



Abstract

Fluids in sedimentary basins: an introduction

Kurt Kyser^{a,*}, Eric E. Hiatt^{b,1}

^aDepartment of Geological Sciences and Geological Engineering, Queen's University, Kingston, Ontario, Canada K7L 3N6

^bDepartment of Geology, University of Wisconsin, Oshkosh, WI 54901, USA

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Abstract

Understanding paleohydrologic systems in terms of basin evolution requires the integration of information derived from the sedimentology, stratigraphy, diagenesis and geology of basin-filling successions. Combination of these is prerequisite for realistic basin analysis and to guide any hydrologic or geochemical modeling. Ancient basins, in particular, represent systems that can record protracted burial histories, thereby constraining the composition of specific fluid events that normally affected vast areas.

The papers in this volume are concerned with tracing the fluid history of several sedimentary basins. These papers, which were presented in a special session at the Geological Association of Canada and Mineralogical Association of Canada meeting in Calgary, Alberta, Canada in May 2000, illustrate some of the methods, techniques and approaches required to document significant fluid events in basins and how this information can be used in some cases to evaluate the economic potential of basins. The focus of these studies deals with the interaction between basinal fluids and both chemical and clastic sediments. Both types of sediments can act as principal aquifers or aquitards for fluids in basins because of their changing reactivity and permeability as basins evolve.

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1. Introduction

Sedimentary basins are the largest structures on the surface of our planet and the most significant sources of the energy-related commodities, such as petroleum, natural gas, coal, uranium and many metals (Fig. 1). They can be defined generally as portions of the earth's crust that have been nonlinearly down-warped and

filled with sediments during intermittent relative uplift and subsidence. Although most people recognize that basins are reservoirs for petroleum, their strategic reserves of metals are generally less recognized. In Canada, for example, the income from all of the energy fuels and over half of the income from metals are derived from deposits in sedimentary basins (Fig. 2). Some of these metalliferous deposits are syndepositional whereas most, like their petroleum equivalents, are products of postdepositional processes, particularly later fluid flow systems. Consequently, understanding critical processes involved with fluid events in basins is paramount not only for understanding earth evolution but also for formulating genetic models and

* Corresponding author. Tel.: +1-613-533-6179; fax: +1-613-533-6592.

E-mail addresses: kyser@geol.queensu.ca (K. Kyser), hiatt@uwosh.edu (E.E. Hiatt).

¹ Tel.: +1-920-424-7001; fax: +1-920-424-0240.

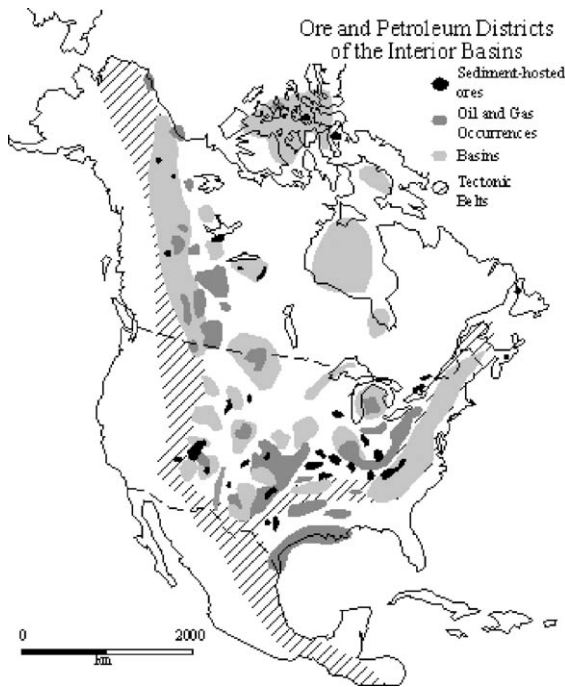


Fig. 1. Distribution of major basins, oil and gas occurrences and sediment-hosted ore deposits in North America and their relation to major tectonic belts. Modified from Ge and Garven (1989).

exploration strategies for many of our most needed commodities.

Sedimentary successions in basins normally are subjected to increasingly intense diagenesis and metamorphism that results in a progressive evolution of its

hydrology. This hydrologic structure is in turn vitally important in determining how and where mineralization may occur. Therefore, it is crucial that controls on diagenetic evolution in basins must be understood to develop predictive capabilities. Although this is precisely what the petroleum industry has been doing for decades, many of these concepts have not yet been extended to exploration and exploitation of sedimentary-hosted mineral deposits.

This special volume is a compilation of papers that are concerned with tracing the fluid history of sedimentary basins and on how these histories reflect the sedimentological, hydrologic, tectonic and geochemical evolution of sedimentary basins. The major thrust of the volume is to illustrate many of the methods, techniques and approaches required to document significant fluid events in basins and how this information can be used to evaluate the evolution and possible economic potential of basins. The results from these studies are prerequisite for constraining large- and restricted-scale flow models, understanding the evolution of the crust and refining exploration and exploitation strategies for mineral and petroleum deposits. Most of the results presented here apply to large-scale basin evolution involving both clastic and chemical sediments.

This introductory paper by Kyser and Hiatt reviews some of the critical parameters that affect the evolution of fluids in basins and outlines some of the specific data needed for holistic basin analysis. The petrography and geochemistry of dolomite and calcite cements

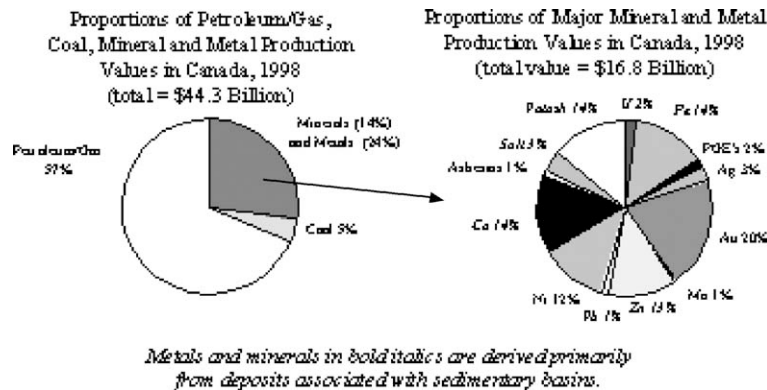


Fig. 2. Proportion of revenue from production of petroleum + gas, coal and mineral + metal production in Canada for 1998 (left) and detail of the proportions of the mineral + metal production (right). Although the relative proportions and total values vary annually depending on market price, the vast majority of the production of these resources comes from basin-related deposits. Data from Statistics Canada Catalogue 26-202-X1B.

in Upper Tertiary sandstones from the Red Sea Graben by Longstaffe et al. are used to document fluid–rock interactions in a relatively young basin and to identify the most prospective units for petroleum accumulation. Chi et al. use petrography and geochemistry of authigenic phases in Carboniferous clastic sediments to elucidate the character of fluids associated with porosity development in the Devonian–Permian Maritimes Basin, and propose that hydrocarbons play a critical role in fluid–rock interactions. Hydrologic and hydrochemical data are integrated with geology by Michael et al. to decipher the origin and migration of brines in Devonian strata in the petroleum-rich Western Canadian Basin.

Using sandstones to reflect basin evolution, Hiatt et al. examine the relations among sequence stratigraphy, diagenesis and paleohydrology in the Paleoproterozoic Thelon Basin, the first study to integrate these with geochemical data to refine the controls on paleohydrology in a Proterozoic basin. In more focused studies of Paleoproterozoic basins, Lorilleux et al. examine the possible significance of clay mineral occurrences in formation of unconformity-type uranium deposits in the Athabasca Basin in Canada, whereas Derome et al. discuss how integrating both classical and new techniques to study fluid inclusion in quartz near uranium showings in the Kombolgie Basin of Australia reveal the complexities of fluid interactions near the basal unconformity.

Although these studies use both established and new techniques in basin analysis, Peevler et al. use the recently developed SIMS to elucidate the fine-scale variations in sulfur isotopic compositions in Phanerozoic MVT deposits and these data constrain the sources of sulfur and some of the processes involved in the formation of the deposits. In another novel application of new technology to understanding fluid histories and basin evolution, Holk et al. present results using Pb isotopes mobilized from uranium deposits in several Paleoproterozoic basins as indicators of high-grade deposits.

2. Major factors in basin evolution

Perhaps the foremost control on basin formation is tectonic environment. However, tectonism is also a major control on fluid evolution and fluid–rock

interactions in basins. Fluids in basins normally will not flow without changes in hydraulic gradients and most of these are tectonically induced. Thus, a fundamental understanding of how basins form and how fluids move through them requires definition (albeit simplified) of the various types of basins in the context of their tectonic settings, such as shown in Table 1.

Given that sedimentary basins are filled predominantly with sediments, sedimentation and stratigraphy using sequence stratigraphic principles, source terrain evaluation and changes in the style of fill with time are required. In effect, original sedimentology, especially in clastic sediments, has a profound effect on the development of both early and late aquifers and aquitards in basins, many of which are prerequisite for the migration of petroleum and formation of metalliferous deposits. The porosity and permeability of chemical sediments vary significantly with different lithologies (Fig. 3). Deposition of clastic sediments and volcanic-derived basin fill depends on a complex variety of factors, including grain size, mechanical properties of the grains, distance from the source (Fig. 4) and rate of erosion of the source terrain (Fig. 5). The latter two factors, in particular, depend greatly on paleoenvironment. For example, uplifted areas in arid terrains weather both mechanically and chemically at slower rates than similar terrains in subtropical environments (Fig. 5). Weathering during the past ca. 400 m.y. has changed profoundly due to the evolution of land plants, which fix the soil on one hand but also supply organic acids to increase chemical weathering on the other. Periods of high atmospheric CO₂ levels would also have enhanced chemical weathering.

Associated with the generation of aquifers and aquitards is a transfer of the inherently unstable original mineralogy in basin sediments to a more stable assemblage during burial diagenesis, with the release (or consumption) of various fluid components. The typical change in the mineralogy of pelitic sediments (Fig. 6) is from montmorillonitic clays, plagioclase and zeolites to a mixture of feldspar, chlorite and muscovite. Quartz in these rocks is normally stable but its solubility increases with temperature, and it may become leached at depth if there is high fluid flux or diagenetic reactions that consume silica. Most biogenic or low-temperature carbonates in these sys-

Table 1
 Classification of basins based on modified versions by [Einsele \(1992\)](#) and [Busby and Ingersoll \(1995\)](#)

Basin category	Style of tectonics and underlying crust	Special basin type	Basin characteristics	Subsidence mechanisms	Basin examples
Continental sag basin	divergence, continental	intracratonic, epicontinental	large areas, slow subsidence; sometimes flooded by fossil rifts	sedimentary and volcanic loading; initiated by crustal thinning	Michigan; Prot. Thelon, Athabasca, Kombolgie
Continental fracture basin	divergence, continental	graben basin, rift basin	narrow, fault-bounded basins with initial rapid subsidence during early rifting	mantle upwelling, crustal thinning and sediment/volcanic loading	Rio Grande rift; Prot. McArthur basin
Basins on passive continental margins	divergence + shear, continental + oceanic	tensional-rifted basins, margin basins	asymmetric basins associated with rifted margins	crustal thinning, tectonic loading, sediment/volcanic loading	E. Paleozoic Canadian Cordillera; Prot. McKenzie
Oceanic basins	divergence, oceanic	ocean basin	large asymmetric, slow subsidence	mantle upwelling primarily at ridges and subsequent cooling during spreading	Pacific and Atlantic oceans; ophiolites; Abitibi basin
Basins related to subduction	convergence for trenches; divergence for all else; oceanic/continental	deep-sea trenches, fore-arc, backarc, interarc, intra-arc basins	partly asymmetric, variable depth and rate of subsidence	tectonic loading, volcanic/sediment loading (crustal thinning in arc basins)	Chile trench, Jurassic Sierra Nevada, Mesozoic Canadian Cordillera
Basins related to plate collision	convergence, oceanic	remnant basins	active subsidence due to rapid loading	sedimentary loading and tectonic loading	Penn-Permian Ouachita basin
	crustal flexure, local convergence, continental	foreland basins, intermontane	asymmetric basins with trend to increasing subsidence, uplift and subsidence	tectonic loading; sediment/volcanic loading	Andes foothills, Laramide basins; Canada Western Interior; Po; Appalachian
Strike-slip/wrench basins	transform motion, continental/oceanic	pull-apart (transtensional) and transpressional basins	small, elongate with rapid subsidence	crustal thinning (transtensional), tectonic loading (transpressional), sediment/volcanic loading	Salton Sea; Carboniferous Magdalen basin

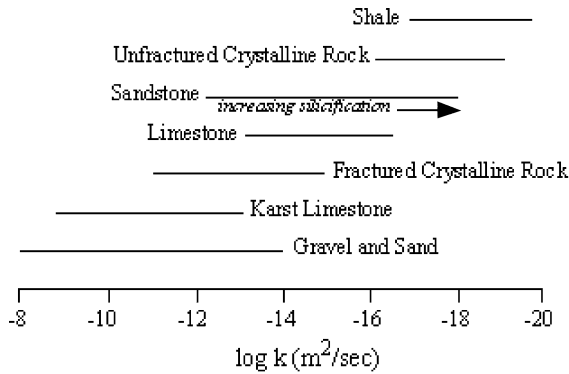


Fig. 3. Range of permeability (k) values for various types of rocks and unconsolidated material (after Nesbitt, 1990).

tems are inherently unstable at the outset, but most diagenetic fluids become saturated with Ca–Mg–Fe carbonate during diagenesis, at least locally.

Inasmuch as we normally examine the minerals or trapped fluids from ancient fluid events, the paragenesis of minerals in stratigraphic units is required before fluid histories can be revealed. This is accomplished via field relations, a variety of petrographic techniques and knowledge of diagenetic mineral reactions and phase equilibria. Fluid inclusions in detrital and authigenic minerals can record salinities, temperatures and pressures of fluids from the source terrain, as well as in the basin. Stable isotopes of the fluids in inclusions as well as in authigenic minerals can be used as tracers of the origin and flow path of fluids. The “timing” of fluid events can be estimated using paleomagnetism recorded in authigenic Fe-oxides, fission tracks in apatite and zircons and radiometric dating of clay minerals (mainly illite), uraninite, salts, phosphates and sulfides. Tracing relatively recent basin histories can be done via noble gas geochemistry, which also reveals past heat generation in basins, data on what components might be contributing to basin evolution and how fluids may interact with petroleum and gas. Actualistic and nonactualistic effects are evident from the comparison of fluid evolution and tectonic styles of Cenozoic, Mesozoic, Paleozoic and Proterozoic basins presented in this volume.

Fluids flow through basins primarily in response to hydraulic gradients at rates that are proportional to the permeability of the lithologies in the basin (Fig. 3). During initial burial, flow rates will be high, on the

order of meters per year depending on the permeability of the strata and the driving mechanism for the fluid. As the basin evolves, flow rates due to compaction are on the order of centimeters per year, whereas topography-driven flow rates, although variable, may approach meters per year (e.g. Harrison and Tempel, 1993). More importantly, as basins evolve, hydrologic characteristics of some lithologies may change as a result of diagenetic reactions and fracturing. This is abundantly evident in older basins where secondary petroleum migration and ore deposition are intimately associated with basinal and basement structures that become reactivated.

Reference is often made in the literature to various types of waters associated with basins, and some of these have genetic connotations whereas others do not. We have adopted the following definitions for different types of fluids after Kyser and Kerrich (1990):

Formation water refers simply to the fluid resident in rocks, and has no significance to origin or age.

Connate water is the fluid deposited with the sediments or rocks and can be modified via reactions with the reservoir rocks.

Meteoric water originates from rain or snow and can be modified via interaction with rocks at elevated temperatures to become a meteoric–hydrothermal fluid.

Metamorphic water is generated by metamorphism although sometimes the ultimate origin of this fluid

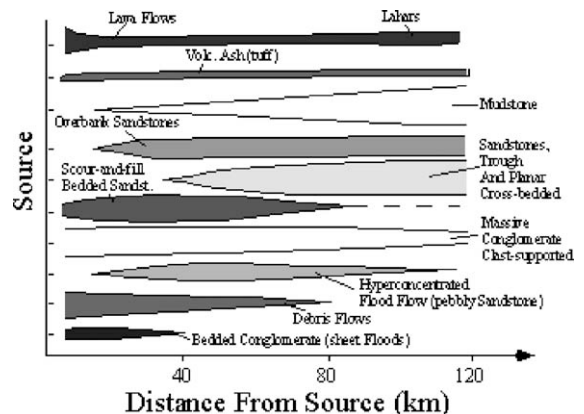


Fig. 4. Range in transport distances from source of various clastic and volcanic lithologies (modified from Einsele, 1992).

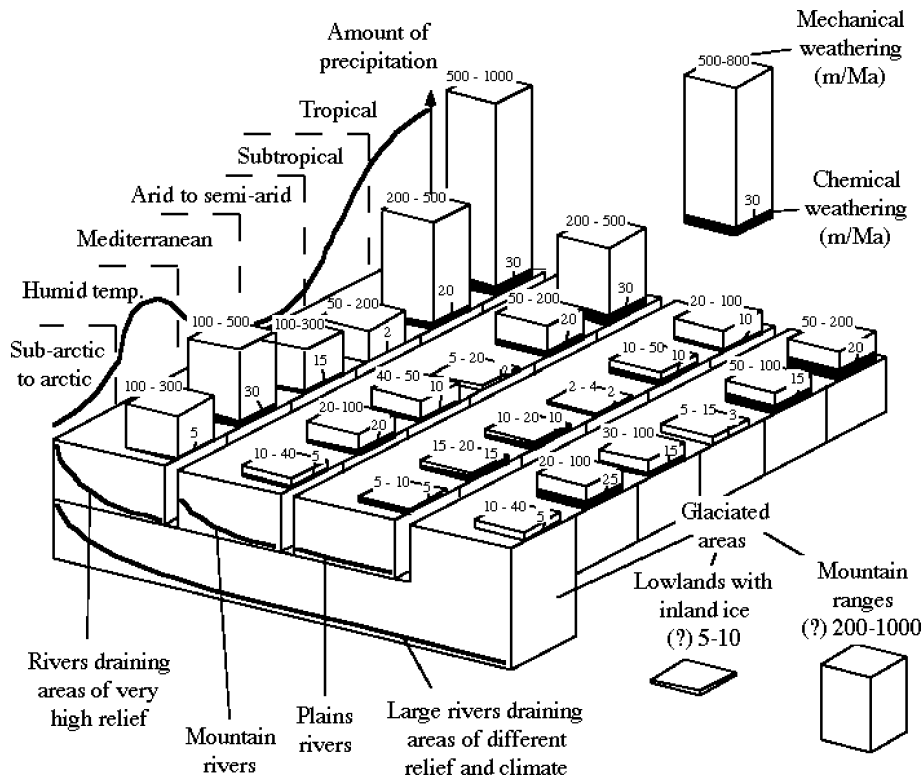


Fig. 5. Mechanical and chemical weathering rates as a function of modern climatic conditions (modified from Einsele, 1992).

(i.e. meteoric water, connate water, seawater or water from dehydration reactions) can be determined with hydrogen and oxygen isotopes.

Magmatic water is that hydrous fluid commonly released from a crystallizing magma.

Other than formation waters, these “categories” are applicable to describing the origin of only some fluids because the extensive interactions between most fluids and rocks obscure their origin. Conservative tracers such as stable isotopes of the fluids or the minerals they formed must be used to discern the origin of the fluids.

3. Tracing the fluid histories of sedimentary basins

Sedimentary basins are not only hosts to economic deposits of petroleum but also to many metals such as Pb–Zn, Cu, Au and U. How are fluid events in basins traced? In contrast to ore deposits in other geologic

environments, the formation of economic mineralization in basins must be placed in the same regional context that is required to understand the generation and location of petroleum deposits. Inasmuch as fluids can be resident in basins for significant time periods, they evolve through interactions with host lithologies to become chemically distinct. Fluids in all basins originate and flow as a result of sedimentological and tectonic events so that fluid histories should reflect directly the control of sedimentology and tectonism on petroleum migration and ore deposition. Exploration for deposits in sedimentary basins can profit from the regional aspects of fluid–rock interactions provided strategic fluids can be characterized and the importance of specific geologic environments and lithologies recognized. For example, if aspects of petroleum and ore deposits can be correlated with specific fluid flow events, areas where those events were most likely concentrated or focused are most favorable for exploration. In the case of petroleum migration or generation of an ore deposit, faults and paleoaquifers provide a

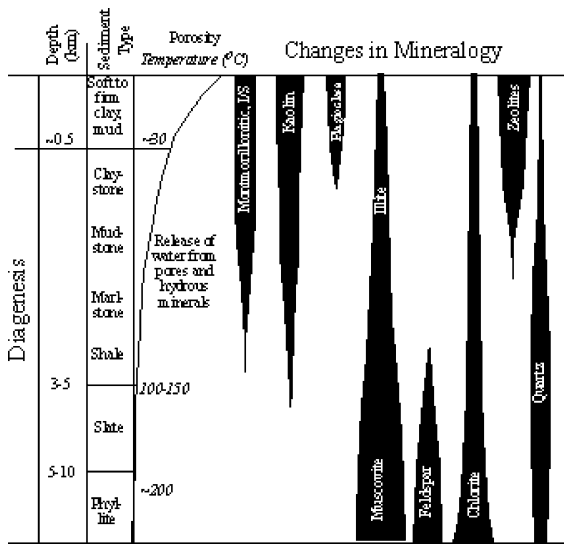


Fig. 6. Changes in the porosity, temperature and mineralogy of typical pelitic sediments during burial and diagenesis. Quartz is relatively stable throughout this interval. Carbonate rocks undergo substantial changes to other carbonate minerals immediately in the subsurface and volcanic rocks begin diagenetic changes on contact with aqueous fluids.

major focusing of fluid flow, thus necessitating an understanding of fluid composition within a stratigraphic unit or at any given fault/stratigraphic intersection. Structural and stratigraphic frameworks provide information on possible fluid flow pathways but additional techniques and strategies are required to characterize the fluids along predicted migration pathways.

Tracing specific fluid events in basins and relating them to economic petroleum or ore deposits requires first and foremost a stratigraphic and geometric geologic base from which the relative timing of sedimentologic and diagenetic processes can be discerned. Once these processes are recognized, documentation of the extent and types of various fluid events, mineral paragenesis to reflect the geochemical consequences of fluid–rock interactions, and characterization of the specific geochemistry and timing of fluids that have interacted with petroleum or ores can be used to understand basin evolution and refine exploration strategies. It should be possible to predict whether a sample comes from a small relatively isolated depocenter, with possible restricted fluid flow, or from a much larger open geometric system where fluid flow

paths may have extended over hundreds of kilometers. Sandstone lithologies, in particular, should reflect fluid flow events because they are normally the major aquifers in basins, although early cementation can transform sandstones to aquitards and other lithologies such as volcanic rocks, carbonate and shale sequences can also record the effects of major fluid events. Fluids are strategically associated with both the formation and preservation of almost every type of economic ore deposit, especially those in basins. As such, knowledge of the geochemical and physical characteristics, timing, origin, reactivity and flow histories of fluids are basic to formulating effective exploration strategies.

To trace the fluid history of sedimentary basins requires integration of relatively diverse subdisciplines including sedimentology, stratigraphy, tectonics, structural geology, petrography, geochemistry and geophysics (Table 2). Among the questions to be addressed in effective “basin analysis”:

- (1) What kind of basin is it (i.e. likely tectonic setting) and what is the original character of the basin fill (Table 1)?
- (2) What are the relative ages (i.e. paragenesis) of diagenetic minerals in the various basin fill lithologies, particularly those that would serve as aquifers in various stages of basin evolution?
- (3) What are the respective roles of various lithologies in contributing organic matter to the petroleum and metals to the sedimentary-hosted ore deposits?
- (4) What are the geochemical and physical (i.e. temperature, pressure, density) characteristics of these fluids?
- (5) What has been the effect of the timing and type of diagenesis on fluid movement in the basin, and how do these relate to tectonic and structural evolution of the basin?
- (6) How extensive are the resulting diagenetic minerals, i.e., are they basin-wide, restricted to specific subbasins, or to certain lithologies or structures?
- (7) What is the probable origin of these fluids, and how did they evolve in the basin? Even for fluids resident in basins this can be an arduous task.
- (8) How do the chemical, physical and age characteristics of the fluids throughout the evolution of the basin compare to those directly associated with economic deposits?

Table 2
Various processes and expected results from “basin analysis”

Process	Result
Field observation	structure of basin possible tectonic setting during origin and evolution
Sedimentology and stratigraphy	relation to possible source of basin fill identification of sequence significance of sequence boundaries lithofacies of basin fill probable basin type preliminary identification of aquifers and aquitards
Petrography	identify detrital and authigenic minerals determine mineral and event paragenesis infer significant fluid–mineral reactions recognition of fluid inclusions
Phase equilibria and fluid inclusions	constrain <i>P</i> , <i>T</i> and composition of fluids from cognetic authigenic minerals or directly from fluid inclusions
Stable isotopes	further refine <i>T</i> of fluids using cognetic minerals analyze the H, C, N, O, S isotopic composition of authigenic minerals and determine the composition of the fluids that formed them determine the composition of fluids in inclusions estimate origin of the fluids, paleoenvironments
Paleomagnetism and radiogenic isotope geochemistry	determine the absolute timing, or time of closure, of fluid events from authigenic minerals
Modeling	integrate above data to constrain in hydrologic, tectonic and thermal evolution

Integration of these factors is required to understand the fluid evolution of a sedimentary basin.

(9) Do later fluids interact with the deposits resulting in dispersion of specific chemical constituents?

4. The importance of mineral paragenesis

When fluids interact with sediments, the reactions that occur depend on the chemical composition of the fluid, the minerals in the sediments, and the temperature and pressure. Just as with crosscutting structures, the relative timing of various fluid events is reflected in the paragenesis of diagenetic minerals. The distribution of these diagenetic events can be traced by examining samples of the same lithologies from throughout the

basin provided there is sufficient stratigraphic and structural refinement. Examination of thin sections from various lithologies and alteration assemblages can reveal the relative timing at which diagenetic minerals formed. The relative appearance of diagenetic minerals and the fluid inclusions contained in some of them can be compared from around the basin to see how extensive the fluid events were and what their chemical compositions would have been to form these minerals. The paragenesis must be detailed at scales ranging from lithological units to hand specimen to thin section to the micrometer scale using combinations of field, petrographic, X-ray diffraction (XRD), infrared (IR) and electron microprobe techniques. Clay minerals and their order of appearance must be determined and visualized, particularly those from lithologies that likely served as basinal aquifers.

5. Determining the characteristics of basinal fluids

Diagenetic minerals and fluid inclusions are not only effective records of the relative timing of ancient fluid flow events but they also contain information about the characteristics of the fluids that have affected the basin. Chemical compositions of fluids can be estimated by using phase equilibria (e.g. at specific temperatures and pressures, coexisting illite, albite, kaolinite and quartz fix the activities of Si, K and Na and the pH of the fluid) or by direct examination of fluids commonly trapped in diagenetic quartz and carbonate. Apparent equilibrium temperatures of coeval minerals also can be determined from their oxygen isotopic compositions, as can the isotopic composition of the fluid itself. The “crystallinity” of clay minerals as determined from XRD analyses also constrains their temperature of formation. For example, 2M illites and dickite are higher-temperature (i.e. in excess of 150 °C) polymorphs of illite and kaolin, respectively. Once the paragenesis of clay minerals has been determined, they can be separated from selected samples of sandstones, volcanics and carbonates and their formation temperature constrained from crystal structure and chemistry.

The exact chemical composition of fluid inclusions can be measured directly using laser extraction and inductive coupled plasma mass spectroscopy (ICPMS), a technique that has significant potential for in situ

analysis of the trace element content of fluids, rocks and minerals. Elements such as Cl, Br, F, S, P, which are effective transporters of metals, can be measured for the first time in fluid inclusions from thin-section chips containing minerals with known paragenesis. This would include inclusions from the earliest fluid events, such as those in quartz overgrowths or carbonate cements, to later critical fluids such as those associated with veins in fault structures. Specific chemical, physical and isotopic characteristics of each fluid as deduced from the compositions of diagenetic minerals or fluid inclusions sometimes can be traced throughout the basin.

The purpose of tracing the extent of specific fluids is to constrain the driving force for flow, i.e., whether major tectonic events were driving specific fluids throughout the basin, or if specific fluids were restricted to certain lithologies, formations or subbasins. Although detailed paragenesis will give both the extent and relative timing of specific fluid events, their relation to tectonics and basin evolution requires knowledge of the absolute ages for the fluids. Relating basin evolution and fluid flow is done by analyzing paleomagnetic directions of diagenetic Fe-oxides associated with specific fluid events or by the radiometric ages and initial isotopic compositions of common diagenetic minerals such as diagenetic salts, illite (Ar–Ar), phosphates (U–Pb) and uraninite (U–Pb). These diagenetic minerals may be present in all lithologies including sandstones, carbonates and volcanics. With detailed paragenetic relations obtained from the petrographic study, a more exact timing of specific fluid events can be determined.

The origin of a fluid is reflected most accurately in the isotopic composition of the major components in most fluids, namely H, C, S and O. The isotopic composition of oxygen in coexisting alteration minerals can reveal their apparent equilibration temperature as well as the isotopic composition of H₂O in equilibrium with the minerals. In conjunction with H isotopes determined from clay minerals or fluid inclusions, the isotopic composition of the water can be calculated thereby constraining the origin, whether from meteoric, basinal or volcanic sources.

Defining the extent and character of fluids that have affected basins can aid exploration for petroleum and mineral deposits in three ways. Where and when specific mineralizing fluids were in the basin can limit

areas to be explored as well as identify critical processes and environments favorable for mineralization. Inasmuch as at least some fluids in the basin are likely to postdate petroleum formation or ore deposition, these fluids may have interacted with the petroleum or high-grade ore and mobilized some of the components. The dispersion of these fluids can be used to trace the location of the deposit using data from the chemical composition (i.e. trace element content), possible flow path and extent of these later fluids.

6. Summary

From an exploration geologist's perspective, there are a small set of fundamental questions to be addressed: (1) what are the spatial and temporal relationships during basin evolution that led to the development of economic deposits and (2) how can understanding basin evolution guide exploration strategies?

This volume includes many new approaches and techniques applied to basin analysis that help address these fundamental questions; they include studies that integrate diagenesis (Derome et al., Lorilleux et al., Longstaffe et al., Chi et al., this volume), paleohydrostratigraphy (Michael et al., Hiatt et al., this volume) and sequence stratigraphy (Hiatt et al., this volume) to understanding the relationships between sedimentary basin fill and fluid flow. Peevler et al. utilized the ion microprobe to analyze the isotopic composition of sulfide minerals in MVT deposits as a means to constrain their genesis. Holk et al. apply a new technique to analyze U–Pb isotopes as an indicator of fluid movement in sedimentary basins.

There are countless publications on basins. Many of them are referred to throughout these papers but a few represent summaries in the form of books that are particularly useful for those seeking information about basins. In addition to books by various publishers, series publications by AAPG, SEPM, Geoscience Canada and the Geological Society include a multitude of volumes relevant to tracing fluid histories of sedimentary basins. A partial list includes the following topics: sedimentology by Kleinspehn and Paola (1988), Allen and Allen (1990), Einsele (1992) and Miall (2000), Eriksson et al. (2001); tectonics by Allen and Homewood (1986), Price (1989) and Busby and

Ingersoll (1995); hydrology by Goff and Williams (1987); diagenesis by Marshall (1987), McIlreath and Morrow (1990), Horbury and Robinson (1993), Crossey et al. (1996) and Montañez et al. (1997); clay–fluid interactions by Manning et al. (1993); clastic diagenesis by McDonald and Surdam (1984); stable isotopes by Arthur et al. (1983), Fritz and Fontes (1980, 1986) and Kyser (1987); geochronology by Clauer and Chaudhuri (1992) and Parnell (1998); paleomagnetic applications by Tarling and Turner (1999); fluid inclusions by Goldstein and Reynolds (1994). This list is meant only to be a starting point for those interested in various topics related to basins and is by no means a complete list.

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