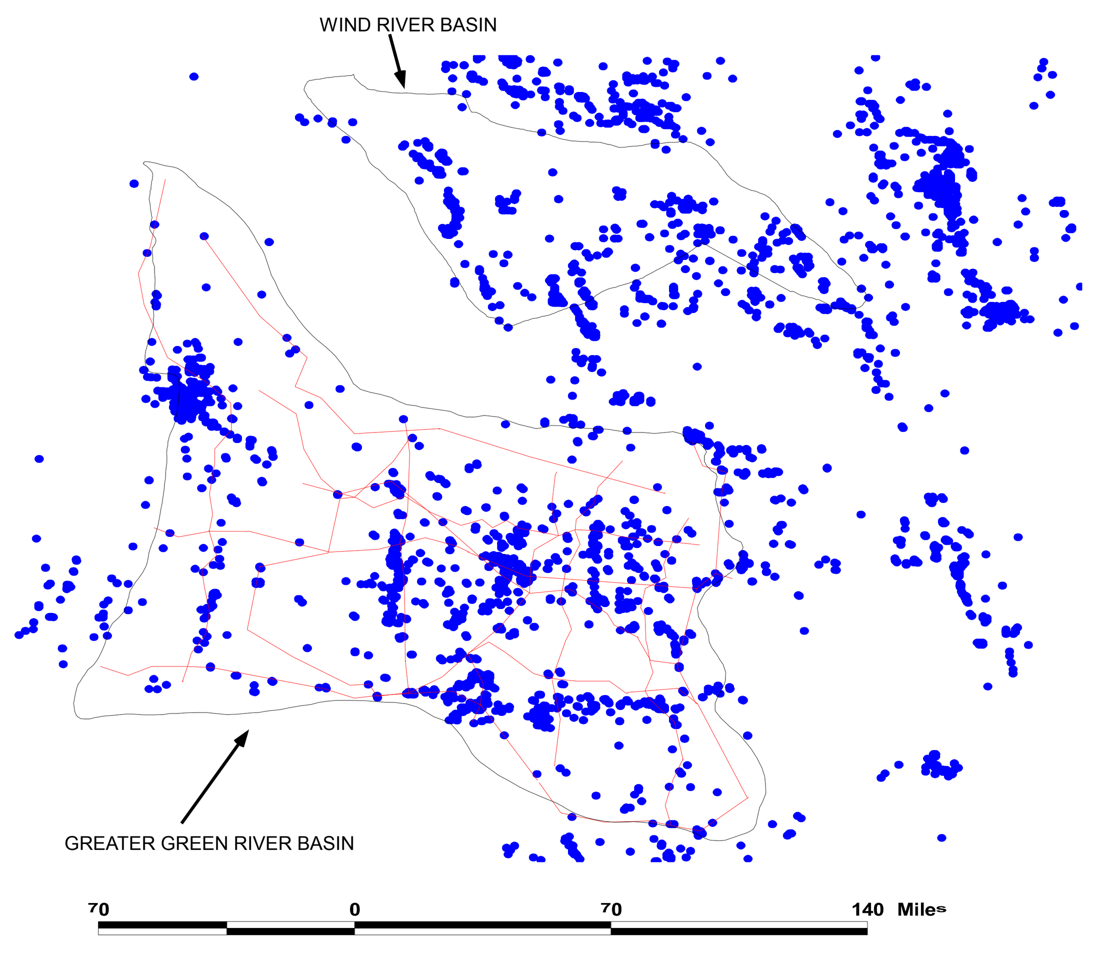
Why Study Water?

- Moveable water is a major technical and operational barrier to the production of identified deep gas resources
- If the nature and occurrence of subsurface water is understood, it should be possible to devise strategies to avoid or ameliorate its negative impact on gas recoveries and operations
- “Fingerprinted” reservoir water can be tracked to define permeability systems
- Water provides significant insights to reservoir development and/or destruction
- Water electrical properties are key to accurate calculations of GIP and pay

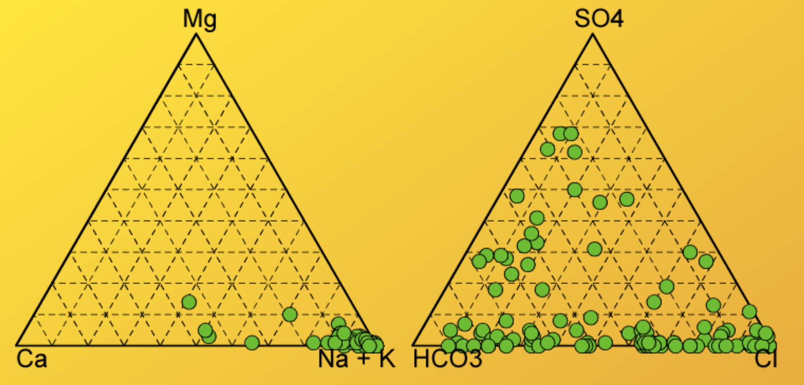
HISTORICAL WATER ANALYSES AREAL DISTRIBUTION



Wells with water analyses in database

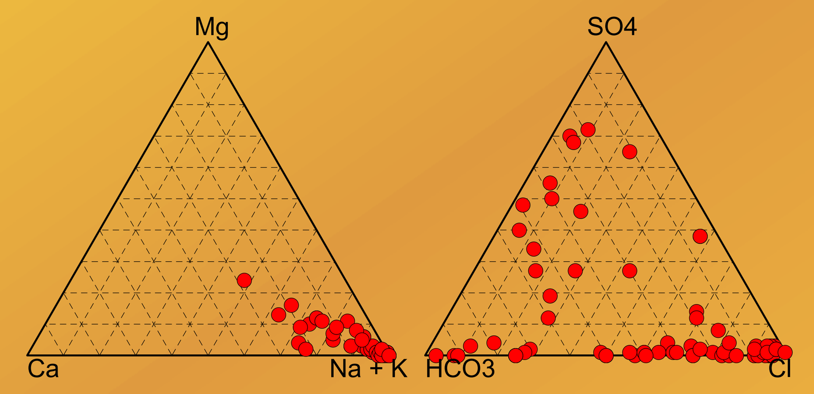
cross-sections from DOE report on sub-economic resources of the Gretaer Green River and Wind River Basins (Boswell et al., 2002)

Lance Formation Water Chemistry



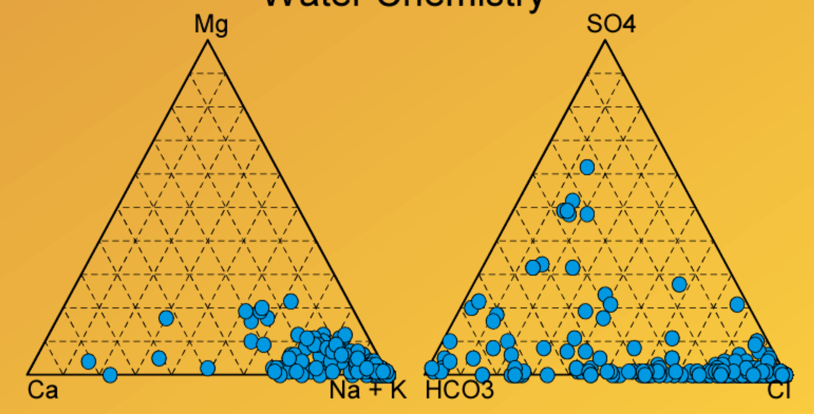
Lance:
Lance Formation water are all dominated by Na+K for the cations. There is considerable scatter in the anions, however, Lance Formation waters are most likely to be dominated by HCO3. 59% of the samples have HCO3 as the dominant anion, compared to only 27% for Cl and 14% for SO4.

Lewis Shale Water Chemistry



Lewis:
Cations in the Lewis Formation water samples are all dominated by Na+K. Mg and Ca, are present in generally equal proportions. Anions are generally dominated by Cl, although a high percentage are dominated by SO4 (22%) or HCO3 (34%).

Almond Formation Water Chemistry



Almond
The Almond Formation water chemistry cations are dominated by Na+K with only a few samples that are dominated by Ca. The anions show considerable range between Cl and HCO3 dominated waters although the majority of the water samples are dominated by Cl. Just over 5% of the samples have SO4 as the dominant anion.

TERNARY DIAGRAMS

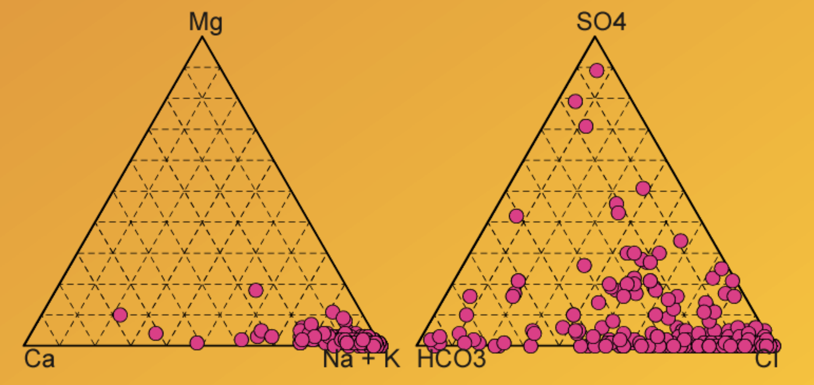
One of the best ways of visually examining trends in water chemistry is with ternary diagrams with cations plotted on one and anions on another. Although the Stiff diagram is also a useful visual tool, a separate Stiff diagram must be constructed for each sample. This dataset consists of over 3000 analyses, and the use of ternary diagrams allows the plotting of multiple points on a single diagram to look for larger trends.

sThis set of diagrams shows these ternary displays for five of the fourteen Upper Cretaceous formations that are represented in the database. A separate diagram compares all Cretaceous samples with all samples from Pennsylvanian and Permian reservoirs.

Two distinct trends emerge from examination of these ternary diagrams. Of the five Upper Cretaceous formations examined thus far, all are pre-dominantly Na and K. However, a number of samples are dominated by Ca and a few are dominated by Mg. For the anions, there is considerably more scatter, with a number of samples being having HCO3 as the dominant anion and a slightly smaller number of samples having SO4 as the dominant anion. By comparing the Cretaceous samples with samples from the Pennsylvanian-Permian, larger trends emerge. The Pennsylvanian-Permian samples tend to have a higher Mg:Ca ratio than the Cretaceous samples. For the anions, the Pennsylvanian-Permian samples are more likely to be dominated by SO4 or Cl, whereas the Cretaceous samples are more likely to be dominated by Cl or HCO3.

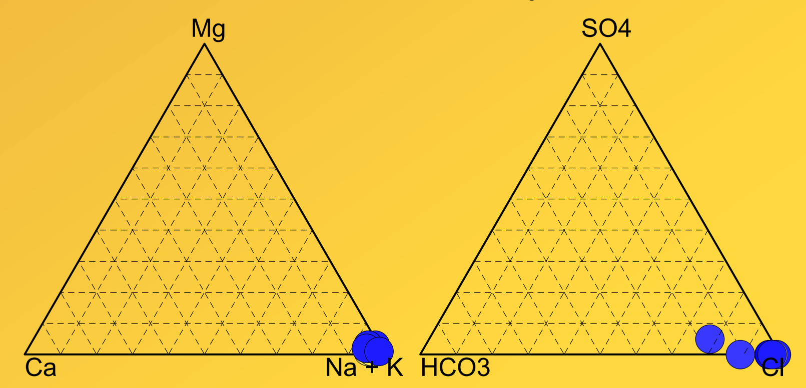
As work progresses on this project, more of these types of analyses will be made with the other formations that are represented in the database. In addition to comparing one formation with another, we will compare the same formation in different areas and the same formation at different depths.

Frontier Formation Water Chemistry



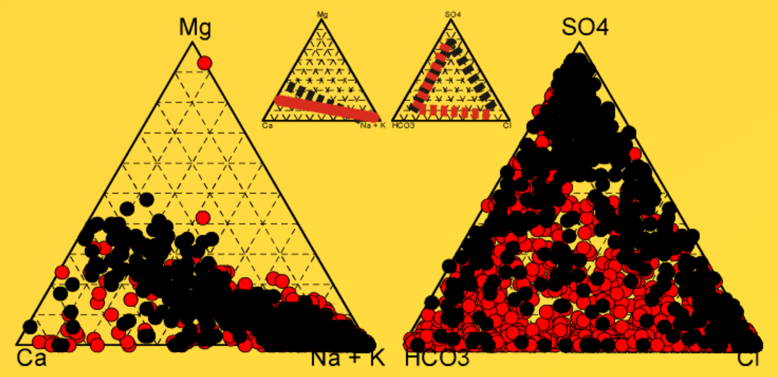
Frontier:
Na+K dominate the cations for all of the Frontier Formation waters. Cl is generally the dominatnt anion although a small number of samples (3% ot the total) have SO4 as the dominant anion.

Niobrara Formation Water Chemistry



Niobrara:
This formation has not been sampled extensively and therefore the samples in this dataset may not represent the true diversity of water chemistry for this formation. There are only eight samples in the dataset from the Niobrara Formation. All of these are strongly Na-Cl dominated.

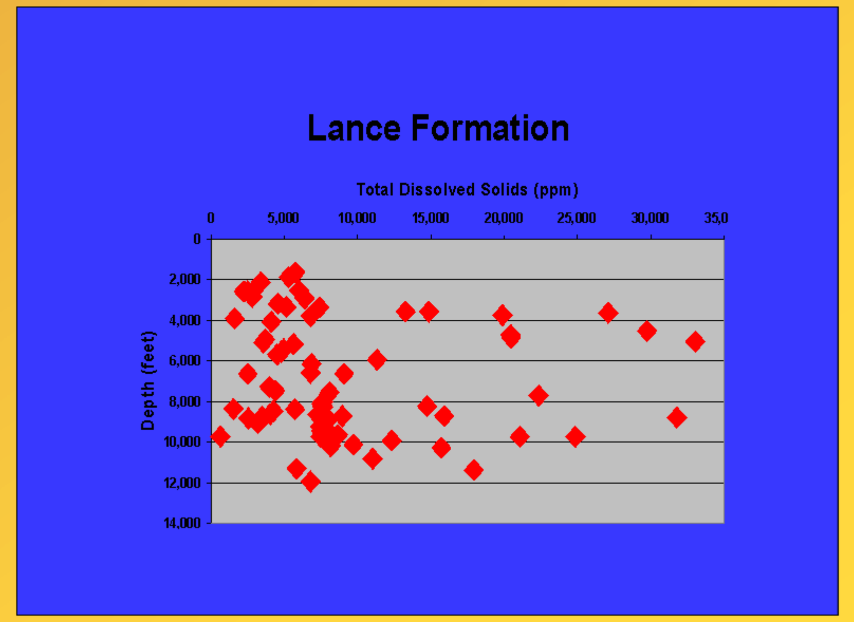
- Pennsylvanian-Permian
- Cretaceous

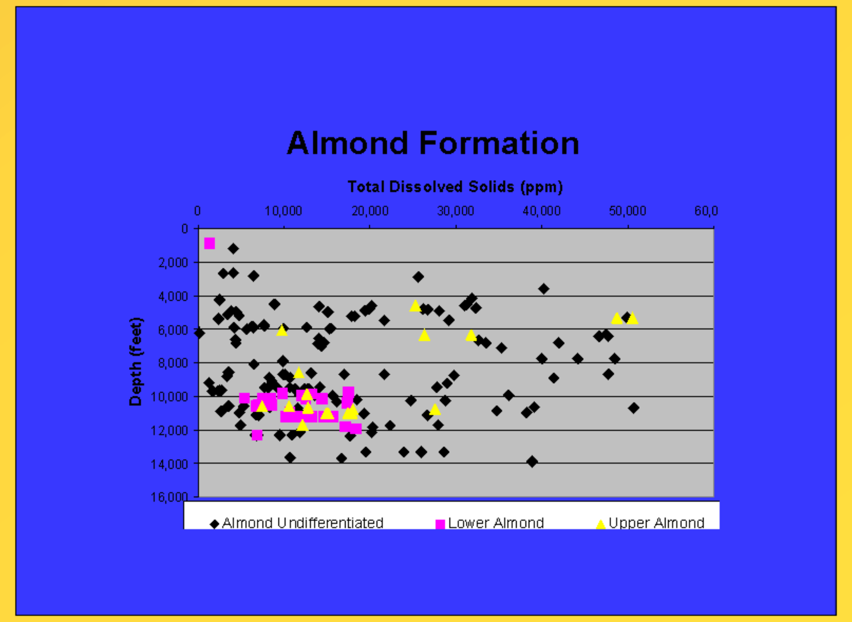


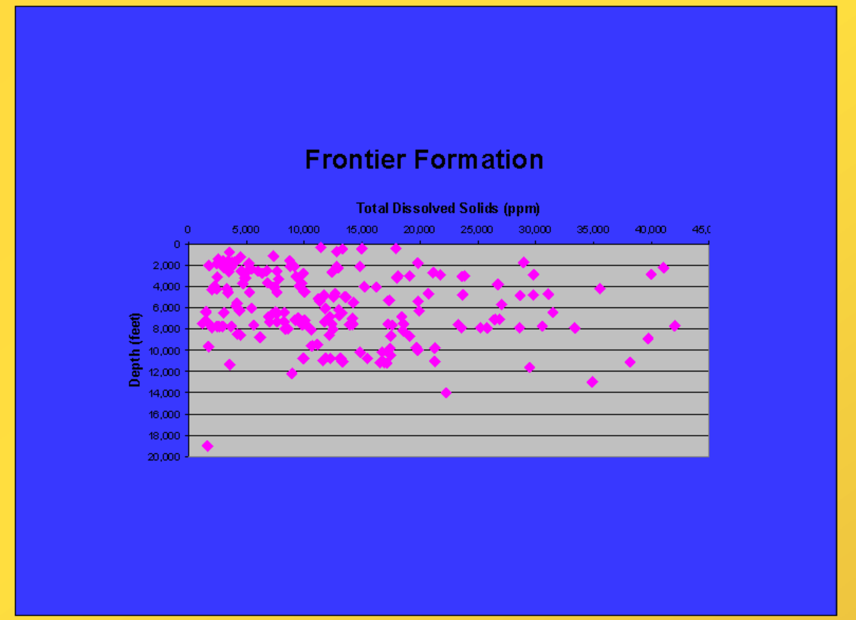
Comparing Cretaceous with Pennsylvanian-Permian:
Taken together, the Cretaceous water samples and the Pennsylvanian-Permian water samples show considerable scatter both in the cations and in the anions. However, a couple of trends emerge.

Cations: Both the Cretaceous and the Pennsylvanian-Permian constant proportion of Ca and Mg. However, the Ca:Mg proportion is different for the two datasets. These are shown schematically in the inset. The Pennsylvanian-Permian samples generally have a Ca:Mg ratio that is 65:35, whereas the Cretaceous samples generally have a ratio that is 80:20.

Anions: As for the cations, there is considerable scatter in both datasets for the anions. However, there are two distinct trends. The Cretaceous samples generally fall along a line between Cl and HCO3 and between HCO3 and SO4, whereas the Pennsylvanian-Permian samples fall along a line between the Cl and SO4 and between SO4 and HCO3. This is shown schematically in the inset.





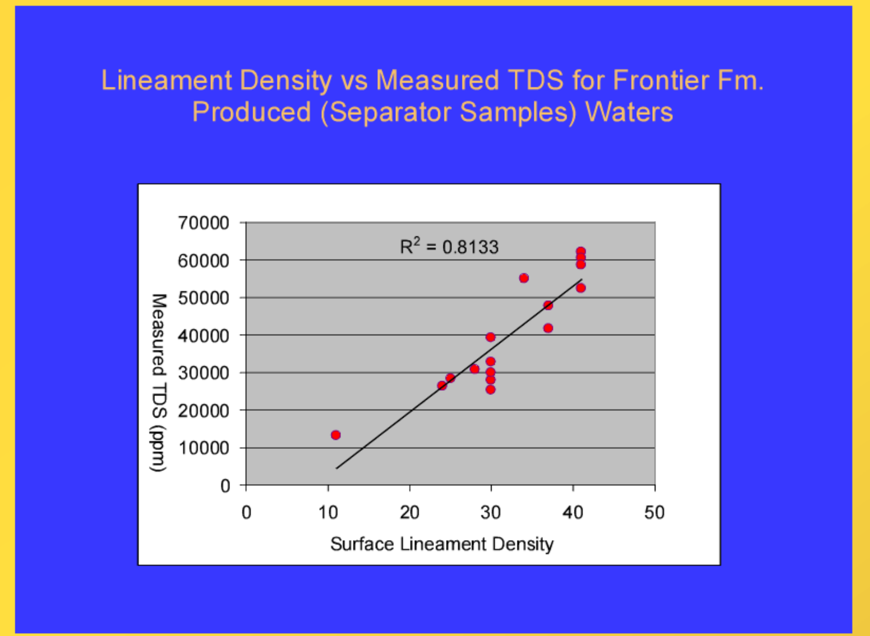


TDS vs Depth Plots

Three of the formations have been examined for potential trends in total dissolved solids (TDS) with depth. These are the Almond, the Lance, and the Frontier formations, whose TDS vs Depth plots are shown above. No clear depth trends have emerged. However, there are some interesting comparisons between the formations. The Almond and the Frontier formations exhibit largest ranges in TDS, having waters between 1,500 and 42,000 ppm for the Frontier and between 1,700 and 50,000 for the Almond. The Lance Formation has water that ranges between 600 and 33,000 ppm.

The overall lower TDS, both in the average and the range is in keeping with its non-marine origin as compared to the marine Frontier Formation. Where the Almond Formation can be divided into Upper and Lower units, two distinct trends emerge. The Upper Almond, of marine origin, shows a wider range of TDS and a higher average TDS than the Lower Almond which is predominantly of non-marine origin. The average TDS of the Upper Almond is 19,000 ppm, whereas that of the Lower Almond is 13,000 ppm. This compares with the Lance whose average TDS is only 9,000 ppm.

TDS vs Surface Fracturing



Well locations for a high quality subset of the Frontier Fm. produced waters were mapped against surface lineament density to evaluate potential relationships between water composition and degree of surface fracturing. A strong positive correlation exists between lineament density and measured TDS. This relationship has been observed qualitatively (Smith, 1998) previously but improved quality control of the database and application of GIS techniques now allows it to be quantified. Developing an improved understanding of this relationship and evaluation of data from other horizons will be a significant part of the conceptual model building process.

Water Technology Summary

- **Water provides vital geotechnical insights as well as production problems in tight gas reservoirs**
- **Technology exists to allow differentiation between native formation waters and secondary contamination**
- **Combining water chemistry with standard methods of subsurface analysis should yield important insights to the nature and occurrence of movable water in the deep, basin centered gas resource**
- **Strategies for avoidance or mitigation can be built upon a science based understanding of subsurface waters and the petrophysics of the host reservoir rock**