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# SUPERNORMAL FLUID PRESSURES IN SEDIMENTARY ROCKS OF SOUTHERN ONTARIO - WESTERN NEW YORK STATE

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## MANAGEMENT PERSPECTIVE

This paper presents and discusses some of the observations of anomolously high hydraulic heads measured across southern Ontario and western New York. The presence of the supernormal fluid pressures is important both with respect to regional groundwater flow and localized contaminant migration. The presence of the supernormal fluid pressures indicates that the vertical components of regional groundwater flow will be extremely restricted (i.e. the pressurized zones act as hydraulic barriers). For example, based on these observations, discharge of deep regional groundwater into any of the Great Lakes is unlikely. In addition, the presence of gas in association with these pressurized zones has caused considerable upward diffusion of salinity and gas associated organic compounds. This has impacted on the quality of shallow groundwater in many areas of Ontario and is occasionally mis-identified as contamination from anthropogenic sources.

Also, structural features play an important role in association with the pressurized zones. Large-scale normal faults as are postulated to be found in southern Ontario, may provide significant release pathways for the overpressure. Evidence from recent earthquake activity has shown that these faults can reactivate during earthquake events, opening new pathways for groundwater and gas migration thus impacting shallow groundwater environments locally.

PERSPECTIVE GESTION

Le présent article présente certaines observations et une discussion concernant les charges hydrauliques anormalement élevées mesurées dans le sud de l'Ontario et l'ouest de l'état de New York. La présence de pressions hydrostatiques supranormales est importante tant du point de vue de l'écoulement des eaux souterraines dans ces régions que de la migration localisée des contaminants. La présence de ces pressions hydrostatiques supranormales indique que les composantes verticales d'écoulement de l'eau souterraine sont très limitées dans ces régions (c.-à-d. que les zones sous pression agissent comme barrières hydrauliques). Par exemple, ces observations nous donnent à penser qu'il est peu probable que de l'eau souterraine à une grande profondeur parvienne dans l'un des Grands Lacs dans ces régions. En outre, la présence de gaz en association avec ces zones sous pression a causé une diffusion considérable de la salinité et de composés organiques associés à ces gaz en direction de la surface. Cette diffusion a eu un impact sur la qualité de l'eau souterraine peu profonde dans de nombreux secteurs en Ontario et est parfois identifiée à tort à une contamination provenant de sources anthropiques.

En outre, des caractéristiques structurales jouent un rôle important en association avec les zones sous pression. Des failles normales de grande envergure, comme on pense qu'il en existe dans le sud de l'Ontario, peuvent servir à relâcher la pression de façon efficace. Les données des récentes secousses sismiques ont montré que ces failles, en se réactivant au cours de séismes, peuvent offrir de nouvelles voies d'accès pour l'eau souterraine et les gaz et avoir ainsi une influence sur des milieux en contact avec de l'eau souterraine peu profonde à certains endroits.

## ABSTRACT

Fluid pressures up to 1.7 times greater than hydrostatic have been measured in argillaceous Paleozoic rocks of low permeability in southern Ontario and western New York State. These supernormal formation fluid pressures were measured at depths of 50-310 m using submersible pressure transducers with multiple-packer casings isolating the test intervals. Measurements were obtained over periods of 7 to 46 months following casing installations. The pressure measurements from eleven monitoring wells are compiled and supporting hydrogeologic data for five selected wells are used as examples to illustrate the occurrence of supernormal fluid pressures in the Ordovician, Silurian and Devonian sedimentary sequence of southern Ontario and western New York State. Possible explanations for the occurrence of supernormal fluid pressures in sedimentary rock are evaluated considering the available geologic and hydrogeologic information obtained from the monitoring wells. Based on this review, it is hypothesized that gas migration and accumulation from deeper distant sources is the most plausible explanation for the observed fluid pressures although secondary contributions from local neotectonic activity are also possible. The implications of such supernormal fluid pressures on regional groundwater flow in sedimentary rocks and related activities such as waste disposal in sedimentary rock are briefly discussed.

RÉSUMÉ

Des pressions hydrostatiques pouvant atteindre 1,7 fois la pression hydrostatique normale ont été mesurées dans les roches argileuses de faible perméabilité du Paléozoïque dans le sud de l'Ontario et l'ouest de l'état de New York. Ces pressions hydrostatiques supranormales dans ces formations ont été mesurées à des profondeurs de 50 à 310 m à l'aide de capteurs de pression submersibles placés dans des tubages comportant plusieurs packers isolant les intervalles de mesure. Les mesures ont été prises au cours d'une période de 7 à 46 mois suivant l'installation des tubages. Les mesures de pression dans onze puits de contrôle ont été compilées et les données hydrogéologiques à l'appui de cinq puits ont été choisis comme exemples pour illustrer la présence de pressions hydrostatiques supranormales dans la succession des couches sédimentaires de l'Ordovicien, du Silurien et du Dévonien dans le sud de l'Ontario et l'ouest de l'état de New York. On évalue les explications possibles à la présence des pression hydrostatiques supranormales dans la roche sédimentaire à partir de l'information géologique et hydrogéologique obtenue des puits de contrôle. À partir de cette étude, on émet l'hypothèse que la migration et l'accumulation de gaz provenant de sources beaucoup plus profondes est l'explication la plus plausible à la présence des pressions hydrostatiques supranormales observées, quoique l'activité néotectonique locale puisse également avoir un effet secondaire. On discute brièvement des effets de telles pressions hydrostatiques supranormales sur le débit régional de l'eau souterraine dans les roches sédimentaires et sur des activités connexes comme l'évacuation des déchets dans la roche sédimentaire.

## INTRODUCTION

Recent hydrogeological investigations of Paleozoic rocks in southern Ontario (Heystee et al., 1987; Novakowski and Lapcevic, 1988, Raven et al., 1990) and western New York State (Tepper et al., 1990) have documented the existence of high pore pressures in formations of low permeability at depths of 50-310 m. These supernormal fluid pressures are significantly greater than hydrostatic and have been measured primarily using multiple-packer casings permanently installed in exploratory boreholes. Such supernormal pressures are well known in many deep (>2000 m depth) low-permeability sedimentary basins located in active depositional environments (Kreitler, 1989) where sediment loading and compaction result in elevated pore pressures. However, the occurrence of supernormal fluid pressures in the relatively shallow, old and overconsolidated Paleozoic rocks in southern Ontario and western New York State has not been systematically documented or discussed in the available literature.

Supernormal fluid pressures may act as hydraulic barriers to groundwater flow and therefore their occurrence may fundamentally alter our understanding of regional groundwater flow systems within sedimentary rock sequences. Consequently, the occurrence of supernormal fluid pressures has important implications for waste disposal and other activities in sedimentary rocks where knowledge of the groundwater flow directions and rates are necessary for assessment of the impact of dissolved contaminant migration.

The objectives of this paper are to systematically document the occurrence of supernormal fluid pressures in the Paleozoic rocks of southern Ontario and western New York State and to evaluate the likely mechanisms responsible for the generation of such pressures. The implications of supernormal fluid pressures to regional groundwater flow and waste disposal activities in sedimentary rocks are also assessed.

## GEOLOGIC SETTING AND BOREHOLE LOCATIONS

The Paleozoic sedimentary sequence of southern Ontario and western New York State is comprised of rocks of Late Cambrian to Late Devonian age (500-350 Million years old) (Hewitt and Freeman, 1972). The rocks are essentially undisturbed resting on an irregular Precambrian surface and are principally carbonate sequences with minor terrigenous units.

The sedimentary rocks in southern Ontario are underlain by a southwest trending Precambrian basement high known as the Algonquin-Findlay Arch from which Cambrian, Ordovician, Silurian and Devonian rocks dip northwesterly into the Michigan Basin and southeasterly into the Allegheny Trough of the Appalachian Basin (Figure 1). Regional dip of the strata flanking the Algonquin Arch is about 5.5 m/km into the Michigan Basin and about 8.5 m/km into the Appalachian Basin (Winder and Sanford, 1972). The Paleozoic sequences range in thickness from at least 1500 m in southwestern Ontario (Figure 2) to 925 m in the Niagara Falls area (Kreidler et al., 1972) and pinch out against the Precambrian basement to the northeast. The Paleozoic sequences attain thickness of several kilometers in both central Michigan and in southern New York State.

The sedimentary rocks of southern Ontario and western New York State are generally overlain by unconsolidated Quaternary deposits of glacial till and to a lesser extent glaciolacustrine clay and silt with minor pockets of sand and gravel. This overburden is generally of low hydraulic conductivity and ranges up to 35 m in thickness. The thin veneer of overburden in conjunction with the limited dip of the sedimentary rocks results in a flat-lying topography throughout most of the subject area.

Tectonic activity in the underlying basement rocks during the Paleozoic is postulated to have created a regional-scale fracture framework throughout the Cambrian, Ordovician, Silurian and Devonian sediments (Sanford et al., 1985). Vertical movements along these fractures caused by tilting and rotation of fault-bounded blocks of basement rock is likely responsible for the formation of oil and gas traps in the overlying sedimentary rocks. Neotectonic activity in the Paleozoic rocks along many of these prexisting fracture and fault structures is a subject that has recently attracted significant research interest (MAGNEC, 1989).

Figure 1 outlines the general geology and locations of eleven monitoring wells reviewed in this paper. Eight of the eleven monitoring wells intersect Middle Silurian to Upper Ordovician rocks in the Niagara Falls area of Ontario and New York State. The remaining three monitoring wells intersect older Paleozoic rocks of Upper to Lower Ordovician age at Bowmanville, Ontario (UN-2) and Mississauga, Ontario (OHD-1) as well as younger rocks of Upper to Middle Devonian age at Sarnia, Ontario (MDMW-1).

In addition to the eleven wells there are an additional eight similar monitoring wells located in Paleozoic rocks of southern Ontario and western New York State. These additional wells are all located in the area of Niagara Falls, Ontario and New York. Because of complicating hydraulic influences created by the Niagara gorge and underground tunnels, these wells are not considered further in this paper, although supernormal pressures also exist in several of these wells.

## FIELD MEASUREMENTS

### Background and Methods

Reliable and representative fluid pressure measurements in low permeability Paleozoic rocks have only recently become available in southern Ontario and western New York State. The availability of such pressure measurements coincides with the use of multiple-packer monitoring casings. These modular monitoring casings, manufactured commercially (Black et al., 1986), allow undisturbed pressure monitoring of many packer-isolated intervals within a single borehole using downhole pressure transducers over periods of months to years. In formations of low permeability such as shale, monitoring periods of several months are necessary to allow the pressures within the monitoring interval to reach equilibrium with pore pressures in the surrounding formation. Pickens et al. (1987) describe field examples of this pressure behaviour for deep boreholes completed in low-permeability rocks. Figure 3 schematically illustrates the method of measurement of formation pressure using the monitoring casings and related equipment. Table 1 summarizes the name, location, date of casing installation, length, number of monitoring intervals, percent packer seal and sedimentary rock age of the eleven monitoring wells discussed in this paper. Percent packer seal is the percentage of the total borehole length sealed with inflatable packers. The greater the percent packer seal, the greater the confidence in the measured fluid pressures for each monitoring well especially for wells completed in formations of low permeability.

The pressure measurements obtained from monitoring casings as presented in this paper are considered to be generally representative of in situ fluid pressures based on quality assurance procedures in the measurement technique (Black et al., 1986) and repeatability of results over several pressure surveys performed between 7 and 46 months after casing installation. Measured pressures from monitoring casings are considered to have precision of $\pm$ 0.2 kPa and accuracy of $\pm$ 2 kPa.

Measurements of formation fluid pressure were also collected in selected boreholes prior to casing installation using straddle packers equipped with pressure transducers. These pressure measurements have similar precision and accuracy to those from the monitoring casings. However, because the monitoring periods for these pressure measurements were relatively short, on the order of hours to a few days, reliable supernormal fluid pressures are available only for a few intervals of high permeability.

Geologic information including rock type and fracture occurrence in monitoring wells was determined from inspection of recovered N-size or H-size diamond core and where available, interpretation of standard borehole geophysical logs.

Profiles of borehole hydraulic conductivity were determined from systematic testing of 3-5 m length intervals using straddle packers equipped with pressure transducers. Results from constant pressure injection tests and transient pressure pulse tests (Heystee et al., 1987) were used to calculate effective hydraulic conductivity for each interval. These test methods provide reliable quantification of effective hydraulic conductivity for rocks with conductivity in the range $10^{-13}$ to $10^{-5}$ m/s.

Gas occurrence in each monitoring well was determined from a variety of complementary methods including gas blow-outs observed at surface during diamond drilling, from interpretation of borehole geophysical logs, from hydraulic testing using straddle packers and from fluid sampling. In several boreholes, gas occurrence was confirmed through visual inspection with a borehole television camera.

Pressures, hydraulic heads and flow directions in groundwater systems are usually interpreted following conventional relations such as (Freeze and Cherry, 1979):

$$h = z + \frac{p}{\rho g} \qquad [1]$$

where h is hydraulic head, z is elevation of pressure measurement point above datum, p is the measured gauge pressure of the formation fluid, $\rho$ is formation fluid density and g is gravitational acceleration. In this paper, only fluid pressures are presented because these parameters are measured directly using downhole pressure transducers and because there is uncertainty in formation fluid density particularly in formations of low permeability.

To allow easy identification of supernormal fluid pressures, measured pressures are converted to dynamic fluid pressures. Dynamic fluid pressure, $p_{df}$, is defined as the difference between the measured formation fluid pressure, p, and the calculated hydrostatic fluid pressure that would exist at the measurement depth assuming a water table at ground surface and an overlying water column of fresh water of uniform temperature with density, $\rho$, of 1000 kg/m$^3$. In equation form:

$$p_{df} = p - d\rho g \qquad [2]$$

where d is depth of pressure measurement point below ground surface. Positive values of dynamic fluid pressure indicate supernormal fluid pressures whereas negative values of dynamic fluid pressure indicate subnormal fluid pressures.

## Results

Figures 4 and 5 show the measured formation pressures versus depth and the calculated dynamic pressures versus depth for the eleven monitoring wells listed in Table 1. Figures 4 and 5 also include formation pressures and dynamic pressures determined from the monitoring casings and from selected tests using straddle packers. In addition, Figures 4 and 5 show hydrostatic pressures that would be determined for fluid densities of 1000 kg/m$^3$ (A), 1100 kg/m$^3$ (B) and 1200 kg/m$^3$ (C). These hydrostatic pressures are discussed in greater detail in the subsequent section of this paper.

The results in Figure 5 indicate that supernormal fluid pressures significantly greater than hydrostatic exist in all of monitoring wells surveyed in this paper. These supernormal pressures are observed at relatively shallow depths of 50 m to maximum depths of about 310 m and at values up to 1.7 times greater than the calculated fresh-water hydrostatic pressures for the depth of the measurement point.

Figures 6 to 10 illustrate the available stratigraphic and hydrogeologic data for five representative monitoring wells (UN-2, OHD-1, MDMW-1, NI-1 and USNI-1). These Figures provide specific borehole information on the nature and occurrence of supernormal fluid pressures in sedimentary rocks of southern Ontario and western New York State. The Figures summarize borehole stratigraphy from recovered core, hydraulic conductivity from packer tests, gas occurrence from drilling, logging, testing or sampling activities and dynamic pressures from representative pressure surveys of the monitoring casings and from results obtained using straddle packers.

As shown in Figures 6 to 10, supernormal fluid pressures exist in association with gas occurrence in argillaceous rocks of low permeability throughout the Ordovician, Silurian and Devonian sequences. The zones of highest supernormal pressure occur in gas producing permeable features such as open fractures or thin limestone beds in otherwise low-permeability shale, shaley limestone and shaley sandstone units. For example, in monitoring well UN-2 (Figure 6) the highest supernormal pressures equivalent to dynamic fluid pressures of 490 - 730 kPa were measured in a gas producing fracture zone at 169 m depth in otherwise relatively impermeable (< 1 x $10^{-12}$ m/s), shaley limestone of the Trenton-Black River Group. Similarly in monitoring well OHD-1 (Figure 7) dynamic pressures of greater than 1000 kPa were measured in permeable gas- producing fracture zones and porous limestone seams in the shaley limestone of the Trenton- Black River Group at depths of 240-310 m. Monitoring well MDMW-1 (Figure 8) showed dynamic pressures of up to 600 kPa, in a permeable limestone horizon at 123 m depth (Rockport Quarry limestone) underlain and overlain by massive low permeability clay shales. The results from monitoring wells in the Niagara Falls area, as shown in Figures 9 and 10, indicate that the highest supernormal pressures are present in gas producing permeable fracture zones in the otherwise low permeability shales and shaley sandstones of the Clinton and Cataract Groups.

Dynamic pressures determined from selected straddle-packer tests shown in Figures 6, 7 and 10 are equal to or greater than those calculated from pressure surveys of the monitoring casings. The higher dynamic pressures determined from these selected tests, although recorded over a shorter monitoring period, are thought to be more representative of in situ conditions than monitoring casing results because the straddle packers provided a more reliable borehole seal and the tested intervals have sufficient permeability to consider the short-term monitoring results reliable. This suggests that some of the dynamic pressures from monitoring casings shown in Figures 4 to 9 may be conservative in that they may underestimate in situ pressures.

Figures 4 to 10 also show zones of subnormal pressures (negative dynamic pressure). In some of the monitoring wells not shown in Figures 6 to 10 these subnormally pressured zones are occasionally associated with the presence of gas. The largest negative dynamic pressures are observed to occur at 80 to 130 m depth in the Niagara Falls monitoring wells and likely reflect groundwater drainage in the Whirlpool sandstone to the Niagara River in the gorge downstream of the Falls (Novakowski and Lapcevic, 1988).

Table 1 Summary of Selected Multiple-Packer Monitoring Wells Completed in Sedimentary Rocks in Southern Ontario and Western New York State

| Monitoring Well | Location | Date Casing Installed | Borehole Length (m) | Number of Monitoring Intervals | Percent Packer Seal | Sedimentary Rock Age |
|---|---|---|---|---|---|---|
| NF-2 | Niagara Falls, Ontario | July, 1984 | 147 | 10 | 6.1 | Middle Silurian to Upper Ordovician |
| NI-1 | Navy Island Niagara Falls, Ontario | October, 1985 | 153 | 23 | 13.5 | Middle Silurian to Upper Ordovician |
| NI-2 | Navy Island Niagara Falls, Ontario | October, 1985 | 135 | 14 | 9.3 | Middle Silurian to Upper Ordovician |
| CH-1 | Chippawa, Niagara Falls, Ontario | December, 1986 | 154 | 15 | 8.8 | Middle Silurian to Upper Ordovician |
| UN-2 | Darlington G.S. - Bowmanville, Ontario | October, 1986 | 243 | 15 | 9.4 | Middle to Lower Ordovician |
| OHD-1 | Lakeview G.S. - Mississauga, Ontario | February, 1987 | 388 | 31 | 13.1 | Upper to Lower Ordovician |
| MDMW-1 | Sarnia, Ontario | October, 1987 | 303 | 28 | 22.0 | Upper to Middle Devonian |
| USN1-1 | Town of Niagara, New York State | November, 1987 | 115 | 17 | 15.6 | Middle Silurian to Upper Ordovician |
| WF-1 | Town of Wheatfield, New York State | November, 1987 | 133 | 21 | 16.5 | Middle Silurian to Upper Ordovician |
| USNF-1 | City of Niagara Falls, New York State | November, 1987 | 107 | 17 | 14.9 | Middle Silurian to Upper Ordovician |
| GI-2 | Town of Grand Island, New York State | November, 1987 | 154 | 23 | 15.6 | Upper Silurian to Upper Ordovician |

## MECHANISMS OF SUPERNORMAL PRESSURE GENERATION

Several review papers (Bredehoeft and Hanshaw, 1968; Graf, 1982; Neuzil, 1986; Kreitler, 1989; and Palciauskas and Domenico, 1989) summarize the mechanisms by which supernormal fluid pressures may be generated in sedimentary rock sequences. From these references ten mechanisms are hypothesized as potential explanations for supernormal fluid pressures in sedimentary rocks. These mechanisms include regional groundwater flow, variations in formation fluid density, sediment loading, uplift and erosion, thermal effects, mineral diagenesis, osmosis, tectonic compression, gas generation and gas migration. Each of these potential mechanisms are assessed in the context of the observed hydrogeologic conditions of the sedimentary sequences of southern Ontario and western New York State.

### Regional Groundwater Flow

Regional groundwater flow is a potential explanation for the occurrence of groundwater pressures above hydrostatic because all of the monitoring wells are located in proximity to major surface water bodies and therefore they are likely in regional groundwater discharge zones. However there are no contemporary recharge areas with elevations equivalent to the measured supernormal pressures within many kilometers of the monitoring wells. In addition, many of the intervals of supernormal pressure are in low-permeability rocks overlain and underlain by normally or subnormally pressured intervals in rocks of higher permeability (i.e., Figures 8, 9 and 10). Consequently, contemporary regional groundwater flow cannot explain the observed supernormal pressures. Alternatively it can be suggested that these pressures are evidence of relic groundwater flow regimes (Toth and Corbet, 1986). This is discussed further in the section on uplift and erosion.

### Formation Fluid Density

Increases in total dissolved solids and fluid density of formation fluids with depth is well known in sedimentary rock sequences and therefore is considered a viable explanation for some of the occurrences of supernormal pressures in sedimentary sequences. Groundwater sampling in several of the monitoring wells indicates increases of formation fluid density from fresh-water conditions

(1000 kg/m$^3$) near surface to maximum densities of about 1240 kg/m$^3$ at depths of 380 m. To accurately assess the contribution of formation fluid density to supernormal fluid pressure requires knowledge of the fluid temperature and fluid density profiles from surface to the pressure measurement point. Because this information is rarely known, the role of dense formation fluids in supernormal pressure development can be approximated by assuming an average isothermal fluid density between ground surface and depth. The resultant pressure lines for fluid densities of 1000, 1100 and 1200 kg/m$^3$ are shown on Figures 4 and 5 as lines A, B, and C. Because groundwater is fresh at surface, the 1200 kg/m$^3$ average density line is considered an upper limit for supernormal pressure development due to dense formation fluids. As shown in Figures 4 and 5, increases in formation fluid density can explain only a few of the measured supernormal pressures and only at depths below 150 m. The supernormal pressures observed shallower in the stratigraphic horizon greatly exceed the pressures predicted by this theory.

## Sediment Loading

Rapid deposition and subsequent compaction of fine-grained sediments, as occurs on continental margins and in intracratonic basins, is a mechanism for generation and maintenance of supernormal fluid pressures (Kreitler, 1989). Supernormal fluid pressures occur as a result of increases in total stress during sedimentation and transfer of this stress to the pore water during compaction. Fluid pressures approaching lithostatic can be produced for a continuous sedimentation rate of 500 m/million years for a sediment column with hydraulic conductivity of $10^{-10}$ m/s or less (Hanshaw and Bredehoeft, 1968). Once the compaction process is complete the overpressuring will dissipate at a rate proportional to the hydraulic properties of the rocks. Therefore, for the Paleozoic rocks studied in this paper, the important question is whether supernormal pressures generated during sediment deposition could exist today.

The persistence of transient pressures in a sedimentary rock environment can be evaluated using a dimensionless characteristic time, $\tau$ defined as (Bredehoeft and Hanshaw, 1968):

$$\tau = \kappa t/\ell^2 \qquad [3]$$

where $\kappa$ is formation hydraulic diffusivity which is equal to hydraulic conductivity divided by specific storage, t is time, and $\ell$ is the representative size dimension or sediment thickness. Transient supernormal pressures are dissipated when $\tau$ exceeds 1.0.

For the Ordovician argillaceous limestones intersected by monitoring wells UN-2 and OHD-1, the formation thickness averages 250 m and the hydraulic conductivity ranges between $10^{-14}$ to $10^{-13}$ m/s. Assuming a representative specific storage of $10^{-6}$ to $10^{-5}$ $m^{-1}$ the likely range of formation hydraulic diffusivity is $10^{-9}$ to $10^{-7}$ $m^2/s$. This is similar to a recent compilation of values for argillite and shale given by Neuzil (1986). For these conditions supernormal fluid pressures would dissipate in a relatively short period of time, approximately 80-8000 years, significantly less than the age of the rocks (about 450 million years). Similar calculations and conclusions can be shown for available data for the Silurian strata at Niagara Falls and the Devonian strata near Sarnia. Consequently, the Paleozoic strata are too old to have retained supernormal pressures generated during sedimentation and compaction.

Uplift and Erosion

Uplift and erosion of sediment are potential explanations for supernormal pressure generation particularly for mature sedimentary basis (Toth and Millar, 1983; Kreitler, 1989) similar to those of the Michigan and Appalachian Basins. Supernormal pressures may develop if the rate of erosion is rapid relative to pressure dissipation caused by pore water flow. However, subnormal pressures may also develop if elastic rebound of the rock due to erosional unloading occurs (Neuzil, 1986).

The significance of uplift and erosion to supernormal pressure development can be evaluated quantitatively, neglecting elastic rebound, using a dimensionless stress term, m defined as (Neuzil and Pollock, 1983):

$$m = \frac{1}{\kappa \rho g} \frac{\partial \sigma}{\partial t} \qquad [4]$$

where $\sigma$ is mean total stress and other variables are as defined previously. Walder and Nur (1984) and Neuzil (1986) show that stress change effects such as those caused by erosion can influence fluid pressures when m is on the order of 0.1 or greater. The monitoring well data for the north shore of Lake Ontario (UN-2, OHD-1) and an average Cenozoic erosion rate of 0.1 m/1000 years (Matthews, 1975) cast in terms of total stress indicate a dimensionless stress change of 0.008 to 0.8. Similar m values are calculated for the argillaceous sediments at Sarnia, Ontario and Niagara Falls indicating that under some circumstances, supernormal fluid pressures may be generated by erosion provided elastic rebound of the rock mass does not occur. However, recent field data (Neuzil, 1989) suggest that neglecting elastic rebound in the rock is physically unrealistic and therefore uplift and erosion is not a viable explanation for the observed supernormal pressures.

## Thermal Effects

Neglecting global changes in the geothermal gradient, the principal mechanism of supernormal pressure generation in sedimentary rocks from thermal effects is heating of strata by the geothermal gradient during sediment deposition (Barker, 1972; Domenico and Palciauskas, 1979; Chapman, 1980). Because, as shown previously, thermally-induced supernormal pressures would have dissipated within thousands of years of sediment deposition, geothermal heating during sedimentation is not a plausible explanation for the observed supernormal fluid pressures.

## Mineral Diagenesis

Hanshaw and Bredehoeft (1968), Graf (1982), and Neuzil (1986) have suggested that mineral diagenesis can be a significant mechanism for generation of supernormal pressures in fine-grained sediments. The diagenetic processes which have the most effect are the gypsum to anhydrite transformation and the montmorillonite to illite transformation. Both reactions occur as irreversible dehydration driven by heat. The reactions generate supernormal pressures through release of minerally bound water. Although these are potentially important reactions, there is currently not an adequate quantitative basis for evaluating them and only indirect assessment is possible.

Gypsum dehydration is likely not a reasonable explanation for observed supernormal pressures in this study as no significant quantities of gypsum or anhydrite have been measured in available argillaceous samples from selected monitoring wells (Grass and Lee, 1986) and because the dehydration reaction likely occurs shortly after sediment deposition (Kreitler, 1989).

The montmorillonite to illite transformation is also not a plausible explanation for supernormal pressures as no montmorillonite or other hydrous, mixed-layer clay minerals have been identified in available shale samples (Grass and Lee, 1986). The thermodynamic requirements for montmorillonite dehydration are such that these reactions will only occur in the temperature range of 62° - 154° C (Hanshaw and Bredehoeft, 1968). Assuming the heat is derived from the existing geothermal gradient, such dehydration would not occur above depths of 2600 m. Considering Cenozoic erosion rates these depths are much greater than depths at which supernormal local pressures are measured today. It also appears unlikely based on thermal maturation studies (Legall et al., 1981), that the majority of the Paleozoic rocks of southern Ontario experienced paleotemperatures much greater than 50-60°C.

<u>Osmosis</u>

The process of osmosis involves the mass transfer of water through a semi-permeable membrane from fluids of lower salinity to higher salinity. In theory this process can generate pressures of several thousand kPa (Hanshaw and Zen, 1965; Marine and Fritz, 1981), on the high salinity side of an osmotic membrane although some laboratory data for deep shale cores indicate actual osmotic pressures of only 10 - 30 kPa (Young and Low, 1975). In sedimentary sequences, osmosis may generate supernormal pressures in a low permeability formation such as a shale, if lower salinity water exists in adjacent permeable formations such as dolomite or limestone and parts of the shale unit behave as a semi-permeable membrane. In all of the monitoring wells there is increasing salinity with depth and therefore osmotically-induced pressures are possible for many of the shallower formations.

For example, in all of the Niagara Falls monitoring wells supernormal pressures are observed in the Rochester shale which contains predominately NaCl-type saline waters with total dissolved solids (TDS) of about 40 g/L (Novakowski and

Lapcevic, 1988). The Rochester shale is overlain by the permeable dolomites of the Clinton and Lockport Groups with a gradual salinity profile that grades upward to 6-7 g/L TDS at the top of the Lockport Dolomite to <1 g/L at the top of the Guelph Dolomite (Noll, 1989). For the predominately illitic clays of the Rochester shale and the described pore water geochemistries, the maximum theoretical osmotic pressures that could be generated in the shale against fresh water can be calculated following the thermodynamic approach of Marine and Fritz (1981) at about 2000 kPa. However, this theoretical osmotic pressure can only be achieved if sections of the Rochester shale actually behave as semi-permeable membranes that restrict the passage of ions. The observation of gradual salinity profiles upward from Rochester shale into the Lockport Group implies migration of ions upward from the shale. Consequently, it appears unlikely that the Rochester shale behaves as a semi-permeable membrane. Similar arguments can be made for the Devonian shales in the Sarnia area and the Ordovician shales on the north shore of Lake Ontario indicating that the argillaceous rocks have sufficient structured porosity to prevent the buildup of osmotic pressures.

## Tectonic Compression

Loading of porous rock due to regional tectonism or glacial effects and the transfer of such load to the pore water through porosity reduction has been suggested by Hubbert and Rubey (1959), Berry (1973), Graf (1982), Mase and Smith (1987) and Palciauskas and Domenico (1989) as an important mechanism for the generation of supernormal pressures in low-permeability sediments. This process may be particularly relevant to the sedimentary rocks of southern Ontario and western New York State as it widely held that these rocks are highly stressed (Lo, 1978; Lee, 1981) likely due to vertical stress migration from the deeper crust (Hasegawa et al., 1985) or possibly due to glacial rebound. Manifestations of these high stress conditions include squeezing ground conditions particularly in shales (Lo, 1978), post-glacial faulting (Adams, 1981) and stress relief features such as pop-ups (McFall et al., 1988).

The significance of stress change to supernormal pore pressure development can be approximately assessed with equation [4]. However, there is significant uncertainty in the current rates of stress change and strain accumulation and the viscoelastic behaviour of sedimentary rocks over geologic times scales and therefore it is difficult to reliably assess this mechanism. Estimated rates of regional stress change in Paleozoic rocks may range from 10-1000 Pa/yr, considering regional tectonics (Zoback and Zoback, 1980; Neuzil, 1986) and glacial rebound (Quinlan, 1984). Consequently a wide range of dimensionless regional stress change, m, of 0.03 - 300 may be calculated, for example, for the Ordovician strata on the north shore of Lake Ontario. A similar wide range of m can be calculated for other sedimentary sequences of low permeability near Sarnia and Niagara Falls. As m values greater than 0.1 can influence pore pressures, regional tectonic compression may contribute to supernormal pressures.

However, because the sedimentary strata are highly stressed it is possible that the argillaceous rocks are at or near their compressional limit and further pore compressional strains may be unlikely without rock failure. Such rock failure as evident by post-glacial faulting, pop-ups and seismic activity along existing structural discontinuities may result in local rapid stress drops and buildup and related porosity and pore pressure changes. Consequently, some of the observed supernormal pressures may, in part, result from such local neotectonic activity. However, it is unlikely that this would be a regional phenomena given the apparent lack of identifiable geologic structure in the argillaceous rocks reviewed in this study. Long term monitoring of pore pressure in argillaceous rocks located in areas of known stress accumulation would be useful in resolving the possible contribution of neotectonic compression to supernormal pressure generation.

## Gas Generation

The strong correlation between gas producing horizons and zones of significant supernormal formation pressure is compelling evidence to suggest that supernormal pressures are in some way related to the presence of gas. Such pressures may be created either directly through gas generation and migration processes or indirectly through the reduction of formation hydraulic conductivity as a result of the presence of a separate gas phase in the rock pore space.

Volume changes associated with transformation of complex organic matter through biogenic and thermochemical processes to simpler gaseous hydrocarbons (mostly methane) have been suggested by Hedberg (1974), Barker (1987a), and Spencer (1987) as a direct mechanism for generation of supernormal pressures in sedimentary rocks. Biogenic gas is generated in immature source rocks at low temperatures by anaerobic microorganisms primarily in the upper few hundred meters of a sedimentary column (Rice and Claypool, 1981). Thermochemical gases, on the other hand, are generated from thermal alteration or cracking of kerogen, petroleum or bitumin in mature and overmature hydrocarbon source rocks generally at depths below 500 m (Hedberg, 1974).

Barker and Pollock (1984) studied the geochemistry and origin of natural gases in southern Ontario and concluded that the gases were produced thermochemically from thermally mature to overmature sources. The apparent absence of biogenic gas in the Paleozoic rocks of southern Ontario is consistent with the age of the sedimentary rocks and the belief that biogenic gas production occurs relatively soon after sediment deposition (Rice and Claypool, 1981).

Although all of the supernormally pressured argillaceous formations reviewed in this paper are located in proximity to hydrocarbon source beds or have sufficient organic matter to be considered as hydrocarbon source beds, they are only thermally immature to marginally mature (Legall et al., 1981) and therefore likely have not been subject to sufficient temperature to allow thermochemical gas generation. This suggests that either low temperature (20-40°C) thermochemical gas generation occurs today or that gas has migrated from deeper in the Michigan and Appalachian Basins or upward from deeper crustal rocks (Barker and Pollock, 1984). Although the geochemical data is inconclusive with respect to the superiority of these two hypothesis, the fact that the formations have been subject to low temperatures for millions of years argues against ongoing low-temperature thermochemical gas generation as the organic substrate for such gas generation would have been consumed millions of years ago. Consequently, it is unlikely that the observed supernormal pressures can be explained by ongoing gas generation in the Paleozoic argillaceous rock surveyed in this study.

## Gas Migration

Upward migration of hydrocarbon gases (mostly methane) is recognized as a significant process in hydrocarbon migration and accumulation in sedimentary rocks

(Stahl, 1981; Tissot, 1987). Such migration has been postulated to occur along geologic structures in southwestern Ontario based on remote sensing of areas of vegetation kill (Morris, 1990) and has recently been observed in western New York State along a major structural discontinuity in the Paleozoic strata known as the Clarendon-Linden Fault (Jacobi, 1990). The Clarendon-Linden gas seep is particularly interesting as it appears to be thermochemical gas released to the surface from fractured argillaceous Devonian rocks at a depth 300 m by the Sagenuay earthquake of 1988.

Migration of gas as a separate phase upward from a source rock through a sedimentary column can theoretically result in increases in fluid pressure in argillaceous rocks if low permeability traps exist to contain the gas and if the gas migration and accumulation rates are greater than the rate of pressure dissipation by groundwater flow. These conditions can exist in the sedimentary sequences because of the very low hydraulic conductivity of the argillaceous rocks measured in the monitoring wells and the enhanced mobility of gas relative to water in sedimentary rocks due to the significantly lower viscosity of gas ($\approx$ 0.01 mPa·s) compared to water ($\approx$ 1 mPa·s). Furthermore, supernormal pressure generation during upward fluid migration would be enhanced because upward migration of separate phase gas in an incompressible fluid column results in fluid pressure increases (Steigemeir and Mathews, 1958) and methane solubility decreases as one moves upward in a typical sedimentary sequence (Barker, 1987b).

Because gas is associated with zones of supernormal pressure in argillaceous rock and such gas is unlikely generated within the argillaceous rocks, gas accumulation and migration from deeper distant sources appears the most logical explanation for the observed supernormal fluid pressures. Such large-scale fluid migration has also recently been suggested by Frape et al. (1989) to explain the chemistry and isotopic composition of the groundwater in the sedimentary rocks of southern Ontario. In addition, the observed occurrence of gas and supernormal pressure in narrow high-permeability horizons in otherwise low-permeability formations indicates that, on at least a local scale, the supernormally pressured zones are intervals of gas transmission and accumulation.

## IMPLICATIONS

The occurrence of supernormal fluid pressures in argillaceous formations of low permeability has implications for regional groundwater flow in sedimentary rocks and related activities such as waste disposal where knowledge of groundwater flow systems are necessary in evaluating the consequences of dissolved contaminant migration. In southern Ontario and western New York State, argillaceous sedimentary rocks underlay or act as potential barriers to contaminant migration at many waste disposal operations. For example, in Lambton County near Sarnia, Ontario, drinking water supply aquifers are separated from past and present deep well disposal operations by Devonian shales of the Hamilton Group. In the area of Niagara Falls, New York many of the known industrial waste disposal sites with contamination in the permeable Lockport Group dolomite are underlain by Silurian shales of the Clinton Group (Koszalka et al., 1985). Sedimentary rocks of low permeability in southern Ontario are also being considered as host rocks or as an overlying geologic barrier for deep disposal of high-level radioactive wastes (Heystee et al., 1990). Such formations may in future also be the focus of disposal operations for hazardous industrial wastes as well as low-level and intermediate-level radioactive wastes.

The existence of supernormal pressures as described in this study implies low hydraulic conductivity of the formation ($\leq 10^{-12}$ m/s) and that the formation acts as an effective vertical hydraulic barrier to groundwater circulation on a regional scale. Consequently, the low permeability strata containing or trapping the observed supernormal pressures (e.g., Rochester shale, Hamilton Group shale, and the Trenton-Black River Group shaley limestone) are likely long-term regional barriers to vertical groundwater circulation. In particular, these strata may not contain pervasive vertical faults or fractures that are open to groundwater and gas migration.

The occurrence of supernormal pressures and a separate gas phase in the sedimentary rocks surveyed in this paper has important implications regarding assessments of waste disposal activities within or beneath sedimentary rock sequences. Appropriate conceptual models for evaluating dissolved contaminant transport in such sedimentary sequences would include advective transport in the permeable normally-pressured strata and possibly diffusion across the low permeability supernormally-pressured strata. Assessments must also consider separate gas phase transport and the interactions between the water and gas phases. Because gas transport will be driven by buoyancy and controlled by the orientation of overlying strata of low permeability and the pore structure of the rocks, the directions and rates of gas and water transport will rarely be the same. In the context of radioactive waste disposal, transport of gaseous-phase radionuclides (e.g., $^{14}C$, $^{3}H$ (tritium)) would have to be considered.

If gas migration and accumulation from deeper distant sources are responsible for the observed supernormal pressures, then gas migration is indeed a significant process in the sedimentary rocks of southern Ontario and western New York State. To maintain a continous overpressure the rate of gas migration must be large over a regional scale and the cap rocks must be very tight. In the context of the available monitoring wells, such gas migration may occur in the permeable sections of the Clinton and Cataract Groups near Niagara Falls, in the Dundee Formation and Detroit River Groups near Sarnia and in the lower Ordovician and Cambrian Formations as well as the deeper basement rocks on the north shore of Lake Ontario.

## CONCLUSIONS

Formation fluid pressures significantly greater than hydrostatic have recently been measured in Paleozoic rocks of low permeability in southern Ontario and western New York State. These supernormal fluid pressures have been measured with straddle packers and monitoring casing having multiple-packers at depths of 50-310 m. The supernormally pressured zones are associated with gas producing intervals within otherwise low-permeability argillaceous rocks of Ordovician, Silurian and Devonian age. The occurrence of such supernormal pressures indicates that the enclosing formations are of very low hydraulic conductivity and likely act as an effective vertical barrier to groundwater circulation on a regional scale.

Regional groundwater flow, formation fluid density, sediment loading, uplift and erosion, thermal effects, mineral diagenesis, osmosis and gas generation are not plausible explanations for the measured supernormal pressures in the sedimentary rocks of southern Ontario and western New York state. Tectonic compression due to glaciation or regional stress changes, is a potentially significant mechanism at a local scale, however detailed quantitative assessment of the contribution to supernormal fluid pressures is not currently possible. The most reasonable explanation for the observed supernormal pressures is the migration and accumulation of gas generated from deeper distant sources in the Michigan and Appalachian Basins or underlying basement rocks. The occurrence of gas with all major zones of supernormal pressure in this study is compelling evidence to support this hypothesis. Additional research on the genesis of these gases would assist in resolving the cause of the observed supernormal pressures and improve our understanding of the nature of liquid and gaseous fluid migration in sedimentary rocks.

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FIGURE CAPTIONS

Figure 1 Geology and location of monitoring wells

Figure 2 Paleozoic stratigraphy of southern Ontario and western New York State (after Hewitt and Freeman, 1972)

Figure 3 Schematic of multiple-packer monitoring well and downhole pressure measurement equipment.

Figure 4 Measured formation fluid pressure versus depth. Lines A, B, and C are hydrostratic pressure lines for fluid densities of 1000, 1100 and 1200 $kg/m^3$ respectively.

Figure 5 Calculated dynamic formation fluid pressure versus depth. Lines A, B, and C are as in Figure 4.

Figure 6 Stratigraphy, hydraulic conductivity, and dynamic fluid pressure for monitoring well UN-2, Bomanville, Ontario

Figure 7 Stratigraphy, hydraulic conductivity, and dynamic fluid pressure for monitoring well OHD-1, Mississauga, Ontario

Figure 8 Stratigraphy, hydraulic conductivity, and dynamic fluid pressure for monitoring well MDMW-1, Sarnia, Ontario

Figure 9 Stratigraphy, hydraulic conductivity, and dynamic fluid pressure for monitoring well NI-1 Navy Island, Niagara Falls, Ontario

Figure 10 Stratigraphy, hydraulic conductivity, and dynamic fluid pressure for monitoring well USNI-1, Town of Niagara, New York

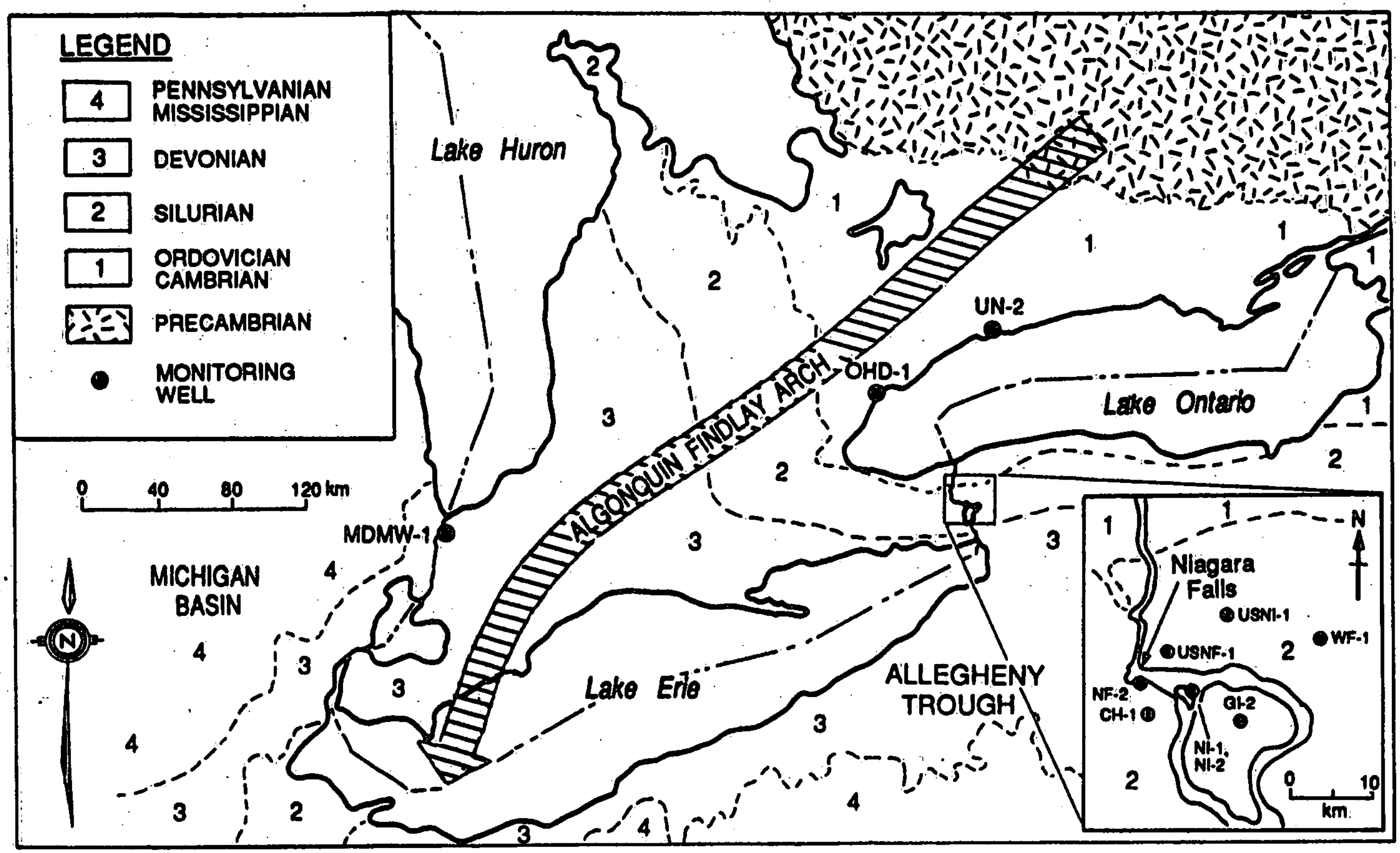

LEGEND
4 PENNSYLVANIAN MISSISSIPPIAN
3 DEVONIAN
2 SILURIAN
1 ORDOVICIAN CAMBRIAN
PRECAMBRIAN
MONITORING WELL
0 40 80 120 km
MICHIGAN BASIN
Lake Huron
Lake Erie
Lake Ontario
ALGONQUIN FINDLAY ARCH
ALLEGHENY TROUGH
MDMW-1
OHD-1
UN-2
Niagara Falls
USNI-1
USNF-1
WF-1
NF-2
CH-1
GI-2
NI-1, NI-2
N
0 10 km

Fig. 1

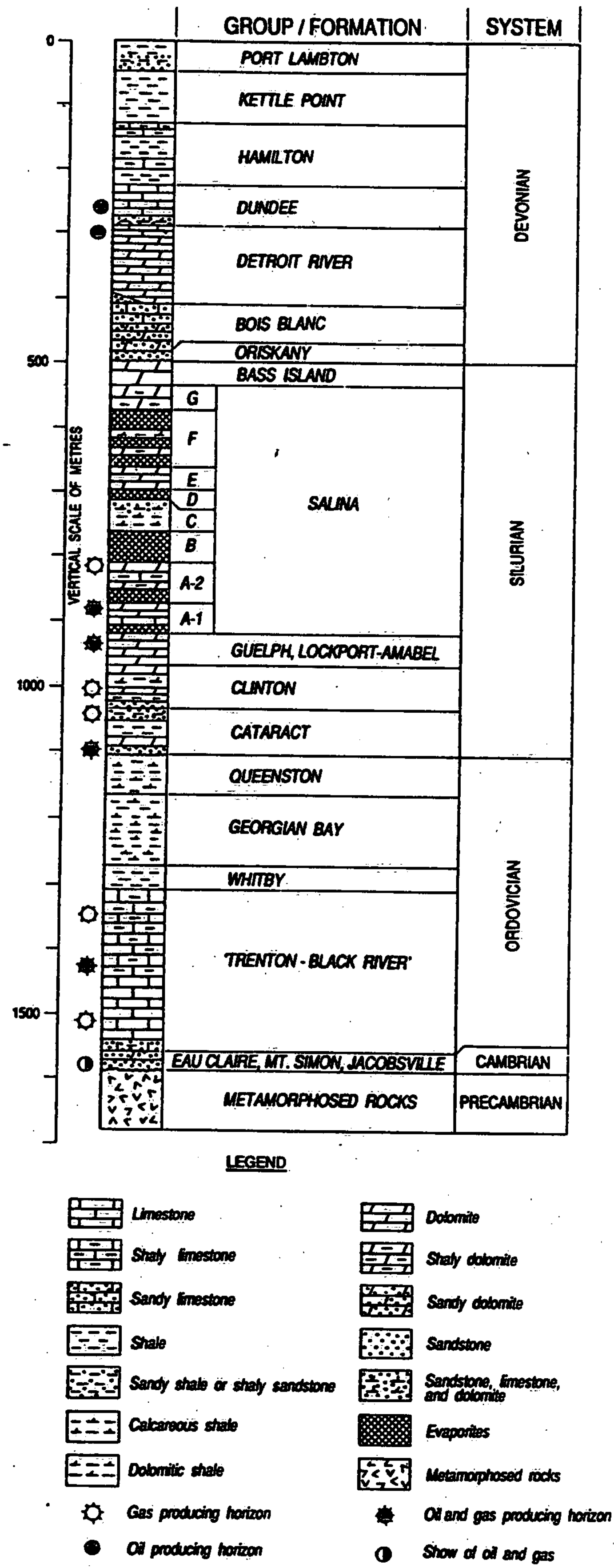

GROUP / FORMATION
SYSTEM
0
500
1000
1500
VERTICAL SCALE OF METRES
PORT LAMBTON
KETTLE POINT
HAMILTON
DUNDEE
DETROIT RIVER
BOIS BLANC
ORISKANY
BASS ISLAND
DEVONIAN
G
F
E
D
C
B
A-2
A-1
SALINA
GUELPH, LOCKPORT-AMABEL
CLINTON
CATARACT
SILURIAN
QUEENSTON
GEORGIAN BAY
WHITBY
'TRENTON - BLACK RIVER'
ORDOVICIAN
EAU CLAIRE, MT. SIMON, JACOBSVILLE
CAMBRIAN
METAMORPHOSED ROCKS
PRECAMBRIAN
LEGEND
Limestone
Shaly limestone
Sandy limestone
Shale
Sandy shale or shaly sandstone
Calcareous shale
Dolomitic shale
Dolomite
Shaly dolomite
Sandy dolomite
Sandstone
Sandstone, limestone, and dolomite
Evaporites
Metamorphosed rocks
Gas producing horizon
Oil producing horizon
Oil and gas producing horizon
Show of oil and gas

Fig - 2

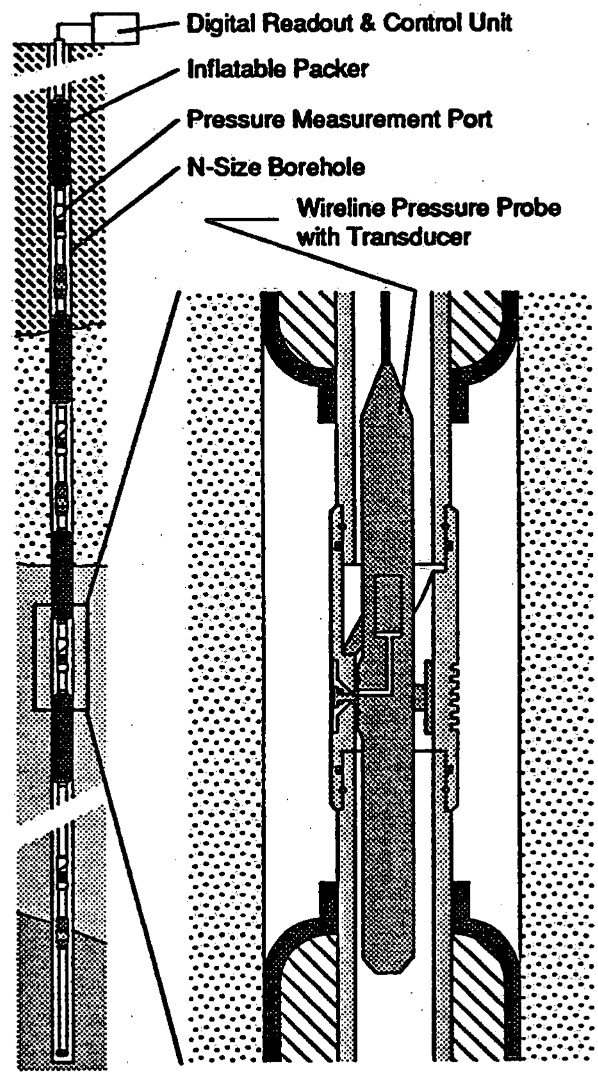

Digital Readout & Control Unit
Inflatable Packer
Pressure Measurement Port
N-Size Borehole
Wireline Pressure Probe
with Transducer

Fig. 3

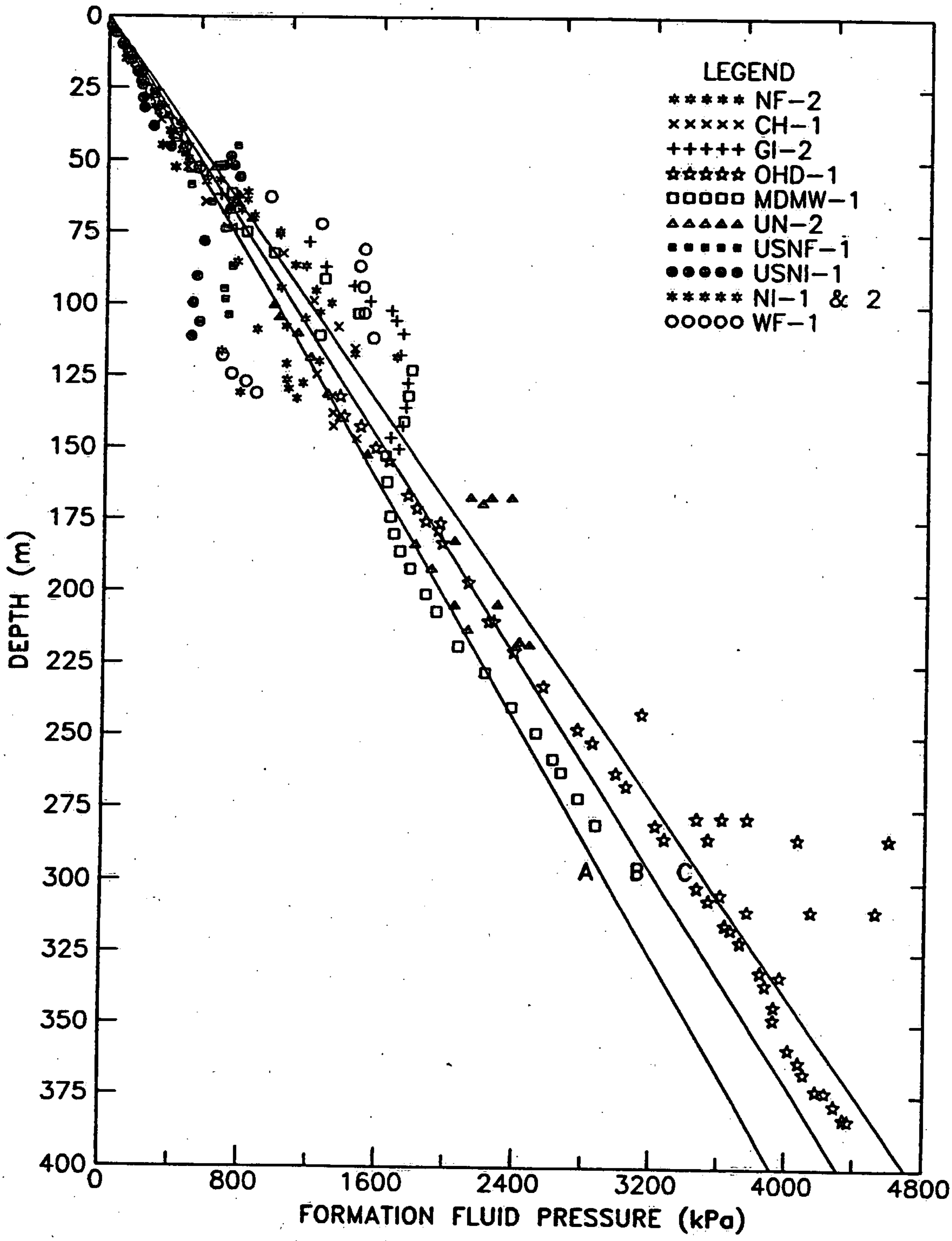
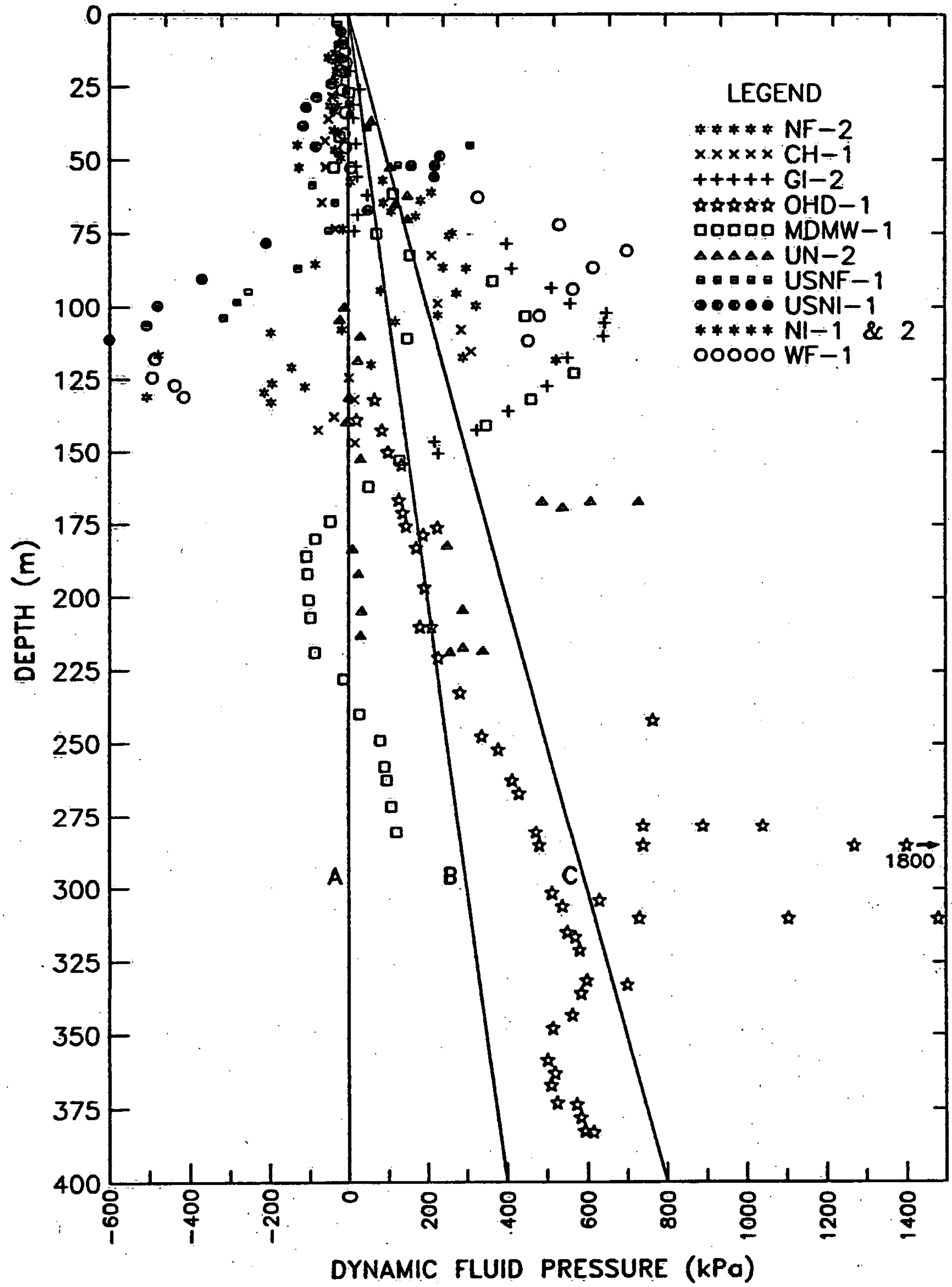

LEGEND
NF-2
CH-1
GI-2
OHD-1
MDMW-1
UN-2
USNF-1
USNI-1
NI-1 & 2
WF-1
DEPTH (m)
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
FORMATION FLUID PRESSURE (kPa)
0
800
1600
2400
3200
4000
4800
A
B
C

Fig. 4



LEGEND
NF-2
CH-1
GI-2
OHD-1
MDMW-1
UN-2
USNF-1
USNI-1
NI-1 & 2
WF-1
A
B
C
1800
DEPTH (m)
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
-600
-400
-200
0
200
400
600
800
1000
1200
1400
DYNAMIC FLUID PRESSURE (kPa)


Fig. 5

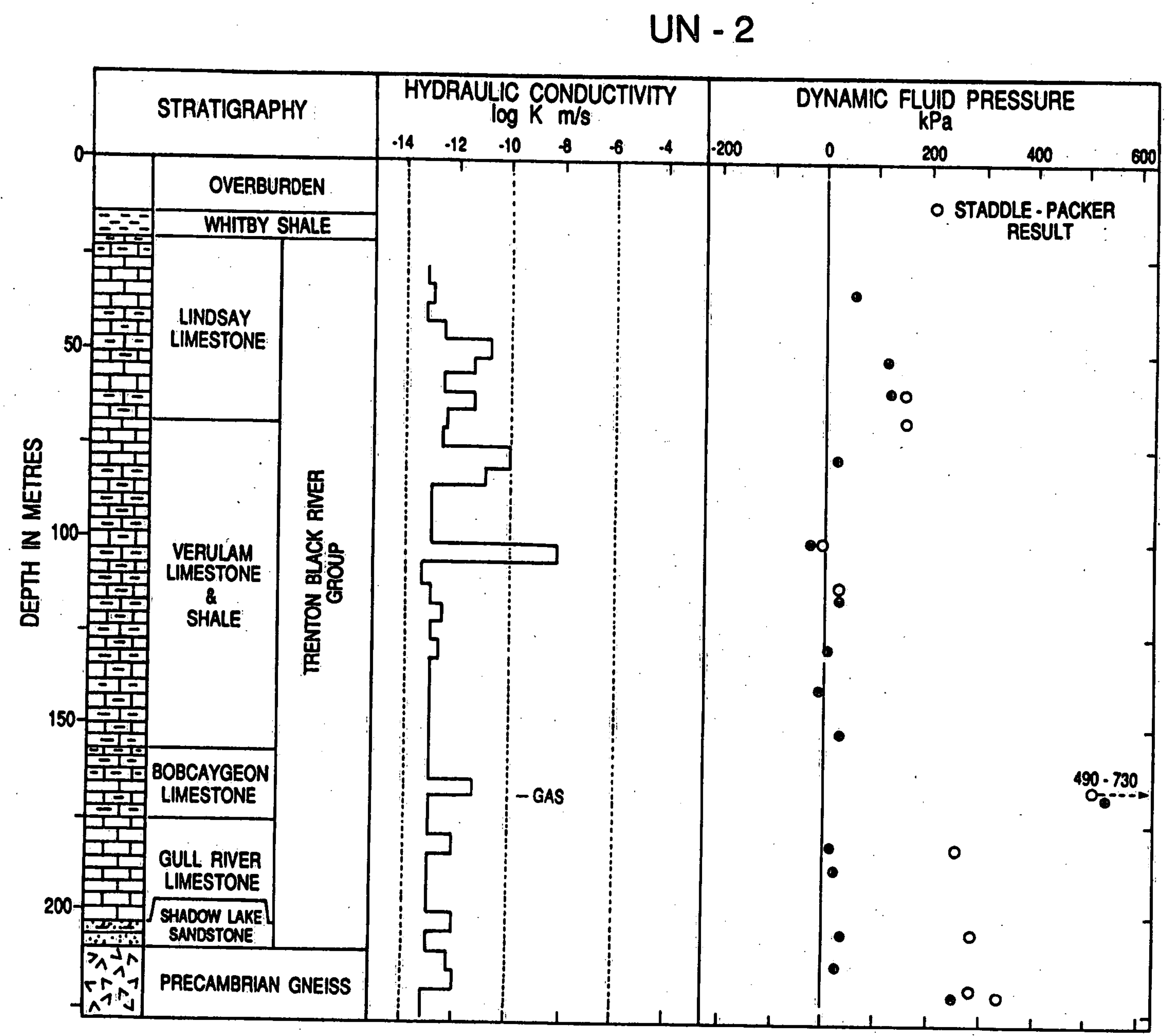

UN - 2
STRATIGRAPHY
HYDRAULIC CONDUCTIVITY
log K m/s
DYNAMIC FLUID PRESSURE
kPa
-14
-12
-10
-8
-6
-4
-200
0
200
400
600
0
50
100
150
200
DEPTH IN METRES
OVERBURDEN
WHITBY SHALE
LINDSAY LIMESTONE
VERULAM LIMESTONE & SHALE
BOBCAYGEON LIMESTONE
GULL RIVER LIMESTONE
SHADOW LAKE SANDSTONE
PRECAMBRIAN GNEISS
TRENTON BLACK RIVER GROUP
— GAS
o STADDLE - PACKER RESULT
490 - 730

Fig. 6

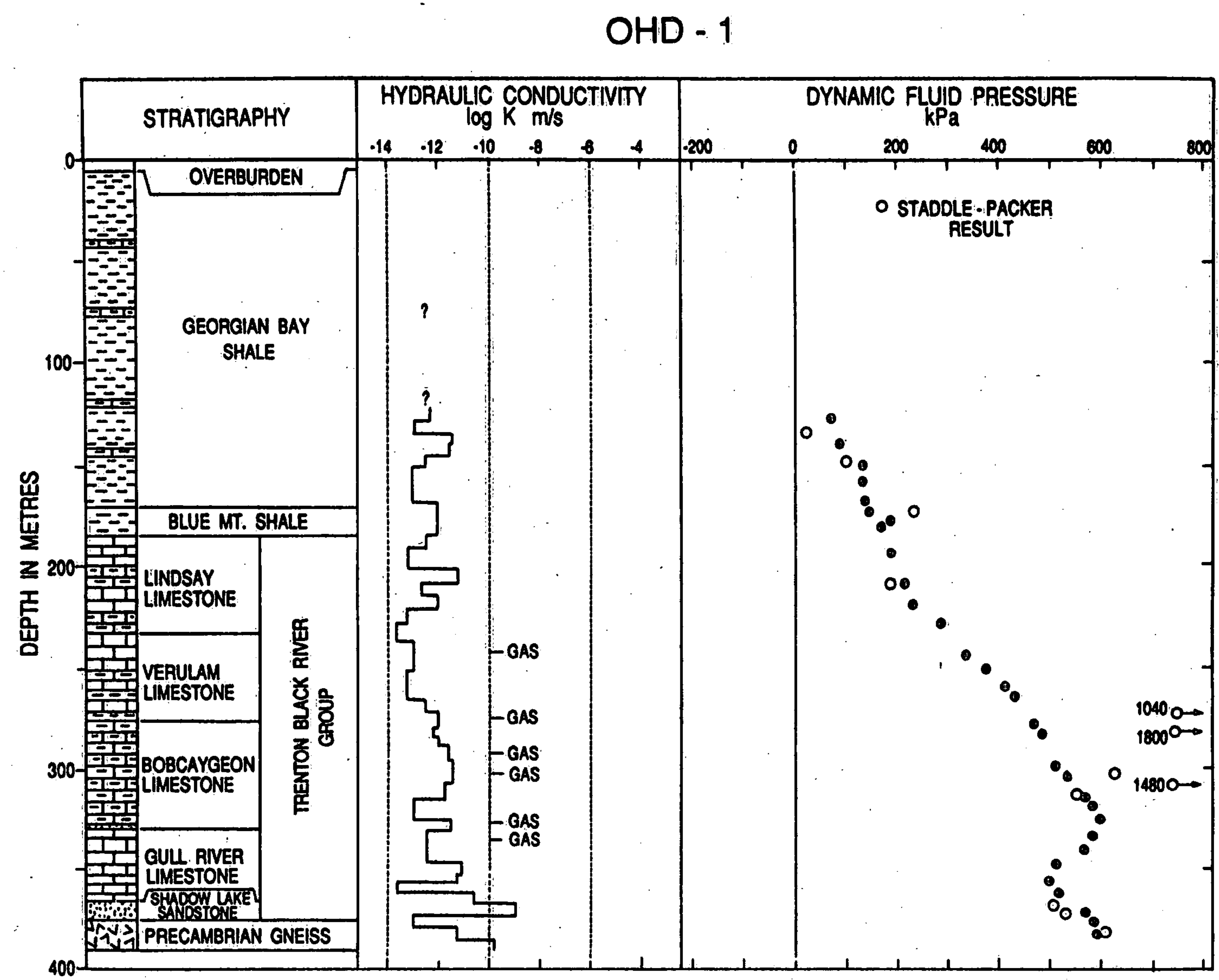
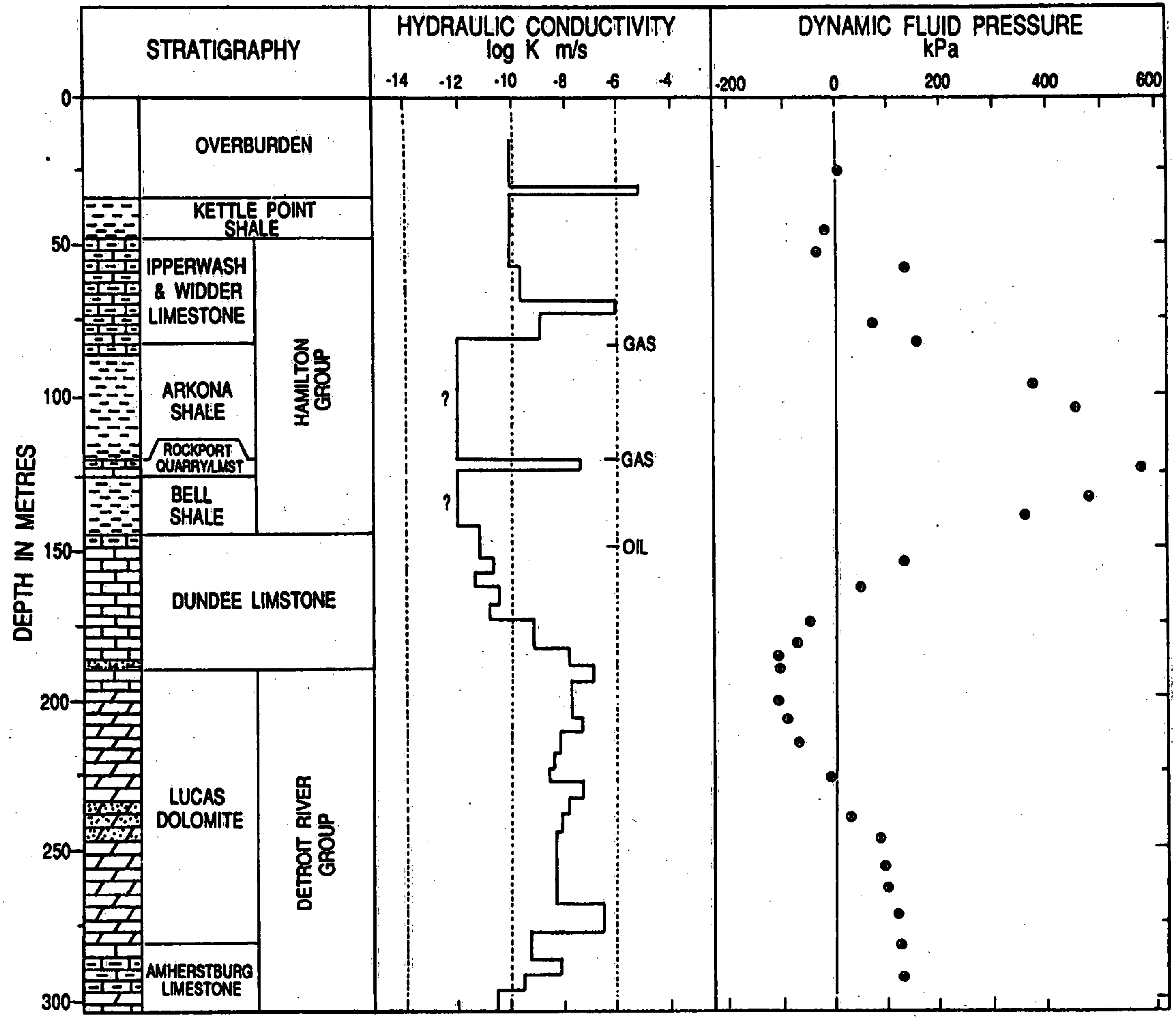

OHD - 1
STRATIGRAPHY
HYDRAULIC CONDUCTIVITY
log K m/s
-14 -12 -10 -8 -6 -4
DYNAMIC FLUID PRESSURE
kPa
-200 0 200 400 600 800
DEPTH IN METRES
0
100
200
300
400
OVERBURDEN
GEORGIAN BAY SHALE
BLUE MT. SHALE
LINDSAY LIMESTONE
VERULAM LIMESTONE
BOBCAYGEON LIMESTONE
GULL RIVER LIMESTONE
SHADOW LAKE SANDSTONE
PRECAMBRIAN GNEISS
TRENTON BLACK RIVER GROUP
?
?
GAS
GAS
GAS
GAS
GAS
GAS
STADDLE - PACKER RESULT
1040
1800
1480

Fig. 7

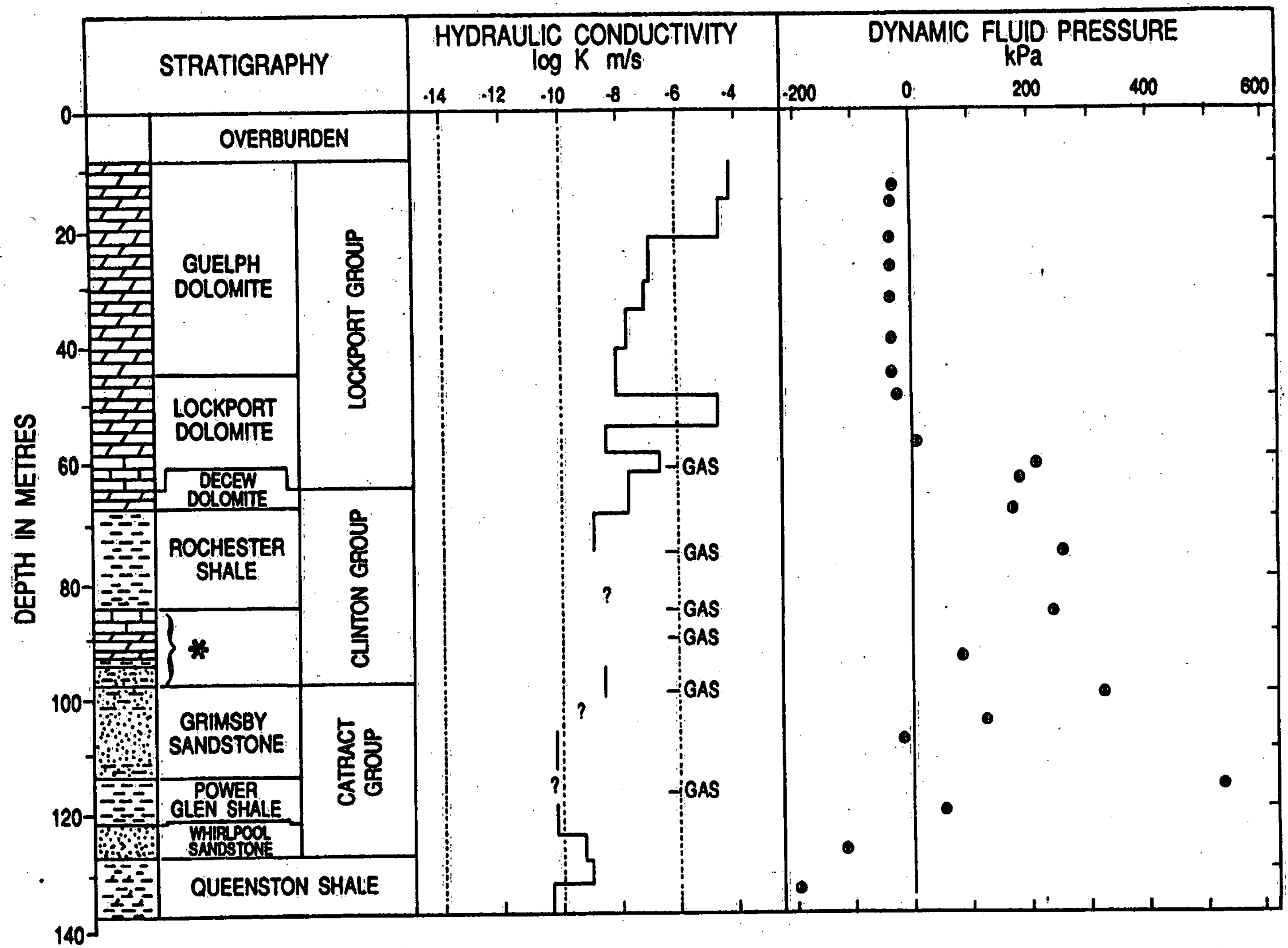
MDMW - 1



STRATIGRAPHY
HYDRAULIC CONDUCTIVITY
log K m/s
DYNAMIC FLUID PRESSURE
kPa
-14
-12
-10
-8
-6
-4
-200
0
200
400
600
DEPTH IN METRES
0
50
100
150
200
250
300
OVERBURDEN
KETTLE POINT SHALE
IPPERWASH & WIDDER LIMESTONE
ARKONA SHALE
ROCKPORT QUARRY/LMST
BELL SHALE
HAMILTON GROUP
DUNDEE LIMSTONE
LUCAS DOLOMITE
AMHERSTBURG LIMESTONE
DETROIT RIVER GROUP
GAS
GAS
OIL
?
?

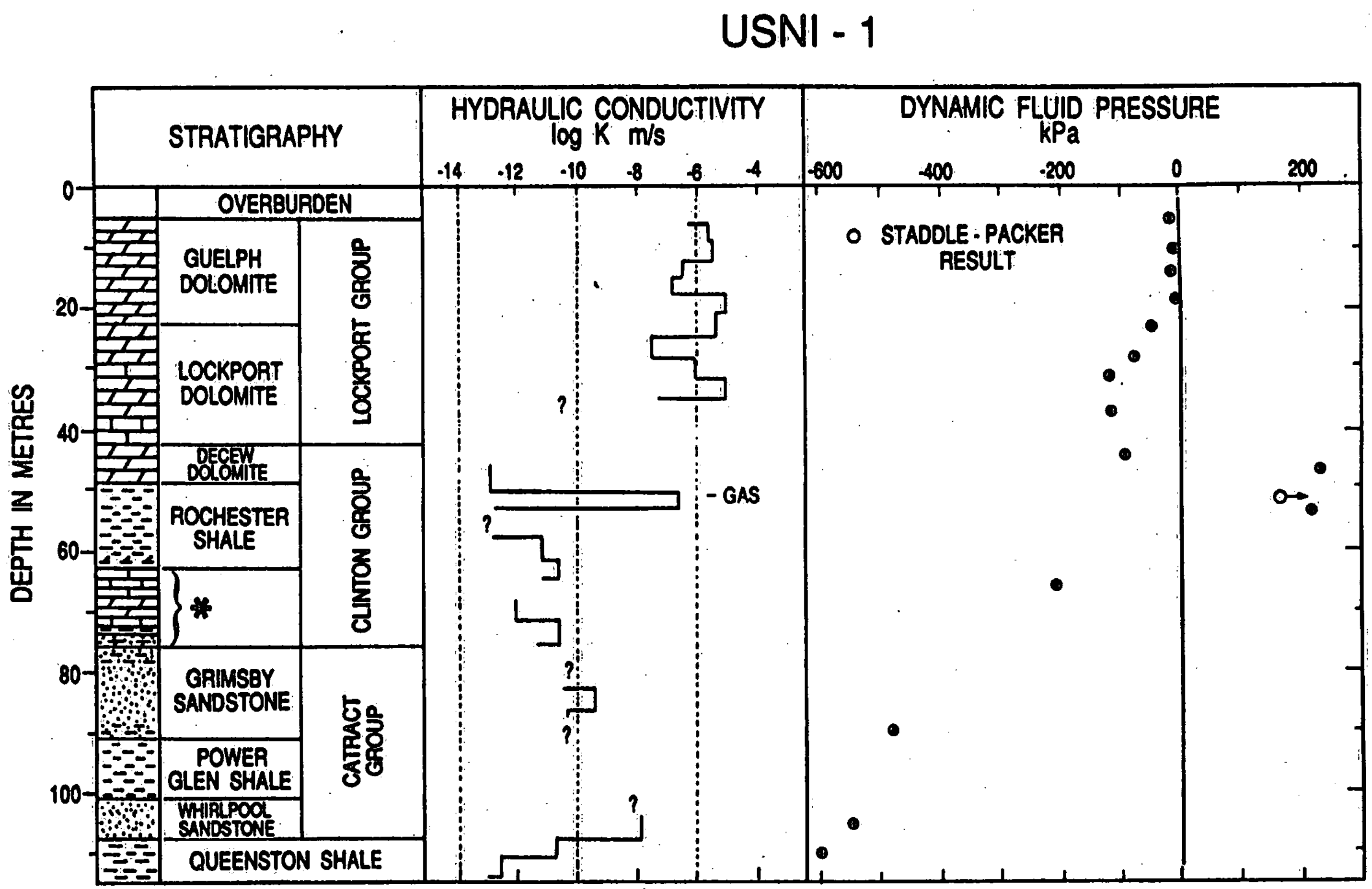

Fig. 8

NI - 1




* IN DESCENDING ORDER: IRONDEQUOIT LIMESTONE, REYNALES DOLOMITE, NEAHGA SHALE, THOROLD SANDSTONE

Fig. 9




* IN DESCENDING ORDER: IRONDEQUOIT LIMESTONE, REYNALES DOLOMITE, NEAHGA SHALE, THOROLD SANDSTONE

Fig. 10

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