Chromite and tourmaline chemical composition as a guide to mineral exploration

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  – Introduction
  – Methodology
  – Comparison between all lithology types
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  – Conclusions

• Part 2 – Tourmaline
  – Introduction
  – Methodology
  – Discussion by ore deposit types
  – Discussion by age
  – Discussion by metamorphic facies
  – Conclusions
Use of chromite composition for...

- Define the geological context?
- Recognize the mineralized zones?
Methodology

• Chromite group mineral database - 26,000 chemical analyses (Barnes et Roeder, 2002)

• Division by geological environment
  - Lithology and tectonic context
  - Metamorphic grade

• Division mineralized/barren
Lithology and tectonic context

- Xenoliths
  - Ophiolites, Oceanic and ‘Alpine’-type peridotites
  - Layered mafic complexes
  - ‘Alaska’-type ultramafic complexes
  - Tholeiitic basalts and boninites
  - Kimberlites, Alkaline rocks and lamprophyres
  - Komatiites

Barren
Mineralized
Note: “mineralized” includes any mineralization type (chromite, nickel, gold, PGE)
Metamorphic facies

- Greenschists
- Amphibolites
- Granulites/ eclogites
Chromite

A solid solution

Iron
magnesio-ferrite, magnetite, franklinite, jacobsite, trevotite

Chrome
magnesio-chromite, mangano-chromite, nichromite, cochromite, zinchromite

Aluminium
spinel, hercynite, gahnite

- Chemical formula: $XY_2O_4$
  $X = (Fe^{2+}, Mg, Ni, Mn, Co, Zn)$
  $Y = (Cr^{3+}, Fe^{3+}, Al, Ti, V)$

- Ideal chemical composition:
  $Cr = 46.46 \%$; $Fe = 24.95 \%$; $O = 28.59 \%$
  $Cr_2O_3 = 67.90 \%$; $FeO = 32.10 \%$
Factors that influence chromite composition

- Temperature
- Fractional crystallization
- Oxygen fugacity
- Simultaneous Fe-Mg-Al silicate crystallization

► Cr/(Cr+Al) ratio is controlled by pressure and crystallization processes
► Fe^{3+}/(Cr+Al+Fe^{3+}) vs. Mg/(Mg+Fe^{2+}) depends on oxygen fugacity
► Mg/(Mg+Fe^{2+}) ratio is controlled by temperature
Chromite replacement

Magnetite veinlets

Chromite partial replacement by magnetite

Chromite complete replacement by magnetite

Magnetite with chromite core

Ilmenite exsolution in chromite
Significant variability for barren rocks (Fe$_2$O$_3$ vs Cr$_2$O$_3$, Y-site)

**Diagram:**
- **Axes:** Fe$_2$O$_3$ (y-axis) vs Cr$_2$O$_3$ (x-axis)
- **Legend:**
  - Alaska-type complexes
  - Kimberlites
  - Layered complexes
  - Komatiites
  - Ophiolites

**Notation:**
- Magnetite – ideal composition
- Chromite – ideal composition
Less variability for mineralized rocks
($\text{Fe}_2\text{O}_3$ vs $\text{Cr}_2\text{O}_3$, Y-site)
Barren rocks
(Al$_2$O$_3$ vs Cr$_2$O$_3$, Y-site)

Spinel, hercynite, gahnite
Mineralized rocks \((\text{Al}_2\text{O}_3 \text{ vs } \text{Cr}_2\text{O}_3, \text{Y-site})\)
Barren rocks (MgO vs FeO, X-site)

Magnesio-chromite

- Alaska-type complexes
- Kimberlites
- Layered complexes
- Komatiites
- Ophiolites
Mineralized rocks
(MgO vs FeO, X-site)

Magnesio-chromite
Mineralized rocks (Cr$_2$O$_3$ vs TiO$_2$, Y-site and FeO vs MnO, X-site)

- Kimberlites: Cr$_2$O$_3$ ▲
- Komatiites: variable Cr$_2$O$_3$
- Ophiolites: variable Cr$_2$O$_3$, TiO$_2$
- Layered complexes: variable Cr$_2$O$_3$, TiO$_2$

- Kimberlites: FeO ▼
- Komatiites: FeO ▲; variable MnO
- Ophiolites: FeO ▼, variable MnO
- Layered complexes: variable FeO, MnO
Mineralized rocks
(Y vs X cation ratios)

- Komatiites: Cr and Fe$^{2+}$-rich, Al and Mg-poor
- Kimberlites: Cr and Mg-rich, Al, Fe$^{2+}$ and Fe$^{3+}$-poor
- Ophiolites: moderately Mg-rich, Fe$^{3+}$-poor, variable Cr and Al
- Layered complexes: Fe$^{3+}$-poor, variable Cr, Al, and Mg
- ‘Alaska’-type: moderately Cr-rich, variable Al, Fe$^{2+}$ and Mg
Geological environments

- Kimberlites
- Komatiites
- Ophiolites, peridotites
- Layered mafic complexes
- ‘Alaska’-type complexes
Mineralized and barren kimberlites
(Fe₂O₃ vs Cr₂O₃, Y-site)

Gradual transition between chromite and magnetite

Low Fe₂O₃
Mineralized and barren kimberlites (FeO vs MgO, X-site)
Kimberlites

- Low Fe$_2$O$_3$ content
- Chromite composition very close to ideal composition
Kimberlite

- **Positive criteria**
  - Low FeO and Fe$_2$O$_3$ content in chromite
  - Magnetite borders
  - Chromite close to ideal composition

- **Negative criteria**
  - Cr$_2$O$_3$ replacement by Fe$_2$O$_3$
Geological environments

- Kimberlites
- Komatiites
- Ophiolites, peridotites
- Layered mafic complexes
- ‘Alaska’-type complexes
Komatiites (Fe$_2$O$_3$ vs Cr$_2$O$_3$, Y-site)

Chromite substitution by magnetite (metamorphism ?)
Barren komatiites (FeO vs MgO, X-site)

MgO between 0% and 17%
Mineralized komatiites
(FeO vs MgO, X-site)

MgO < 5%
Metamorphic komatiites
(Fe$_2$O$_3$ vs Cr$_2$O$_3$, Y-site)

Very good correlation for amphibolite facies
Relatively good correlation for greenschist facies
Lack of correlation for granulite and eclogite facies
Al content in the greenschist facies is higher in respect to amphibolite, granulite and eclogite facies

Cr content is very low in the granulite-eclogites facies in respect to amphibolite and greenschist facies
Three tendencies:

**Greenschist**: regular $\text{Fe}^{2+}$ replacement by Mg

**Amphibolite**: decrease in Mg and $\text{Fe}^{2+}$ contents (other chemical elements are involved)

**Granulite – eclogite**: increase in Mg and $\text{Fe}^{2+}$ contents (the only two elements in X-site)
Komatiites

- **Positive criteria**
  - Low MgO contents (<5%)
  - Lack of FeO substitution by MgO

- **Negative criteria**
  - High MgO contents (> 5%)
  - FeO substitution by MgO
Metamorphism effects

- When metamorphic grade increases:
  - $\text{Cr}_2\text{O}_3$ content decreases
  - $\text{Al}_2\text{O}_3$ content decreases

- $\text{Cr}_2\text{O}_3$ frequent replacement by $\text{Fe}_2\text{O}_3$ for the mineralized and barren komatiites probably reflects the metamorphic grade
Geological environments

- Kimberlites
- Komatiites
- Ophiolites, peridotites
- Layered mafic complexes
- ‘Alaska’-type complexes

**OPHIOLOITE SEQUENCE**

- Pillow Basalts: These formations are the result of the rapid cooling of hot, fluid magma that comes into contact with water.
- Sheeted Dyke Complex: Consist of swarms of basaltic dykes, the feeder channels for the overlying pillow basalts.
- Gabbros: Usually banded or layered resulting from the crystallisation in the magma chamber at the base of the crust.
- Peridotites: This section represents the lower part of the mantle and has usually been hydrated to serpentinites.

The diagram illustrates a typical ophiolite sequence based on the ophiolites from Oman, which is where the accompanying photographs were taken. (Photos from: “The Mid-Oceanic Ridges: Mountains below the Sea”, A. Nicolas)
Barren ophiolites, peridotites
\( \text{Fe}_2\text{O}_3 \) vs \( \text{Cr}_2\text{O}_3 \), Y-site

Cr substitution by other elements

\begin{align*}
\text{Fe}_2\text{O}_3 & \quad \text{MAGNETITE} \\
\text{Cr}_2\text{O}_3 & \quad \text{CHROMITE}
\end{align*}
Mineralized ophiolites, peridotites

(MgO vs FeO, X-site)
Ophiolites, peridotites (Cation ratios)

Mineralized \( n = 2272 \)
Barren \( n = 3051 \)

No significant differences between mineralized vs barren ophiolites
Ophiolites, peridotites

• **Positive criteria**
  – Magnesio-chromite presence
  – Chromite substitution by other Al$_2$O$_3$-rich minerals such as spinel, gahnite and hercynite
  – Lack of Cr$_2$O$_3$ replacement by Fe$_2$O$_3$

• **Negative criteria**
  – Cr$_2$O$_3$ replacement by Fe$_2$O$_3$
Geological environments

- Kimberlites
- Komatiites
- Ophiolites, peridotites
- Layered mafic complexes
- ‘Alaska’-type complexes
Layered mafic complexes
(Fe$_2$O$_3$ vs Cr$_2$O$_3$, Y-site)

Significant variability
Two tendencies

To magnetite
To other minerals
Layered mafic complexes

Layered mafic complexes - Barren

Layered mafic complexes - Mineralized

Magnetite/ilmenite-rich borders

Cr\(^{3+}\)-poor

Cr\(^{3+}\)-rich

Mineralized and Barren

Barren
Layered mafic complexes

No significant differences between chromites of mineralized vs barren complexes
Layered mafic complexes

Layered mafic complexes - Barren

Layered mafic complexes - Mineralized

Layered mafic complexes - Mineralized and Barren

Magnetite/ ilmenite-rich borders

Cr$^{3+}$-rich / Fe$^{3+}$-poor

Barren

Mineralized
Most mineralized layered complexes have (Sum X)/32.1 ratios between 0.80 and 0.95, while most barren layered complexes have ratios between 0.90 and 1.05.
Layered mafic complexes

- **Positive**
  - $\text{Cr}_2\text{O}_3$ partial substitution by $\text{Fe}_2\text{O}_3$

- **Negative**
  - $\text{Cr}_2\text{O}_3$ partial substitution by $\text{Al}_2\text{O}_3$
  - Chromite substitution by other minerals such as spinel, gahnite and hercynite
Geological environments

- Kimberlites
- Komatiites
- Ophiolites, peridotites
- Layered mafic complexes
- ‘Alaska-type’ ultramafic complexes
‘Alaska-type’ ultramafic complexes

Chromite partial remplacement by magnetite
‘Alaska-type’ ultramafic complexes

- ‘Alaska-type’ complexes - Barren
  - No significant difference

- ‘Alaska-type’ complexes - Mineralized
  - Fe³⁺-poor, Cr³⁺-rich chromites
  - Al and Cr³⁺-poor chromites

→ No significant difference
‘Alaska-type’ ultramafic complexes

Mineralized: n = 220
Barren: n = 166

Mineralized: Mg and Cr-rich, variable Al, Fe\(^{3+}\) and Ti contents
Barren: Mg-poor, variable Cr, Al, Fe\(^{3+}\) and Ti contents
‘Alaska-type’ ultramafic complexes

• Only few differences between the mineralized and barren complexes

Positive:
- MgO ▲
- FeO ▼

Negative:
- MgO ▼
In brief,

- Chromite chemical composition depends on:
  - Lithology;
  - Metamorphic grade
  - Physicochemical crystallization parameters
  - Chemical composition of initial magma
• Presence or absence of oxide substitution in Y-site;

• \(\text{Fe}^{2+}\) replacement by \(\text{Mg}^{2+}\) in X-site;

• Variation of absolute (e.g. komatiites) or relative (e.g. layered mafic complexes) oxide contents;

• Presence or absence of other minerals than chromite (magnetite, gahnite, spinel, magnesio-chromite);

• Variation of contents normalized to atomic weight
Part 2
Tourmaline
Objectives

• Evaluate tourmaline chemical composition in various contexts:
  • lithologic
  • tectonic
  • metallogenic

• Evaluate tourmaline use as indicator mineral for mineralized environments

• Define tools to aid differentiating between tourmaline of mineralized vs barren host rocks
Methodology

• Compilation of published tourmaline group chemical analyses (by electronic microprobe only)

• Division mineralized/barren

• Tourmaline database divided by:
  – Deposit type
  – Host lithology
  – Metamorphic facies
  – Metallogenic model

Tourmaline group chemical analyses
Structural formulae
Description
References
Tourmaline - Age

Geotime division used in the tourmaline database

- Cenozoic
- Mesozoic
- Paleozoic
- Proterozoic
- Archaean
Tourmaline – Deposit types

- Tourmaline group minerals are found in:
  - hydrothermal deposits associated to granitoids and pegmatites
  - volcanogenic and sedimentary massive sulfide deposits (SMS and VMS)
  - orogenic gold deposits
  - iron formations
  - epithermal, porphyry or Carlin-type deposits
  - placer deposits
Tourmaline – Host lithology and metamorphic facies

Host rocks divided in:
- volcanic
- igneous
- sedimentary
- metamorphic

Metamorphic facies divided in:
- Greenschists
- Greenschists–Amphibolites
- Amphibolites
- Amphibolites–Granulites
- Granulites

Unmetamorphosed
Tourmaline classification

Three main groups:

1. Na-rich tourmaline
2. Ca-rich tourmaline
3. X-site vacant tourmaline
Factors that influence tourmaline composition

- Bore concentration
- Metasomatism
- Petrographic composition of host lithology
- Leach processes of the host lithology
- Temperature
Tourmaline – mineralized vs barren (alkali vs Fe#)

No difference between tourmaline chemical composition associated to mineralized vs barren rocks.
No difference between tourmaline chemical composition associated to mineralized vs barren rocks
Tourmaline – Deposit type

\[ ((\text{FeO} + \text{MgO}) \text{ vs } \text{SiO}_2) \]

- Fe+Mg variability in pegmatites
- Si variability in massive sulfides
- Higher Fe+Mg contents in porphyry and skarn in respect to epithermal
- Similar Fe+Mg and Si contents in orogenic gold, massive sulfides and iron formations
- Good correlation between Mg and Fe# for all deposit types
- Significant variability of pegmatites and massive sulfides
- Three groups can be defined:
  - 1: pegmatites;
  - 2: orogenic gold, massive sulfides, iron formations and epithermal;
  - 3: porphyry and skarn

- Significant variability of pegmatites and massive sulfides

Tourmaline – Deposit type ($\text{FeO}_t$ vs $\text{Al}_2\text{O}_3$)
Tourmaline – Deposit type (Fe-Mg-Ca)

- Significant Fe and Mg variability for orogenic gold and massive sulfides
- Most pegmatites are Fe-rich, while other deposit types have higher Mg contents
- Porphyry/skarn and epithermal show very little chemical variability
- Most tourmalines associated to orogenic gold and iron formations are Ca-poor;
- Higher Ca variability in massive sulfides in respect to other deposits
Tourmaline – Deposit type (FeO_t-MgO-Na_2O)

- Less Na variability for all deposit types, but pegmatites
- Significant Fe and Mg variability for orogenic gold and massive sulfides
Tourmaline – Chemical composition vs Age

Chemical composition doesn’t vary with tourmaline deposition age

High chemical variability of the Mg/(Mg+Al+Fe) ratio applies to all tourmalines, regardless of age
Tourmaline – Chemical composition vs Age

Significant variability of alkali metal ratios

Chemical composition (cations) doesn’t vary with the tourmaline deposition age
Tourmaline – metamorphic facies

Metamorphic facies affects tourmaline alkali metal ratios
Tourmaline – metamorphic facies

MgO vs Fe# correlation

Mg and Fe metal ratios are not affected by metamorphism
Conclusions

Tourmaline chemical composition characteristics that can be used as discrimination criteria

A. Tourmaline associated to orogenic gold and iron formations is Ca-poor;

B. Fe+Mg contents are higher in porphyry and skarns in respect to epithermal deposits

C. Al content:
   porphyry and skarn < orogenic gold, massive sulfides, iron formations and epithermal < pegmatites

D. Metamorphic facies influences the tourmaline alkali ratios
Conclusions

Tourmaline chemical composition characteristics that **cannot be used** as discrimination criteria

- Alkali metal ratios, the Fe# and cation ratios cannot be used to discriminate between tourmaline associated to mineralized vs barren rocks. In the barren rocks, tourmaline composition reflects the chemistry of host rocks rather than that of the mineralizing fluids.

- Tourmaline Fe+Mg and Si contents cannot discriminate between orogenic gold, massive sulfides and iron formations.
  - High variability of Fe et Mg contents of orogenic gold and massive sulfides
  - No evident relationship between tourmaline chemical composition and the deposition age.
Thank you