THE USE OF STABLE ISOTOPES TO DETERMINE THE SOURCE OF BRINES IN SASKATCHEWAN POTASH MINES

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ABSTRACT

Recent mine floods at the International Minerals and Chemical Corporation K-2 Mine and the Potash Corporation of Saskatchewan Mining Limited, Rocanville Division, have shown the need to identify accurately the source of mine-water leaks in order to undertake proper preventative or remedial action. Chemical compositions of the waters are inadequate as tracers of leaks because:

1) *the erroneous assumption is made that the concentrations of at least some of the elements do not change during migration of the fluids,*
2) *interpretation of the significance of chemical composition data relies largely on results from experimental data, and*
3) *chemical compositions are greatly altered by passage through the Prairie Evaporite Formation.*

Stable isotopes of oxygen and hydrogen are considered conservative elements of water. Within a basin the δD and $\delta^{18}O$ values of pore waters typically increase with depth because of increasing influence of connate waters. Thus, the water in each aquifer within the basin generally has a characteristic isotopic composition which, when compared to the isotopic composition of the floor or leak waters, allows an identification of the brine source irrespective of other changes in chemical composition of the water during migration.

Results indicate that the oxygen and hydrogen isotopic compositions of waters are valid tracers and that this technique can be used to map the flow of water between formations.

INTRODUCTION

Since potash mining began, water leaks have been a major concern. In Saskatchewan, they have created severe problems ever since the first mine shafts penetrated the Mannville Group aquifers (Fuzesy, 1982). Subsequent major leaks include that at the Cominco mine (Prugger, 1979) and recent mining-level floods at International Minerals and Chemical Corporation (IMC) K-2 Mine and the Potash Corporation of Saskatchewan (PCS) Mining, Rocanville Division. The recent loss of a Russian potash mine due to flooding reflects the ultimate severity of water leaks in potash deposits.

Knowledge of the source of the brines is essential in undertaking proper preventative or remedial action. In the past, determination of the origin of the inflowing brine has been interpreted largely from chemical composition of the brine. This method is, however, unreliable because brine compositions are radically altered by the brines' interaction with evaporites during migration to the mining level. Stable isotopic composition of the waters has been proposed as a more satisfactory indicator of the sources of brines leaking into the potash mines.

In the present study, stable isotopes of hydrogen and oxygen were used to compare water leaking at the mine levels with waters collected from strata above the mining levels. Samples were taken from PCS Mining mines at Cory, Allan, Lanigan and Rocanville (Fig. 1). Samples were collected from sites within the mine shafts and from leaks at mining levels (Fig. 2), except the Lanigan shaft which was too dry to sample. Samples were analysed for D/H, $^{18}O/^{16}O$, Cl, Na, K, Ca, Mg, Br, I, F, pH, alkalinity and density. The chemical components, although not discussed at length in this paper, were analysed in order to study brine composition, and to have a basis for comparison with previous work.

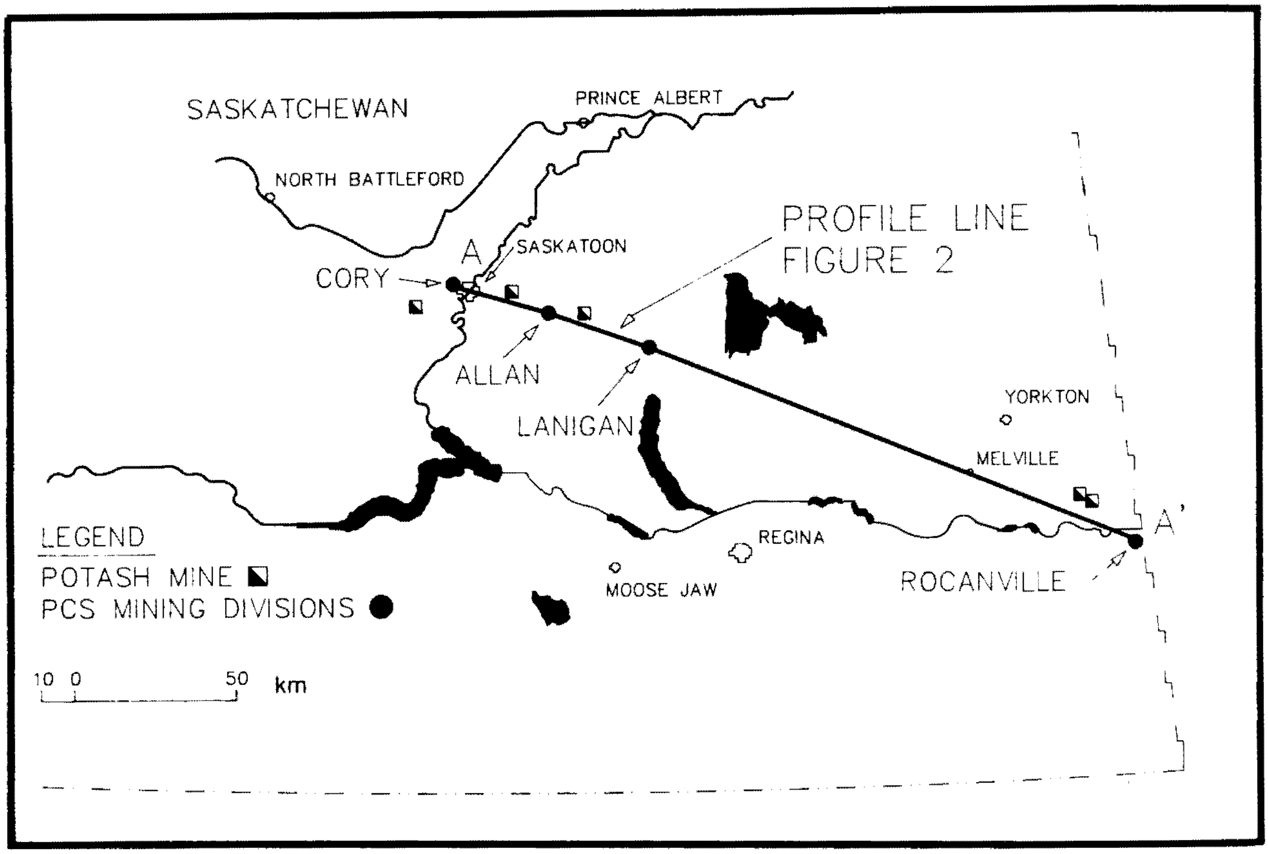

Figure 1. Location map.

GEOLOGICAL SETTING

Potash deposits of economic interest occur in the upper 70 m of the Middle Devonian Prairie Evaporite Formation within the Elk Point Basin at depths of around 1,000 m below surface. Four potash-bearing members are, in descending stratigraphic level: the Patience Lake, Belle Plaine, White Bear and Esterhazy Members (Fig. 2). The Patience Lake Member is mined at the Cory, Allan and Lanigan mines and the Esterhazy Member is mined at Rocanville. The geology of the Prairie Evaporite Formation has been described by Holter (1969) and Fuzesy (1983).

The Prairie Evaporite Formation is underlain by the dolomitic Winnipegosis Formation which has an irregular topography created by reefs and reef-like mounds. The movement of fluids through the Winnipegosis is considered to control local salt dissolution within the evaporite sequence (Gendzwill, 1978). The Prairie Evaporite Formation is overlain by the Second Red Bed Member of the Dawson Bay Formation. The Dawson Bay is the first of a series of Upper Devonian cyclic deposits of limestone, dolomite and evaporites which include the Dawson Bay, Souris River, Duperow and Nisku Formations (Fig. 2). Additional Upper Devonian and Mississippian strata occur in Rocanville area and Jurassic rocks are present in the Allan and Lanigan areas. These sequences are overlain unconformably by the Lower Cretaceous Mannville Group and by a younger section of Cretaceous shales, all capped by Pleistocene glacial deposits and recent sediments (Fig. 2).

The Mannville Group at the base of the Cretaceous contains many porous and permeable sands and forms a large regional aquifer. Formational-fluid movement between the Mannville Group and the Dawson Bay Formation is thought to be continuous (Dunn, 1982). A large fluid system is capped by the relatively impervious Cretaceous shales and is sealed at the bottom by the impervious Prairie Evaporite Formation and the salt-plugged Dawson Bay Formation.

Formational fluids within the basin flow horizontally and vertically. Recharge by meteoric waters occurs at the Central Montana Uplift; this recharge occurred during the latest glaciation and continues to the present times. Direction of fluid flow is largely north to northeast (i.e. towards the formational intersections with the erosional surface). Interformational, or vertical flow, is largely controlled by fractures and by collapse structures caused by the periodic dissolution of the Prairie Evaporite.

In the basin, salinity of formational waters generally increases with depth, even where evaporites are absent. Mechanisms proposed to explain this observation include the complete dissolution of evaporites, brine density flow and membrane filtration. A non-uniform increase in salinity occurs when fluids moving through the formations intersect an evaporite sequence.

The original salinity of the brine within each formation is invariably altered by solution of the evaporite as shown by

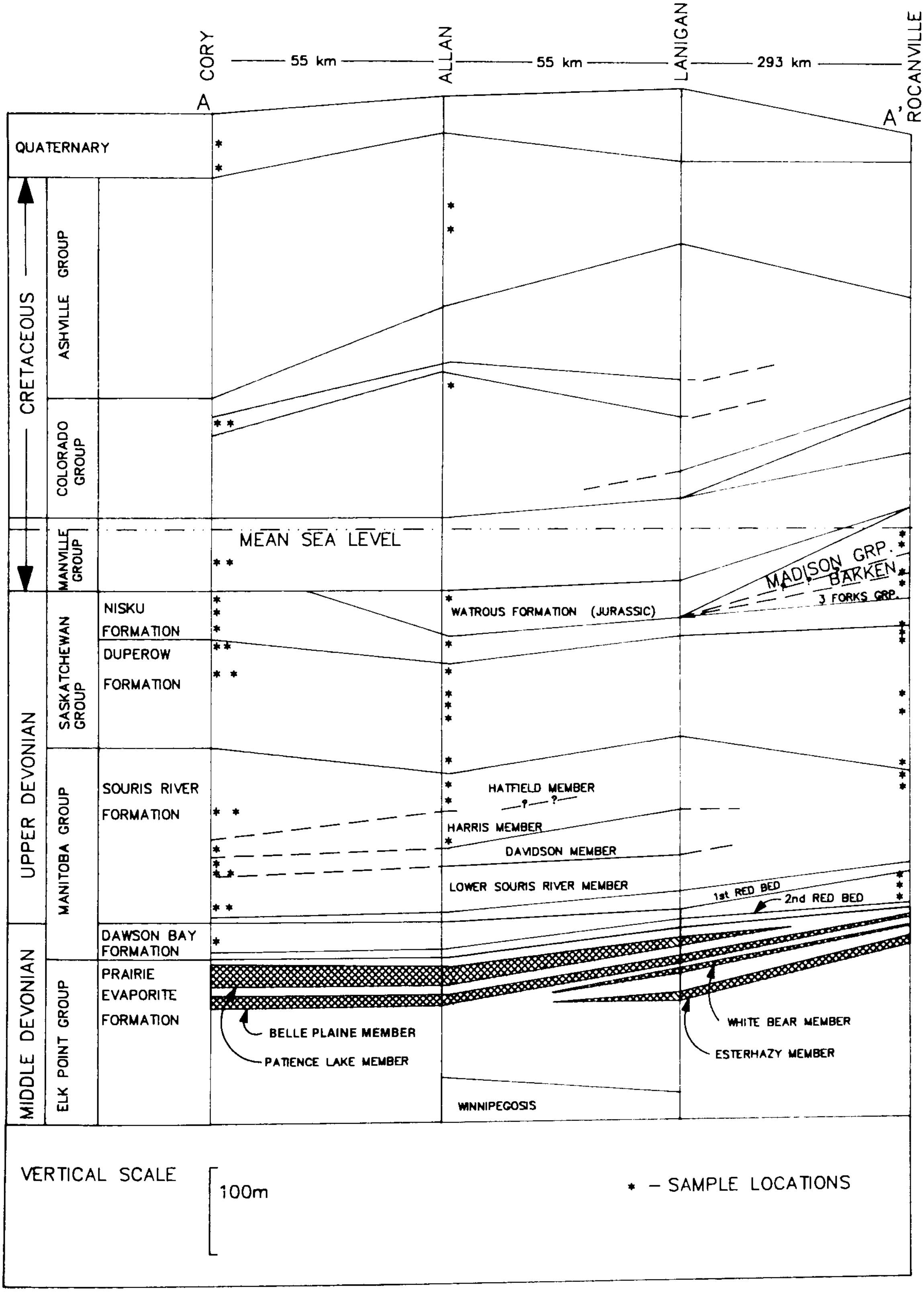

Figure 2. Stratigraphy at the PCS Mining mines in Saskatchewan.

samples collected from the mine shafts or the mining levels. For this reason the dissolved components in the brine are changed in concentration. However, stable isotopes of the water are conservative elements because of:

1) the large reservoir of hydrogen and oxygen which exists in the water itself, and
2) the relatively slow exchange of stable isotopes between waters and rocks at low temperatures.

Consequently, stable isotopic compositions were chosen for determination of the brine sources.

STABLE ISOTOPES

Water is composed of hydrogen and oxygen which have two and three stable isotopes, respectively. Relative global abundances are reported in Table 1.

Table 1. Stable isotopes of hydrogen and oxygen (Faure, 1977).

Element	Stable Isotope	Global abundance (per cent)
Hydrogen	^{1}H	99.985
	^{2}H or D (Deuterium)	0.015
Oxygen	^{16}O	99.756
	^{17}O	0.039
	^{18}O	0.205

The mass of a given sample of water depends upon the isotopic composition of the water molecules. A water molecule of $^{1}H_2{}^{16}O$ has a mass of 18 whereas a water molecule of $D_2{}^{18}O$ has a mass number of 22. The isotopic composition of waters is reported as the D/H or $^{18}O/^{16}O$ in the sample relative to these ratios in standard mean ocean water (SMOW). These variations normally are small and are reported as delta values (δ) in units of per mil, for example:

$$\delta^{18}O = \left[\frac{(^{18}O/^{16}O)\text{ sample}}{(^{18}O/^{16}O)\text{ SMOW}} - 1\right] \times 1{,}000$$

The vapour pressure of water varies inversely with the mass number; that is, the lower the mass number the higher the vapour pressure because water molecules with lower mass numbers are more stable in the vapour phase than are water molecules with heavier mass numbers. Fractional distillation occurs as water goes through repeated evaporation and precipitation during the meteoric water cycle. Evaporating water is depleted in heavier isotopes and condensing water is enriched in the heavier isotopes. The depletion-enrichment occurs in a regular way with respect to the starting composition of waters. Because the isotopic composition of meteoric water during distillation-evaporation is determined by the mass-difference between the H and D atoms and the ^{18}O and ^{16}O atoms, the δD and $\delta^{18}O$ values of meteoric waters are always proportional (i.e. $\delta D = [8 \times \delta^{18}O] + 10$).

The partitioning of stable isotopes of water among various phases is dependent on both temperature and the vapour pressure of the water so that the isotopic composition of precipitation (rain or snow) becomes a function of latitude, altitude and climatic conditions. In addition, as water is removed from a cloud as it passes from the oceans to the continents, the remaining water in the cloud becomes increasingly depleted in the heavy isotopes. Meteoric water in Saskatchewan in very depleted in ^{18}O and D relative to seawater because of latitude, cool climate and distance from the ocean. This evolution of the δD and $\delta^{18}O$ values in precipitation on a global basis is represented by the meteoric water line (MWL) depicted in Figure 3.

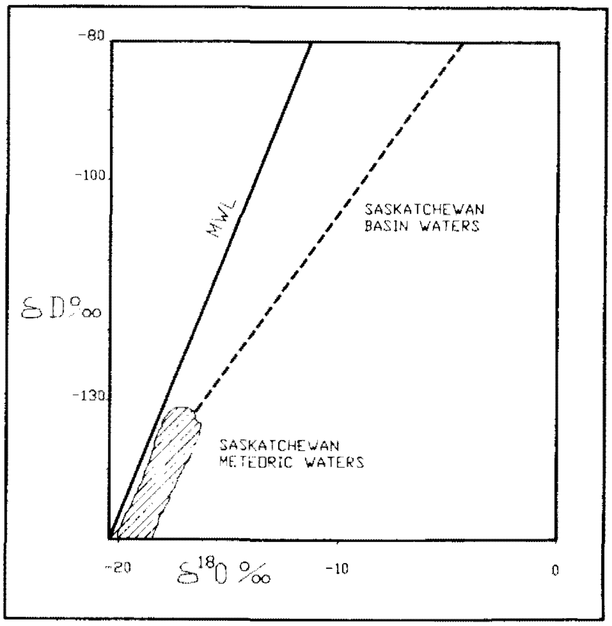

Figure 3. δD o/oo versus $\delta^{18}O$ o/oo.

When meteoric water enters the ground, fractional distillation is no longer effective and ratios of the stable isotopes are altered only as a result of exchange with host rocks. This exchange affects only the oxygen isotopes in the water because of the large reservoir of oxygen in rocks, but the effect can only be measured after millions of years of contact. In Saskatchewan, the median value for meteoric water is approximately -150 for δD and -20 for $\delta^{18}O$. These values, however, vary over a small range due to changes in seasons and precipitation patterns. These values are not believed to have altered significantly since the Pleistocene glaciations.

Waters presently in sedimentary basins consist largely of post-glacial meteoric waters which have displaced or mixed with pre-existing basin waters (Clayton et al, 1966). The δD and $\delta^{18}O$ values within a basin have been shown to increase with depth in a reasonably uniform manner, and each geological basin develops a unique δD vs $\delta^{18}O$ trend (Hitchon and Friedman, 1979). Schwartz et al (1981) noted that the basinal trend could be generated by stacking values of individual aquifers. Therefore, δD and $\delta^{18}O$ values increase downward in a given vertical profile and with distance from source within a given aquifer. Schwartz et al (1981) also noted that values of the stable isotopes vary with the flow rates within an aquifer. In a vertical section, δD and $\delta^{18}O$ values of waters may differ from the general uniformity of the enrichment trend with depth by having lower values where the formation is flushed more thoroughly and higher values where the fluid flow is more restricted.

The main mechanism by which δ D and δ ¹⁸0 values decrease with decreasing depth is the mixing of meteoric waters with isotopically distinct formation waters. The formational water may be true connate water or water which has resided long enough in the basin to become ¹⁸0 rich due to reactions between water and rocks. For recent waters, reactions between water and rocks probably contribute a small amount of heavier isotopes to the water due to the slow reaction of hydrogen with clays and of oxygen with carbonates and silicates.

If water depleted in D and ¹⁸0 is found below an aquifer exhibiting normal isotopic increases with depth, some major disruption in the flow pattern has occurred. The flow pattern has been "short circuited", allowing isotopically lighter water to enter the formation. Processes that permit the decrease of δ D and δ ¹⁸0 with depth are rare.

Short circuiting in the Elk Point Basin is likely caused by the vertical movement of fluids through collapse structures and related features. Collapse structures form when fluids dissolve and periodically remove portions of the Prairie Evaporite with the subsequent collapse of overlying formations (Christiansen, 1971; Christiansen et al, 1982; DeMille et al, 1964; Bishop, 1974; Parker, 1967). Dissolution at depth may be caused by the driving of undersaturated waters by a brine density flow mechanism (Anderson and Kirkland, 1980). The collapse structures allow the waters to follow a path they would not normally take; they allow less saturated, isotopically lighter fluids to enter lower formations.

RESULTS

The data collected to date have been plotted as δ D and δ ¹⁸0 values (Figs. 3, 4 and 5). Generally, the values increase with depth as expected. Some minor variations exist but they are within the ranges expected due to different formational flow rates.

CORY AND ALLAN DIVISIONS

Values of δ D and δ ¹⁸0 increase with depth in a normal manner to the mining levels. At Cory Division, both values decrease slightly in waters of the Duperow Formation (Figs. 4 and 5) — this may be due to a faster formational flow rate or to a more permeable formation so that the Duperow waters are less isolated from mixing with meteoric waters.

Isotopic compositions of water samples from the mining levels at both localities indicate that the majority of water leaking into these mines originates either from the overlying Dawson Bay Formation or from water trapped in the salt. Evidence that some of the leaks result from short circuiting of shallower aquifers is currently limited.

LANIGAN DIVISION

No water samples were available from the Lanigan shaft. Assuming that the waters in formations above the Lanigan Mine have similar values to those above the Cory and Allan Mines, the isotopic compositions of water leaking into the mine are compatible with an origin from shallower aquifers than the Dawson Bay, such as from the Souris River Formation (Fig. 5).

ROCANVILLE DIVISION

Analysis of data from the Rocanville Mine is more complex. Water samples collected from the mine shaft show normal increases in δ D and δ ¹⁸0 values down to the mine level. At

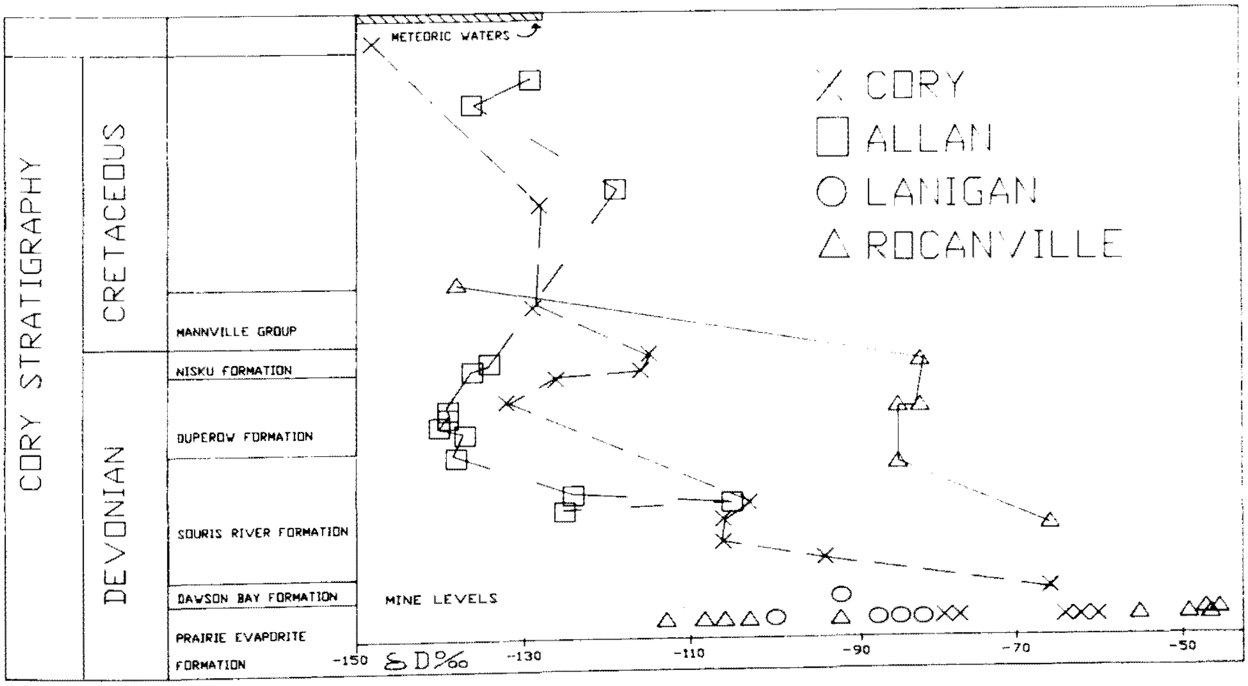

Figure 4. δ D versus depth.

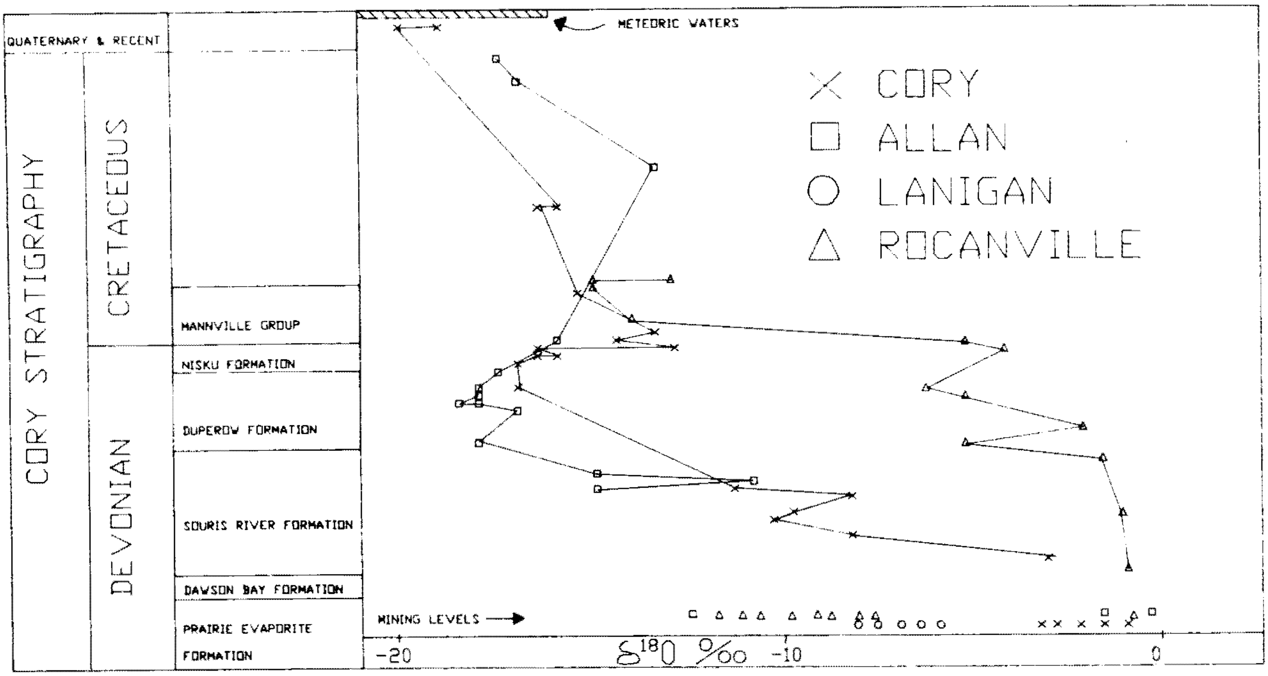

Figure 5. $\delta^{18}O$ versus depth.

the mining level, the data form two clusters (Figs. 4 and 5), one indicating fluids with isotopic compositions similar to those in the Dawson Bay, the second having much lower values. Water with the low values ($\delta^{18}O$ of -12 to -8 and δ D of -110 to -95) compare most closely with the values obtained from waters of the Mannville Group (Blairmore) or the Nisku Formation.

DISCUSSION

Waters at the Cory and Allan Divisions appear to be normal through to the brines encountered on the mining levels. Any leak in these mines should be monitored in case short circuiting of the formational fluids from shallower aquifers takes place. Mine-level brines in these two mines are unlikely to cause a serious flooding problem because they are in approximate chemical equilibrium with their surroundings.

Rocanville and Lanigan, however, because of the presence of waters from shallower aquifers at the mining level, should be monitored continually as any flooding is potentially more serious. The absence of short-circuited water in the shaft profile at Rocanville is encouraging and indicates that the observed short circuiting is not pervasive. At Rocanville, water sampling from the Mannville and lower formations should be continued in order to determine whether or not the regional flow regime has changed significantly due to the nearby IMC K-2 flood problem.

CONCLUSIONS

Continued isotope-monitoring programs may allow detection of changes in the local flow regimes around potash mines and evaluation of potentially hazardous water flow. A change to short-circuited water is a matter of great concern. A more widespread sampling program involving stable isotopes would greatly increase the knowledge of formation-fluid movement.

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