Geochemical Classification of Glacial Till Stratigraphy

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1.0 Executive Summary

Classification of tills into a stratigraphic framework based on multielement geochemical analyses of the -63µm (silt+clay) fraction is feasible within the AGA AOI. Far-traveled northwest provenance tills are easily distinguished from locally-derived northeast provenance tills based on major element geochemical signatures. Major- and trace-element signatures further indicate significant variability within basal northeast provenance tills, indicating that incorporation of local bedrock strongly influence till composition. Based on geochemical criteria, two northwest provenance and seven northeast provenance till subgroups have been defined. Seven till subgroups in total are recognized from surficial and borehole samples in the AGA AOI.

2.0 Introduction

This memo presents results of an investigation into the utility of devising a geochemically based till stratigraphic framework to aid in interpreting the significance of -63µm (silt+clay) fraction till geochemical results collected as part of ongoing exploration efforts.

A basic stratigraphic framework is critical to interpreting the results of till geochemical and mineralogical data at the property scale. Within a glaciated landscape, discrete till depositional units can be generally categorized as either relatively homogeneous, displaying great lateral continuity in textural, mineralogical, and geochemical characteristics, or as relatively heterogenous, displaying significant local variability in textural, mineralogical, and geochemical characteristics. The relatively homogeneous tills are typically dominated by sediment that has been transported a great distance from its source (100-1000km), while the relatively heterogeneous tills are dominated by sediment transported only a short distance from its source (1-10 km). Distinguishing between the two end members is critical to evaluating whether a given till might contain a locally derived geochemical or mineralogical signal.

Similarly, evaluating whether the basal till in a given sequence is a far-traveled homogeneous till, or a short-traveled heterogenous till is critical evaluating if there is a geochemical or mineralogical signal of bedrock mineralization at all.

2.1 Lithostratigraphic Classification of Tills in Minnesota

Since ca.1970, the Minnesota Geological Survey has developed a lithostratigraphic classification of Minnesota tills (Johnson et al. 2016). Eighty (80) distinct till units covering the glaciated portion of the state have been defined based on the matrix texture (relative proportions of sand, silt, and clay in the -2 mm fraction) and the lithology of the 1-2 mm sand grain fraction.

Unfortunately, this lithostratigraphic classification has little prospect of being effectively applied to regional- or property-scale mineral exploration.

The lithostratigraphic classification scheme initially developed based on investigations in the southern and western portions of the state, a region characterized by homogeneous, laterally extensive till sheets composed primarily of far-traveled sediment. These till sheets are characterized by low variability and high spatial continuity in their lithologic and textural components, allowing correlation over long distances. In contrast, the northeastern portion of the state, where most of the tills characterized by short-traveled sediment are located, has as yet seen no formal attempt to apply these classification principles in detail. It is reasonable to anticipate that the high variability and low spatial continuity of textural and lithologic components in these tills will hinder regional-scale definition of distinct till units.

In addition, the laboratory methods used to generate the data used to correlate and categorize tills in the existing lithostratigraphic framework are costly and time consuming. Matrix texture is determined by hydrometer on the -2 mm fraction of tills, a costly and time consuming method that does not correlate well with cheaper, automated laser particle size analyses.

Lithologic characterization of the 1-2 mm sand fraction is conducted by observation under binocular microscope. Conducting reproducible grain counts requires significant experience, and is a skill not reliably translated outside the Minnesota Geological Survey. In addition to the time, cost, and training necessary to produce reliable data, the characterization scheme is itself non-specific, incorporating very generic categories ('carbonate', 'darks', 'reds', etc.). While this scheme may work well on a statewide basis, it has not been demonstrated to produce useful data in the short-traveled, heterogeneous tills of greatest utility to mineral exploration.

In addition to the time, cost, and training barriers to effectively applying the lithostratigraphic classification scheme to property-scale exploration, it is worth noting that this scheme relies on essentially two sets of intensive variables.

The low cost and high turnaround rate of modern multivariate geochemical analytical techniques promise to provide a more useful classification scheme with which to evaluate the significance of geochemical and mineralogical data collected from till. In addition, standard sample collection and analytical techniques promise to eliminate the high training barriers necessary to reproduce MGS-quality data. Significantly, just as the textural and lithologic characteristics reflect to a great extent the composition of the sediment source area, so does the major- and trace-element signature of the -63µm till fraction.

2.2 Data Sources

Till analytical results utilized in this analysis were derived from the following legacy data sources, 840 samples in total collected between 2002 and 2016:

- NRRI Technical Report 2003-23 (Larson) (2004) (144 samples)
- Minnesota DNR Report 365 (Dahl) (2005) (32 samples)
- Minnesota Geological Survey OFR-07-1 (Thorleifson et al.) (2007) (263 samples)
- Agate Lake Resources exploration data (2010) (80 samples)
- Twin Metals Minnesota exploration data (2014) (130 samples)
- Minnesota DNR Open-File Project 392 (Elsenheimer) (2014-2016) (191 samples)

In addition, 174 samples collected by AngloGold Ashanti are incorporated into the analysis. Of this number, 50 are from surface exposures and 124 are from archived rotosonic boreholes. The rotosonic borehole samples are of particular importance, as they are presumably significantly less weathered than shallow surface samples. In particular, they can be expected to retain something approaching true original sulfide S concentrations and associated trace elements.

Of the 1014 'till' samples, 55 are excluded from this analysis because:

- The samples show variance from AGA AOI samples attributable solely to geographical distance (principally MGS OFR-07-1 samples),
- The samples were collected from glacial landforms that are not characteristic of tills (surface samples only), or
- The samples were collected from saprolites at the bedrock surface (borehole only).

In each case, ambiguities regarding the sample type were expressed as highly anomalous geochemical signatures relative to the bulk of the data set.

2.3 Analytical Methods

All selected till samples were analyzed using equivalent methods:

- Screen to -63µm (silt+clay fraction)
- Preparation by 4-acid digestion
- Major- and trace-element determination by ICP-AES (major) or ICP-MS (trace)
- Au assay by fire assay (15 g to 50 g) with an ICP-AES finish in most cases.

Analyses for samples collected by AngloGold Ashanti were completed by ALS Geochemistry. Samples were disaggregated at dry screened using stainless steel screens to recover the -63µm (silt+clay) fraction (prep code SCR-44). A 50 g subsample was analyzed for Au by fire assay with an ICP-AES finish (method code Au-ICP22). A second subsample was prepared using a 4-acid near total digestion prior to determination of 48 major- and trace-elements by ICP-MS (method code ME-MS61). A third subsample was analyzed for total carbon by coulometry (LECO) (method code C-IR07).

Total inorganic carbon values for the 263 samples from MGS OFR-07-1 were calculated by converting total Chittick calcite and dolomite carbonate concentrations to equivalent carbon concentrations.

Adherence to a standard protocol is particularly important for interpretation of till geochemical data. Anomalous concentrations of elements present in low abundance in background (e.g. Cu, Ni, Zn) rarely exceed 2x background values, placing critical importance on reduction of sampling and analytical variability.

3.0 Till Stratigraphic Framework

The fundamental division recognizable from till compositional data is between relatively homogeneous, carbonate-rich tills and relatively heterogeneous, carbonate-poor tills. In the vicinity of the AGA AOI, the carbonate-rich tills are generally associated with ice flowing from the northwest and are designated the **NW** group, while the carbonate-poor tills are generally associated with ice flowing from the northeast and are designated the **NE** group. Tills associated with each group have clear associations with tills outside the AGA AOI, and the groupings and nomenclature are applied to the entire data set.

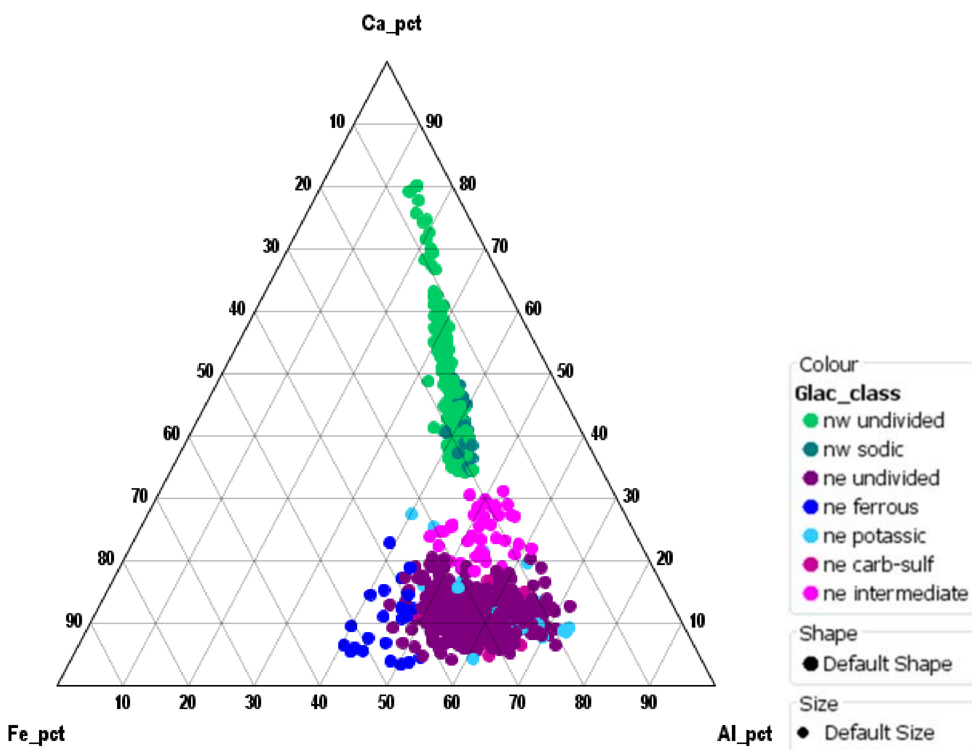

Figure 1. Ca-Fe-Al ternary plot of till. Variation along the Fe+Al to Ca axis reflects relative carbonate content, while variation on the Fe-Al axis reflects variability of the crystalline basement component.

3.1 Northwest group tills

Northwest group tills are represented by 214 of the 959 samples in the dataset (Fig. 2). Northwest group tills are broadly characterized by high carbonate content, expressed geochemically by high concentration of, and strong correlation between, C, Ca, and Mg (Figs. 3 and 4). Matrix carbonate contents range from 15% to 70%. The strong linear relationship between C, Ca, and Mg reflects a mixing trend between a carbonate-rich sediment source and a generic carbonate-poor source derived from crystalline basement rocks.

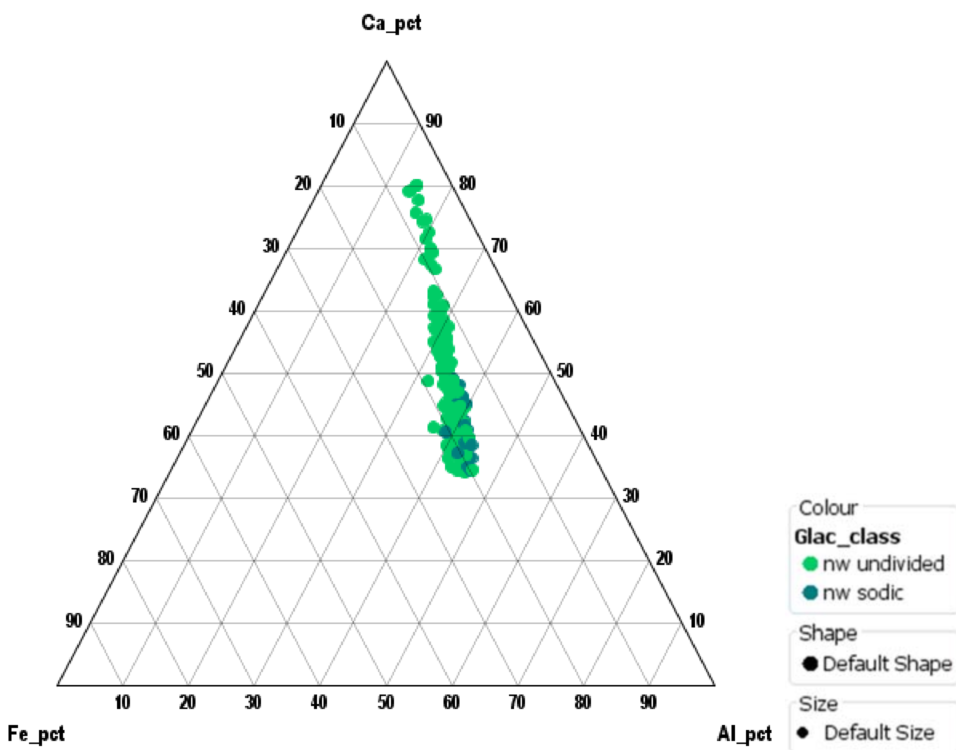

Figure 2. Ca-Fe-Al ternary plot of NW group tills. The narrow range of variability on the Fe-Al axis reflects the homogeneity of the crystalline basement end member of these tills.

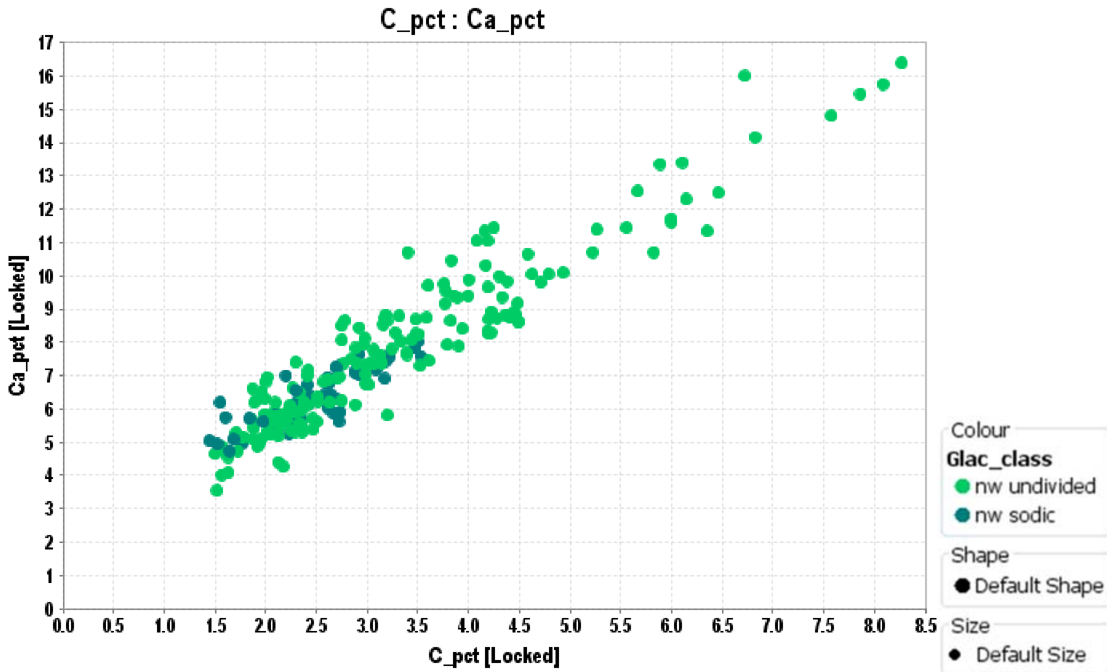

Figure 3. Ca vs total C plot of NW tills. The linear trend indicates that Ca and C are primarily associated with the carbonate component of the till.

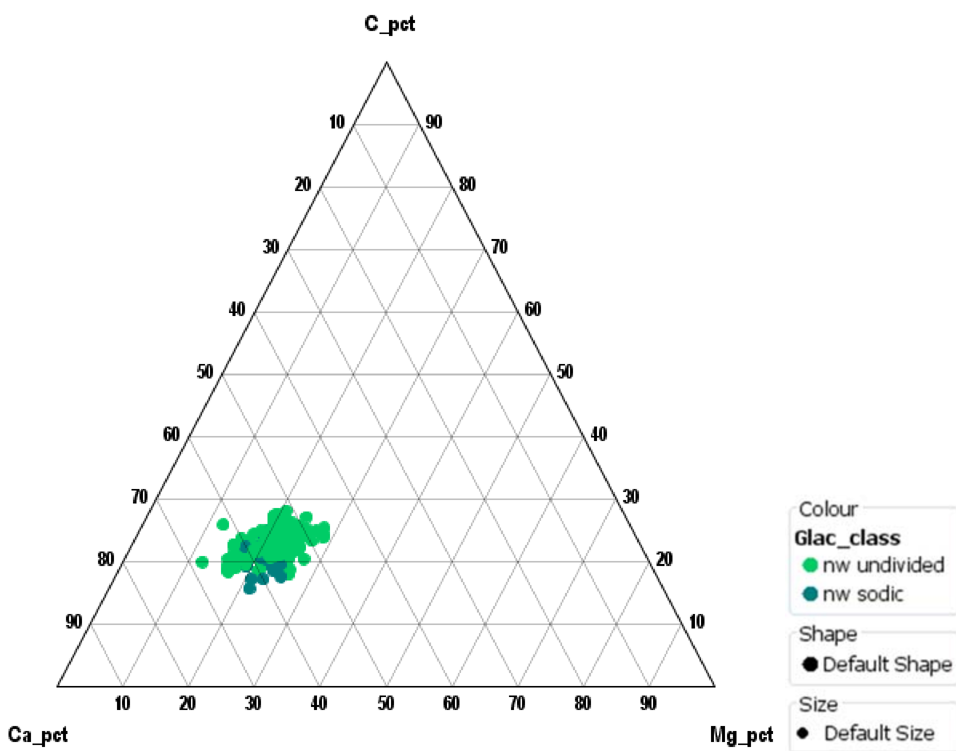

Figure 4. C-Ca-Mg ternary plot of NW tills. The tight cluster of values reflects the homogeneity of the carbonate end member, composed of roughly equal proportions of calcite and dolomite.

On a regional scale, the highest carbonate contents are associated with tills in northwestern Minnesota, with systematically decreasing concentrations to the south and east (Fig. 5).

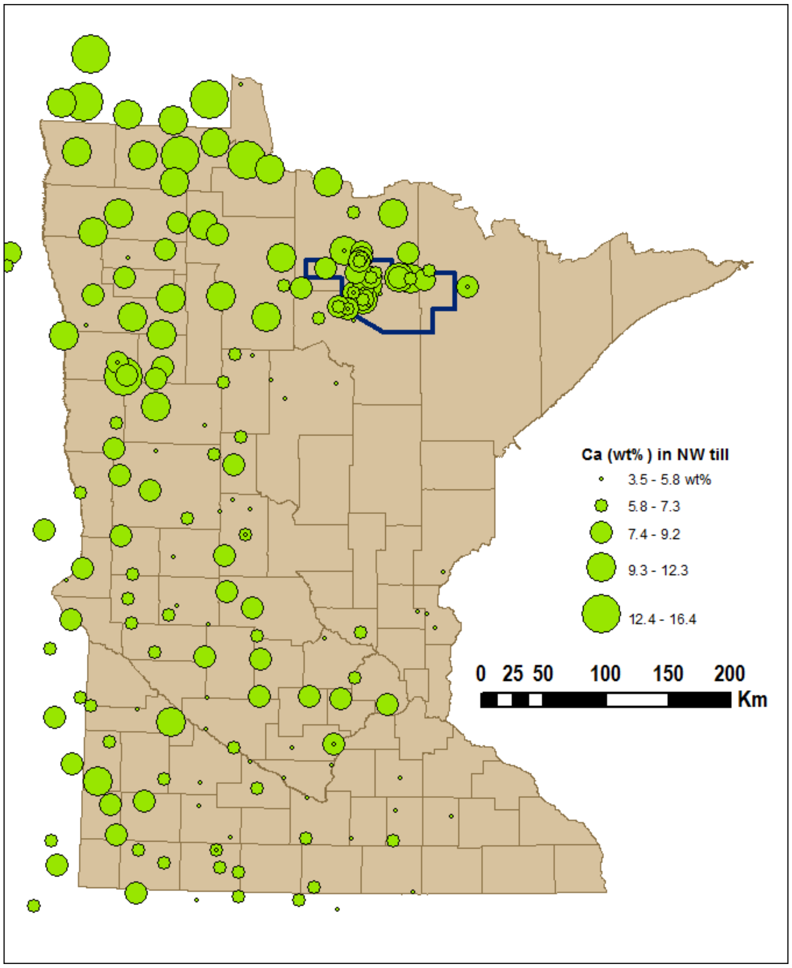

Figure 5. Map showing relative Ca (carbonate) content of NW group tills in Minnesota.

In common, NW group tills show little, if any, evidence for significant incorporation of locally derived bedrock. Consequently, they are of no utility for evaluating bedrock prospectively, or vectoring to mineralized bedrock.

3.1.1 NW undivided

The majority of NW group tills (167 of 214 samples) are lumped into the NW undivided subgroup (Figs. 2,3,4,6). This till comprises the surficial till over roughly the western half of the AGA AOI (Fig. 7).

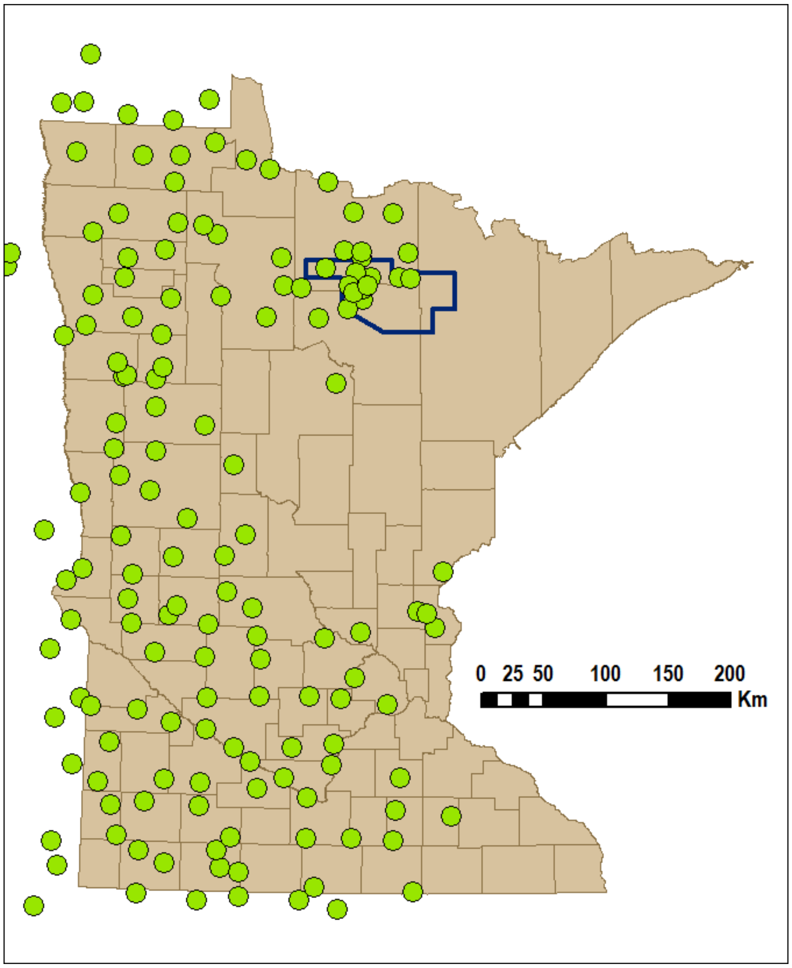

Figure 6. Map showing location of NW undivided till subgroup in Minnesota.

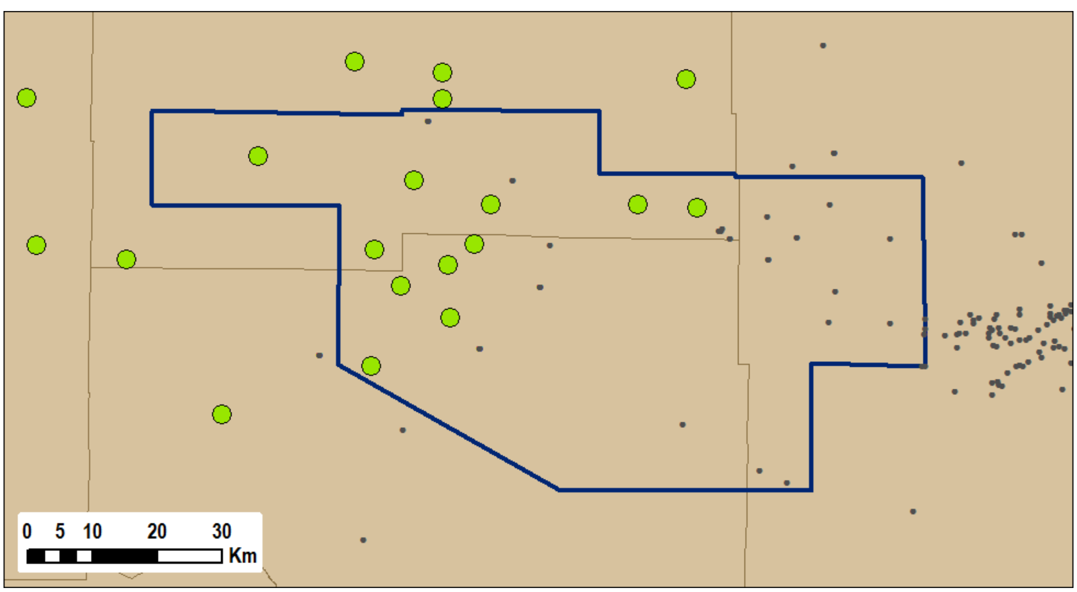

Figure 7. Map showing location of NW undivided till subgroup in AngloGold Ashanti area of interest.

3.1.2 NW sodic

Within the broader NW group tills, a subset (47 of 214 samples) is characterized by distinctly higher Na concentrations (Figs. 8,9). This subgroup likely reflects mixing between NW group carbonate-rich and a relatively sodium-rich crystalline basement endmembers. This till is found at depth in the western half of the AGA AOI, underlying sodium-poor NW undivided tills (Fig. 10). Locally in the central third of the AOI, it is found at shallow depths.

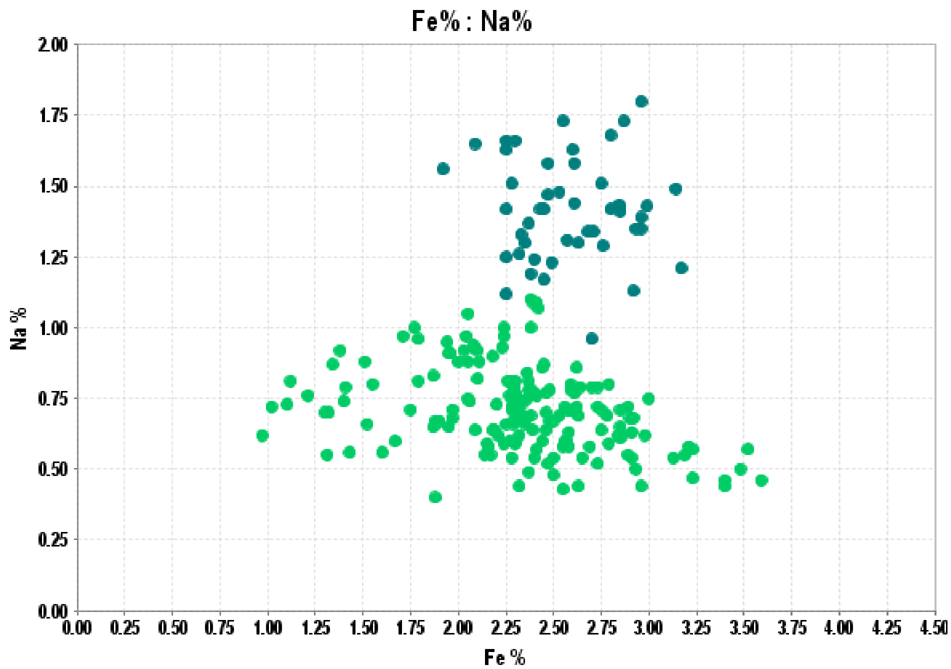

Figure 8. Na versus Fe plot, highlighting the clear grouping and relative high Na content of the NW sodic till subgroup.

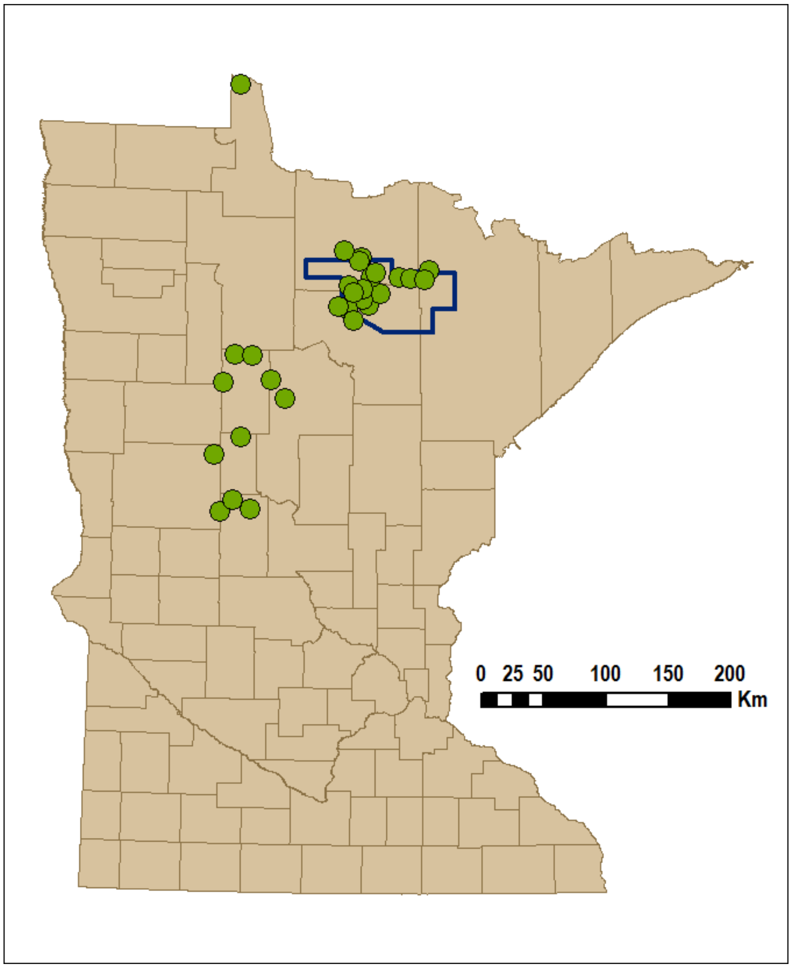

Figure 9. Map showing location of NW sodic till subgroup in Minnesota.

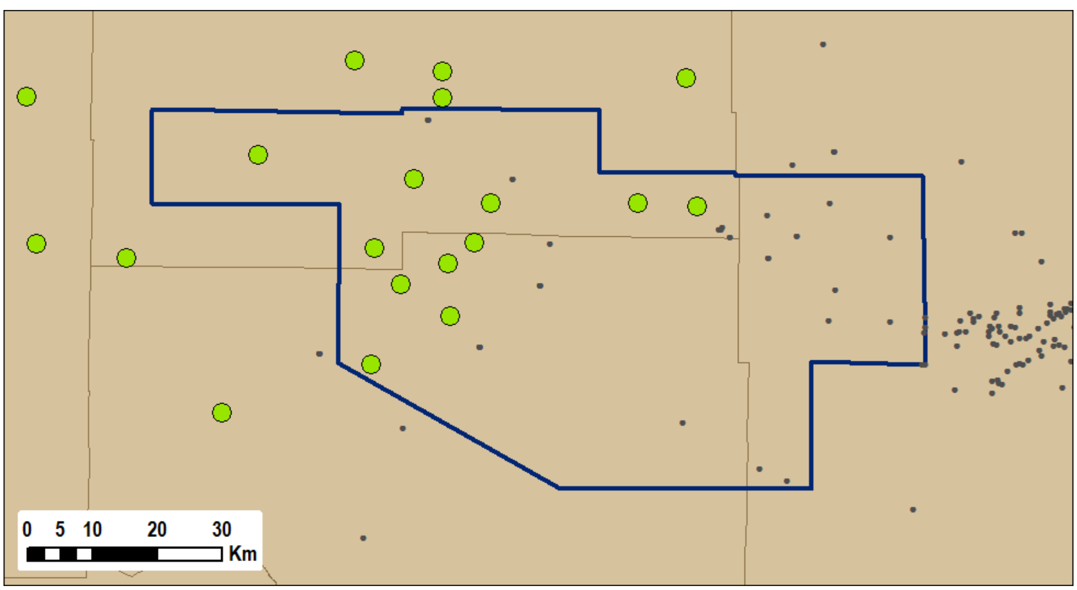

Figure 10. Map showing location of NW sodic till subgroup in AngloGold Ashanti area of interest.

3.2 Northeast group tills

Northeast group tills are represented by 745 of the 959 samples in the dataset (Fig. 11). Northeast group tills are broadly characterized by low carbonate contents, and significant heterogeneity in major- and trace-element composition. This heterogeneity is a direct reflection of the influence of local bedrock erosion and entrainment on till composition. Consequently, NE group tills include those with the greatest utility for detecting and vectoring to bedrock mineralization.

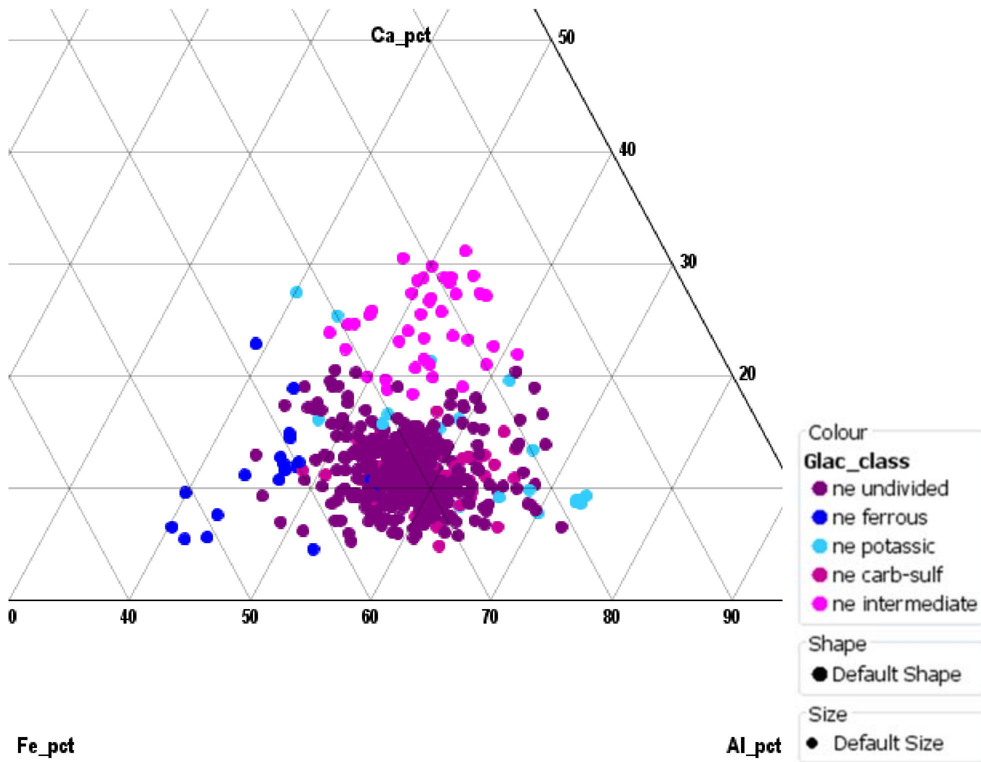

Figure 11. Ca-Fe-Al ternary plot highlighting compositional variability of the NE till group.

3.2.1 NE undivided

The majority of NE group tills (575 of 745) are lumped into the NE undivided subgroup (Figs. 11,12). This grouping reflects that these samples are not characterized by the elemental associations used to define the other NE till subgroups, and does not necessarily imply a single, compositionally homogeneous subgroup.

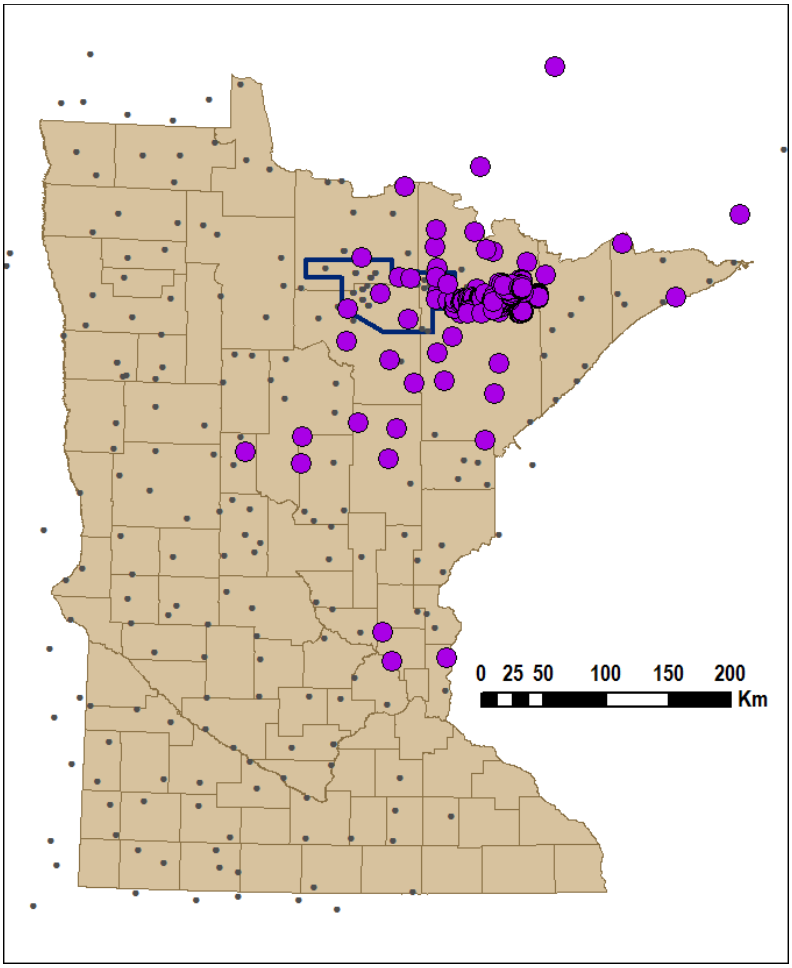

Figure 12. Map showing location of NE undivided till subgroup in Minnesota.

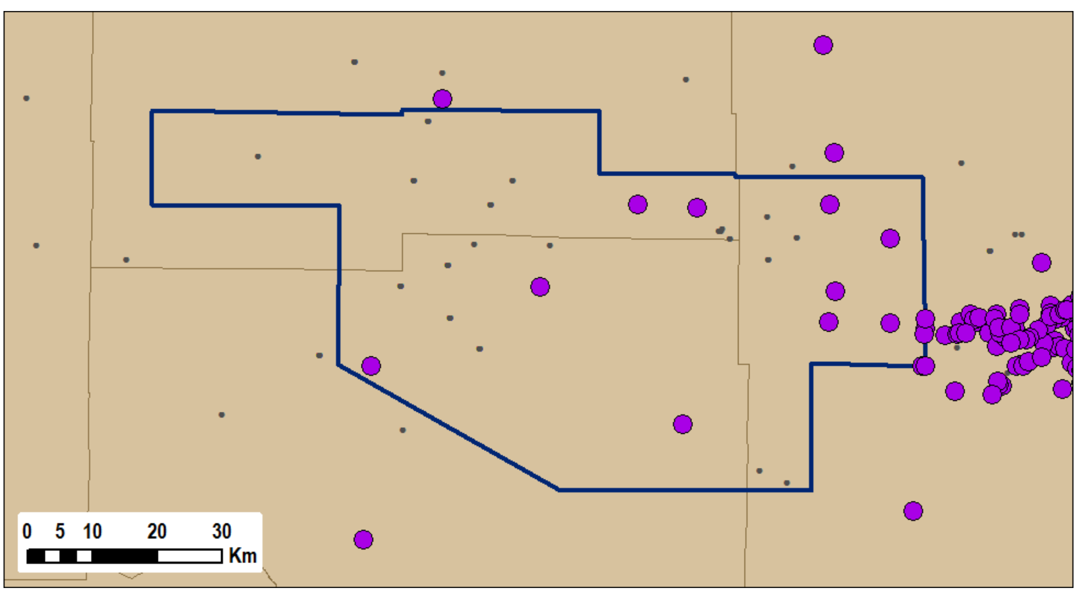

Figure 13. Map showing location of NE undivided till subgroup in AngloGold Ashanti area of interest.

3.2.2 NE dlcp (Duluth Complex)

The NE dlcp till subgroup contains seven (7) samples geographically associated with the Mesoproterozoic Duluth Complex (Fig. 14). They contain distinct elemental markers and associations (elevated Fe, Al, Ni, etc.) derived from erosion and entrainment of mafic intrusive rocks. Consequently, they are distinct from tills derived from erosion and entrainment of Archean granite-greenstone rocks. No NE DLCP subgroup tills are present in the AGA AOI.

3.2.3 NE superior

The NE superior till subgroup contains thirty (30) samples geographically and compositionally associated with Mesoproterozoic Midcontinent Rift volcanic, intrusive, and sedimentary rocks (Fig. 14). Consequently, they are distinct from tills derived from erosion and entrainment of Archean granite-greenstone rocks. They are generally correlative with tills associated with the Late Wisconsin Superior Lobe. No NE SUPERIOR subgroup tills are present in the AGA AOI.

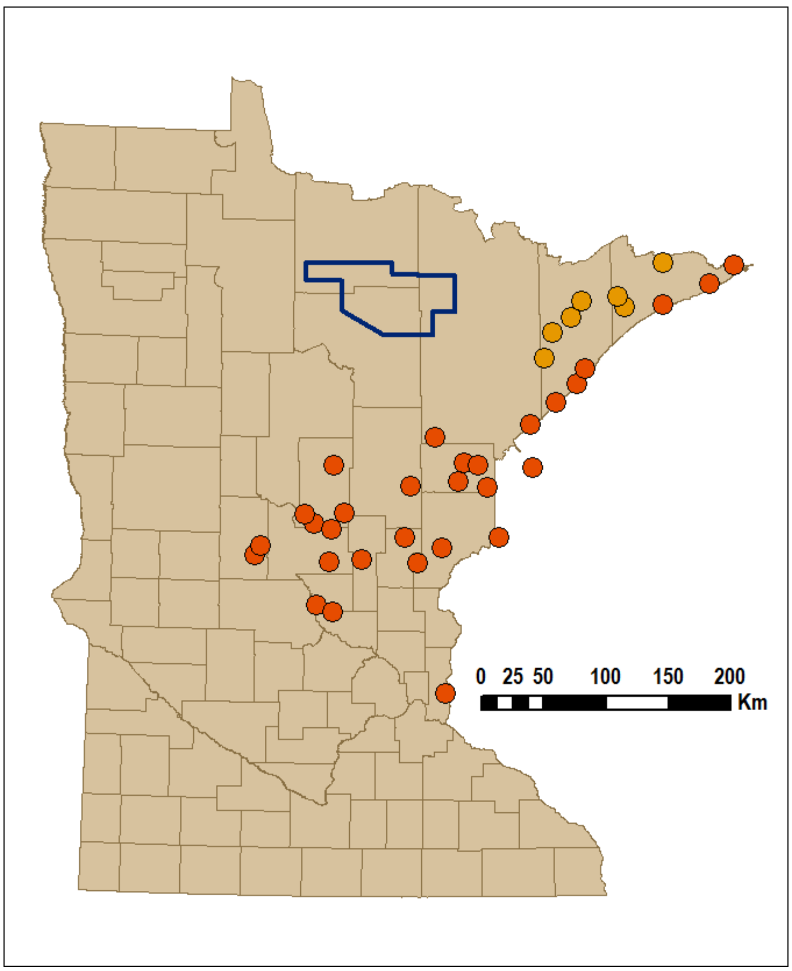

Figure 14. Map showing location of NE DLCP (orange) and NE SUPERIOR (red) till subgroups in Minnesota.

3.2.4 NE ferrous

The NE ferrous till subgroup consists of thirty (30) till samples characterized by high Fe concentrations (>5.75% Fe) (Figs. 15,16). The majority of these samples are surficial samples collected from the Vermilion greenstone belt ~40 km east of the AGA AOI. Their compositions reflect erosion and entrainment of Archean iron-formation.

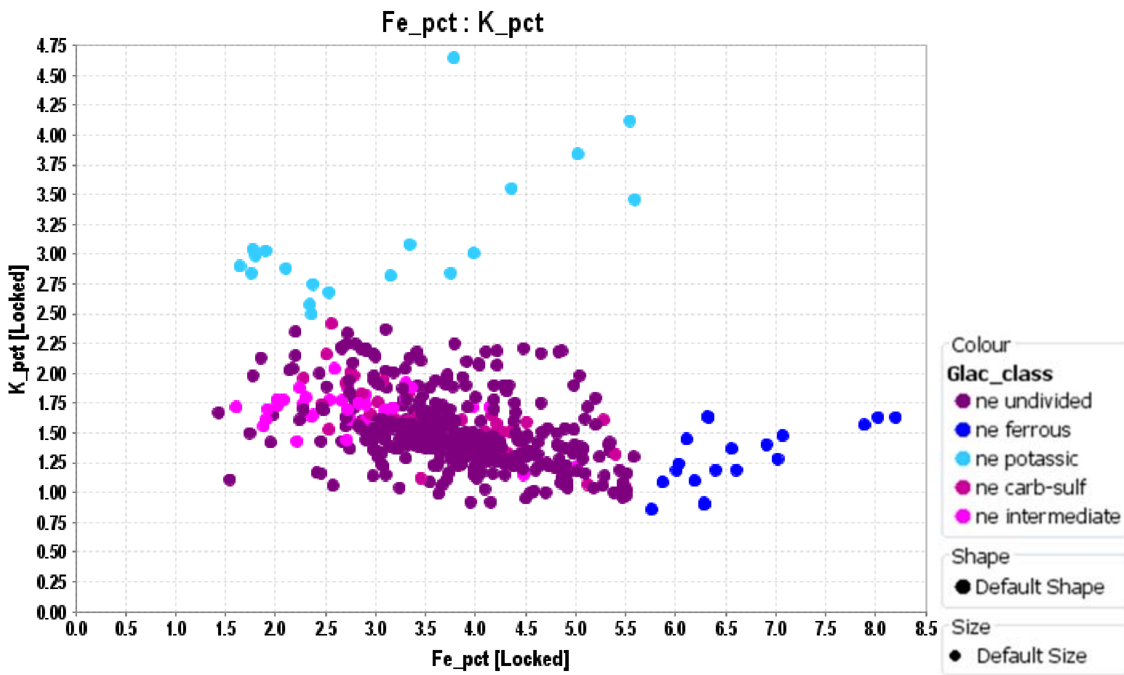

Figure 15. K versus Fe plot of NE group tills, highlighting the anomalous geochemical signatures of the NE ferrous and NE potassic till subgroups.

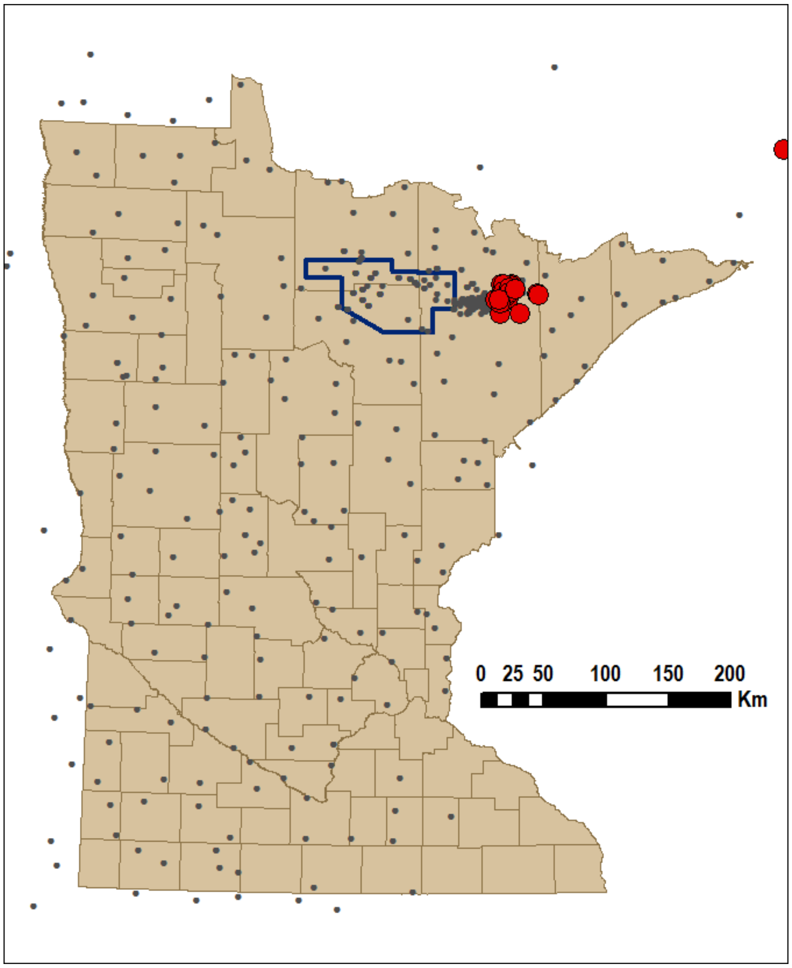

Figure 16. Map showing location of NE ferrous till subgroup in Minnesota.

Significantly, NE ferrous tills are characterized by significantly higher -63µm Au fire assay results (median 0.005 ppm; mean 0.047 ppm) than NE undivided tills as a whole (median 0.002 ppm; mean 0.006 ppm) (Fig. 17). No NE ferrous tills have been identified in the AGA AOI, however given the known presence of iron-formation in the AOI, it is reasonable to anticipate that similar tills will be encountered in boreholes.

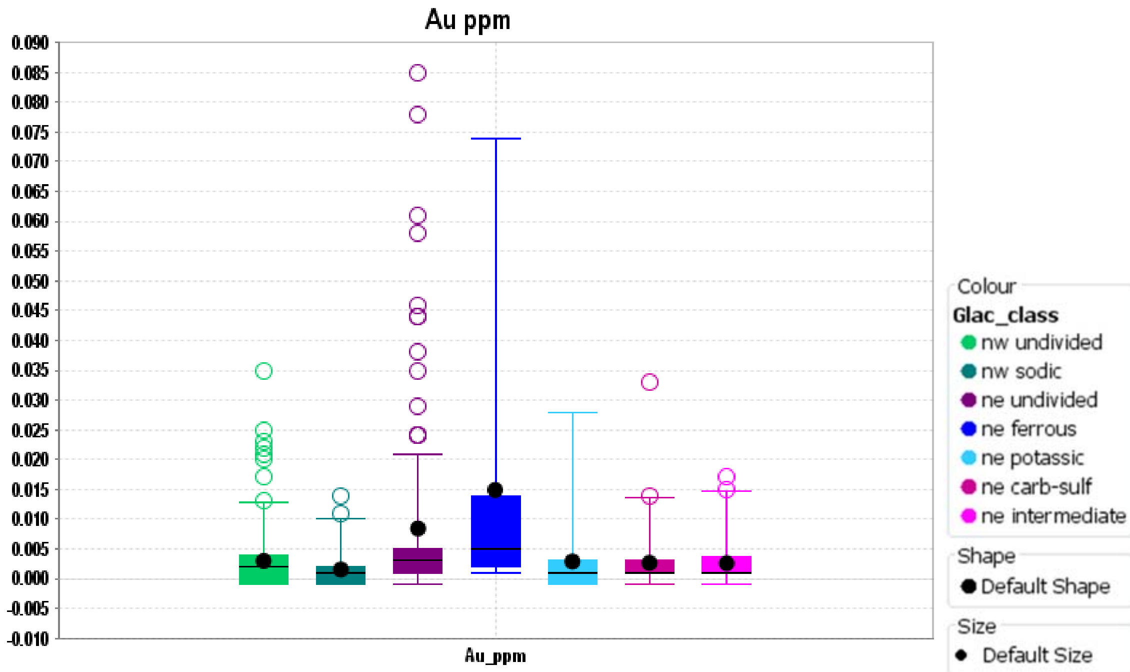

Figure 17. Tukey boxplot of -63µm fraction Au fire assay in NW and NE group tills.

3.2.5 NE potassic

The NE potassic till subgroup consists of twenty-two (22) till samples characterized by high K concentrations (>2.5% K) (Figs. 15,18). In addition to K, P, Ce, La, Ba, Sr, and Th are present in elevated concentrations. These samples are divided between surficial samples collected near shear-hosted potassic alteration zones in the Vermilion greenstone belt, and borehole samples collected overlying or adjacent to alkali intrusions in the AGA AOI (Fig. 19).

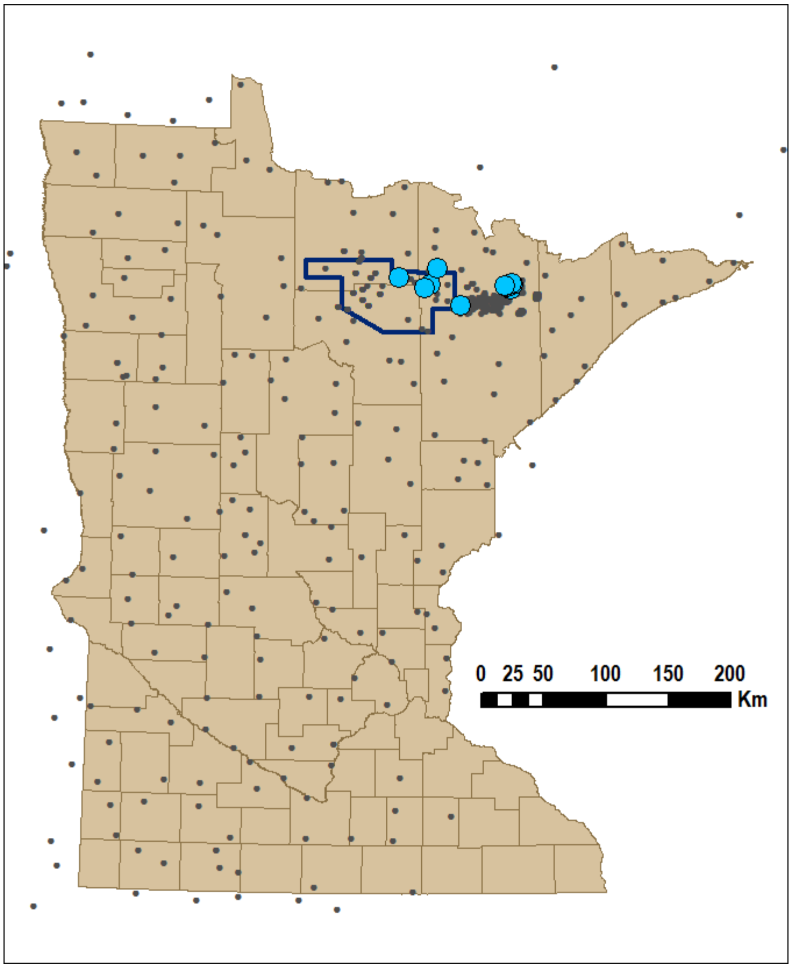

Figure 18. Map showing location of NE potassic till subgroup in Minnesota.

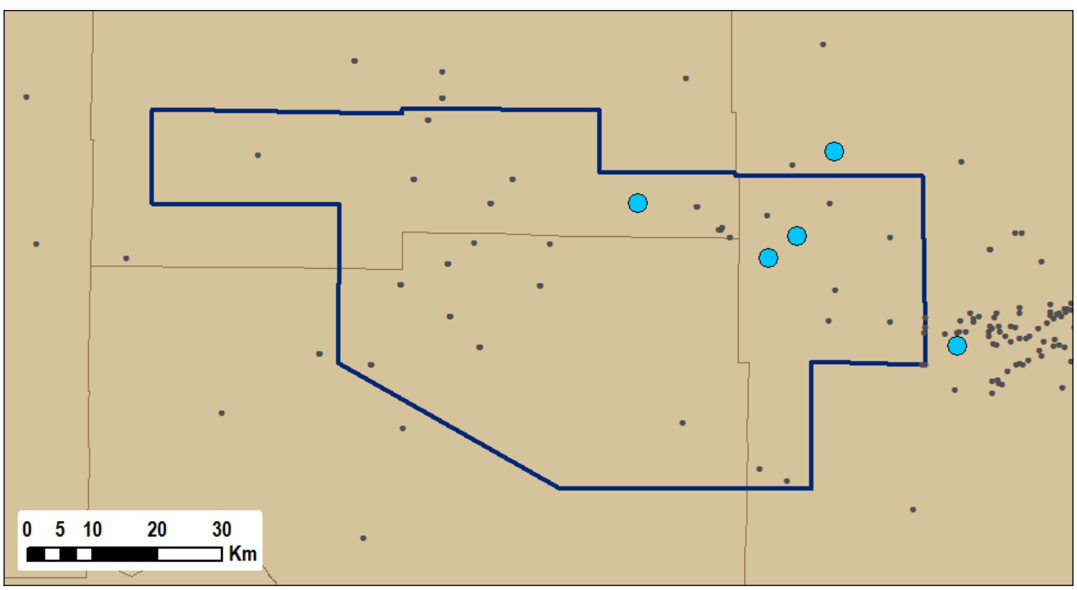

Figure 19. Map showing location of NE potassic till subgroup in AngloGold Ashanti area of interest.

3.2.6 NE carb-sulf

The NE carb-sulf till subgroup consists of forty-one (41) till samples characterize by relatively high C and (or) high S concentrations relative to the overall NE till group (Figs. 20-22). To a great extent, definition of this subgroup is based on the higher sensitivity of the total coulometric C assay utilized by AGA relative to the Chittick carbonate method utilized by the Minnesota Geological Survey. However, the subgroup also encompasses higher S values assayed in several borehole samples. It is also distinct from the very low C content NE undivided tills in both legacy data sets and in new AGA till samples.

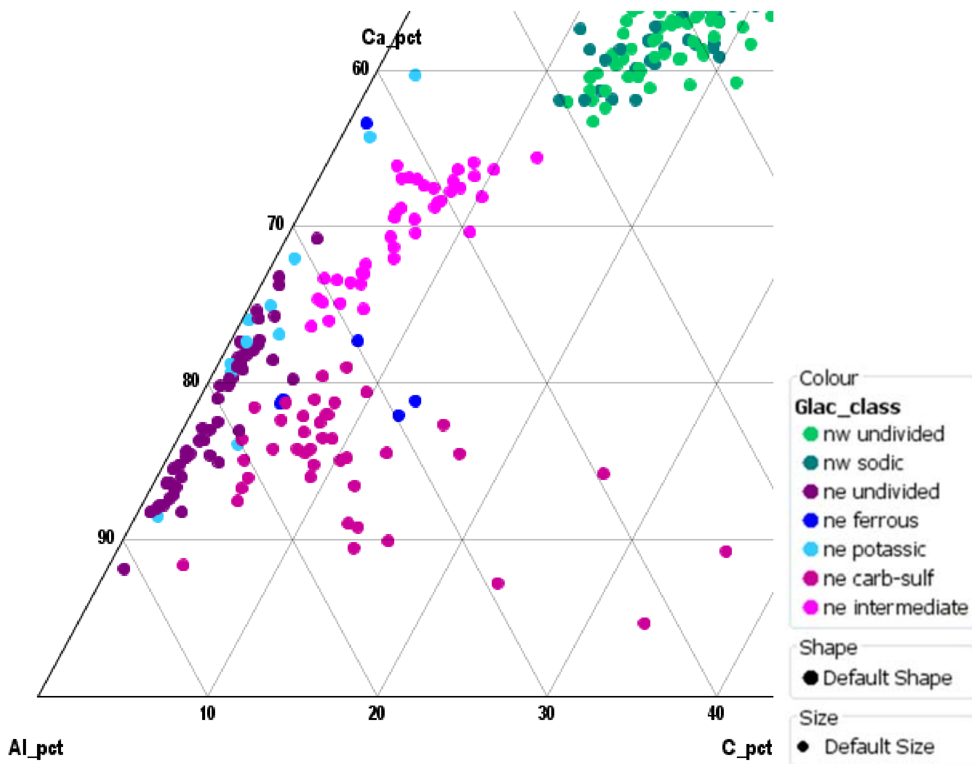

Figure 20. Ca-Al-C ternary plot highlighting the relatively high total C content of NE carb-sulf subgroup tills.

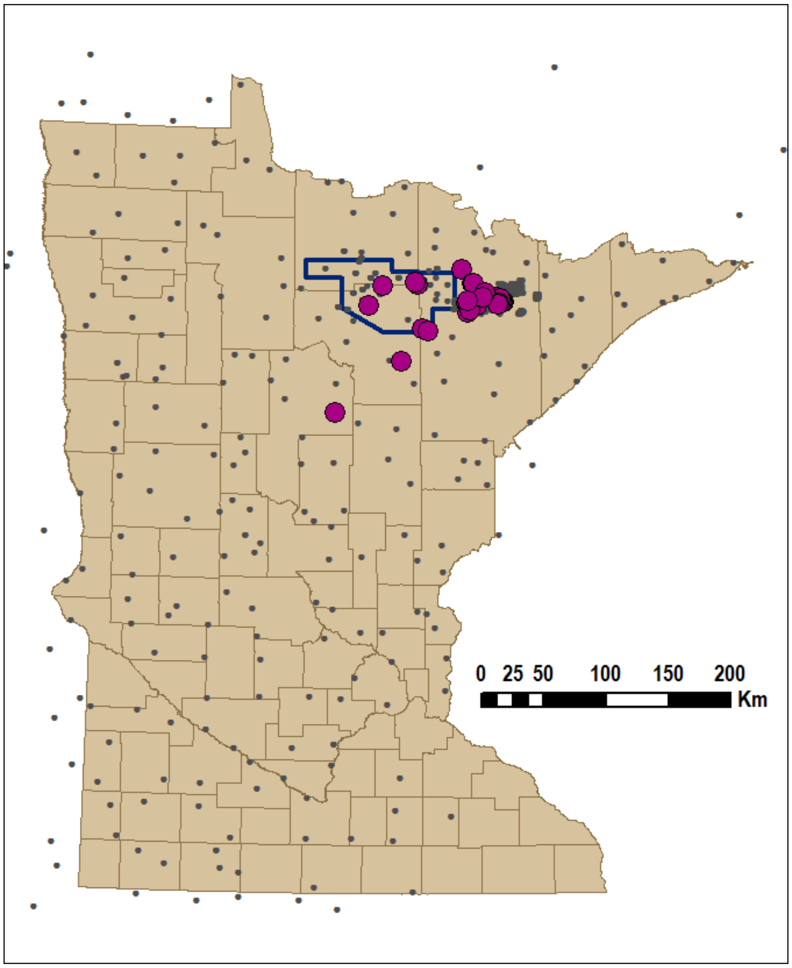

Figure 21. Map showing location of NE carb-sulf till subgroup in Minnesota.

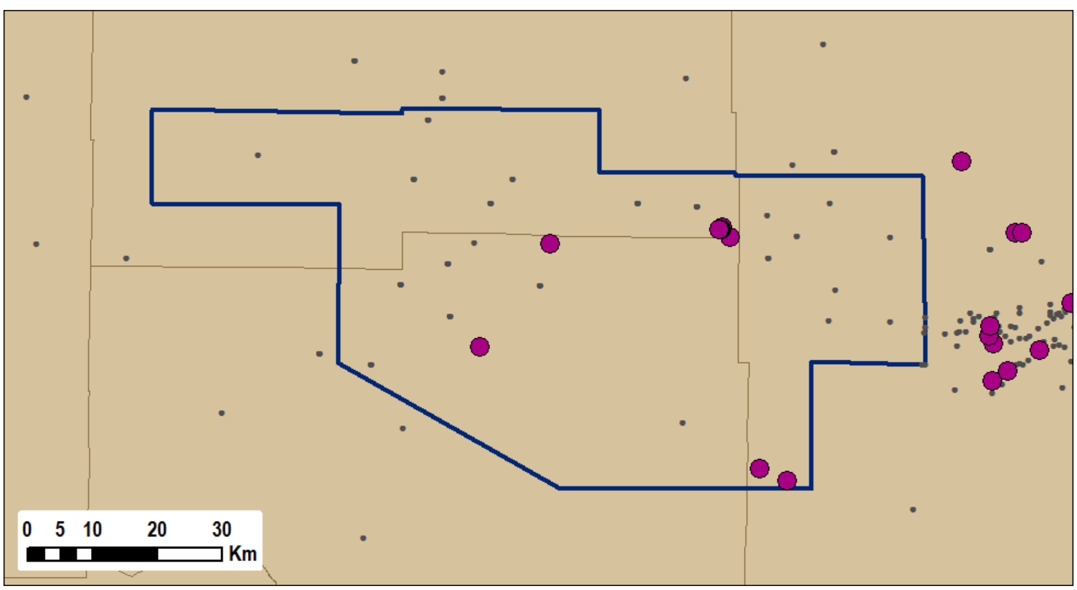

Figure 22. Map showing location of NE carb-sulf till subgroup in AngloGold Ashanti area of interest.

3.2.7 NE intermediate

The NE intermediate till subgroup consists of forty (40) till samples falling along a mixing trend between heterogeneous crystalline bedrock and homogeneous carbonate end members (Fig. 23). There is a distinct compositional gap between these tills and the similar NW till group. NE intermediate tills contain on the order of 5% to 15% carbonate.

NE intermediate tills occur as the basal till in the western half of the AGA AOI (Fig. 25). They may represent either 1) deposition of a till containing a carbonate-bearing, far-traveled sediment load that has been substantially diluted by incorporation of non-carbonate crystalline basement rock, or 2) local reworking of pockets of older carbonate-bearing tills into a crystalline basement-dominated, substantially locally-derived till.

Limited data suggest these tills may be pre-Wisconsin in age.

It is my opinion that scenario 2 is the more likely, meaning NE intermediate tills are potentially useful for detecting and vectoring to bedrock mineralization.

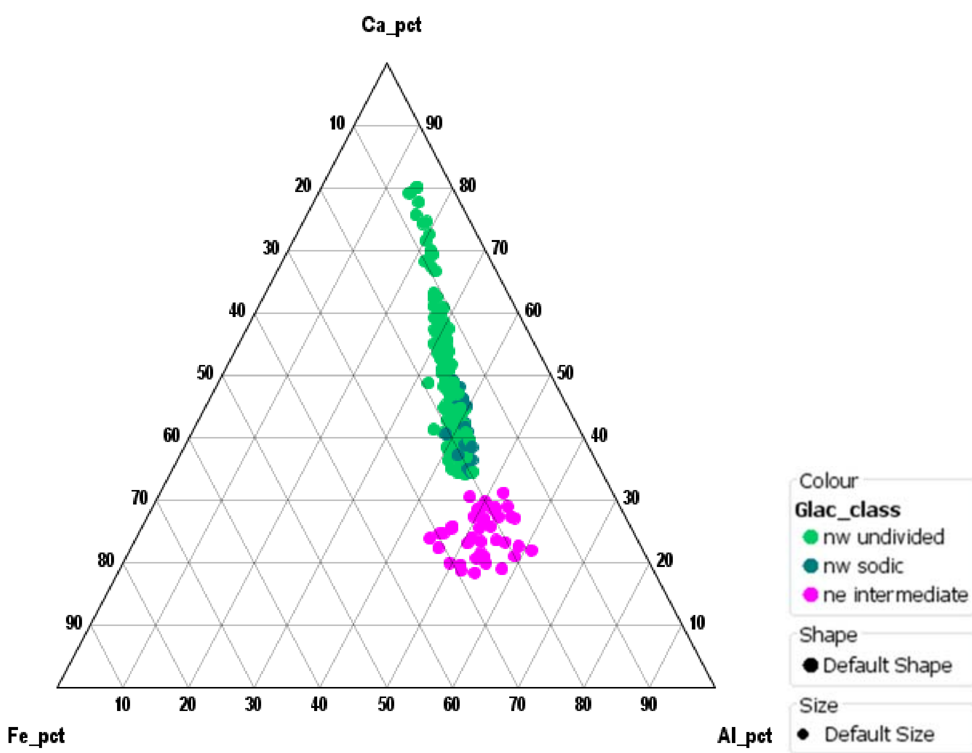

Figure 23. Ca-Fe-Al ternary plot of NW group tills and NE intermediate subgroup till. Note the compositional gap between the NW and NE groups and high variability along the Fe-Al axis of the NE intermediate group tills.

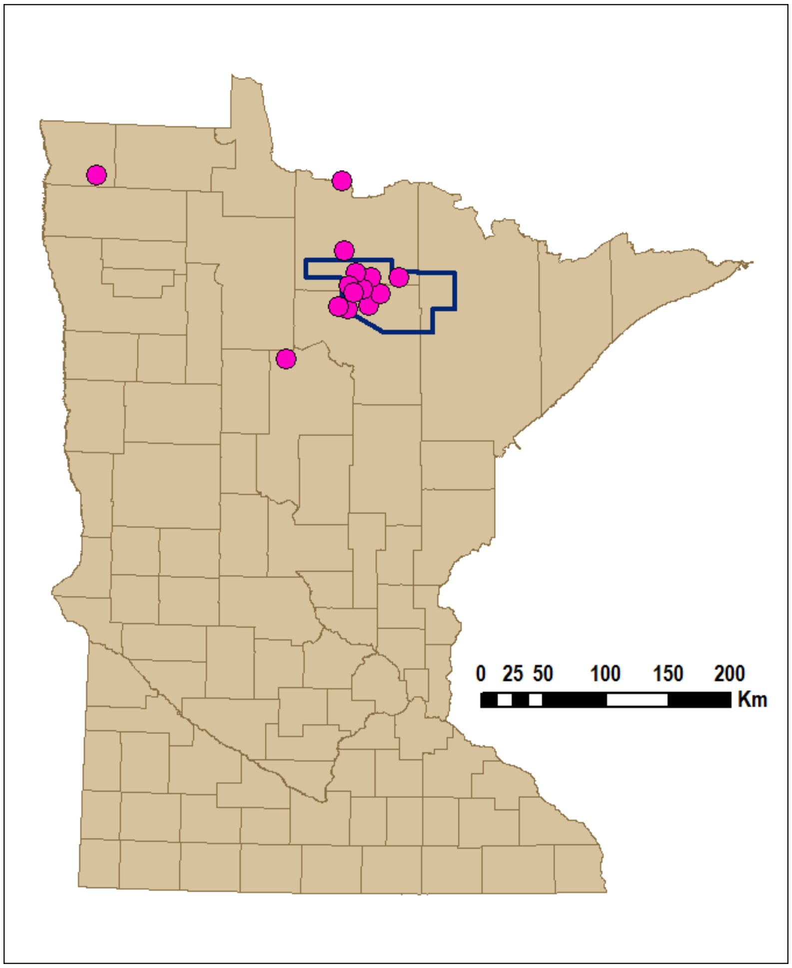

Figure 24. Map showing location of NE intermediate till subgroup in Minnesota.

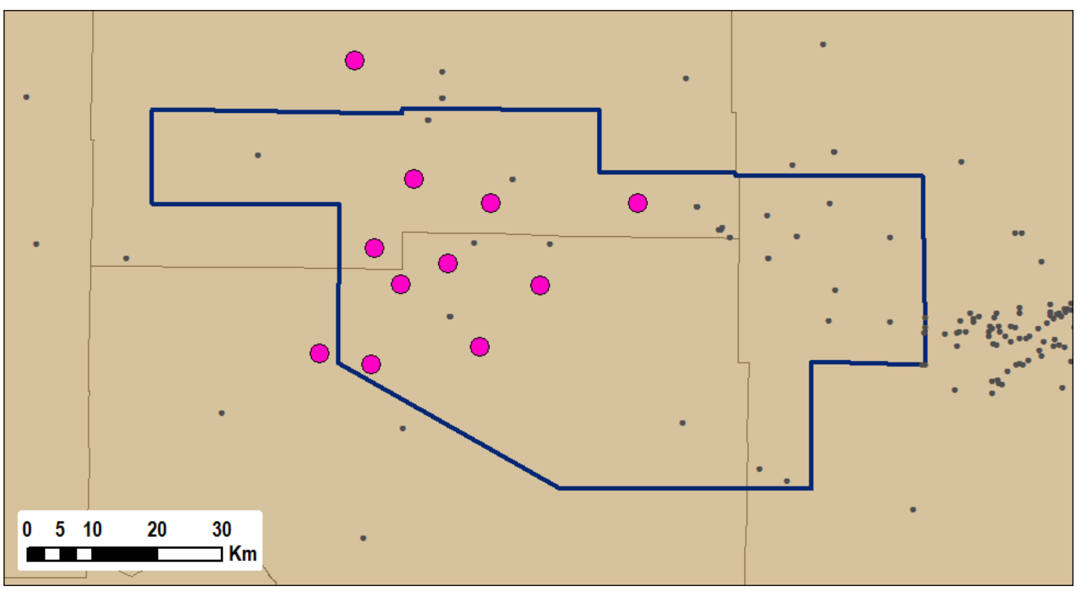

Figure 25. Map showing location of NE intermediate till subgroup in AngloGold Ashanti area of interest.

4.0 References

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