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Evaluation of the Confining Properties of the Maquoketa Formation in the SEWRPC Region of Southeastern Wisconsin

A Final Report Prepared for the Wisconsin Department of Natural Resources

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EVALUATION OF THE CONFINING PROPERTIES OF THE MAQUOKETA FORMATION IN THE SEWRPC REGION OF SOUTHEASTERN WISCONSIN

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WISCONSIN DEPARTMENT OF NATURAL RESOURCES

Prepared by
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I. INTRODUCTION

This project was designed to integrate data from the study of rock core, downhole geophysical logging, in-situ hydraulic testing, and isotopic and geochemical analysis of porewater from the Maquoketa Formation at two sites in Waukesha County, Wisconsin, in order to investigate the hydraulic properties of this major regional confining unit.

The period of the project was from July 1, 1997 to August 31, 1998. Funding was provided by the Wisconsin Department of Natural Resources. We would also like to acknowledge the assistance of many other staff members and student assistants of the Wisconsin Geological and Natural History Survey who participated in the drilling, collection of core and instrumentation of the coreholes. Use of the field sites was granted courtesy of the Waukesha County Parks and Planning Commission and the Wisconsin Department of Transportation

II. BACKGROUND/NEED

A. Importance of the aquitard for deep groundwater protection

The Maquoketa Formation, of Ordovician age, consists mostly of low-permeability shale and is probably the most important aquitard in Wisconsin. The Maquoketa is present in eastern and southeastern Wisconsin, where it acts as a confining unit between the upper Silurian dolomite aquifer and the lower Cambrian-Ordovician "sandstone" aquifer. Both these aquifers are heavily used in southeastern Wisconsin. The Maquoketa has long been considered a major aquitard which limits the exchange of water between the two major aquifers. It also serves as a protective cover for the sandstone aquifer, preventing or slowing the downward migration of surface contaminants.

Hydraulic head in the underlying sandstone aquifer has historically been much higher than the base of the Maquoketa confining unit, and indeed before the beginning of this century, was commonly above land surface, causing artesian conditions to occur when wells were first drilled into the deep sandstone (Drescher et al., 1953). At that time, hydraulic gradient would have been upward through the overlying Maquoketa confining unit. Increasing pumpage in the twentieth century has caused water levels in the deep sandstone to decline to 450 ft below land surface by mid-century, and approximately 480 below land surface at present in the vicinity of pumping wells in eastern Waukesha County. This has caused a reversal of hydraulic gradient across the Maquoketa confining unit, and resulting leakage through the shale could affect water quality in the sandstone aquifer.

B. Important component to understanding regional groundwater flow

The Wisconsin Geological and Natural History Survey (WGNHS), with the cooperation and financial support of the Southeastern Wisconsin Regional Planning Commission (SEWRPC), the Wisconsin Department of Natural Resources (WDNR), and the U.S. Geological Survey (USGS), is currently (1998) undertaking a multi-year study of the hydrogeology of the SEWRPC area, with the goal of constructing a 3-dimensional groundwater flow model for use in water resources planning, delineation of wellhead protection areas, and understanding the overall groundwater flow system in the area. This model will require hydraulic parameters of the Maquoketa (hydraulic conductivity, specific storage, thickness) in order to simulate the exchange of water between the Silurian aquifer and underlying sandstone aquifer. Quantification of this exchange is of immediate importance because a regional groundwater model could be very sensitive to the hydraulic properties of this confining unit.

C. Lack of previous studies at this level of detail

In spite of its importance as a regional aquitard in eastern Wisconsin, the hydrogeology of the Maquoketa has received little study in the past. According to Young (1992, p B45) "*....Estimates of the vertical hydraulic conductivity K' of the Maquoketa confining unit are available only indirectly from flow-net analyses or digital models.*" Most estimates can be traced back to Walton (1960), who conducted a flow-net analysis of downward leakage to the Cambrian-Ordovician aquifer in the Chicago area. In addition, prior to this study, the basic lithology and stratigraphy of the Maquoketa in southeastern Wisconsin were known only from well cuttings, and there were no core samples of this unit available south of Fond du Lac. In addition to shale, the Maquoketa Formation is known to contain dolomitic and/or limestone facies which could have significantly higher conductivity than the shaley facies, but the thickness and extent of these lithologies are uncertain.

III. OBJECTIVES

A. Obtain reliable estimates of hydraulic properties, flow rates and leakage

Fieldwork for this project was designed to vertically isolate different intervals within the approximately 180 ft-thick Maquoketa Formation in order to investigate hydraulic properties throughout the thickness of the formation. This is the first time to our knowledge that a detailed view of the distribution of hydraulic conductivity within the Maquoketa Formation has been obtained. Assuming reasonable anisotropy values, dependent on lithology, vertical hydraulic conductivity values were estimated for each interval, then combined to obtain an overall value of vertical permeability for the formation.

B. Characterize stratigraphy based on core study, downhole geophysical logging

Detailed sedimentological study of the core recovered in conjunction with analysis of downhole geophysical logs taken of the coreholes enabled correlation of particular geologic facies with their geophysical signature. Since many geophysical logs exist of wells penetrating the Maquoketa Formation in southeastern Wisconsin, these facies should be recognizable throughout the region. Hydraulic properties were correlated to the geophysical logs and stratigraphy.

C. Analyze porewater geochemistry, tritium and oxygen isotopic age dating for flow rates.

Groundwater samples collected from the different isolated intervals in the coreholes were analyzed for major ions, tritium, deuterium and oxygen-18. Major ion geochemistry was modeled using PHREEQC, equilibrium modeling software, to obtain charge balances and mineral saturation indices. Preliminary isotopic analysis was used to constrain residence times and groundwater ages.

IV. METHODS

A. Selection of field sites

We selected two field sites in Waukesha County (Figure 1) in an area within the cone of depression of the potentiometric surface of the deep sandstone aquifer, and where bedrock is close to the surface. The fieldsites are on land owned by the Wisconsin Department of Transportation (DOT) and Minooka County Park within a mile or two of municipal pumping wells. The field site on DOT land is within the Village of Pewaukee, on land known as the Ryan Parcel, at NE,NE,SE,NE Section 16, T7N, R19E. The field site in Minooka County Park is southeast of the City of Waukesha, at SE,NW,NE,NW Section 13, T6N, R19E.

B. Drilling, collection of core, and borehole development.

A private well-drilling firm was contracted with to install 4-inch casing down to Silurian bedrock, which was encountered at approximately 50 ft depth at both field sites. We began coring with the WGNHS wireline coring rig but ran into problems with the upper fractured and weathered bedrock both at the DOT site and subsequently at the Minooka Park site. Both holes were stabilized by cementing, then drilling resumed at the Minooka Park site.

At the Minooka County Park site, the Maquoketa Formation was encountered at approximately 230 ft below the surface. Some clayey intervals of the shale caused delays but we encountered the underlying Sinnipee Formation at about 410 ft below the surface by the third week in October, 1997. Nearly 100% core recovery was achieved throughout the corehole, which was finished at 438 ft depth. The core was boxed and transported back to WGNHS and subsequently to the UW-Madison Department of Geology and Geophysics for detailed study. The corehole at the DOT site was completed in April, 1998 to a depth of 399 ft below the surface, and the top and bottom of the Maquoketa were encountered at depths of 175 and 342 ft below the surface, approximately 50 ft shallower than in the Minooka Park corehole.

In order to facilitate the installation of the multi-level packer and monitoring equipment, and to remove excess cuttings and drilling water, we developed both coreholes by pumping. At the Minooka Park corehole we lowered 0.5 inch diameter PVC tubing into the corehole and pumped 4 GPM for about 5 hours from a depth of 425 ft below the surface. Over 5 bore volumes were pumped, causing the water level to drop briefly between 3 and 4 ft. At the DOT site, we improved our pumping technique by using a submersible pump positioned within the Maquoketa at about 300 ft depth, and partially blocked water entering the corehole from the overlying Silurian aquifer. We pumped between 4 and 5 bore volumes at several different flow rates from the DOT corehole.

C. Core study

The Maquoketa section of the core recovered from the Minooka Park corehole was transported to the Sedimentology Lab of the UW-Madison Dept. of Geology and Geophysics for detailed study. Samples of the core was distributed to cooperating researchers and the lithology was carefully described. Core from the DOT corehole was transported to the WGNHS, but time did not permit detailed study of the second core within the scope of this project, although the lithology appeared quite similar to that of the Minooka Park core.

D. Instrumentation of corehole(s)

In order to design appropriate packer and monitoring systems for the two coreholes, full suites of downhole geophysical logs were collected at each site, including gamma, resistivity, caliper, spontaneous potential, temperature, electrical conductivity and borehole flow. Plots of these logs are shown in Figures 2, 3, and 4 (Minooka Park site) and 5, 6, and 7 (DOT site); and interpretation of these logs is discussed in Section V below. Most logs indicated very similar lithologies in the two coreholes. The only significant difference was two major horizontal fracture flow features in the Minooka Park hole, which dominated the flow system within the open corehole.

A six packer system was designed for the Minooka Park corehole to isolate lithologies and fracture features assumed to have different hydraulic properties. Dedicated double-valve nitrogen-driven pumps and vibrating wire pressure transducers were installed at ports in the lower six intervals of the corehole between the nitrogen-inflated packers (Figure 8). Installation of this system at Minooka County Park was completed in late December, 1997. Over the next few months, as the heads equilibrated in each of the intervals, data from the transducers was continuously recorded to an on-site CR10 datalogger.

In late spring 1998, a similar system was anticipated for the DOT corehole. However, given the ease with which the packer system was installed at Minooka County Park, a temporary movable straddle packer system was designed to conduct hydraulic tests at closer intervals in the DOT corehole. Data was collected from the bottom 75 ft of the corehole before the packer system became jammed in the corehole at the DOT site. Work is ongoing on methods to remove the packer system from the corehole but we were not able to monitor heads or collect porewater samples at the DOT site due to this setback.

E. Monitoring of heads at different intervals in corehole

Heads in the different intervals in the corehole at Minooka County Park stabilized within a week or two, with one exception, at significantly different values, indicating that the packers were effective in hydraulically isolating the intervals. We discovered that the packers lost pressure over time, probably due to nitrogen diffusing through the rubber. Weekly visits were necessary to reinflate the packers in order to maintain isolating pressures of between 150 and 200 psi.

The corehole extended down into the the Sinnipee Group dolomite, the aquifer underlying the Maquoketa confining unit, and the lowest interval (Port 1) is open to this aquifer (Figure 8). Head in this interval dropped over eighty feet in the first week, and continued to decline over the next six months until it stabilized at a level over 250 ft below the heads in the Maquoketa.

F. Hydraulic testing of different intervals in corehole

Drawdown and recovery were recorded at one minute intervals during porewater sample collection using the CR10 datalogger at the Minooka Park site, and recovery rates varied considerably among intervals. Heads in the lower intervals in the corehole were drawn down between 100 and 300 ft, and recovered over a week or two, whereas heads in other intervals were drawn down less than 10 feet and recovered in an hour or less. Heads in two intervals recovered in less than one minute, and recovery was recorded manually. The data were analyzed using standard slug testing methods (Bouwer and Rice, 1976; Cooper et al., 1967; Hvorslev, 1951).

At the DOT site, the bottom 75 ft of the corehole, including the Sinnipee Group dolomite and 20 ft of the overlying Maquoketa confining unit were tested at 5 ft intervals using the movable straddle packer setup. A standard 5 ft long PVC slug was dropped into the water column open to the packed-off interval, and head change was monitored and recorded using a PST slug test transducer and datalogger system.

G. Porewater sampling

We collected water samples from the Minooka Park site in late April, 1998. The collection methodology utilized individual, down-hole, gas-driven sampling pumps installed adjacent to each of the six sampling ports. These pumps delivered water to the surface through closed polyethylene sampling lines under positive pressure. A seventh sample was obtained from water in the well annulus above the top packer; this sample was obtained using a peristaltic pump. All samples were field-filtered through 0.45 um membrane filters, with the exception of those from Port 5, which were so silty they had to be filtered through a glass fiber filter. We measured temperature, pH, Eh, dissolved oxygen, and electrical conductivity in the field. Samples were placed into polyethylene containers on ice in the field for delivery to the Wisconsin State Laboratory of Hygiene, where they were analyzed for major ions and trace metals. Standard analytical techniques were used. Samples were also sent to the University of Waterloo (Ontario) isotope laboratory for isotopic analysis.

Sample acquisition proved to be difficult and time-consuming due to the depth of the sampling ports, the limited volume of water in the hole, the small diameter of the sampling lines, and the low yield of the Maquoketa Formation. The three deepest ports (Ports 1, 2,and 3, at depths of 422, 403, and 358 feet) did not yield enough water for complete analyses during the April sampling activities; these ports were resampled at a later date.

V. RESULTS AND DISCUSSION

A. Downhole geophysical logs and interpretation

Downhole geophysical logs for each corehole are shown in Figures 2-7. Logs of natural gamma radiation (Figs. 2 and 5) from the two sites are remarkably similar and provide the best signature for detailed stratigraphic and sedimentologic correlation. Natural gamma radiation is usually associated with clay and feldspar minerals in the subsurface, and is measured in counts per second (cps) using a scintillation detector. In general, increasing radiation (increasing cps) is associated with increasing clay content. The elevation of the top of the Maquoketa is about 30 ft lower at the Minooka Park site than at the DOT site. This offset is probably due to a combination of the Minooka Park site being several miles downdip from the DOT site and downthrow on the Waukesha Fault, which passes between the two sites.

Features common to the gamma logs at each site include the distinctive abrupt decrease in cps at the boundary between the Maquoketa Formation and the underlying Sinnipee dolomite; the consistently high gamma readings (150 cps) in the lower part of the formation, indicating greater shale composition; the plateau (75 cps) about 1/3 of the way from the top; and some of the transitions between low and high readings.

The caliper logs (Figures 2,5) measure borehole diameter, and can also indicate places where fractures intersect the boreholes. The logs from both holes show two zones of multiple openings, probably fractures, in the upper half of the formation, which at the Minooka Park site appeared to be important horizontal groundwater flow features identified by heat-pulse flowmeter logging. At the DOT site, these zones appear to be areas where the corehole is noticably larger in diameter, perhaps due to washing out of material during drilling.

Spontaneous potential (SP) and resistivity logs respond to the electrical properties of the formation, and like the gamma logs, can help distinguish lithologies in the subsurface. In general, pure dolomite has higher electrical resistivity than clay or shale. On both the SP and Resistivity logs, the Maquoketa appears much more uniform than the dolomite aquifers above and below. Noticable deviations occur at approximately the same stratigraphic level at both sites where the gamma log shows low readings, which corresponds to more dolomitic intervals in the Maquoketa.

The temperature and fluid resistivity logs (Figures 3,6) have a fairly uniform gradient with depth at the DOT site, but show distinctive inflections at the Minooka Park site. The stratigraphic level of the inflection (Figure 3) corresponds to the lower of the two fracture features at 320 ft depth, and suggests that significantly different water was present in the corehole above and below this elevation.

Heat pulse flowmeter logging (Figures 4,7) measures vertical borehole flow at discrete elevations in the corehole. Hence, a change in direction of flow (upwards or downwards) indicates that significant inflow or outflow exists between measured elevations (horizontal bars). The Minooka Park log (Figure 4: no hydraulic stress) shows changes from slight upward flow to significant downward flow at about 270 ft and from significant downward to slight upward flow at 320 ft. These correspond to the fracture features identified in the caliper log. We infer that significant flow into the open corehole occurred from the upper fracture and drained out into the rock at the lower fracture. This explains the kink in the temperature and fluid resistivity logs because water in the corehole below 320 ft would be relatively stagnant compared to that above, and shows the effect of the geothermal gradient. Changes in flow rate and direction are apparent above 125 ft depth in the corehole, which is open to the Silurian aquifer. Flowmeter logging after pumping the corehole (Figure 4: pumping recovery) shows dominant inflow from the Silurian, as expected

Heat pulse flowmeter logging at the DOT site (Figure 7) shows considerably less variability. An increase in flow upward at about 70 ft depth and reversal of flow direction at about 130 ft depth are the major features of this log. Below 210 ft, no flow features were detected. Our interpretation is that inflow occurs at about 130 ft, corresponding to a significant fracture on the caliper log, which is within the Silurian aquifer just above the Maquoketa Formation. From this point, there is both upward and downward flow in the corehole, the upward flow disappearing into a fracture between 60 and 70 ft, and the downward flow dissipating into a series of fractures between 170 and 200 ft deep in the upper part of the Maquoketa Formation. Minor inflections in the temperature and fluid resistivity logs (Figure 6) correspond to this analysis.

B. Lithologic and stratigraphic interpretation of core

Only the core collected from the Minooka County Park site was described in detail for this study due to time constraints. The core from the DOT site is quite similar. Six major facies, or lithologic types, were identified in the stratigraphy of the Maquoketa Formation at the Minooka Park site (Figure 9), and the three members of the formation were recognized (Ostrom, 1967; Kolata and Graese, 1983).

1) Upper cyclic packstone-mudstone

This unit extends from the bottom of Silurian dolomite at 230 ft depth down to 272 ft. It consists of alternating beds of greenish-gray soft fossiliferous mudstone and clayey to crystalline light olive gray vuggy dolomite. Occasional copper sulfide minerals (probably calcopyrite and pyrite) occur, and the greenish-gray mudstone increasingly dominates toward the base of the unit.

2) Brown-banded silty dolomite

This unit extends from 272 ft down to 314 ft depth. It consists of harder interbedded olive gray to light olive gray to yellowish brown occasionally laminated silty dolomite. Some carbonate horizons, chert nodules, large concretions and evidence of soft sediment deformation can be found. Fine calcite-filled fractures are present in a porous-looking siltier matrix toward the bottom.

3) Carbon and sulfide (C&S) rich grainstone-packstone

This very coarse, silicified, and fossiliferous dolomitic unit, from 314 ft to 318.5 ft depth, apparently only occurs in the core from the Minooka Park site. It is characterized by an abundance of dark copper sulfide mineralization and a globule of viscous tar encountered in a fracture at about 315 ft depth. Because of its position in the approximate center of the Maquoketa Formation, the tar is probably naturally occurring.

4) Burrowed brownish-gray dololutite

This is a much finer-grained light olive to brownish gray clayey dolomite extending from 318.5 ft to 334 ft depth. It is characterized by abundant bioturbation, occasional small fossils and two soft, unlithified clay seams, one of which corresponds to gamma and caliper responses at about 320 to 325 ft.

5) Lower cyclic packstone-mudstone

This unit extends from 334 ft to 357.5 ft depth, and it has a very similar lithology to the unit at the top of the formation. It consists of interbedded olive to brownish gray mudstone with intervals of mottled brownish to light gray fossiliferous dolomite. These dolomitic beds can be seen as low cps pulses on the gamma log, the largest of which is at 350 ft, corresponding to the thickest bed.

6) Fissile greenish-gray mudshale

The lowermost unit in the Maquoketa Formation, from 357.5 ft to 409 ft depth, underlain by the Sinnipee Group dolomite, is a very uniform fine-grained, soft greenish-gray shale, which disintegrates when wet. It contains fossils, mostly brachiopods, occasional fine silty pyrite-rich laminae, and one soft unlithified plastic clay seam at approximately 379 ft, which is apparent on the caliper log.

C. Vertical distribution of hydraulic head

The hydraulic gradient across the Maquoketa Formation is not uniformly downward as might be assumed given the difference in hydraulic heads between the overlying Silurian aquifer and the underlying Cambrian-Ordovician aquifer. According to head measurements before pumping at the vertically spaced ports throughout the thickness of the formation, gradients range between 0.823 ft/ft to 90.61 ft/ft across packers (Table 2), and the gradients in the upper part of the formation are directed downward while the gradients in the lower part of the formation are directed upward (Figure 8).

The immediate interpretation of these opposing gradients within the Maquoketa Formation is that the hydrostatic pressure field within the unit has not yet equilibrated with the boundary conditions in the overlying and underlying aquifers. These boundary conditions changed with the reversal in gradient at the turn of the century, and it is unclear how long is needed before the system comes to equilibrium, i.e. a uniform downward gradient. Pressure adjustment times to boundary condition changes across a 1500 ft thick low permeability shale unit in Alberta have been calculated to be in the millions of years (Toth, 1995).

However, an alternate explanation of the nonequilibrium gradients might be that during the few months before the packers were installed, the horizontal fractures, particularly the one at 320 ft depth, acted as a drain for the system, causing gradients to converge toward it from above and below. Approximately three months elapsed between when the packers were inflated (Day 0), and when the intervals were pumped (Day 107) for groundwater sampling. This may not have been long enough for this transient drainage effect to dissipate, and in fact, head in the lower two ports (3 and 2) still seems to be declining during that period (Figure 8).

A combination of these long-term and short-term transient conditions may be the explanation for the observed head distribution. This implies that, at least locally, the horizontal fracture in the interval corresponding to Port 4 dominates the flow system, an analysis which is supported by the groundwater chemistry results (Section G below). Overall, the largest head drop (>250 ft) and largest downward gradient occurs across the bottom packer, which corresponds to the lithological contact between the Maquoketa Formation and the Sinnipee Group dolomite (Figure 8). This is significant because it emphasizes the difference in hydraulic properties between the two formations and their relative roles as regional confining units

D. Vertical distribution of hydraulic conductivity

Horizontal hydraulic conductivities calculated from the analysis of recovery data after pumping each port range over 5 orders of magnitude, from 1.7E-9 ft/s to 8.5E-5 ft/s (Figure 10). There is little variation in the results using three commonly used analysis methods. Testing of Port 6 gave hydraulic conductivity values of approximately 3E-7 ft/s, whereas Ports 5 and 4 gave higher values from 4.3E-6 ft/s to 8.5E-5 ft/s. Ports 3 and 2 gave considerably lower values ranging from 1.3E-9 ft/s to 4.8E-9 ft/s. The observed vertical distribution in hydraulic conductivity in the Maquoketa Formation is related to differences in lithology and fracturing of the rock. No analysis was possible from pumping Port 1, because no recovery occurred after pumping. However, slug testing of the lower part of the corehole at the DOT site resulted in values of 9E-7 ft/s to 7E-7 ft/s for the underlying Sinnipee Group dolomite.

Log drawdown versus time plots of data for Ports 6 and 4 are notable for the dual slope aspect of the recovery curve, whereas plots of data for other ports are straight or gently curving. It is significant that major fracture flow features identified in caliper (Figure 2) and heat pulse flowmeter logging (Figure 4) for the Minooka Park corehole are located within the intervals tested by Ports 6 and 4. The dual slopes indicate a dual permeability hydraulic response in each interval which is probably dominated by rapid inflow at first from the corresponding fracture feature, followed by slower inflow from the rock matrix at later times.

We were able to analyze two sets of recovery data for Ports 3 and 4 because of the extremely different recovery times in different intervals. Head in Port 3, like that in Port 2, recovered slowly over several weeks and a test on data for about 1 week (Figure 10: solid symbols) shows only slightly lower values than a test on data for 3 weeks (open symbols). This is probably due to a scale effect of a larger volume of rock contributing porewater to the corehole over the longer interval.

Recovery of hydraulic head after pumping in Ports 4, and especially Port 5, was extremely rapid, ranging from a few minutes to less than one minute. Initial testing of Port 4 using one minute head recording intervals produced a somewhat scattered dual-slope data plot, and results (Figure 10: solid symbols) are about one order of magnitude less than for analysis of data recorded at seven-second intervals (open symbols). This corroborates the aforementioned dual permeability response, where the rapid response data results (every seven seconds) correspond to the higher fracture permeability only, whereas the longer interval data results correspond partly to rock matrix permeability.

E. Correlation of geophysical signature, lithology and hydraulic properties

The geophysical signature of the corehole at the Minooka Park site can be closely correlated to the variations in lithology and hydraulic properties. The gamma log is most informative regarding lithology, being very sensitive to the clay content of the rock, but the SP and resistivity logs are also useful. High cps gamma peaks correspond to more argillaceous siltstones or shales, which in turn have very low hydraulic conductivities, for instance the interval between 357.5 ft and 409 ft. below the surface (Figures 2,9,10). The SP and resistivity curves tend to be very smooth except for noticeable deviations at intervals with more carbonate lithologies, such as at 250 ft, 292 ft, 315 ft, and 350 ft below the surface (Figure 2).

More resistant purer carbonate beds can also be identified by low cps gamma deviations, particularly in the two cyclic packstone-mudstone facies and the carbon and sulfide-rich grainstone-packstone (Figure 9). Since the hydraulic testing occurred over intervals spanning these cyclic lithologies, resulting values represent a composite hydraulic conductivity of the mixed lithologies. For instance, values resulting from testing Port 3 represent a composite hydraulic conductivity of the lower cyclic packstone-mudstone and the burrowed brownish-gray dololutite facies (Figures 9,10). These values are quite low, similar to those of the fissile greenish-gray mudshale facies, tested in Port 2 (Figure 10). In contrast, similar cyclic packstone-mudstone facies at the top of the section, tested at Port 6, has hydraulic conductivity values two orders of magnitude higher. This difference may be due to the slightly more abundant carbonate facies in the upper cyclic facies, but is more likely a consequence of greater fracturing in that interval compared to the lower cyclic facies (Figure 2).

Hydraulic conductivity of the brown-banded silty dolomite facies was tested in Port 5 and is surprisingly high, at the upper end of all values obtained (Figures 9,10). No prominent fractures or flow features were observed in that interval (Figures 2,4), so the rock matrix must be relatively permeable. Indeed, relatively low gamma readings, particularly in the lower part of the facies, between about 290 ft and 310 ft below the surface, indicate less argillaceous mineralogy and correspond to observations of apparently more porous lithology in the core.

F. Estimates of vertical hydraulic conductivity and travel time

Calculated values of hydraulic conductivity, presented above, represent hydraulic properties of the rock in a horizontal direction, perpendicular to the corehole. Estimating vertical hydraulic conductivity, and flow or leakage through the Maquoketa Formation, requires consideration of anisotropy or the directional nature of rock structure. Most sedimentary sequences present layered heterogeneity, or greater variations in lithology in the vertical direction than the horizontal direction. This is apparent in the case of the Maquoketa Formation, as can be seen in the stratigraphic log of the core (Figure 9) and the similarity of the downhole geophysical logs at the two field sites (Figures 2,4), to which the stratigraphy has been correlated. An additional factor in this case is the horizontal fracturing in certain intervals in the corehole.

Layered heterogeneity causes hydraulic conductivity to be considerably lower in the vertical direction (Kz) than in the horizontal direction (Kx). The ratio of Kx to Kz is known as the anisotropy ratio, and varies from 1 to 1000 according to lithology or bedding (Domenico and Schwartz, 1990). Most anisotropy ratios are derived from groundwater modeling and laboratory testing, and relatively little work has been done on deriving anisotropy from lithology descriptions. A method for calculating anisotropy ratios has been applied to glacial sediments (Anderson, 1989), but relies on estimates of relative magnitude of hydraulic conductivity, which may vary over a significant range. Neuzil (1994) states that stratification of argillaceous sediments, such as shales, may cause permeability anisotropy of up to three orders of magnitude. Estimates of anisotropy for each of the facies types described in the core from the Minooka Park site are shown in Table 1

Assuming that no significant vertical fracturing is present in the Maquoketa Formation, horizontal hydraulic conductivity values calculated for intervals with significant horizontal fracturing were not considered representative of matrix hydraulic conductivity for those lithologies, and not used in Table 1. Fortunately, in the case of the cyclic packstone-mudstone facies (Figure 9), the lower interval tested was not fractured, and provides reasonable values for estimating vertical hydraulic conductivity.

Both the cyclic packstone-mudstone and the burrowed brownish-gray dololutite facies were included in the same hydraulic conductivity group (1) because the interval that was tested (Port 3) contained both. These are more prominently bedded than the brown-banded silty dolomite facies, but less than the fissile greenish-gray mudshale, and were assumed to have a moderate anisotropy ratio of 100

The brown-banded silty dolomite was assigned an anisotropy ratio of 10 because of its relative homogeneity, and combined in hydraulic conductivity group 2 with the C & S rich grainstone-packstone because of the coarseness of the latter lithology. Finally, the fissile greenish-gray mudshale facies (hydraulic conductivity group 3) was assigned an anisotropy ratio of 1000 because of its numerous fine bedding planes.

Using these values of estimated vertical hydraulic conductivity for each lithology, an overall equivalent vertical hydraulic conductivity can be calculated for the Maquoketa Formation as a whole. The equivalent vertical hydraulic conductivity can be expressed as:

$$K_z = \frac{\sum m_i}{\sum (m_i/K_i)}$$

where K_i and m_i are the respective vertical hydraulic conductivities and thicknesses in a layered system (Freeze and Cherry, 1979; Domenico and Schwartz, 1990). The resulting values of equivalent vertical hydraulic conductivity range from 4.9E-12 ft/s to 9.5E-12 ft/s, which are similar to previously published values (Young, 1992).

Assuming an effective porosity of 0.02, reasonable for carbonates and shales (Domenico and Schwartz, 1990), a rough overall pore velocity can be calculated for flow through the Maquoketa shale using Darcy's Law:

$$v = Q/n_eA = (K_v/n_e)(dh/dl)$$

where K_v is the composite vertical hydraulic conductivity, n_e is the effective porosity, and dh/dl is the vertical gradient across the formation, which is about 1.7 ft/ft. Resulting values range from 4.2E-10 ft/s to 8.1E-10 ft/s, which correspond to 0.01 ft/yr to 0.03 ft/yr. In other words, at these rates, water infiltrating down from the Silurian aquifer would take from 6000 to 18000 years on average to seep through the thickness of the Maquoketa Formation.

G. Groundwater geochemistry

1) Major ions and indicator parameters

The geochemistry of groundwater in the Maquoketa Formation at the Minooka Park site differs significantly from the geochemistry of water in the overlying Silurian dolomite. Table 3 summarizes the geochemical results by sampling port and elevation; Port 7 samples water from the overlying Silurian rocks, while Ports 2 to 6 sample water from the Maquoketa Formation and Port 1 samples water from the underlying Sinnipee rocks. Figure 11 shows bar graphs of the equivalents per million (EPM) electrical balance between anions and cations for each sample. The cation/anion balances in all samples have less than 10% error. The figure illustrates the geochemical difference between water in the Silurian aquifer and water in the Maquoketa

Formation. Water in the Silurian (Port 7) is dominated by magnesium and bicarbonate, as expected in a dolomitic formation. Water in the Maquoketa contains significantly more calcium, sodium, and bicarbonate. The Maquoketa water also contains elevated strontium, at concentrations ranging from 1.7 to 2.7 mg/l. While strontium is usually not considered a significant constituent in potable groundwater (Hem, 1992), Nichols and McNall (1957) reported strontium levels greater than 1 mg/l in many wells in eastern Wisconsin.

Plots of indicator parameters and major ions with depth (Figure 12) show systematic geochemical changes with depth through the Maquoketa Formation. Temperature and pH both increase systematically with depth in the shale. Two curves are shown for temperature, one measured at the surface while sampling, and one by in-situ transducers. Concentrations of other parameters (electrical conductivity, Ca, Mg, Na, K, SO_4, Cl) vary with depth, and the most significant variations seem to occur between sampling ports 4 and 5. Ports 4 and 5 bracket a major fracture apparent on geophysical logs and the significance of this fracture is discussed below.

2) Trace constituents

The Minooka Park samples were tested for nitrate, sulfide, iron, manganese, copper, arsenic, and zinc, all of which usually occur only as trace constituents in Wisconsin groundwater, but which sometimes can occur at elevated levels. Nitrate and copper were not present above the analytical limit of detection (LOD) in any samples. Sulfide, iron, manganese, arsenic, bromide, and zinc were each detected at trace quantities in one or more samples (Table 3) but none of these detections exceeded Wisconsin drinking-water standards listed in Chapter NR 809.09 of the Wisconsin Administrative Code.

3) Saturation indices

Groundwater in the Maquoketa Formation is near equilibrium with respect to calcite and dolomite, but is undersaturated with respect to gypsum and the strontium-bearing minerals celestite and strontianite. We used the geochemical speciation program PHREEQC (Parkhurst, 1995) to calculate the speciation of ions in the water, to determine saturation indices with respect to major mineral phases expected to be present, and to calculate the partial pressure of carbon dioxide (pCO_2) in the water. Table 4 shows the speciation results. Positive saturation indices indicate oversaturation with respect to a particular mineral phase, while negative saturation indices indicate undersaturation with respect to a particular mineral phase. A saturation index of 0 indicates perfect equilibrium between the water and the mineral phase. As shown in Figure 13b, the calcium and dolomite saturation indices differ significantly between Port 7, sampling the Silurian dolomite, and Ports 2-6, sampling the Maquoketa Formation. The difference is probably due to the higher pCO_2 in the Maquoketa, which increases the ability of the water to dissolve mineral phases. The pCO_2 in the Silurian rocks is -3.57 bars, in near equilibrium with atmospheric pCO_2 (-3.5 bars). Water in the Maquoketa is highly oversaturated with CO_2 compared to the atmosphere (Figure 13a). The change in pCO_2 at Port 3 may not be significant because alkalinity was not measured for Port 3.

4) Isotopes of oxygen and hydrogen

Oxygen-18 (^{18}O) and deuterium (^{2}H) are naturally-occurring stable isotopes of hydrogen and oxygen present in small amounts in the atmosphere and in groundwater. These isotopes are often used as conservative groundwater tracers. Isotopic compositions are expressed as del (δ) permil (o/oo, or parts per thousand) relative to the composition of ocean water, where negative numbers indicate that the proportion of the given isotope in the sample is less than the proportion of the isotope in ocean water. At a given site, the ^{18}O composition of groundwater can often be related to variations in recharge temperature (Freeze and Cherry, 1979). Analysis results from the Minooka Park site are shown in Table 5.

Groundwater originating as recharge on the land surface should have an isotopic composition similar to the composition of modern precipitation. This precipitation, in turn, should have a composition close to that predicted by the meteoric water line, a worldwide statistical relationship between ^{18}O and ^{2}H (Freeze and Cherry, 1979). Figure 14 shows the ^{18}O :^{2}H relationship for the Minooka Park site, along with a meteoric water line for southeastern Wisconsin presented by Simpkins (1989). The four Minooka Park samples are consistent with the regression line, suggesting that the water has not been fractionated by lake evaporation, biological activity, or hydrothermal activity. Therefore, any shift in groundwater ^{18}O signature with depth is interpreted as resulting from temperature variations in the recharge area.

The ^{18}O profile at the Minooka Park site (Figure 13c) shows a negative shift of about 2o/oo in the upper part of the formation (between Ports 5 and 6), followed by an positive shift in the vicinity of Port 4. (Although sampled, analytical results from Ports 1, 2, and 3 were not yet available at the time of this report). Our preliminary interpretation of these data is that the negative shift at Port 5 represents water that recharged in a much cooler climate than found at the site today. If so, the groundwater at Port 5 must be several thousand years old.

Qualitative analysis of the profile of preliminary tritium (^{3}H) results (Figure 13d) shows that water in the Maquoketa is much older than that in the Silurian aquifer because tritium concentrations (TU) are much lower. Concentrations of less than 2 TU indicate groundwater which recharged prior to the peak of atmospheric tritium in the mid-1960s caused by atomic bomb testing, and perhaps considerably earlier. Tritium levels in Ports 5 and 6 were below the detection limit of 0.8 TU. Concentrations of groundwater tritium between 2-10 TU indicate younger groundwater (Hendry, 1988). These results support the oxygen isotope data analysis above.

5) Discussion

The geochemical and isotopic results for the Minooka Park site are consistent with a conceptual model of slow, downward groundwater movement through the upper part of the Maquoketa Formation This model is also consistent with the downward vertical hydraulic gradient measured between Ports 5 and 6. However, the downward profiles are interrupted between Ports 4 and 5, and Port 4 is within the interval where a permeable near-horizontal fracture intersects the core hole. Geophysical logs show that this fracture carries significant groundwater flow.

Based on the data currently available, we believe the horizontal fracture at elevation about 580 ft moves groundwater laterally through the Maquoketa Formation, possibly from the Maquoketa subcrop several miles to the west. Such lateral movement would explain the geochemical changes observed at this elevation and might introduce younger groundwater into the formation, which would be consistent with the del ^{18}O value measured just below the fracture at Port 4. Although confirmation of this hypothesis must await further analytical data and modeling, this is the first time to our knowledge that preferential flow paths through the Maquoketa Formation have been identified.

VI. CONCLUSIONS/IMPLICATIONS/RECOMMENDATIONS

This study has advanced our knowledge of the Maquoketa confining unit in southeastern Wisconsin and its hydraulic, sedimentologic and geochemical characteristics. Detailed information has been obtained using downhole geophysics, and by study of continuous core which traversed the formation, the only such core available south of Fond du Lac. Hydraulic testing, monitoring and porewater sampling were accomplished at several levels vertically within the formation. This is the first fieldwork to study the hydraulic properties of the Maquoketa, the most important regional confining unit in Wisconsin.

Downhole geophysical logging at two field sites shows that the Maquoketa Formation is lithologically remarkably similar over a distance of 15 miles or less. Important horizontal fracturing occurs at two levels in the upper half of the formation, but these fractures are significant flow features at only one of the sites. The vertical lithology consists of soft fine greenish gray fissile mudshale in the lower third of the formation, which probably corresponds to the Scales Member (Ostrom, 1967; Kolata and Graese, 1983). This is overlain by interbedded packstone-mudstone, and finer dololutite, up through a coarse sulfide-rich grainstone, which likely constitute the Fort Atkinson Member, and the overlying silty dolomite and interbedded packstone and mudstone would be the Brainard Member.

The vertical distribution of heads, and particularly the greater than 250 ft contrast in head across the Maquoketa-Sinnipee Group contact, indicate that the Maquoketa has much greater confining properties than the underlying dolomite at this site, which is significant since the combined Maquoketa-Sinnipee Group have previously been considered as a single confining unit (Young, 1992). The large range in hydraulic conductivity (5 orders of magnitude) measured at different levels in the Maquoketa, although partly due to horizontal fracture permeability, shows that this formation is hydraulically very heterogeneous, and that preferential fracture flowpaths may be locally important. Estimated composite vertical permeability ranges from 4.9E-12 ft/s to 9.5E-12 ft/s, and resulting pore velocity calculations suggest pore-water residence times of 6000 to 18000 years. Variable direction hydraulic gradients with depth in the Maquoketa indicate complex internal flow patterns.

Geochemical and isotopic results are consistent with slow downward flow through the upper part of the Maquoketa Formation and saturation indices indicate porewater with a long residence time, perhaps a few thousand years. Significant deviations in major ion concentrations and field parameters with depth at the level of a prominent horizontal fracture imply younger lateral groundwater flow, possibly from the Maquoketa subcrop a few miles to the west. Additional isotopic and geochemical results, not available for this report, will provide further details of age dating

This study provides important data which will enable further investigation of confining properties of the Maquoketa Formation using groundwater flow modeling and solute transport modeling. The two field sites can be used for further investigations of the hydraulic relations between the Maquoketa and underlying Sinnipee Group dolomite. The complex internal flow patterns indicated by the variable hydraulic gradient directions and magnitudes warrant further investigation. In addition, cooperating researchers are working on other aspects of the lithology of the recovered core, its geochemistry and rock mechanical properties, which will add to our knowledge of the sedimentology and hydraulic properties of this very important regional confining unit

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VIII. TABLES AND FIGURES

Table 1 : Estimated Anisotropy and Vertical Hydraulic Conductivity for Maquoketa lithologies

Hydro Group	Facies type/lithology	Calculated Horizontal Conductivity (Kx)	Estimated Anisotropy Ratio (Kx/Kz)	Estimated Vertical Conductivity (Kv)
1	Unfractured cyclic packstone-mudstone, Burrowed brownish-gray dololutite	1.3E-9 ft/s to 4.8E-9 ft/s	100	1.3E-11 ft/s to 4.8E-11 ft/s
2	Brown-banded silty dolomite (unfract. C&S-rich grainst./packstone)	6.8E-5 ft/s to 8.5E-5 ft/s	10	6.8E-6 ft/s to 8.5E-6 ft/s
3	Fissile greenish-gray mudshale	1.7E-9 ft/s to 3.0E-9 ft/s	1000	1.7E-12 ft/s to 3.0E-12 ft/s

Table 2: Calculation of vertical hydraulic gradients across packers, Day 107, Minooka Park site

Elevation of top of 3 ft packer (ft above msl)	Head above packer (ft above msl)	Head below packer (ft above msl)	Vertical gradient (ft/ft) - down, + up
666.5	895.55	848.72	-15.61
626.5	848.72	841.36	-2.45
590.5	841.36	844.89	+1.18
575	844.89	854.99	+3.37
540.5	854.99	857.46	+0.823
496	857.46	585.63	-90.61

Table 3: Water Chemistry Results-- Minooka Park all results in mg/l except as indicated							
Port number	7	6	5	4	3	2	1
Depth from surface, ft	20	271.5	307	322.5	358	402.5	422
elevation, ft	900	0	900	0	900	0	900
sample date	5/5/98	4/30/98	4/30/98	5/1/98	5/2/98	7/28/98	7/28/98
Diss. Oxygen, ppm.	2	2	0.6	2.7	3	0.1	0.8
pH, units	8.72	7.37	7.53	7.37	8.06	8.36	8.45
Eh, mv	20.6	-41.9	-53.2	-107.9	-87.1	-236	-274.3
Cond, uS	0.344	0.673	0.869	0.673	0.484	0.83	0.684
Temp, °C	12.9	12.5	9.7	11.7	13.2	15.5	14.8
Ca	9.1	52	28	56	45	20	17
Mg	34	24	12	28	34	8.9	8.3
Na	6.4	54	160	52	17	170	120
K	3.7	5.4	9.8	5.1	3	8.8	7.3
Fe	0	0.16	0.33	0.19	0.28	0.04	0.08
Mn	0.0087	0.0047	0.004	0.0096	0.005	0.0035	0.0059
As	0.0007	0.0007	ND**	0.0008	0.0008	ND**	ND**
Br	0.15	0.14	0.18	0.14	0.14	0.16	
Sr	0.058	2.768	2.232	1.912	1.743		
Zn	ND**	ND**	0.009	ND**	ND**	ND**	ND**
Alkalinity, as $CaCO_3$	151	340	467	371	*329**	446	337
HCO_3***	166.8	405.7	560.6	441.9	*329*	521.4	392.5
Cl	6.95	3.45	6.98	3.58	4.5	8.8	16.4
SO_4	17.6	12	0.38	16.9	19.1	6.7	7
NO_3	ND**	ND**	ND**	ND**	ND**	ND**	ND**
Sulfide	0.1	0.1	0.1	0.3			
Cu	ND**	ND**	ND**	ND**		ND**	ND**

Notes: * alkalinity for port 3 was estimated from EPM balance

** ND denotes concentration below analytic limit of detection. Detection limits were 0.0006 mg/l (As), 0.022 mg/l (NO_3), 0.008 mg/l (Zn), and 0.003 mg/l (Cu).

***HCO_3 calculated using PHREEQC speciation model

Table 4: Minooka Park saturation indices									
Port	Depth	elev	date	pCO_2, bars	calcite	dolomite	gypsum	celestite	strontianite
7	20.0	880.0	5/5/98	-3.57	0.29	1.33	-3.15	-3.63	-1.38
6	271.5	628.5	4/30/98	-1.84	0.04	-0.09	-2.63	-2.21	-0.71
5	307.0	593.0	4/30/98	-1.87	0.00	-0.25	-4.39	-3.78	-0.55
4	322.5	577.5	5/1/98	-1.81	0.08	0.02	-2.47	-2.23	-0.85
3	358.0	542.0	5/2/98	-2.64	0.57	1.20	-2.49	-2.20	-0.32
2	402.5	497.5	7/28/98	-2.71	0.73	1.34	-3.31	-7.01	-4.17
1	422.0	478.0	7/28/98	-2.92	0.64	1.19	-3.32	-6.48	-3.71

Table 5: Isotope data, Minooka Park site					
Port number	Depth below surface, ft	elevation, ft	sample date	del ^{18}O, permil SMOW	del ^{2}H, permil SMOW
7	20	880	5/5/98	-8.58	-64.37
6	271.5	628.5	4/30/98	-10.38	-76.35
5	307	593	4/30/98	-12.44	-94.76
4	322.5	577.5	5/1/98	-9.69	-71.66
3	358	542	5/2/98		
2	402.5	497.5	7/28/98		
1	422	478	7/28/98		

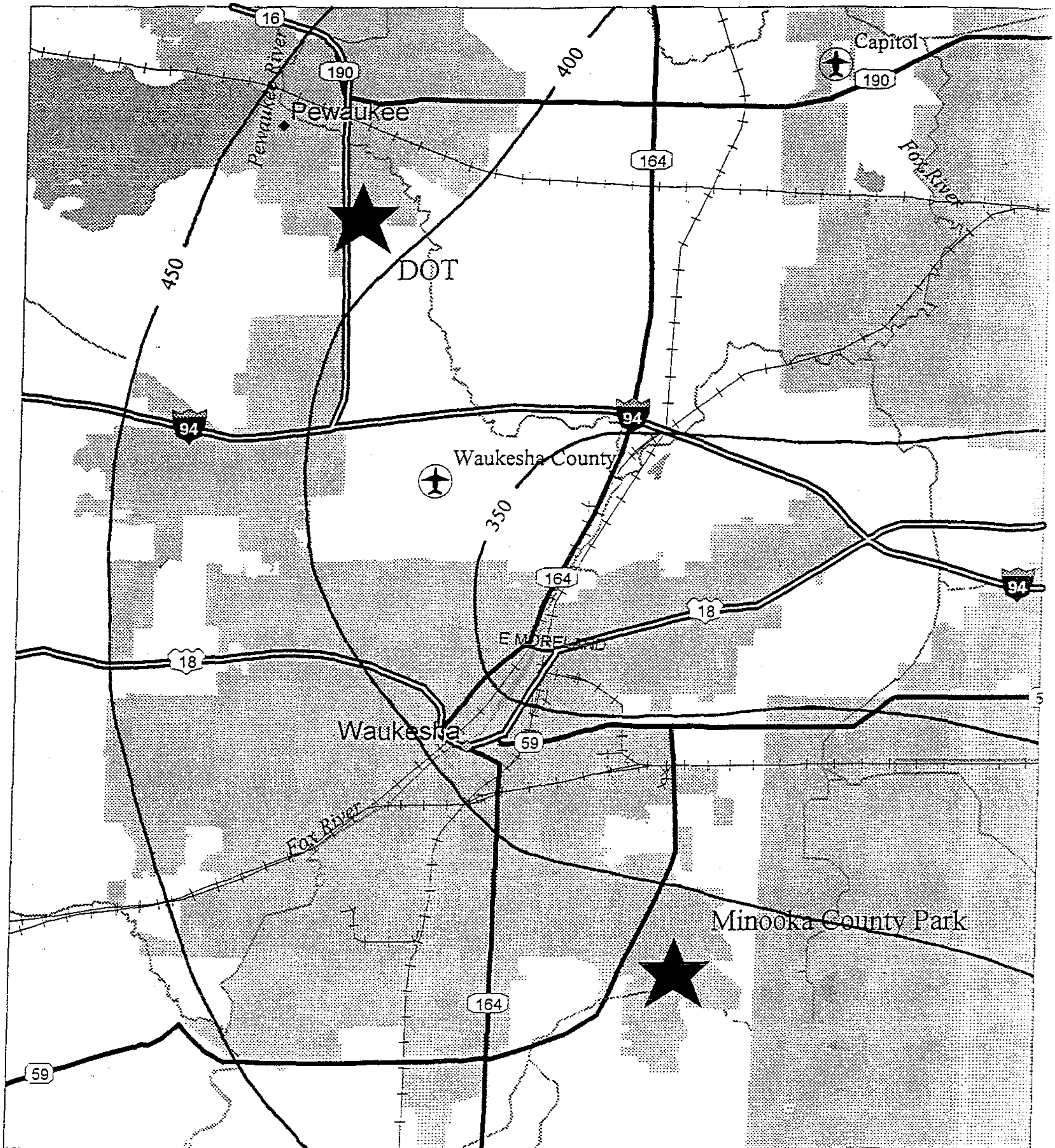


Figure 1: Map of field sites, Waukesha County, southeastern Wisconsin

N

400 Potentiometric surface (ft above msl) of deep sandstone aquifer (from Bonestroo et al, 1998)

Scale: 1 inch = 2 miles

Figure 2: Gamma, caliper, SP and resistivity logs at Minooka Park field site.

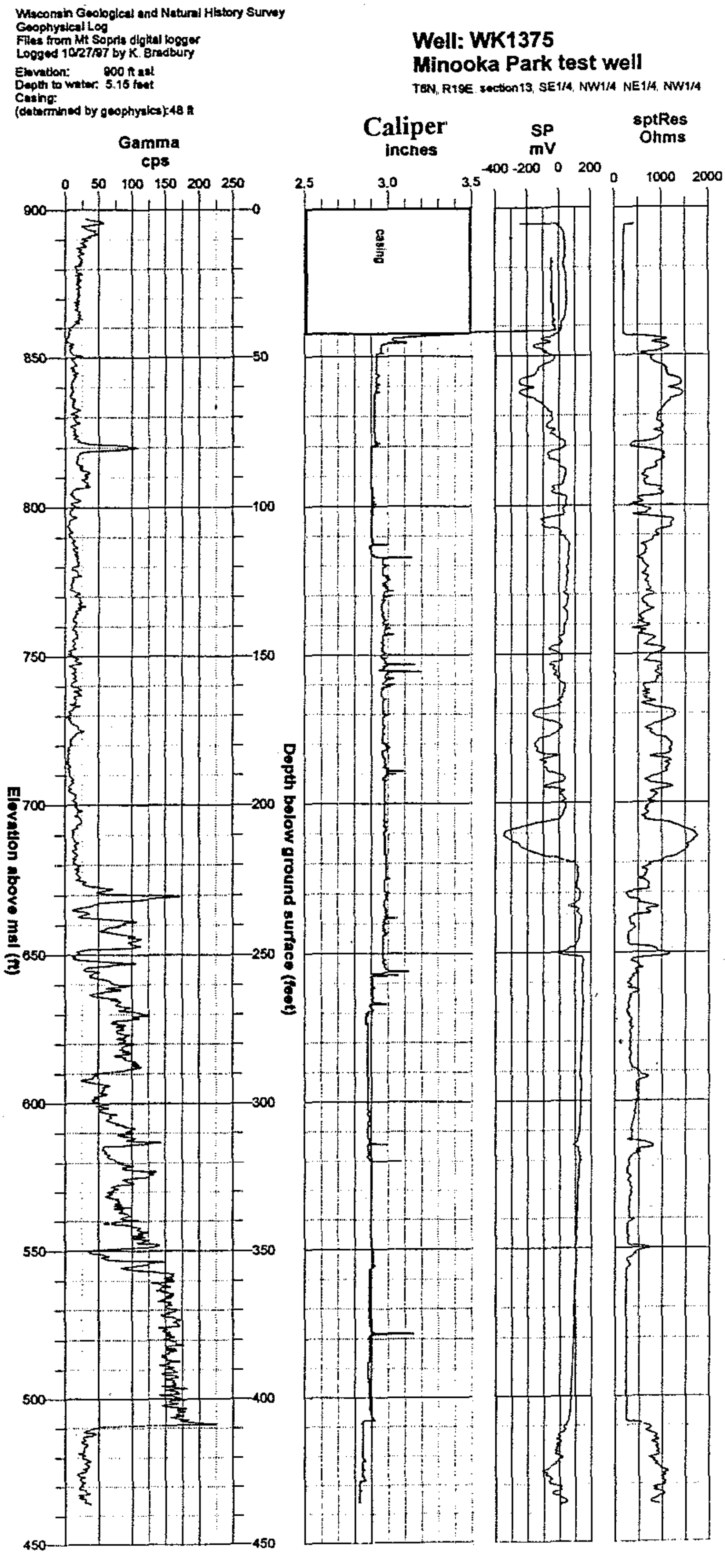


Figure 3: Fluid temperature and fluid resistivity logs at Minooka Park field site.

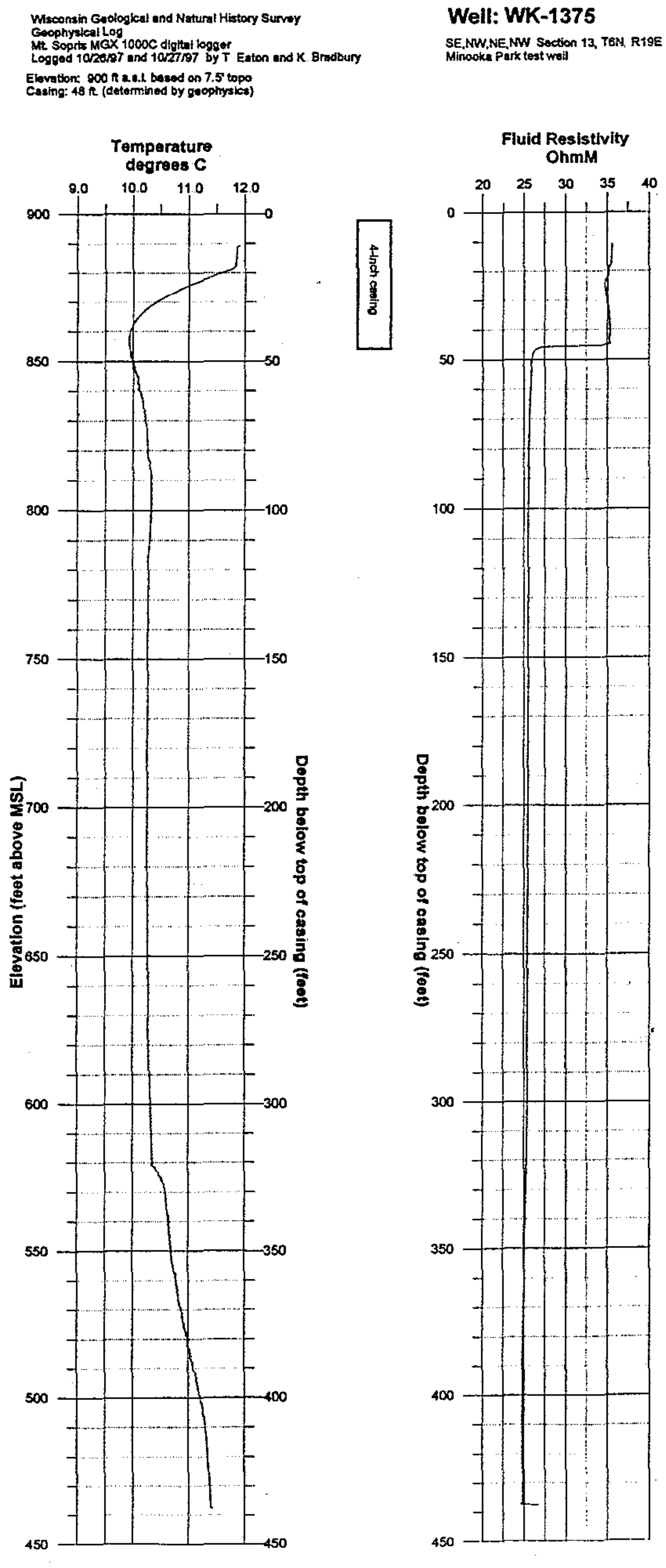


Figure 4: Heat-pulse flowmeter logs at Minooka Park field site

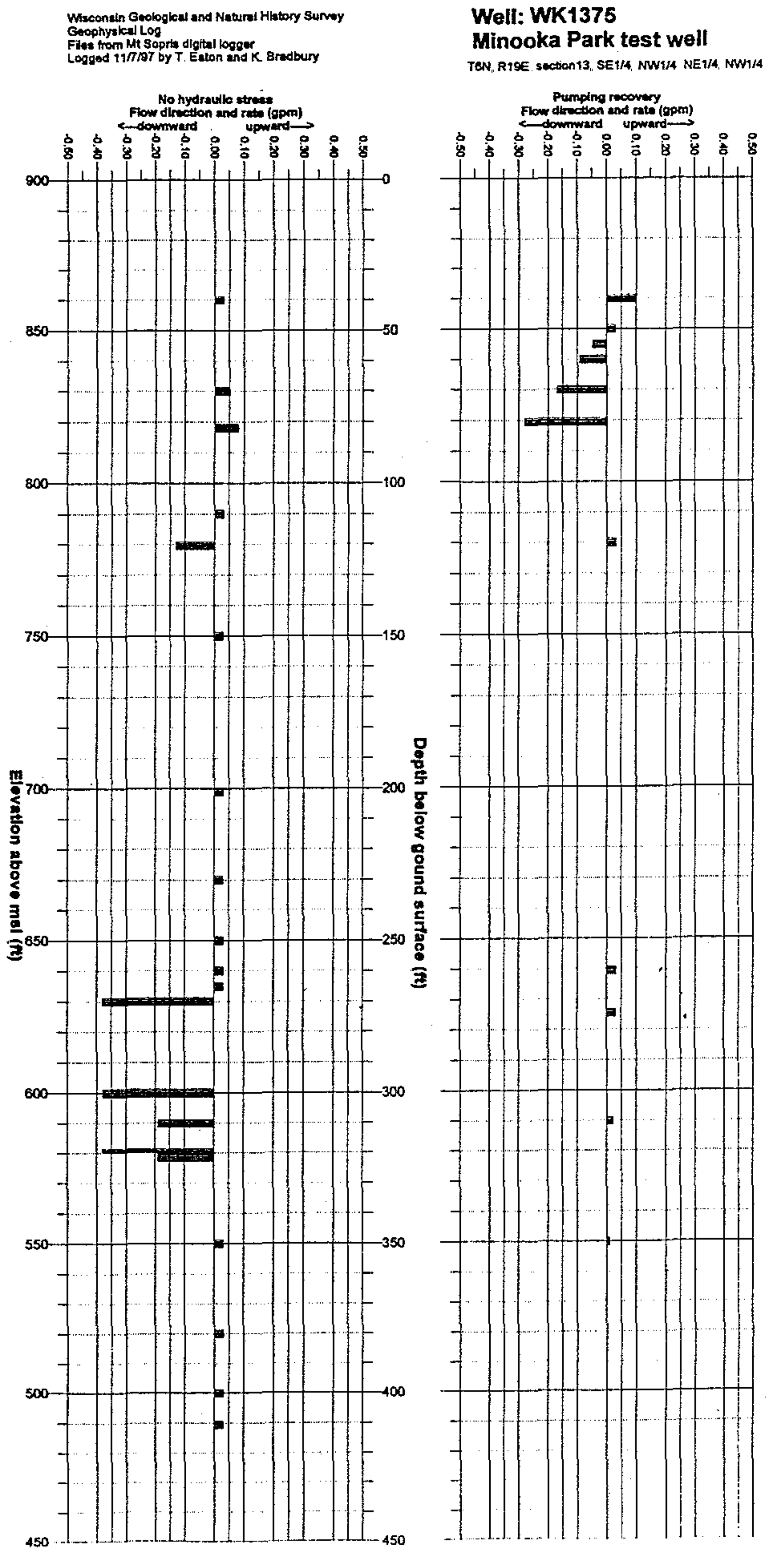


Figure 5: Gamma, caliper, SP and resistivity logs at DOT field site.

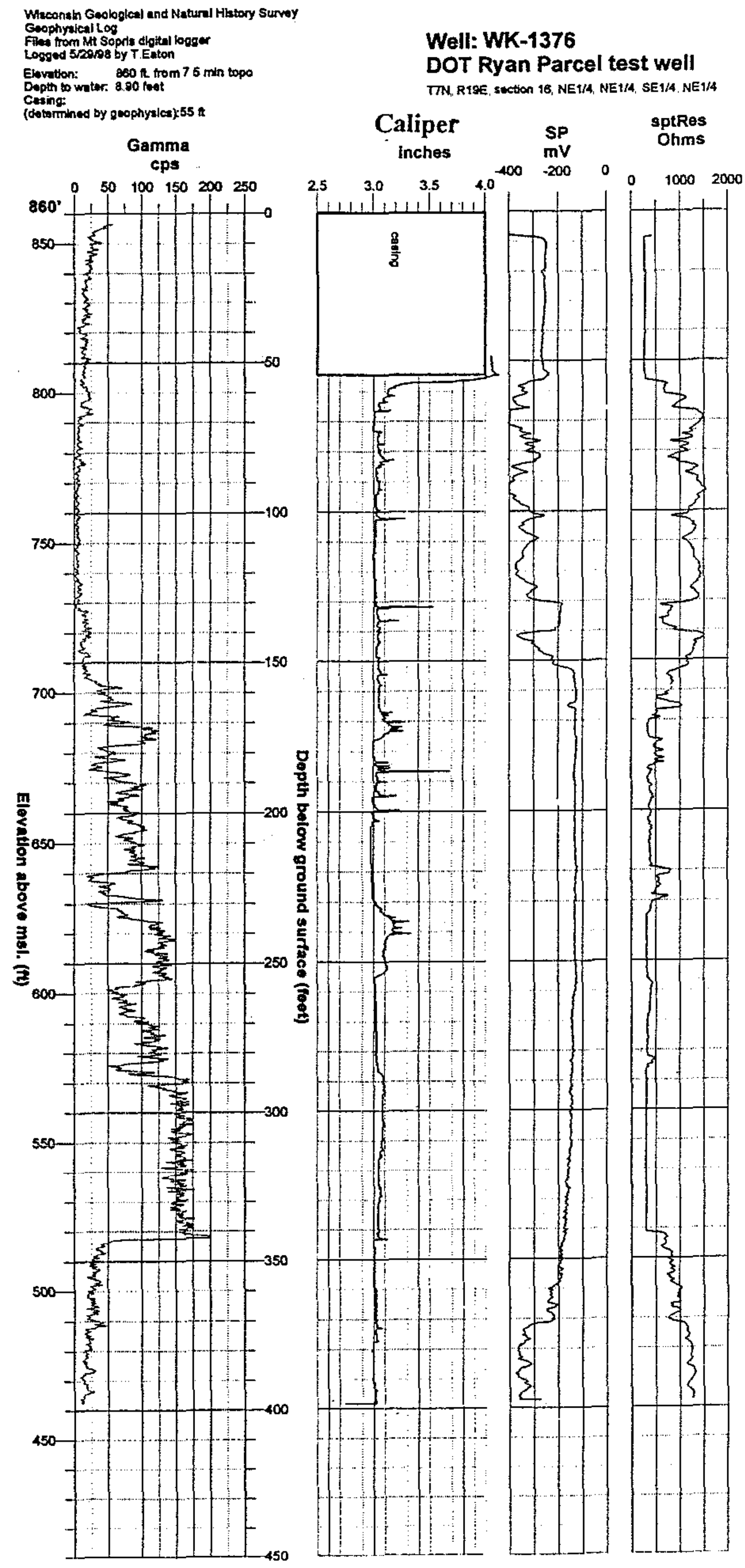


Figure 6: Fluid temperature and fluid resistivity logs at DOT field site.

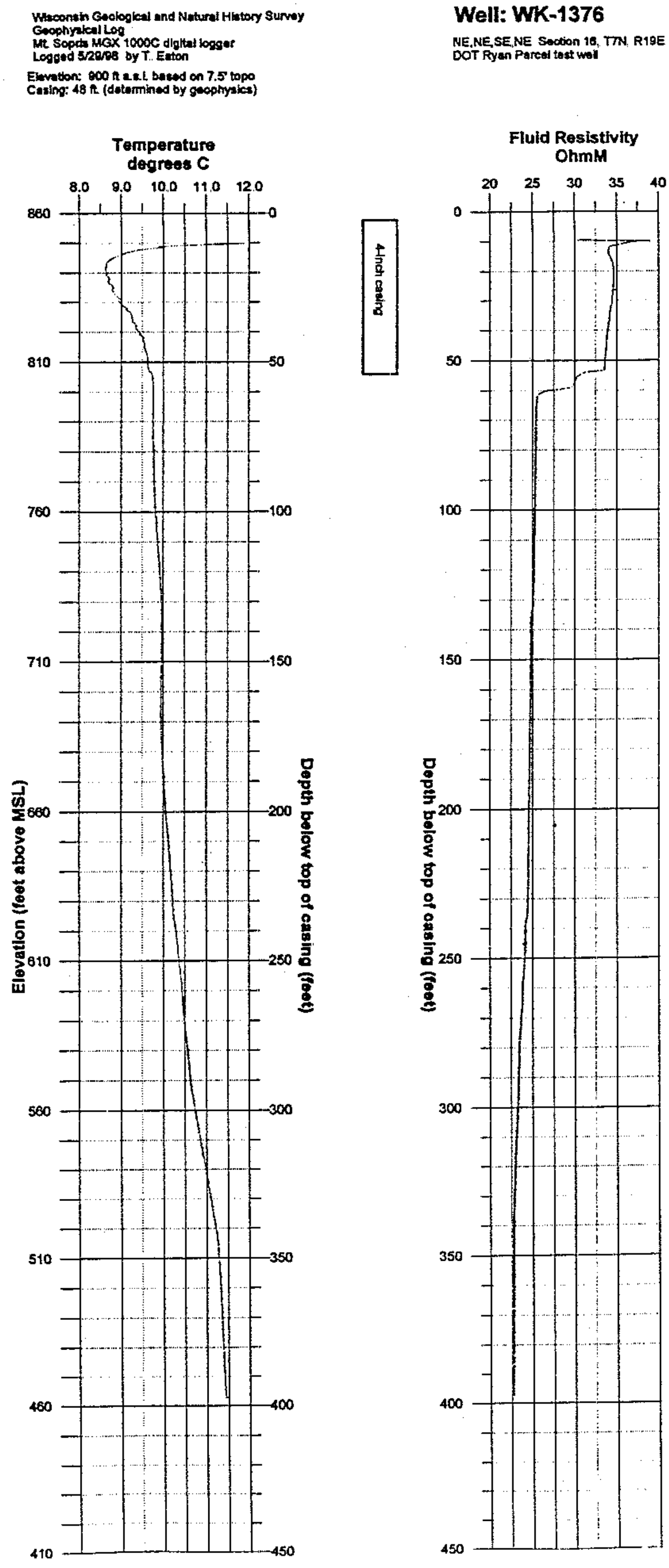


Figure 7: Heat-pulse flowmeter log at DOT field site.

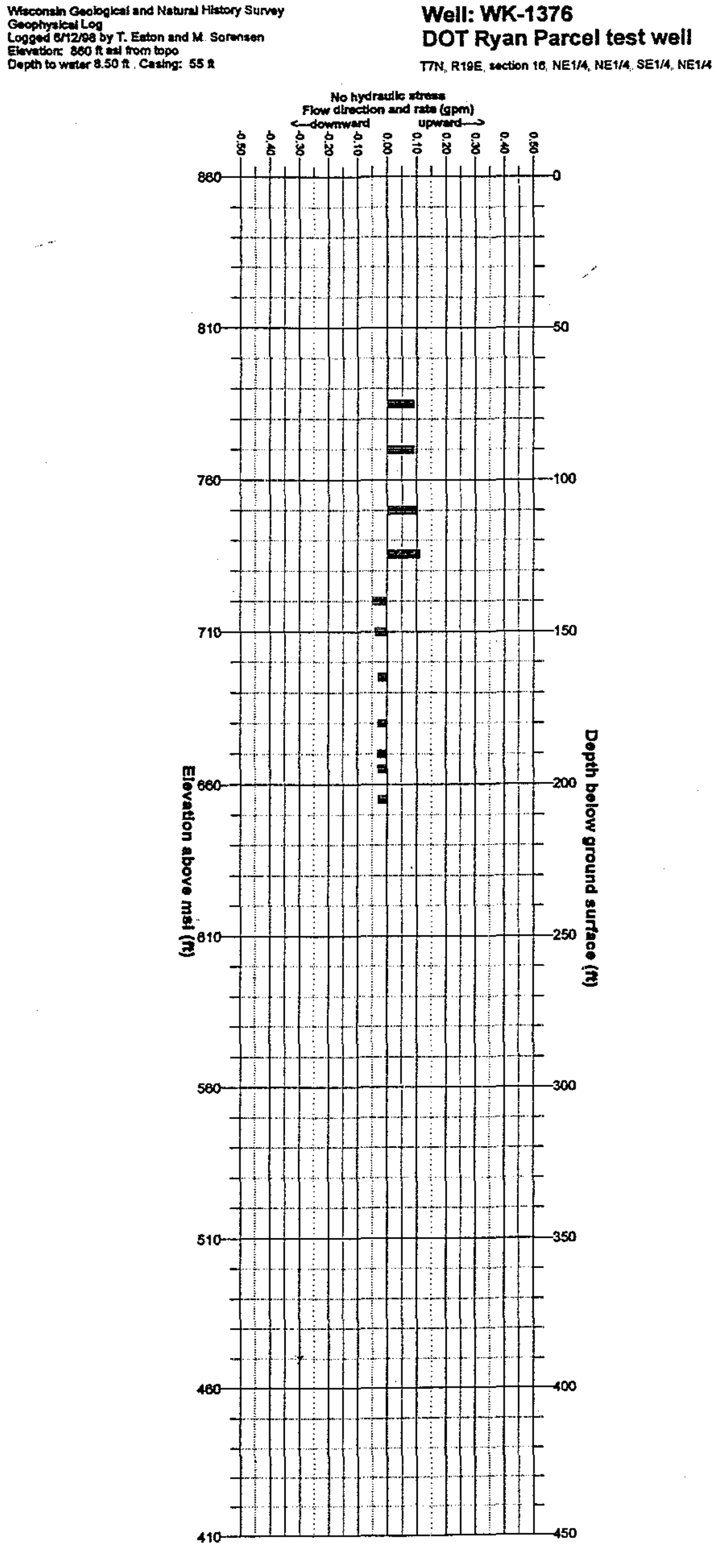


Figure 8: Multi-level packer and monitoring system after packer inflation, and resulting vertical hydraulic gradients at Minooka Park field site.

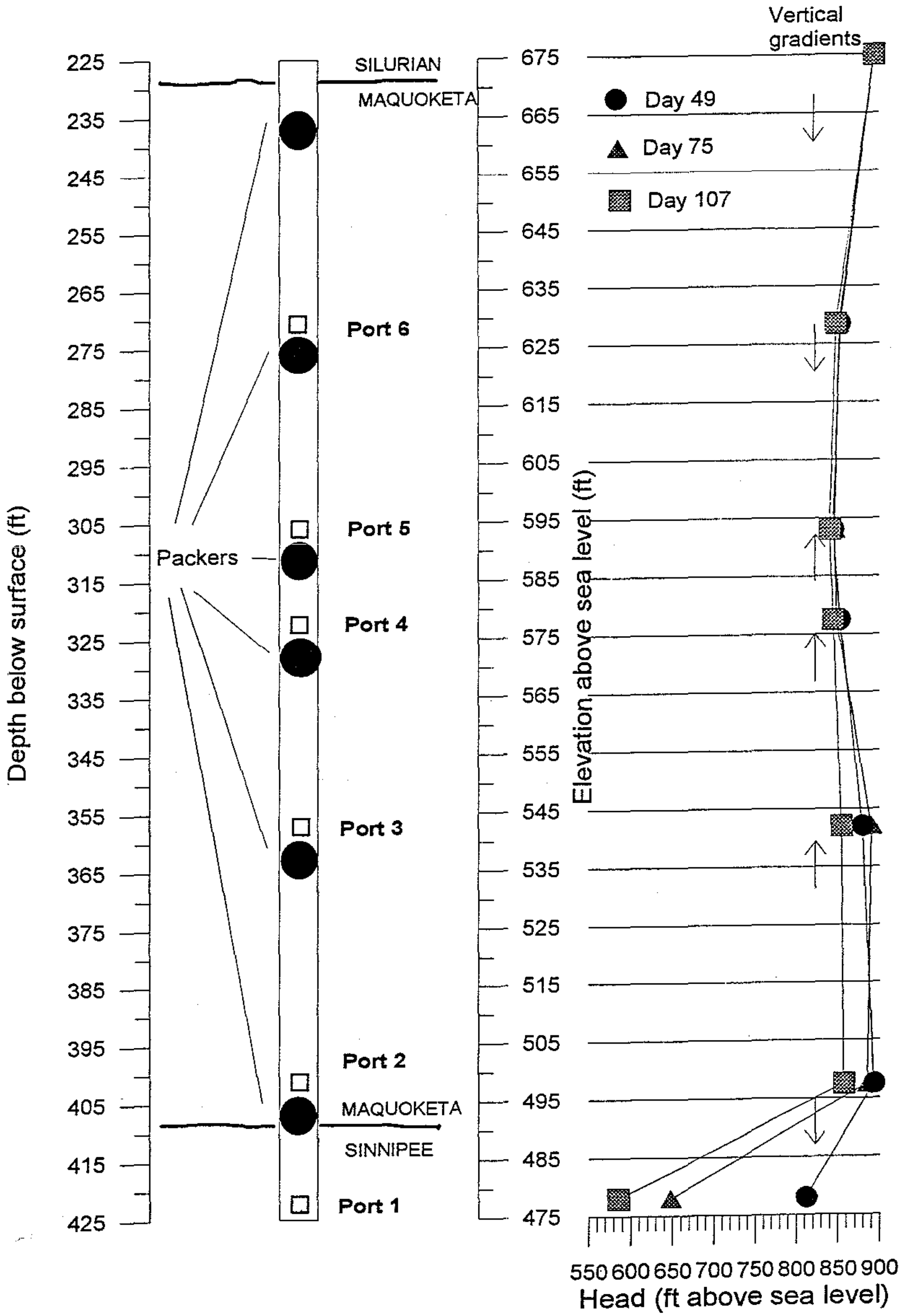


Figure 9: Gamma log and lithology from core description at Minooka Park field site. (for Hydro group number, see Table 1)

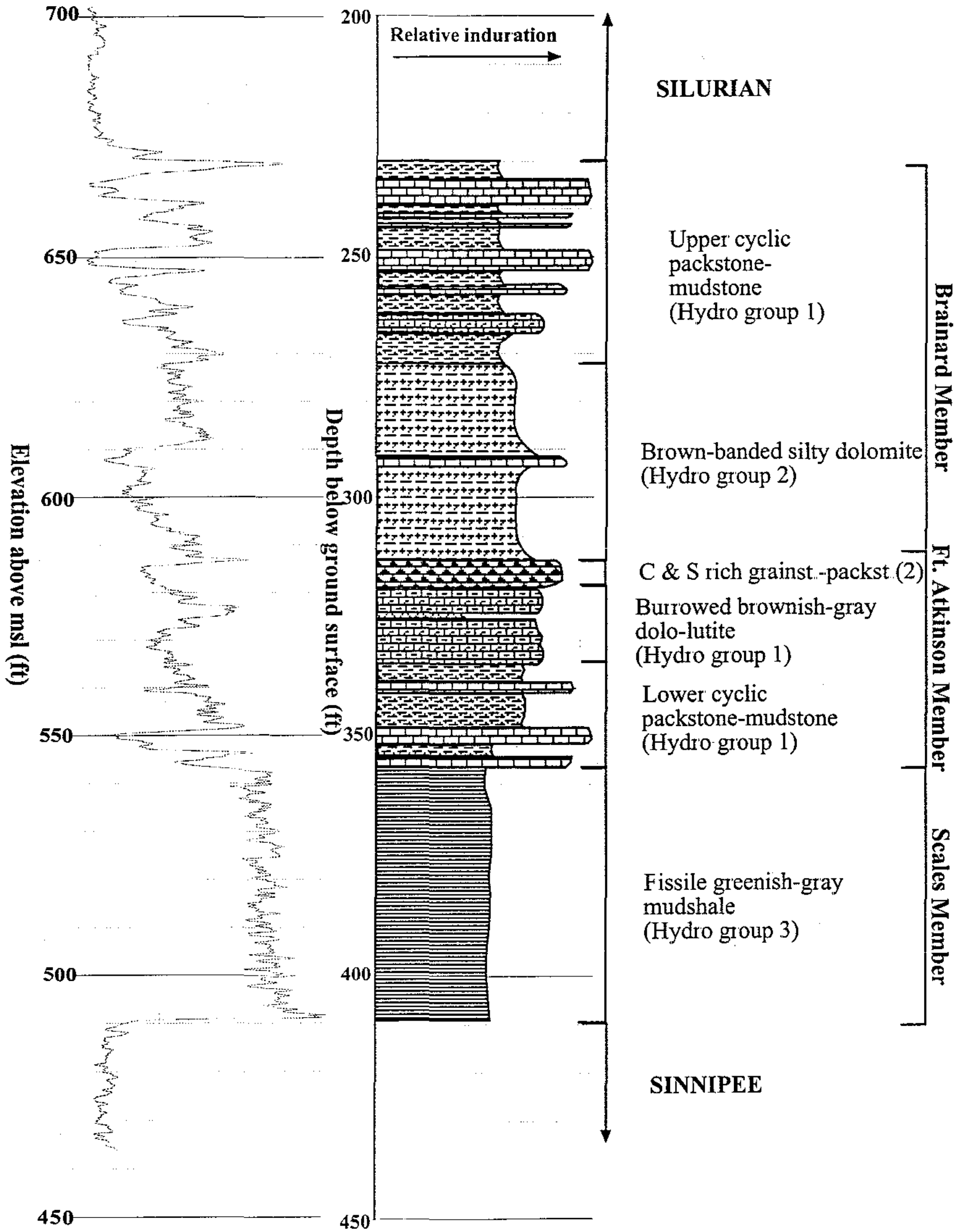


Figure 10: Distribution of measured horizontal hydraulic conductivity, Maquoketa formation, Minooka Park field site

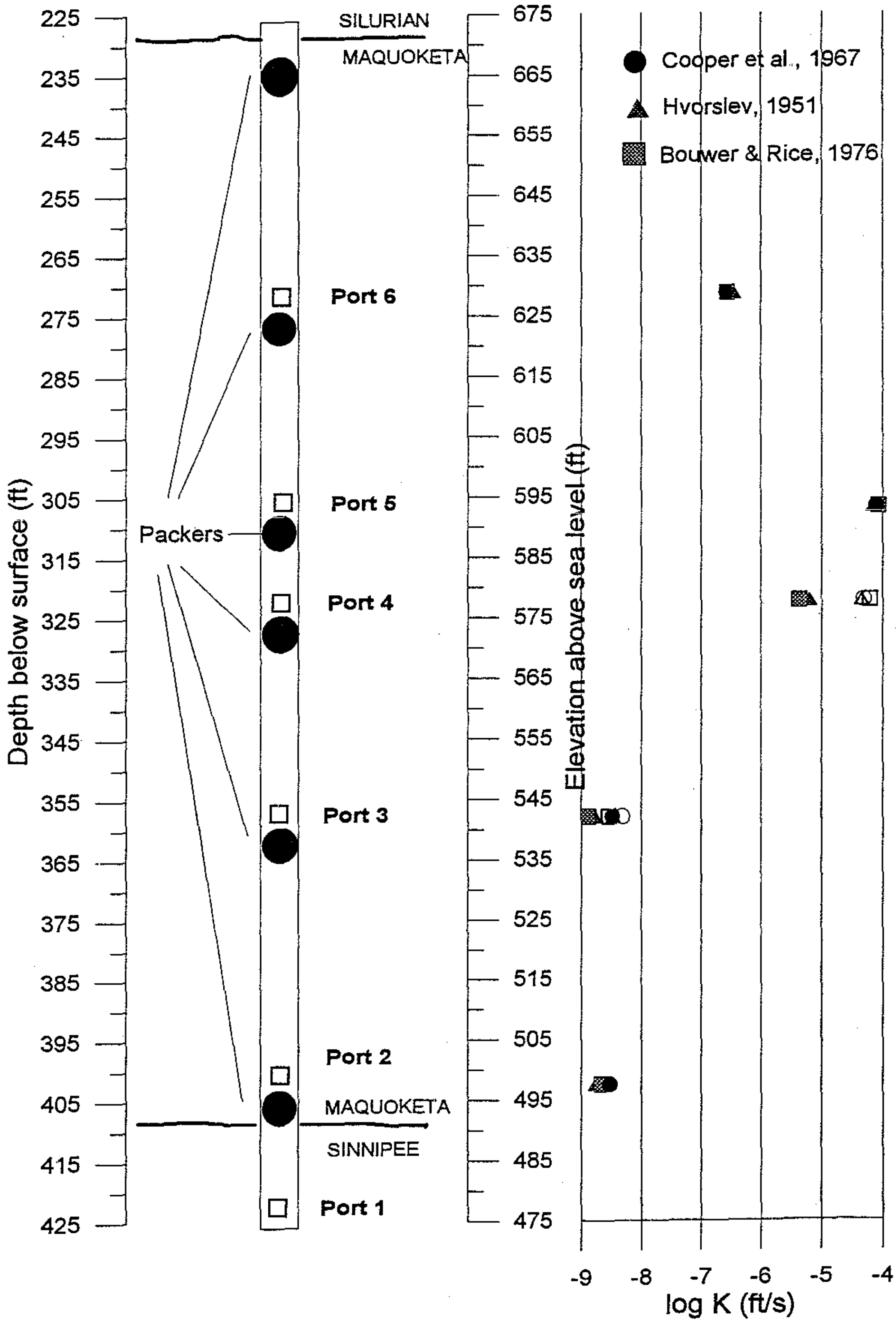


Figure 11: Charge balance for porewater geochemistry at different levels, Minooka Park field site.

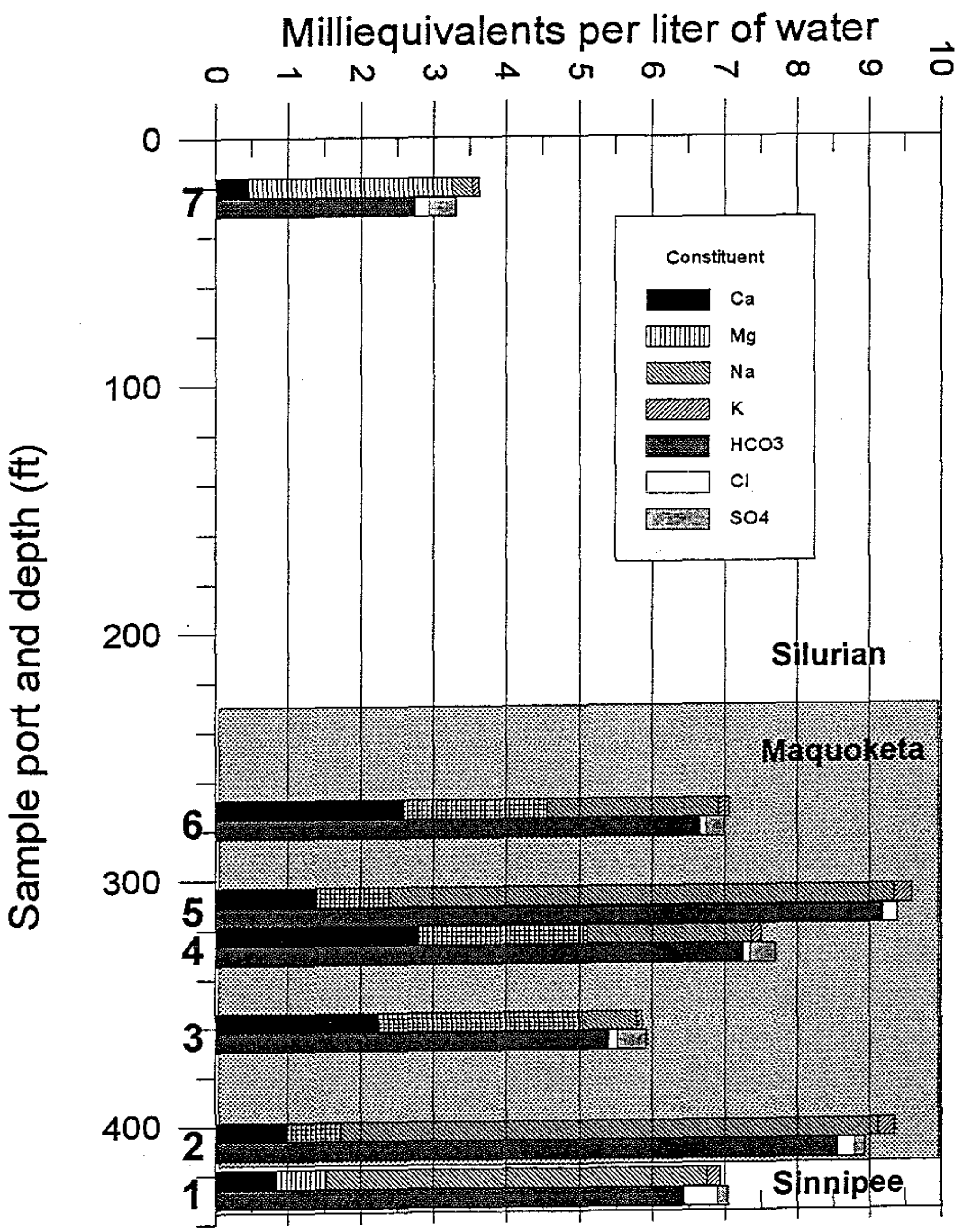


Figure 12: Field parameters and analyte distributions at different levels, Minooka Park field site.

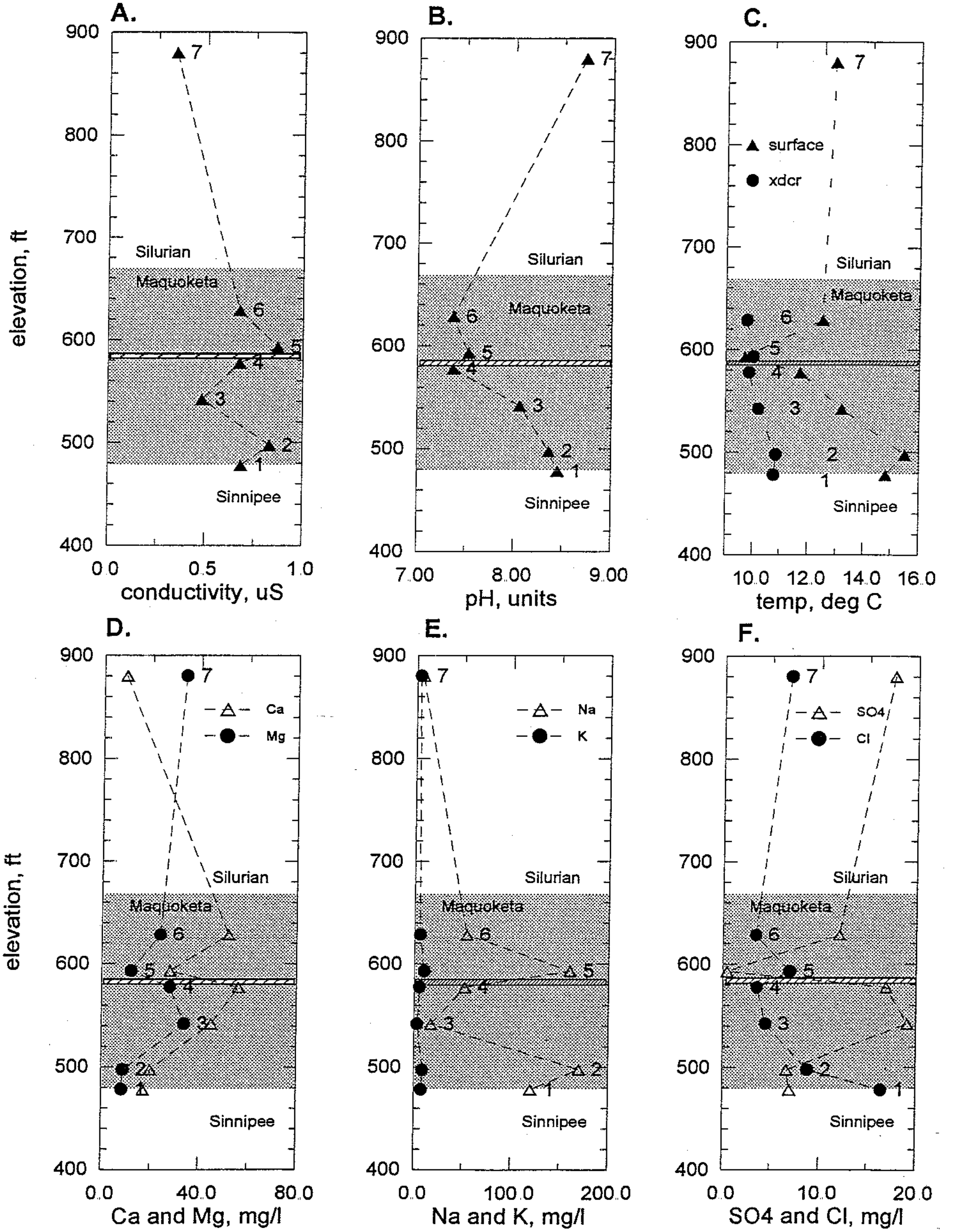


Figure 13: A: Partial Pressures CO2(g), B: Saturation Indices, C: Oxygen isotopes data and D. Tritium, at different levels, Minooka Park field site

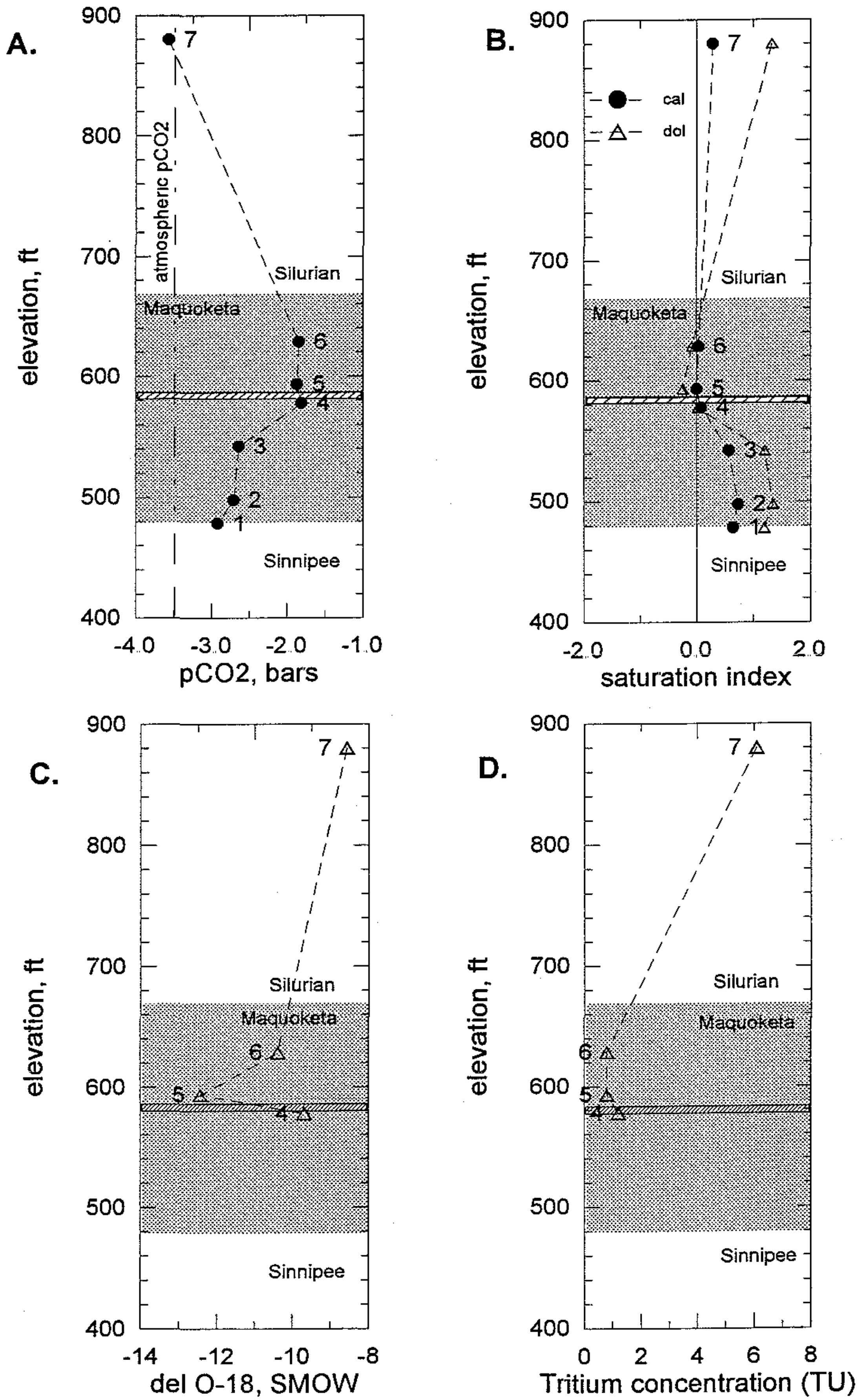
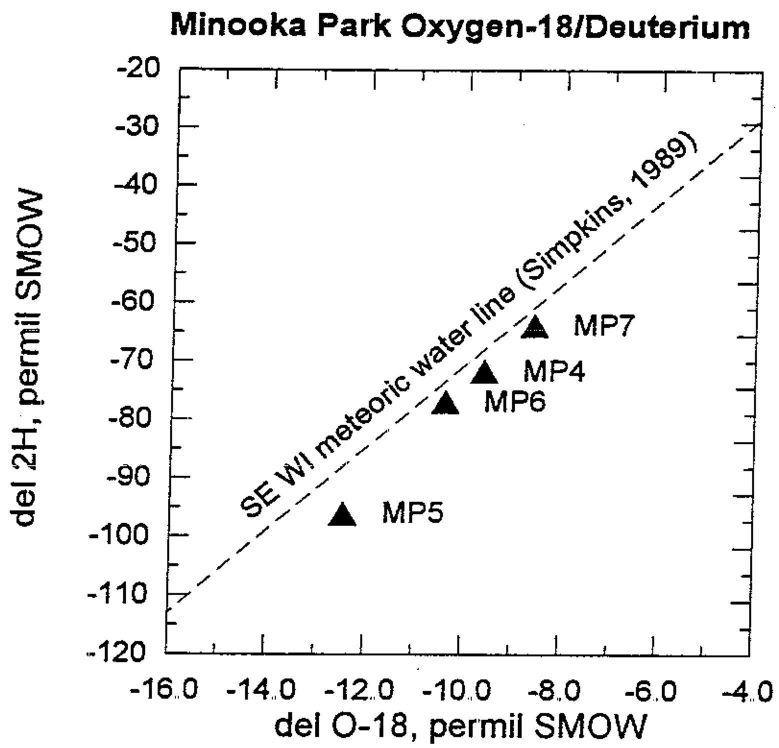


Figure 14: Oxygen-18/Deuterium isotopes relationship, Minooka Park field site



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