11015

INTERNATIONAL GROUNDWATER SYMPOSIUM

ON

GROUNDWATER RESOURCES UTILIZATION AND CONTAMINANT HYDROGEOLOGY

1984 May 21-23
Montreal, Quebec, Canada

Volume I: Groundwater Resource Utilization

Compiled by Ray Pearson

Sponsored by
The International Association of Hydrogeologists
Canadian National Chapter

AVANT-PROPOS

Le Chapître national canadien de l'Association internationale des hydrogéologues a le plaisir de présenter ce compte rendu du Congrès international sur les eaux souterraines, sur l'utilisation des ressources des eaux souterraines et de l'hydrogéologie des contaminants. Le congrès fut planifié afin de donner une occasion unique aux spécialistes des eaux souterraines travaillant au Canada, de se rencontrer avec d'autres individus de la communauté hydrogéologique pour discuter les problèmes d'intérêts mutuels. Plus de 50 papiers techniques sur les études des eaux souterraines dans onze différents pays ont été incorporés dans le compte rendu. Alors que l'utilisation des ressources des eaux souterraines augmente continuellement dans plusieurs régions du monde, il y a un besoin accru pour des communications efficaces parmi les individus et les agences engagés dans des activités ayant rapport aux eaux souterraines. C'est espéré que les résultats de ce congrès seront mesurables, non seulement aux individus qui y participent, mais aux autres qui liront le compte rendu.

Plusieurs individus et agences ont fait un don de leur temps, ressources et énergies au congrès. Au nom du Chapître national canadien, j'aimerais particulièrement remercier les membres du Commité d'organisation, pour leur travail ardent et leur persévérance, et à l'exécutif de l'Association canadienne des eux de puits et l'Association de forage des eaux de puits du Québec pour leur support dans la réalisation de ce congrès. En plus, j'aimerais remercier tous les auteurs qui ont contribué des papiers, les orateurs et enfin, les présidents de les rencontres.

Alan Kohut
Président
Comité d'organisation

FOREWORD

The Canadian National Chapter of the International Association of Hydrogeologists is pleased to present these Proceedings of the International Groundwater Symposium on Groundwater Resources Utilization and Contaminant Hydrogeology. The Symposium was planned to provide a unique opportunity for groundwater specialists working in Canada to meet with other individuals from the world hydrogeologic community to discuss problems of mutual interest. Over 50 technical papers outlining groundwater studies in eleven different countries have been incorporated in the Proceedings. As the utilization of groundwater resources continues to grow throughout many parts of the world there is an increased need for effective communication among individuals and agencies involved in groundwater related activities. It is hoped that the results of this Symposium will be measurable not only to those individuals that participated but to others that may read the Proceedings.

Many individuals and agencies donated their time, resources and energies to the Symposium. On behalf of the Canadian National Chapter I would particularly like to thank the members of the Organizing Committee for their hard work and perserverance and the Executive of the Canadian Water Well Association and the Quebec Water Well Drilling Association for support in making the symposium a reality. I wish to thank moreover, all of the authors that contributed papers, the speakers and finally the chairmen that presided over the meetings.

Alan Kohut
Chairman
Organizing Committee

INTRODUCTION

L'idée d'organiser un Chapître national canadien de l'Association internationale des hydrogéologues a pris naissance à Montréal aussi récemment que 1972. En dépit des difficultées considérables faisant face aux quelques douzaines de membres dispersés dans un vaste pays tel que le Canada, une Conférence nationale hydrogéologique fut tenue à Edmonton en 1978, et ensuite à Winnipeg en 1983, avec la coopération de l'Association canadienne des eux de puits (CWWA). Basé sur le succès de la conférence à Winnipeg, le CWWA a invité le CNC/AIH à être hôte au composant scientifique-technique à une autre réunion de cette association à Montréal en 1984.

Le défi fut accepté et la décision prise d'organiser ce qui serait la première conférence internationale dans l'histoire du Chapître national canadien. La décision fut suivie d'un travail ardent, dévoué et bien coordiné par un Comité du programme technique, composé de membres de l'Association venant de sept des dix provinces canadiennes d'une côte à l'autre du pays. L'effort des organisateurs est comblé et abrégé par ce compte rendu contenant plus de 50 papiers contribués par des hydrogéologues de onze pays.

En fonction de président sortant de charge et ayant vu et pris part à la naissance et la croissance du Chapître national canadien de l'Association internationale des hydrogéologues pendant les derniers douze ans, c'est avec grand plaisir et intérêt pour moi d'introduire cette excellente collection de papiers à la communauté internationale hydrogéologique. Le Congrès international de 1984 à Montréal et le volume de ce compte rendu qui en résulte, constituent l'évidence la plus forte et la plus récente que l'hydrogéologie entre en sa majorité au Canada et de la vitalité du CNC/AIH. C'est mon sincère désir que le Congrès et le compte rendu seront la contribution tangible de notre Chapître national à l'avancement de la science de l'hydrogéologie, à la consolidation de l'identité hydrogéologique canadienne et mieux encore, à l'approfondissment de la bonne volonté et du rapport mutel entre les hydrogéologues des différentes régions du monde.

J. Toth
Ancien président
Chapître national canadien
Association internationale des hydrogéologues

INTRODUCTION

The idea to organize a Canadian National Chapter of the International Association of Hydrogeologists was born in Montreal as recently as in 1972. Notwithstanding the considerable difficulties faced by a small membership of only a few dozen scattered in a vast country like Canada a National Hydrogeological Conference was held in Edmonton already in 1978, and then, in co-operation with the Canadian Water Well Association, in Winnipeg in 1982. Based on the success of the Winnipeg conference the CWWA invited CNC/IAH to host the technical-scientific component of yet another meeting of that Association in Montreal in 1984.

The challenge was accepted and the decision made to organize what was to be the first international conference in the history of the Canadian National Chapter. The decision was followed by the hard, devoted and well co-ordinated work of a Technical Program Committee composed of Association members from seven of the ten Canadian provinces, from coast to coast. The effort of the organizers is crowned and epitomized by this Proceedings volume containing over 50 papers contributed by hydrogeologists from 11 countries.

As the outgoing President, who has seen and taken part in the birth and growth of the Canadian National Chapter of the International Association of Hydrogeologists for the last twelve years, it is a matter of particular pleasure and pride for me to introduce this collection of fine papers to the international hydrogeological community. The 1984 International Syposium at Montreal and the resulting Proceedings volume are the latest and most convincing evidences of Hydrogeology coming of age in Canada and the vitality of CNC/IAH. It is my sincere wish that through the Symposium and the Proceedings our National Chapter will have tangibly contributed to furthering the science of hydrogeology, strengthening the Canadian hydrogeological identity, and last but not least, deepening the good will and mutual respect among hydrogeologists of different parts of the world.

J. Toth
Past President
Canadian National Chapter
International Association of Hydrogeologists

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For Publishing Proceedings: Technical Information Services
Atomic Energy of Canada Limited
Whiteshell Nuclear Research Establishment
Pinawa, Manitoba

For Translations: The Department of Secretary of State - Government of Canada has granted financial assistance towards the provisions of translated services.

For Donations: Filtrite Inc., Quebec, Quebec

Les Consultants Carrier, Trotier, Aubin et associes, Saint-Foy, Quebec

Tuyaux Atlas, Atlas Pipe, Montreal, Quebec

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VOLUME I - GROUNDWATER RESOURCE UTILIZATION

L'APPLICATION DE DIAGRAPHIES DE FORAGE AUX RECHERCHES EN HYDROGEOLOGIE

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RESUME

Les diagraphies instantanées de forage ont été développées depuis quelques années en France. Ces diagraphies pratiquées pendant le forage même permettent essentiellement une reconnaissance continue des caractéristiques physiques et mécaniques du sous-sol par l'instrumentation des paramètres de forage: Vitesse de pénètration instantanée de forage, dureté de la roche, pression de poussée de la foreuse, vitesse de rotation des tiges, pression du couple du taillant de forage, pression du liquide d'injection de forage etc. Les diagrammes obtenus permettent de distinguer les horizons stratigraphiques différents et de discerner à l'intérieur d'une même formation les zones fissurées ou fracturées. Les diagraphies permettent ainsi de reconnaître les réservoirs souterrains de perméabilité de fissures.

L'auteur décrira les équipements couramment employés et leur adaptabilité aux foreuses en recherche d'eau, et concluera avec un aperçu sur les développements en enregistrement sur bande magnétique et traitement des données enregistrées par ordinateur.

ABSTRACT

Instantaneous drilling recordings have been successfully used in France for some time. These recordings allow an identification of subsurface physical and mechanical characteristics by the measurement of parameters such as: Instantaneous rate of penetration, rock hardness, bit thrust, rotation speed of rod stem, torque on bit, pressure of the cooling liquid, etc. The characteristics, in soils as well as in rock, appear on diagrams. Their interpretation will identify the stratigraphy, as well as fissured or fractured zones within a specific horizon. It is then possible to delineate aquifers and aquicludes.

The different equipements currently used, and their mounting on various drill rigs, are described. The author also covers the more recent recordings on magnetic tape and illustrates an example of computerized interpretation.

INTRODUCTION

Les techniques d'instrumentation de foreuses ou de trous de forage sont connues depuis plusieurs décennies et pratiquées de façon courante dans l'industrie des forages d'exploration pétrolière.

L'adaptation de ces techniques au domaine du génie civil et de l'hydrogéologie en particulier est cependant plus récente et date d'une dizaine d'années seulement. Les Français, qui avaient inventé les logs Schlumberger des puits de pétrole, ont été encore une fois les pionniers dans le développement de ces techniques et des outils pour les réaliser. Plusieurs firmes ont démarré à la même époque, au début des années '70, la recherche d'appareils d'enregistrement de paramètres de forage.

Les appareils actuellement disponibles fonctionnent déjà suivant les principes de l'électronique de pointe et peuvent être offerts aujourd'hui avec enregistrement sur bande magnétique pour traitement éventuel par ordinateur. La Figure 1 montre l'équipement le plus couramment utilisé. Les Figures 2 à 5 illustrent des exemples d'utilisation sur différentes foreuses.

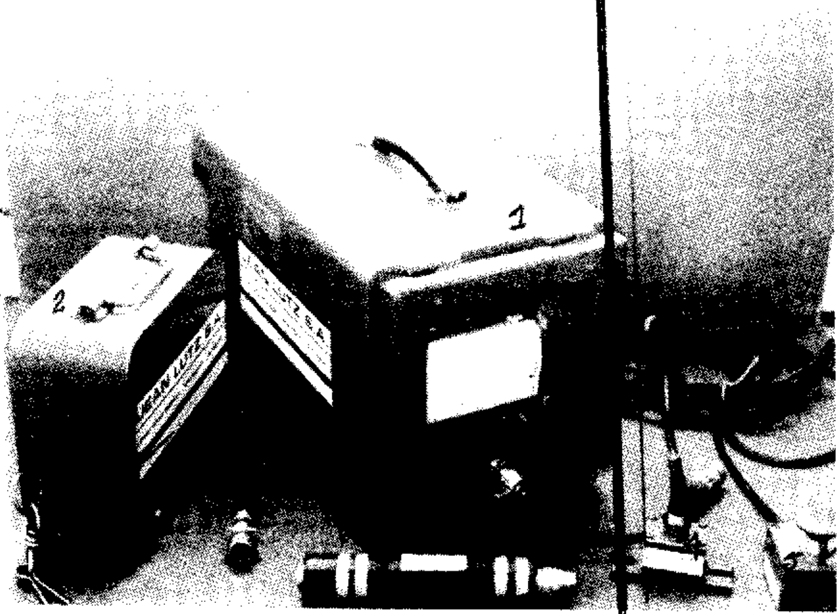

Figure 1: Exemple d'une panoplie d'enregistrement de paramètres de forage comprenant l'unité d'enregistrement (1), le capteur de vitesse de pénétration du forage (2), un capteur de pression hydraulique (3), le capteur de dureté réfléchie de la roche (4) et l'interrupteur de redémarrage d'enregistrement du foreur (5).

LES PARAMETRES ET LEUR MESURE

Les techniques d'enregistrement des paramètres de forage impliquent deux grands ensembles de mesures, l'un relatif aux qualités intrinsèques des matériaux du sous-sol traversé tels que leur densité, leur dureté, leurs variations et leurs discontinuités et l'autre relatif aux caractéristiques de l'outil et des efforts de forage.

Dans le premier ensemble de mesures on trouve la vitesse d'avancement du forage, la dureté "réfléchie" de la roche et la perméabilité relative du matériau foré que l'on mesure d'après le gain ou la perte de la pression du fluide d'injection.

Les paramètres mesurés sur la foreuse qui permettent de caractériser la forabilité du matériau sont la pression hydraulique de poussée, la pression du marteau de frappe en percussion, le couple et la vitesse de rotation du train de tiges, la pression de retenue sur le train de tiges, etc.

La Vitesse Instantanée d'Avancement du Forage

La mesure de la vitesse d'avancement constitue la base des paramètres enregistrés en diagraphies de forage, les variations de la vitesse de pénétration étant reliées aux variations lithologiques et aux variations de la fracturation des roches.

Le capteur de la vitesse d'avancement est généralement fixé au sommet du mât de la foreuse et enregistre au moyen d'un câble flexible les déplacements de la tête de la foreuse. Ces capteurs peuvent être conçus pour détecter la vitesse instantanée du forage ou la vitesse moyenne d'un intervalle choisi en fonction de la rapidité du forage (de 0.1 cm à 20 cm).

L'appareil enregistreur permet de sélectionner l'échelle graphique verticale d'enregistrement (entre 1/10 et 1/1000 de la profondeur forée) et l'échelle horizontale d'enregistrement (entre 5m/hre/cm et 2000m/hre/cm dépendant de la vitesse instantanée du forage). Dans les zones de roc soupçonnées de renfermer des fissures, des vides ou des cavités, on installe en parallèle un capteur de grande vitesse (1000 m/hre) qui reste insensible aux faibles vitesses et indique nettement les passages à grande vitesse.

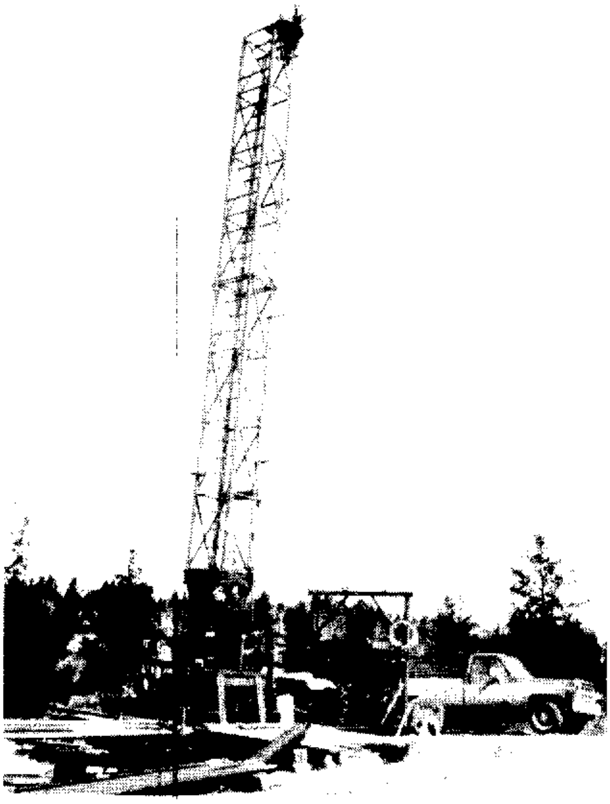

Figure 2: Exemple de montage sur une foreuse pour des recherches en eaux souterraines.

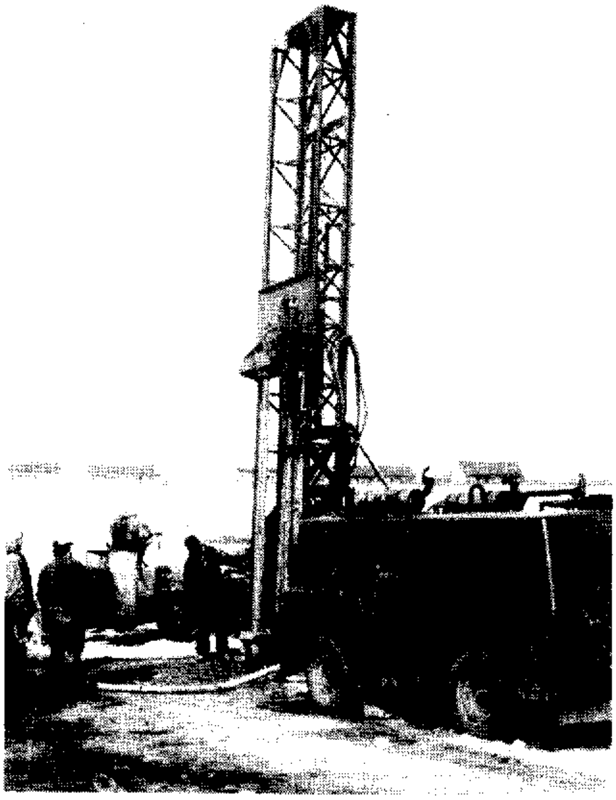

Figure 3: Enregistrements de paramètres sur une foreuse à roto-percussion pour sondage du mort-terrain (on peut entrevoir le Diagrafor au haut du mât).

La Dureté "Réfléchie" de la Roche

En forage à percussion ou roto-percussion avec un marteau à air ou hydraulique, un marteau fond de trou ou un mouton de battage, les ondes de percussion non absorbées par la roche sont réfléchies par le train de tige: une roche dure (granite, calcaire, etc) transmettra des ondes sonores percuttantes tandis qu'une roche tendre (talc, shale) et friable rendra des ondes étouffées.

Le capteur des ondes réfléchies est attaché à la tête de forage dans l'axe du marteau. Grâce à sa grande sensibilité il est possible d'enregistrer les variations lithologiques, les degrés de fracturation de la roche et également de distinguer entre les fissures remplies de fines résiduelles et les fissures claires.

Dans les forages à percussion, l'enregistrement des ondes réfléchies constitue un complément appréciable aux diagraphies des vitesses d'avancement.

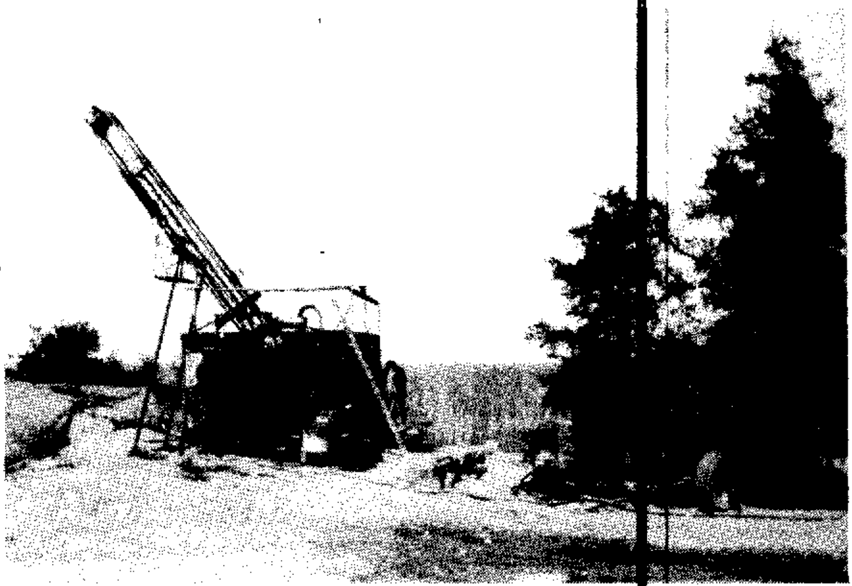

Figure 4: Enregistrement des paramètres en carottage de roc sur une foreuse hydraulique pour recherche de fissures.

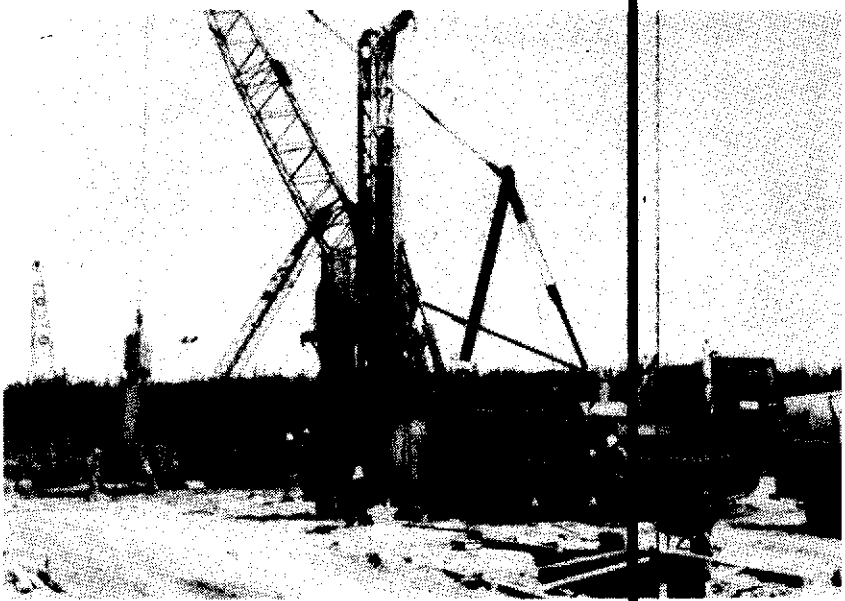

Figure 5: Enregistrement de paramètres sur une foreuse Becker en roto-percussion (marteaux Diesel et pneumatique) pour différensier entre les zones de blocs et le roc dans un chantier de paroi moulée.

La Pression de Poussée de l'Outil

Parmi les paramètres qui permettent de caractériser et d'évaluer la relativité de la vitesse d'avancement, la pression de poussée sur l'outil de forage constitue l'un des paramètres les plus importants. La pression de poussée est une caractéristique dépendant d'une part du type et de la dimension de la foreuse, et d'autre part des difficultés de forage et de la façon spécifique du foreur d'attaquer son terrain.

Dans un même terrain, la vitesse d'avancement différera suivant qu'on fore avec une petite foreuse au tricône ou une foreuse à percussion au marteau fond de trou.

D'autre part, dans un terrain de densité et de consistance homogènes, un foreur maintiendra une pression de poussée constante et régulière. Dans un terrain hétérogène et accidenté le foreur aura tendance à faire varier la pression de poussée suivant la difficulté du moment. Pour interpréter convenablement une diagraphie de vitesse d'avancement, il est donc utile et nécessaire d'enregistrer et de consulter les diagraphies de pression de poussée. Les capteurs de poussée sont généralement reliés directement aux conduites hydrauliques de la foreuse au niveau du piston de poussée de la tête de forage.

La Pression de Retenue

Dans les forages profonds, particulièrement en hydrogéologie et en exploration pétrolière, lorsque le poids des tiges de forage devient significatif le forage se fait davantage par retenue et freinage du train de tiges que par poussée. La diagraphie de la pression de retenue a dans ce cas une importance analogue à celle de la diagraphie de la pression de poussée dans les forages de plus faible profondeur. Les pressions de retenue sont mesurées par des capteurs de pression ou par l'intermédiaire de dynamomètres bridés au train de tiges.

La Vitesse et le Couple de Rotation des Tiges

La vitesse et le couple de rotation des tiges sont également des paramètres caractéristiques de l'énergie de forage utilisée. Une analyse approfondie des relations résistance du terrain vs efforts de forage doit tenir compte de ces derniers paramètres.

Le couple de rotation trouve son expression dans la mesure de la pression hydraulique ou pneumatique du mécanisme de rotation. La vitesse de rotation se mesure au moyen d'un capteur électro-magnétique.

Les variations de la vitesse et du couple de rotation peuvent également renseigner sur le degré d'activité des matériaux traversés (accélération de la vitesse dans les vides, ralentissement dans les matériaux cohésifs ou gonflants).

La Pression du Marteau de Frappe

En forage à percussion ou par battage, la force du marteau de frappe peut être enregistrée au moyen de la mesure de la pression hydraulique ou pneumatique admise dans le marteau de frappe. Le capteur est installé sur la conduite d'amenée de pression au marteau. Cette mesure est comparable à celle de la pression de poussée en forage hydraulique.

La Pression du Liquide d'Injection

L'enregistrement des variations de la pression d'injection renseigne sur la capacité du matériau foré à absorber ou non le fluide d'injection pompé: eau ou boue. Dans un sol granulaire et perméable ou dans un roc fissuré, la pression d'injection demeurera relativement stable. Dans un sol cohérent, dans un roc massif ou face à des fissures remplies d'argile, la pression d'injection aura tendance à augmenter.

Les capteurs de pression d'injection sont généralement branchés directement sur la pompe à injection.

LES ENREGISTREMENTS ET LEUR INTERPRETATION

Ces enregistrements sont généralement obtenus sur un tracé graphique direct et instantané par des appareils à trois, quatre ou six traces. Des exemples d'enregistrements sont montrés aux Figures 6 et 7. Les appareils existants sont compacts, de dimension réduite et se transportent aisément par un seul homme. Ils peuvent être adaptés à n'importe quel type de foreuse et leur installation exige peu de modifications de la foreuse et peu de temps d'installation. Leur fonctionnement n'interfère pas avec les opérations de forage et ne les gênent aucunement. Il arrive parfois que le foreur lui-même se charge de l'installation et du fonctionnement de l'enregistreur.

Le choix des paramètres à enregistrer dépend du but du forage et du type et de la précision de la qualité d'informations requise.

En forage hydraulique rotary, par exemple, on enregistrera systématiquement la vitesse d'avancement, la pression de poussée et la pression d'injection. Les autres paramètres peuvent être sélectionnés secondairement.

En forage à percussion on choisit plutôt la vitesse d'avancement, la dureté réfléchie et la pression de poussée (pression de l'air, pression hydraulique ou frappe du marteau).

Les graphiques obtenus peuvent être généralement lus et interprétés directement. Les démarcations des couches stratigraphiques et le contact entre le mort-terrain et le roc en particulier sont visibles immédiatement. Le tracé des coupes géologiques se fait alors avec une plus grande certitude et avec moins de corrélations hypothétiques (Figures 8 et 9).

Dans le mort-terrain, la fréquence, la position et la dimension des blocs de roche, des cailloux et même de gravier est d'interprétation facile.

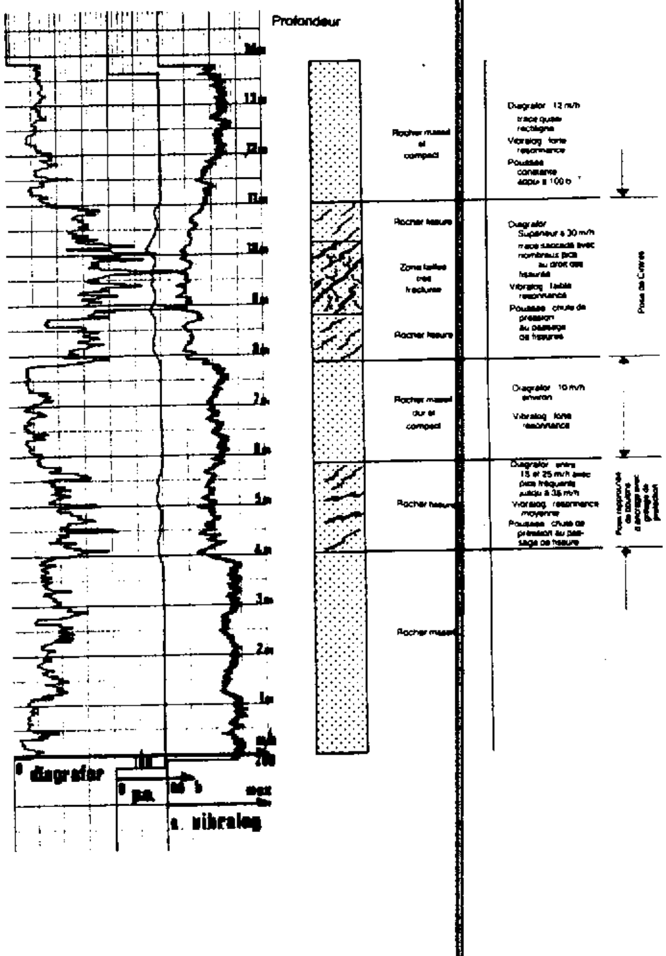

Figure 6: Exemple d'enregistrement direct des paramètres de forage et d'interprétation qualitative de la qualité du roc foré. (Tiré de la brochure publicitaire Jean Lutz S.A. France).

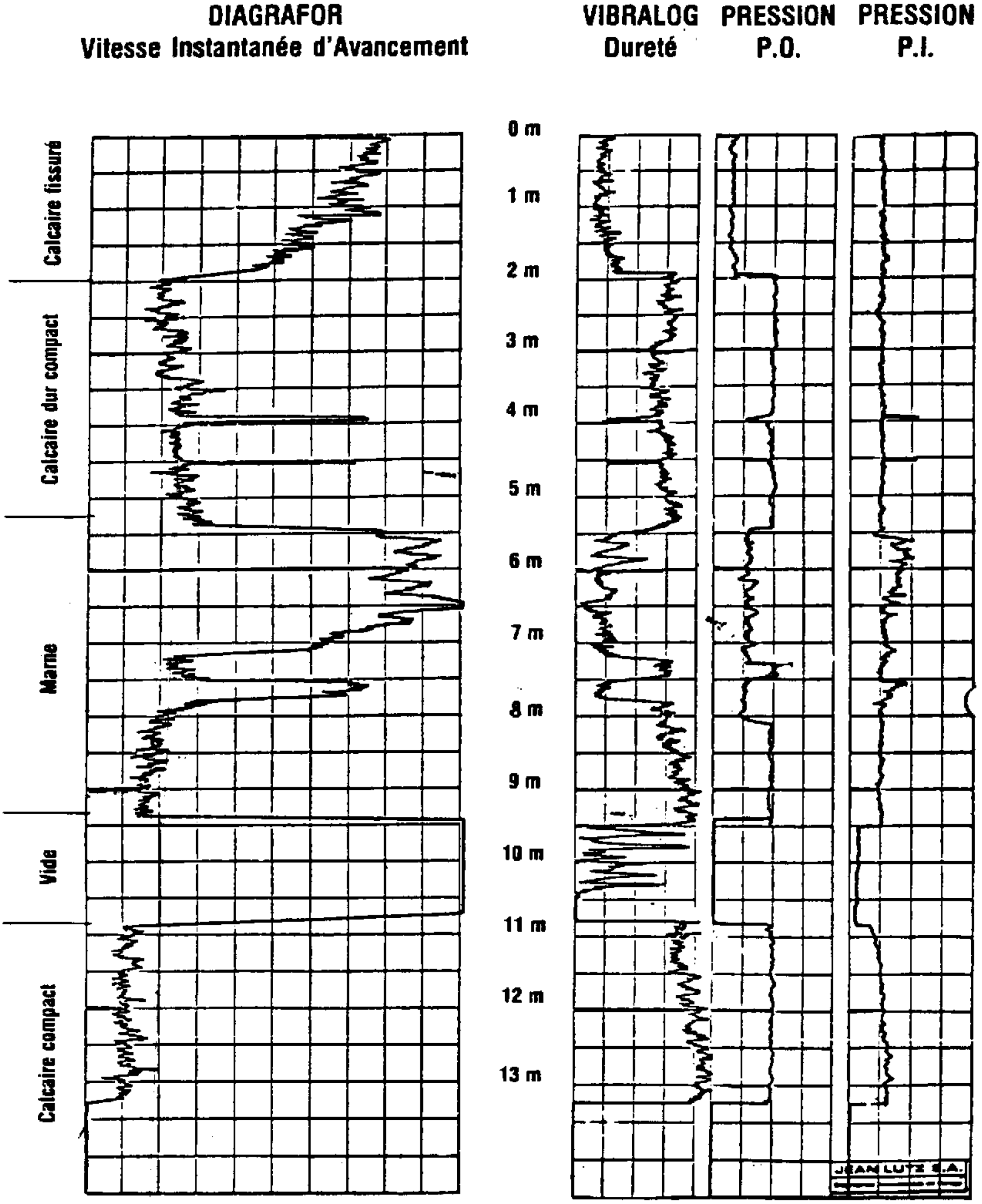

Figure 7: Exemple d'enregistrement de quatre Diagraphies Instantanées sur une foreuse "Wagon-Drill" avec marteau à air en surface (Tiré de la brochure publicitaire Jean Lutz S.A.).

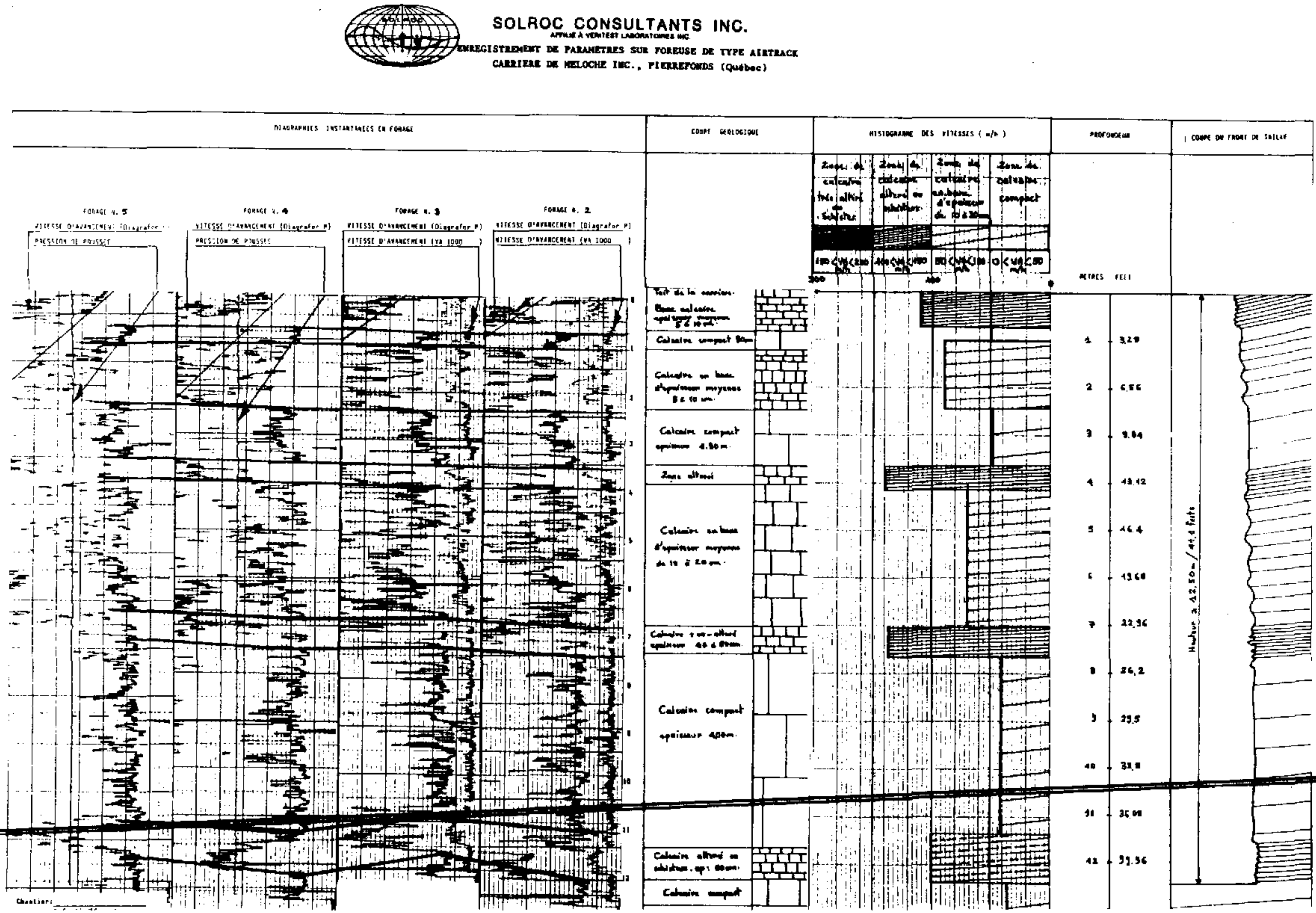

Figure 8: Exemple de corrélations entre quatre forages en percussion.

Grâce à l'enregistrement de la perte ou du gain de la pression d'injection on peut différencier les sols mous cohérents et imperméables des sols lâches pulvérulents et perméables.

Dans le socle rocheux les différentes formations, les différents horizons, les discontinuités structurales, les zones fracturées, les zones dures et les zones tendres se détectent à vue d'oeil. Les diaclases et les fissures, les systèmes de joints, leur fréquence et leur orientation peuvent également être obtenus.

Ces interprétations directes offrent une image fidèle et complète des variations les plus mineures des propriétés physiques et mécaniques des strates forées, sol ou roc, et une connaissance intime du sous-sol et du milieu dans lequel on travaille.

Les progrès et les raffinements des méthodes de diagraphie de forage et la complexité de traitement de toutes les données enregistrées ont amené les chercheurs à s'orienter vers le développement de programmes de traitement des données par ordinateur. Les paramètres de forage sont alors enregistrés simultanément sur papier et sur bande magnétique.

Les enregistrements sur bande magnétique présentent de plus l'avantage de pouvoir reproduire les diagraphies en autant d'exemplaires qu'on le désire. L'élaboration de programmes d'ordinateurs basés sur la combinaison des différents paramètres de forage permet de déterminer des diagrammes de données spécifiques: définition de zones d'altération, de zones de fissuration définie, de zones de dureté définie, de zones non consolidées, de zones de vides effectifs etc.

Dans les travaux de routine l'usage de programmes d'ordinateur est encore l'exception. L'emploi de la bande magnétique d'enregistrement en parallèle devient cependant plus courant.

CONCLUSION

L'instauration et la pratique des diagraphies de forage a permis de revaloriser le forage d'exploration et le forage destructif rapide en particulier. Pour un coût raisonnable et parfois minime il est en effet possible de transformer une opération de forage sèche et parfois stérile en une collecte d'informations précieuses qui peut conduire à une étude rationnelle, efficace et peu onéreuse du sous-sol.

La caractérisation et la connaissance des zones fissurées du massif rocheux par des forages destructifs rapides enregistrés en diagraphies permet de circonscrire les réservoirs aquifères potentiels, ou de déterminer l'étendue et la variabilité d'un aquifère connu. Dans le mort-terrain, l'enregistrement du paramètre Pression d'Injection est celui qui permet de différencier les strates perméables, généralement porteuses d'eau souterraine, des strates silteuses ou argileuses stériles.

Les techniques de diagraphies de forage apportent donc aux professionnels impliqués dans le forage de reconnaissance en hydrogéologie un outil de grande utilité, d'application facile et de coût modeste.

Nous croyons que l'usage de ces nouvelles méthodes se répand de plus en plus et qu'il devrait trouver auprès de hydrogéologues, des foreurs et des puisatiers un écho particulièrement favorable.

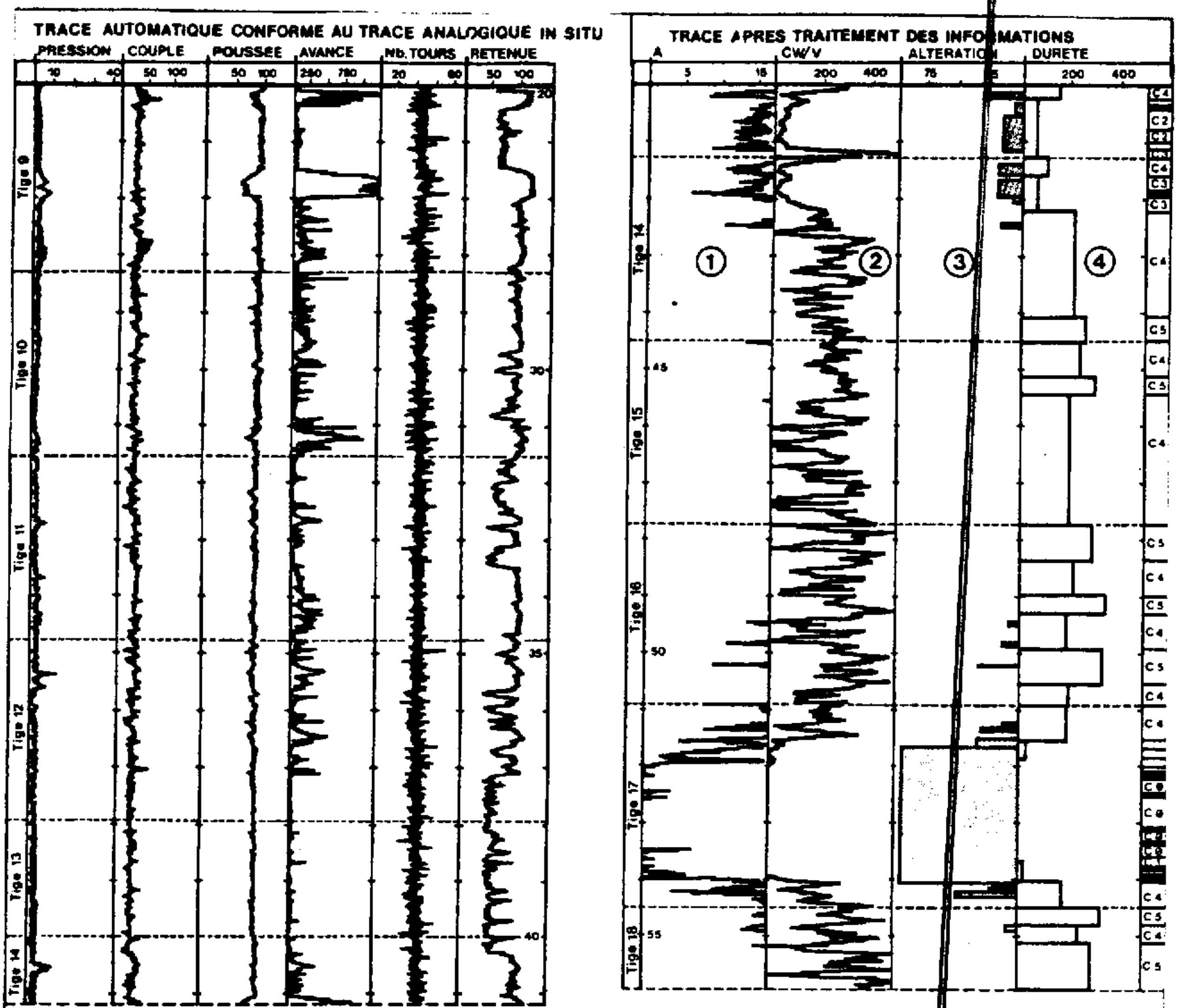

Figure 9: Exemple d'enregistrement direct des paramètres de forage et de traitements des données par ordinateur pour interprétation de la qualité de la roche. (Tiré du Bulletin AIGI No 26-27, Paris 1983).

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IMPACT OF GROUNDWATER UTILIZATION ON THE DURLINGVILLE AQUIFER SYSTEM

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ABSTRACT

The projected rapid growth in water demand by industries and municipalities in the Cold Lake - Beaver River Basin in Alberta required an evaluation of the basin's groundwater resources. The groundwater supply potential of a regional confined aquifer system, the Durlingville Formation, was assessed quantitatively with a two dimensional, finite element aquifer flow model. The aquifer system is of interglacial origin and is largely confined within a network of preglacial bedrock valleys. The study area (about 14,200 km²) has significant adequate geological information compared to the limited hydrogeological data base. Aquifer recharge was estimated and areas of data deficiency were identified during model calibration. The hydrological impact on the aquifer was assessed for several groundwater withdrawal schemes. Simulation results indicated that the projected low water demand of potential water users could be met by the aquifer. Under a high withdrawal scenario, additional sources of water supply would be needed to supplement two industrial users (Mobil and Union Texas). Based on the aquifer response to these withdrawal schemes, feasible groundwater withdrawals at potential pumping centres were determined.

INTRODUCTION

The Cold Lake-Beaver River basin in Alberta is best known for its oil sand development potential. Since large quantities of water are required to generate steam for bitumen extraction and upgrading, and the waste water produced by these processes has to be disposed of properly, public concern has been expressed over the impact of this development on the region's water supply and water quality. Due to the basin's proximity to the Alberta-Saskatchewan boundary, the quantity and quality of water crossing the interprovincial boundary has to satisfy provisions established by the Prairie Provinces Water Board. A water management study was initiated in January 1981 by the Planning Division of Alberta Environment with the objective of formulating framework plans for managing the surface water and groundwater resources in the region. The Earth Sciences Division was requested to participate in this multi-disciplinary study and to provide groundwater resources evaluation for the basin.

In recent years, the Earth Sciences Division of Alberta Environment has been conducting a program of mapping surficial and bedrock stratigraphy of buried channels in East-Central Alberta (Yoon and Vander Pluym, 1974; Gold, 1978). One of the purposes of this program is to delineate a regional hydrogeologic framework on which an assessment of a basin's groundwater resources can be made using a mathematical model. This paper describes the application of a numerical model to obtain quantitative assessments of the groundwater supply potential of a regional confined aquifer system (Durlingville Aquifer). The purposes of the present study are:

(1) to synthesize and interpret available hydrogeologic information and to examine the adequacy of the data base along with model calibration results;

(2) to use the predictive capability of the model to study the response of the aquifer system under several projected groundwater demands.

The study area, about 14,200 square kilometres, lies between longitudes 110° and 112° west and latitudes 54° and 55° north. It covers parts of townships 58 to 69, within ranges 1 to 14, west of the fourth meridian. The area was chosen to include present and anticipated groundwater withdrawals in the basin.

GEOLOGICAL BACKGROUND

The bedrock in the area consists of the Upper Cretaceous Lea Park shale, with the overlying Belly River sandstone occurring only at the southwest limit of the study area. Late preglacial drainage of the area was to the southeast on a regional basis, and within the study area it varies between northeast and southeast (Yoon and Vander pluym, 1974; Gold, 1983). The two main valleys are: the Helina, entering the area in the northwest under Lac La Biche, changing direction from southeast to northeast in the centre of the study area and exiting under Cold Lake in the east; and the Beverly, entering the area in the southwest and flowing northeast until it joins the Helina just west of Cold Lake (figure 1). Preglacial sands and gravels of the Empress Formation are found in these valleys. Three tributaries of significance occur: the Bronson Lake valley to the southeast, the Big Meadow to the east and the Sinclair to the north, west of Cold Lake.

Following the first observed glacial advance into the area, further sands and gravels were deposited on the resulting glacial till (Gold, 1978; Andriashek and Fenton, in preparation). These deposits, previously termed the Durlingville but now called the Muriel Lake Formation by Andriashek and Fenton, occupy the pre-existing valleys. Due to the partial infilling of the valleys by till, the Durlingville deposits are more laterally extensive than the underlying Empress sands and gravels, and appear to have a greater groundwater potential. Three subsequent overlying till units have been identified in the area, but the inter-till deposits do not appear to be of regional extent.

Subsurface geological information in the area was primarily obtained from several thousand oil well and water well drilling records, which permitted the delineation of the major till and sand or gravel layers. Till identification on the basis of chemical and mineralogical properties has formed the basis of the correlation of individual stratigraphic units. This work was initiated by Gold and extended by Andriashek and Fenton. Geological formation boundaries are, of course, not necessarily hydrological boundaries, but the aquifer outline shown in figure 1 was obtained by estimating where the Durlingville becomes less than five metres in thickness, or becomes markedly silty or clayey in composition. The aquifer material itself is known to be interglacial in origin by the presence of significant amounts of pink feldspathic granite derived from the Canadian Shield that could only have been transported westward by glacial activity. Except in the southeast portion of the study area, the aquifer is confined by the Cretaceous valley walls. Where it is not so confined, it may be

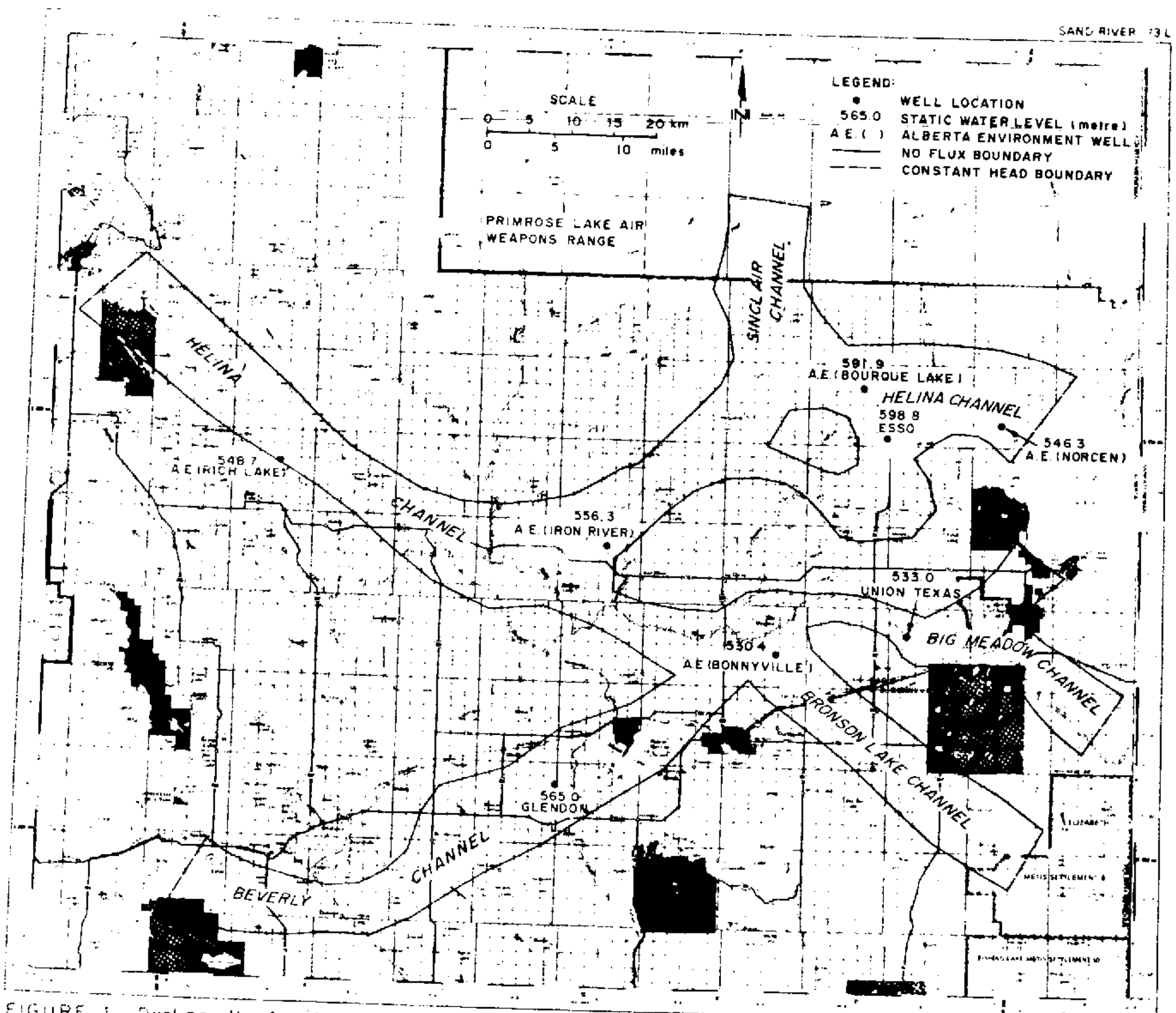


FIGURE 1 Ourlingville Aquifer Configuration and Observation Well Network

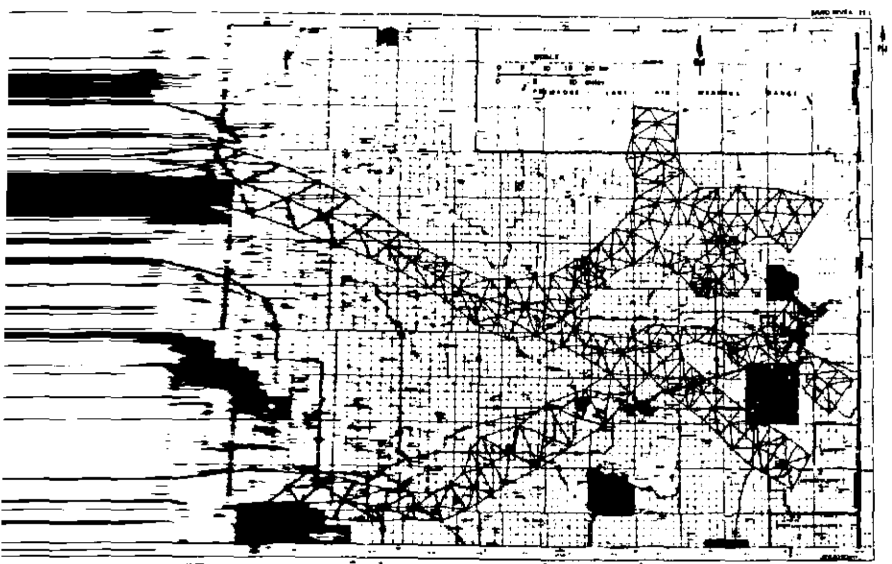


FIGURE 2: Finite Element Grid of Durlingville Aquifer

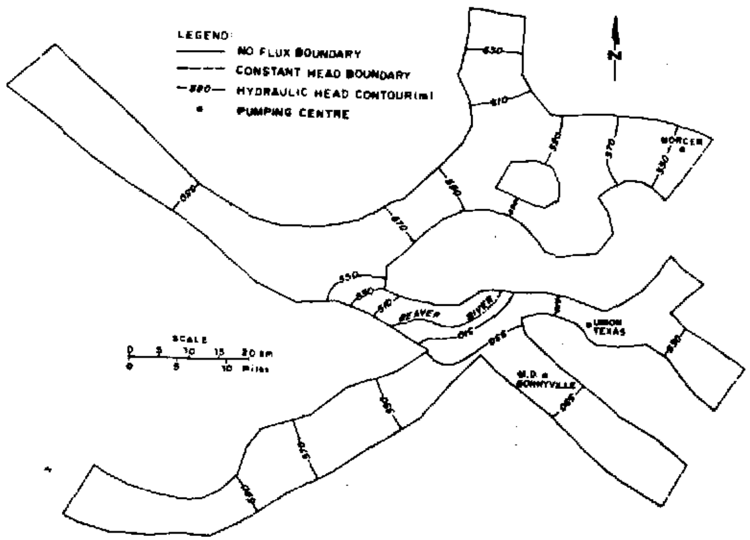


FIGURE 3: Simulated Steady State Hydraulic Head Distribution at the Beginning of 1980

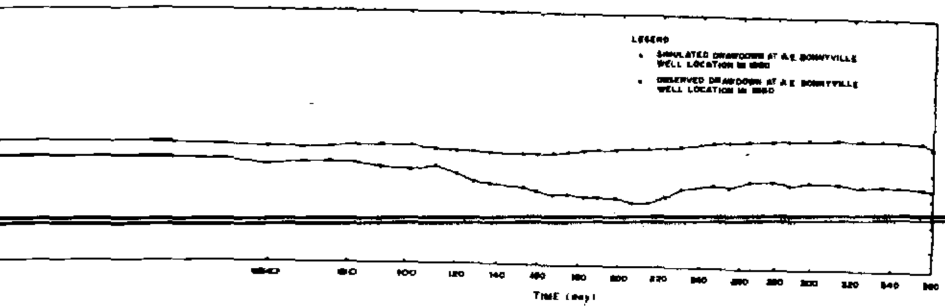


FIGURE 4: Comparision Between Observed and Simulated Drawdowns

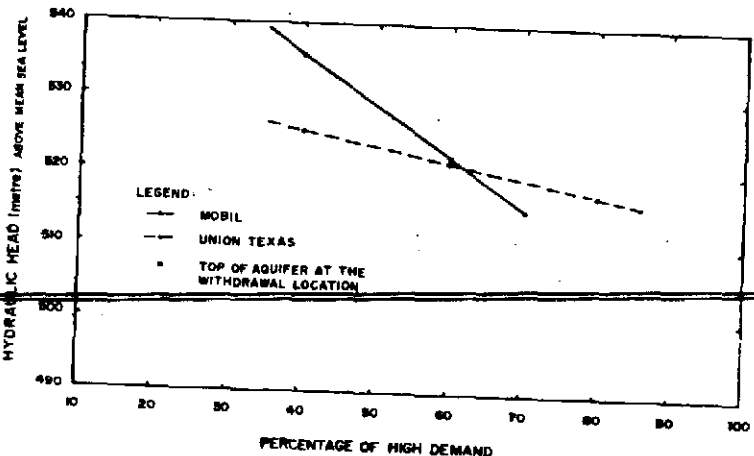


FIGURE 5: Demand Response Curves for Mobil and Union Texas

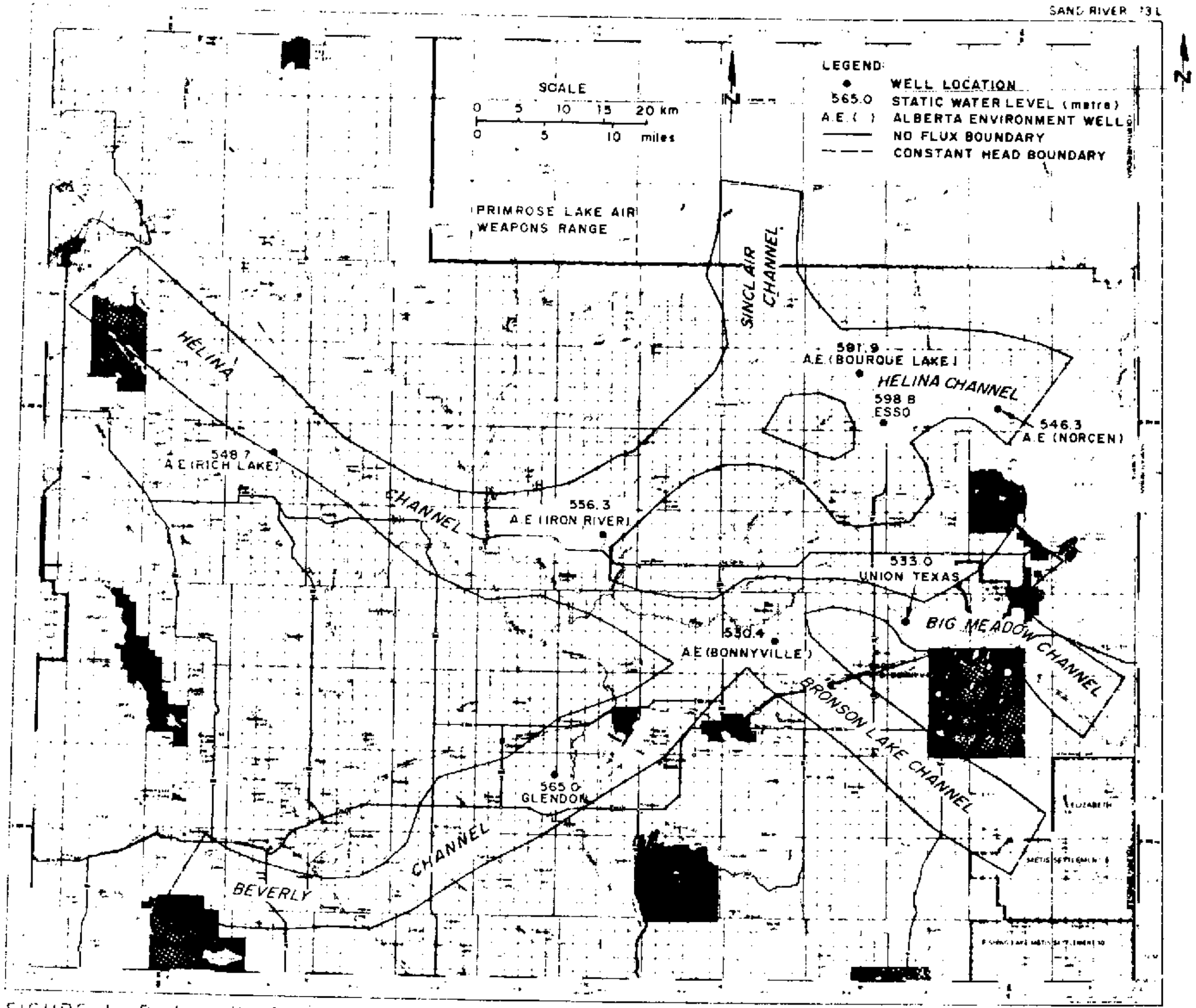


FIGURE 1 Durlingville Aquifer Configuration and Observation Well Network

relatively thin, dirty, discontinuous and, in places, removed by erosion due to subsequent glacial activity. Nevertheless, it is of geological importance in the area. The aquifer's identification may be questioned in a few localities but its general configuration and extent have been well defined.

AVAILABLE DATA

Figure 1 summarizes static water levels (above mean sea level) of observation wells in the Durlingville Aquifer. Ground elevations of all Alberta Environment (A.E.) wells have been surveyed to obtain accurate water levels. Since hydraulic heads were constructed from static water levels measured at different times (several years apart between two measurements in some cases), the hydraulic heads should not be taken as a snapshot of the aquifer response at some point in time. These heads, in effect, could reflect changes in hydrogeologic events in the basin over a period of many years. Continuous water level records are available for the A.E. (Bourque Lake) well since March, 1980 and for the A.E. (Bonnyville) well since August, 1977. The rest of the Environment wells (without recorders) were constructed during 1981 and 1982 to determine aquifer properties and flow direction.

A summary of aquifer parameters obtained by pumping tests was contained in the report prepared by MLM Groundwater Engineering (1982). Based on their results plus logs and lithology data, transmissivities were estimated for the aquifer domain. Since some of the pumping tests were performed with only a source well, the storage coefficient could not be estimated by conventional pumping test techniques. Hence, the data base for the storage coefficient over the modelling region was very limited.

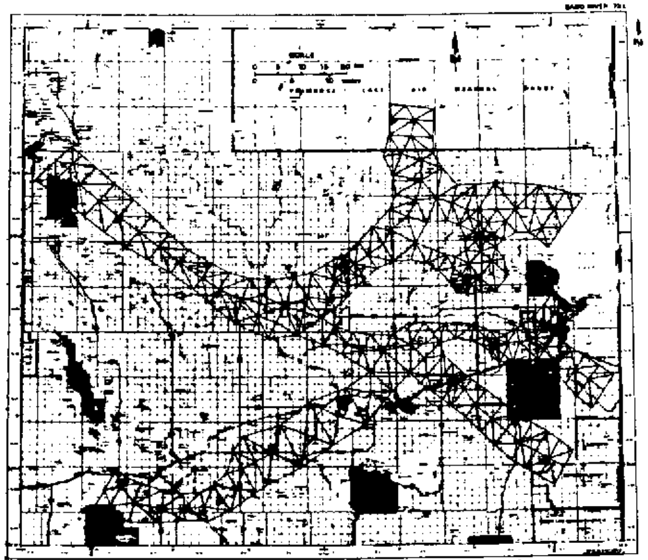
Stresses acting on an aquifer result primarily from groundwater withdrawal and recharge. Union Texas of Canada Ltd., Municipal District of Bonnyville and Norcen Energy Resources Ltd. obtained groundwater from the Durlingville Aquifer during the simulation period. Pumping records submitted by these users to the Ground Water Rights Branch of Alberta Environment were provided as weekly or monthly production volumes. Based on 1980 records, average monthly pumping rates were calculated at each groundwater withdrawal centre. Groundwater recharge from the overlying till unit to the aquifer could not be estimated from Darcy's Law because of scarce hydrogeologic information on the distribution of hydraulic heads and hydraulic conductivities. In this study, the net recharge rate to the aquifer was estimated through a trial-and-error approach during the steady state calibration of the model.

AQUIFER MODELING

A finite element aquifer flow model, which has flexibility in representing the complicated aquifer geometry and in handling various boundary conditions acting on the aquifer system, was chosen for this study. This aquifer model, AQUIFEM-1 (AQUIfer Finite Element Model-1-layer), was developed by Townley and Wilson (1980) at the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Massachusetts Institute of Technology. The model solves the equation describing two-dimensional, horizontal groundwater flow in a non-homogenous anisotropic aquifer with leakage. It is formulated using the Galerkin finite element technique and uses linear interpolation functions with triangular elements. Steady state or transient solutions for confined, phreatic and changing status (confined to phreatic or vice versa) aquifers can be computed. Both steady state and transient responses of the aquifer system were studied with this numerical model.

Model application started with calibration of the flow model, a process by which different model input parameters were verified or determined. It involved choosing a period in the past (1980) for which data were available on the excitation (pumpage and recharge) and response (water level) behaviour of the aquifer. With this excitation as input, the model response for this period was compared with water levels recorded at an observation well. The A.E. (Bonnyville) well, having continuous water level readings during 1980, was used for model calibration. In addition to production wells in a pumping centre, there were associated observation wells for monitoring water level changes during the simulation period. The measured responses at these observation wells were not used for model calibration because the finite element grid was primarily designed for regional application. A very fine mesh is required in the proximity of the production wells in order to generate the transient responses for comparsion with those observed at these observation wells. The finite element grid representing the modelling domain is presented in figure 2. It was discretized into 444 elements (triangles) with 312 nodes. The shortest distance between nodes is about 800 metres.

Both boundary and initial conditions had to be specified for the aquifer region. No flux or constant head boundary conditions were prescribed along the boundaries of the aquifer domain. A preliminary geological evaluation indicated that there is a hydraulic connection between the Beaver River and the Durlingville Aquifer. The process of river-aquifer interaction was simulated in the model by applying a mixed type boundary condition to the nodes denoting the river. This condition relates the difference in heads between the river and the aquifer to the flux across the river-aquifer boundary. The aquifer outflow locations along the river were not known. That reach of the river crossing the Beverly Channel was assumed to be the aquifer outflow boundary. Since there was no gauging station along the river-aquifer interaction reach, the 1980 mean river level (496 m) determined at a gauging station (SE 15-62-2-W4) about 35 kilometres downstream was used for the simulation period. At the time this study was performed, a crude estimate of the upstream river level based on the steady, uniform flow assumption could not be obtained because the gradient of the river bed for that reach was unknown. These assumptions could introduce an error in computing the quantity of aquifer outflow to the river. A spatial hydraulic head distribution at the start of the simulation period was required to provide the initial condition for the transient simulation. It was unable to generate the initial hydraulic heads at all nodal points of the aquifer domain with the limited observation wells. This initial condition was obtained by assuming a steady state condition prevailed at the start of the simulation period and a steady state hydraulic head distribution was computed with the boundary conditions and stresses acting at the beginning of 1980. To determine the recharge input, a sensitivity study was performed with various uniformly distributed recharge rates. The recharge rate that gave the best match between observed and computed steady state heads was considered to be the best estimate of the recharge component. The



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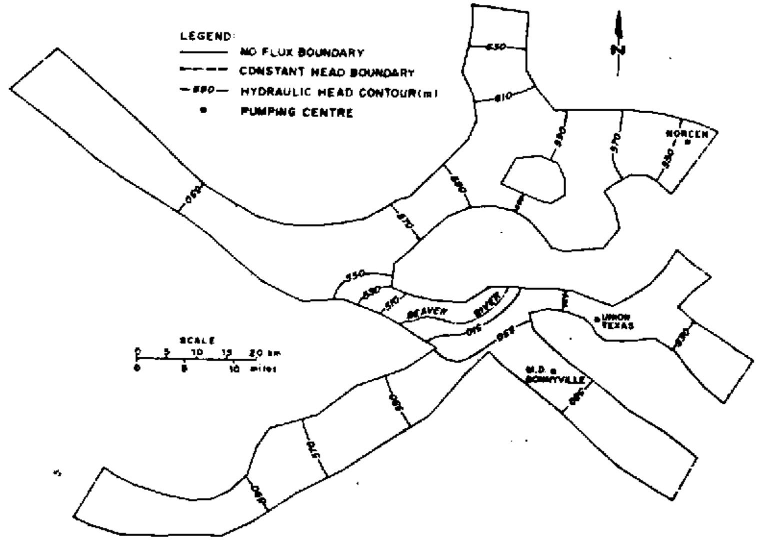

FIGURE 3: Simulated Steady State Hydraulic Head Distribution at the Beginning of 1980

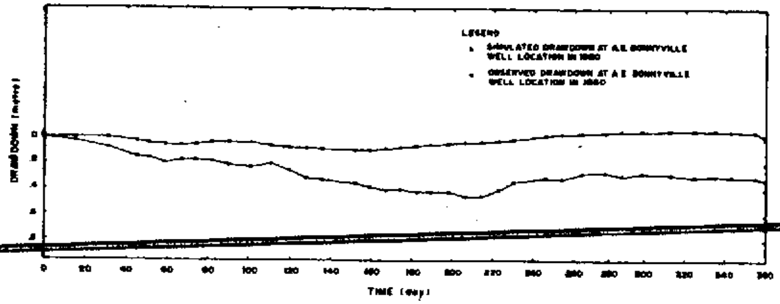

FIGURE 4: Comparision Between Observed and Simulated Drawdowns

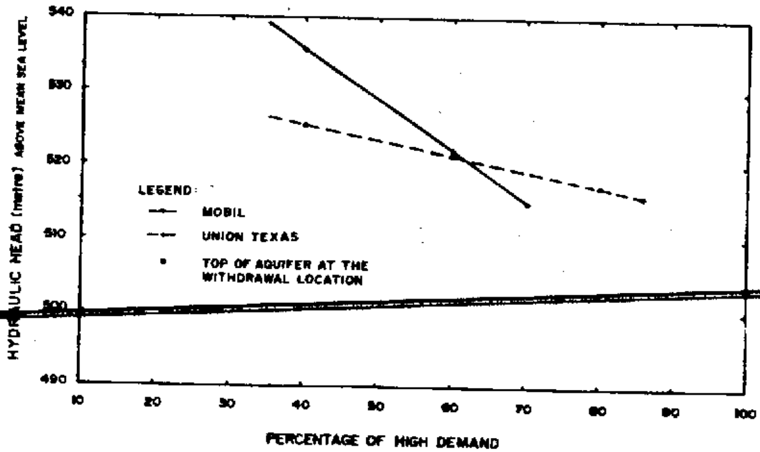

FIGURE 5: Demand Response Curves for Mobil and Union Texas

estimated recharge rate (2.5×10^{-6} m/day) was used in the subsequent transient simulation and in the prediction of aquifer responses to various groundwater withdrawal scenarios.

The steady state hydraulic head distribution computed at the beginning of 1980 is presented in figure 3. Compared with figure 1, there is good agreement in heads at most locations except at the A.E. (Bourque Lake) well and the Esso well. The discrepancies are due to the lack of reliable well data to define the boundary head of the Sinclair Channel. This steady state hydraulic head distribution served as the initial condition for the transient simulation of the aquifer response during 1980. In the transient analysis, a range of storage coefficients were used as model input. The set giving the best agreement between observed and simulated responses was assigned to the aquifer system. The computed and observed drawdowns at the A.E. (Bonnyville) well are shown in figure 4. Drawdowns computed with the model were less than those observed. Since the aquifer system responds to pumping changes on a smaller time scale, the use of constant monthly pumpages to represent the actual state of stress acting on the aquifer could introduce a source of error in the transient computation. However, the available pumping records did not justify using constant pumping rates of duration less than a month.

Low and high groundwater demands from industrial and municipal users have been projected by the Planning Division. The potential groundwater users include Husky Oil Operations Ltd., Municipal District of Bonnyville, Union Texas of Canada Ltd., Mobil Oil Canada Ltd. and Village of Glendon. To evaluate the suitability of a particular demand, the main criterion employed for this study was maintenance of a confined aquifer status at all times. Under constant pumping in time, a steady state solution would best describe the ultimate response of the aquifer system. Simulation results indicated that the hydraulic head was above the aquifer top at all withdrawal locations for the low demand scheme. However, computed heads were below the top of the formation at Union Texas and Mobil locations for the high demand scheme. Further simulations were then carried out with various withdrawal schemes. Each scheme consists of different percentages of high demand by Mobil and Union Texas while maintaining other users at their respective high demands. Table 1 presents the steady state aquifer response results for several groundwater withdrawal schemes. When the computed hydraulic head fell below the top of the aquifer, the calculated head based on the confined aquifer assumption did not necessarily represent the water table under unconfined conditions. However, it did demonstrate that a change of aquifer status had taken place. Consequently, the specified pumping demand at that location was not feasible. Based on schemes 1 to 4, confined hydraulic head and percentage of high demand for Mobil and Union Texas were plotted as shown in figure 5. A linear relationship exists between the two variables. These demand reponse curves were used to decide on feasible withdrawals at the two pumping centres. A feasible pumpage at each withdrawal centre was estimated from its linear response curve by choosing a demand that gave rise to a hydraulic head above the top of the aquifer. To be conservative, pumpage for the feasible scheme was chosen so that the computed hydraulic head remained about 10 metres above the top of the aquifer. The feasible withdrawal scheme consists of the following percentages of high demand: 55% for Mobil, 45% for Union Texas, 100% for Husky, 100% for M.D. Bonnyville and 100% for Glendon. This scheme was

TABLE 1

Steady State Responses to Several Pumping Schemes*

Pumping location	Aquifer top elevation (m)	Scheme 1		Scheme 2		Scheme 3		Scheme 4		Feasible Scheme	
		Pumping rate (m^3/day)	Head (m)	Pumping rate (m^3/day)	Head (m)	Pumping rate (m^3/day)	Head (m)	Pumping rate (m^3/day)	Head (m)	Pumping rate (m^3/day)	Head (m)
Husky	509	3342.8	544.4	3342.8	547.0	3342.8	549.5	3342.8	552.0	3342.8	550.1
Mobil	515	5973.2	———	4778.6	———	3584.0	522.1	2389.3	535.7	3285.3	525.5
Union Texas	516	2000.2	———	1600.2	517.2	1200.1	521.3	800.1	525.4	900.1	524.4
M.D. Bonnyville	503	657.6	536.0	657.6	536.1	657.6	536.2	657.6	536.4	657.6	536.3
Glendon	533	739.8	552.5	739.8	552.5	739.8	552.6	739.8	552.6	739.8	552.6

*Scheme 1 - 100% of high demand

Scheme 2 - same as scheme 1, except 80% withdrawals at Union Texas and Mobil

Scheme 3 - same as scheme 1, except 60% withdrawals at Union Texas and Mobil

Scheme 4 - same as scheme 1, except 40% withdrawals at Union Texas and Mobil

Feasible Scheme - same as scheme 1, except 50% withdrawals at Mobil and 45% withdrawal at Union Texas

——— - hydraulic head below the top of the formation derived based on the confined aquifer constraint, efforts are under way to introduce other objective functions and constraints into the model through a linear programming formulation for managing the aquifer system.

The steady state hydraulic head distribution resulting from the feasible withdrawal scheme is presented in figure 6. The pumping centres (Husky and Mobil) influence and alter the regional flow in the Helina Channel. The deepening of the cones of depression around Mobil is clearly illustrated in figure 7. In general, steeper hydraulic gradients exist within the aquifer domain for the higher withdrawal case as compared to the condition at the beginning of 1980.

CONCLUSIONS

Interpretation and synthesis of available data indicated that hydrogeologic information for the aquifer system is scarce compared to the relatively large geological data base. The existing observation well network has to be expanded to better define the regional flow pattern and boundary conditions. Information on the location of hydraulic connections between the Beaver river and the aquifer is lacking.

The model was used to predict the steady state responses of the aquifer system for several projected groundwater withdrawal schemes. Results showed that the aquifer will meet the projected low withdrawal at all pumping centres. Under the projected high demand, the full capacity of the aquifer was exceeded at the two withdrawal centres, Union Texas and Mobil. If the high demand has to be met, other means of water supply (e.g. surface water derived based on the confined aquifer constraint; efforts are under way to introduce other objective functions and constraints into the model through a linear programming formulation for managing the aquifer system.

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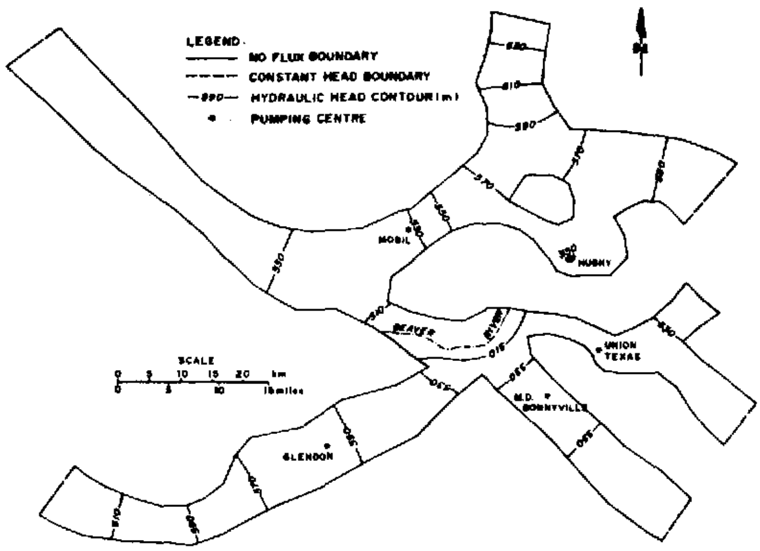

FIGURE 6: Predicted Steady State Hydraulic Head Distribution Using the Feasible Withdrawal Scheme

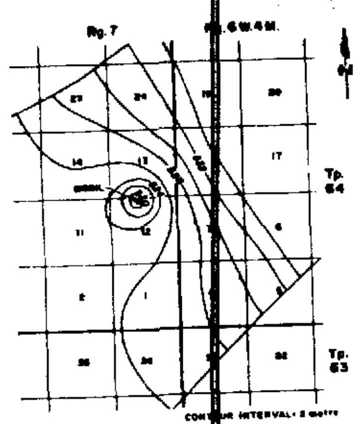

FIGURE 7: Predicted Steady State Aquifer Response Around Mobil Using the Feasible Withdrawal Scheme

CONCLUSIONS

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GEOCHEMISTRY AND GEOTHERMAL EXPLORATION

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ABSTRACT

Recent advances in the understanding of inorganic geochemistry and isotopes in thermal groundwaters have provided valuable techniques for exploration and evaluation in areas with a potential for geothermal resources. These relatively inexpensive methods can, and have, provided very useful hydrogeologic information for assessment of geothermal resources in British Columbia.

Geothermal reservoir temperatures can be estimated by examining the geochemical composition of thermal waters from hotsprings and temperature gradient test holes. A series of cationic (Na-K-Ca-Mg, Mg-k, Li-Na and silica), and isotope (sulphate - oxygen-18) geothermometers are presented to demonstrate their use in a number of case studies.

The relationship between oxygen-18 and deuterium in precipitation is affected by the temperature of condensation and becomes a function of latitude, altitude and location of the recharge environment. The interaction of groundwater with hot rocks will affect this relationship. The oxygen-18 and deuterium contents in various forms of water, including thermal and non-thermal groundwaters, surface water, glacier ice and precipitation in the study areas, have proved to be useful in interpreting recharge environments and subsurface histories of groundwater flow systems in geothermal areas.

The relative age of waters can be estimated by measuring naturally occuring radioactive isotopes in groundwater. Radiocarbon dating, based on concentrations of carbon-14 in dissolved inorganic carbon, can be applied in areas where atmospheric or biogenic carbon dioxide predominates. However, this method is not reliable in volcanic areas where massive inputs of "dead" volcanogenic CO_2 interferes with the interpretation methods. Residual aqueous tritium, from thermonuclear bomb testing is shown to be a useful minimum age dating tool.

INTRODUCTION

Geothermal resources in British Columbia have remained until recently an unknown and unexplored energy potential. However, in the past decade the Department of Energy, Mines and Resources and British Columbia Hydro, in an effort to foster alternate energy sources, have initiated and supported a number of geothermal exploration and test drilling programs. Among the various exploration techniques, which include geophysics, geological mapping and drilling, geochemical methods have been found to be useful as a tool to help understand the recharge and thermal history of a geothermal flow system.

Providing hotsprings exist, and thermal waters can be sampled during drilling, techniques using environmental isotopes and major and trace element geochemistry can be applied at the outset of exploration.

Environmental isotope techniques rely on the variances of heavy isotopes (^{18}O and ^{2}H) in precipitation, surface waters and groundwaters, which reflect their source and any alteration they may have experienced through exchange processes, particularly at elevated temperatures. Geochemical techniques are based upon alteration reactions with minerals along the flow path in geothermal systems. These reactions are largely a function of temperature and the residence time in the system and, therefore, the aqueous chemistry will often reflect the subsurface history of the fluid. In particular, maximum temperatures along the flow path can be estimated by using a series of empirical chemical relationships developed as geothermometers. Other techniques include dating thermal waters using radiogenic carbon and tritium in order to establish when recharge occurred.

Over the past five years, these methods have been applied at three hotspring areas related to Quaternary volcanic centres in the Coast Mountains and at a series of hotsprings related to regional faults in British Columbia (Fig. 1). Mount Meager has been the site of an extensive exploration program since 1973 which eventually led to three deep test wells. Mount Cayley has been the focus of more recent geothermal exploration, (Souther, 1980) and represents the first geothermal lease to be acquired in B.C. under the new Geothermal Resources Act. Both Mount Meager and Mount Cayley are composite volcanos ranging in composition from basalt to rhyolite underlain by Tertiary granitic and metamorphic rocks of the Coast of Plutonic Complex. Mount Meager has two principal hotspring areas: the Meager Creek Hotsprings issuing 50°C water at 40 L/s from gravel deposits along Meager Creek which bounds the complex to the south, and Pebble Creek Hotsprings which discharge from fractured granodiorites along the Lillooet River on the east side of the complex. Mount Cayley has two groups of thermal springs which issue from basement rocks at high levels on the complex. Mount Edziza, the centre of most recent volcanism in Canada (within 1000 yr. b.p.), comprises a series of highly fractionated lavas and pyroclastic cones superimposed on Mesozoic basement rocks and normal faulted Tertiary sandstone and conglomeratic beds with high level acid plutons (Souther, 1984). There are two hotspring sites, Elwyn and Taweh Hotsprings, situated in river valleys incised into the volcanic complex. Mount Edziza was recently designated as a provincial park. West of Mount Edziza are the Mess Creek Hotsprings which issue at creek level from granitic and metamorphic rocks in a fault controlled valley. In southern B.C., the Skookumchuck, Sloquet and Harrison Hotsprings are situated along the Pemberton Belt of Late Tertiary plutons which may also be associated with a fault zone along the Lillooet River.

Analytical work has been carried out in the Environmental Isotope Laboratory at the University of Waterloo, and at Analytical Services Laboratories Ltd. in Vancouver. ^{18}O and ^{2}H contents of water were determined by mass spectrographic analysis of unpreserved samples collected from thermal springs and artesian wells, as well as for cold springs, runoff waters, precipitation and glacier ice. ^{18}O and ^{2}H results are expressed as per mil differences from Standard Mean Ocean Water ($\delta^{18}O$ ‰ and $\delta^{2}H$ ‰ SMOW).

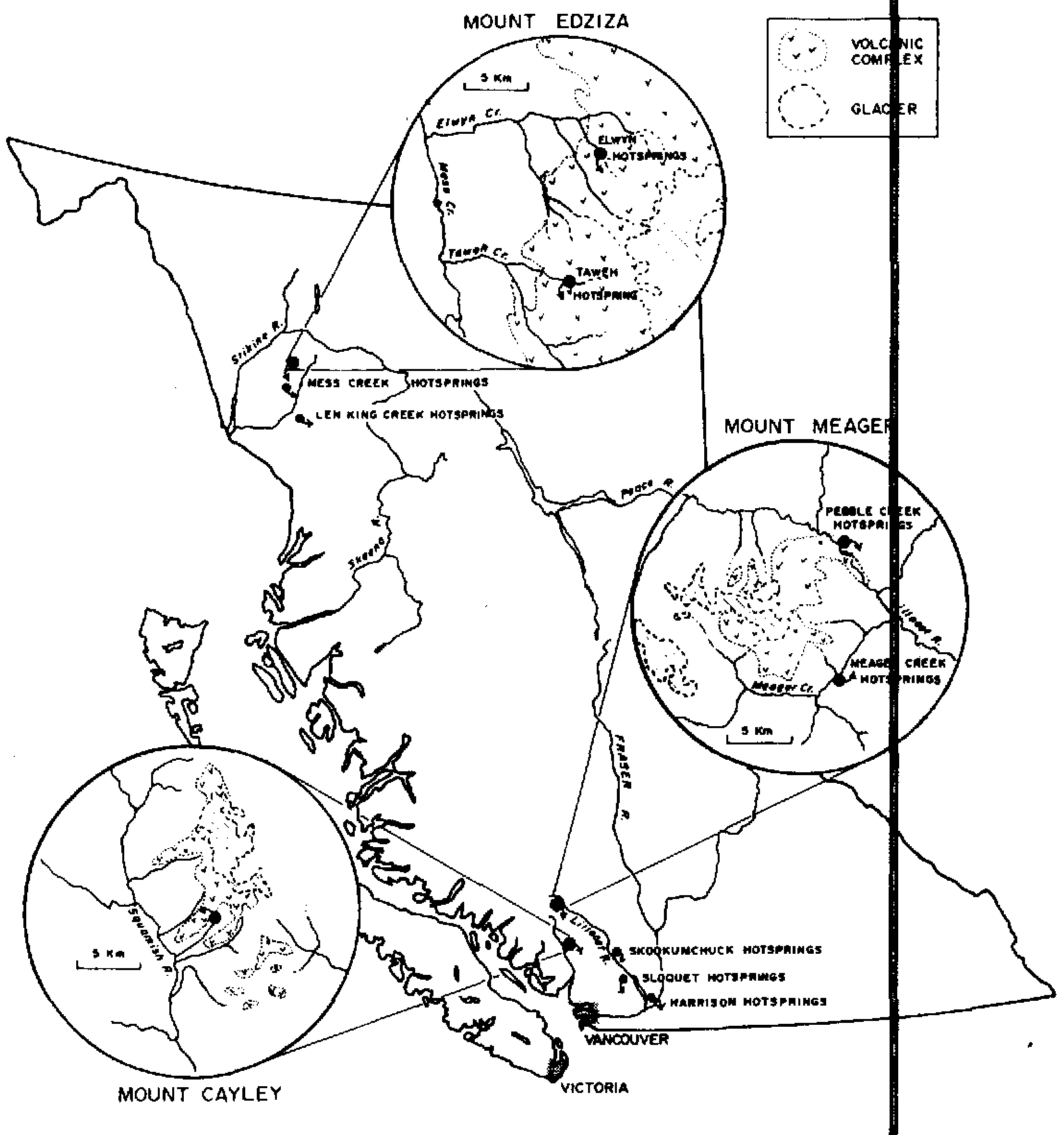

Fig. 1 Location of hotspring areas in British Columbia from this study.

Tritium contents are expressed in tritium units (TU, 1 TU = 1 $^3H \times 10^{-18}$ ^1H). Carbon-14 and tritium determinations were made by direct and liquid scintillation counting of radioactive decay events in dissolved inorganic carbon (DIC) samples (precipitated as $BaCO_3$) and water samples, respectively. Isotopes of oxygen (^{18}O) and sulphur (^{34}S) in dissolved sulphate were analyzed by mass spectrometer using CO_2 and SO_2 gas prepared from samples of $BaSO_4$ precipitated from thermal waters using $BaCl_2 \cdot 2H_2O$ and NaOH.

Samples collected from thermal and cold spring waters for determination of major and trace element concentrations were field filtered (0.45 micron filter paper) and preserved (metals only) at pH 2 with nitric acid. Field measurements of temperature, pH, Eh, dissolved oxygen, electrical conductivity and alkalinity (as HCO_3^-) were made at the time of sampling. Anions were analyzed according to standard methods and metals by inductively coupled argon plasma spectometry.

GEOTHERMOMETRY

Determining the reservoir temperatures in a geothermal area can be accomplished by gradient test hole drilling, deep production drilling or by assessing geothermal waters using a series of chemical and isotope geothermometers. Geochemical methods, although limited by problems such as cold water mixing and by uncertainties of whether the thermal waters discharge from the principal reservoir, are inexpensive and valuable as a preliminary and ongoing exploration tool.

Chemical and Isotope Geothermometers

The equilibrium concentrations of Na, K and Ca involved in alteration reactions with alkali minerals have been shown by Fournier and Truesdell (1973) to vary with temperature. They developed a semi-empirical relationship to describe this correlation which was later modified with a correction factor to accommodate the role played by magnesium in high Mg waters (Fournier and Potter, 1979). Fournier and Potter discuss the relationship between high Mg waters and temperature, showing that below approximately 175°C magnesium plays a significant role in exchange reactions. They also provide a temperature dependent relationship between magnesium and potassium which can be used to substantiate other geothermometers. Similarly, Fouillac and Michard (1981) determined that the Na/Li ratio in thermal waters is sensitive to temperature of equilibration and can provide estimates of reservoir temperatures which are perhaps less affected by mixing than are more classical geothermometers.

The relationship between temperature and the solubility of quartz and its polymorphs has long been recognized as an indicator of the maximum temperatures experienced by geothermal waters (Fournier and Rowe, 1966; Arnasson, 1977). The concentration of reactive silica in a thermal fluid is generally above quartz saturation due to loss of enthaply during ascent. Providing amorphous silica has not been dumped from solution prior to discharge and mixing has not been significant, the equilibrium temperature can be calculated from the silica concentration. In circumstances where significant mixing of thermal waters and shallow meteoric waters takes place, the reservoir temperature and percent mixing can be estimated through a formulation which assumes that the deep fluids have cooled adiabatically (through steam loss only) and that the silica content of the thermal water represents equilibration with quartz at depth (Fournier and Truesdell, 1974).

The equilibrium distribution of ^{18}O between dissolved sulphate and water is a function of temperature (Lloyd, 1968; Mitzutani and Rafter, 1969; Mitzutani, 1972; Fig. 2). Providing isotopic equilibrium is attained in the geothermal reservoir and no new sources of sulphate are encountered prior to discharge, this relationship can be quite reliable in estimating reservoir temperatures. An exponential increase in time required for re-equilibration at lower temperatures ensures that the reservoir temperature estimates are not compromised by cooling during ascent to the surface. Sulphur-34 isotope data can be used to verify whether new sources of sulphate are present in the sample waters.

Geothermometer Applications in British Columbia

An initial survey of hotspring temperatures using silica and cation geothermometers was carried out at sites throughout British Columbia (Souther, 1975). Subsequent to this evaluation, specific areas of geothermal potential have been more closely investigated.

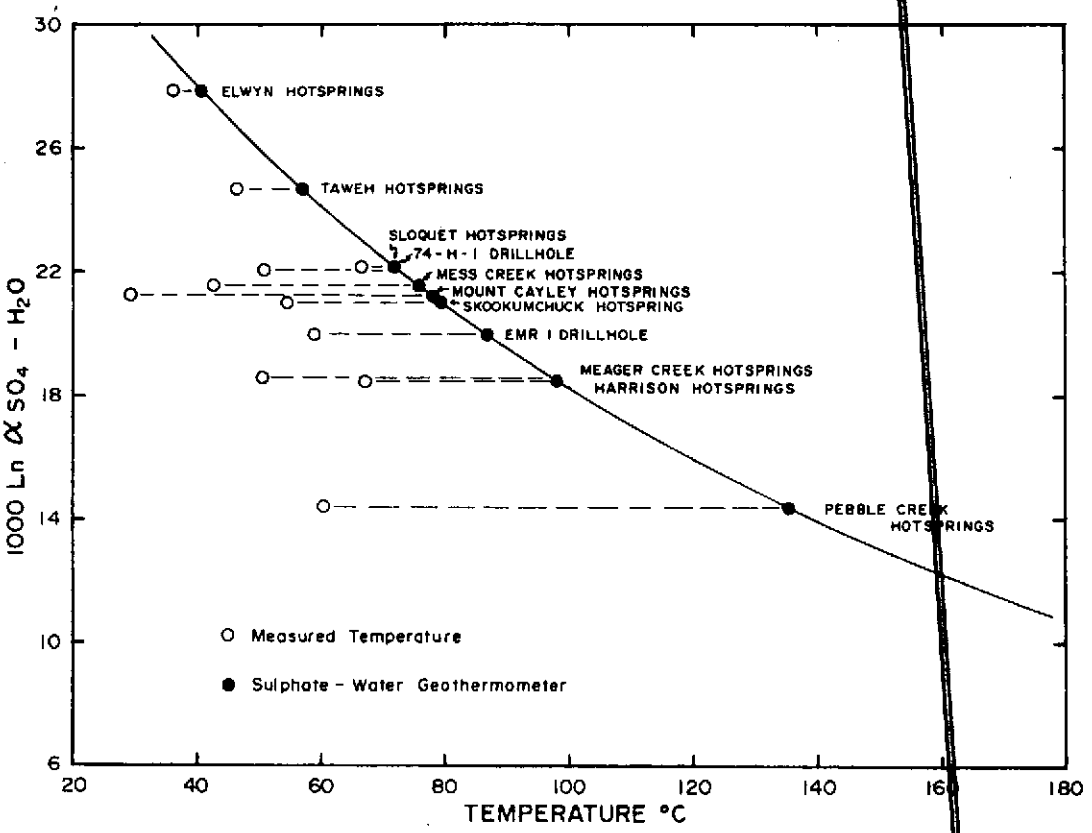

Fig. 2 Oxygen-18 fractionation between sulphate and water. Measured temperatures are for discharge point. The equilibrium fractionation line is from equation given by Lloyd (1968).

Mount Edziza and Mess Creek thermal waters have been tested using the isotope and cationic geothermometers, with indications that they have not undergone a significant degree of heating in the subsurface. Na-K-Ca geothermometer estimates for Taweh and Elwyn Hotsprings are 151°C and 169°C. However, the high magnesium content of these waters (Mg = 60.6 to 116 mg/L) casts doubt on these temperature estimates. The magnesium correction factor of Fournier and Potter (1979) reduces the Na-K-Ca temperature estimates to less than 50°C, suggesting that the waters come from a relatively cool underground environment with temperatures not much greater than the measured spring temperatures (Table 1). Mess Creek thermal waters have an Na-K-Ca-Mg estimate of 83°C. The Li-Na and Mg-K geothermometer estimates provide a similar temperature for these springs (Table 1). The SO_4-H_2O isotope geothermometer also provides values which are very close to other estimates, substantiating that the thermal waters from Mount Edziza and Mess Creek have not been heated above about 80°C to 90°C. Silica geothermometer results provide a range of temperature estimates slightly higher than those of the ionic and isotope geothermometers. Assuming equilibrium with quartz in the Edziza volcanic complex, subsurface temperatures would be closer to 115°C. However, silica leached from glassy volcanic rocks rather than equilibration with quartz could account for high concentrations of reactive silica in solution. If equilibrium with crystobalite or chalcedony is assumed, temperature estimates are a more consistant 60 to 80°C.

TABLE 1

SUMMARY OF GEOTHERMOMETER APPLICATIONS

HOTSPRINGS	TEMPERATURE (°C)							
	MEASURED	Na-K-Ca-Mg	Mg-K	Na-Li	Qtz	Chalc.	SO_4-H_2O	MEAN VALUE
Mount Edziza								
Taweh	45.9	<50	64	80	113	80	41	84
Elwyn	36.0	<50	60	77	114	81	57	83
Mess Creek	42.5	83	56	105	100	64	76	82
Mount Meager								
Meager Creek	50.1	77	81	-	164*	147*	98	85
Pebble Creek	59.8	105	70	-	124	95	136	106
EMR 1 Borehole	58.5	64	78	-	160*	142*	87	76
74-H-1 Borehole	50.5	40	85	-	138*	113*	73	66
Mount Cayley	28.8	49	68	-	131*	103*	78	65
Skookumchuck	54.5	-	-	-	-	-	79	79
Sloquet	66.2	-	-	-	-	-	72	72
Harrison	67.0	92	84	-	110	79	98	93

*Subsurface equilibration with amorphous silica; not included in mean value.

Thermal waters from the Mount Meager area have geothermometer determinations ranging between 40°C and 164° (Clark et al, 1982; Table 1). The greatest consistency in estimates for particular samples was found using the cationic and sulphate-water geothermometers. Pebble Creek Hotspring waters have the highest temperature estimates with Na-K-Ca-Mg and SO_4-H_2O temperatures of 105°C and 136°C. Meager Creek Hotspring water geothermometer estimates are about 30°C cooler. The silica geothermometer has been evaluated for the Meager Creek thermal waters but apparent equilibration with an amorphous silica phase near the point of discharge, rather than with quartz at depth, precluded its application (Clark, 1980).

Mount Cayley thermal waters are magnesium rich (159 mg/L), indicating that they are probably part of a shallow, low temperature geothermal flow system. Isotope and cation geothermometers provide temperature estimates ranging from 49°C to 78°C. Dissolved silica in Mount Cayley thermal waters provides a quartz equilibrium temperature of 131°C. However, similar to Mount Meager, equilibrium with amorphous silica near the point of discharge is suspected which provides anomolously high temperatures.

The sulphate-water geothermometer has been applied to hotsprings occurring along the Lillooet Valley fault system, providing temperature estimates from 72°C to 98°C. Chemical data, available for Harrison Hotsprings only (Souther, 1980) provide cationic and silica geothermometer estimates between 84°C and 110°C.

ISOTOPE HYDROGEOLOGY

In a normal, non-thermal groundwater, oxygen-18 and deuterium contents in most cases reflect the average annual temperature of the recharge area and hence can be used as tracers for the origin of groundwater. In geothermal areas, oxygen exchange between minerals and water at elevated temperatures often results in an ^{18}O enrichment in the water due to high ^{18}O contents in most rocks (Epstein and Taylor, 1967). However, because deuterium is not affected, the original meteoric waters can be identified (Arnasson, 1977).

Precipitation samples from Mount Meager and Victoria, B.C. have been used to establish the meteoric waterlines shown in Fig. 4. No precipitation data has been collected in the Mount Edziza area. Subsequently, the global meteoric line, developed by Craig (1961), using continental precipication from throughout the world, is used in Fig. 3 for a reference line. Normal, cold groundwaters will fall on the meteoric waterline, whereas thermal waters may be displaced to the right. The position along this line at which a point plots reflects the temperature of condensation, which on an annual basis is generally a function of altitude. In alpine environments, a decrease of 0.15 to 0.5‰ in ^{18}O per 100 m rise is common (Gat, 1980).

Mount Edziza

Oxygen-18 and deuterium data for the Taweh and Elwyn Hotspring waters clearly show that they have lower contents of these heavy isotopes than all other waters sampled in the volcanic complex, with the exception of two glacier ice samples (Fig. 3). Although these data plot to the right of the any substantial exchange of oxygen-18 with hot rocks has taken place. The locus of data points from both hotspring sites indicates a common or similar recharge area for each. Quite clearly, these thermal flow systems are recharged at a high elevation on the volcanic complex. The elevation ^{18}O relationship in the Mount Edziza area suggests a decrease of close to 0.5‰ per 100m rise. Accordingly, recharge to the hotsprings would occur at an elevation between approximately 2000 to 2600 m asl. The elevation of the glacier is between 1800m and 2700m. The low concentrations of oxygen-18 and deuterium in the two glacier samples suggests that ablation at its base may be the principal source of recharge to the thermal springs. A high heat flow at this elevation is reasonable considering that the complex has a history of subglacial eruptions.

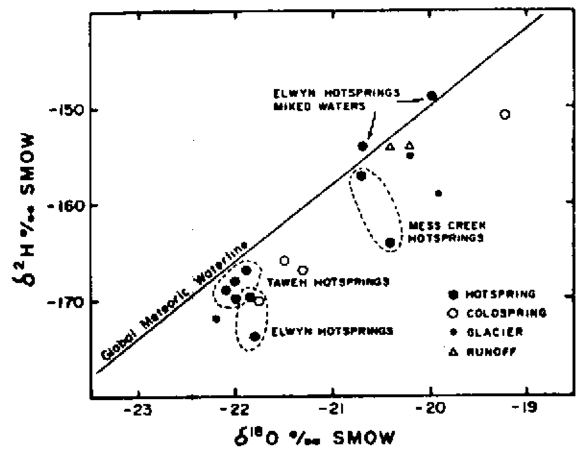

Fig. 3 ^{18}O - ^{2}H plot for the Mount Edziza Mess Creek thermal areas.

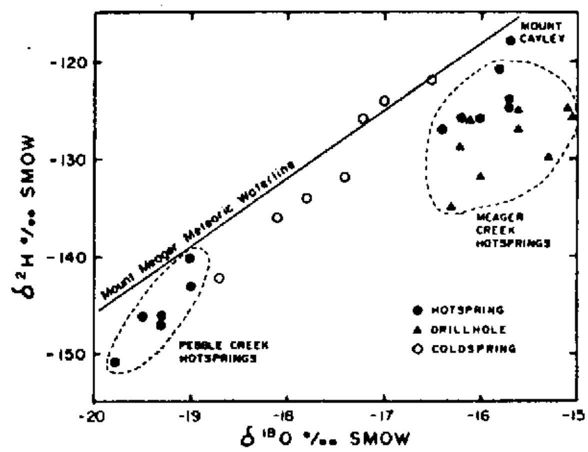

Fig. 4 ^{18}O - ^{2}H plot for the Mount Meager, Mount Cayley and Lillooet River thermal areas.

Mount Meager

Observations of data from the Meager Creek and Pebble Creek Hotsprings indicates that two quite distinct thermal systems exist, with different recharge areas and thermal histories (Fig. 4). Meager Creek thermal waters exhibit a positive ^{18}O shift from the meteoric waterline of approximately 1.5‰ which is an indication that a certain degree of oxygen-18 exchange has occurred. The original pre-^{18}O exchange value of -17.0 to -18.0‰ is in the same range as found for low altitude cold springs on the Mount Meager volcanic complex. These cold springs discharge isotopically constant waters which represent an average of annual precipitation and glacial meltwater inputs at higher elevations on the complex. The same recharge source was therefore concluded for these thermal waters (Clark et al, 1982).

By contrast, the nearby Pebble Creek thermal waters exhibit a minor oxygen-18 shift of less than 0.5‰ and have an original ^{18}O value of between -19.5 and -20.5‰ (Fig. 3). These thermal waters are apparently recharged at a much higher elevation, most probably to the north or east of Mount Meager, and have experienced less exchange with hot rocks due to a shorter subsurface residence time and for lower temperatures of exchange (Clark et al, 1982).

Mount Cayley

Mount Cayley thermal waters have an ^{18}O-^{2}H relationship very similar to local meteoric waters. No observable ^{18}O shift due to oxygen exchange exists and the high concentration of the heavy isotopes indicates that local recharge, affected by summer precipitation (sample collected in September) predominates. The flow rate of these springs is affected by variations in precipitation.

AGE DATING

Tritium

Natural tritium (half life = 12.43 years), created in the upper atmosphere by cosmic radiation, has an abundance in precipitation of between 5 and 20 TU (Brown, 1961). Between 1952 and 1964 thermonuclear bomb testing in the upper atmosphere elevated this abundance to several thousand TU. Groundwaters recharged since the early 1950's are then, "tagged" with ^3H whereas recharge prior to this time will have undetectable tritium concentrations. Cold spring water from Mount Meager contained measurable amounts of tritium indicating that recharge occured less than 20 to 30 years ago. Thermal waters by contrast, had only trace concentrations, attributable to minor mixing with cold groundwater, and are greater than about 30 years old. Similarly, cold groundwaters at Mount Edziza had ^3H concentrations of 8 to 18 TU, whereas the thermal waters tested had no measurable tritium.

Carbon-14

In groundwater recharge waters, dissolved atmospheric and biogenic CO_2 has a modern carbon-14 activity. However, once out of atmospheric contact, radiogenic carbon decays (half-life of 5730 years), thus providing a tool to estimate the age of waters up to thousands of years old. This method however, requires that there are no inputs of "dead" carbon from such sources as carbonates, hydrothermal calcite minerals or volcanogenic CO_2. Unfortunately, hotsprings related to Quaternary volcanic centres generally have very high CO_2 partial pressures. ^{13}C data from Mount Edziza, Mount Meager and Mount Cayley indicate a volcanogenic orgin for CO_2, which accounts for the low (less than 6 pmC) carbon-14 activities. Carbon-14 dating of thermal waters unrelated to volcanic complexes, such as Skookumchuck, Sloquet and Harrison Hotsprings, may be more successful.

SUMMARY AND CONCLUSIONS

The results of isotopic and geochemical methods applied to various geothermal areas in British Columbia have advanced our understanding of the hydrogeology and geothermometry of these systems.

Geothermal waters related to Quarternary volcanic centres in the Coast Mountains apparently discharge from dominantly shallow, relatively low temperature flow systems. A summary of geothermometer results for Mount Edziza, Mount Meager and Mount Cayley thermal waters provide no indications that subsurface temperatures in these flow systems are in excess of 120°C. Most geothermometer estimates are less than 100°C. Oxygen-18 and deuterium data show that with the exception of the Meager Creek thermal waters, ^{18}O exchange with minerals at elevated temperatures is minimal. Meager Creek Hotspring waters have been shifted by up to +1.5‰, indicating a greater degree of thermal alteration.

Recharge waters feeding the Elwyn and Taweh Hotsprings at Mount Edziza, the Meager Creek Hotsprings at Mount Meager and the hotsprings found at Mount Cayley were determined to be local, probably as a combination of precipitation on the volcanic complexes and ablation at the base of the glaciers. Age dating by tritium indicates that recharge took place prior to at least 1955.

Thermal waters from hotsprings located along the Lillooet River valley with the exception of the Pebble Creek Hotsprings have apparently experienced subsurface heating to less than 100°C. The deep permeability afforded by the fault zone in this area plus the residual heat related to intrusions along the Pemberton plutonic belt have likely created the physical conditions for these hotsprings to exist. The Pebble Creek Hotsprings, although discharging from a geothermal flow system quite separate from the Meager Creek Hotsprings, derive their heat from the volcanic complex. Interestingly, these hotsprings, having the highest geothermometer temperature estimates of all sites, discharge most closely to the presumed location of the Bridge River Ash volcanic unit. This volcanic vent, on the eastern flank of Mount Meager, is the youngest in southern B.C. (2440 years BP; Read, 1978).

In assessing geothermal areas for potential development in B.C., geochemical and isotopic methods are an inexpensive means of providing valuable information for further exploration. Difficulties can arise, however, when deep geothermal resources are masked by shallowly circulating flow systems of high discharge rates. Relatively high rates of precipitation in the Coast Mountains make this a problem. This may be the case at Mount Meager, where rock temperatures in excess of 250°C have been measured. Although no commercial quantities of steam have been developed to date, a permeable zone in one deep test hole has shown some potential, indicating that a deeper resource may exist. However, as this potential geothermal reservoir has no apparent surficial expressions in the Mount Meager area, more imaginative applications of isotope geochemistry are needed to evaluate its hydrogeology and geothermometry.

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CHARACTERIZATION OF AQUIFER ZONES IN A FRACTURED POROUS MEDIA

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ABSTRACT

A series of hydrogeological tests has been undertaken at a study site in the Maritime Carboniferous Basin to determine the factors controlling flow and transport through the upper 60 metres of a sandstone aquifer which appears from a stratigraphic standpoint to be relatively homogeneous.

Profiles of hydraulic conductivity, sandstone content, and fracture geometry and frequency have been developed from four coreholes by means of in situ constant head injection tests and reconstruction and orientation of the core. The injection tests and laboratory core tests indicated that the fractures were the primary source of permeability and that variations in their properties controlled both fluid flux and fluid velocity in the aquifer. The profiles suggest that four hydrostratigraphic zones exist in the sandstone unit.

To determine the effect of fracture geometry on the directional permeability of the aquifer, a 72-hour constant discharge pumping test was carried out in which hydraulic head response was monitored in the coreholes. Using the Papadopulos (1965) method for evaluating horizontal anisotropy, it was found that directional permeability exists in the three lower aquifer zones with $T_{max}:T_{min}$ ratios of approximately 9:1, 2:1, and 3:1. The orientations of T_{max} for all zones were quite similar, with azimuths ranging from 136 to 157 degrees. This trend is sub-parallel to the strike of the vertical fracture set in the area.

INTRODUCTION

Sedimentary bedrock formations are important aquifers and petroleum reservoirs in many parts of Canada. This is certainly true on Prince Edward Island and in parts of New Brunswick and Nova Scotia where essentially all water supplies are obtained from a Permo-Carboniferous red bed sequence. Attempts to investigate and describe these aquifers within the classical concepts of flow through porous media can be misleading, for in fact many of the units are "fractured porous media" deriving their hydraulic properties from a combination of primary intergranular (matrix) porosity and permeability and secondary porosity and permeability due to fractures.

As part of a comprehensive study of the hydrogeology of the Winter

River Basin, Prince Edward Island, a series of tests has been carried out (1) to determine the nature and relative importance of the fractures and matrix in the underlying aquifer and (2) to evaluate the effect of fractures on lateral anisotropy. By detailed measurement of the basic hydraulic parameters in the upper 60 metres of this unit, it was expected that a better understanding of the processes governing flow and transport in these and other fractured porous aquifers would be attained.

The fracture geometry and spacings and profiles of rock mass hydraulic conductivity obtained from four diamond coreholes are described by Francis (1981) and Gale and Francis (1983). The magnitude of horizontal anisotropy in the aquifer was evaluated by means of a constant discharge pumping test, in which hydraulic head changes were monitored at fourteen measuring points distributed in horizontal and vertical arrays about the pumping well (Gale et al., 1982).

SITE DESCRIPTION

The location chosen for these ongoing studies is the Union Well Field, situated in the southwestern portion of the Winter River Basin (Figure 1). This well field supplies the city of Charlottetown with approximately two billion litres of water each year.

In the vicinity of the well field an average of 5 m of sandy glacial till overlie the bedrock. The upper 200 m of bedrock are composed of horizontal beds of fine- to medium-grained, poorly sorted, argillaceous sandstone. Infrequent partings and lenses of claystone and siltstone less than 0.5 m thick occur within this sequence. Depth to the water table varies seasonally from 4 to 7 m.

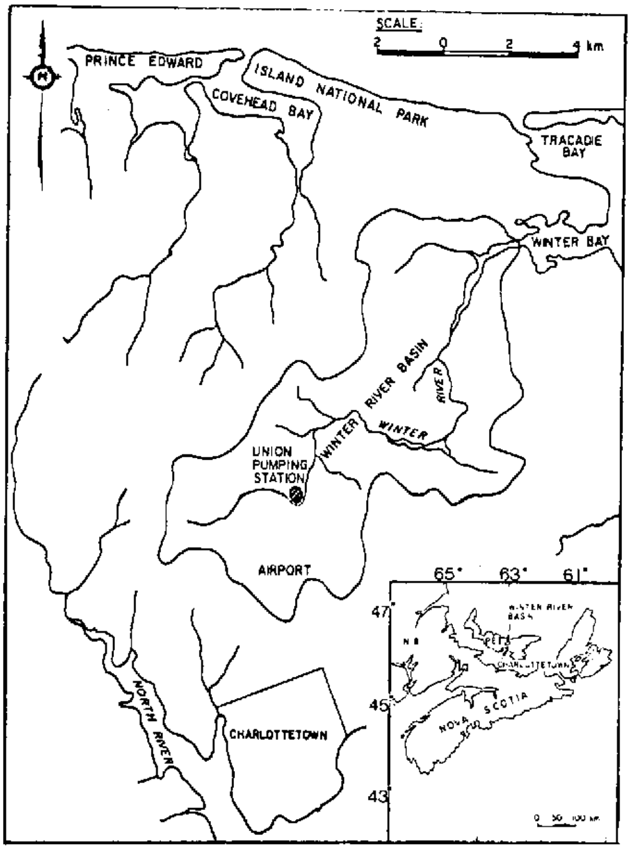

Figure 1: Location Map, Winter River Basin.