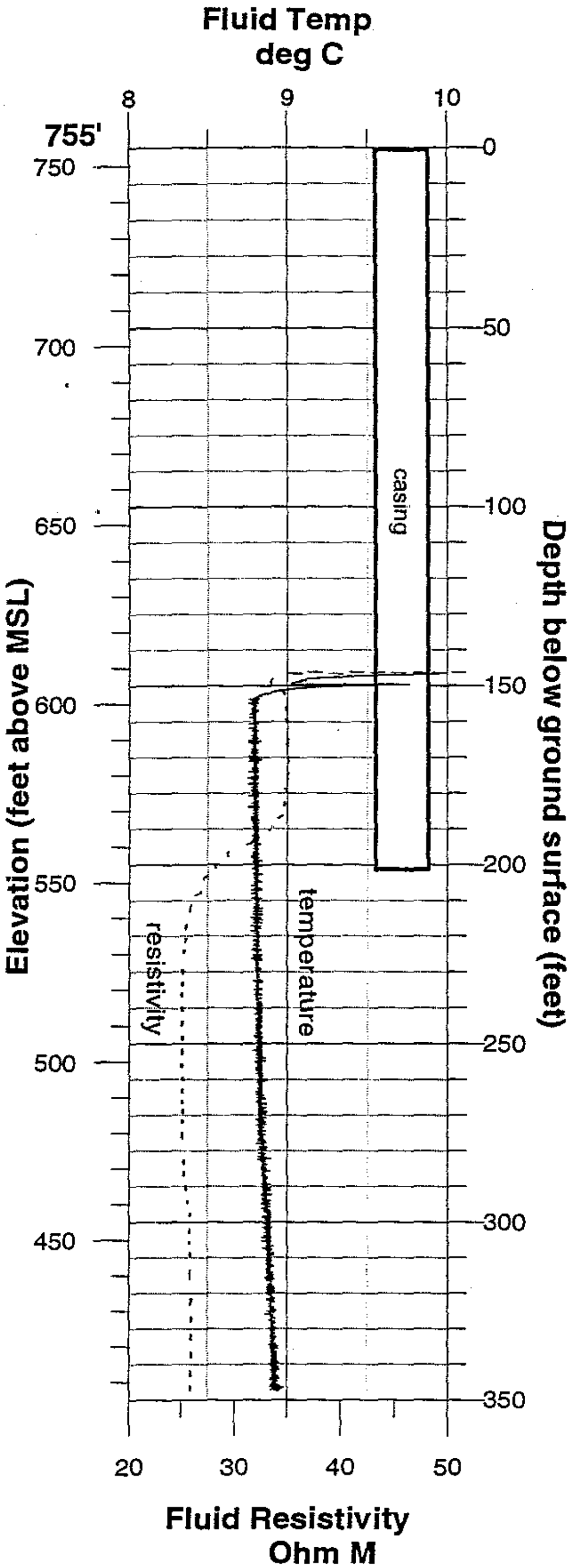
80a

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 8/30/95 by G. Gianniny and W. Linquist

Well: DR-24
Reynolds

Elevation: est 755 ft
Depth to water: 149 ft

T28N, R26E, section 8, NW1/4, SW1/4, NE1/4



Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: U.S.G.S. Water-level monitoring well, Highway Garage

Project: Sturgeon Bay Wellhead Protection **Date Logged:** 9/27/94

WGNHS Geologic Log Number: DR-265

Estimated Elevation: 615 ft **County:** Door

Personnel: Ken Bradbury and Maureen Muldoon

Location: NE1/4, NE1/4 section 5 ,T27N, R26 E/W
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) U.S.G.S. water-level monitoring well

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: __________

Measured Static Water Level: __________

Hole Depth (reported by driller)______ **Casing Depth** (reported by driller)____

Hole Depth (from logging) __________ **Casing Depth** (from logging)________

Casing Diameter __________ (circle one) by driller from logging

Open-hole Diameters ________ (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 7 inch

Pumping Information:

Pump used: none

Depth of pump in hole: ______________ (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) ____________________

Heat-pulse File Information:

Filename(s): dr265flo.pa0

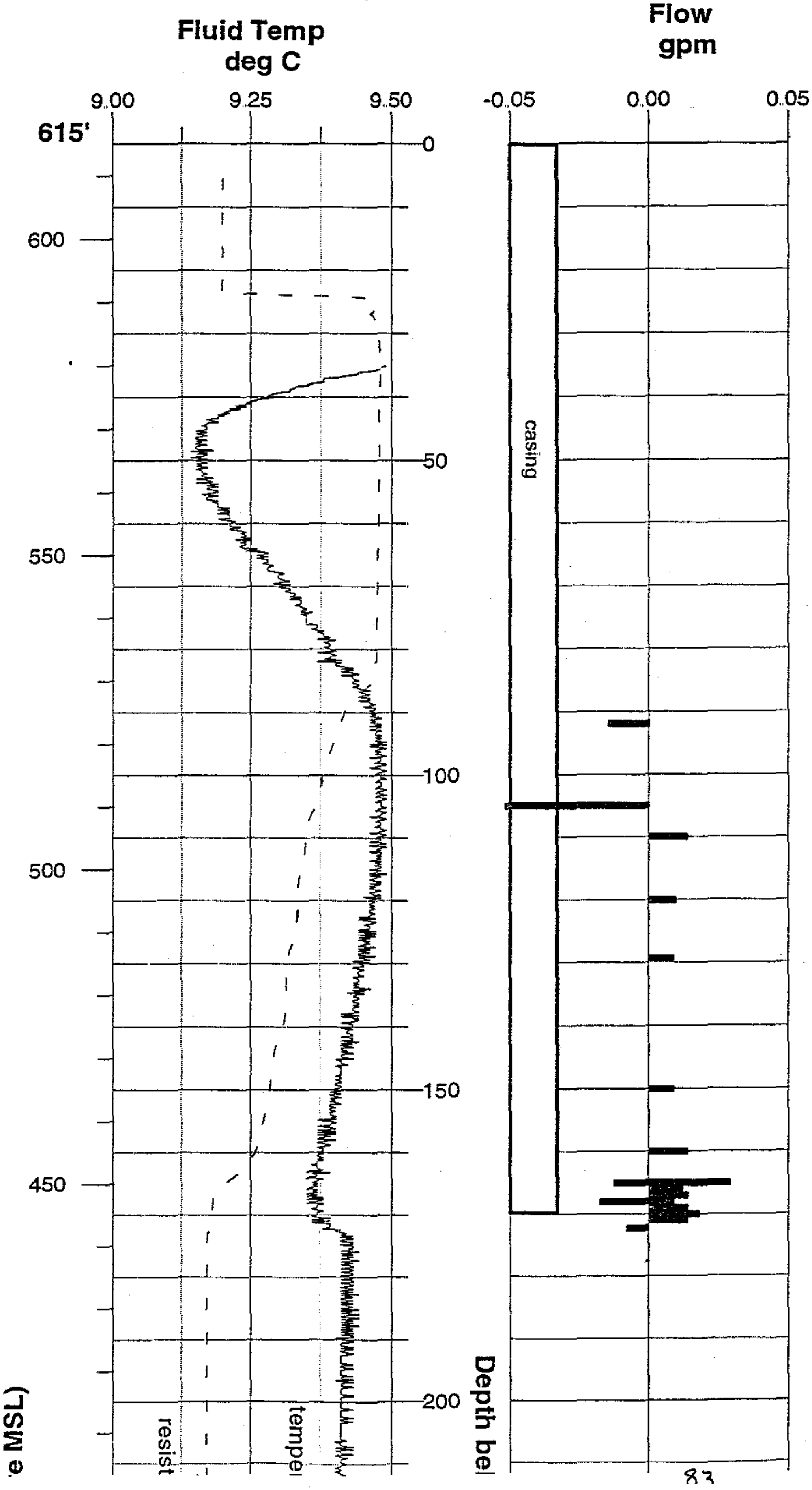
File Format: (circle one): summary record expanded

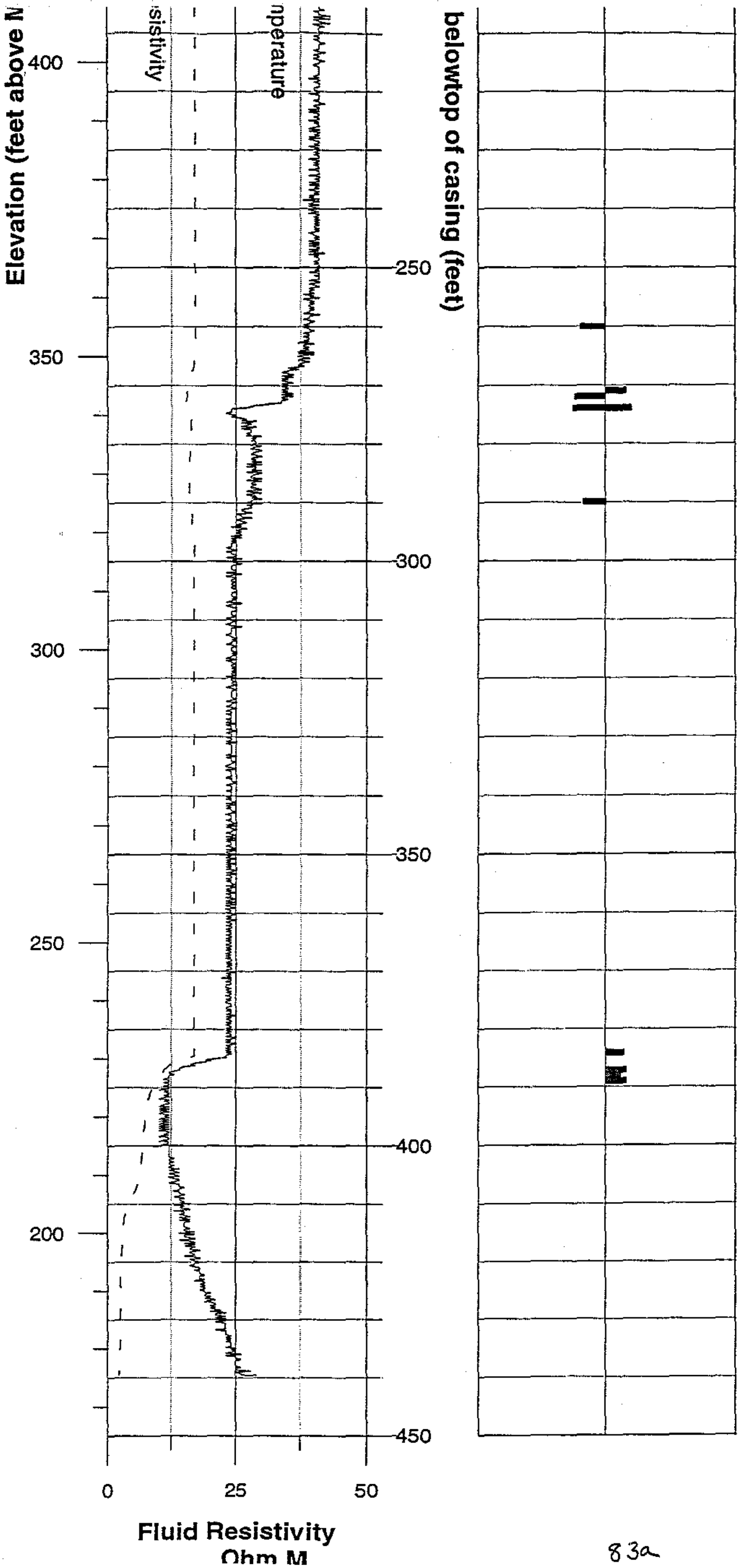
Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 9/27/94 by K. Bradbury and M. Muldoon

Well: DR-265
U.S.G.S. well at highway garage

T27N, R26E, section 5, NE1/4, NE1/4

Elevation: est 615 ft
Depth to water: ft
Flow conditions for heat-pulse logging:





Elevation (feet above M
400
350
300
250
200
sistivity
nperature
belowtop of casing (feet)
250
300
350
400
450
0
25
50
Fluid Resistivity
Ohm M

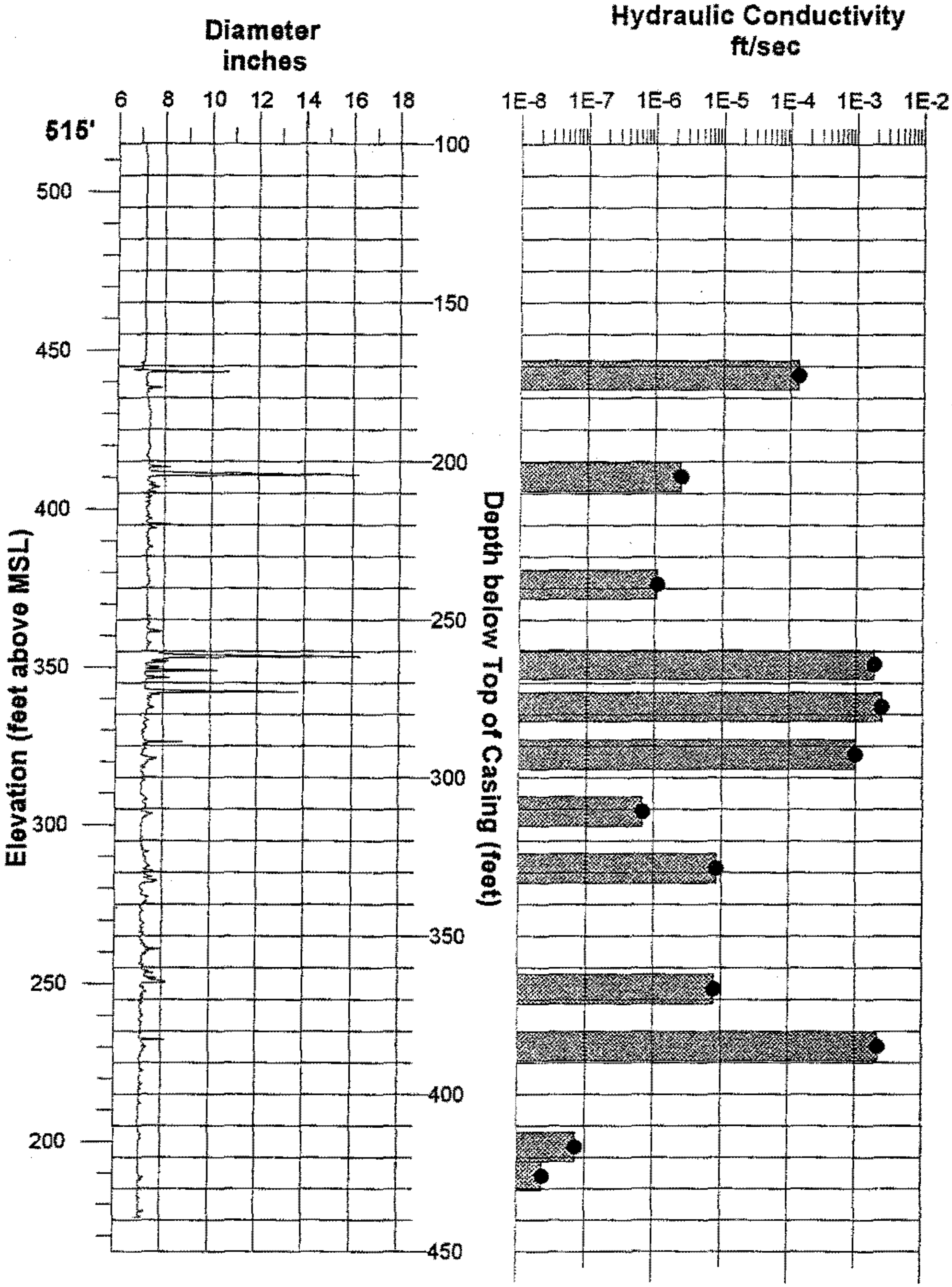
83a

Wisconsin Geological and Natural History Survey
Packer Testing (with USGS)
Test conducted 10/24 to 11/2/96
by K. Bradbury, E. Oelkers, and J. Rauman

Elevation: est 615 ft
Depth to water:
Casing:
(determined by geophysics): 170 ft

Well: DR-265
U.S.G.S. well at highway garage

T27N, R26E, section 5, NE1/4, NE1/4

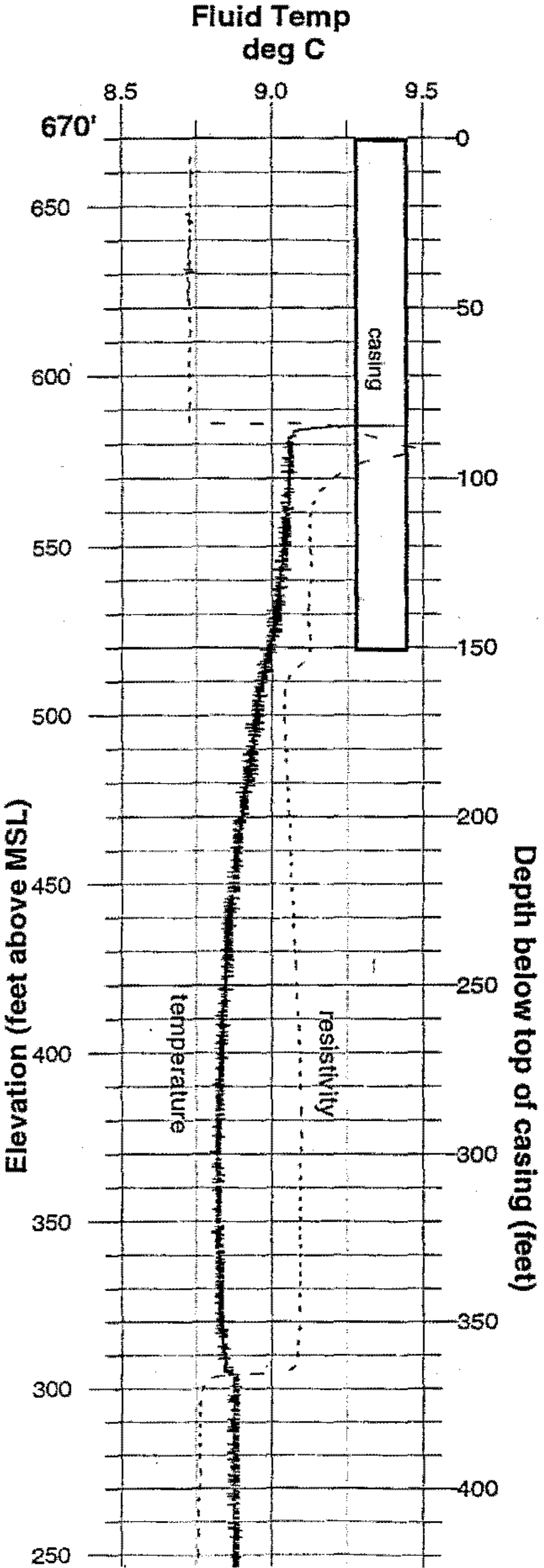


Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged8/23/94 by P. Roffers

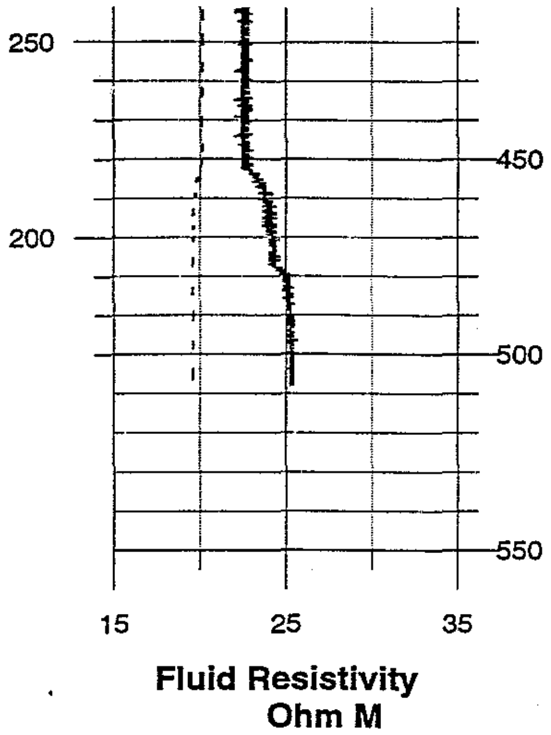
Elevation: est 670 ft
Depth to water: 82.8 ft

Well: DR-292
Sturgeon Bay City Well #9

T27N, R26E, section 18, SW1/4, SE1/4, NE1/4



85

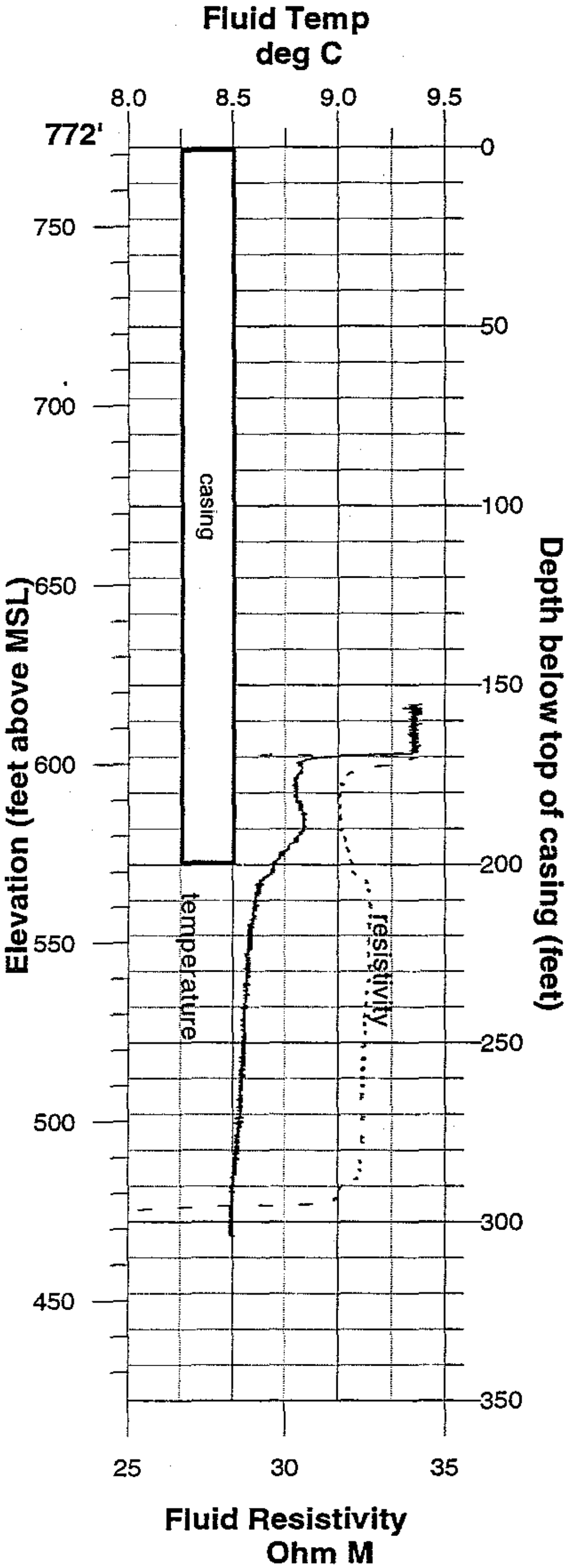

250
200
450
500
550
15
25
35
Fluid Resistivity
Ohm M

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 8/23/95 by G. Gianniny and J. VanderVelden

Well: DR-391

T28N, R26E, section 20, NW1/4, SE1/4, SW1/4

Elevation: est 772 ft
Depth to water: 169.3 ft



Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: VanderHoof (owner)

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 8/31/95

WGNHS Geologic Log Number: DR-392

Estimated Elevation: 665 ft **County:** Door

Personnel: Gary Gianniny and Wylie Linquist

Location: SW1/4, SW1/4, SW1/4 section 17 ,T28N, R27 E
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169
Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: 2.5 ft above grade

Measured Static Water Level: 60.5 ft

Hole Depth (reported by driller) 241 **Casing Depth** (reported by driller) 170

Hole Depth (from logging) 249.5 **Casing Depth** (from logging) 172

Casing Diameter 6" (circle one) by driller from logging

Open-hole Diameters 6" (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 7 inch

Pumping Information:

Pump used: 4 inch submersible

Depth of pump in hole: 79 ft (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) ______

Heat-pulse File Information:

Filename(s): 392flow.pa0

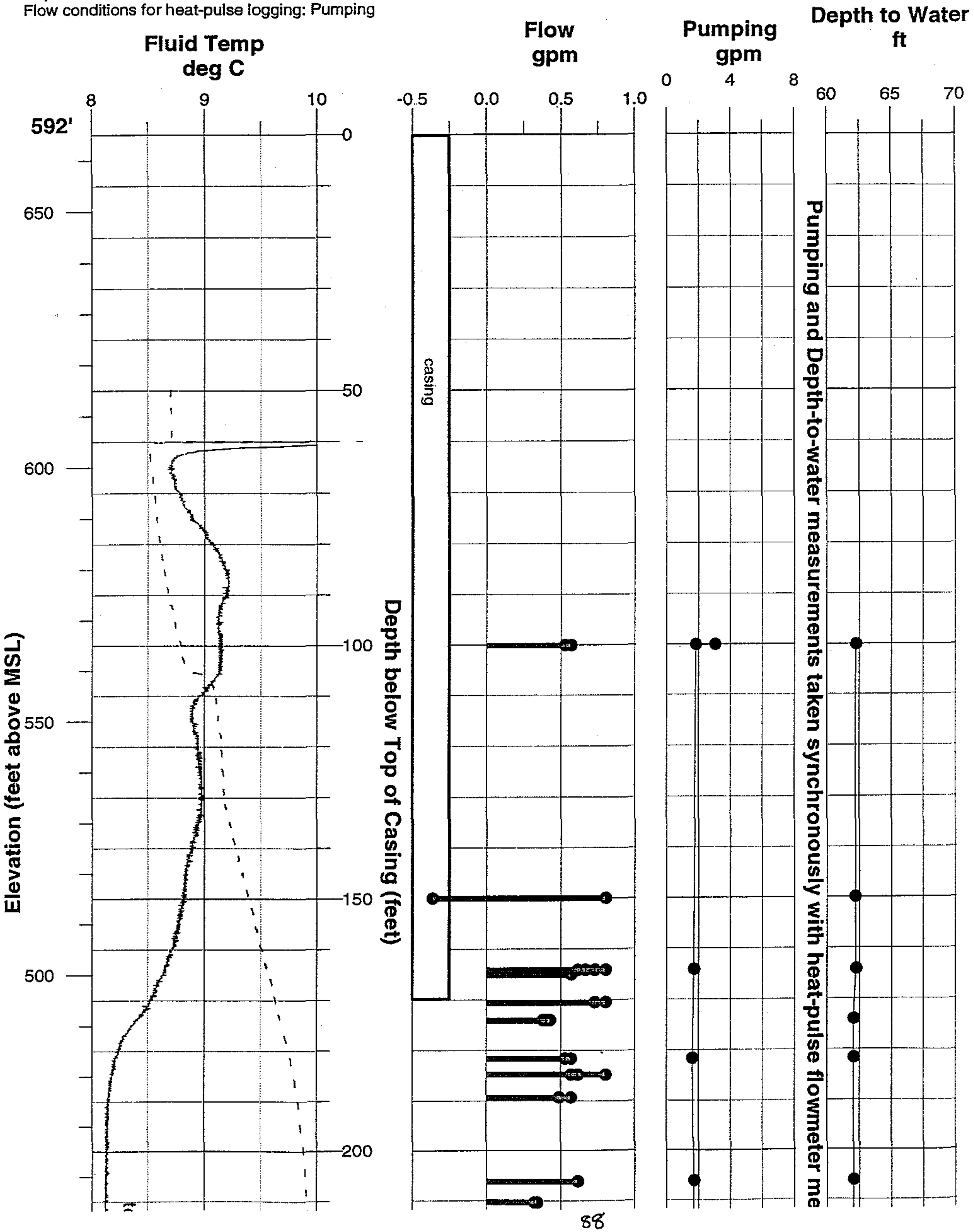
File Format: (circle one): summary record expanded

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 8/31/95 by G. Gianniny and W. Linquist

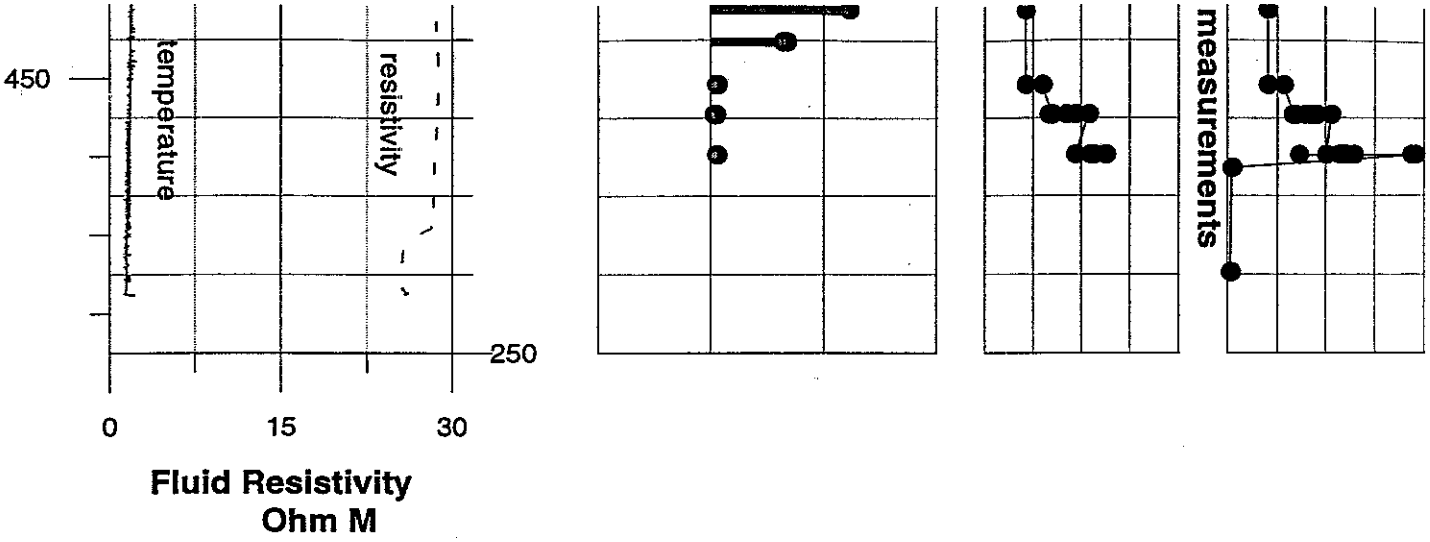
Well: DR-392

T28N, R27E, section 17, SW1/4, SW1/4, SW1/4

Elevation: est 665 ft
Depth to water: 60.5 ft
Flow conditions for heat-pulse logging: Pumping



88


450
temperature
resistivity
250
0
15
30
Fluid Resistivity
Ohm M
measurements

Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: ______

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 9/1/95

WGNHS Geologic Log Number: DR-393

Estimated Elevation: 592 ft **County:** Door

Personnel: Gary Gianniny

Location: SW1/4, NW1/4, NW1/4 section 22, T28N, R27 E; 4386 Glidden Rd.
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169
Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______ Ground Surface
______ Other (include in sketch on back)
Distance from top of casing to ground surface: 1.5 - 2 ft above grade

Measured Static Water Level: artesian (1-2 gpm)

Hole Depth (reported by driller) 241 **Casing Depth** (reported by driller) 170

Hole Depth (from logging) 243.5 **Casing Depth** (from logging) 170

Casing Diameter 6" (circle one) by driller from logging

Open-hole Diameters 6" (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 7 inch

Pumping Information:

Pump used: none

Depth of pump in hole: ______ (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) ______

Heat-pulse File Information:

Filename(s): 393flost.pa0

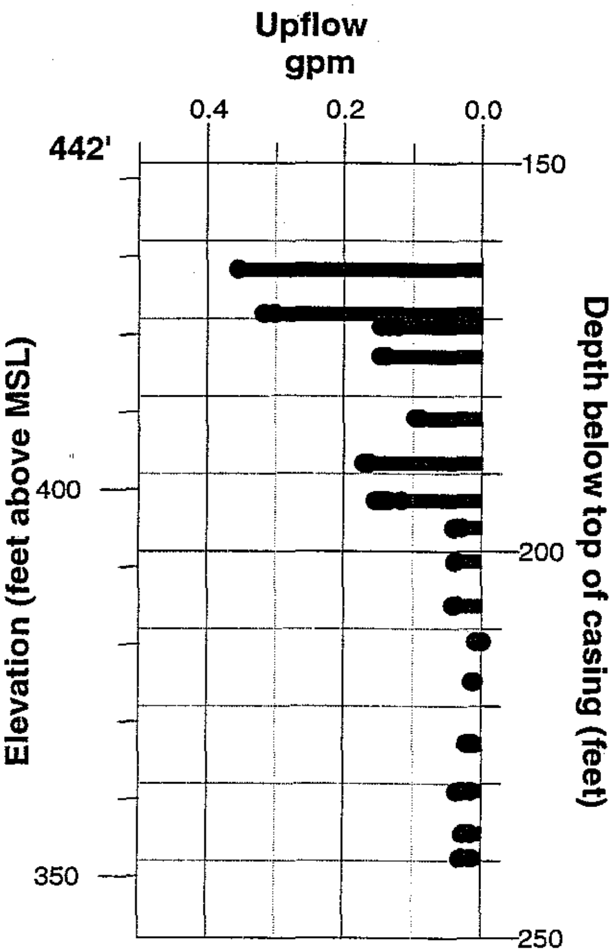
File Format: (circle one): summary record expanded

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 9/1/95 by G. Gianniny

Elevation: est 592 ft
Flow Conditions: flowing well (1-2 gpm)

Well: DR-393

T28N, R27E, section 22, SW1/4, NW1/4, NW1/4
4386 Glidden Road



Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: Jarmen Road Corehole (drilled by Mark Harris, UWM)

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 7/11/95

WGNHS Geologic Log Number: DR-394

Estimated Elevation: 798 ft **County:** Door

Personnel: Gary Gianniny, Dan Hegrenes, Maureen Muldoon

Location: SW1/4, NW1/4, SE1/4 section 2, T28N, R26E; Jarman Road Site
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169

Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: 1.4 ft above grade

Measured Static Water Level: 138

Hole Depth (reported by driller) 540 **Casing Depth** (reported by driller) 2

Hole Depth (from logging) 435 **Casing Depth** (from logging)______

Casing Diameter 3" (circle one) by driller from logging

Open-hole Diameters 3" (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 5"

Pumping Information:

Pump used: None

Depth of pump in hole: ______ (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) ______

Heat-pulse File Information:

Filename(s): flowup.pa0 (435 - 210), flowup.pa1(210 - 145), flowup.pa2 (145 - 139)

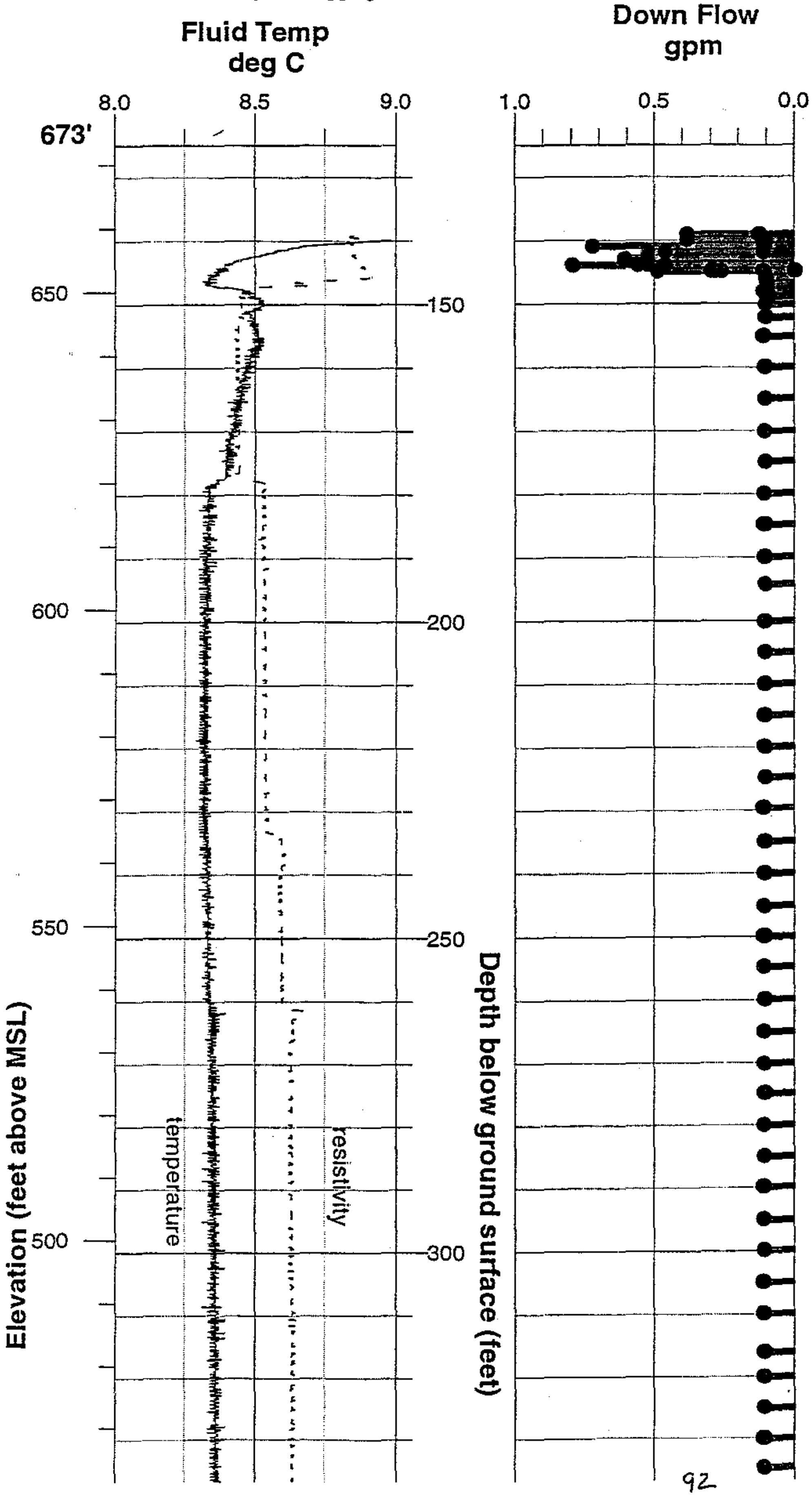
File Format: (circle one): summary record expanded

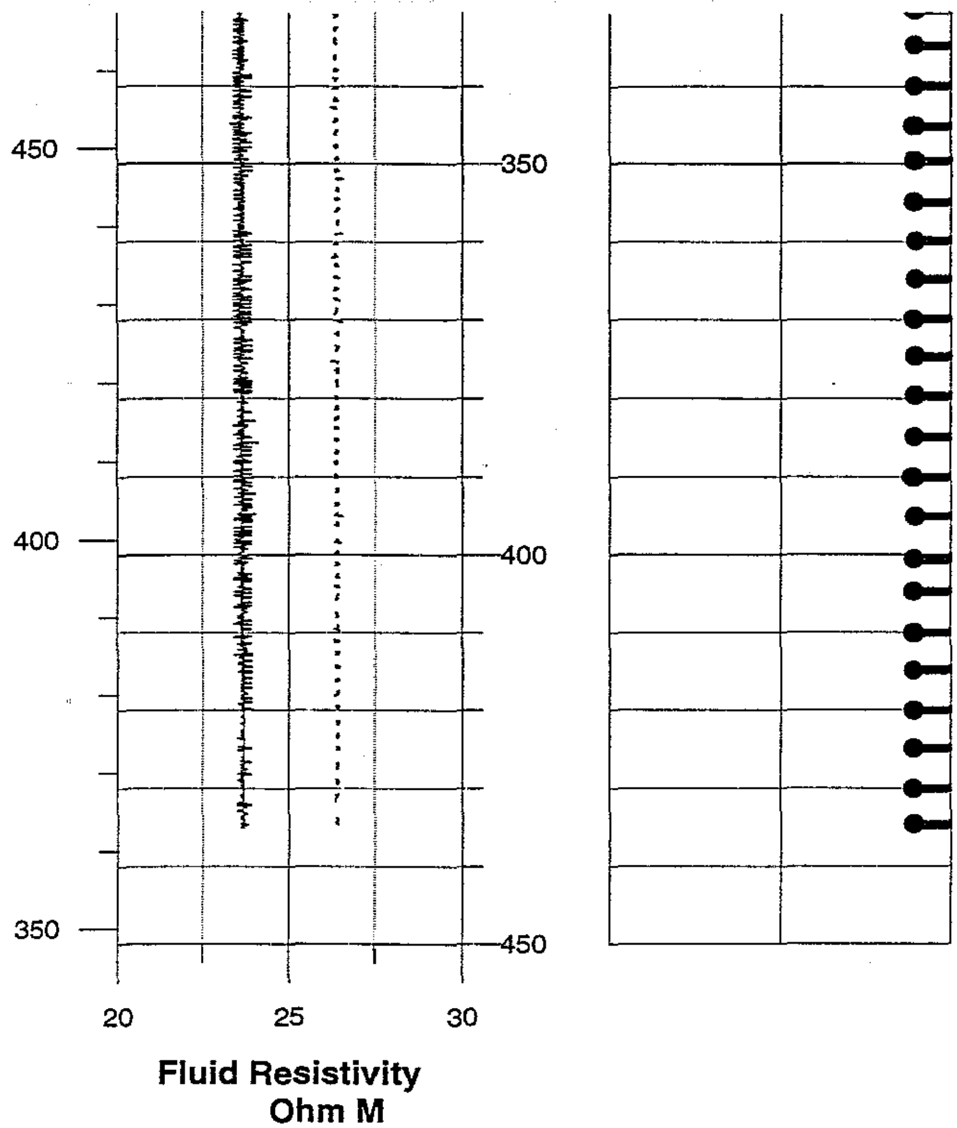
Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 7/11/95 by G. Gianniny, D. Hegrenes, M. Muldoon

Well: DR-394
Jarmen Road Corehole

T28N, R26E, section 2, SW1/4, NW1/4, SE1/4

Elevation: est 798 ft
Depth to water: 138 ft
Flow conditions for heat-pulse logging: Static





92a

Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: ____________________

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 9/12/95

WGNHS Geologic Log Number: DR-395

Estimated Elevation: 770 ft **County:** Door

Personnel: Gary Gianniny and Bill Raatz

Location: SW1/4, SW1/4, NW1/4 section 5, T26N, R24E
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169
Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ____________

Reference Point for logging: ____Top of Casing X Ground Surface
____Other (include in sketch on back)
Distance from top of casing to ground surface: 2 ft above grade

Measured Static Water Level: 198.42

Hole Depth (reported by driller)____ **Casing Depth** (reported by driller)____

Hole Depth (from logging) 805 **Casing Depth** (from logging) 170

Casing Diameter 6" (circle one) by driller from logging

Open-hole Diameters 6" (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 7"

Pumping Information:

Pump used: None

Depth of pump in hole: ____________ (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) ____________

Heat-pulse File Information:

Filename(s): 395stat.pa0

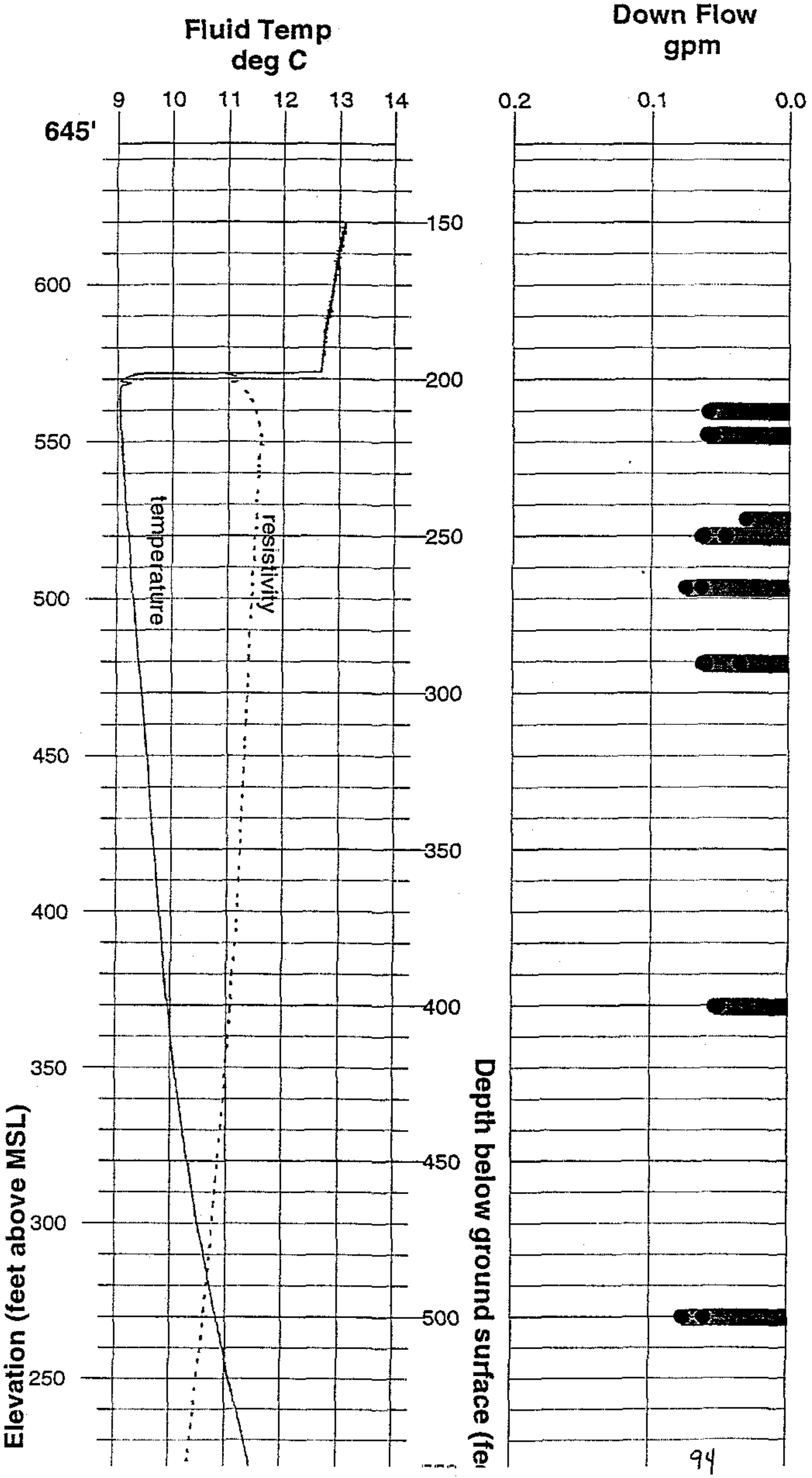
File Format: (circle one): summary record expanded

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 9/12/95 by G. Gianniny and W. Raatz

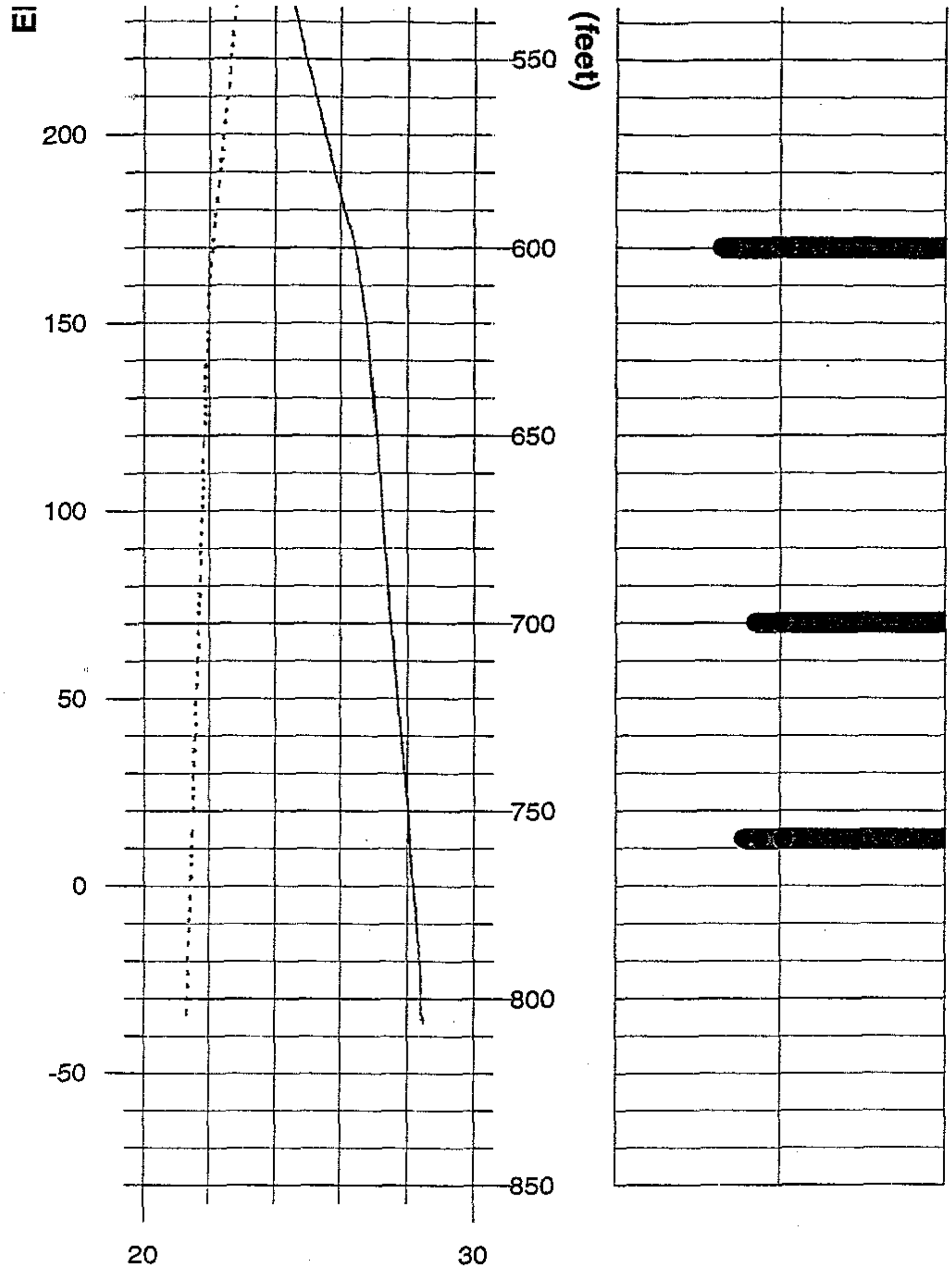
Well: DR-395 (saturated portion is Maquoketa and Sinnipee)

T26N, R24E, section 5, SW1/4, SW1/4, NW1/4

Elevation: est 770 ft
Depth to water: 198.42 ft
Flow conditions for heat-pulse logging: Static



94



Fluid Resistivity
Ohm M

Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: William Ruff (owner)

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 9/27/95

WGNHS Geologic Log Number: DR-396

Estimated Elevation: 725 ft **County:** Door

Personnel: Gary Gianniny

Location: SE1/4, NW1/4, NW1/4 section 6, T26N, R26E (Hornspier Rd)
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169
Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______ Ground Surface
______ Other (include in sketch on back)
Distance from top of casing to ground surface: ______

Measured Static Water Level: 27.7

Hole Depth (reported by driller) 260 **Casing Depth** (reported by driller) 125

Hole Depth (from logging) 259 **Casing Depth** (from logging) 126

Casing Diameter 6" (circle one) by driller from logging

Open-hole Diameters 6" (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 7"

Pumping Information:

Pump used: 4 inch submersible

Depth of pump in hole: 100 ft (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) Dr396flo.wk1

Heat-pulse File Information:

Filename(s): 396puls.pa0(static, 131.6-236.1); 396pmp.pa1 (pumping, 108-200.2); 396pmp2.pa0 (pumping, 205.2-247.3)

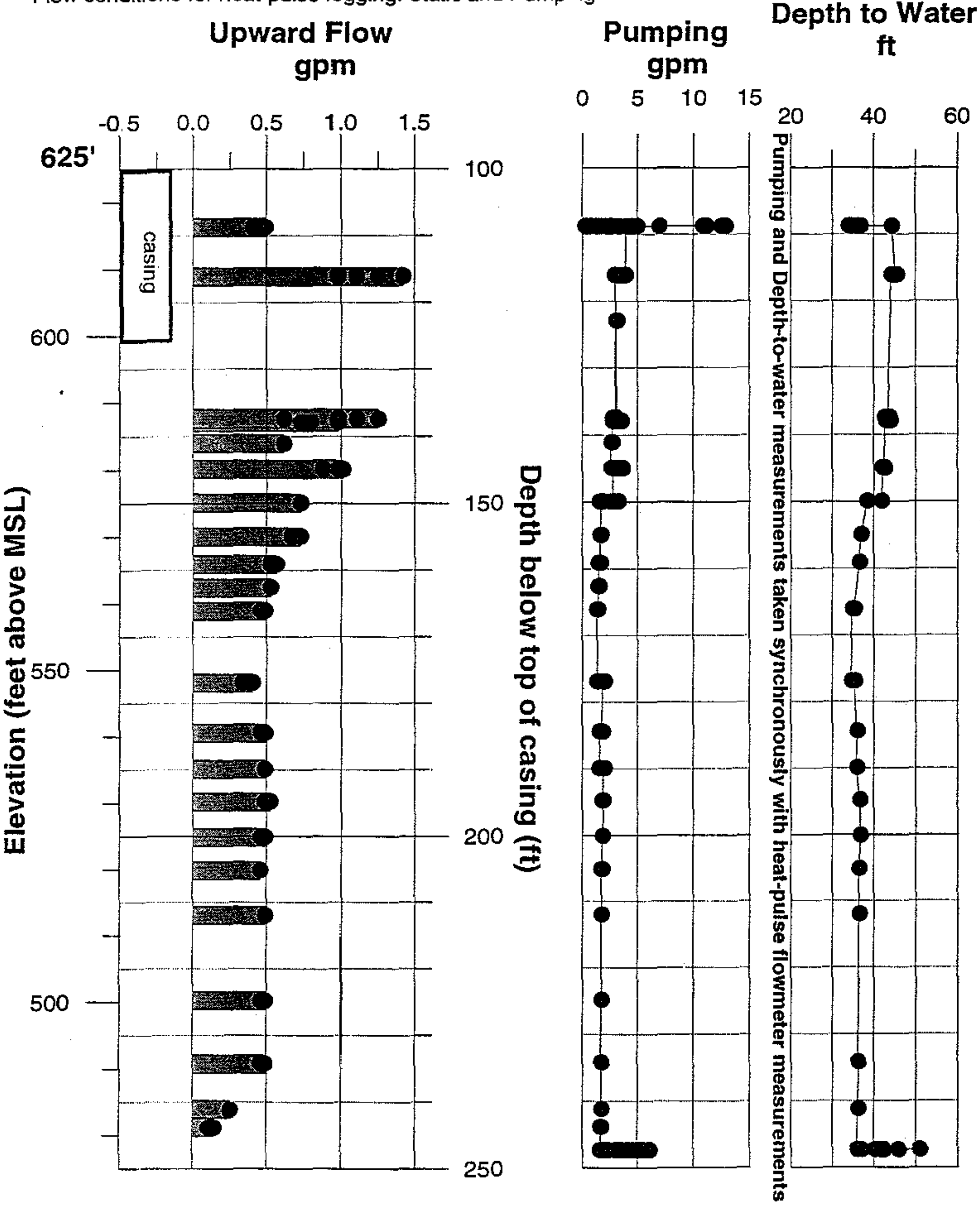
File Format: (circle one): summary record expanded

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 9/27-28/95 by G. Gianniny

Well: DR-396

T26N, R26E, section 6, SE1/4, NW1/4, NW1/4

Elevation: est 725 ft
Depth to water: 27 7 ft
Flow conditions for heat-pulse logging: Static and Pumping



Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: Sturgeon Bay City Well #11

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 10/4/95

WGNHS Geologic Log Number: DR-397

Estimated Elevation: 588 ft **County:** Door

Personnel: Gary Gianniny and Pete Roffers

Location: NW1/4, SE1/4, SE1/4 section 6, T27N, R26E
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169
Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ____

Reference Point for logging: ____Top of Casing ____Ground Surface
X Other (include in sketch on back)
Distance from top of casing to ground surface: ____

Measured Static Water Level: 10.1

Hole Depth (reported by driller)____ **Casing Depth** (reported by driller)____

Hole Depth (from logging) 229 **Casing Depth** (from logging) 203

Casing Diameter 8" (circle one) by driller from logging

Open-hole Diameters 8" (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 9 inch

Pumping Information:

Pump used: 4 inch submersible

Depth of pump in hole: 75 ft (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) Dr397flo.wk1

Heat-pulse File Information:

Filename(s): 397pump.pa0 (pumping), 397stat.pa0 (static)

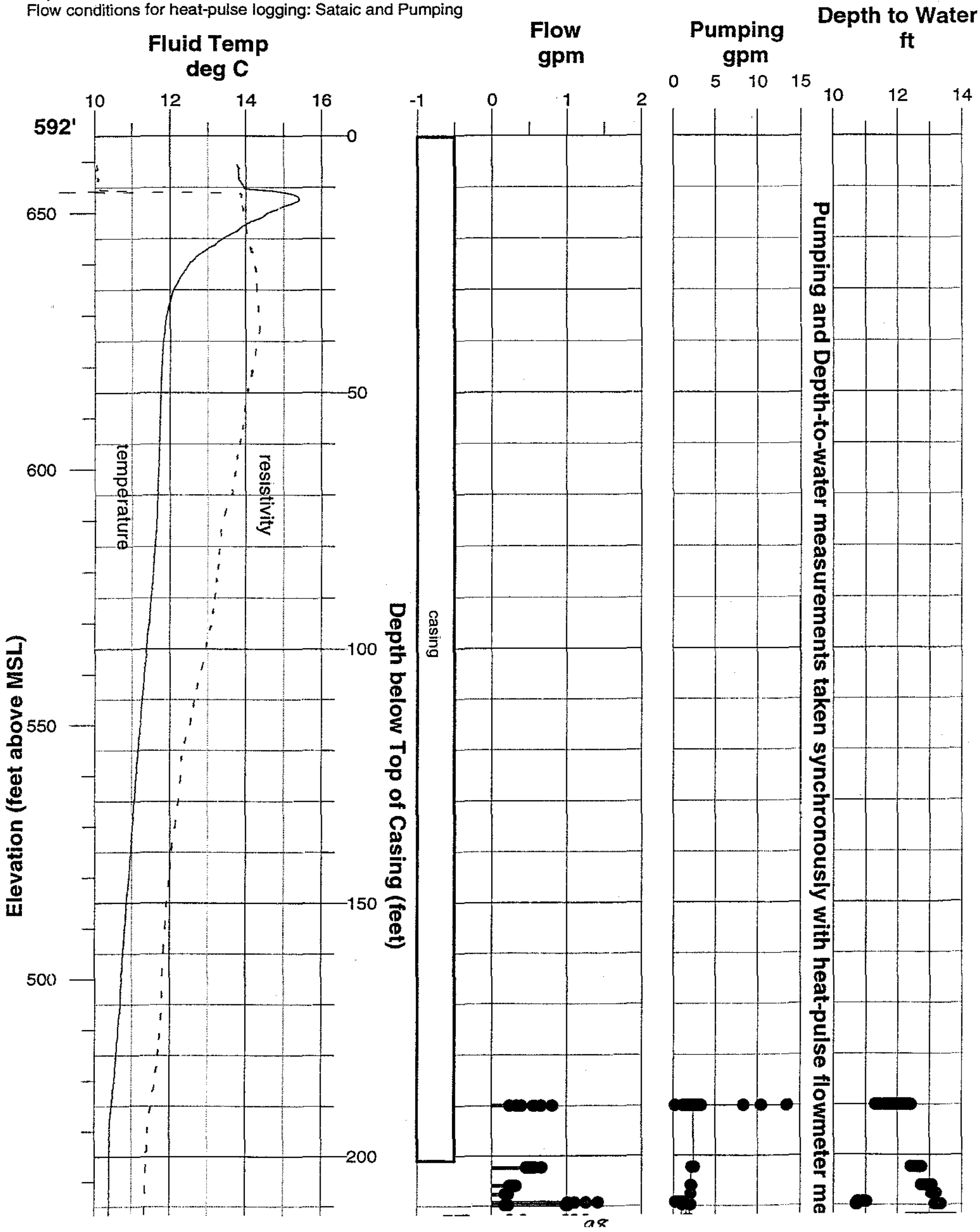
File Format: (circle one): summary record expanded

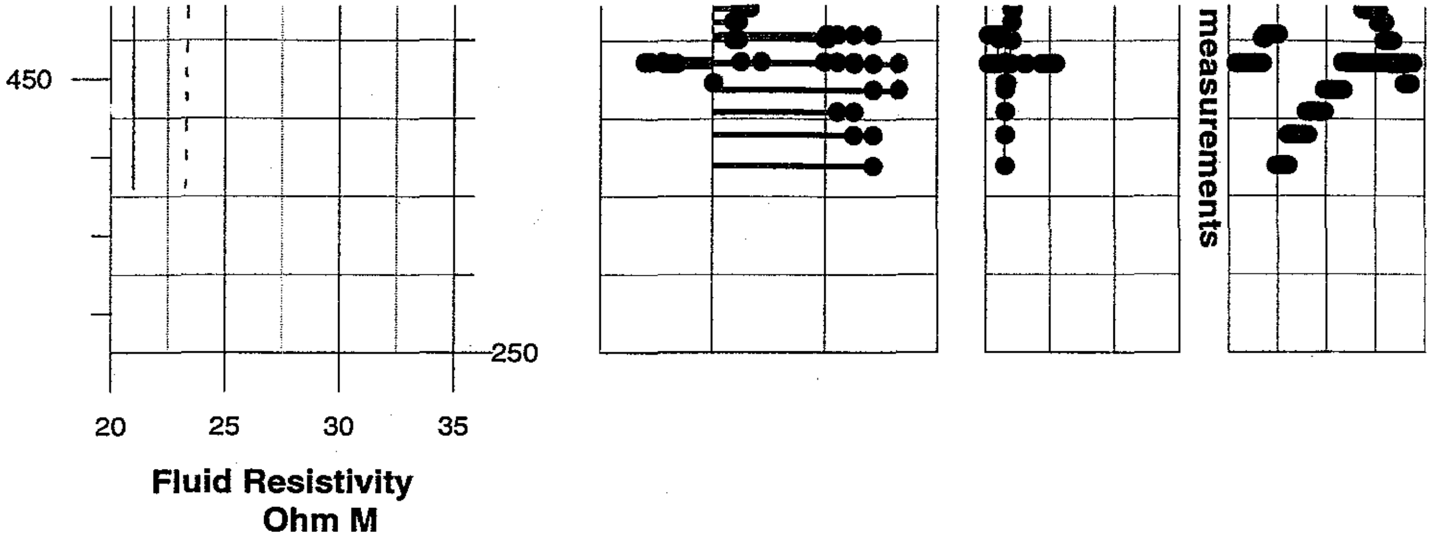
Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 10/4/95 by G. Gianniny and P. Roffers

Well: DR-397
Sturgeon Bay city well #11

T27N, R26E, section 6, NW1/4, SE1/4, SE1/4

Elevation: est 588 ft
Depth to water: 10.1 ft
Flow conditions for heat-pulse logging: Sataic and Pumping




450
250
20
25
30
35
Fluid Resistivity
Ohm M
measurements

Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: Sturgeon Bay City Well #11

Project: Correl of high-permeability zones w/ stratigraphic features, Sturgeon Bay, WI **Date Logged:** 11/16/95

WGNHS Geologic Log Number: DR-397

Estimated Elevation: 588 ft **County:** Door

Personnel: Ken Bradbury

Location: NW1/4, SE1/4, SE1/4 section 6, T27N, R26E
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169
Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ____________

Reference Point for logging: ____Top of Casing ____Ground Surface
X Other (include in sketch on back)
Distance from top of casing to ground surface: ____________

Measured Static Water Level: ____________

Hole Depth (reported by driller)________ **Casing Depth** (reported by driller)____

Hole Depth (from logging) 229 **Casing Depth** (from logging) 203

Casing Diameter 8" (circle one) by driller from logging

Open-hole Diameters 8" (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 9-inch

Pumping Information:

Pump used: City Well # 7 was being pumped

Depth of pump in hole: ____________ (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) ____________

Heat-pulse File Information:

Filename(s): Sb11flow.pa0 sb11flo2.pa0, sb11flo3.pa0

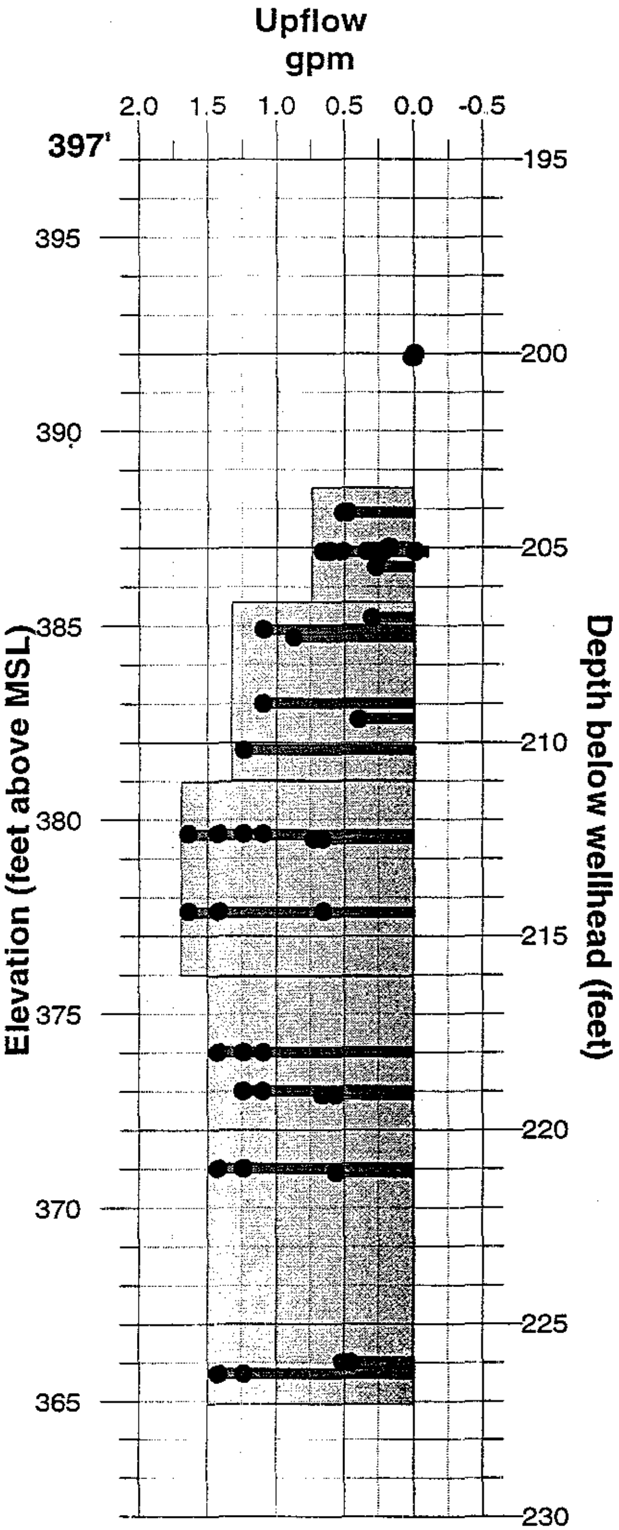
File Format: (circle one): summary record expanded

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Logged 9/1/95 by K. Bradbury

Elevation: est 588 ft
Flow Conditions: City well # 7 was being pumped

Well: DR-397
Sturgeon Bay city well #11

T27N, R26E, section 6, NW1/4, SE1/4, SE1/4



Heat-pulse Flowmeter Logging Documentation

Well or Hole Name: Bissen hole #13

Project: Tracer Study for characterization of groundwater movement and contaminant transport in fractured dolomite **Date Logged:** 9/28/94

WGNHS Geologic Log Number: ______

Estimated Elevation: 685 ft **County:** Door

Personnel: Ken Bradbury, Maureen Muldoon

Location: NE1/4, NW1/4, NW1/4 section 21 ,T27N, R25 E
(include sketch location map on back)

Equipment: Mount Sopris Digital Logger, serial number - 0169
Heat-pulse probe, serial number - 0138

Type of hole(circle one): domestic well high-capacity well stratigraphic borehole
Other (explain) ______

Reference Point for logging: X Top of Casing ______Ground Surface
______Other (include in sketch on back)
Distance from top of casing to ground surface: ______

Measured Static Water Level: ______

Hole Depth (reported by driller) 35 **Casing Depth** (reported by driller)______

Hole Depth (from logging) 38 **Casing Depth** (from logging)______

Casing Diameter 3" (circle one) by driller from logging

Open-hole Diameters 3" (circle one) by driller from logging

Flow Conditions: (circle one) Static Flowing well Pumping

Flow-diverter Diameter: 5 inch

Pumping Information:

Pump used: submersible Keck

Depth of pump in hole: just below water (if variable record in notebook)

Method of recording flow rate: (circle one) Bucket/watch Digitally Other

Method of recording water levels: (circle one) Water-level tape Digitally Other

Filename (if recording digitally) ______

Heat-pulse File Information:

Filename(s): mw13flow.pa0, mw13pump.pao

File Format: (circle one): summary record expanded

Wisconsin Geological and Natural History Survey
Geophysical Log
Mt. Sopris MGX 1000C digital logger
Fluid temperature log 4/21/94 by M. Muldoon and K. Bradbury
Heat-pulse flow logging 9/28/94 by K. Bradbury and M. Muldoon

Well: Bissen hole #13

T27N, R25E, section 21, NE1/4, NW1/4, NW1/4

Elevation: est 685 ft
Depth to water:
Flow conditions: both static and pumping