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Application of fracture-flow hydrogeology to acid-mine drainage at the Bunker Hill Mine, Kellogg, Idaho

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Abstract

The mechanics of groundwater flow through fractured rock has become an object of major research interest during recent years. This project has investigated the flow of groundwater through fractured Precambrian metaquartzite rocks in a portion of the Bunker Hill Mine near Kellogg, Idaho. Groundwater flow through these types of rocks is largely dependent upon the properties of fractures such as faults, joints and relict bedding planes. Groundwater that flows into the mine via the fractures is acidic and is contaminated by heavy metals, which results in a severe acid mine drainage problem. A more complete understanding of how the fractures influence the groundwater flow system is a prerequisite of the evaluation of reclamation alternatives to reduce acid drainage from the mine.

Fracture mapping techniques were used to obtain detailed information on the fracture properties observed in the New East Reed drift of the Bunker Hill Mine. The information obtained includes fracture type, orientation, trace length, the number of visible terminations, roughness, waviness, infilling material, and a qualitative measure of the amount of water flowing through each fracture. The hydrogeologic field data collected include routine measurements of the discharge from four individual structural features and four areas where large quantities of water are discharging from vertical rock bolts, the depths to water in three piezometer nests at the ground surface, the pressure variations in four diamond drillholes, and constant discharge flow tests conducted on three of the diamond drillholes.

The field data indicate that relict bedding planes are the primary conduits for groundwater flow, and suggest that the two major joint sets that are present connect water flowing through the discontinuous bedding planes. The three minor joint sets that are present do not seem to have a significant impact on groundwater flow, but along with the two major joint sets may store relatively large quantities of water. It appears that rock-bolt holes in the central portion of the drift primarily intersect relict bedding planes, whereas rock-bolt holes in the southeastern portion of the drift primarily intersect joints; this probably is related to the shallower angle of dip of the bedding planes in the central portion of the drift. It also appears that recharge from the surface directly above the mined-out openings is the primary source of water in the upper workings of the mine, and that the large seasonal head variations in the potentiometric surface are primarily responsible for the observed temporal variations in mine inflow. Infilling material

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may control the hydrogeologic character of the faults, with those filled with gouge having low hydraulic conductivities and those filled with breccia having relatively high hydraulic conductivities. In addition, one of the faults may act as a positive (constant head–recharge) hydrogeologic boundary. A double-porosity approach probably is the most appropriate for simulating the groundwater flow system in the vicinity of the New East Reed drift. Finally, grouting of a combination of breccia-filled faults and relict bedding planes may offer the best hope for minimizing mine-water inflow or recharge.

1. Introduction

Fracture-flow hydrology has received increased attention in recent years as a result of environmental concerns over potential groundwater contamination associated with hazardous and radioactive waste disposal (Hancox and Whitaker, 1986; Lever and Woodwark, 1990). Much of the research directed towards characterizing advective transport of contaminants through fractured rock has focused on developing more sophisticated methods of manipulating assumed values for the input parameters to various types of mathematical models (Nuclear Energy Agency, 1990; Stephenson et al., 1990; Ababou, 1991; Barnard and Dockery, 1991; Shepard et al., 1991). Funding agencies only recently have been willing to support field studies designed to improve and test models that describe flow and transport of contaminants through heterogeneous materials (Brotzen, 1986; Steele et al., 1989; Rasmussen et al., 1990; Erikson, 1991; Abelin et al., 1991a,b). Therefore, the applicability of many of these models to realistic problems is somewhat suspect (Barnard and Dockery, 1991).

In contrast, this research has been directed toward: (1) explaining the spatial and temporal distribution of groundwater flow through fractured rocks in a portion of the Bunker Hill Mine on the basis of a set of various types of hydrogeologic field data, many of which were collected underground; (2) making a qualitative assessment of the applicability of several approaches for simulating groundwater flow through fractured rocks to the hydrogeologic system at the mine; (3) evaluating possible alternatives for restricting the production of acid mine-water in these rocks.

The Bunker Hill Mine is a large underground lead–zinc mine located in the Coeur d'Alene Mining District of north Idaho (Fig. 1). The mine was opened in 1885 and operated nearly continuously until 1981, when it was shut down for economic reasons. It was operated on an inactive but maintained status from October 1981 until September 1988. Pumps, hoists, ventilation fans and other major pieces of equipment continued to operate and be serviced to keep the mine open. Consequently, access to much of the mine was excellent during this 7 year period. In September 1988 part of the mine was reopened to allow a limited amount of zinc to be produced. The Bunker Hill Mine was closed permanently in 1991.

The status of the US National Pollutant Discharge Elimination System (NPDES) permit for the Bunker Hill Mine requires lime, aeration, settle and filter treatment of an average mine discharge of approximately 100 l s^{-1} of water with a pH of 2.8 and a

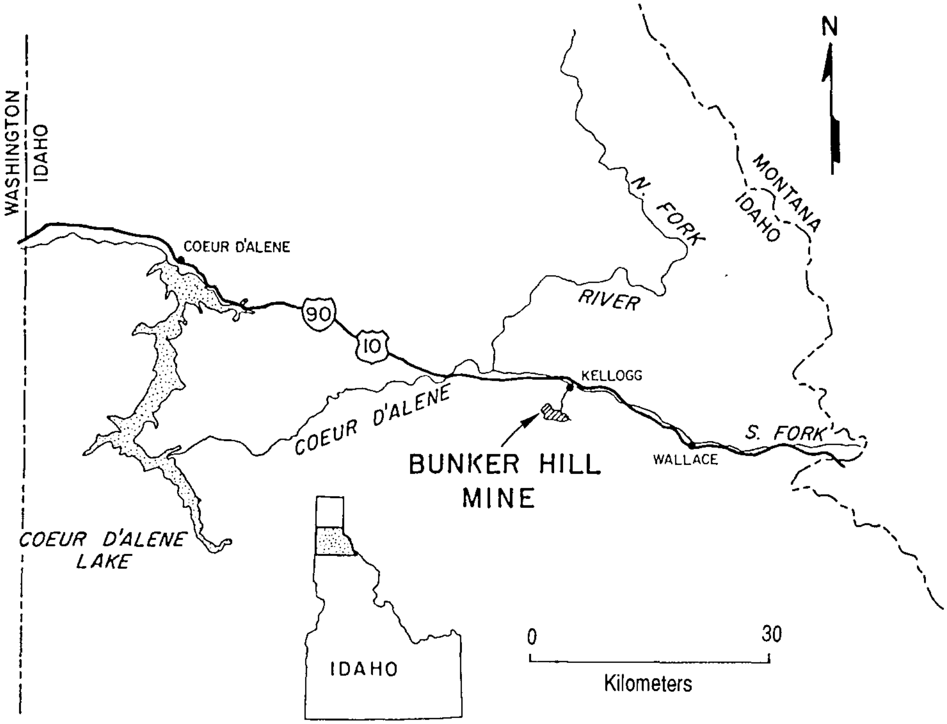


Fig. 1. Location map of the Bunker Hill Mine (Eckwright, 1982).

zinc concentration of about 120 mg l^{-1}. This government requirement obviously is not a long-term solution to the problem. A more complete understanding of the control of fractures on the groundwater flow system is a prerequisite of the evaluation of reclamation alternatives to reduce acid drainage from the mine, thereby reducing treatment costs.

The area of the Bunker Hill Mine selected for emphasis in this project was the New East Reed drift, which is located in the southeastern portion of the five-level workings in the upper portion of the mine (Fig. 2). The New East Reed drift was selected for detailed study for several reasons, including its accessibility, its isolation from other workings, its location between two major fault zones, the freshness of rock surfaces, the existence of shut-in exploratory diamond drillholes for hydraulic testing, its proximity to Milo Creek, a possible source of significant recharge, and its proximity to the Flood–Stanly ore body, which has been shown to be a major acid-producing area of the mine.

Survey information on the elevation of the New East Reed drift is not available; however, the elevation of the portal of the Reed Tunnel is approximately 940 m above sea-level. The New East Reed is slightly higher than the portal because water entering the drift leaves the mine at the portal. The five-level workings are shown at an elevation of 945 m on mine maps. The elevation of the land surface above the New East Reed varies from about 1065 m at the NW end of the drift to 1220 m at the SE

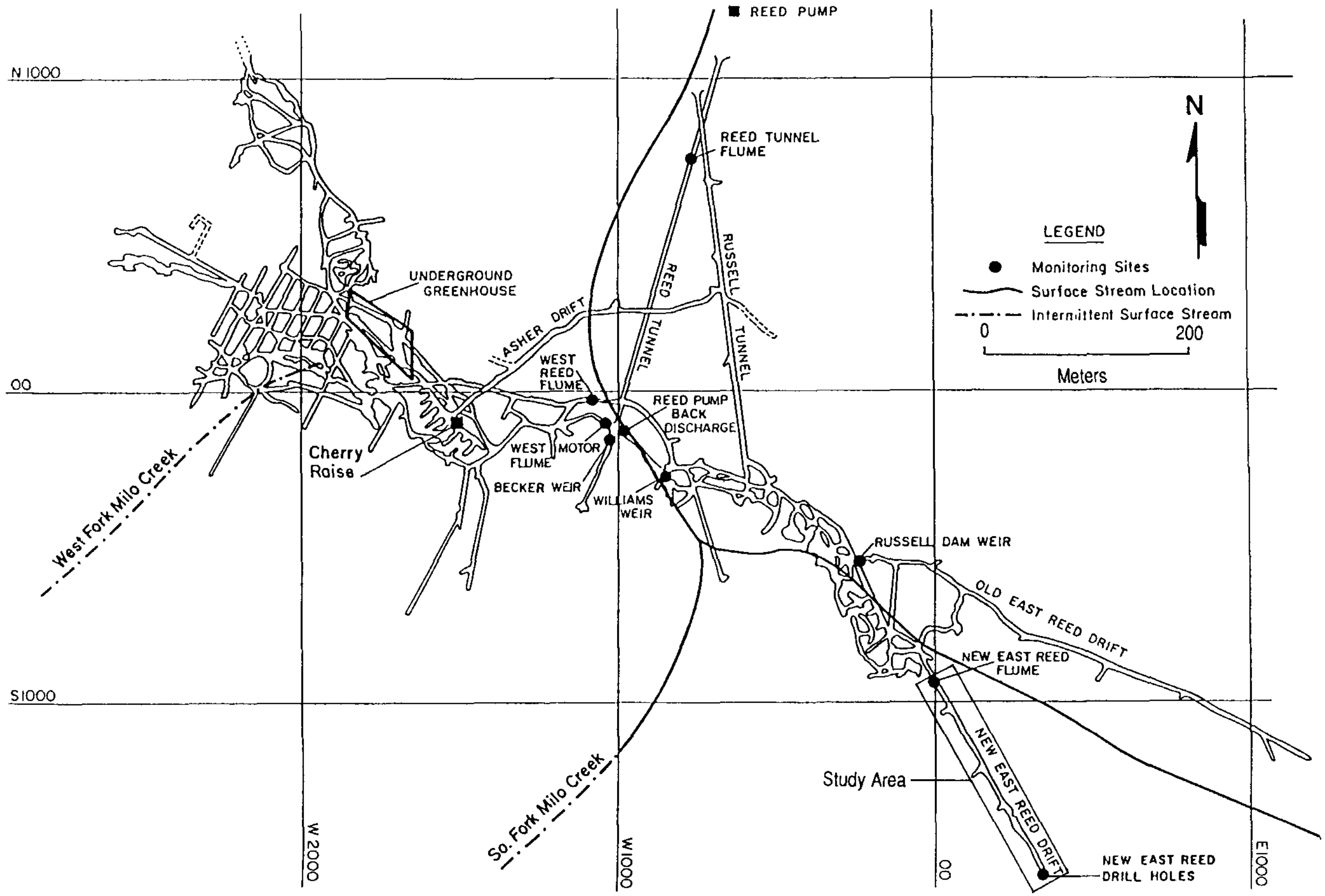


Fig. 2. Level 5, Bunker Hill Mine (Erikson, 1985).

end. Thus, the New East Reed is roughly 120 m below the ground surface at its NW end and about 275 m below the surface at its SE end.

2. Geology

The geology of the Bunker Hill Mine and surrounding area is characterized by a thick sequence of Precambrian quartzites, siltites and argillites (Ransome and Calkins, 1908). These rocks have been assigned to the Revett and St. Regis Formations of the Ravalli Group of the Belt Supergroup (Hobbs et al., 1965). The vast majority of the rocks in the vicinity of the mine have been placed in the Revett Formation (White, 1976, 1982; Winston, 1977), which is composed predominantly of quartzite with some sericitic quartzite and siltite–argillite.

Most of the Bunker Hill Mine is in a steeply dipping, overturned, isoclinal anticline trending WNW. The two main periods of large-scale folding have produced older folds trending NNW, and younger folds along WNW trends. The locations of the older NNW folds in the vicinity of the mine can be determined from the plunge directions of the folds trending WNW (Juras, 1982).

The most important fault in the immediate vicinity of the mine is the Cate Fault (see Fig. 9 below). The mine has been developed roughly along the Cate because the main ore bodies have been emplaced along this fault. The Cate is a sinuous shear zone that strikes roughly NW and dips about 45° SW. Several other faults are associated with the Cate in the Bunker Hill region, including the Dull, Kruger, Sullivan, Buckeye, Katherine and Marblehead Faults. Together these faults form a braided system that separates the country rock into large irregularly shaped blocks.

3. Hydrology

Most of the Bunker Hill Mine is dry. The vast majority of the groundwater flowing into the mine enters in a few relatively small locations. Recharge to the Bunker Hill is believed to occur primarily from snowmelt in the Milo Creek drainage basin, which overlies the SE portion of the mine. From a comparison of hydrographs of flows within the mine with those of local streams, Trexler (1975) concluded that surface recharge to the mine from snowmelt in the spring is the main source of water; however, he was unable to identify the areas where this recharge occurs. Hunt (1984) identified a number of sites where direct infiltration into the mine occurs, including mine workings directly underlying Milo Creek, intersections between Milo Creek and major fracture zones (primarily the Cate Fault), and the Guy Cave area, a relatively large stope near the ground surface where block caving was performed.

The quartzites that form the bulk of the Bunker Hill Mine have relatively low matrix porosities and matrix hydraulic conductivities. Consequently, the flow of groundwater into the mine from the ground surface, where recharge occurs, is prob-

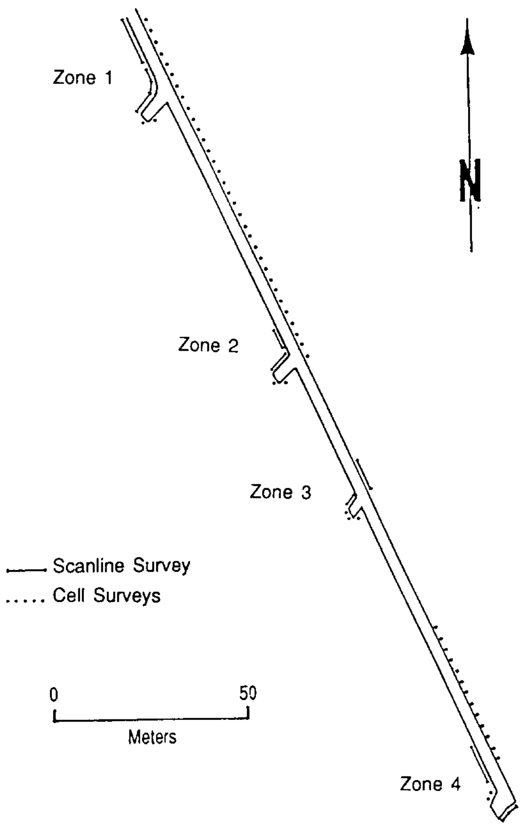


Fig. 3. Mapping locations and delineation of zones in the New East Reed drift (Haskell, 1987).

ably controlled by bedding planes and by the fractures produced by repeated episodes of deformation.

An analysis of hydrographs collected from selected areas within the internal drainage network of the mine, when correlated with information from mine maps and geologic records, suggests that flow in the groundwater system surrounding the mine is controlled by a hierarchical distribution of hydraulic conductivity, with the greatest conductivity occurring near the Cate Fault and other NW-trending faults (Erikson, 1985). Relict bedding planes and joints are thought to have lower hydraulic conductivities, with the unfractured blocks of rock having the lowest conductivity of all.

4. Structural data

Detailed structural mapping was conducted in the New East Reed drift using two methods: scanline surveys and cell surveys (Fig. 3). A scanline survey is a method of spot-mapping a population of rock fractures (Halstead et al., 1968; Call et al., 1976),

Table 1
Proportions of water-bearing fractures of the major fracture sets (Haskell, 1987)

Zone	Fracture set	Proportion of water-bearing fractures
2	Bedding	0.51
	Joint A	0.16
	Joint B	0.12
3	Bedding	0.38
	Joint A	0.09
	Joint B	0.04
4	Bedding	0.80
	Joint A	0.11
	Joint B	0.21

in which a measuring tape is stretched horizontally along the drift wall and each fracture greater than 15 cm in length that crosses a band of 30 cm width (15 cm above and 15 cm below the tape) is mapped. The information obtained includes rock type (quartzite or sericitic quartzite), fracture type (joints, faults or relict bedding planes), location of the fracture, its orientation, its trace length, the number of visible terminations, its roughness (small-scale asperities), its waviness (larger-scale undulations), the infilling material, and a qualitative measure of its flow rate (dry, wet, dripping or flowing, from lower to higher discharge). Fractures were classified as wet if water was visible but no flow could be discerned. Fractures that produced individual drops of water were classified as dripping, and fractures that produced a steady stream of water were classified as flowing.

A cell survey is an alternative structural mapping technique, in which a rock exposure is divided into 'cells' of arbitrary dimensions (Miller, 1984). Subparallel fractures within each cell are grouped into sets, and then the following information is collected for the longest member of each set: rock type; fracture type; orientation; minimum dip; trace length; number of terminations. In addition, the following data are recorded for each cell: number of fractures per set; cumulative spacing of each fracture set; number of dry, wet, dripping and flowing fractures in each set. Obviously, scanline surveys provide more detailed information on the structural characteristics of the rock, but are more time consuming than cell surveys.

The New East Reed drift has been separated into four zones, primarily on the basis of where good rock exposures could be found for scanlines, as much of the drift is obscured by artificial tunnel support or thick localized deposits of an iron oxide known as 'yellowboy'. These four zones are shown on Fig. 3. Zone 1 is similar structurally to Zone 2, but virtually no water enters Zone 1. The orientations of the relict bedding planes are significantly different in Zones 2, 3 and 4 (Haskell, 1987).

Two major and three minor joint sets were identified from an analysis of the structural data (Haskell, 1987). Within each zone except Zone 1, the proportion of relict bedding planes that are wet is significantly greater than the proportion of wet fractures in each of the two major joint sets (Table 1). This suggests that bedding planes are the primary conduits for groundwater flow through the fractured rock mass in the vicinity of the New East Reed. The bedding planes have the longest trace

Table 2
Infilling material for the major fracture sets and faults (Haskell, 1987)

Zone	Fracture	Total no. of observations	No. of observations					
			Clay	Sericite	Ore	No infilling	Breccia	Gouge
1	Bedding	20	0	0	0	20	–	–
	Joint A	68	8	6	0	54	–	–
	Joint B	26	0	0	0	26	–	–
	Faults	10	–	–	–	–	1	9
2	Bedding	3	0	2	0	1	–	–
	Joint A	35	4	1	0	30	–	–
	Joint B	22	1	0	0	21	–	–
	Faults	11	–	–	–	–	1	10
3	Bedding	23	0	0	0	23	–	–
	Joint A	22	2	0	2	18	–	–
	Joint B	15	0	0	0	15	–	–
	Faults	11	–	–	–	–	0	11
4	Bedding	17	6	0	0	11	–	–
	Joint A	38	2	0	2	34	–	–
	Joint B	37	0	0	2	35	–	–
	Faults	4	–	–	–	–	1	3

lengths, and are the smoothest and straightest of the three major fracture sets (Haskell, 1987), and it may well be these properties that make the bedding planes the most important fractures with respect to groundwater flow.

Table 2 shows that the vast majority (33 of 36) of the faults observed in the New East Reed are filled with gouge. A total of only three faults, one each in Zones 1, 2 and 4, were recorded as having brecciated fault zones. Two of the three breccia-filled faults are wet, but only eight of the 33 gouge-filled faults are wet.

5. Hydrologic data

Measurements were made of the total flow discharging from the New East Reed drift using a cutthroat flume. In addition, the flow entering the drift from four individual structural features (two bedding planes, one fault zone and one well-jointed area) and from four areas where large quantities of water are discharging from a large number of vertical rock bolts emplaced in the back (ceiling) of the drift for tunnel support. These measurements were obtained by suspending tarps beneath these features and measuring the time required to obtain a specific quantity of water. The locations, approximate sizes and orientations of the eight tarps are shown in Fig. 4. These measurements indicate that the tarps contribute only 7% of the flow leaving the drift.

The flow rate measurements obtained from the eight tarps indicate that the rock-bolt holes (tarps 1, 3, 6 and 8) contribute far more water than the individual structural

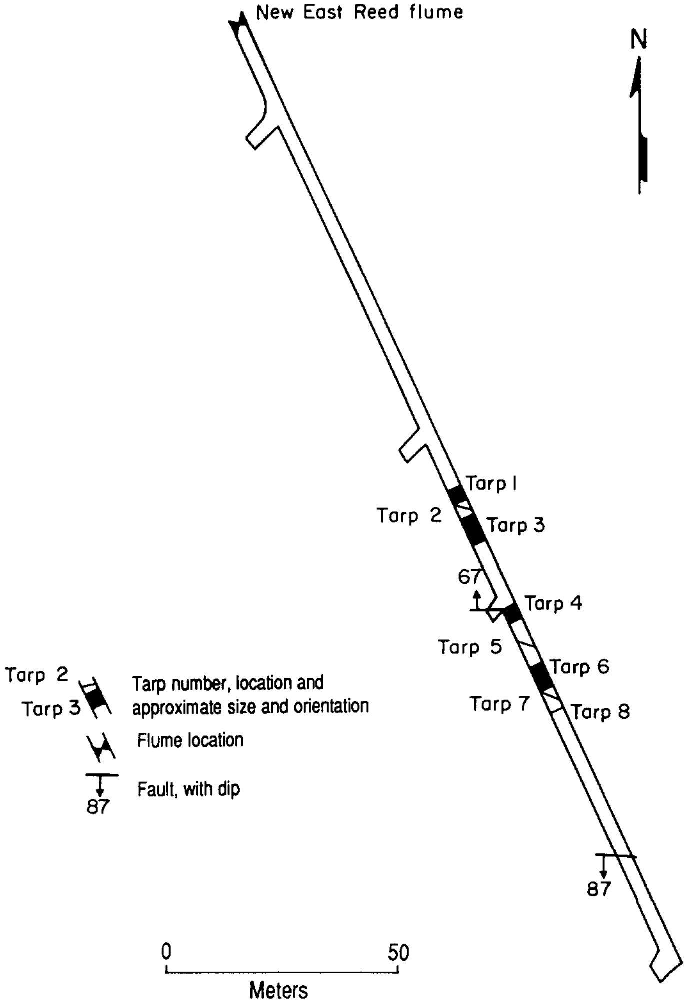


Fig. 4. Fault and flume locations, and locations and approximate sizes and orientations of tarps in the New East Reed drift.

features (Table 3), although not all of the bolt holes above each of these four tarps produce water. Because they are short (only about 1–1.5 m in length), they probably intersect and drain the fluid-filled joints and bedding planes as opposed to major fault zones. The joints and bedding planes are much more abundant and more closely spaced than the faults (Haskell, 1987). Although it could be argued that the rock-bolt holes may influence the locations of wet and dry areas, it is much more likely that the wet areas would be wet even if the bolt holes were not present because the holes are so short. Experience in mining suggests that the rock-bolt holes were needed because of the instability that commonly exists in water-producing portions of a mine. Of the structural features, relict bedding planes (tarps 2 and 7) contribute the

Table 3
Maximum, minimum and average flow rates of bolt holes and structural features in the New East Reed drift

Tarp no.	Feature	1985			1986		
		Maximum ($l\,day^{-1}$)	Minimum ($l\,day^{-1}$)	Average ($l\,day^{-1}$)	Maximum ($l\,day^{-1}$)	Minimum ($l\,day^{-1}$)	Average ($l\,day^{-1}$)
1	Bolts	4010	2420	3220	4430	2990	3710
2	Bedding	180	140	160	190	140	165
3	Bolts	7990	4730	6360	8020	4660	6340
4	Fault	5.4	3.8	4.6	5.0	4.2	4.6
5	Joints	35	29	32	36	30	33
6	Bolts	7120	5600	6360	7080	5750	6415
7	Bedding	210	160	185	190	140	165
8	Bolts	610	450	530	570	450	510

most water, the fault zone (tarp 4) contributes the least, and the well-jointed area (tarp 5) is intermediate between the bedding planes and the fault zone (Table 3).

The bedding plane hydrographs display steep rising and falling limbs and large seasonal variations in flow rate relative to the hydrographs for the well-jointed area and the fault zone, which show virtually no seasonal variations (Fig. 5). The shapes of the hydrographs for Tarps 1 and 3 are very similar to those for Tarps 2 and 7 (Fig. 5). This similarity suggests that rock-bolt holes primarily intersect bedding planes in the central portion of the drift. On the other hand, the rock-bolt holes in the SE portion of the drift appear to intersect joints predominantly, as indicated by the similarity in the shapes of the hydrographs for Tarps 5 and 8. This difference probably is a consequence of the shallower dip angle of the bedding planes in the central portion of the drift (Haskell, 1987).

Three piezometer nests were installed at the ground surface in the vicinity of the New East Reed drift (Fig. 6). The piezometer nests were located along South Milo Creek because of the inaccessibility to a drilling rig of the extremely rugged terrain along the east fork of Milo Creek above the confluence with the south fork. Two of the nests were completed with four piezometers and one with three. All of the piezometers in each nest were installed inside the steel surface casing (15 cm in diameter) that was driven during drilling to prevent the borehole from caving. The individual piezometers have been numbered, from shallowest to deepest, as follows: 1a, 1b and 1c for the upper South Milo Creek nest; 2a, 2b, 2c and 2d for the lower South Milo Creek nest; 3a, 3b, 3c and 3d for the Milo Creek Dam nest.

Piezometers 1a and 2d are dry, and the water levels in Piezometers 1b and 3d are near the bottoms of the screens and display virtually no fluctuations (Fig. 7). This probably indicates that these two piezometers are actually completed in the unsaturated zone; the water in them being left over from when they were drilled, as the boreholes were drilled with water as the drilling fluid and were full of water when the standpipes were installed. The water levels in these two piezometers then gradually declined until they reached the bottoms of the screens. Further decline of the water levels was prevented by the end caps placed on the bottoms of the screens to prevent

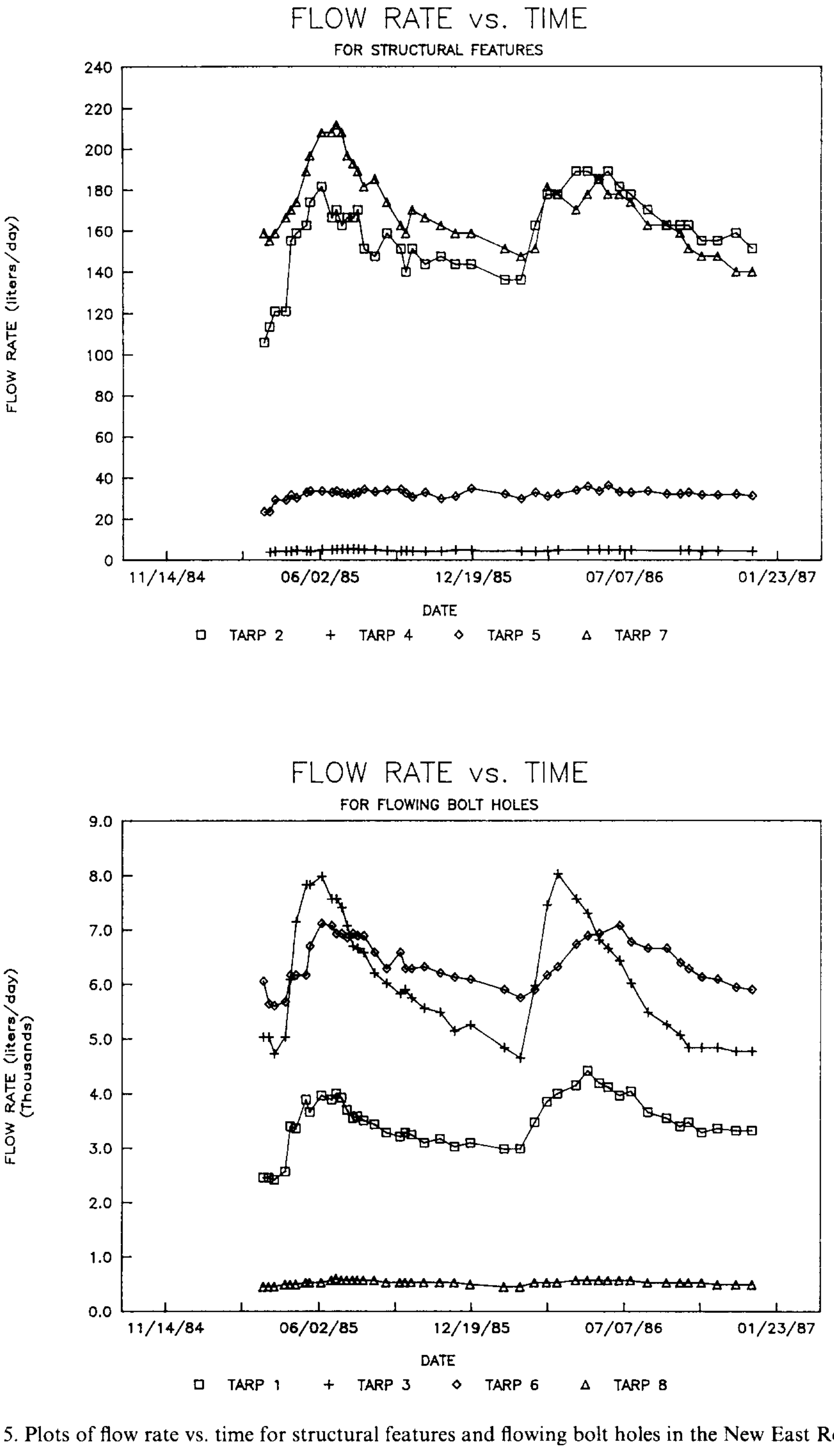


Fig. 5. Plots of flow rate vs. time for structural features and flowing bolt holes in the New East Reed drift.

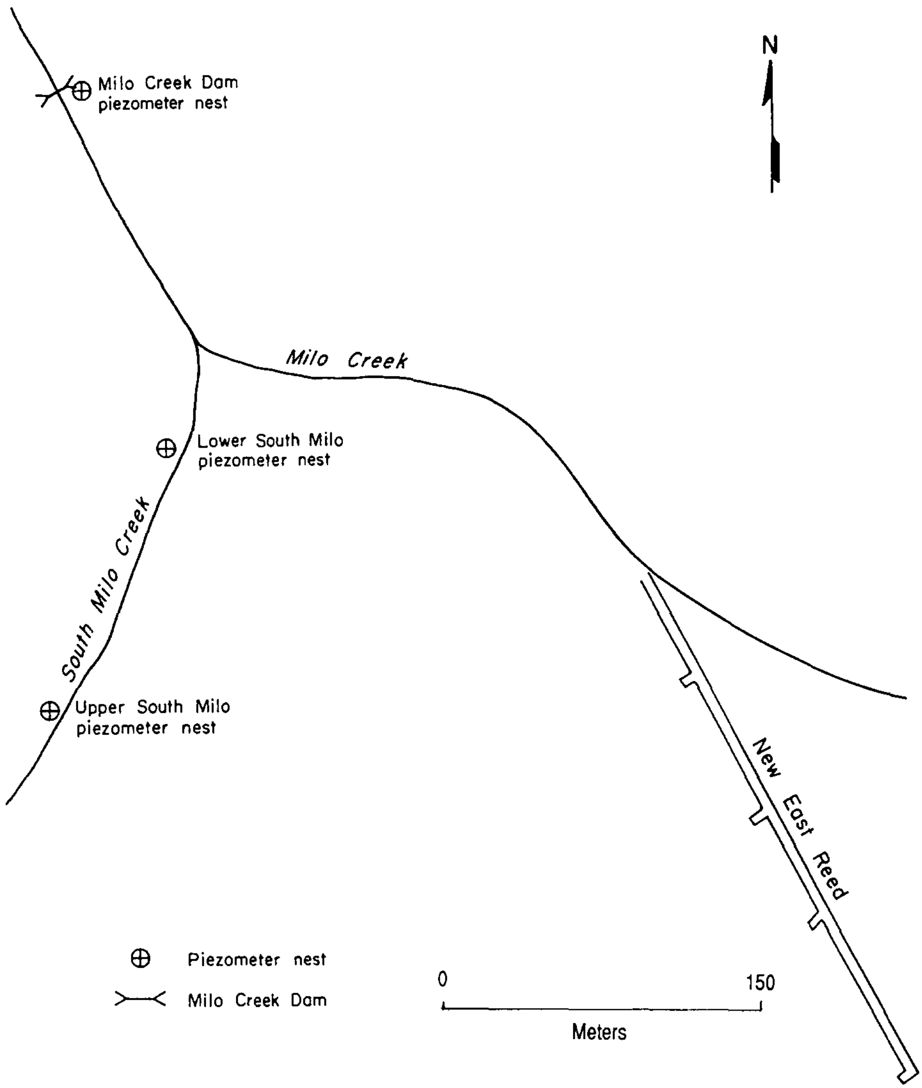


Fig. 6. Piezometer nest locations in the Milo Creek drainage.

the upward migration of geologic materials into the piezometers. Piezometers 3a, 3b and 3c have very similar water levels (Fig. 7), and have hydrographs that are not similar to those of the piezometers in the other two nests (Fig. 8). The water levels in these three piezometers probably reflect the water level in the small pond formed behind the dam. The water level of the pond is approximately 1001 m above sea-level. The hydrographs for Piezometers 1c, 2a, 2b and 2c are similar to those for the tarps suspended beneath the relict bedding planes (Fig. 5) and the four high-discharge diamond drillholes (Fig. 10).

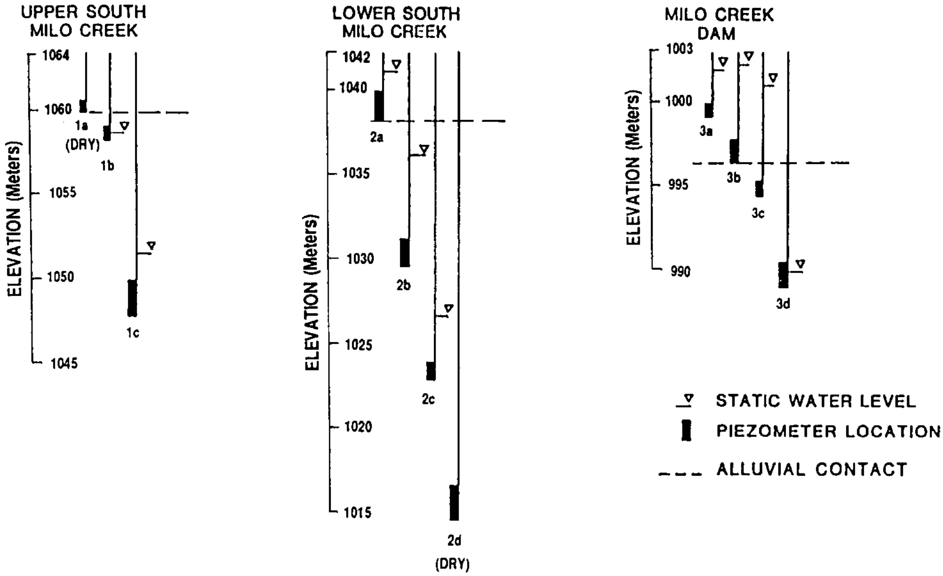


Fig. 7. Schematic diagram of piezometer nests and approximate fluid potential levels in Milo Creek drainage (Hunt, 1984).

Seven exploratory diamond drillholes are present in the New East Reed drift (Fig. 9). Five of these drillholes are shut in and discharge large quantities of water when they are opened up. The pressures in four of these five high-discharge drillholes were measured; the fifth one (DDH 2184) leaks around its collar. Sixty per cent of the flow discharging from the drift is from leakage around the collar of Drillhole DDH 2184. The hydrographs for the four securely shut-in drillholes (Fig. 10) are similar to those for the tarps suspended beneath the relict bedding planes (Fig. 5) in that they display steep rising and falling limbs, and large seasonal pressure variations. The lower pressures in the drillholes at the SE end of the drift probably reflect the influence of the leaking high-discharge drillhole.

Three successful constant discharge flow tests were performed, one on each of three of the high-discharge exploratory diamond drillholes (DDH 2147, DDH 2256 and DDH 2290). The durations of the three tests were 5581 min, 4322 min and 10 080 min for Drillholes DDH 2256, DDH 2290 and DDH2147, respectively. These tests were conducted during either the late spring–early summer or the late winter when the pressures had reached relatively constant maximum or minimum values. An industrial rate-control valve was installed on the drillhole being tested, and the pressures in the two observation drillholes were measured using pressure transducers and recorded on a battery-operated data logger. The rate-control valve maintains a constant discharge rate regardless of pressure fluctuations on either the upstream or downstream side of the valve.

Graphs of the decrease in pressure in each of the two observation drillholes with time during the constant discharge flow tests plotted on log–log paper reveal a flattening of the drawdown curve for Drillhole DDH 2290 during testing of DDH

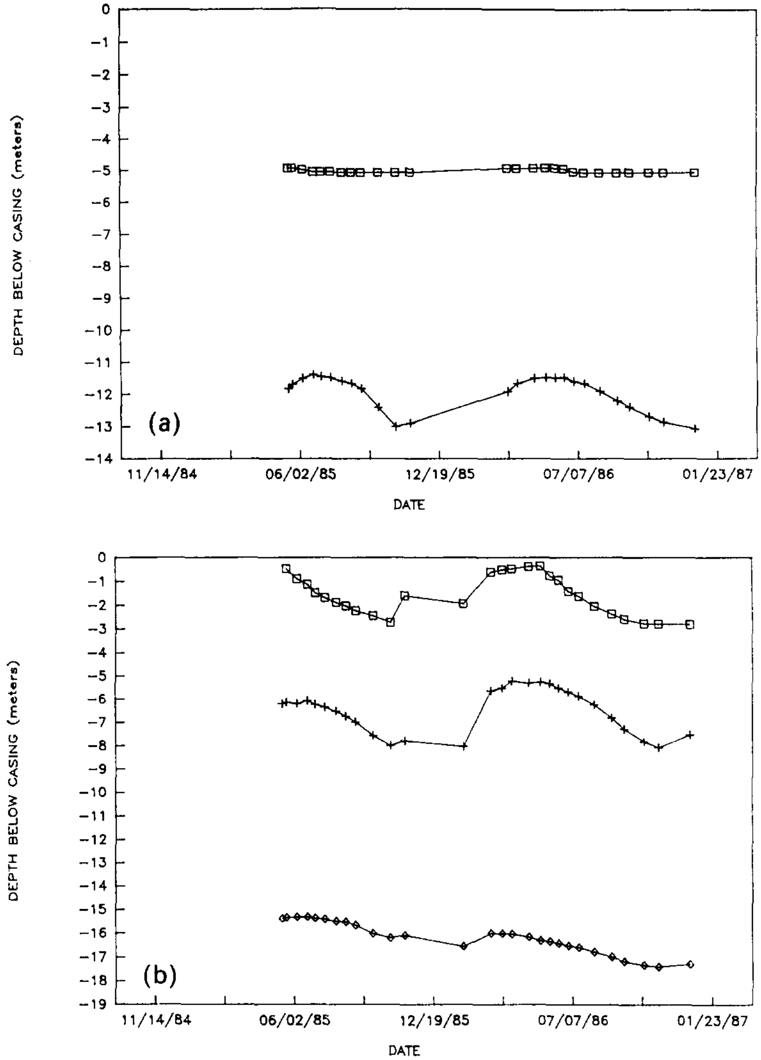


Fig. 8. Plots of water levels vs. time for piezometer nests. (a) Upper South Milo piezometer nest: □, Piezometer 1b; +, Piezometer 1c. (b) Lower South Milo piezometer nest: □, Piezometer 2a; +, Piezometer 2b; ◇, Piezometer 2c. (c) Milo Creek dam piezometer nest: □, Piezometer 3a; +, Piezometer 3b; ◇, Piezometer 3c; △, Piezometer 3d.

2256, but not of the curve for DDH 2256 during testing of DDH 2290 (Fig. 11). Furthermore, no drawdown was recorded in Drillhole DDH 2147 during testing of either DDH 2256 or DDH 2290, and only a slight decrease in the pressures in these two drillholes was recorded during testing of DDH 2147 despite the 10 080 min duration of the test. This behavior suggests that a positive (constant head–recharge) boundary exists between Drillholes DDH 2147 and DDH 2290. This boundary may be the fault that crosses the New East Reed about 30 m from the

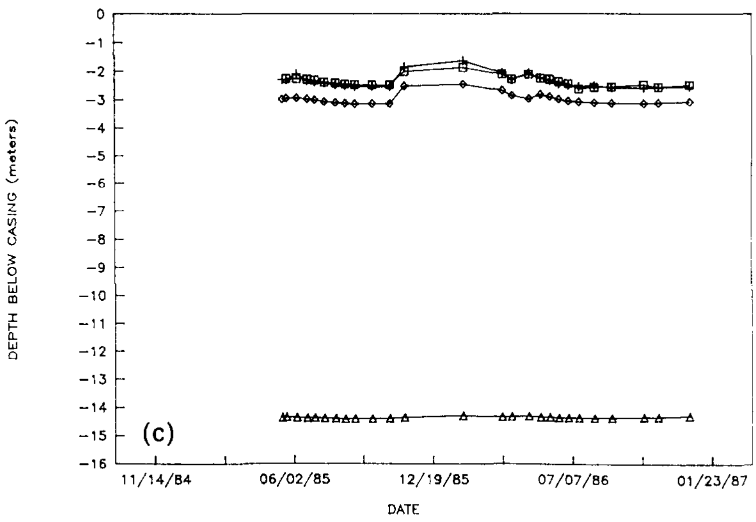


Fig. 8 (Continued).

SE end of the drift (see Fig. 4), which produces roughly 30% of the flow discharging from the drift. Furthermore, the discharge from the drift would be reduced by 60% if the leakage from DDH 2184 was eliminated, and this fault then would produce roughly three-quarters of the remaining flow discharging from the drift.

6. Data analysis

Much compelling evidence supports the hypothesis that relict bedding planes constitute the most important geologic features with regard to groundwater flow at this mine. This evidence includes the observation that the proportion of wet bedding planes is far greater than the proportion of major joints that are wet in the New East Reed drift (Table 1). In addition, the significantly greater flow rates measured from the two tarps suspended beneath bedding planes than from the two tarps suspended beneath a well-jointed area and a minor fault zone (Table 3) also suggest that the bedding planes are important conduits for groundwater flow in the undisturbed rock. Finally, the relatively steep recessional limbs of the bedding plane hydrographs (Fig. 5) indicate that the hydraulic diffusivity of the bedding planes is greater than the diffusivity of the well-jointed area or the fault zone.

The two major joint sets mapped in the New East Reed drift appear to be more important than the minor joint sets with regard to groundwater flow. The fracture mapping data show that the minor joints are less abundant and significantly shorter than the major joints, and that the minor joints are rarely wet (Haskell, 1987). The two major joint sets probably connect the groundwater flowing along the discontinuous bedding planes. However, the most important function of both the major and minor joint sets may be to store groundwater in the natural, undisturbed system, as by

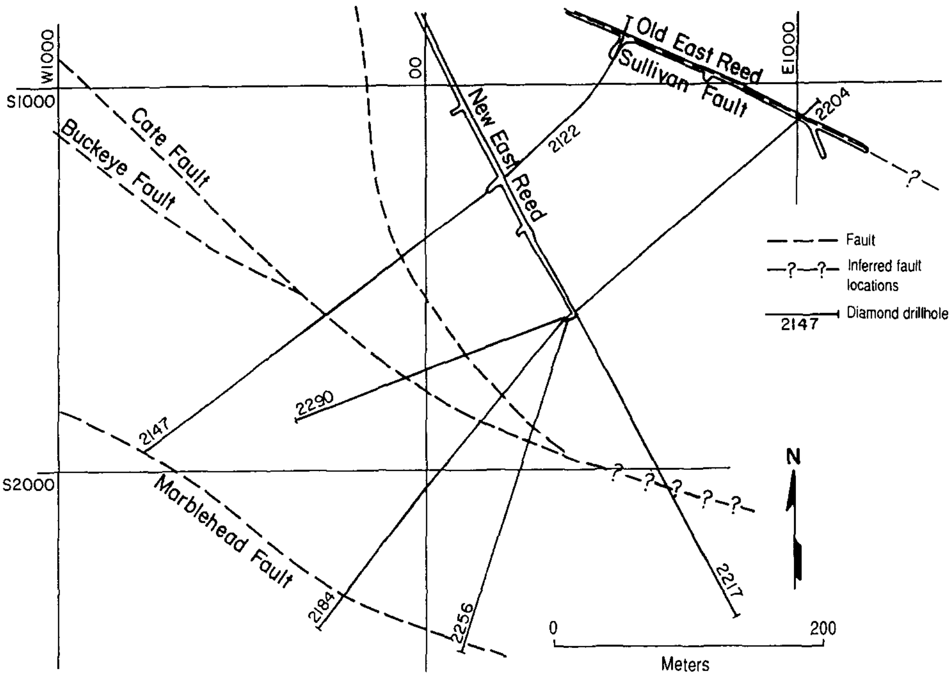


Fig. 9. Locations of diamond drillholes in the New East Reed drift (Erikson, 1985).

their relatively great abundance, they would be expected to have a higher storage capacity than the bedding planes.

The faults are the most difficult features to characterize hydrogeologically. It appears that some of the minor faults can act as major conduits for groundwater flow. The fault that crosses the New East Reed drift about 30 m from the SE end of the drift is the best documented example of a fault that acts as a water-producing structural feature. It is possible that this fault acts as a positive hydrogeologic boundary, as suggested by the drawdown data obtained during the constant discharge flow tests. However, the fault above Tarp 4 does not appear to be a significant hydrogeologic feature, as shown by the similarities in the flow rates (Table 3) and in the shapes of the hydrographs (Fig. 5) obtained from the bedding plane and rock-bolt hole tarps on either side of this fault.

The role that the Cate and other major faults play in the groundwater flow system at the Bunker Hill Mine is still unclear. That these major fault zones may act as groundwater flow barriers is supported by the observation that the majority of the faults in the New East Reed are filled with gouge (Table 2). In fact, the type of infilling material may dictate the hydrogeologic character of the faults, with those filled with gouge having low hydraulic conductivities and those filled with breccia having relatively high hydraulic conductivities. As the faults are the longest structural features mapped in the New East Reed, they may be the most important hydrologic

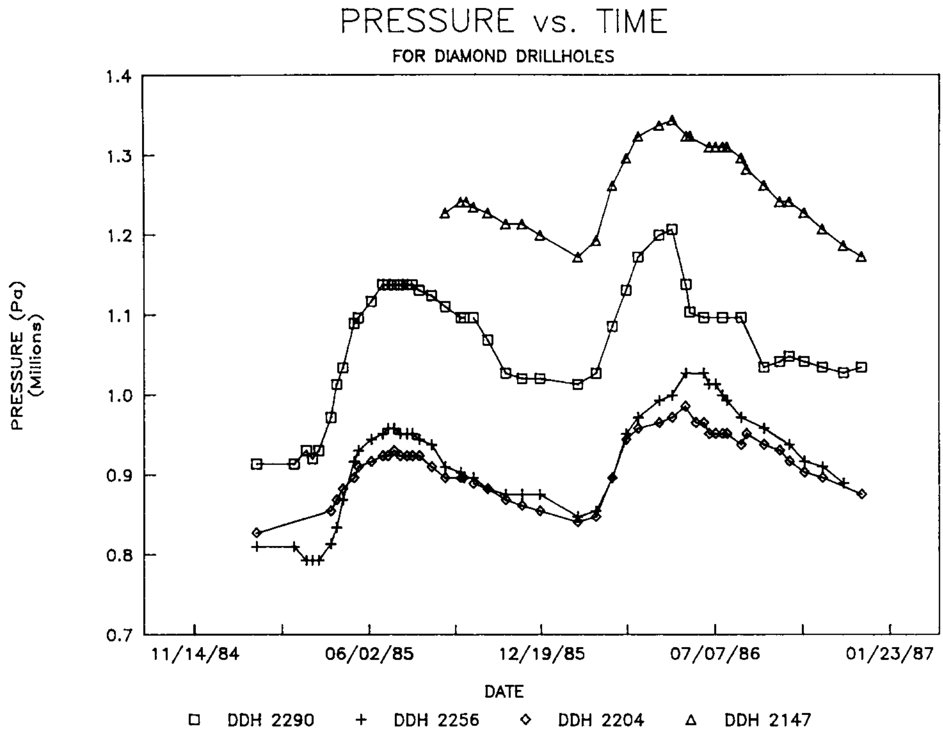


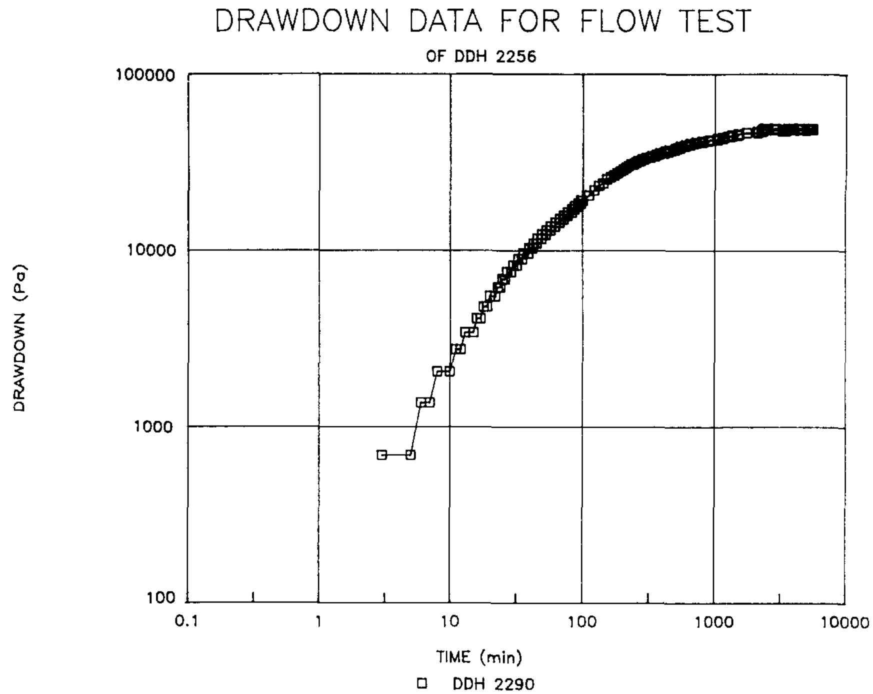
Fig. 10. Plot of pressure vs. time for diamond drillholes in the New East Reed drift.

features on a more regional scale, with most of them acting as barriers to groundwater flow.

7. Applicability of theoretical approaches for simulating groundwater flow through fractured rocks to the Bunker Hill Mine

The two mathematical methods of approaching fracture-flow hydrology that have evolved are those that employ deterministic techniques and those that employ probabilistic techniques. Deterministic models generally describe groundwater flow through the use of partial differential equations, which are usually solved based upon restrictive assumptions with respect to the hydraulic coefficients. For example, many models consider only uniform, homogeneous, isotropic media. However, the hydrologic properties of fractured rocks frequently exhibit a pronounced spatial variability, because fracture characteristics are rarely uniform. For this reason, many recent developments in fracture-flow theory have tended to regard the hydrogeologic properties of fractured rocks as random or regionalized variables. This approach has resulted in models that predict groundwater flow on the basis of stochastic or geostatistical procedures.

The four general approaches for simulating the flow of groundwater through



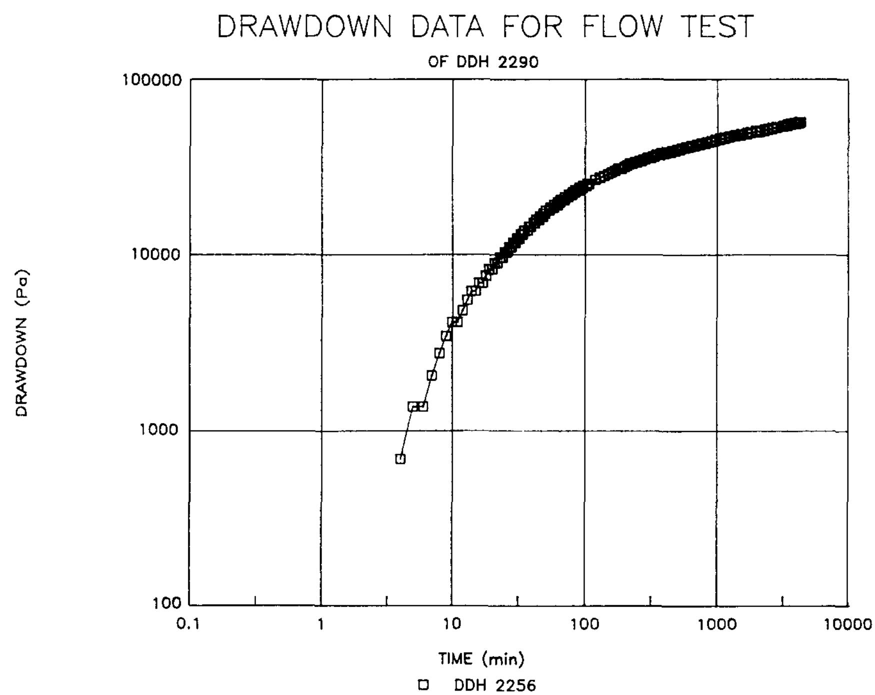


Fig. 11. Log–log plots of drawdown data for flow tests of diamond drillholes DDH 2256 and DDH 2290.

fractured rocks that have been developed thus far using the two techniques mentioned above are the discrete approach, the equivalent porous medium approach, the double-porosity approach, and various probabilistic approaches. The discrete approach to the flow of groundwater through fractured rocks examines groundwater flow through individual fractures, which is used to determine the flow velocity through the fracture network. The discrete approach may be either deterministic or probabilistic. Most of the deterministic models developed using this approach treat the fractures as smooth parallel plates. Such models also assume that groundwater flow through the fractures is Darcian; that is, steady, viscous and laminar. These assumptions lead to a solution of the Navier–Stokes equation known as the 'cubic law' (Hsieh et al., 1983). The cubic law states that the discharge rate (Q) per unit change in head (Δh) is proportional to the cube of the distance between the two parallel plates (b), or: $Q/\Delta h \propto b^3$.

The equivalent porous medium approach assumes that average values for the hydraulic properties of a fractured rock mass, such as porosity, hydraulic conductivity and specific storage, can be obtained if a volume of rock is selected that contains a sufficiently large number of fractures. This approach treats the unfractured blocks of rock as impermeable; thus fluid flow occurs only through the fractures. The representative elementary volume (REV) over which the average values can be applied is a function of the fracture geometry (orientation, spacing, aperture and roughness). The rock mass is assumed to be homogeneous at the scale of the REV, and therefore heterogeneities can be incorporated only at larger scales (Evans et al., 1983). This is one of the major limitations of the approach, because fractured rocks are heterogeneous by nature. A further limitation of the equivalent porous medium approach is that there is no well-defined method for estimating the equivalent porous medium properties from the fracture geometry. It is generally thought that a fractured rock behaves like an equivalent porous medium when fracture density is increased, apertures are constant, orientations are distributed rather than constant, and larger sample sizes are considered (Long et al., 1982).

The double-porosity approach utilizes two distinct sets of values for the hydraulic properties, one for the fractures and one for the blocks of unfractured rock. The fractures are characterized by high hydraulic conductivity and low specific storage, and the blocks of unfractured rock are characterized by low hydraulic conductivity and high specific storage. Thus, under transient conditions the fractures control the early-time response of the system, and the late-time response is controlled by the blocks of unfractured rock (Hsieh et al., 1983).

The most recent approach to the theory of groundwater flow through nonhomogeneous, anisotropic media utilizes probabilistic techniques to characterize aquifer properties. This approach has become popular in solving groundwater problems only since the late 1970s, primarily because of the advent of digital computers (Neuman, 1982). The probabilistic methods that have evolved can be divided into two main categories: those that treat the hydraulic properties as independent random variables, and those that treat them as spatially dependent random variables. The relative positions of the samples are ignored for an independent random variable, and it is assumed that all sample values have an equal probability of being selected at any point in space. However, the value of a spatially dependent random variable is a function of the location where it is measured.

The appropriateness of each of these four approaches is evaluated below according to three criteria: (1) how well the assumptions behind each approach are met by the conditions that exist in the drift; (2) whether the length of the drift is an appropriate scale for each approach; (3) whether a sufficiently large data base exists to employ each approach. The discrete approach is not a suitable method for simulating the flow of groundwater through the fractured metaquartzites of the Bunker Hill Mine for at least two reasons. First, this approach requires a relatively simple and constant fracture geometry. This definitely is not the case in the New East Reed drift, let alone over the entire mine (Haskell, 1987). The second reason that an accurate groundwater flow model of the Bunker Hill Mine cannot be constructed using the discrete approach is that data are not available on the aperture sizes of the major structural features. The two primary reasons such data were not collected are the difficulty in making such measurements and the large number of fractures that were covered with iron oxide deposits ('yellowboy') or detritus from previous mining operations. In addition, blasting during excavation of the drift probably has widened the fractures at the surface of the drift faces. Even if such data had been collected, it seems likely that a relatively wide variation in aperture sizes would have been observed as a result of the intense and repeated deformation of the quartzites that form the bulk of the rocks in the vicinity of the New East Reed drift. Uniformity of aperture size is desirable when applying the discrete approach to field situations. Thus, this approach seems more suited to regularly jointed crystalline rocks than to highly deformed metasediments.

Although the entire mine can be viewed as an equivalent porous medium from a conceptual model standpoint, Long et al. (1982) stated that fracture systems behave more like porous media when the orientations are distributed rather than constant and when the apertures are constant rather than distributed. As mentioned above, the apertures of the fractures in the New East Reed probably are distributed rather than constant. Although the orientations also are distributed rather than constant, as revealed by an inspection of lower-hemisphere Schmidt plots of the fracture data, closer examination reveals that the orientations are relatively constant within each of the four zones (Haskell, 1987). Thus, it appears that the scale of the drift is not large enough to justify using an equivalent porous medium model.

The double-porosity approach probably constitutes the most defensible conceptual model for simulating the groundwater flow system in the vicinity of the New East Reed drift. As stated above, this approach utilizes two distinct sets of values for the hydraulic properties, one for the fractures and one for the unfractured rock matrix. In this approach, the bedding planes would constitute the high hydraulic conductivity, low specific storage fractures. The two main reasons for this designation are that the bedding planes appear to have a relatively high hydraulic diffusivity compared with the joints, as shown by the steeper recessional limbs of the hydrographs for the tarps (see Fig. 5), and that the bedding planes are significantly less abundant, longer and farther apart than the joints (Haskell, 1987). In addition, their orientations are relatively constant as opposed to distributed.

The low hydraulic conductivity, high specific storage rock matrix under the double-porosity approach would be the jointed rock in the New East Reed drift. The two main reasons for this designation are the relatively low hydraulic conductivity of the unjointed quartzite, and the observation that the joints are relatively abundant, short and closely spaced, and have orientations that are distributed rather than constant (Haskell, 1987). Therefore, the hydraulic properties of the jointed rocks probably can be approximated as a low permeability equivalent porous medium in a double-porosity model.

Another possible conceptual model would designate the faults as the high hydraulic conductivity, low specific storage fractures. In this case, the bedding planes would be incorporated into the matrix portion of the double-porosity model. This conceptual model might be valid at the scale of the entire mine, but it seems inapproriate at the scale of the New East Reed drift for the reasons listed above in the discussion on the applicability of the equivalent porous medium approach. In addition, the evidence that is available does not support designating the faults as units with relatively high hydraulic conductivity and low specific storage, as most of the faults were observed to be dry and filled with gouge (see Table 2).

Probabilistic approaches for simulating the groundwater flow system at the Bunker Hill Mine seem promising, except for the limited hydrogeologic data. Although ample data on the fracture characteristics in the New East Reed have been collected (Haskell, 1987; Lachmar, 1989), no data on the apertures are available, as stated above. Thus, the hydraulic properties of individual fractures and fracture sets cannot be characterized using the discrete approach. Other probabilistic techniques also might be employed successfully, but a sufficient number of values of the hydraulic properties of the fractured rock would have to be collected so that reliable modeling results could be obtained.

8. Conclusions

Results of the analyses of the hydrogeologic data discussed in this paper lead to a number of conclusions on the groundwater flow system in the immediate vicinity of the New East Reed drift and the Bunker Hill Mine in general, as follows:

(1) The proportion of water-bearing bedding planes is significantly greater than the proportion of major joints that are wet. This suggests that the bedding planes are the primary conduits for groundwater flow through the undisturbed rock in the vicinity of the New East Reed drift. Additional evidence supporting this conclusion is the relatively high flow rates measured from the bedding plane tarps as compared with tarps beneath a well-jointed area and a minor fault zone, and the relatively steep slopes of the recessional limbs of the hydrographs for the bedding plane tarps. The longer trace lengths and smoother, less wavy surfaces of the bedding planes may explain their importance with respect to groundwater flow.

(2) Two major joint sets are present and appear to connect water flowing through the discontinuous bedding planes. In addition, three minor joint sets are present

which do not seem to have a significant impact on groundwater flow, but together with the two major joint sets may store relatively large quantities of water

(3) The relatively steep slopes of the recessional limbs of the hydrographs from tarps suspended beneath bedding planes and from tarps suspended beneath rock-bolt holes in the central portion of the drift suggest that rock-bolt holes discharge water primarily because they intersect bedding planes in this portion of the drift. The relatively shallow slopes of the recessional limbs of the hydrographs from tarps suspended beneath a well-jointed area and flowing bolt holes in the SE portion of the drift suggest that rock-bolt holes in this portion primarily intersect joints. This difference appears to be related to the shallower angle of dip of the bedding planes in the central portion of the drift.

(4) Infilling material may control the hydrogeologic character of the faults in the New East Reed drift, with those filled with gouge having low hydraulic conductivities and those filled with breccia having relatively high hydraulic conductivities. Of the 36 faults mapped in the New East Reed drift, 33 are filled with gouge, suggesting that most faults act as barriers to groundwater flow, although the brecciated fault zones may be the primary flow paths for groundwater movement on a regional scale.

(5) The shapes of the hydrographs of flow rates from tarps suspended beneath bedding planes and flowing rock-bolt holes that intersect bedding planes, water levels in piezometers at the ground surface, and pressures in horizontal diamond drillholes in the New East Reed are similar to those of local streams (see Trexler, 1975), confirming that recharge from snowmelt at the surface in the spring is the primary source of water in the upper workings of the mine. As there are no surface streams or major fault zones directly upgradient of the drift, the recharge probably flows into the workings through bedding planes located directly above the mined-out openings. In addition, the similarities in the shapes of the hydrographs for the two tarps suspended beneath relict bedding planes and the two tarps suspended beneath rock-bolt holes that intersect bedding planes, and the pressures in the diamond drillholes, support the conclusion that the large seasonal head variations (14–21 m), as documented by the pressures in the diamond drillholes, are primarily responsible for the temporal variations in discharge into the New East Reed drift.

(6) The drawdown data obtained during constant discharge flow tests conducted on three of the diamond drillholes appear to reflect the influence of a positive (constant head–recharge) boundary lying between Drillholes DDH 2147 and DDH 2290. This boundary may be the fault that crosses the New East Reed about 30 m from the SE end of the drift, as indicated by the fact that a considerable quantity of water discharges from the base of the fault at the point where the floor meets the western wall of the drift.

(7) A double-porosity approach probably is the most appropriate for simulating the groundwater flow system in the vicinity of the New East Reed drift. In such a conceptual model, the rock matrix would consist of the jointed rock, because it probably has a relatively low but still significant hydraulic conductivity and high specific storage, and the bedding planes would constitute the high hydraulic conductivity, low specific storage fractures. However, this model has not yet been evaluated by performing numerical simulations using the field data.

Greater understanding of the groundwater flow system at the Bunker Hill Mine sheds light on the reclamation alternatives that might minimize the production of acid mine drainage. The workings themselves obviously are the primary conduits for the movement of water within the disturbed rock. The upper workings are riddled with an extensive and irregular network of drifts and stopes. Consequently, it seems unlikely that the production of poor-quality water could ever be halted completely. It has been hypothesized that draining the major fault zones by tapping into them with drillholes at mine levels below the Flood–Stanly ore body (below 10 level) might reduce the amount of water available for chemical degradation within the ore body (Hampton, 1985). Dewatering of the fault that crosses the New East Reed about 30 m from the SE end of the drift by installing dewatering wells at a level below the New East Reed might well reduce the amount of inflow to the drift; however, it would be more problematic to determine which, if any, faults within the Flood–Stanly should be drained, as the workings in this ore body are old and extremely unsafe. Dewatering of the major fault zones probably would not cause a significant reduction in the amount of poor-quality water produced, as it now appears that most of these faults are filled with gouge and have low hydraulic conductivities. Grouting of a combination of breccia-filled faults and relict bedding planes may offer the best hope for minimizing mine-water inflow or recharge.

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