Provenance of siliciclastic sediments in the Duvernay Formation from immobile trace element ratios

Gracia Nicolas, Nicholas B. Harris, Robert Creaser
University of Alberta

Summary

Duvernay mudstones consist of intrabasinal (autochthonous) carbonate minerals and organic matter and extrabasinal (allochthonous) clastic minerals. The source of the clastic sediments is largely unknown, although stratigraphic patterns suggest a contribution from northern sources and possibly from the west in some areas.

In this contribution, we test the application of two ratios of immobile trace elements as a proxy for sediment source: Th/Sc and TiO_2/Zr. Both ratios serve to differentiate felsic from mafic igneous rocks. Thorium and zirconium are relatively incompatible elements and are fractionated into felsic melts. Scandium and zirconium exhibit contrasting behavior; they are highly compatible and therefore enriched in mafic melts. Thus, high Th/Sc and low TiO_2/Zr ratios are characteristic of relatively felsic source terranes, while the low Th/Sc and high TiO_2/Zr ratios are characteristic of mafic terranes.

These ratios exhibit systematic stratigraphic and geographic variation that we relate to stratigraphic sequences identified by Knapp et al. (2019). Wells in the West Shale Basin exhibit elevated Th/Sc ratios in the upper two stratigraphic sequences (DS2 and DS3) indicative of a relative felsic source in comparison to DS1. Integration of both Th/Sc and TiO_2/Zr ratios enables to identify three distinct endmember sources. Neodymium isotope data from a Kaybob well provide independent support for inferences based on trace element data.

Theory / Method / Workflow

Selected trace elements are associated with heavy minerals such as zircon and rutile. Of these trace elements, certain ones are considered compatible and are fractionated into minerals relatively early in the crystallization process. Compatible elements such as scandium and zirconium are enriched in crystallizing mafic melts. Others trace elements such as thorium and scandium are relatively incompatible and are therefore excluded from early-crystallizing minerals. These elements thus enriched in felsic melts. The ratios of compatible to incompatible elements Th/Sc and TiO_2/Zr is therefore indicative of the overall composition of continental crust.

Sediments derived from source terranes of differing composition may therefore be distinguished on the basis of Th/Sc (Unterschutz et al., 2002) and TiO_2/Zr ratios (Hallberg, 1994), provided that further fractionation of these elements does not occur during sediment transport and deposition. Because all of the elements are concentrated in the heavy minerals of similar density, significant sedimentological fractionation is unlikely. Because the heavy minerals are relatively unreactive during diagenesis, the ratios should be insensitive to variation in thermal maturity.

In this paper, we test the application of Th/Sc and TiO_2/Zr ratios to five long drill cores in the Duvernay Formation, Western Canada Sedimentary Basin (Fig. 1). These cores have been the subject of sedimentological analysis (Knapp et al., 2017), stratigraphic analysis (Knapp et al., 2019), and geochemical analysis (McMillan, 2016; Harris et al., 2018). Th/Sc and TiO_2/Zr ratios were calculated from data in McMillan (2016) and Harris et al. (2018) and plotted stratigraphically, applying the sequence stratigraphic nomenclature of Knapp et al., 2019). Two wells (Esso Redwater 16-28 and EOG Cygnet 08-20) are located in the East Shale Basin, and three wells are located in the West Shale Basin (GuideX Gvillee 09-06; Shell Kaybob 02-22 and Encana Cecilia 11-04).

Four samples from the Shell Kaybob core were analyzed for neodymium isotopic compositions, which provide insight into both the composition and age of the source terrane (e.g. Unterschutz et al., 2002). Samples were selected from the different stratigraphic sequences identified by Knapp et al. (2019).

Results, Observations, Conclusions

Stratigraphic profiles through the wells present significant variation that can be related to sequence stratigraphic units identified by Knapp et al. (2019). Examples are presented from the Shell Kaybob and Encana Cecilia wells (Figure 2). Relatively mafic values are presented in the Majeau Lake Formation that underlies the Duvernay and in the lowermost Duvernay sequence DS1. Values trend toward more felsic compositions in the overlying sequences DS2 and DS3, then revert in the Ireton Formation to the relatively mafic compositions that are characteristic of the Majeau Lake Formation. Thus, these trace element ratios suggest that the Duvernay Formation had a fundamentally different source of clastic material than the Ireton Formation, contradicting interpretations that the Duvernay simply represents a down-deposition-dip equivalent of prograding Ireton clinoforms.

Neodymium isotope compositions from the Shell Kaybob well provide additional insight into the provenance of the Duvernay Formation. Compositions are presented in εNdT format, where relatively negative values are indicative of felsic or old continental crust and more positive values are indicative of mafic or young continental crust. In our dataset, a sample from the base of the Duvernay DS1 had the most negative values (Table 1). Values become more positive in DS2 and DS3 and then decrease in the Ireton Formation. Because the trace element ratios consistently indicate a sediment contribution to DS2 and DS3 from a felsic source (Figure 2), we interpret the neodymium isotopes to indicate that the source of sediment to these units was young in comparison to the source for the Majeau Lake and Ireton formations.

By combining the two ratios in cross-plots (Figure 3), we infer that three endmember sediment sources contributed clastic sediment to the Duvernay Formation. Wells in the West Shale Basin were sourced from a relatively felsic (and by inference from the neodymium isotope data, relatively young) source, whereas the East Shale Basin wells, especially the Esso Redwater well, had a greater contribution from a mafic source.

Novel Information

Our analysis of trace element ratios in selected Duvernay cores from Alberta suggests that there is significant potential in this approach for understanding sediment sources and the spatial evolution of depositional systems in a shale formation. The wells selected for this study have remarkably rich datasets, ideal for developing the detailed profiles presented here. But sparser datasets from the Duvernay Formation can now be interpreted, given the framework developed in this analysis.

Acknowledgements

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References

Hallberg, J.A., 1984. A geochemical aid to igneous rock type identification in deeply weathered terrain. *Journal of Geochemical Exploration*, *20*(1), pp.1-8.

Harris, N.B., McMillan, J.M., Knapp, L.J. and Mastalerz, M., 2018. Organic matter accumulation in the Upper Devonian Duvernay Formation, Western Canada Sedimentary Basin, from sequence stratigraphic analysis and geochemical proxies. *Sedimentary Geology*, *376*, pp.185-203.

Knapp, L.J., 2016. Controls on Organic-Rich Mudstone Deposition: The Devonian Duvernay Formation, Alberta, Canada. Unpublished M.Sc. thesis, University of Alberta, 165 pp.

Knapp, L.J., McMillan, J.M. and Harris, N.B., 2017. A depositional model for organic-rich Duvernay Formation mudstones. *Sedimentary geology*, *347*, pp.160-182.

Knapp, L.J., Harris, N.B. and McMillan, J.M., 2019. A sequence stratigraphic model for the organic-rich Upper Devonian Duvernay Formation, Alberta, Canada. *Sedimentary Geology*, *387*, pp.152-181.

McMillan, J.M., 2016. Expression of major and trace element signatures of the Frasnian Duvernay Formation within a sea level context: Insights into the processes that control mudstone composition, paleoredox conditions and organic matter enrichment. Unpublished M.Sc. thesis, University of Alberta, 422 pp.

Unterschutz, J.L., Creaser, R.A., Erdmer, P., Thompson, R.I. and Daughtry, K.L., 2002. North American margin origin of Quesnel terrane strata in the southern Canadian Cordillera: Inferences from geochemical and Nd isotopic characteristics of Triassic metasedimentary rocks. *Geological Society of America Bulletin*, *114*(4), pp.462-475.

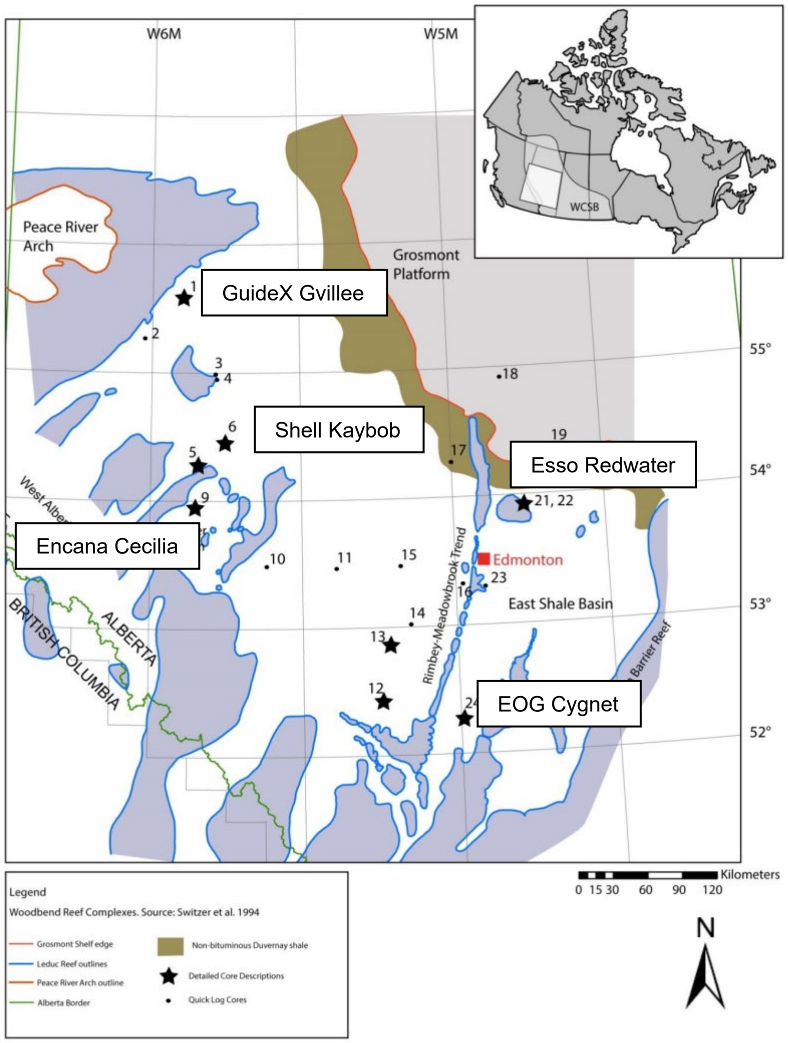
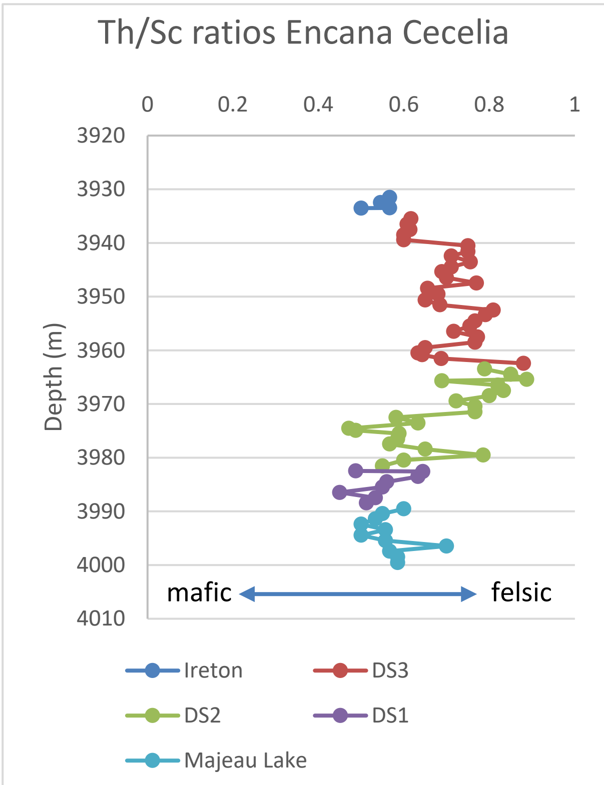


Figure 1. Location of wells presented in this study. Modified from Knapp (2016).



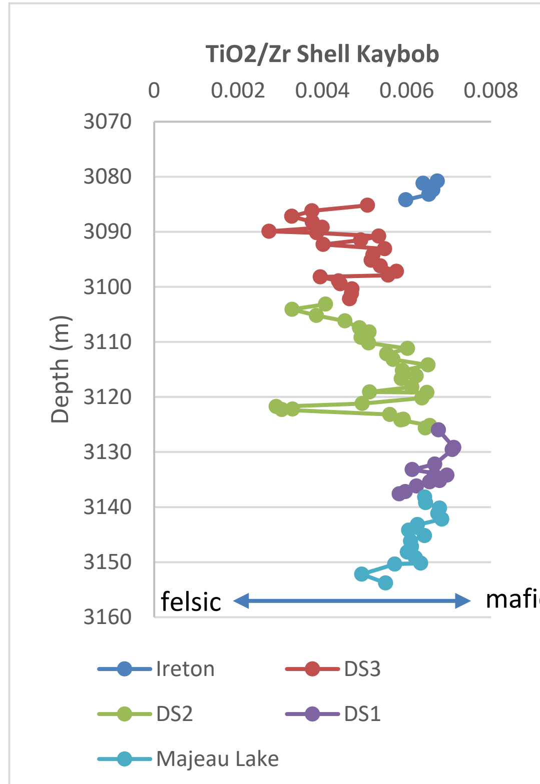


Figure 2. Left: Thorium/scandium ratios from samples in the Encana Cecelia well. Right: Titanium/zirconium ratios in the Shell Kaybob well. Both datasets indicate a systematic change from a relatively mafic provenance in the Majeau Lake Formation and DS1 of the Duvernay to a more felsic provenance in DS2 and DS3, followed by a reversion to the mafic provenance in the Ireton Formation.

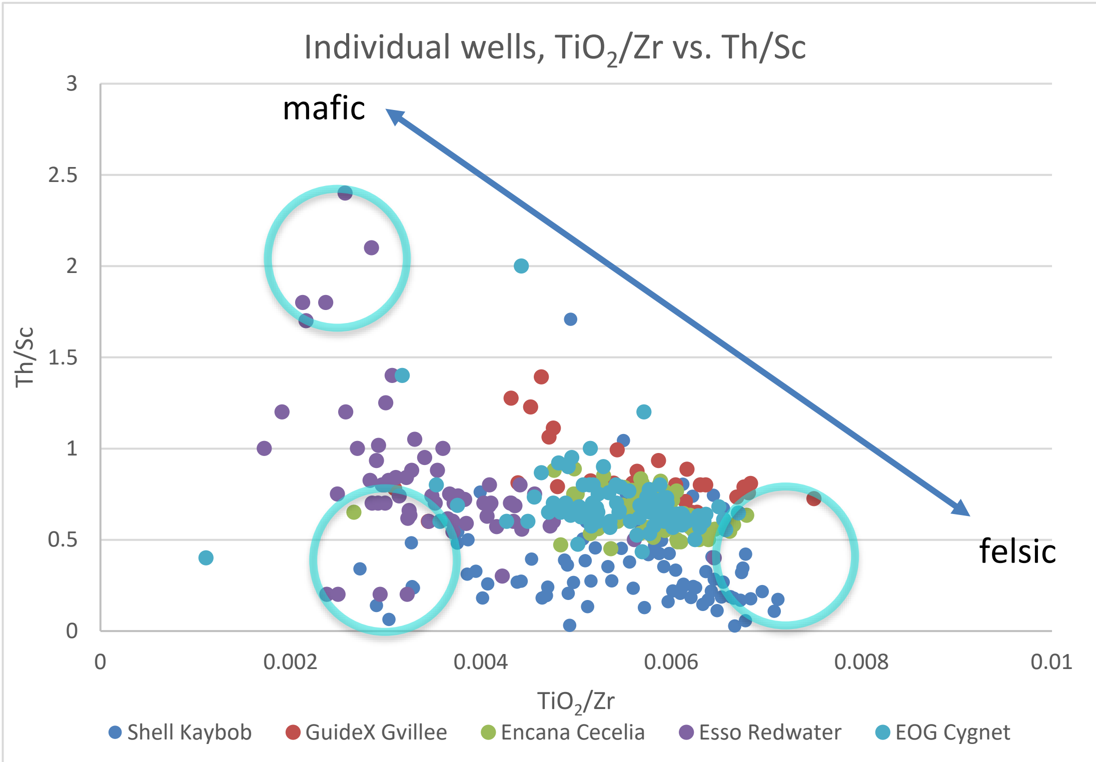


Figure 3. Crossplot of Th/Sc and TiO2 ratios, distinguished by well

Table 1. Neodymium isotope compositions of four samples from the Shell Kaybob well.

Sample	Depositional Sequence	εNdT
3068.5	Ireton	-9,3
3074.5	DS3	-8.8
3097.5	DS2	-8.3
3125.5	DS1 (base)	-11,0