An example of alternative correlation techniques in a low-accommodation setting, nonmarine hydrocarbon system: The (Lower Cretaceous) Mannville Basal Quartz succession of southern Alberta

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ABSTRACT

Chemostratigraphy and heavy-mineral techniques have been applied to the Lower Cretaceous Basal Quartz in the Western Canada sedimentary basin. The aim of the study is to demonstrate that these two techniques can be used to help understand the complex stratigraphy of reservoirs deposited in low-accommodation fluvial settings. The Basal Quartz is an ideal unit to demonstrate their applicability in stratigraphic studies of hydrocarbon reservoirs because extensive mapping and petrographic studies have enabled the establishment of a rigorous stratigraphic framework despite its complexity resulting from deposition in a low-accommodation fluvial setting.

The three component units analyzed in the Basal Quartz (Horsefly unit, Bantry–Alderson–Taber [BAT] unit, and Ellerslie unit) each have unique geochemical and heavy-mineral characteristics. Chemostratigraphic analysis shows that silty claystones from the Horsefly, BAT, and Ellerslie units have distinctly different geochemistry from one another, with the variations being caused by changes in clay mineralogy and other components, such as feldspar, apatite, and zircon. The geochemistry also suggests periodic volcanogenic input influenced the silty claystones of the Basal Quartz. Heavy-mineral analysis shows that sandstones from the three units can be distinguished on the basis of ratio parameters, such as apatite/tourmaline, rutile/zircon, and zircon/tourmaline, which are controlled by differences in provenance and intensity of weathering during transport.

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INTRODUCTION

Low-accommodation nonmarine settings commonly contain significant oil and gas accumulations in clastic reservoirs (e.g., Zaitlin et al., 2002, Pearce et al., 2003, Ratcliffe et al., 2002). These reservoirs are commonly compartmentalized, which makes understanding field-scale and regional stratigraphy important. However, erection of rigorous stratigraphic frameworks in low-accommodation clastic reservoirs is commonly problematic because of polyphase erosion and incision that result in lithologically similar but chronostratigraphically different units being juxtaposed. The common lack of regionally extensive marker beds in low-accommodation settings and poor biostratigraphic control associated with nonmarine deposits make efficiently exploiting low-accommodation nonmarine sequences problematic. Therefore, in these types of settings, alternative stratigraphic techniques that enable each depositional tract to be characterized, regardless of its spatial distribution, are required. Two such techniques, chemostratigraphy and heavy-mineral analysis, have been applied in tandem to the Basal Quartz of the Western Canada sedimentary basin, southern Alberta (Figure 1), as an objective test of the traditional petrographic and sequence-stratigraphic analysis undertaken in Zaitlin et al. (2002).

The Basal Quartz, together with the overlying Ostracod Beds, forms the Aptian lower Mannville Group (Canadian Society of Petroleum Geology, 1990) (Figure 2). Together with the upper Mannville Group, which comprises the succession from the Glauconite Member to the base of the Colorado Group, this group is one of the most prolific hydrocarbon-bearing successions in the Western Canada sedimentary basin. The lower Mannville Group is estimated to contain 32% of the conventional oil and 53% of the gas reserves for the Mannville Group (Porter, 1992). Approximately 390 oil pools (each >100,000 bbl) and 961 gas pools (each >2 bcf) have been developed in the lower Mannville, totaling 1213 million bbl of oil and 7.1 tcf of gas (Energy Resources Conservation Board, 1997). A variety of proprietary and government resource base assessments estimate an additional 200–500 million bbl of oil and 4–5 tcf of gas remain in the lower Mannville Group. However, the Basal Quartz reservoirs have been shown to exhibit significant variation in reservoir quality, recovery factor, oil quality, and performance characteristics (e.g., Arnott et al., 2000, Zaitlin et al., 2002). Therefore, to better exploit the interval, a more detailed understanding of the reservoir and trapping configurations is required. This paper demonstrates two techniques that can provide this enhanced understanding.

In the study area (Figure 1), the Basal Quartz is generally less than 100 m (330 ft) thick and is composed of dominantly fluvial to estuarine quartzose sandstones and pedogenically altered claystones (Zaitlin et al., 2002). The unit is ideal to demonstrate that chemostratigraphy and heavy-mineral analysis can be successfully applied in low-accommodation settings because a stratigraphic framework has already been erected in the study area (Figure 2) (Zaitlin et al., 2002). The work of Zaitlin et al. (2002), which correlated more than

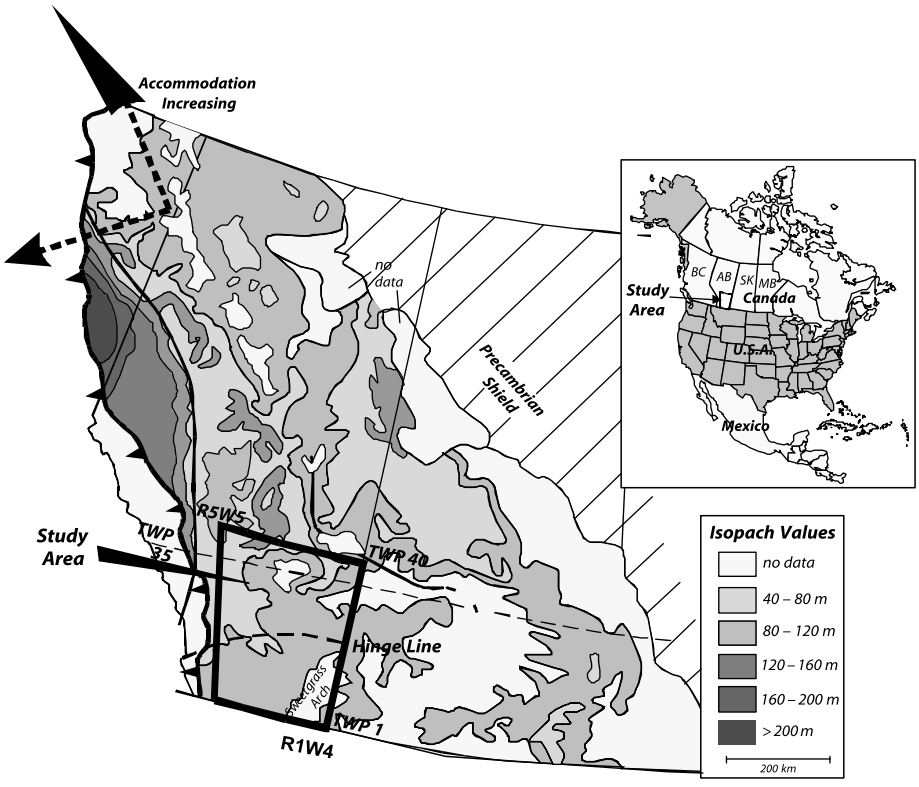


Figure 1. A map showing the location of study area in North America, with a detailed map of the study area in Alberta on which isopach grades for the lower Mannville are displayed. Revised from Zaitlin et al. (2002).

9000 wells in Townships 1–40, Ranges 1W4–5W5 and used core descriptions from more than 1350 conventional cores and more than 750 petrographic thin sections, demonstrated that within the Basal Quartz, there are two cycles, each of which records upward increasing sediment maturity (Figure 2). The upper part of these two cycles is further subdivided by Zaitlin et al. (2002) into three informal units, namely, in stratigraphic order, the Horsefly unit, the Bantry–Alderson–Taber (BAT) unit, and the Ellerslie unit. Chemostratigraphy and heavy-mineral analysis have been applied to these three units. As is typical in polyphase depositional systems, the sandstones from each of these units have different reservoir characteristics (Zaitlin et al., 2002), making them important to be able to determine the spatial distribution of each unit.

To demonstrate the validity of the techniques, conventional cores through each of the Horsefly unit (wells Devon Canada 1-35-1-20 W4, Talisman Energy 2-4-1-17 W4, and Imperial Oil 7-9-1-16 W4), the BAT unit (well Nexen Canada 6-11-26-28 W4), and the Ellerslie unit (wells Canadian Forest Oil 10-29-36-27 W4 and Canadian Forest Oil 3-30-37-27 W4) were sampled (Figure 3). The wells were chosen because of the high confidence of the stratigraphic assignment of each core, based on the petrographic work of Zaitlin et al. (2002). Sandstone units and finer grained facies were sampled for heavy-mineral analysis and chemostratigraphy, respectively. No single well is known to the authors to contain all three study units vertically stacked in core, and no such core was identified in the work of Zaitlin et al. (2002).

In addition to the heavy-mineral and chemostratigraphic analyses, eight of the silty claystones samples were analyzed using x-ray diffraction to determine their whole rock and greater and less than 4-μm mineralogical composition (Figure 4). This was done to help elucidate the mineralogical associations of selected key elements for the chemostratigraphic study.

Because the stratigraphic assignment of each of the cored intervals selected for this study was already known, the aim of this study is not to test the stratigraphic assignment, but rather to demonstrate the applicability of chemostratigraphy and heavy-mineral analysis in a low-accommodation setting. Although the sequences sampled for this study are from a relatively wide geographic area, they were deposited by a single drainage system mappable from south to north in excess of 250 km (160 mi) (Zaitlin et al., 2002) (Figure 3).

The Techniques

Chemostratigraphy, or chemical stratigraphy, involves the characterization and correlation of strata using major- and trace-element geochemistry. For this study,

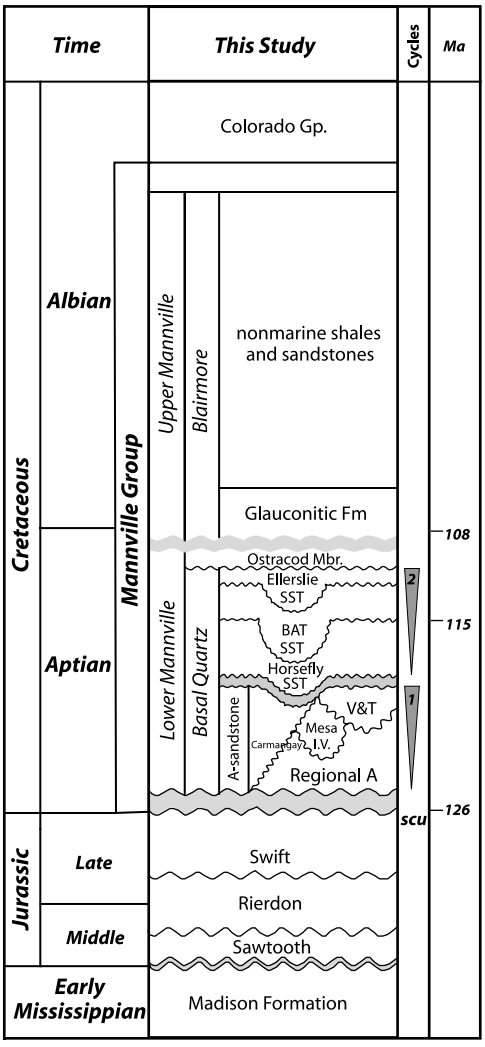


Figure 2. Lower Cretaceous stratigraphic nomenclature used in this study. Basal Quartz, Horsefly, Bantry–Alderson–Taber (BAT), and Ellerslie are informal stratigraphic units defined in Zaitlin et al. (2002). Cycles 1 and 2 refer to mineralogical and textural cycles described in Zaitlin et al. (2002). Geologic ages are from Gradstein et al. (1994). Gp = Group; Fm = Formation; Mbr = Member; SCU = sub-Cretaceous unconformity. Reprinted with permission from the Bulletin of Canadian Petroleum Geology.

inductively coupled plasma–optical emission spectrometry and inductively coupled plasma–mass spectrometry were used to determine the concentrations of 47 elements (10 major elements, 23 trace elements, and 14 rare-earth elements) from 90 samples in 6 wells. The sample preparation and analytical procedures used in this study are the same as those detailed in Jarvis and Jarvis (1995) and Pearce et al. (1999a). Chemostratigraphy, as with most stratigraphic techniques, is a subjective and interpretive technique. In any rock and even in a single stratigraphic unit, the large number of variables that potentially affect elemental concentrations means that not all samples fall within the typical geochemical signature defined for that unit. This is exacerbated when dealing with core, where inhomogeneities occur on all scales. Therefore, in any chemostratigraphic study, a sufficiently large data set is required to negate any flyers in the data.

Heavy-mineral assemblages are sensitive indicators of sandstone provenance and sediment-transport history. However, the composition of heavy-mineral assemblages is not entirely controlled by source rock mineralogy because other processes that operate during the sedimentation cycle (principally weathering, hydrodynamics, and diagenesis) may overprint the original provenance signal (Morton and Hallsworth, 1999). The effects of these overprinting processes can be counteracted by determining ratios of stable minerals with similar densities, because these are not affected by changes in hydraulic conditions during sedimentation or by diagenetic processes (Morton and Hallsworth, 1994). The ratios used in this study are apatite/tourmaline, rutile/zircon, and zircon/tourmaline. Of these, rutile/zircon reflects provenance, whereas apatite/tourmaline is controlled by both provenance and the extent of weathering during fluvial transport, and zircon/tourmaline is influenced by both provenance and hydrodynamics.

Both chemostratigraphic and heavy-mineral techniques have been applied to sequences throughout the stratigraphic column and from many of the world's hydrocarbon provinces (Morton and Berge, 1995; Preston et al., 1998; Pearce et al., 1999a, b, 2003; Wray 1999; Craigie et al., 2001; Morton et al., 2002, 2003; Ratcliffe et al., 2002). Although both techniques are used widely in the oil industry, the majority of the studies is proprietary, and results remain unpublished. Additionally, much of the work carried out is from sequences where traditional stratigraphic techniques did not supply sufficiently detailed characterization for exploration and exploitation purposes. The paucity of meaningful traditional stratigraphic data in many of these studies makes it impossible to demonstrate that the alternative techniques are providing a characterization that is comparable to lithostratigraphy or biostratigraphy. However, because of the extensive previous stratigraphic studies on the Basal Quartz and its stratigraphic complexity and proven hydrocarbon potential, the unit is an ideal sequence in which traditional stratigraphic zonation can be compared to the characterization obtained from chemostratigraphy and heavy-mineral analysis.

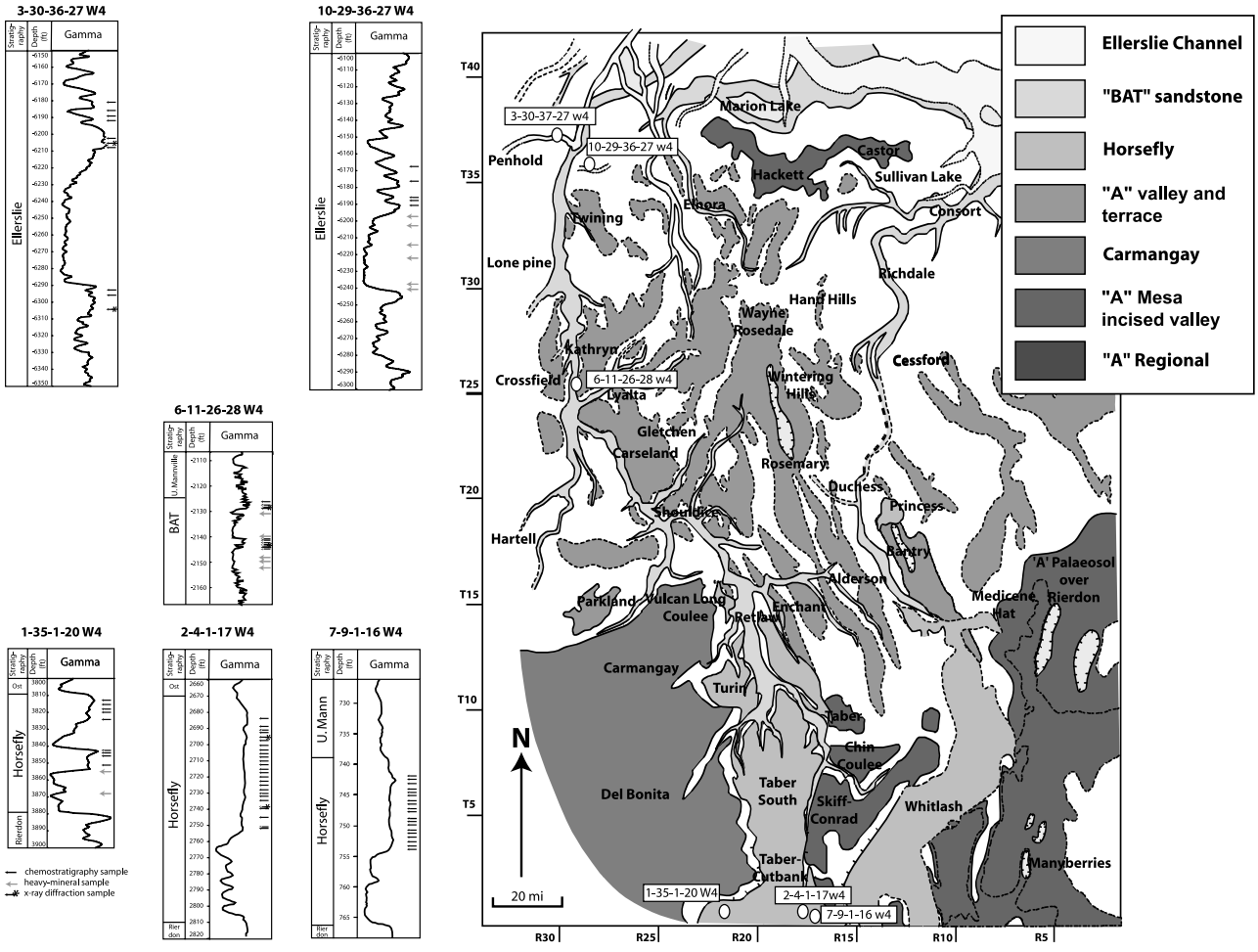


Figure 3. Spatial distribution of the Horsefly, BAT, and Ellerslie units (modified from Zaitlin et al. (2002)). The channel systems and paleodrainage for each of the study units are clearly defined on this distribution map. Well locations and gamma responses for the study intervals are shown, together with the locations of chemostratigraphic, heavy-mineral, and x-ray diffraction samples. Latitude and longitude for the map are lat. 52°6″N, long. 114°7″W; lat. 52°6″N, long. 110°E; lat. 49°S, long. 114°W; lat. 49°S, long. 110°E.

Sedimentology of Study Units

In the study area, total thickness for the lower Mannville Group ranges between 40 and 120 m (130 and 400 ft) (Figure 1), having net sedimentation rates of 1.3–6.6 m/m.y. (4.3–22 ft/m.y.) (Zaitlin et al., 2002). The study area during deposition of the lower Mannville Group is considered as accommodation limited, i.e., long-term subsidence rates are low compared to sediment supply (Zaitlin et al., 2002). The area is characterized by mappable valley systems (Figure 3) that define a south-to-north paleodrainage system. The Horsefly and the BAT units are typified by sheetlike to channelized, meandering, fluvial sandstones and overbank claystones that commonly show evidence of paleosol development. The Ellerslie unit comprises finer grained, meandering fluvial to fluvioestuarine sandstones and silty claystones. Details of the sedimentology are supplied in Zaitlin et al. (2002).

RESULTS AND DISCUSSION

Geochemical and Heavy-Mineral Characterization

The most effective ways to display geochemical variations and changes in heavy-mineral suites are profiles and binary and ternary diagrams (graphically). Profiles for single sections are constructed by plotting element concentrations, element ratios, heavy-mineral abundances, or heavy-mineral ratios against depth. These act as an effective method for visually differentiating

units. In this study, however, it was not possible to sample a core with all three stratigraphic units. Therefore, for visual analysis here, the samples have been plotted in their correct stratigraphic order, but with no implication of depth, to construct synthetic profiles (Figures 5, 6).

Although Al_2O_3 concentrations show that lithological variation (sand-silt-clay) is not a major influence on this data set, elements have been normalized against Al_2O_3 to minimize the influence of any subtle variations in silt-clay content (Figure 5). Despite the gross lithological similarity of the samples analyzed from Horsefly, BAT, and Ellerslie units, there are geochemical variations. The Horsefly unit is characterized by low values of Zr/Al_2O_3 but high values of K_2O/Al_2O_3 and Rb/Al_2O_3. The BAT unit is differentiated from the Horsefly and Ellerslie units by its low P_2O_5/Al_2O_3 values. Although most of the Al_2O_3 normalized element values in the Ellerslie unit are intermediate between those of the Horsefly and BAT units, the Ellerslie unit is differentiated by its high values of K_2O/Rb (Figure 5).

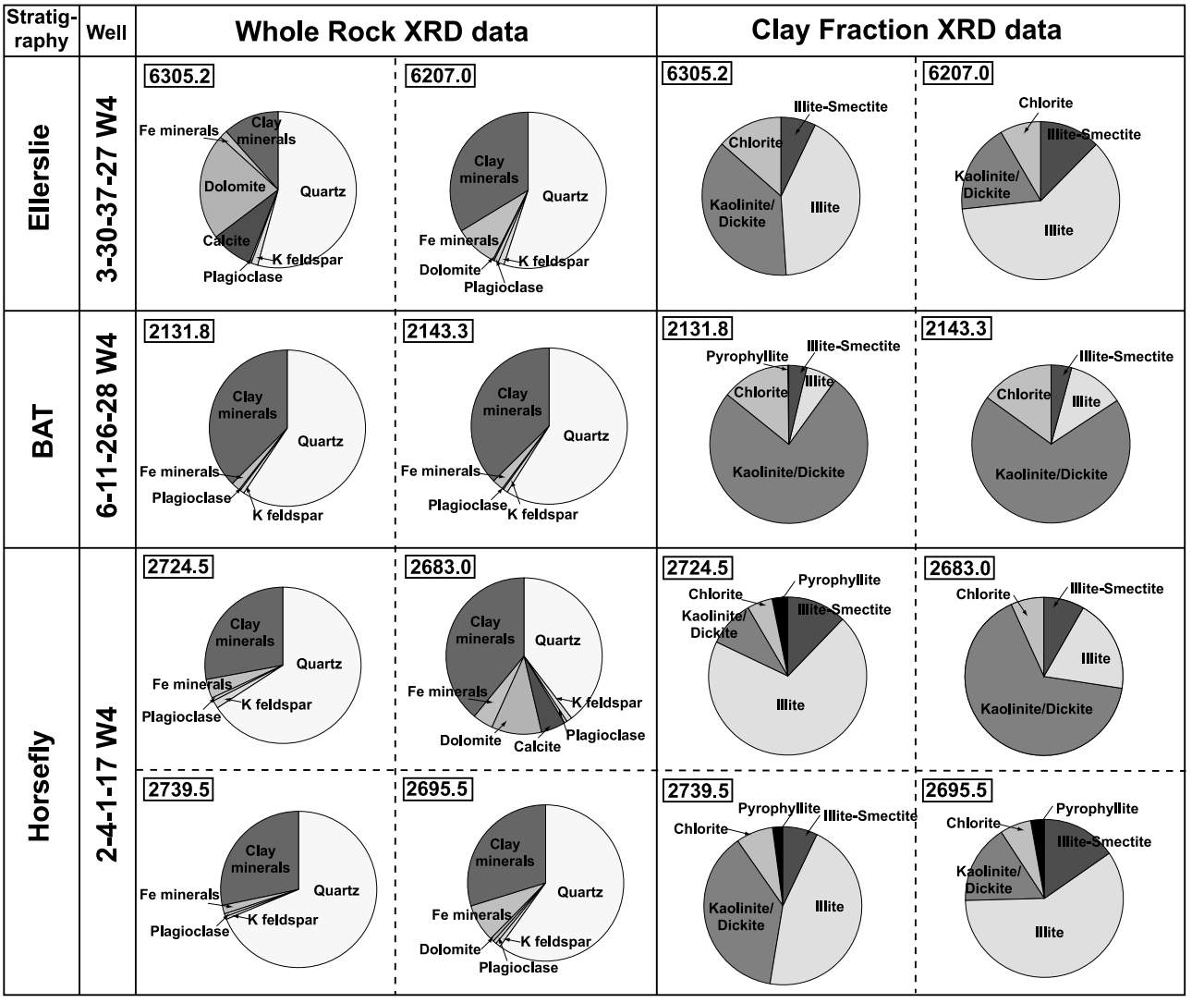


Figure 4. Whole rock and clay-size fraction x-ray diffraction (XRD) data. Sample depths are in the top left of each pie chart; for location relative to other samples, refer to Figure 3. Quartz and clay minerals are the predominant components with variable carbonate (calcite and dolomite) contents. More important for geochemical characterization are changes in feldspar content (these potentially influence the K_2O/Rb and K_2O/Al_2O_3 values). Clay mineral assemblages of the BAT are dominated by Al_2O_3-rich kaolinite and dickite, whereas the Horsefly and Ellerslie contain more K_2O-rich illite. The changes in these two clay minerals control the K_2O/Al_2O_3 values in the claystones.

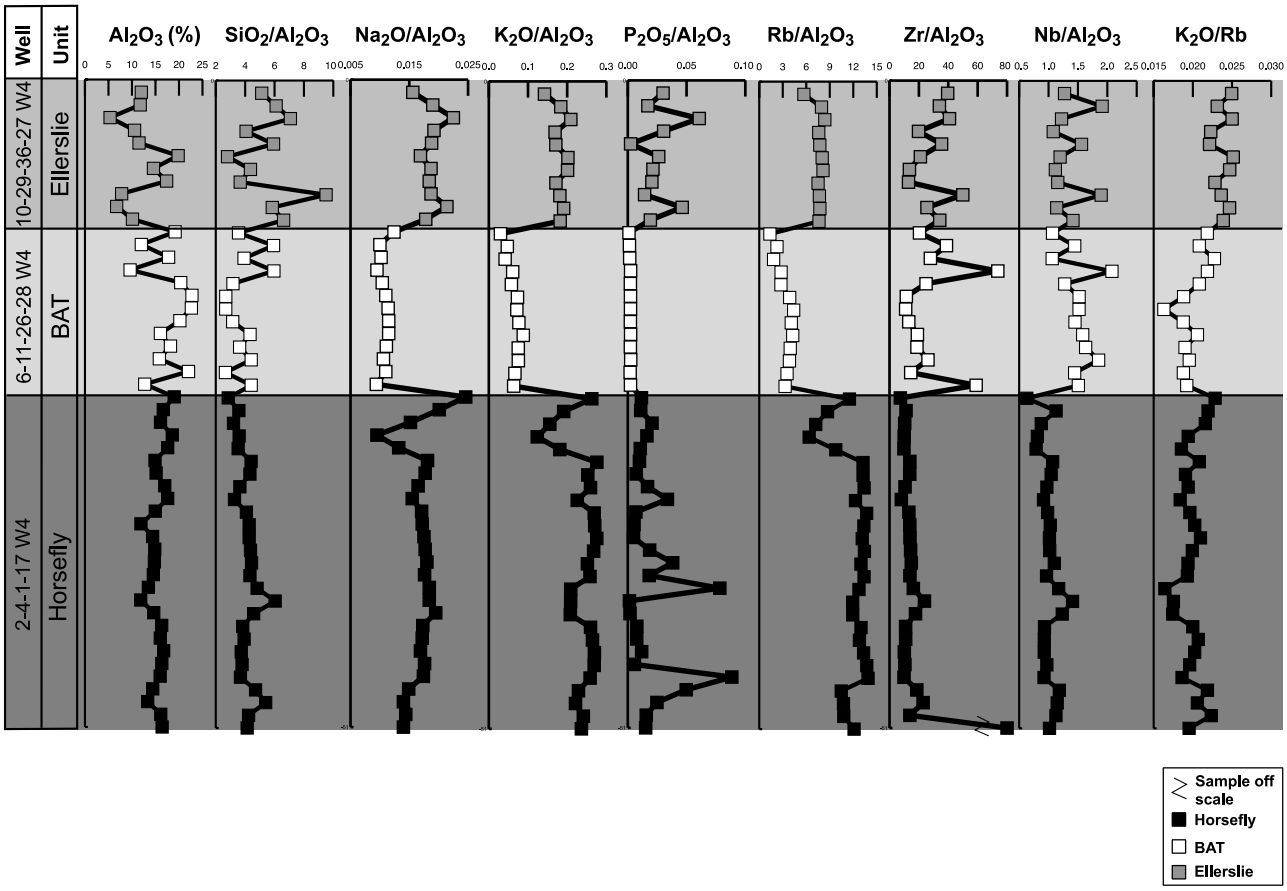


Figure 5. Synthetic geochemical profiles constructed for silty claystone samples from the Horsefly (well 2-4-1-17 W4), BAT (well 6-11-26-28 W4), and Ellerslie (well 10-29-36-27 W4) units. The profiles are constructed to visually display geochemical differences between the units, such that each sample is in the correct stratigraphic order, but there is no inference of its absolute depth (see text for discussion and Figure 3 for sample locations). Each square represents an analyzed core sample. Al_2O_3 and SiO_2 values demonstrate that there are only minor differences in silt/clay content of the samples. However, to minimize the influences of subtle changes in silt content, elements are normalized against Al_2O_3. Differences in values of Na_2O/Al_2O_3, K_2O/Al_2O_3, P_2O_5/Al_2O_3, Rb/Al_2O_3, Zr/Al_2O_3, Nb/Al_2O_3, and K_2O/Rb are all used to characterize the three study units.

Stratigraphic variations are evident in the key heavy-mineral index parameters: apatite/tourmaline, rutile/zircon, and zircon/tourmaline. The Horsefly unit can be distinguished on the basis of higher apatite/tourmaline and lower rutile/zircon (Figure 6). The Ellerslie unit can be distinguished from the BAT unit by its lower zircon/tourmaline, and it also contains the highest rutile/zircon values in the data set.

By using the variations seen on profiles, selected elements and heavy-mineral indices are used to graphically differentiate the three units (Figures 7, 8). The binary diagrams in Figure 9 are constructed primarily to help elucidate element-to-element relationships, but they can also be useful for unit differentiation. In Figure 7a–d, the samples from each unit plot in relatively well-separated fields when two variables are plotted. When three variables are plotted on a ternary diagram, samples from each unit define discrete clusters (Figure 8). In any whole rock geochemical study, the number of variables potentially affecting the element distributions means that on binary and ternary diagrams, there will always be anomalous data points. Therefore, in Figures 7–9, there is a need to use judgment when defining the fields into which samples are expected to fall. However, by acting as a template, binary and ternary diagrams are powerful predictive tools.

Controls on Element Concentrations in the Silty Claystones

The elements used on profiles and on graphical plots to differentiate the claystone units are Al_2O_3, Na_2O, K_2O, P_2O_5, Rb, Zr, Cr, and Nb. Using mineralogical data (x-ray diffraction and petrography) in association

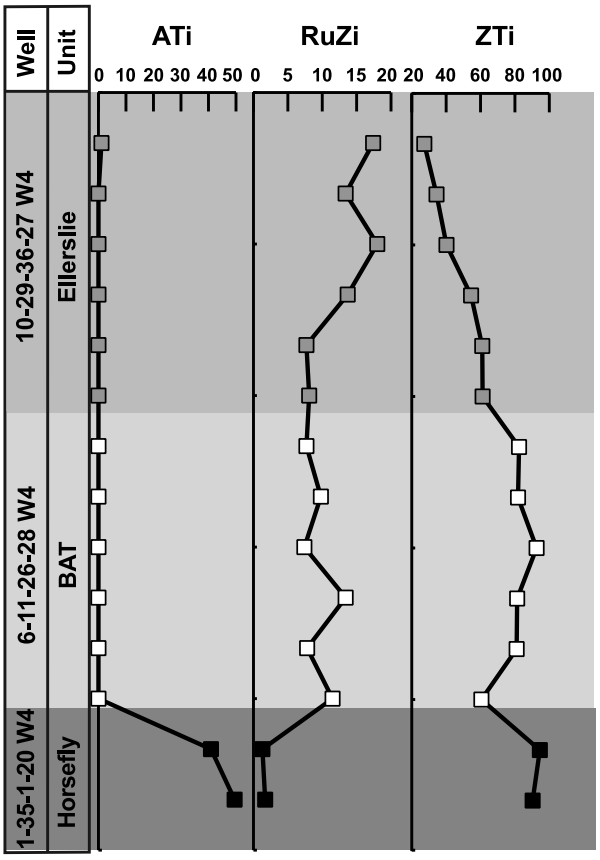


Figure 6. Synthetic heavy-mineral profiles constructed for samples from the Horsefly, BAT, and Ellerslie units. The profiles are constructed to visually display differences in heavy mineralogy between the units, such that each sample is in the correct stratigraphic order, but there is no inference of its absolute depth (see text for discussion and Figure 3 for sample locations). Each square represents an analyzed sample. ATi = apatite/tourmaline index (% apatite in total apatite + tourmaline); RuZi = rutile/zircon index (% rutile in total rutile + zircon); ZTi = zircon/tourmaline index (% zircon in total zircon + tourmaline).

with element-vs.-element binary diagrams (Figure 9), it is possible to elucidate the main mineralogical controls on these key elements. By understanding the main mineralogical controls on the sediment geochemistry, it is then possible to comment on the geological controls responsible for the geochemical differentiation. The correlation coefficient (R^2) values are used in the discussion below. An R^2 value of +1 indicates a perfect positive linear relationship and −1 a perfect inverse relationship. If two elements display an R^2 value of greater than 0.75, their concentrations in the sediment are being controlled by a similar mineralogical phase.

Petrographic Variations in the Basal Quartz

To help better understand the geochemical variations in the silty claystones, petrographic data reported by Zaitlin et al. (2002) were considered, particularly variations in detrital components that may influence the geochemistry. Zaitlin et al. (2002) demonstrate that subtle variations exist between the sandstones of the Horsefly, BAT, and Ellerslie units. From a geochemical perspective, the important petrographic features of the Horsefly unit are the significant amounts of ductile clay-rich sedimentary grains, low-grade schistose metamorphic grains, and small amounts of potassium feldspar present. Potassium feldspar is absent in the overlying BAT unit and relatively scarce in the Ellerslie unit. The Horsefly unit is also characterized by an absence of carbonaceous material in comparison to overlying BAT unit sandstones.

The BAT unit sandstones may contain abundant carbonaceous debris, especially north of Township 5 but insignificant amounts of ductile clay-rich sedimentary rock fragments and essentially no feldspar.

The Ellerslie unit sandstones commonly consist of fine-grained, well- to very well-sorted quartz arenites containing very minor amounts of potassium feldspar. The Ellerslie sandstones contain little or no dark-colored chert, which allows them to be petrographically differentiated from the older Basal Quartz sandstones.

X-Ray Diffraction Analysis of Claystone Samples

To help calibrate the geochemical variations seen in the silty claystones, eight samples were selected for analysis by x-ray diffraction (Figure 4). The whole rock composition of all formations is dominated by quartz (about 40–70%) and clay minerals (10–40%). However, one sample from the Horsefly unit (2683 m; 8854 ft) has significant Fe dolomite (about 10%), and one from the BAT unit (6305.2 ft; 1911 m) has significant dolomite (about 20%).

The main clay minerals in all three units are kaolinite, illite, mixed-layer illite-smectite, and chlorite. Samples from the Horsefly unit have lower chlorite than either the BAT or Ellerslie units. Both the Horsefly and Ellerslie units have high illite and illite-smectite contents as compared to the BAT unit, and the BAT unit has high concentrations of crystalline dickite. Less crystalline dickite is recorded from the Horsefly unit and is absent in the Ellerslie unit.

Typically, the control on distribution of the clay mineral species in paleosols is paleoclimate (Wright, 1992), with kaolinite (and dickite) being typical of paleosols that have been subjected to relatively intense chemical weathering (Retallack, 1992).

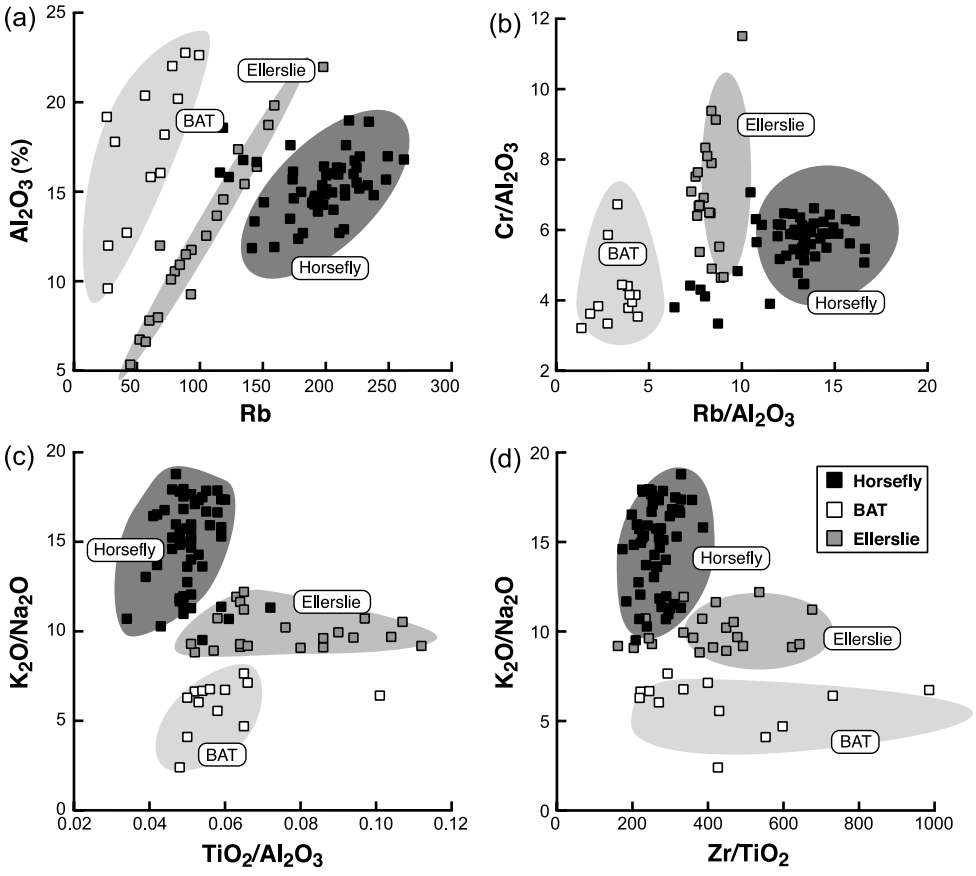


Figure 7. Binary diagrams constructed to demonstrate geochemical differences between each of the study units. Each square represents an analyzed sample, and all analyzed samples are depicted on the graphs.

Influence of Clay Minerals and Feldspar on Geochemistry

Al_2O_3 is present in clay minerals and feldspars, both groups potentially influencing the distribution of Al_2O_3 in the silty claystones of the Basal Quartz. X-ray diffraction data indicate that although feldspars are present, clay minerals are volumetrically the most important source of Al_2O_3, suggesting that clay mineral distribution and type will be the primary control on Al_2O_3 distributions. K_2O is also present in clay minerals and potassium feldspar. When K_2O is plotted against Al_2O_3, the samples form three positive linear trends. R^2 values for the BAT and Ellerslie units are greater than 0.76 (Figure 9a), indicating that K_2O in these units is also primarily controlled by clay mineral distributions. The lower R^2 value for Horsefly unit samples in Figure 9a is probably a result of combined clay mineral and potassium feldspar influences on the K_2O values. The three positive trends, one for each stratigraphic unit, indicate that the main clay mineral phases are different in each unit. The Horsefly unit (trend 1) is enriched in K_2O when compared to the other two units, suggesting abundance of illite. Samples from the BAT unit (trend 2) have low K_2O/Al_2O_3 ratios, suggesting the dominance of an Al_2O_3-enriched, K_2O-depleted clay mineral, such as kaolinite and/or dickite. This geochemically based interpretation is confirmed by the x-ray diffraction results (Figure 4). Trend 3 (Ellerslie unit) has intermediate K_2O/Al_2O_3 ratios.

Rb is found in a range of rock-forming minerals, commonly clay minerals and feldspar. In Figure 9b, an overall positive linear relationship is exhibited between these elements, indicating that Rb and K_2O are found together in the same minerals. However, samples from the Horsefly and Ellerslie units plot on a separate linear trend (trend 2) to samples from the BAT unit (trend 1). The Horsefly and Ellerslie units have higher K_2O/Rb values than the BAT unit. The K_2O/Rb ratio is higher in potassium feldspar than in clay minerals, suggesting that the silty claystones of the Horsefly and Ellerslie units have marginally more potassium feldspar than those of the BAT unit. This geochemical interpretation is supported by the x-ray diffraction data (Figure 4) and the petrographic data from the sandstones (Zaitlin et al., 2002).

Na_2O is present in a wide range of rock-forming minerals, such as clay minerals, feldspar, and evaporites. The majority of samples in this study form two

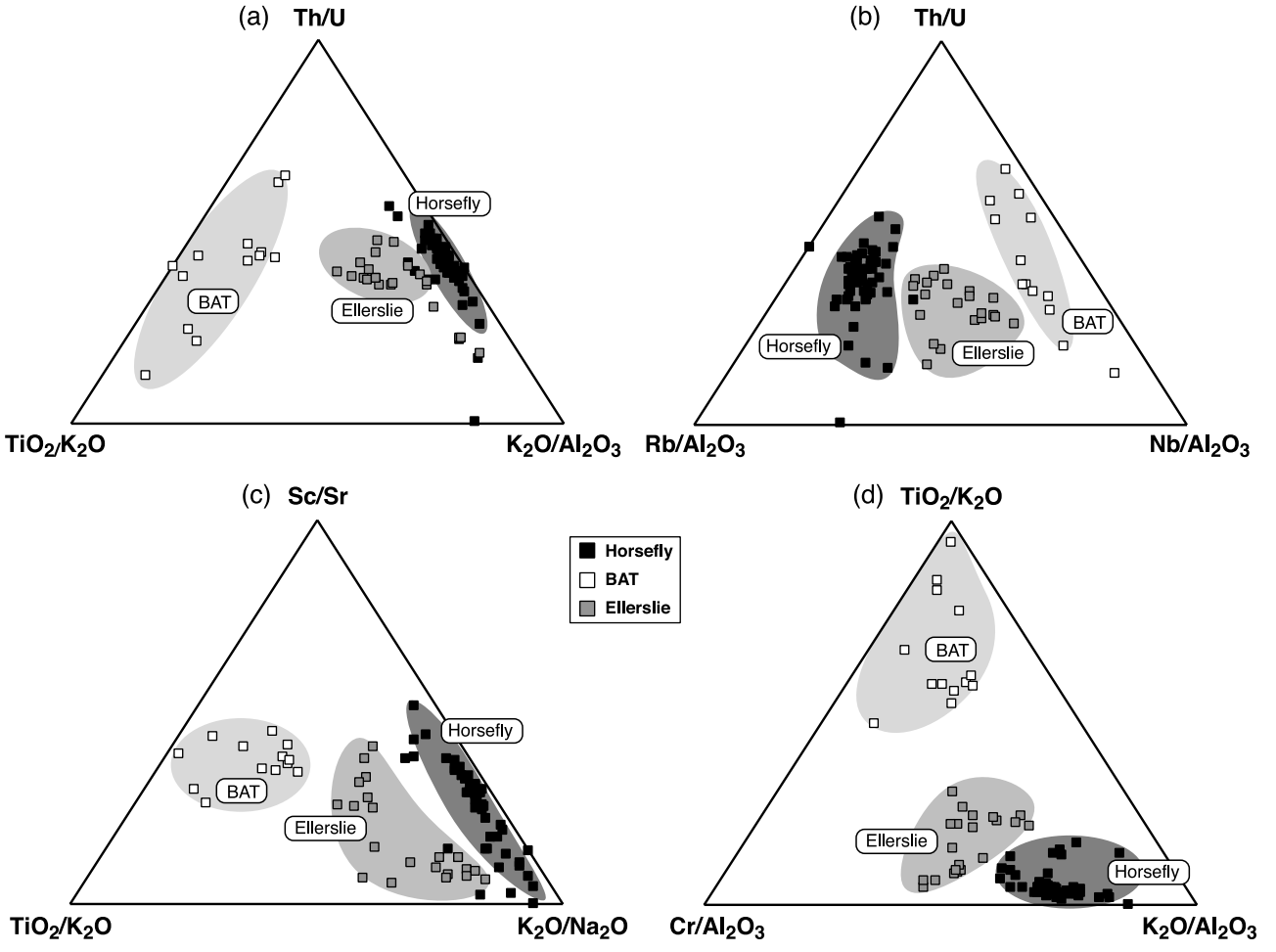


Figure 8. Ternary diagrams constructed to demonstrate geochemical differences between each of the study units. Each square represents an analyzed sample, and all analyzed samples are depicted on the graphs.

positive linear trends when Na_2O and Al_2O_3 are plotted against each other (Figure 9c). Trend 1 is formed by the majority of samples from the Horsefly and Ellerslie units, whereas trend 2 is defined by samples from the BAT unit. This indicates that Na_2O is primarily controlled by clay mineral distributions. X-ray diffraction indicates that illite-smectite is present, which may be the primary controlling factor in Na_2O distributions. If this is the case, the geochemistry suggests that the BAT unit has less smectite-illite than the Horsefly and Ellerslie units, a suggestion supported by the x-ray diffraction data.

Cr is present in heavy minerals (e.g., chrome spinel). However, its positive linear relationship with K_2O (Figure 9g) suggests that the primary control in this sequence is related to differing clay mineral species. As support, the heavy-mineral data indicate that sandstones contain very little chrome spinel.

Influence of Heavy Minerals on Geochemistry

Although not quantified by the x-ray diffraction work, it is likely that heavy-mineral grains exert an influence on the geochemistry of the silty claystones. Of the key elements in this sequence, those potentially associated with heavy minerals are Zr (zircon), TiO_2, and Nb (rutile).

Zr values are generally controlled by the abundance of the heavy-mineral zircon. Zr values are low and constant in the Horsefly unit, whereas the BAT and Ellerslie units have more variable and, on average, higher Zr contents, suggesting that the silty claystones of the BAT and the Ellerslie contain more zircons. Increased zircon may be caused by changes in provenance, or it may be a subtle increase in the amount of silt-grade material. The overall similar appearance of Zr/Al_2O_3 and SiO_2/Al_2O_3 on the synthetic geochemical profiles (Figure 5) implies the latter.

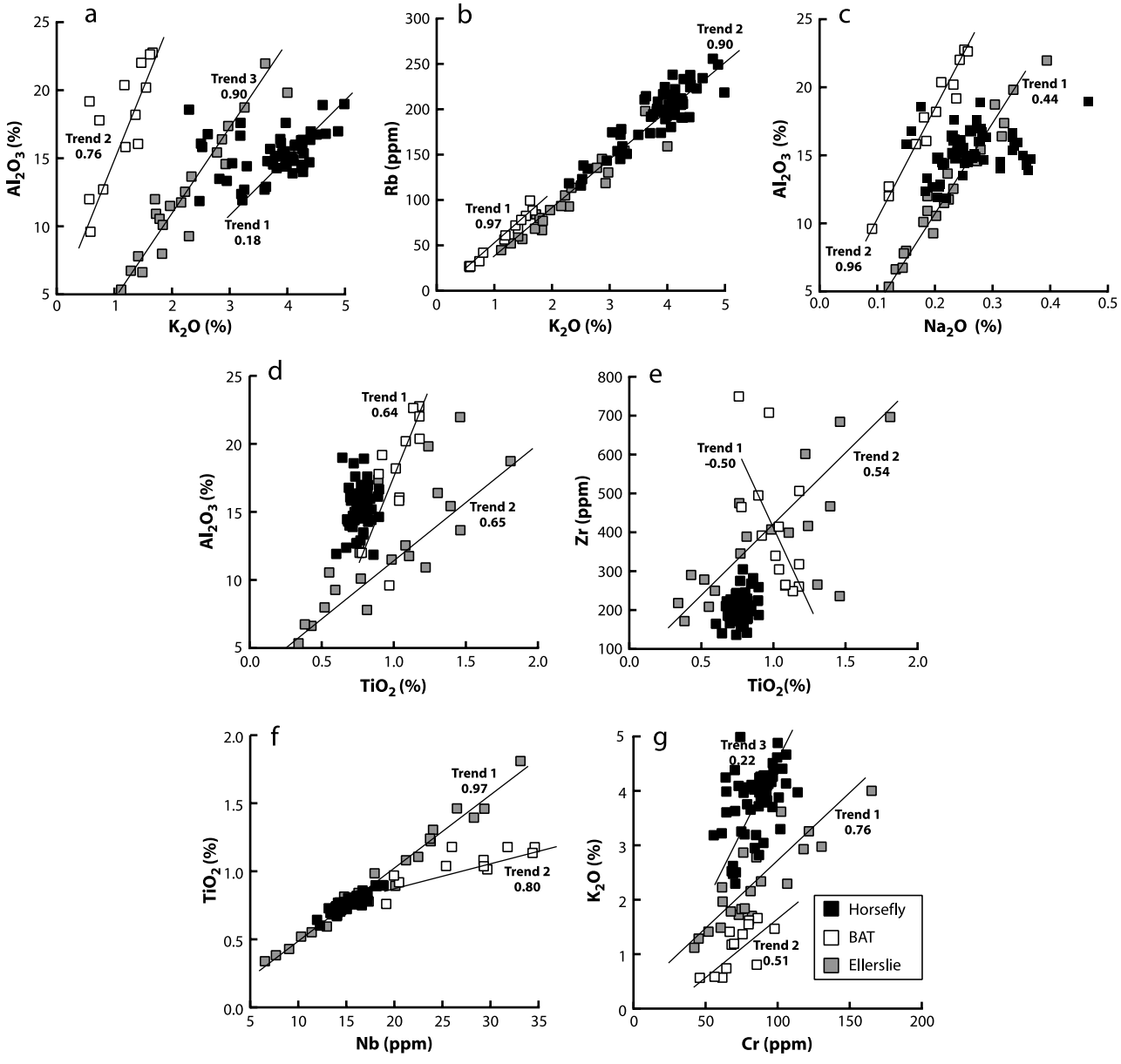


Figure 9. Binary diagrams constructed to display colinear relationships between elements. The numerical value below each trend line is the R^2 coefficient calculated for that trend. If $R^2 \geq 0.75$, the elements have a strong colinear relationship, which implies that they are present in the same single mineral in the sediment. (a) K_2O and Al_2O_3 ratio values indicate that the BAT unit (trend 2) has abundant kaolinite (and/or dickite), whereas the Horsefly unit (trend 1) is more illitic. (b) The BAT has lower K_2O/Rb values (trend 2), indicating higher potassium feldspar contents. (c) The BAT unit has low Na_2O/Al_2O_3 values (trend 2), tentatively suggesting lower smectite/illite contents. (d) TiO_2 has a colinear relationship with Al_2O_3 in the BAT and Ellerslie units, but the relatively low R^2 values (0.64 and 0.65) suggest that there may be a multimineral control on TiO_2. (e) The positive colinear trend between Zr and TiO_2 in the Ellerslie suggests that the TiO_2 in this unit is partly influenced by heavy minerals. The negative colinear relation displayed on trend 1 implies that TiO_2 in the BAT is inversely related to grain size, i.e., is enriched in the clay-size fraction. (f) TiO_2 and Nb commonly display strongly positive colinear relationships in sediments, but the marked difference in slope of trends 1 and 2 indicates that an Nb-rich clay mineral is present in the BAT that is not present in the other units. (g) Cr is used in Figures 7 and 8, but it has a complex relationship to other elements, including Zr, which makes understanding its mineralogical affinities problematic.

TiO_2 can occur in clay minerals, most notably illite, as well as heavy minerals, such as rutile and anatase. If illite is the primary control on TiO_2 concentrations, a positive linear relationship would be expected when the silty claystones samples are plotted on a TiO_2 vs. Al_2O_3 binary diagram. Therefore, in the Ellerslie and

BAT units (Figure 9d, trends 1 and 2), it appears that clay minerals do exert some influence on the distribution of TiO_2. However, the low R^2 values of trends 1 and 2 suggest that TiO_2 in these units is influenced by other minerals. If TiO_2 is linked solely to detrital heavy minerals, it would be expected to have a positive linear association with Zr, which is displayed in samples from the Ellerslie unit (Figure 9e). Samples from the Horsefly unit display no relationship between TiO_2 and Zr, and samples from the BAT unit show a negative linear relationship between Zr and TiO_2. Although TiO_2 has a complex mineralogical affinity in the silty claystones that is not fully understood, the sum of all the controlling mineralogical factors results in variations in the TiO_2 concentrations that can be used to recognize the component units of the study interval.

Nb is generally closely associated with TiO_2, whether in clay minerals, diagenetic anatase, or in detrital heavy minerals. As such, it generally displays a positive linear relationship with TiO_2 on binary diagrams. Figure 9f shows that the samples here form positive linear trends, but that the slope of the line formed by the Horsefly and Ellerslie units is different to that of the BAT unit samples. This indicates the presence of a mineral species that is preferentially enriched in Nb over TiO_2 in the BAT. The source of this Nb-rich mineral could be the kimberlite volcanic complexes on the Canadian shield. Whatever the source of the Nb, its relative enrichment over TiO_2 in the BAT provides a clear geochemical tool for differentiation of the BAT unit from the Horsefly and Ellerslie units.

Controls on Heavy-Mineral Assemblages in the Sandstones

The stratigraphic variations in mineralogy of the sandstones of the Basal Quartz (Figure 6) result from a combination of factors. Provenance is the fundamental control on the heavy-mineral assemblages, but other processes that operate during the sedimentation cycle may have also played a role. The parameters that discriminate the three stratigraphic units are apatite/tourmaline, rutile/zircon, and zircon/tourmaline (Figure 6). As shown in the binary plots (Figure 10), Horsefly unit sandstones are markedly different to those of the BAT and Ellerslie units, having much higher apatite/tourmaline and lower rutile/zircon. The difference in rutile/zircon indicates that Horsefly unit sandstones had a different source than the BAT and Ellerslie units. The higher apatite/tourmaline could also be caused by a

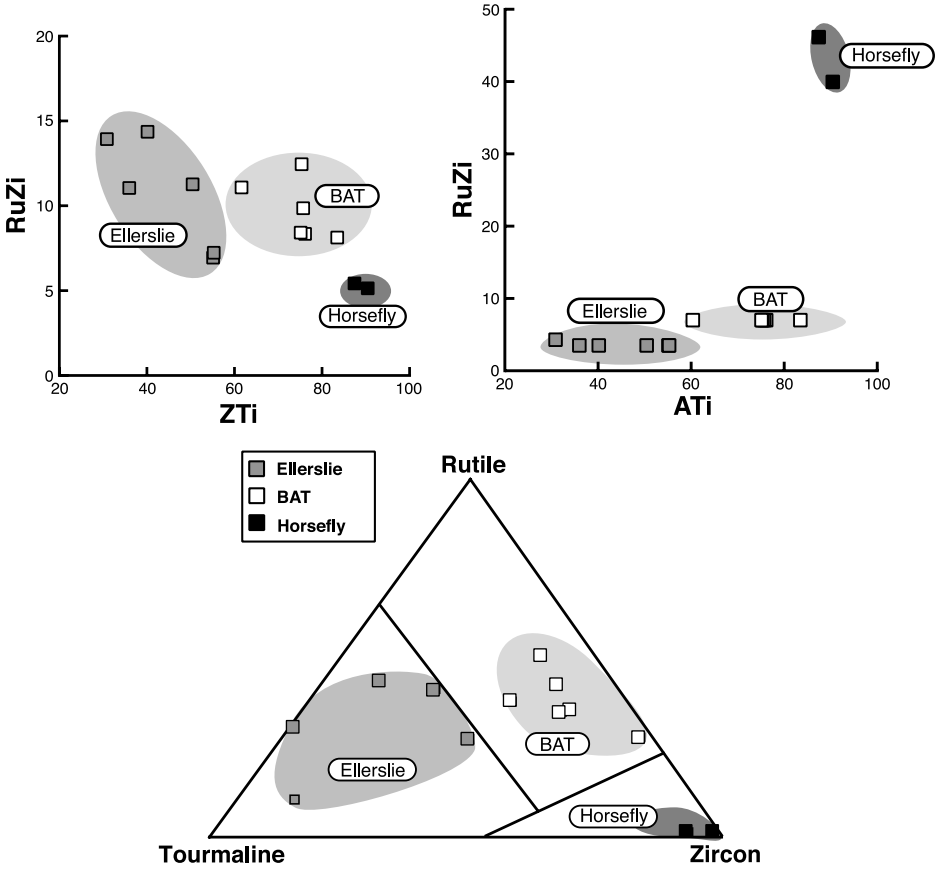


Figure 10. Binary and ternary diagrams graphically displaying differentiation of the heavy-mineral composition of the Horsefly, BAT, and Ellerslie units. ATi = apatite/tourmaline index; RuZi = rutile/zircon index; ZTi = zircon/tourmaline index (see Figure 6 for definitions).

difference in source, but it could also indicate less prolonged weathering during sediment-transport history. Apatite is unstable in weathering during alluvial storage under humid conditions (Morton and Hallsworth, 1999).

Heavy-mineral assemblages in BAT and Ellerslie unit sandstones are distinguished from the Horsefly unit by having lower apatite/tourmaline and higher rutile/zircon (Figure 10). The results imply that the BAT and Ellerslie unit sandstones have a markedly different source to the Horsefly unit. The BAT unit is distinguished from Ellerslie unit on the basis of higher zircon/tourmaline and slightly lower rutile/zircon. Although zircon/tourmaline is partly controlled by provenance, zircon and tourmaline have contrasting hydrodynamic behavior, and consequently, variations in hydraulic conditions at the time of deposition could also account for the differences in zircon/tourmaline between the BAT and Ellerslie units. However, the BAT and Ellerslie units have subtly different rutile/zircon values, indicating that the two units have different sources, suggesting that the variations in zircon/tourmaline are also related to differences in source.

Given that the variations in rutile/zircon and zircon/tourmaline appear to be largely related to provenance instead of hydrodynamic conditions, it is valid to use the abundances of zircon, rutile, and tourmaline for stratigraphic discrimination. On the ternary plot of these three parameters (Figure 10), the three units form discrete, nonoverlapping fields, confirming that heavy-mineral analysis is an effective method for identifying and discriminating stratigraphic units in the Basal Quartz.

CONCLUSIONS

The fine-grained facies of the Horsefly, BAT, and Ellerslie units can be readily differentiated from one another by considering the elemental compositions of the silty claystones.

- The Horsefly unit has systematically higher K_2O/Al_2O_3 and Rb/Al_2O_3 values than the BAT and Ellerslie units, but lower Zr/Al_2O_3 and Nb/Al_2O_3 values.
- The BAT unit has low values of K_2O/Al_2O_3, Na_2O, P_2O_5, and Rb values, but high values of Nb and high Na_2O/Al_2O_3 ratios when compared to the other two units.
- The Ellerslie unit has values of K_2O/Al_2O_3 and Rb/Al_2O_3 that are intermediate between those of the Horsefly and BAT units but has higher TiO_2/Al_2O_3 and Cr/Al_2O_3 values than those units.

The primary geological controls on the elemental variations are clay mineralogy (kaolinite, illite, illite/smectite, and chlorite), detrital mineralogy (feldspar contents), and heavy mineralogy (abundances of zircon). The clay mineralogy is controlled by the syndepositional climate, whereas the detrital mineralogy and heavy mineralogy are mainly controlled by changes in sediment provenance with time. Additionally, during deposition of the BAT unit, a source of Nb-rich clay minerals was supplying sediment to the area. The provenance of these sequences lies to the south and west of the depositional area.

The sandstones of the Horsefly, BAT, and Ellerslie units can be readily differentiated from one another by considering their heavy-mineral suites.

- The Horsefly unit has high apatite/tourmaline, high zircon/tourmaline, and low rutile/zircon.
- The BAT unit has low apatite/tourmaline, high zircon/tourmaline, and relatively high rutile/zircon.
- The Ellerslie unit has low apatite/tourmaline, low zircon/tourmaline, and relatively high rutile/zircon.

The primary geological controls on the heavy-mineral variations are changes in provenance, with some modification from hydrodynamic sorting, and changes in weathering style of the source area.

Chemostratigraphy and heavy-mineral analysis are valuable techniques that can be applied to understanding the stratigraphic controls on reservoir development, including mineralogical and textural maturity and the presence of paleosols and shales that act as vertical permeability barriers in accommodation-limited settings, such as the Basal Quartz of the Western Canada sedimentary basin (Zaitlin et al., 2002). The technique is easily transportable to such settings in other basins and would be able to provide detailed stratigraphic breakdowns similar to those needed in the Western Canada sedimentary basin.

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