Project Summary

PREDICTING RESPONSE OF AN AQUIFER SYSTEM TO URANIUM EXTRACTION
Oakville Aquifer, Texas Coastal Plain

by

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ABSTRACT

Initiation or expansion of uranium mining by both open-pit and in situ leach methods in the Texas Gulf Coastal Plain raises questions about the potential impact of mining on ground water within mineralized aquifers and about the most efficient protection and restoration methods to be employed. The Oakville Sandstone, a major Coastal Plain aquifer, was selected as a natural laboratory to examine the interrelationships among hydrodynamics, hydrochemical evolution, and matrix geochemistry, and their impact on the effectiveness of mining technology in coastal plain aquifer systems.

The Oakville Sandstone consists of deposits of several major fluvial systems. Facies geometry and composition, plus superimposed structure and topography, are primary determinants of ground-water flux, aquifer transmissivity, and regional hydrochemical evolution. Ground-water flux patterns, particularly in shallow portions amenable to mining, may be highly complex.

Water hydrochemistry within the Oakville aquifer exhibits a clearly defined compositional change from predominantly sodium-chloride waters in the southwest to calcium-bicarbonate waters in the northeast. Large areas of sodium-chloride and sulfate-enriched ground water result from the natural mixing of Oakville water with water from stratigraphically deeper horizons. Upward migration of water having high total dissolved solids (TDS) occurs along faults associated with the Wilcox structural trend; cogenetic reduced sulfur mixes with meteoric ground water of low TDS and is rapidly oxidized to sulfate anions.

The regional distribution of trace amounts of uranium, molybdenum, selenium, and arsenic in Oakville ground water demonstrates a reasonably close correlation to

known sites of uranium mineralization. These same elements exhibit higher background concentrations in the southwestern portion of the study area. In the southwest, lower rainfall and poor recharge characteristics contribute to the buildup of toxic (e.g., arsenic) and aesthetically unpleasant (e.g., chloride) ground-water components; the converse is true to the northeast.

Uranium deposits occur along elongate geochemically zoned belts within transmissive portions of the aquifer. Associated metals typically include molybdenum, selenium, and arsenic. Post-mineralization modification has superimposed complex mineralogical and geochemical host environments on original ore bodies. Solid phases capable of reacting with released ions or trace metals include iron sulfides, iron oxyhydroxide and other oxide phases, clay minerals, zeolites, and organic matter.

A total of 78 water samples was collected from the Oakville aquifer in both mineralized and unmineralized areas to evaluate natural controls of trace-element concentrations. Potential controls include precipitation of reduced minerals in reducing environments and adsorption in either oxidizing or reducing environments. A modified version of the computer model WATEQF was used to calculate equilibrium between dissolved and solid trace-element species. Concentrations of the trace elements are low except within some mineralized zones, and only uranium among the trace elements fits thermodynamically predicted behavior. For these reasons it is not possible to predict completely the fate of trace elements released from surface or in situ uranium mines. However, controls to reduce concentrations are abundant in most geologic settings.

Complete management of uranium mining impact on an aquifer system requires (1) pre-mining baseline characterization, (2) monitoring during mining activity, (3) restoration or reclamation of the site to an acceptable condition, and (4) long-term site monitoring. Mining companies are traditionally responsible for the first three requirements, which are site-specific. Appropriate public institutions can provide regional data syntheses, long-term monitoring, and directed research required to document and to predict aquifer response more fully.

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INTRODUCTION

The exploratory drilling for and extraction of uranium resources intensified with the rise in unit price of U_3O_8 and the accompanying domestic energy shortfalls experienced during the past decade. After a period of modest development, the South Texas uranium province expanded dramatically as known deposits became economically exploitable and exploration discovered additional reserves. In 1978, nearly 3,000,000 m (10,000,000 ft) of exploration and development drilling was reported, presaging further expansion of exploitation activity.

Uranium production for 1980 is estimated to have ranged from 2,275 t (5,000,000 lb) to 2,725 t (6,000,000 lb) of U_3O_8. Nine companies operated in situ leach mine projects within the province. Three companies were actively mining by conventional open-pit methods. Indications are that leach mining will play an increasingly important role in future development of the province because of (1) the increasing depth of known deposits, (2) the minimal disruption of the land surface, and (3) the lower capital investment compared to surface mining. Further, portability of many leach systems makes them particularly appropriate in South Texas, where individual uranium deposits are typically small, widely dispersed, and commonly segmented by private ownership boundaries.

Uranium deposits of the South Texas uranium province occur primarily within highly transmissive portions of the Gulf Coast aquifer, a principal source of municipal, domestic, industrial, and agricultural water in the Texas Coastal Plain. The increasing mining activity poses an economically important alternate use of small but potentially significant portions of the Gulf Coast aquifer. Although the volume of aquifer matrix and contained ground water physically or geochemically modified directly by mining is infinitesimally small in comparison with the total aquifer volume, the dynamics of the aquifer system may spread effects beyond the mined area. Recognition of the importance of maintaining the integrity of the fresh-water resource has led to state regulation of both open-pit and leach mining activities. The Oakville Sandstone was chosen for study because it is the most productive fresh-water aquifer of the principal uranium host units of the South Texas uranium province. Mining activity has included both open-pit and in situ methods.

Potential adverse modification of ground water during mining operations can occur at three points. First, injected leachate or mine water may escape the mine perimeter. Second, the aquifer may not respond to the best available restoration technology. Third, short-term restoration may be successful initially, but later degenerate as kinetically slow or positive feedback reactions become significant. Short-term monitoring may not detect long-term changes in the geochemistry or hydrodynamics of the aquifer.

Our research program contained elements that address all three potential alternatives. Specific research objectives included

(1) Description and quantification, where possible, of the three-dimensional geometry of ground-water flux within a major uranium-bearing coastal plain aquifer, the Oakville Sandstone.

(2) Development of a regional baseline description of ground-water quality within the Oakville aquifer through the integration of existing and acquired data and application of appropriate models of hydrochemical evolution.

(3) Determination of natural ranges of dissolved major and trace components within hydrochemical facies of the Oakville aquifer, and evaluation of probable hydrologic parameters or water/rock interactions that control solution chemistry.

(4) Identification of any particularly sensitive areas for uranium mining on the basis of water use, water quality, and possible aquifer modification by mining.

(5) Identification of optimal criteria for locating and monitoring surface mine or in situ leach effluents during mining and reclamation/restoration.

(6) Identification and evaluation of the effectiveness of natural geochemical and hydrodynamic interactions within the aquifer system that could act to modify or dilute mine effluents.

(7) Assessment of present knowledge to predict the ultimate fate of mine effluents, particularly trace elements, on the basis of quantified aquifer parameters, mapped ground-water flux patterns, and expected geochemical reactions at specific mine sites.

DEPOSITIONAL AND HYDROGEOLOGIC FRAMEWORK

The Oakville Sandstone comprises a major sand-rich fluvial system composed of the deposits of several major and minor rivers that drained the interior of Texas and surrounding states. Broad bed-load fluvial axes, including the Hebbronville, George West, and New Davy trends, lie south of the San Marcos arch and host significant reserves of uranium (Figure 1). To the north, the Moulton streamplain consists of deposits of numerous small, flashy to ephemeral streams that drained the inland margin of the ancient coastal plain. The Burton/Penn mixed-load fluvial axes traverse the coastal plain in the general area of the modern Colorado and Brazos Rivers. Each fluvial axis consists of diagnostic sand and mudstone facies deposited in river channel, crevasse splay, and floodplain environments. Sand percentage, sand-body dimensions and lateral relationships, and composition vary systematically among the various axes.

The Oakville Sandstone closely corresponds to the Jasper aquifer system as discussed by hydrologists in various county and regional ground-water reports. The overall ability to transmit ground water, or transmissivity, of the Oakville, correlates directly with mapped facies composition and trend. Size of contained uranium deposits shows a strong positive correlation with associated aquifer transmissivity. Sand-rich, highly transmissive areas host the largest deposits.

Commercial uranium deposits lie within channel and interbedded crevasse splay sands in or along the margin of major fluvial belts, typically in close proximity to shallow faults. The mineralization occurs as narrow, elongate fronts separating geochemically altered, commonly pyritic, host sand from epigenetically sulfidized pyritic reduced sand. Deposits show pronounced spatial zoning of trace metals and iron disulfide, carbonate, and clay mineral phases across mineralization fronts.

HYDROCHEMISTRY

Regional appraisal of total dissolved solids in the Oakville aquifer reveals two hydrochemical regimes, confined largely to relatively shallow depths downdip from the outcrop of the Oakville Sandstone: (1) from Grimes County southwest to Karnes County, low TDS values indicate the dominance of shallow aquifer recharge; (2) from the middle of Karnes County through Duval County, more restricted recharge and leakage of saline ground water upward along faults associated with the Wilcox fault system strongly influence composition.

Fluvial channels characterized by high transmissivity relative to surrounding lithofacies constitute pathways that influence the direction and rate of ground-water flux. Tongues of fresh water (low TDS) extend downdip in response to permeability trends in fluvial axes. These permeable zones are also outlined by ground-water temperature data. Farther downdip and basinward from the zone of recharge-influenced shallow ground water is a zone of brackish water with only minor variability in TDS values. Beyond this zone, TDS values rapidly increase as the region of connate ground waters is approached. The increase in TDS content likely indicates the basinward discharge zone for Oakville ground waters.

Regional trends in bicarbonate content in Oakville waters indicate an approximately twofold increase in bicarbonate content as Oakville ground water migrates downdip towards the zone of regional discharge. Areas of high or relatively high bicarbonate within closed contours appear to coincide with interfluvial areas where there is increased clay for cation exchange and possibly increased residence time for reactions to occur.

A good correlation exists between sulfate and chloride content within areas of probable fault discharge in Duval, Live Oak, Bee, and Karnes Counties. Local areas with a high content of reduced sulfur species can be positively correlated with faults inferred to be discharging more evolved, higher TDS water into the Oakville aquifer. A sequence of events entails discharge of chloride-rich, hydrogen-bisulfide-bearing water along fault planes, followed by updip movement of the water, and oxidation of the hydrogen bisulfide to sulfate as the water mixes with recharging meteoric Oakville water. This sequence accounts for linear zones of high chloride and sulfate water in portions of the Oakville aquifer. The ratio of sodium to calcium increases downdip, illustrating the regional effect of cation exchange for sodium by calcium in the clay fraction of the Oakville sediments.

Ground-water facies as depicted on Piper diagrams and plotted in map form (Figure 2) illustrate regional changes in water hydrochemistry within the Oakville aquifer. The overall change is from sodium-chloride waters in Duval County to calcium-bicarbonate waters in Washington and Grimes Counties. Superimposed on the map in Figure 2 are known and probable fault zones interpreted to be discharging compositionally different water from the deeper subsurface.

Trace Metals

Isograds of uranium, molybdenum, and selenium concentration define regional trends in background trace-metal content and numerous anomalies within the Oakville aquifer. The coincidence of geochemically anomalous areas having permeable fluvial axes (or margins of fluvial axes) and uranium occurrences is readily demonstrated by comparing geochemical and lithostratigraphic maps that illustrate the distribution of active and abandoned mines. For example, the 10 ppb uranium isograd delineates a large wing-shaped anomaly oriented down a major channel axis in the George West mining district. Regions of anomalous uranium and associated selenium overlap in map view, especially in those areas where significant anomalies can be directly related to known uranium deposits. The general level of uranium, molybdenum, and selenium is higher in the southwestern part of the Oakville aquifer than in the parts of the aquifer along strike to the northeast. This could be caused by the combination of greater original abundance of metals available for mobilization, as well as less dilution by circulating meteoric waters. Conversely, the greater recharge dilution factor to the northeast, because of a wetter climate, may decrease trace-metal levels in this area.

GEOCHEMICAL CONTROLS OF OAKVILLE WATER COMPOSITION

The objective of this study is to determine the effect of both surface and solution mining on an aquifer, especially on the chemical quality of water. Trace metals bound up in uranium deposits and various components of the leach fluid could alter the composition of ground water and make it unusable. We wish to examine possible effects of mining to determine how severe they may be, what factors control severity, and whether natural or artificial mitigation is possible.

To accomplish this assessment, three interrelated approaches were used: (1) existing ground-water chemistry in the Oakville aquifer was analyzed to provide baseline information and to examine natural controls of trace-metal concentrations; (2) theoretical or experimentally determined controls of trace-element concentrations in water were examined; and (3) Oakville water chemistry around sites of uranium mineralization was examined to evaluate natural alteration of a deposit. In some ways, this third approach simulates the effects of mining and may indicate how an aquifer will respond to mining.

Oakville hydrochemistry was examined by collecting and analyzing 60 water samples from wells along 10 dip-oriented regional cross sections. Sections chosen represent different physical environments, that is, the different depositional systems within the Oakville aquifer. Additionally, 21 samples were collected from wells around 2 major uranium mining areas to determine the water chemistry in these critical areas and to supplement regional information.

Well-sampling locations were selected using the hypothesis that the physical and chemical framework (including total thickness and percentage of sand, mineralogy, and chemical composition of the aquifer, all of which vary locally and regionally) should control water chemistry. Thus, different depositional environments in the Oakville Formation may possess different characteristic water chemistries. Generally, examination of data in dip profile assumes that ground water is recharged in the outcrop area and flows downdip. Therefore, downdip water should evolve from water updip. Under this assumption, the evolution of water chemistry can be studied by sampling a series of wells from the recharge area into the subsurface. This assumption is incomplete; the Oakville aquifer is highly anisotropic and ground-water does not flow simply straight downdip.

Major Ion Chemistry

Oakville water encompasses a wide variety of chemical types. Total dissolved solids range from less than 500 mg/L to more than 3,000 mg/L. There is a geographic zonation of chemical types with East Texas water distinct from South Texas water.

East Texas water is generally low in dissolved solids and shows an evolution from calcium-magnesium-bicarbonate water near the surface and in recharge areas to sodium-bicarbonate water in the deepest sampled parts of the aquifer. This zonation is common to many clastic aquifers in Texas and elsewhere, and results from a combination of calcite dissolution and cation exchange with smectite.

Water of South Texas has higher concentrations of total dissolved solids than water in East Texas. Chloride concentrations illustrate this point; almost all are greater than 100 mg/L, and they range up to 1,000 mg/L. There are two major sources of the higher total dissolved solids in South Texas water: (1) solution of evaporites within low permeability parts of the Oakville Sandstone, and (2) discharge of chloride-rich, high total dissolved solid water into the Oakville. Nevertheless, South Texas water also shows the effect of calcite dissolution and cation exchange.

Oxidation and Reduction

The oxidation state of Oakville ground water was investigated because of its importance in evaluating oxidation-reduction reactions and trace-element solubility. Oxidation state was determined in several ways. Dissolved oxygen and Eh were measured directly at the time of sampling. Eh was also calculated from the oxidized-reduced couples NO_3-NH_3 and SO_4-H_2S by the Nernst equation. Measured Eh was also compared with Eh values predicted from dissolved oxygen concentrations under different assumptions. Measured Eh gives the best and most consistent results.

Eh values of this study cluster in three groups. Eh shows a regular pattern of decrease with position and depth only in part of the Oakville aquifer. In other parts, Eh values display an irregular pattern. Overall, Eh decreases with depth but with reversals.

Water with Eh values greater than 300 mV contains measurable dissolved oxygen. This oxidizing zone occurs in areas of recharge and extends to variable depths within the Oakville. Eh is probably controlled by reaction between dissolved oxygen and hydrogen peroxide. Eh values determined from the NO_3-NH_3 couple are similar to measured values but the NO_3-NH_3 reaction is probably not in equilibrium.

An intermediate zone with Eh values between 110 and 10 mV occurs downdip of the oxidizing zone. About half of the intermediate Eh water contains low but detectable concentrations of hydrogen sulfide. In some areas, the deepest wells sampled are still in this intermediate zone. Within this range, Eh is probably controlled by ferrous-ferric mineral reactions. Both the NO_3-NH_3 and SO_4-H_2S couples appear to be out of equilibrium.

A highly reducing zone with Eh less than -40 mV occurs in the deepest parts of the Oakville Sandstone in several areas, as well as at very shallow depths in other areas. In these latter areas, the reducing water appears to be associated with faults that have provided conduits for the rise of highly reducing, sulfide-rich waters from deeper formations. All waters from this reducing zone contain dissolved hydrogen sulfide, and Eh is probably controlled by the presence of hydrogen sulfide or by oxidation of pyrite. Pyrite in the Oakville has two sources: (1) syngenetic species formed by reduction of organic matter, and (2) epigenetic species formed by reaction of highly reducing, sulfide-rich waters, leaked along faults from deeper formations, with iron in the Oakville.

Trace-Element Distribution

Uranium, molybdenum, arsenic, and selenium all have somewhat similar geochemical behavior; their occurrence together in epigenetic uranium deposits is one indicator of the similarities. All have two or more common oxidation states. In oxidized valence states, molybdenum, arsenic, and selenium can form soluble oxyanions in water. Uranium in the oxidized 6+ valence forms the uranyl ion (UO_2^{2+}), which commonly forms negatively charged complexes with inorganic ligands such as carbonate or phosphate. Reduction from the higher to lower valences leads to formation of relatively insoluble minerals, including sulfides, oxides, silicates, or the native element. This reduction is the general basis for formation of uranium ore deposits and accumulation of molybdenum, arsenic, and selenium with the uranium.

Controls on solubility of the elements include adsorption and mineral precipitation. In general, oxidized valence minerals of the elements are highly soluble and, except under unusual circumstances, do not place significant limits on concentrations in oxidizing waters. Adsorption by a variety of natural colloids, especially amorphous iron hydroxide, is probably the dominant control of concentrations and mobility in oxidizing ground water. Equilibrium with insoluble reduced minerals should control the concentrations of the trace elements in reducing water.

Uranium

Uranium concentrations within the Oakville aquifer range from below detection limits (0.2 µg/L) to 99 µg/L. However, only four samples have concentrations greater than 10 µg/L, and these occur in South Texas water samples. Also, higher concentrations of uranium are restricted to oxidizing water where the concentrations may be controlled by adsorption. Concentrations in samples of intermediate Eh and reducing water are low and appear to be controlled by equilibrium with coffinite, a uranium silicate.

Molybdenum, Arsenic, and Selenium

Molybdenum, arsenic, and selenium show a geographic zonation similar to uranium; that is, the highest concentrations occur in South Texas water samples. The geochemical controls on concentrations are not clear, however. The elements do not follow behavior predicted from available thermodynamic data, which indicates that they should occur in low or undetectable concentrations in reducing water and be in equilibrium with various reduced minerals. Typically, the water samples are highly oversaturated with respect to the reduced minerals. Probably, complexing by organic or inorganic ligands, unaccounted for by our chemical model, increases the solubility of the elements.

HYDROGEOLOGIC SETTING AND IMPACT OF MINING

The Oakville Sandstone produces most of its ore in the George West and Ray Point districts, Live Oak County.

The Ray Point district covers approximately 24 km^2 (9 mi^2) and lies in an area of aquifer recharge. Associated shallow faulting physically separates the basal sand aquifer and produces a major flow boundary. Ground water moves within the mined Oakville sands through a local flow cell and may in part return to the surface nearby as discharge into Sulfur Creek. Encroaching near-surface oxidation has locally remobilized metals associated with the ore body, producing unusually mineralized shallow ground water. Ore depths are shallow (less than 100 m), and mining includes both open-pit and leach operations.

The George West district contains large reserves of ore at depths from 60 to 200 m (200 to 700 ft). All mining is by in situ leaching and encompasses an area of about 50 km^2 (20 mi^2). The district lies within a regional recharge zone for the Oakville aquifer, which is semiconfined. Ground-water flow is nearly strike parallel and is part of an intermediate flow cell directed toward the valley of the Nueces River. Uranium deposits occur both entirely within pyritic reduced sands and at boundaries between oxidized and pyritic sands. Local oxidation of ore and remobilization of uranium and associated metals by actively circulating meteoric waters continues.

CONCLUSIONS AND RECOMMENDATIONS

Our examination of the interrelationships among the geology, hydrodynamics, and hydrochemistry of a uranium-bearing aquifer system has provided the basis for several conclusions, which are listed below. These conclusions are applicable not only to the Oakville but also to analogous aquifers of the Texas Coastal Plain and elsewhere. Recommendations are directed both to private and public organizations.

1. Uranium mining in South Texas and in other uranium districts will increasingly be by in situ leaching or by integrated solution and open-pit mining involving several different operators.

Recommendation

As mining becomes geographically or geologically dispersed within a uranium province, regional studies (which summarize existing knowledge of the hydrodynamics, water quality, and current use of aquifers within the context of their natural geologic subdivisions) are needed to provide a systematic framework for integrating and evaluating new baseline data.

2. Aquifer sensitivity, as it relates to present and future ground-water demands, should be determined in view of the overall hydrologic budget and land/water use patterns within the area impacted by mining. For example, water quality, climate, and land use all vary systematically within the Oakville aquifer and its area of use.

Recommendation

The Oakville (and other aquifers) should be divided into zones of aquifer sensitivity on the basis of the factors mentioned above. Evaluation of potential mining impact should consider the relative sensitivity of each zone. In Figure 3, three zones of aquifer sensitivity are suggested for the Oakville aquifer. A zone of Oakville ground-water use with relatively higher sensitivity to the effects of drought and human activities is flanked by zones of lower aquifer sensitivity. Each zone has separate recharge and water-quality characteristics created by regional differences in climate and geology. Recognizing regional differences in aquifer sensitivity is critical to efficiently regulating development and restoration practices.

3. Circulation of ground water within an aquifer system occurs in geometrically complex flow cells, including regional, intermediate, and local flow systems. Only regional and intermediate flow systems are adequately defined by most available data; the effects of mining may be influenced primarily by the local flow systems.

Recommendation

The hydrodynamic setting of a mine permit area should be adequately described, including:

(A) Hydraulic head within the ore-bearing unit.

(B) Vertical head distribution for principal water-bearing zones above and directly below the ore-bearing aquifer, if present.

(C) Interpretation of the permeability of surrounding aquitards, and of permeability anisotropy within the aquifer. Duration of tests and analytical techniques employed in reported pump tests from the permit area commonly have been inadequate to these tasks.

(D) Aquifer permeability and transmissivity.

(E) General flow direction(s) in the permit area, calculated (if appropriate) to reflect significant measured permeability anisotropy.

(F) Complete documentation of pump-test methodology and calculations.

4. Meteoric recharge, local oxidation-reduction (redox) conditions within the aquifer, adsorption of dissolved ions by matrix minerals, and buffering by carbonate content characteristic of Oakville lithologies all influence the concentrations and migration of potentially toxic constituents within and around the mine site.

Recommendation

To monitor accurately and to understand the relationship between aquifer matrix and ground-water quality in a potential mine area, the following steps should be taken:

(A) The suite of analyses selected to monitor uranium mining and subsequent reclamation or restoration will be most effective if designed to account for elements indigenous to the ore zone, the composition of the lixiviant used in in situ leaching, and related water chemistry and matrix factors that have a bearing on mineral solubility and complexing.

(B) Cation exchange capacity of the principal representative permeable matrix facies should be determined.

(C) The quality of ground-water analyses should be monitored periodically.

5. Ground-water monitoring at mine sites includes both short-term monitoring during mining and long-term monitoring following reclamation or restoration. Effective programs must be tailored to the particular mine site.

Recommendation

(A) Active leach mine--Monitor wells should sample the affected aquifer around the periphery of the permit area, all aquifers above the injection zone, and any aquifer below and separated from the injection zone by a demonstrably leaky aquitard. Chloride, which can be adequately monitored by conductivity changes (as a component of total dissolved solids), appears to be an optimum choice for routine measurement. In general, routine measurement of additional constituents ought to be tailored to the individual leach solution chemistry used.

(B) Restored leach mine site--Follow-up monitoring of wells along the downflow periphery of mined ground should be incorporated into the state water-quality grid. If changes in water chemistry are detected during this time, existing or new wells at an appropriate distance downflow (on the basis of calculated flow velocity) should be monitored to determine the velocity and magnitude of downflow dilution or mitigation of the chemical plume.

(C) Open-pit mine site--A limited number of monitor wells should be established along the downflow periphery of disturbed ground and analyzed for trace metals and TDS. Monitoring should continue for several years following reclamation. In addition, waters in pits converted to stock tanks should be tested regularly.

6. Most impacts on water quality and the chemical reactions that produce or mitigate them are, at present, only qualitatively predictable, especially in regard to long-term migration of potentially toxic trace elements.

Recommendation

(A) Pre-mining conditions--Better knowledge of pre-mining conditions is necessary, including baseline water quality discussed in conclusion 4 above, but also mineralogical form of the trace elements and mineralogy of the deposit area in general. Both of these latter affect release and mobility of the trace elements during and after mining.

(B) Restoration studies--More complete, thoroughly documented studies of restoration, to examine actual behavior of contaminants in a natural system, are needed.

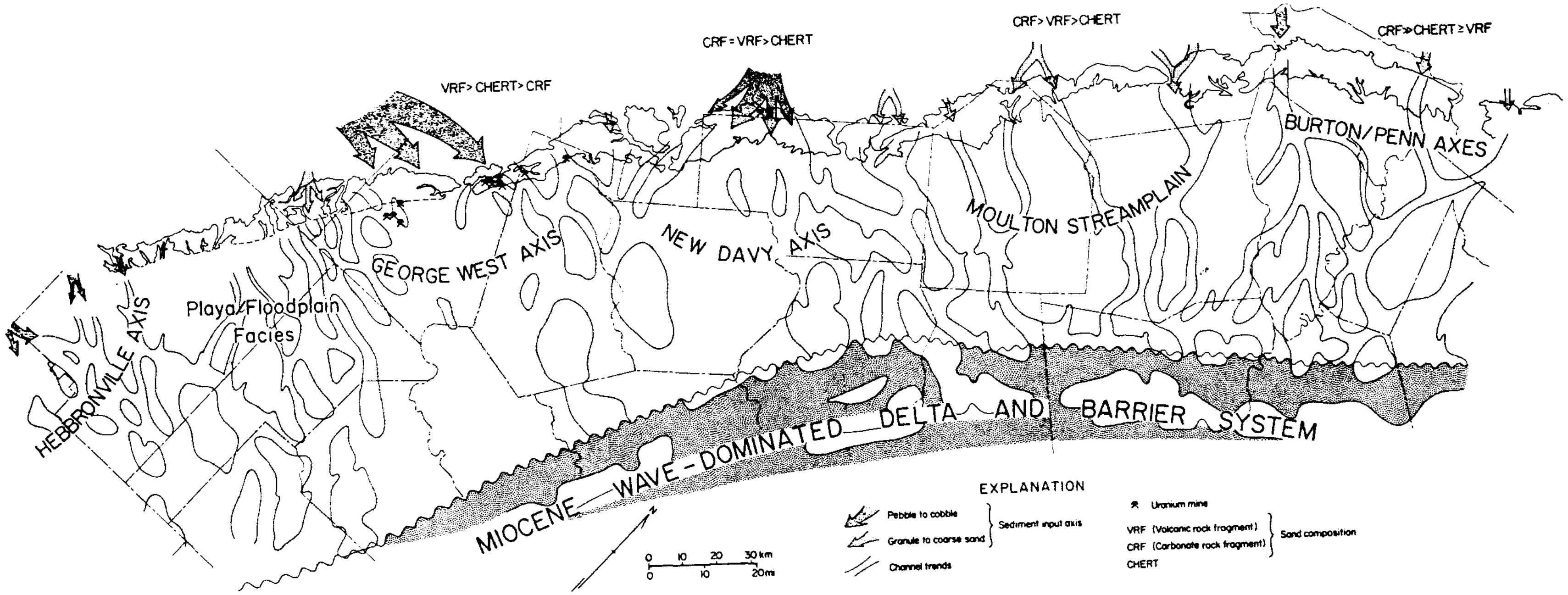
(C) Experimental data--Better knowledge of the thermodynamic data and behavior of trace elements in common ground waters is necessary.

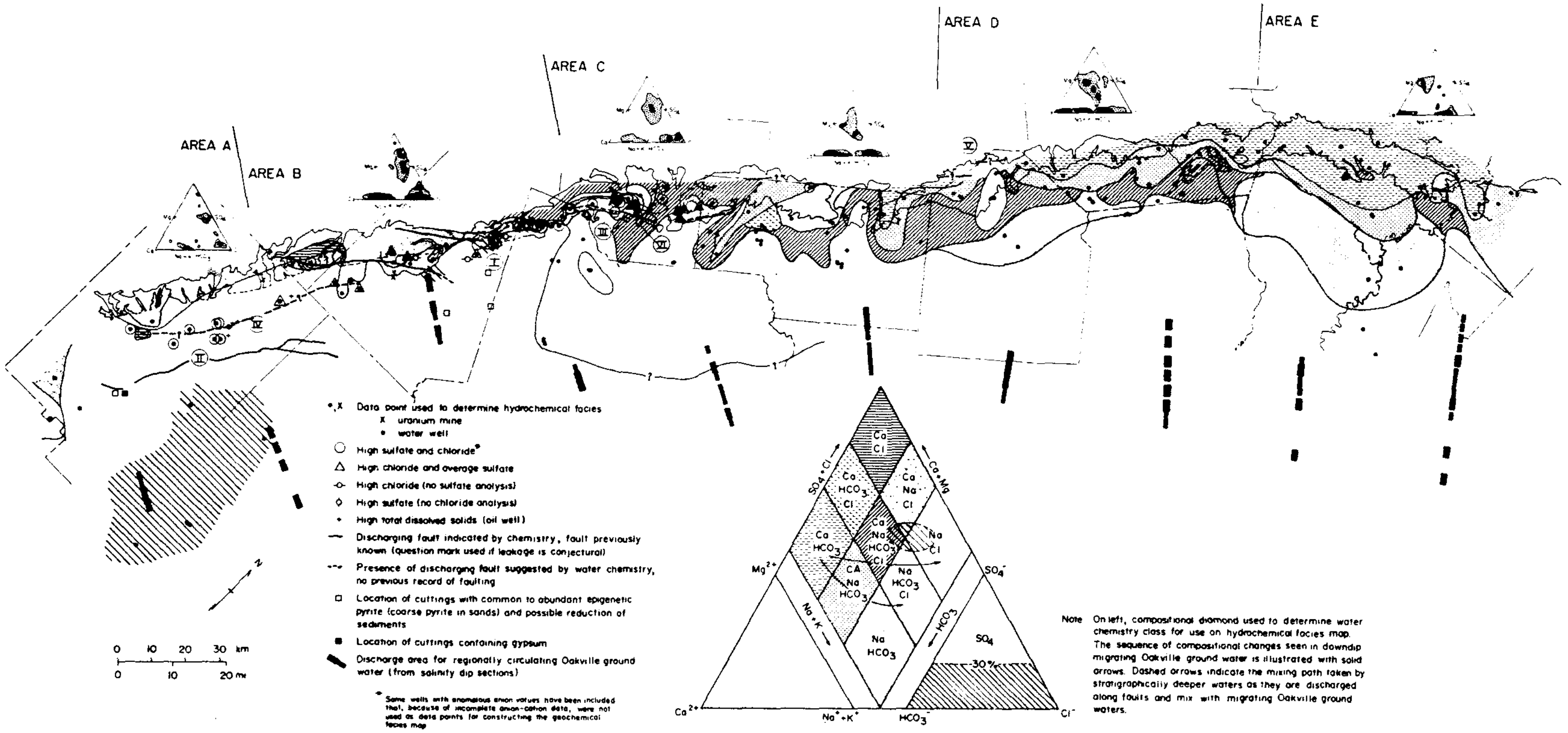
FIGURE CAPTIONS

Figure 1. Depositional elements of the Oakville fluvial system. Entry of major rivers onto the coastal plain is recorded by the Hebbronville (which lies largely south of the study area), George West, New Davy, and Burton/Penn fluvial axes. The Moulton streamplain is a broad, interaxial area characterized by deposits of numerous local, flashy to ephemeral streams. The dip-oriented fluvial elements merge downdip with strike-oriented facies of the equivalent strandline sands of Miocene delta and barrier systems. Composition of lithic grains in sands confirms the presence of at least three different source terranes for the rivers.

Figure 2. Hydrochemical facies patterns within the Oakville aquifer. Water with a normal downdip evolutionary sequence is found in the northeast; to the southwest, fault leakage and subsequent mixing has lead to a predominance of ground water having a sodium chloride composition and various local hybrid water types.

Figure 3. Summary of Oakville hydrology and land use with consequent, interpreted aquifer sensitivity.


VRF> CHERT> CRF
CRF = VRF> CHERT
CRF> VRF> CHERT
CRF≫CHERT ≥ VRF
BURTON/PENN AXES
MOULTON STREAMPLAIN
NEW DAVY AXIS
GEORGE WEST AXIS
Playa/Floodplain Facies
HEBBRONVILLE AXIS
MIOCENE WAVE-DOMINATED DELTA AND BARRIER SYSTEM
N
0 10 20 30 km
0 10 20 mi
EXPLANATION
Pebble to cobble
Granule to coarse sand
Sediment input axis
Channel trends
Uranium mine
VRF (Volcanic rock fragment)
CRF (Carbonate rock fragment)
CHERT
Sand composition



•, X Data point used to determine hydrochemical facies
  X uranium mine
  • water well

○ High sulfate and chloride*

△ High chloride and average sulfate

-○- High chloride (no sulfate analysis)

◊ High sulfate (no chloride analysis)

• High total dissolved solids (oil well)

— Discharging fault indicated by chemistry, fault previously known (question mark used if leakage is conjectural)

--- Presence of discharging fault suggested by water chemistry, no previous record of faulting

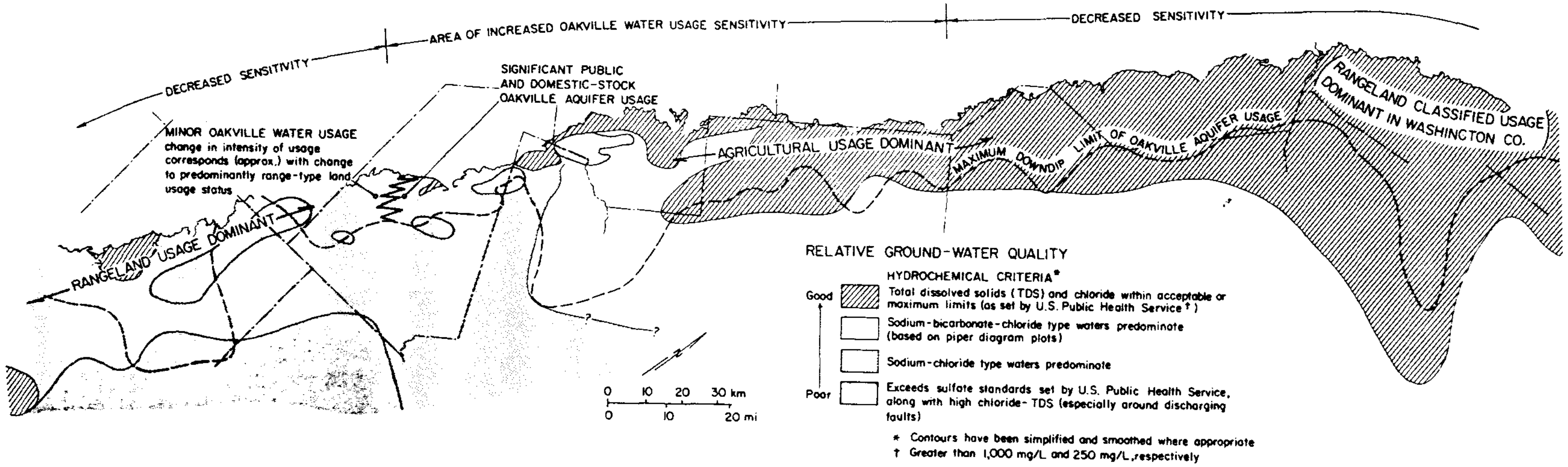
□ Location of cuttings with common to abundant epigenetic pyrite (coarse pyrite in sands) and possible reduction of sediments

■ Location of cuttings containing gypsum

▬ Discharge area for regionally circulating Oakville ground water (from salinity dip sections)

* Some wells with anomalous anion values have been included that, because of incomplete anion-cation data, were not used as data points for constructing the geochemical facies map

Note On left, compositional diamond used to determine water chemistry class for use on hydrochemical facies map. The sequence of compositional changes seen in downdip migrating Oakville ground water is illustrated with solid arrows. Dashed arrows indicate the mixing path taken by stratigraphically deeper waters as they are discharged along faults and mix with migrating Oakville ground waters.


DECREASED SENSITIVITY
AREA OF INCREASED OAKVILLE WATER USAGE SENSITIVITY
DECREASED SENSITIVITY
SIGNIFICANT PUBLIC AND DOMESTIC-STOCK OAKVILLE AQUIFER USAGE
MINOR OAKVILLE WATER USAGE
change in intensity of usage corresponds (approx.) with change to predominantly range-type land usage status
RANGELAND USAGE DOMINANT
AGRICULTURAL USAGE DOMINANT
MAXIMUM DOWNDIP LIMIT OF OAKVILLE AQUIFER USAGE
RANGELAND CLASSIFIED USAGE DOMINANT IN WASHINGTON CO.
?
?
0 10 20 30 km
0 10 20 mi
RELATIVE GROUND-WATER QUALITY
HYDROCHEMICAL CRITERIA*
Good
Poor
▨ Total dissolved solids (TDS) and chloride within acceptable or maximum limits (as set by U.S. Public Health Service†)
☐ Sodium-bicarbonate-chloride type waters predominate (based on piper diagram plots)
☐ Sodium-chloride type waters predominate
☐ Exceeds sulfate standards set by U.S. Public Health Service, along with high chloride-TDS (especially around discharging faults)
* Contours have been simplified and smoothed where appropriate
† Greater than 1,000 mg/L and 250 mg/L, respectively