The Importance of Geological Investigations in Modelling the Effects of Dewatering Open Pit Mines – A Case Study

By B.A. Dudgeon[1] and C.R. Dudgeon[2]

1 Hydrologic Consultants Inc., Lakewood, Colorado, USA
2 Water Research Laboratory, School of Civil Engineering, University of New South Wales, Sydney, Australia

ABSTRACT

There is a tendency in modelling groundwater flow to mines to ignore or oversimplify the complex reality of the geology of the mine site and surrounding region. This is partly attributable to the difficulty and cost of obtaining detailed geological data but may also be due in part to a lack of awareness by some modellers of the nature of flow close to mines and the extent to which the local flow characteristics can affect the wider region around the mine.

This paper outlines a case study in which initial lack of sufficiently detailed geological data caused difficulty in reconciling the results of modelling and field measurements. Adjustment of the model taking into account additional geological information resulted in improved performance.

The study deals with the relatively slow mining of limestone from an open pit in Queensland, Australia. In this case it has been possible to proceed at a leisurely pace over a period of several years to adjust the conceptual model to take into account new geological data as it was revealed by additional geological mapping and drilling, petrographic examination of interbeds and intrusions encountered in the mine and expansion and deepening of the pit.

The example quoted illustrates the need for greater awareness by exploration geologists, mining executives and modellers of the need to pay sufficient attention to investigating the influence of geology on mine dewatering and consequent environmental effects.

INTRODUCTION

Computer modelling has become an almost obligatory part of any groundwater investigation. The proliferation of models and modelling has been fostered in universities and other research organisations by free access to computers of ever increasing power to size ratio and the relative difficulty of obtaining funds for field investigations and physical laboratory experiments. The imbalance is probably also due in part to the relative cleanliness and comfort in which computers can be used compared with the discomfort and hard reality of the outside world of geology and engineering.

A manifestation in mine water investigations of the situation referred to above is the tendency to model flow near mines without attempting to investigate and account properly for the local geological features which may have a controlling influence on inflows and piezometric heads. Since the scale of the inhomogeneity which must be addressed in modelling flow near a mine is much smaller than that which must be accounted for in "regional" flow modelling more detailed investigation of geological features is required.

At open pit mines with relatively large water inflows or discharges from pumped wells in or near the pit a large proportion of the drawdown of the piezometric surface occurs close to the pit and convergence of flow lines is strong. This is particularly so if most of the water is conducted in a relatively small number of flow paths such as fractures or shear zones. It is therefore important that geological features which have a significant influence on these flow paths or which act as boundaries be investigated adequately and accounted for in modelling.

Unfortunately many exploration geologists intent on proving up a resource seem to be unaware of the need to draw attention to situations which would influence mine dewatering and associated modelling. A combination of lack of geological knowledge by modellers and lack of hydrogeological knowledge by exploration geologists can reduce the effectiveness and add to the cost of modelling.

The economics of most mining ventures are unlikely to support the type of detailed geological investigation which has been mounted for nuclear waste disposal. Nor is such detail necessary in most cases since only those features likely to have a significant influence on substantial water inflows or water table levels are of interest. For modelling purposes the requirement is to be able to subdivide the zone around the mine into elements which can be treated as homogeneous and to which storage and permeability values can be ascribed.

Since many mining situations have strongly three dimensional characteristics the ideal general purpose model is three dimensional and able to handle thin features such as faults, shear zones, interbeds and volcanic intrusions as well as irregular bulk elements defined by the geology. Readily available quasi three dimensional models developed for regional flow modelling are generally not suitable since they can not properly deal with complex geometry and highly convergent flow into a mine. It might be possible in some circumstances to apply such a model successfully to a dewatering scheme which uses wells located some distance from the pit boundary. Such a scheme might be more amenable to analysis but it will not minimise pumping requirements since the closer the flow is allowed to approach the pit the greater the convergence and throttling effect on the flow.

In the initial stages of modelling mine water inflow it is unlikely that sufficient geological detail will be available to allow a comprehensive fully three dimensional model to be developed, calibrated and used to predict required pumping rates and piezometric heads with great accuracy. However, unless the rate of mining is very fast it should be possible to progressively develop and calibrate a model which allows an increasing level of complexity to be introduced.

It is also important to account properly for geology when modelling the wider region which provides the recharge and/or storage from which the inflow to the mine is drawn. Changes induced by mining in this region are frequently the cause of environmental and economic concern. They are affected by both the small scale geology near the mine since this has a disproportionate effect on inflow to the mine and the larger scale geology of the region from which water is drawn.

Arbitrarily changing permeability and storage values of elements of a model to force model results to conform to limited field data is no substitute for developing an understanding of the geology of both the mine site and the surrounding region and using it to develop a valid conceptual model on which to base the numerical model. Unless the geological framework is correct a model calibrated for a limited range of flows and piezometric heads may fail completely when mine dewatering and/or seasonal conditions apply greater stress to the aquifer system.

The case study outlined in this paper describes the acquisition and use of more detailed geological data to refine a model used to predict flow into an open pit mine in Queensland, Australia. It is shown how initial lack of details of interbeds and intrusions in limestone affected the results.

EAST END LIMESTONE MINE

Location and regional geology

The East End limestone mine is operated by Queensland Cement Ltd to supply material for its large cement manufacturing plant near Gladstone, Queensland, Australia. A location map is given in Figure 1.

The company holds four leases over what were initially considered to be separate limestone bodies spaced several kilometres apart. Subsequent more detailed mapping of outcrops showed that most occur in three main bands trending approximately south east to north west and spaced about three kilometres apart. The main outcrops and some of the smaller outcrops located in the intervening rocks are shown in Figure 2. Whether the three main bands are repetitions caused by deep folding of one deposit or are separate deposits in the geological sequence has not yet been determined.

The hydraulic connection of the deposits to be mined is of greater importance than the geological connection when mine dewatering and environmental effects of dewatering are being considered. Current evidence is that two of the limestone bodies to be mined are isolated hydraulically while the other two may be well connected hydraulically since they outcrop in the same band. However undetected faulting may affect the degree of connection.

Water is extracted by landholders from some of the minor bands of limestone. It is assumed that these result from minor depositional events and are hydraulically "insulated" from the main deposit(s) by low permeability metamorphosed volcanics or sediments.

The limestone generally occupies the floors of valleys because of its high vulnerability to weathering and erosion compared with that of the surrounding rocks. Consequently mine dewatering and diversion of surface water away from mines present significant problems. Since the valley floors and streams fed by the limestone are used for farming and also provide habitat for a rich variety of plant and animal life the potential for adverse economic and environmental effects of mine dewatering must be considered carefully. Monitoring conditions attached to the mining leases have led to a wider ranging water investigation than usual while the need to plan mine dewatering resulted in a more detailed investigation at the first mine site at East End.

The limestone is of lower Devonian age and is believed to have been deposited in an island arc environment. It is interbedded with volcanic rocks and sediments. The depositional environment accounts for the irregularity of thickness and areal extent of the limestone.

The limestone and surrounding rocks form part of the Mount Holly fault block which consists of a sequence of volcanic and sedimentary rocks up to 5000 m thick. The volcanics are andesites and tuffs while the sedimentary rocks are mudstones, lithic and feldspathic sandstones (greywackes), conglomerates and limestones. The limestones are corraline and/or crinoidal.

The Mount Holly beds have undergone low grade regional metamorphism which has hardened the sediments, producing a well defined cleavage. The original sedimentary structures and textures have been largely or completely obliterated by the metamorphism. The limestones have recrystallised to form marble with a wide range of colour and grain size.

The deposits covered by the mining leases lie within the East End anticline, one of two main structures in the large fault block. The steep and variable nature of the dip suggests that the limestone may be associated with small tight folds superimposed on a limb of the major structure.

Local geology of East End mine site

Figure 3 is an enlargement of the relevant part of Figure 2 and shows the location of the East End mine in relation to the band of outcropping limestone. Measured dips in the band range from 70 deg. to the north east to 70 deg. to the south west over a range of locations along the strike. There is every reason to expect minor faulting across the strike over the whole length of outcrop and this could account for the variation in dip

Existing geological and hydrogeological evidence indicates that the limestone currently being exploited by the East End mine is hydraulically separated from other limestone to the north east and south west by adjoining beds of low permeability rocks. At the north western end the limestone either peters out or is cut off by a fault which cuts across the strike. The latter appears most likely. At the south eastern end the limestone is overlain by a few metres of clayey soil but appears to terminate at another fault which is assumed to generally follow the line of two creeks which cut across the strike from opposite directions before joining and then following the strike towards the southeast.

More detailed geological investigations in and around the open pit mine were carried out as the pit expanded. This work was co-ordinated with measurements of water table level and water quality. More closely spaced drilling (at intervals ranging from 25 m close to the pit to 100 m), inspection of the pit walls and water table variations all pointed to relatively complex local hydreogeological conditions. In particular the presence of previously undetected thin bands of non-calcareous rock (locally described as andesite) in the main body of limestone pointed to the need for careful consideration of their potential to have a major effect on groundwater flow.

A point which was considered to support a closer examination of the "andesite" bands was the observation by cement chemists that a variety of types of clay was being encountered in the weathered surface layer of limestone being mined. Some of the clay caused problems in the operation of filter presses used to remove water from the slurry pumped to the clinker plant. The surface solution channels in the limestone are filled with a reddish clay, a product of weathering washed in from adjacent rocks. The other clays are the result of in situ weathering of the "andesite" bands. If these were, as then assumed, all volcanic intrusions there seemed to be no reason for the differences in properties of the residual clays.

Petrographic and X-ray fluorescence tests on samples of surrounding country rock and several of the "andesite" bands showed that the bands were not of identical material and came from at least three sources. The three types represented were pyroclastic beds (dacitic tuff) up to 3m thick laid down conformably with the limestone, thin siltstone and sandstone interbeds in the limestone and volcanic intrusions (andesite).

The pyroclastic beds are well jointed below the layer of surface weathering and contain no solution channels at depths where solution channelling in the limestone is still significant. At these depths the beds still act as barriers to the lateral flow of groundwater as they do closer to the surface where it is the residual clay which forms a highly impermeable barrier. At greater depths where the solution channelled limestone aquifer gives way progressively to a fractured aquifer the permeability difference between the limestone and the pyroclastics could be expected to decrease and possibly disappear. Since the pyroclastics will have been deposited over a wide area they can be expected to extend beyond the limestone and have a significant regional effect as well as a local effect on the groundwater flow.

The thin interbedded sediments result from surface water inflow into the reef environment and are not likely to be as extensive as the pyroclastic beds. Their effect on groundwater flow will be similar but probably not as great because of their relative thinness and possibly more limited areal extent.

The volcanic intrusions mainly follow the near vertical bedding of the limestone but in places offshoots cut irregularly across the bedding at joints. A particularly irregular group of intrusions visible in the mine occurs at what appears to be a weathered lateral shear zone. Some intrusions follow interfaces between limestone and pyroclastic to form composite bands which are difficult to distinguish by eye in the pit wall from intrusions alone. Boudinage (pinch and squeeze structure) helps identify the intrusions. Intrusions encountered to date are up to 0.5m thick.

An important difference between the intrusions and the interbedded pyroclastics is the extent to which each will confine the flow in the highly permeable upper layer of limestone to travel preferentially in the strike direction and thus result in significant local and/or regional anisotropy. Since the extent of the intrusions is likely to be less than that of the pyroclastics they might not have as great a regional effect on flow. However their local effect could be just as significant and much more difficult to predict because of their greater irregularity.

At greater depths where the flow of groundwater would be expected to depend on the frequency and apertures of fractures rather than solution channelling the effect of the interbedded rocks and intrusives in the limestone should decrease. With the deepening of the mine and lowering of the water table through mine dewatering the degree of anisotropy exhibited by the effective aquifer might be expected to progressively decrease.

Local groundwater investigation

An investigation was carried out to provide predictions of water inflow to the East End mine at various stages of development. The results could be used if necessary as input to a later assessment of the effect of mine dewatering on surrounding water table levels. No water supply wells other than those on property acquired by Queensland Cement Ltd appeared to draw water directly from the limestone deposit being mined so no immediate effect on surrounding wells was anticipated. A more likely scenario was a slow draining of the low permeability surrounding rocks through a seepage face into the more easily drained limestone body causing limited lowering of the water table outside the limestone. The eventual extent of the fall would depend to a large extent on recharge from rainfall.

Mine water inflow model

Since there was little data available to support the development of a complex three dimensional model of flow to the mine when inflow predictions were first required it was decided to use an available radial flow model which could handle finite pit diameter, flow convergence in the vertical plane and non-Darcy flow. Previous reference has been made to the use of this model by Dudgeon [1,2]. The cost of developing and calibrating a true three dimensional model would also have been hard to justify in the circumstances.

No pumping test had been carried out to determine hydraulic characteristics of the aquifer prior to the commencement of mining so it was decided to select Forchheimer coefficients for the model aquifer by matching a computed water table profile with the actual profile developed during pumping from the initial pit. Inflow to the pit predicted by the model for the existing conditions was then compared with the actual pumping rate. After adjustment of the model, predictions were made of groundwater inflows to be expected for various stages of development of the pit.

In the absence of any data on anisotropy the early modelling assumed a homogeneous isotropic aquifer. Even after the surface clay was cleared away from an extensive area revealing a very uneven limestone surface no indication was given of anisotropy in plan. Inspection of the solution channelling in the walls of the initial pit did not indicate the need to adopt different horizontal and vertical Forchheimer coefficients since most of the flow appeared to occur in channels which allowed free vertical as well as horizontal movement.

Although a good fit could be obtained to the water table profile in the direction of strike, the only direction in which detailed water level data was available in exploration boreholes, actual and computed pumping rates could not be matched. The actual rate was about half the computed rate. It was concluded that because of different hydraulic conductivities along and across the strike direction the aquifer was behaving effectively as if water were approaching the pit from two quadrants rather than the full circle modelled. Since the need to select pumping equipment and obtain a licence to discharge water from an expanded mine dictated that inflow predictions could not be delayed until more detailed hydrogeological data could be obtained, half the computed water inflow values were adopted as maximum inflows to pits of larger diameters and depths. These were determined for high water table levels surrounding the pit in case lengthy periods of high rainfall occurred during the excavation of the pit to its final level.

The more detailed local geological investigation described earlier, subsequent observations made in the expanded pit and continuing measurement of water table levels have provided information which will allow a more complex three dimensional model to be set up if it is ever required and can be justified.

Variation of hydraulic conductivity with depth

Assumptions about the variation of hydraulic conductivity and anisotropy with depth which were based on the known geological information and used in the radial flow modelling have been verified by inspection of the pit walls and interpretation of changes in pumping rate and water table levels as the depth of the pit increased. The effect of solution channels and interbedded rocks and intrusions in causing preferential flow in the strike direction has decreased with depth causing the lower part of the aquifer to act more like a homogeneous fractured rock mass. As the water table close to the mine has fallen approximately 10 m the shape of the drawdown "cone" has altered from one elongated in the strike direction to one close to circular. Water table contours close to the pit at and approximately 5 and 10 years after the commencement of mining are shown in Figures 4 to 6. The rate of inflow of water in dry weather is now controlled mainly by lower level fractures and not by significant solution channels as was the case in the early stages of mine dewatering. Unfortunately most of the vertical boreholes which were drilled near the mine for resource assessment and then cased with slotted PVC to act as water level observation holes have been lost in the course of mining. There is not now enough data to allow detailed water table contours near the mine to be drawn.

Regional effects

Obvious lowering of the water table around the mine has so far been confined to the limestone in which the mine is situated. The geologically determined boundaries of the limestone deposit being mined closely match the limits of major effect on the water table. The problem of differentiating between the effects of mining and other factors affecting groundwater and surface water conditions over a wider region are dealt with in a separate paper.

Future developments

Current indications are that further development of the groundwater inflow model is not warranted as it is not proposed to mine below the current depth of 50 m at this site. As the mine expands in area, direct inflow of water from prolonged heavy rainfall with an average return interval of about 10 years is likely to be the main problem.

CONCLUSION

The experience gained in relating geology to the flow of groundwater to the East End mine will be invaluable in predicting inflows to mines in other similar limestone deposits in this area.

It is hoped that this case study which demonstrates the major effect which relatively minor geological features can have on flow near an open pit mine will encourage more modellers to concentrate as much on the geology as on numerical procedures.

ACKNOWLEDGEMENTS

The co-operation of the staff of Queensland Cement Ltd over the past fifteen years in facilitating the collection of data and the use of this example in research publications has been greatly appreciated.

REFERENCES

1. Dudgeon C.R. Effects of non-Darcy flow and partial penetration on water levels near open-pit excavations. International Association of Hydrogeologists, Proc. 18th Congress, Cambridge, England, Sept 1985, 122-132.
2. Dudgeon C.R. Unconfined non-Darcy flow near open-pit mines. International Mine Water Association, Proc. 2nd Congress, Granada, Spain, September 1985, 443-454.

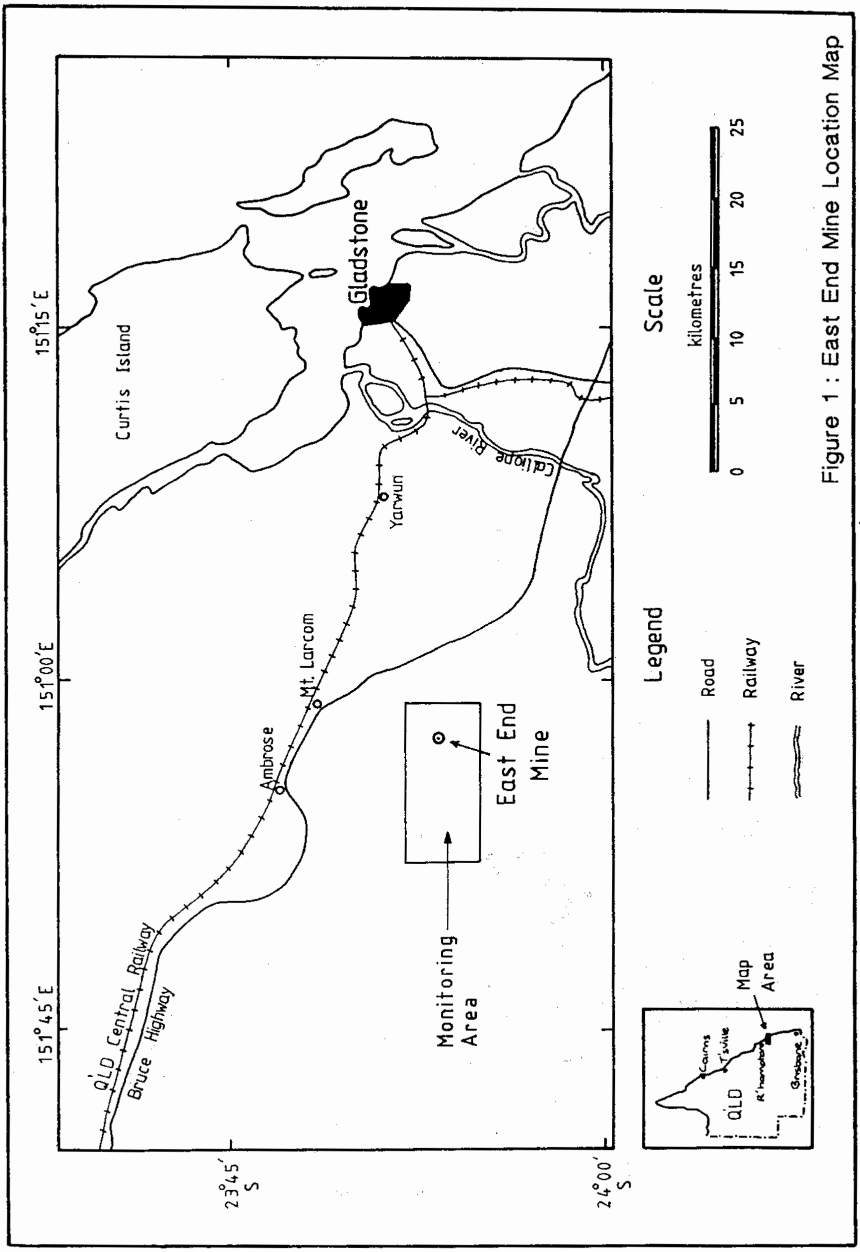

Figure 1 : East End Mine Location Map

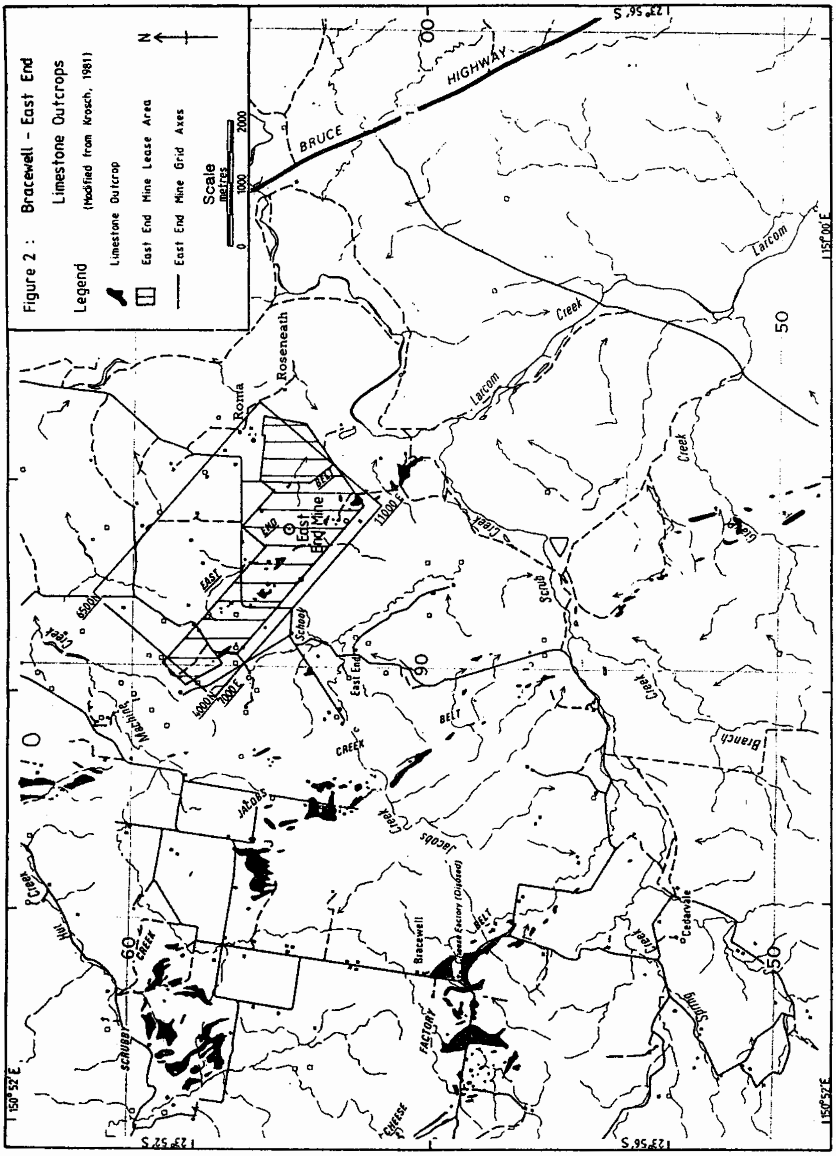

Figure 2 : Bracewell - East End Limestone Outcrops (Modified from Krosch, 1981)

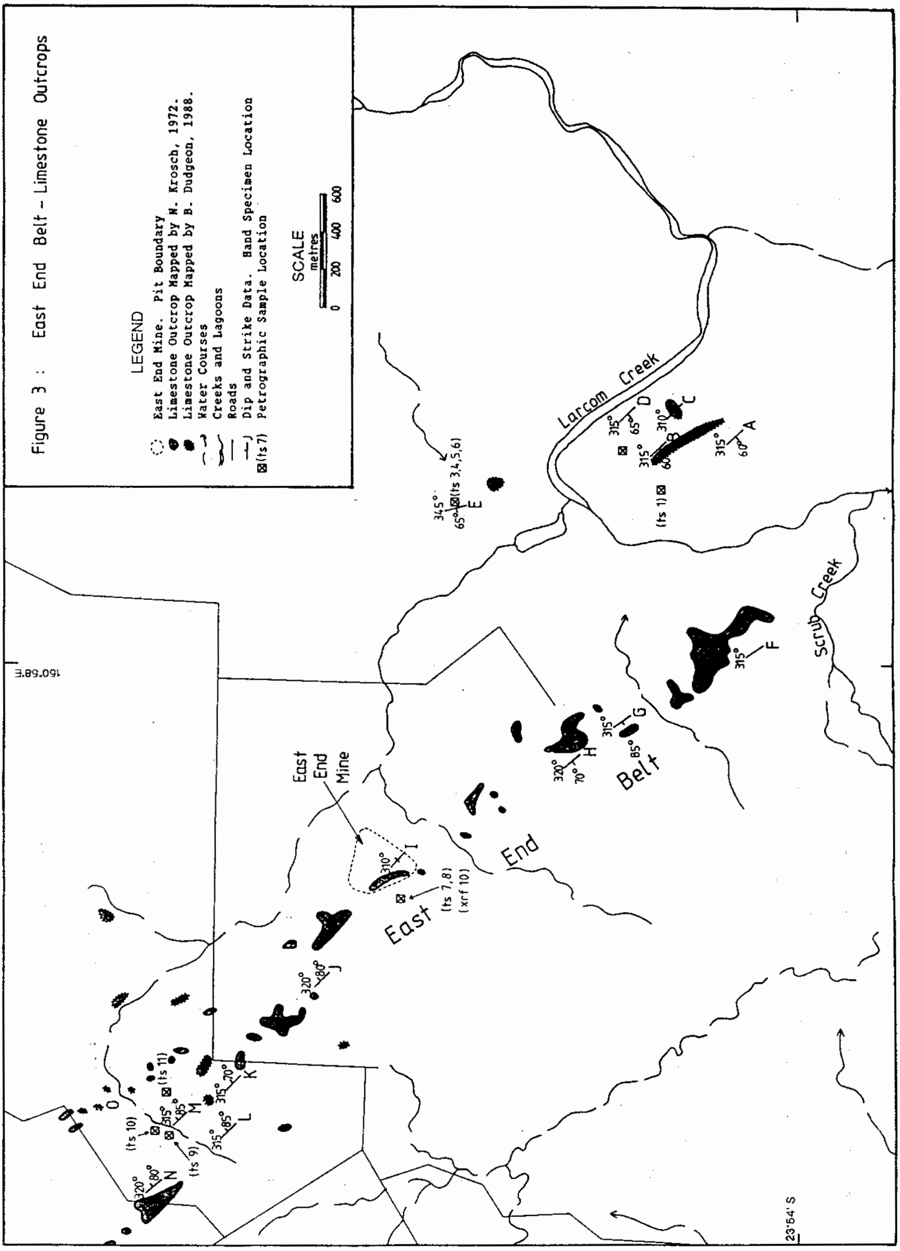

Figure 3 : East End Belt - Limestone Outcrops

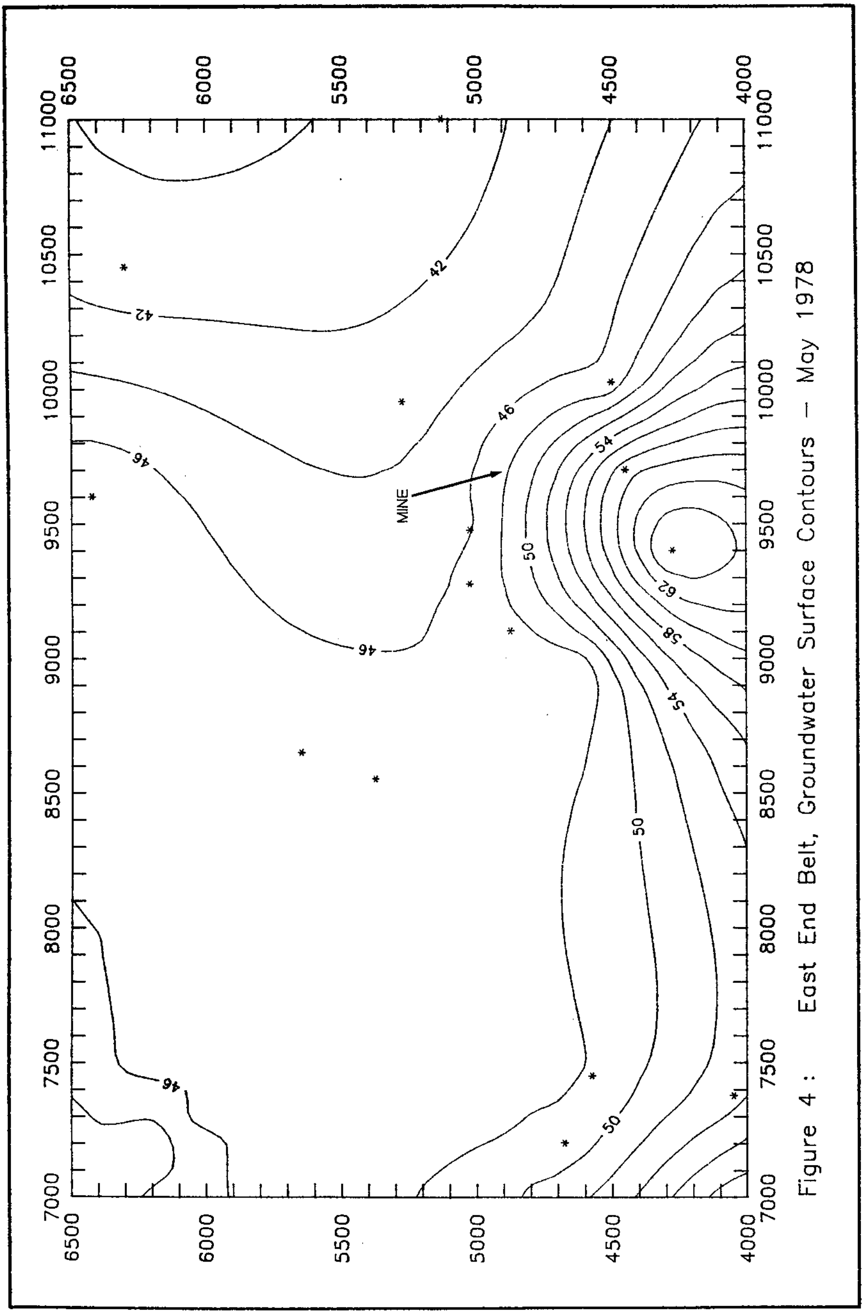

Figure 4 : East End Belt, Groundwater Surface Contours — May 1978

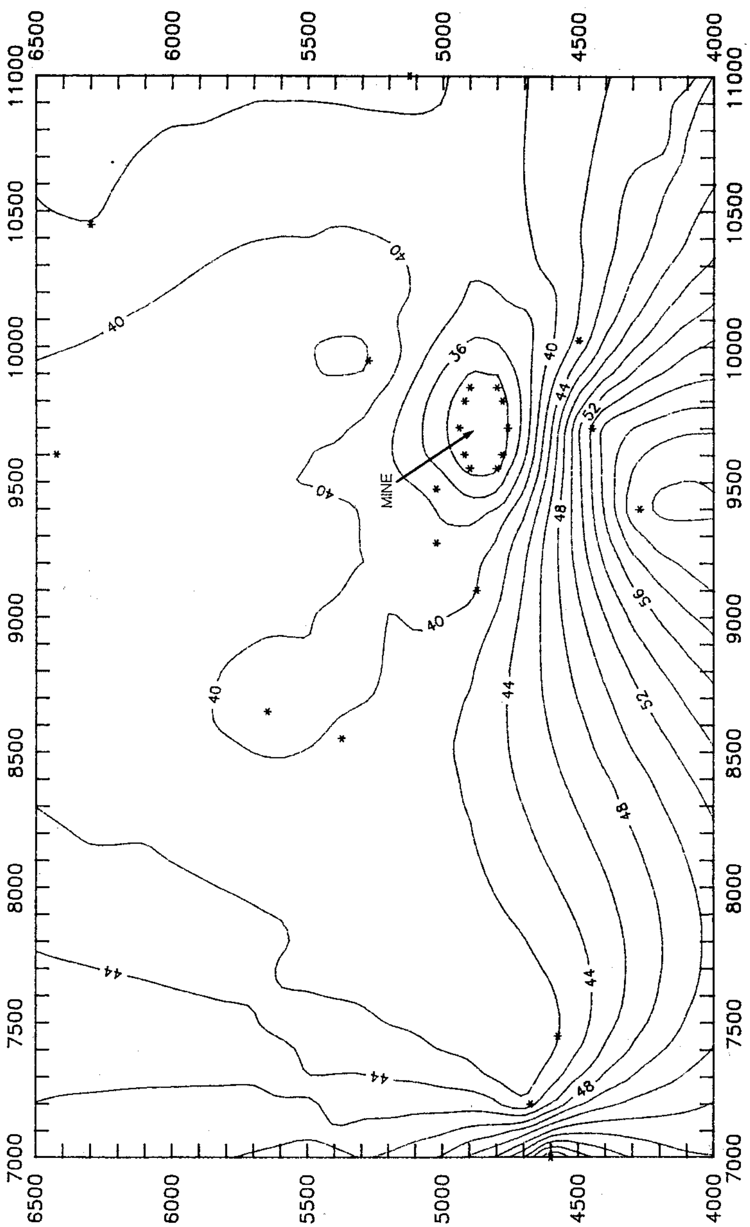

Figure 5 : East End Belt, Groundwater Surface Contours — December 1982

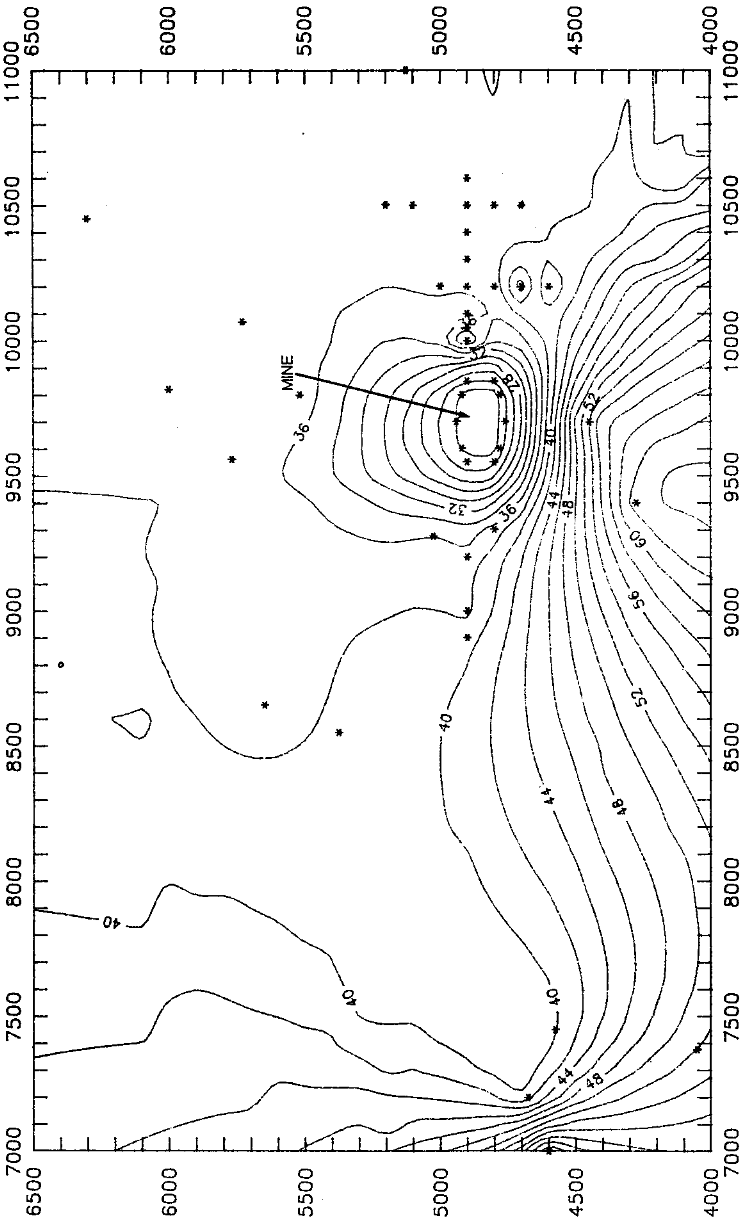

Figure 6 : East End Belt, Groundwater Surface Contours – December 1987