Chromite and tourmaline chemical composition as a guide to mineral exploration

Gabriel Voicu

Université du Québec à Montréal, Canada

and

Cambior Management Services

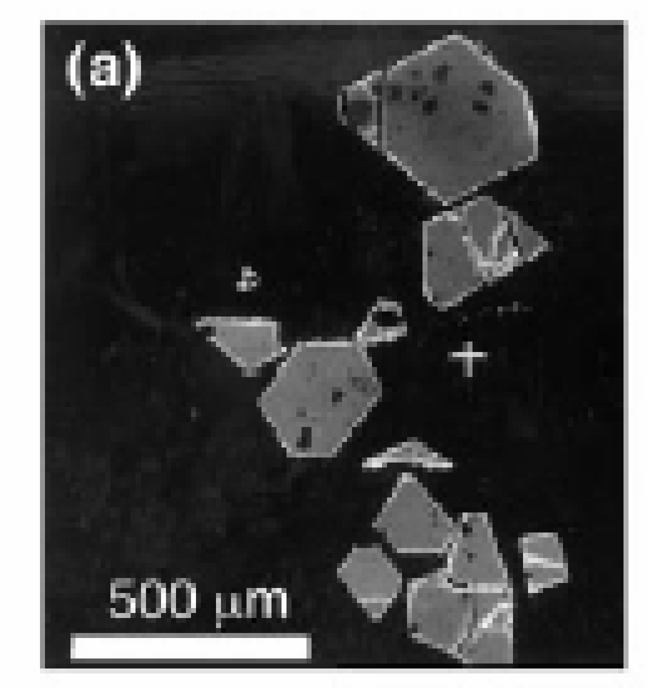
Content of presentation

- **Part 1 – Chromite**
  - Introduction
  - Methodology
  - Comparison between all lithology types
  - Discussion for each lithology type
  - Conclusions
- **Part 2 – Tourmaline**
  - Introduction
  - Methodology
  - Discussion by ore deposit types
  - Discussion by age
  - Discussion by metamorphic facies
  - Conclusions

PART 1
CHROMITE

Use of chromite composition for…

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

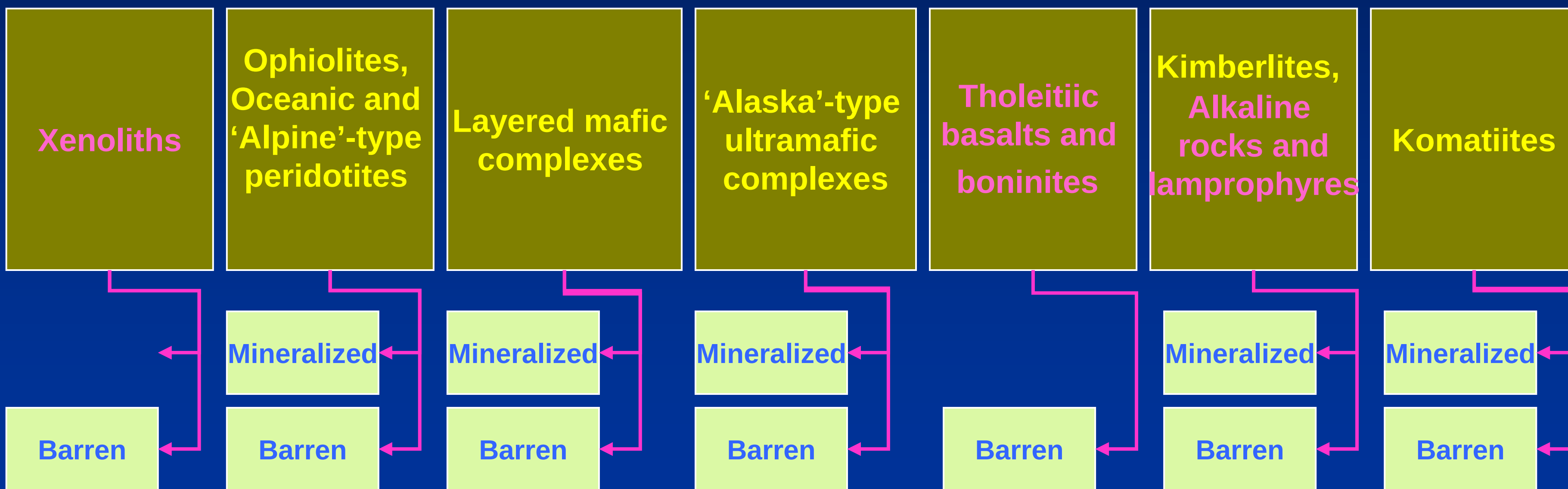


Methodology

Chromite chemical analyses:
SiO2, TiO2, V2O3, Al2O3,
Cr2O3, Fe2O3, FeO, MnO,
MgO, CaO, Na2O, K2O,
ZnO, NiO
Cationic formula
Description
References

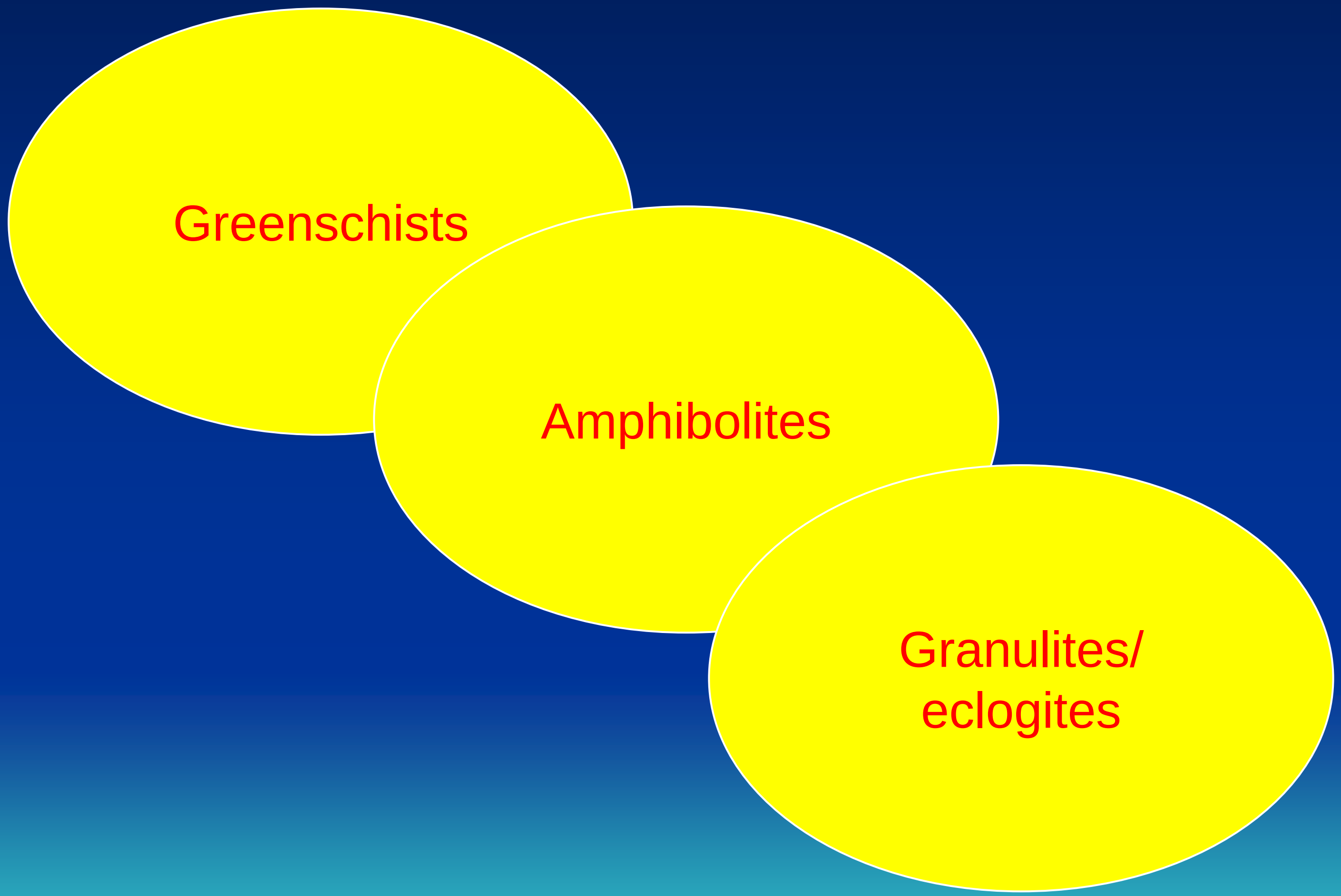
- Chromite group mineral database - 26,000 chemical analyses (Barnes et Roeder, 2002)
- Division by geological environment
    - Lithology and tectonic context
    - Metamorphic grade
- Division mineralized/barren

Lithology and tectonic context



Note: "mineralized" includes any mineralization type (chromite, nickel, gold, PGE)

Metamorphic facies



Chromite

A solid solution

Iron

magnesio-ferrite, magnetite, franklinite, jacobsite, trevotite

- **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 %

Chrome

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

Aluminium

spinel, hercynite, gahnite

Factors that influence chromite composition

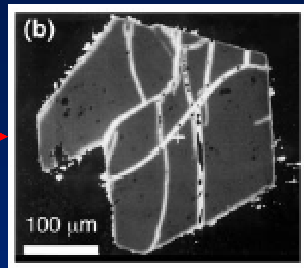
- Temperature
- Fractional crystallization
- Oxygen fugacity
- Simultaneous Fe-Mg-Al silicate crystallization

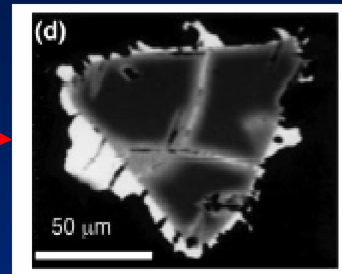
► $Cr/(Cr+Al)$ ratio is controlled by pressure and crystallization processes

► $Fe^{3+}/(Cr+Al+Fe^{3+})$ vs. $Mg/(Mg+Fe^{2+})$ depends on oxygen fugacity

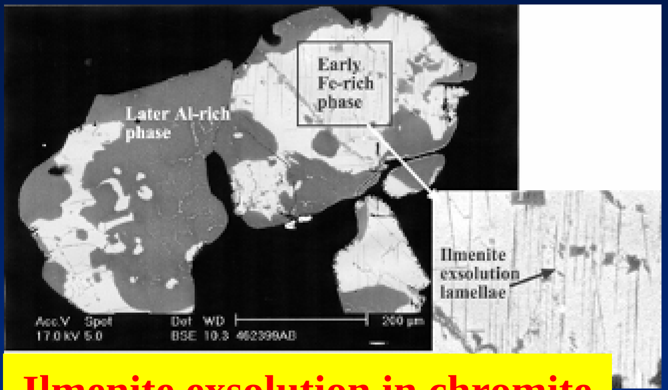
► $Mg/(Mg+Fe^{2+})$ ratio is controlled by temperature

Chromite replacement

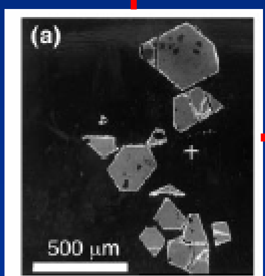




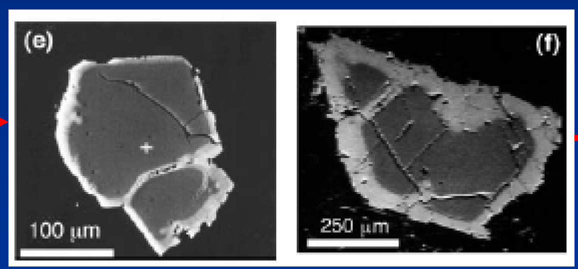
Magnetite veinlets



Ilmenite exsolution in chromite

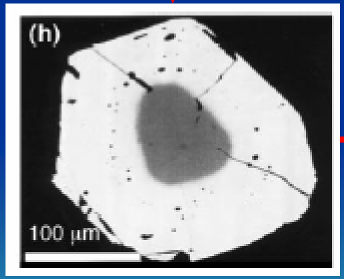


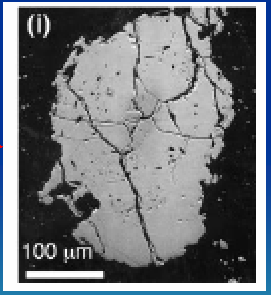
Chromite



Chromite partial replacement by magnetite

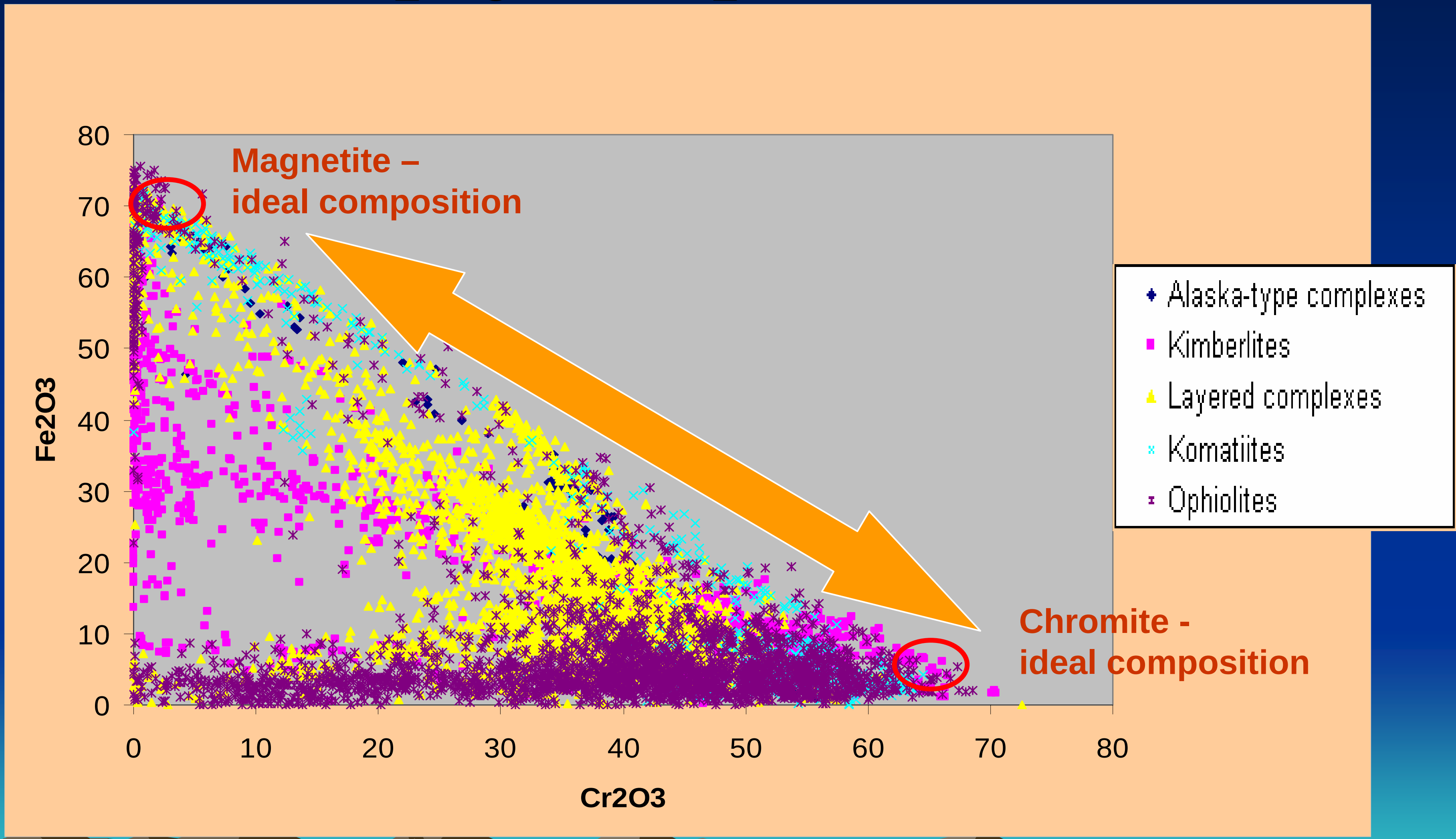
Chromite complete replacement by magnetite



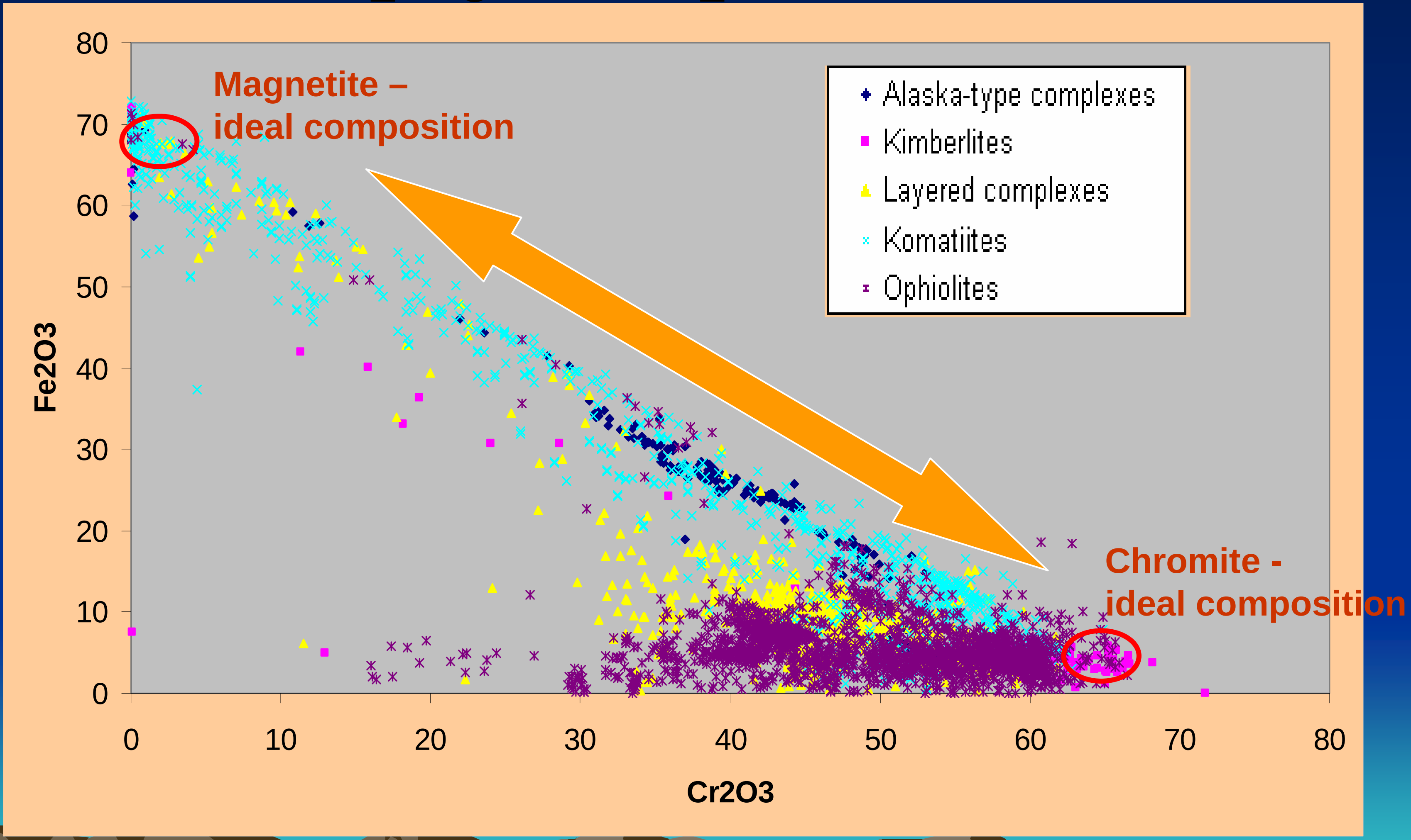


Magnetite with chromite core

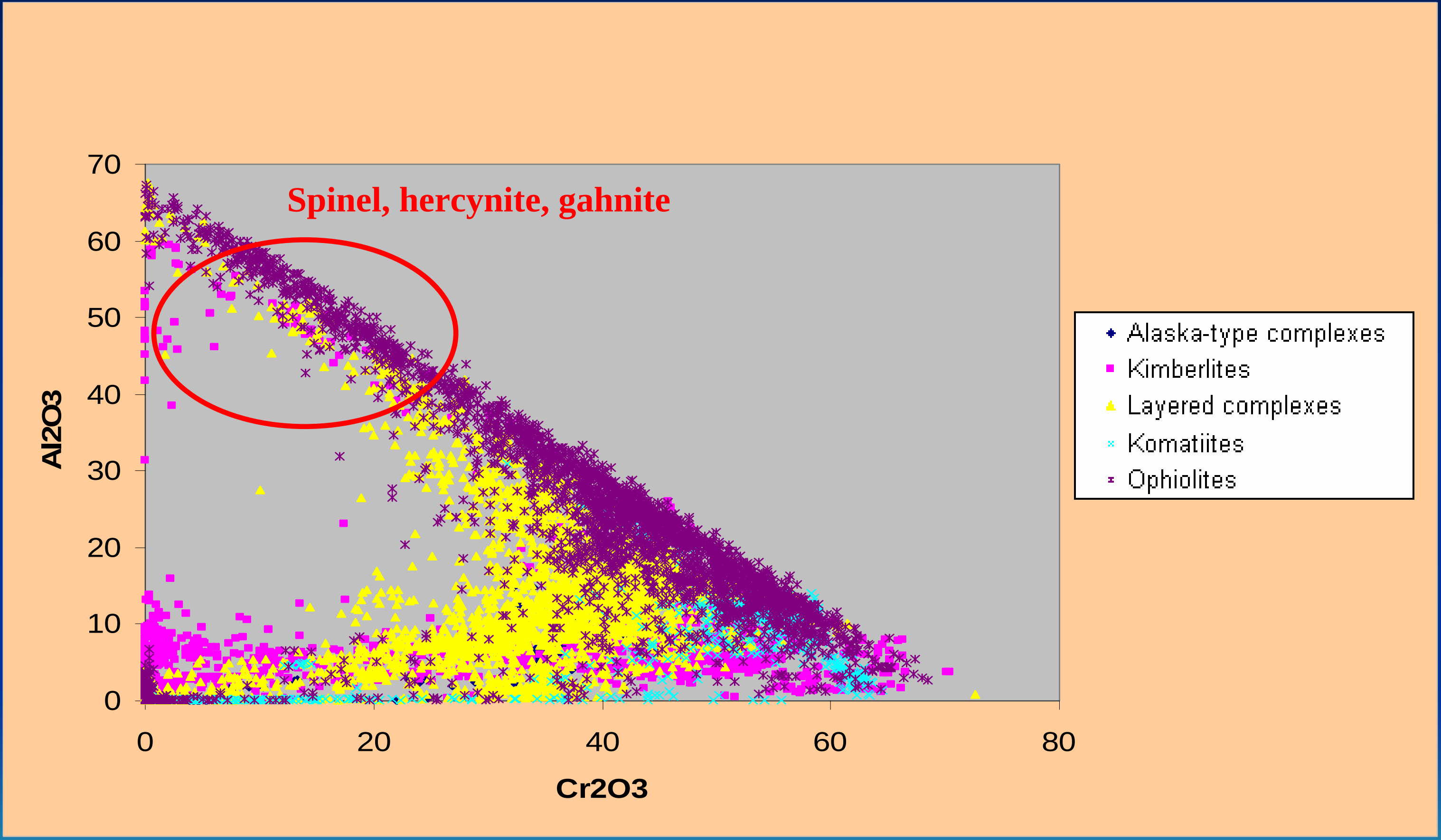
Significant variability for barren rocks (Fe_2O_3 *vs* Cr_2O3, Y-site)



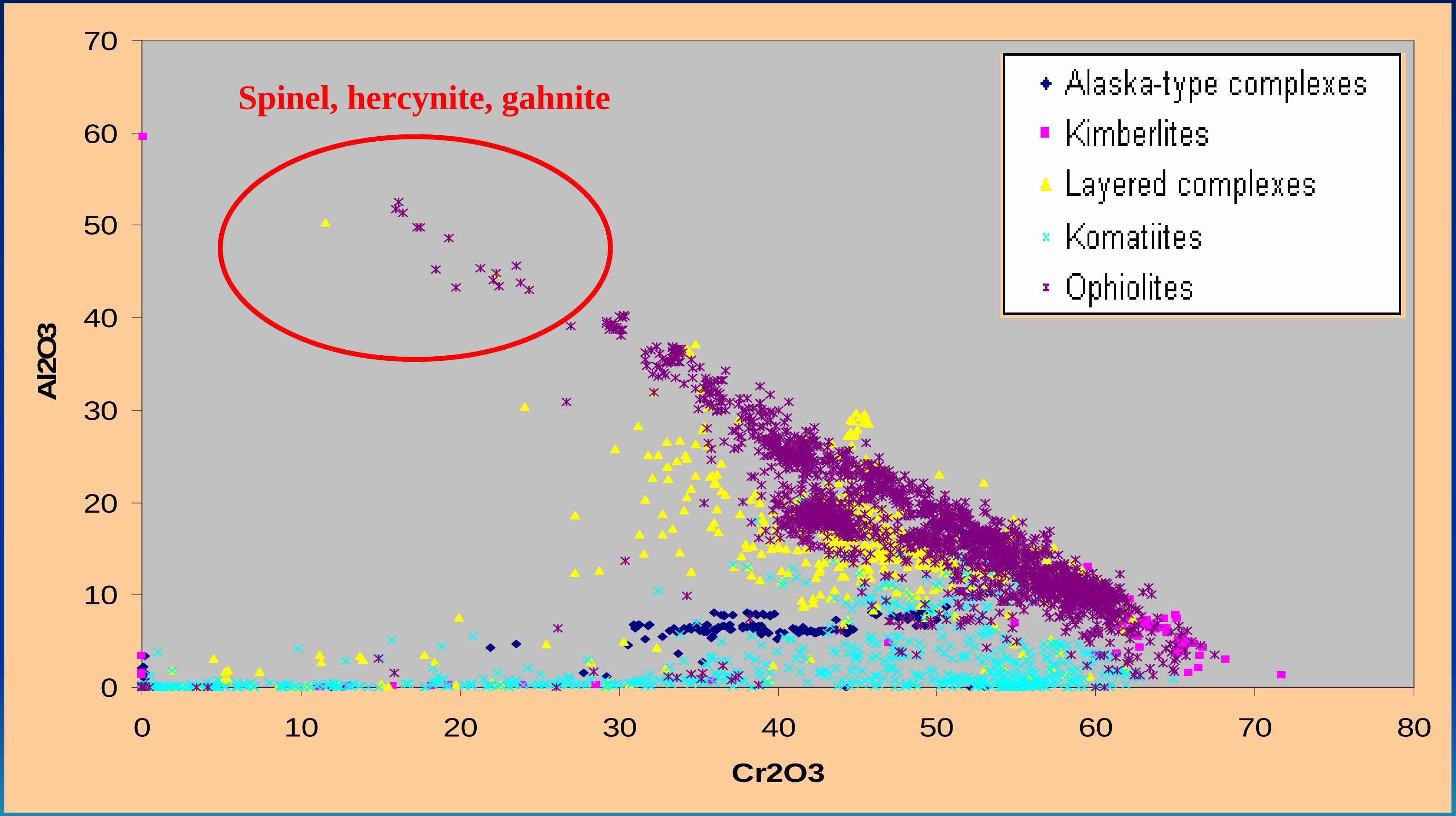
Less variability for mineralized rocks (Fe_2O_3 *vs* Cr_2O3, Y-site)



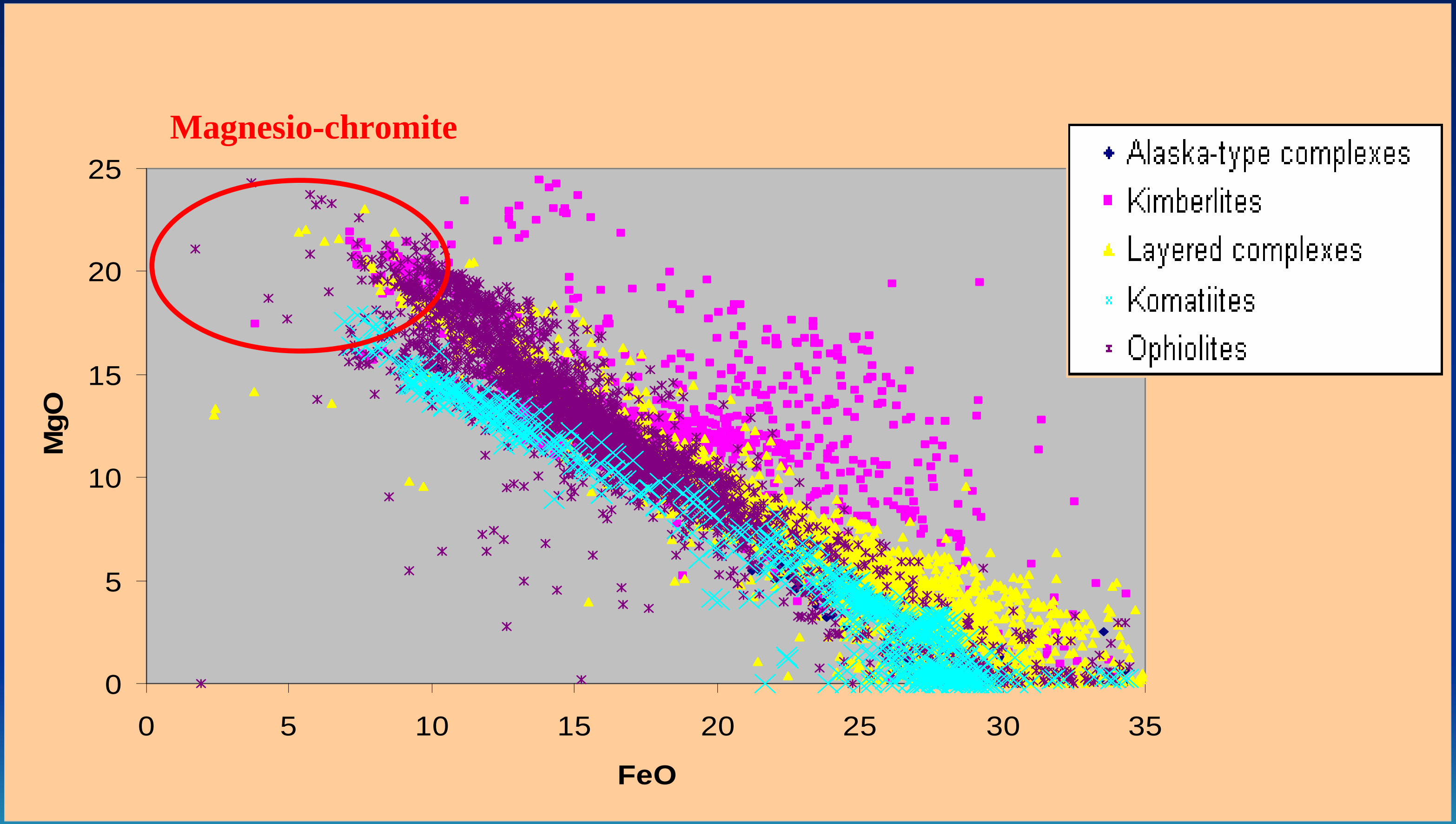
Barren rocks
(Al_2O_3 *vs* Cr_2O_3, Y-site)



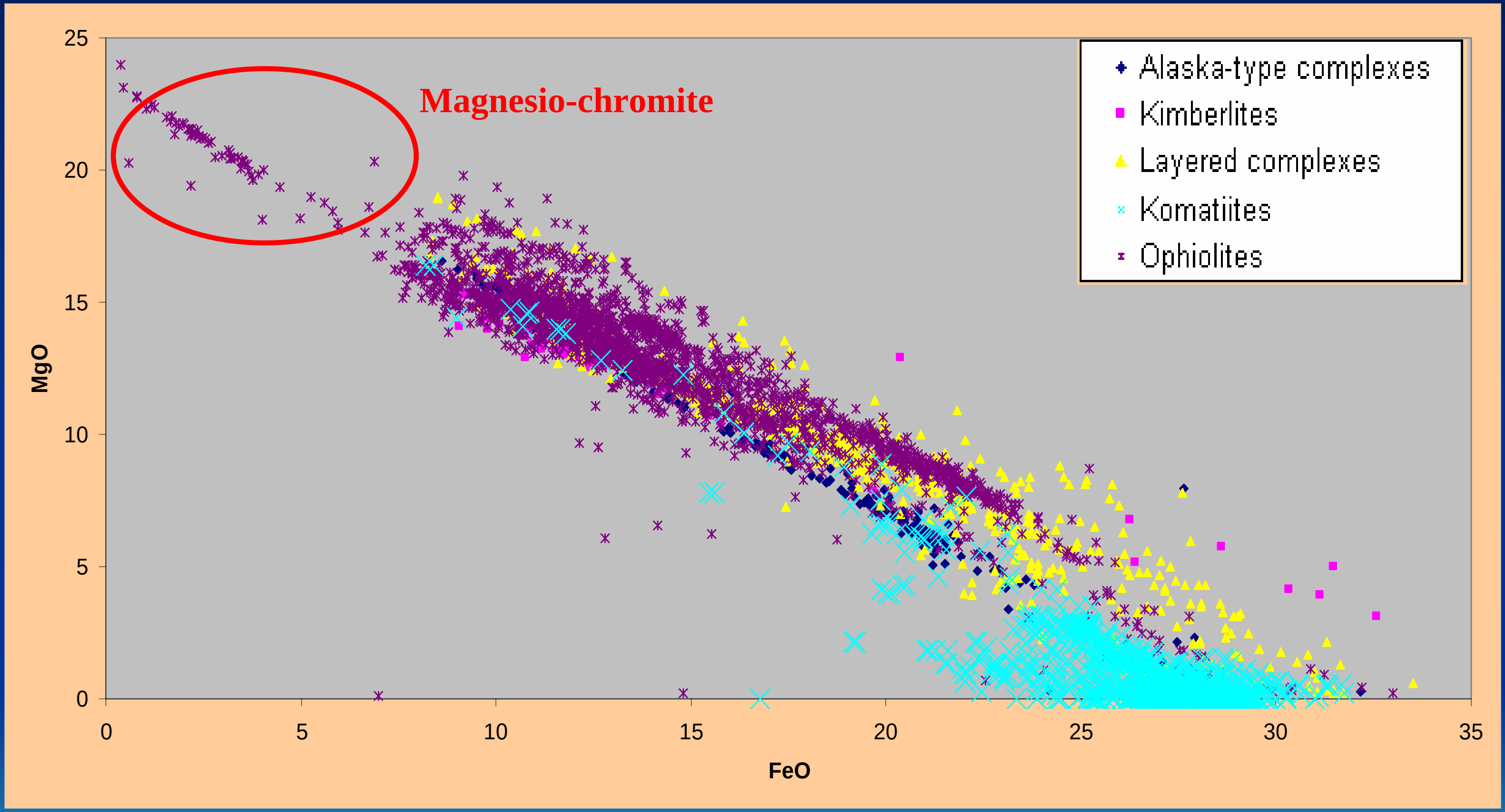
Mineralized rocks (Al_2O_3 *vs* Cr_2O3, Y-site)



Barren rocks (MgO *vs* FeO, X-site)



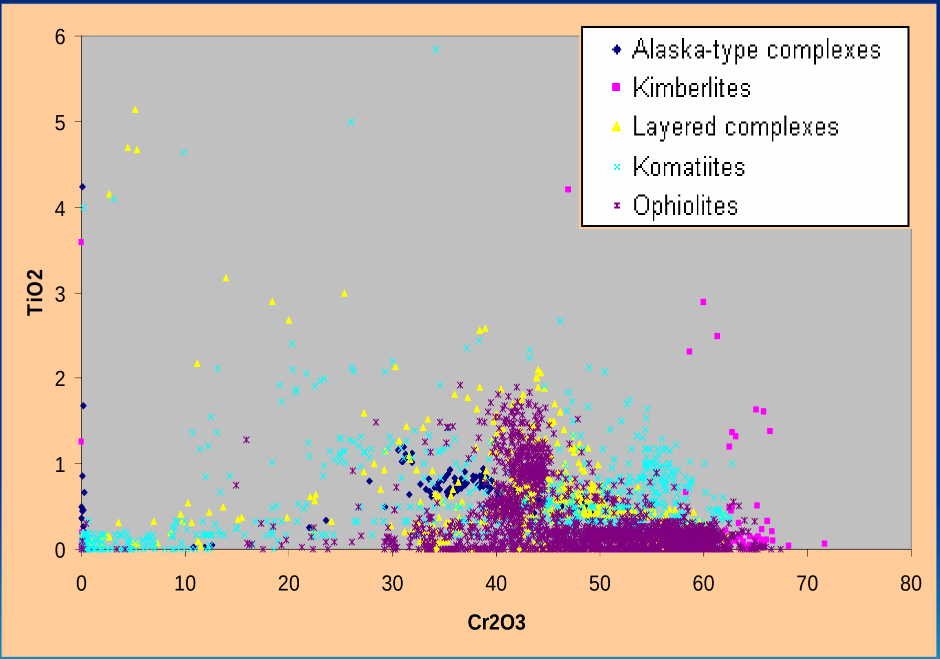
Mineralized rocks (MgO *vs* FeO, X-site)

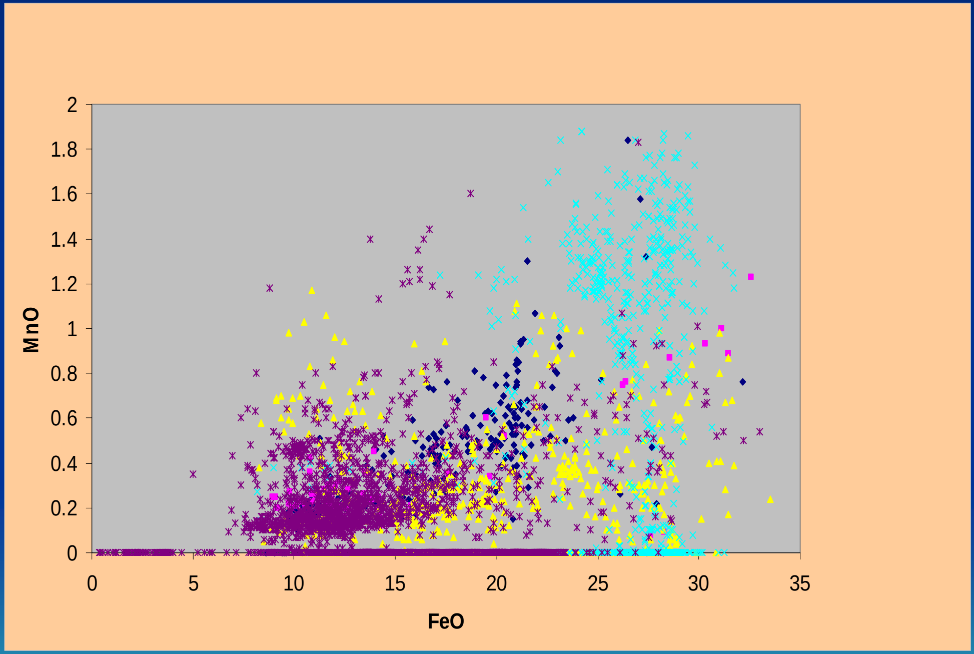


Mineralized rocks (Cr_2O_3 *vs* TiO_2, Y-site and FeO *vs* MnO, X-site)

- Kimberlites: Cr_2O_3▲
- Komatiites: variable Cr_2O_3
- Ophiolites: variable Cr_2O_3, TiO_2
- Layered complexes: variable Cr_2O_3, TiO_2

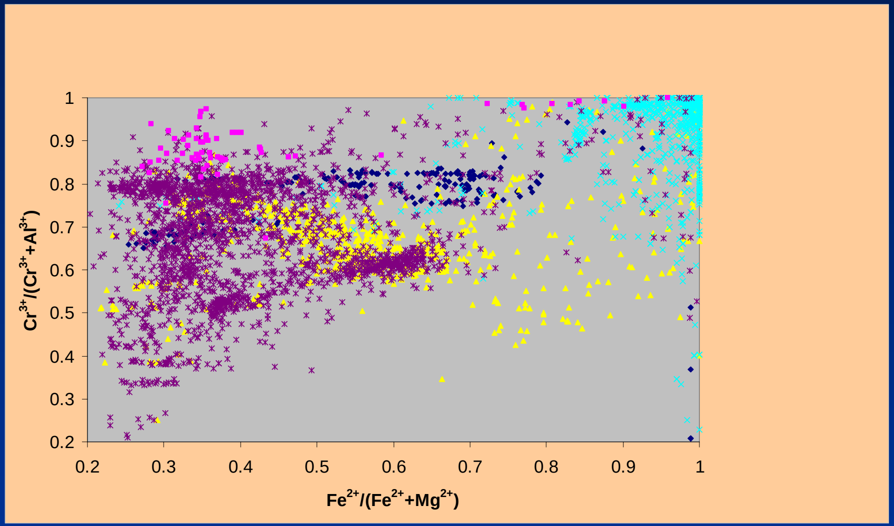
- Kimberlites: FeO▼
- Komatiites: FeO ▲; variable MnO
- Ophiolites: FeO ▼, variable MnO
- Layered complexes: variable FeO, MnO

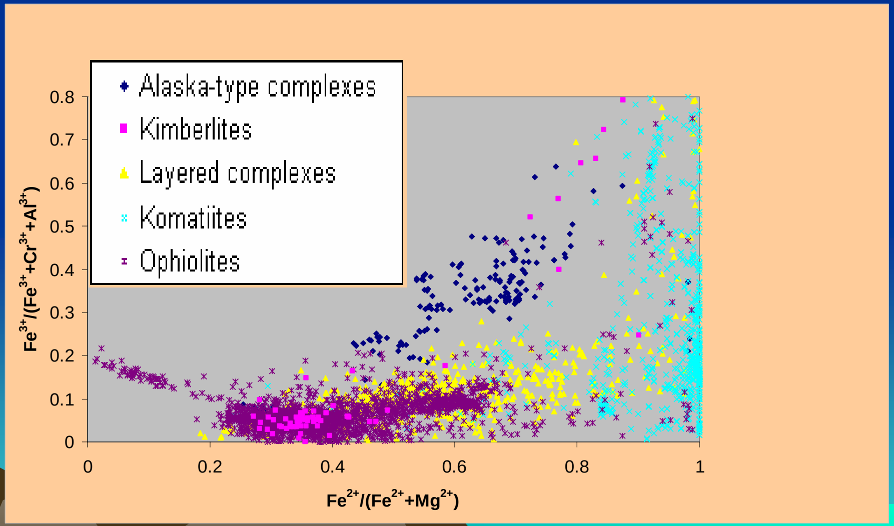




Mineralized rocks (Y *vs* X cation ratios)

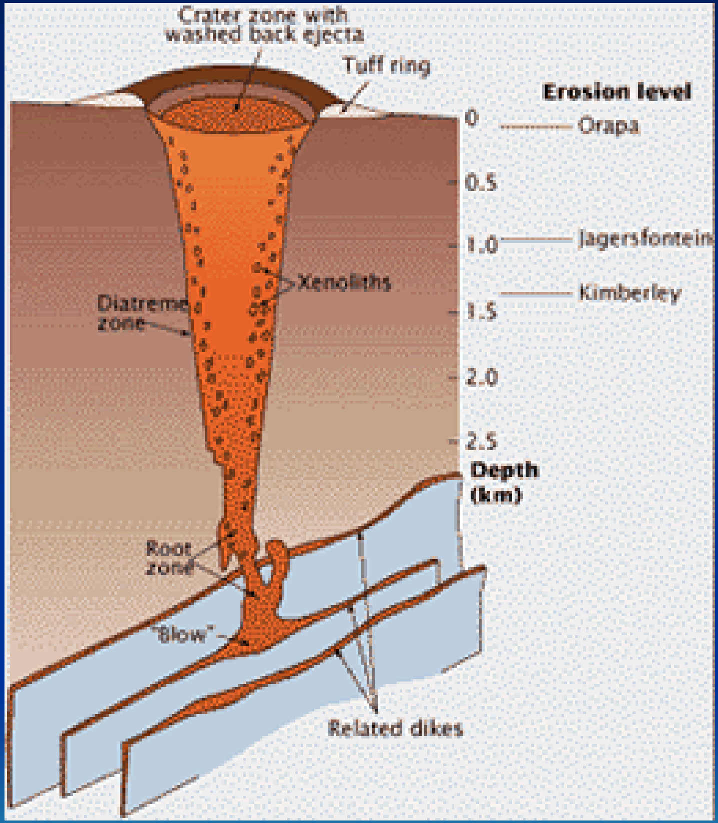
- **Komatiites: Cr and Fe^{2+}-rich, Al and Mg-poor**
- **Kimberlites: Cr and Mg-rich, Al, Fe^{2+} and Fe^{3+}-poor**
- **Ophiolites: moderately Mg-rich, Fe^{3+}-poor, variable Cr and Al**
- **Layered complexes: Fe^{3+}-poor, variable Cr, Al, and Mg**
- **'Alaska'-type: moderately Cr-rich, variable Al, Fe^{2+} and Mg**



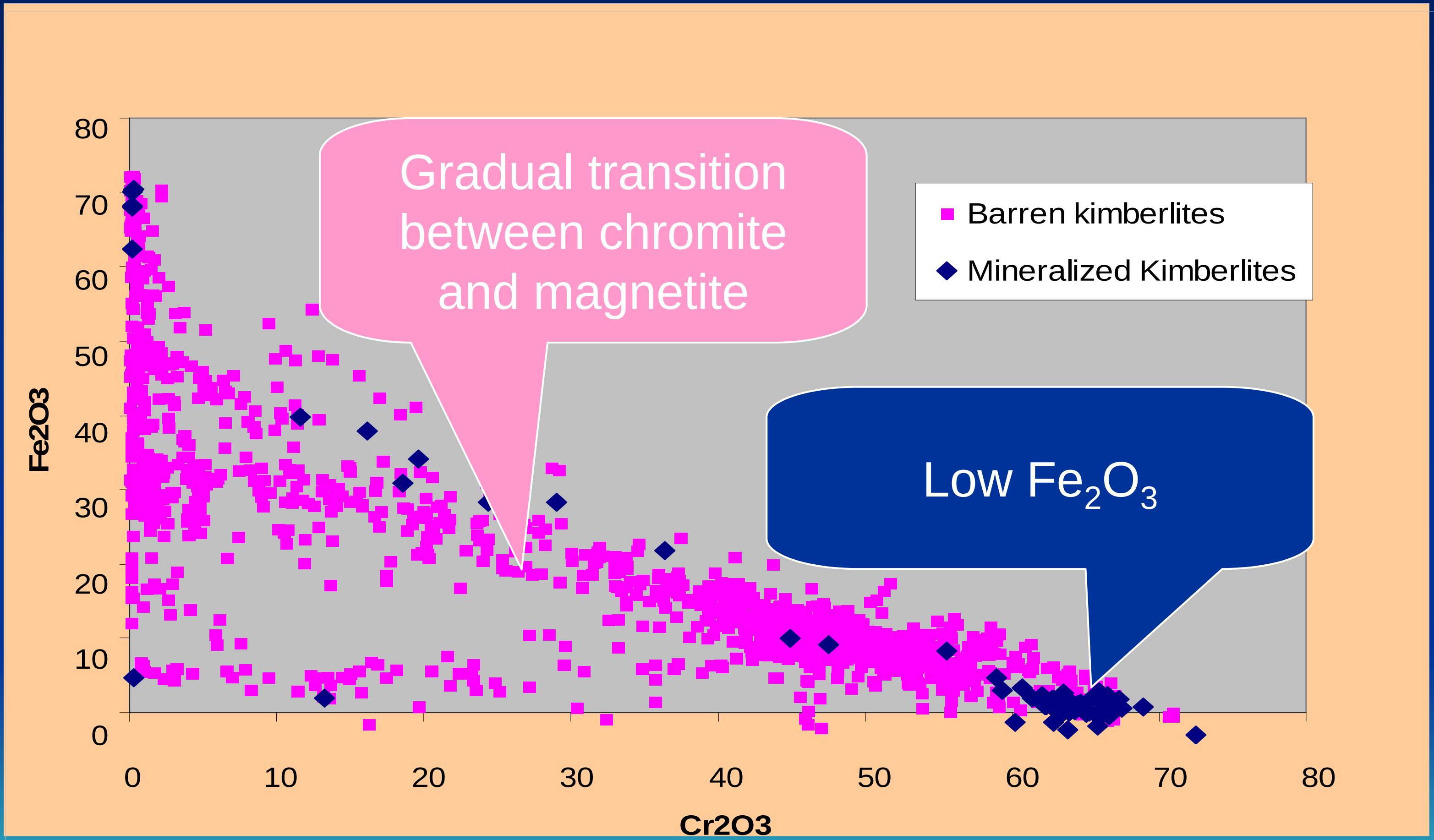


Geological environments

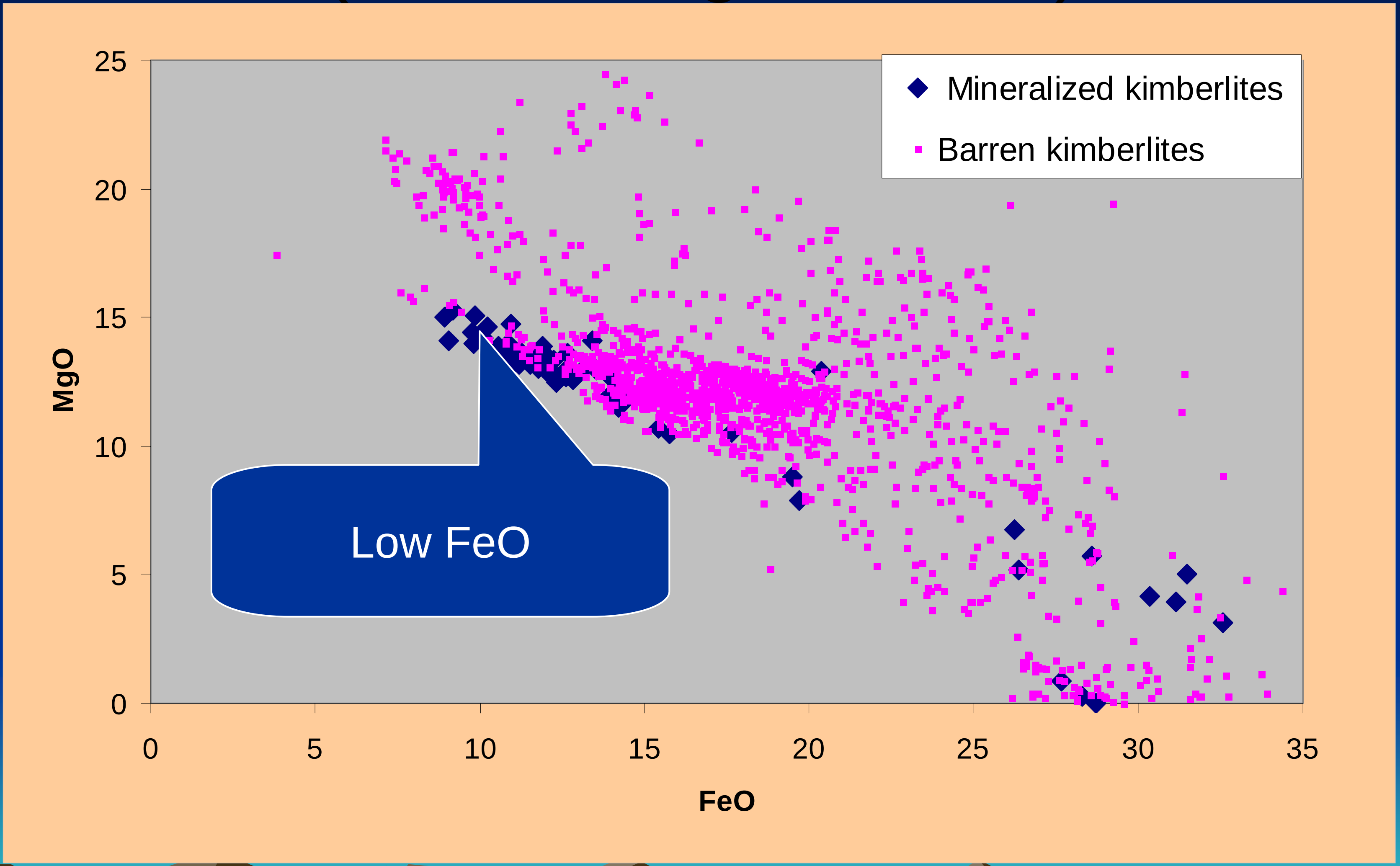
- Kimberlites
- Komatiites
- Ophiolites, peridotites
- Layered mafic complexes
- ‘Alaska’-type complexes



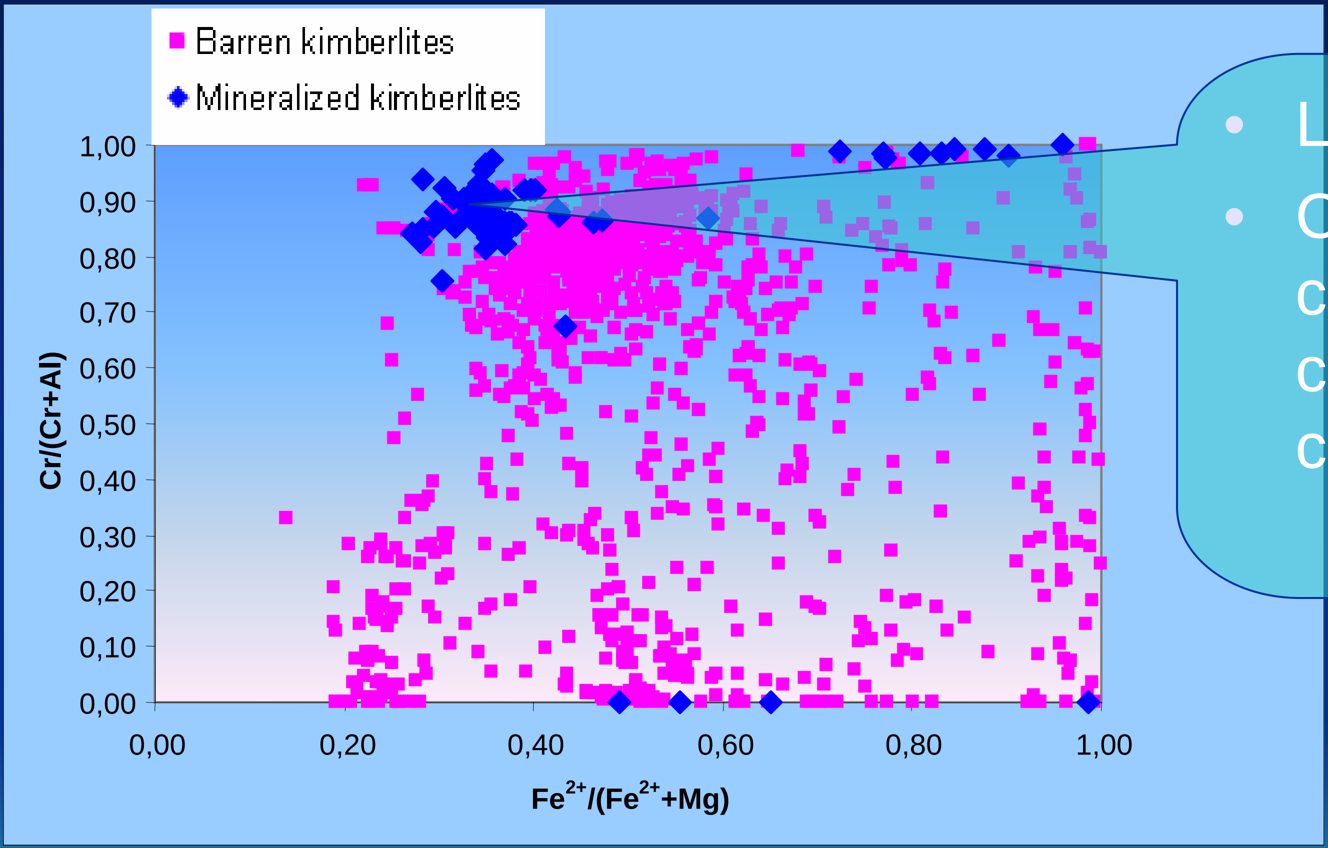
Mineralized and barren kimberlites
(Fe_2O_3 *vs* Cr_2O3, Y-site)



Mineralized and barren kimberlites (FeO *vs* MgO, X-site)



Kimberlites



- Low Fe_2O_3 content
- Chromite composition very close to ideal composition

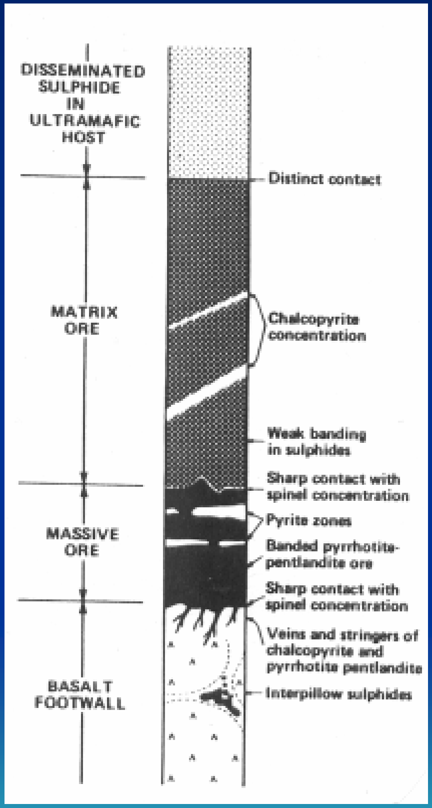
Kimberlite

- **Positive criteria**
  - **Low FeO and Fe_2O_3 content in chromite**
  - **Magnetite borders**
  - **Chromite close to ideal composition**

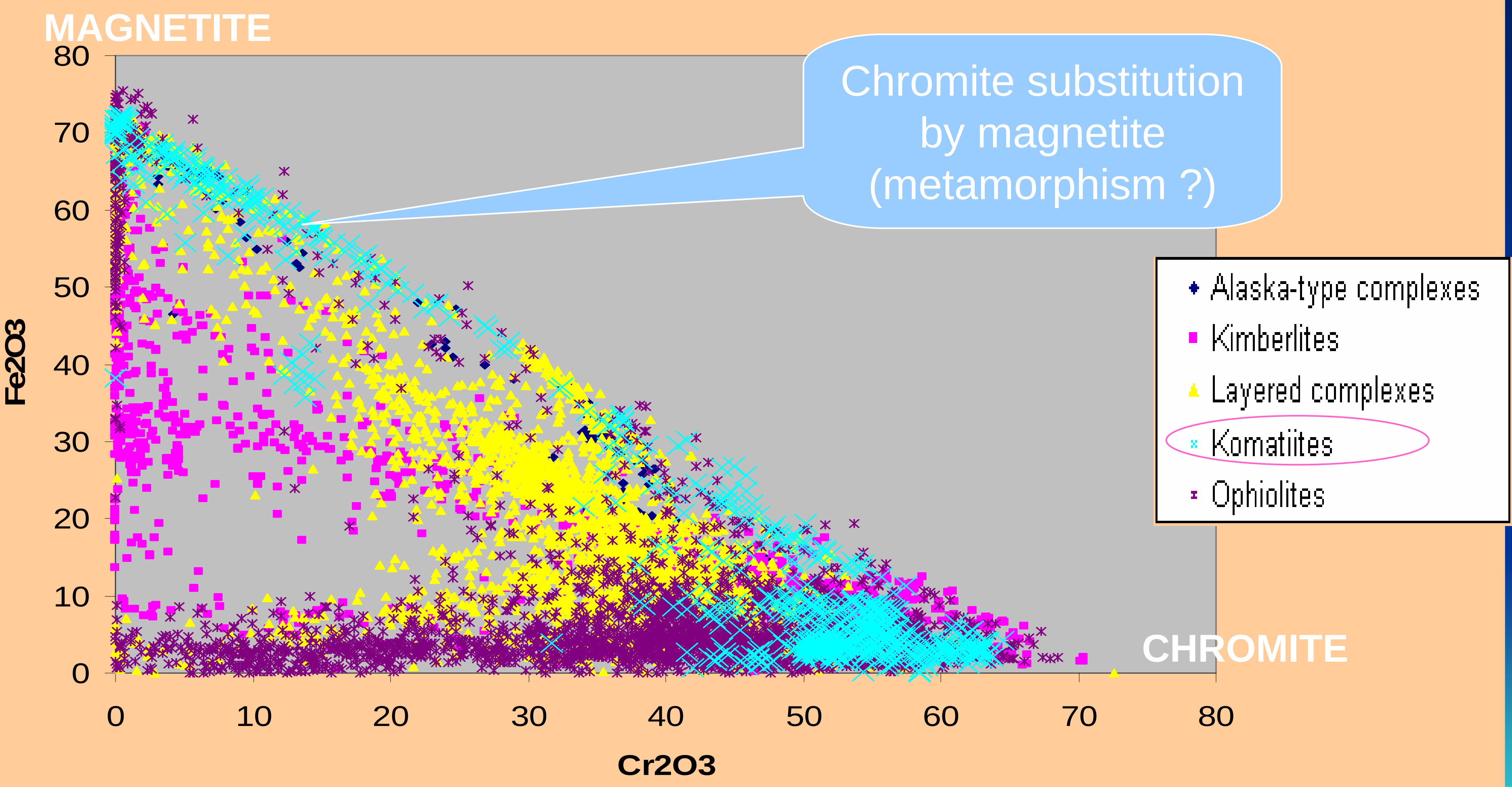
- **Negative criteria**
  - **Cr_2O_3 replacement by Fe_2O_3**

Geological environments

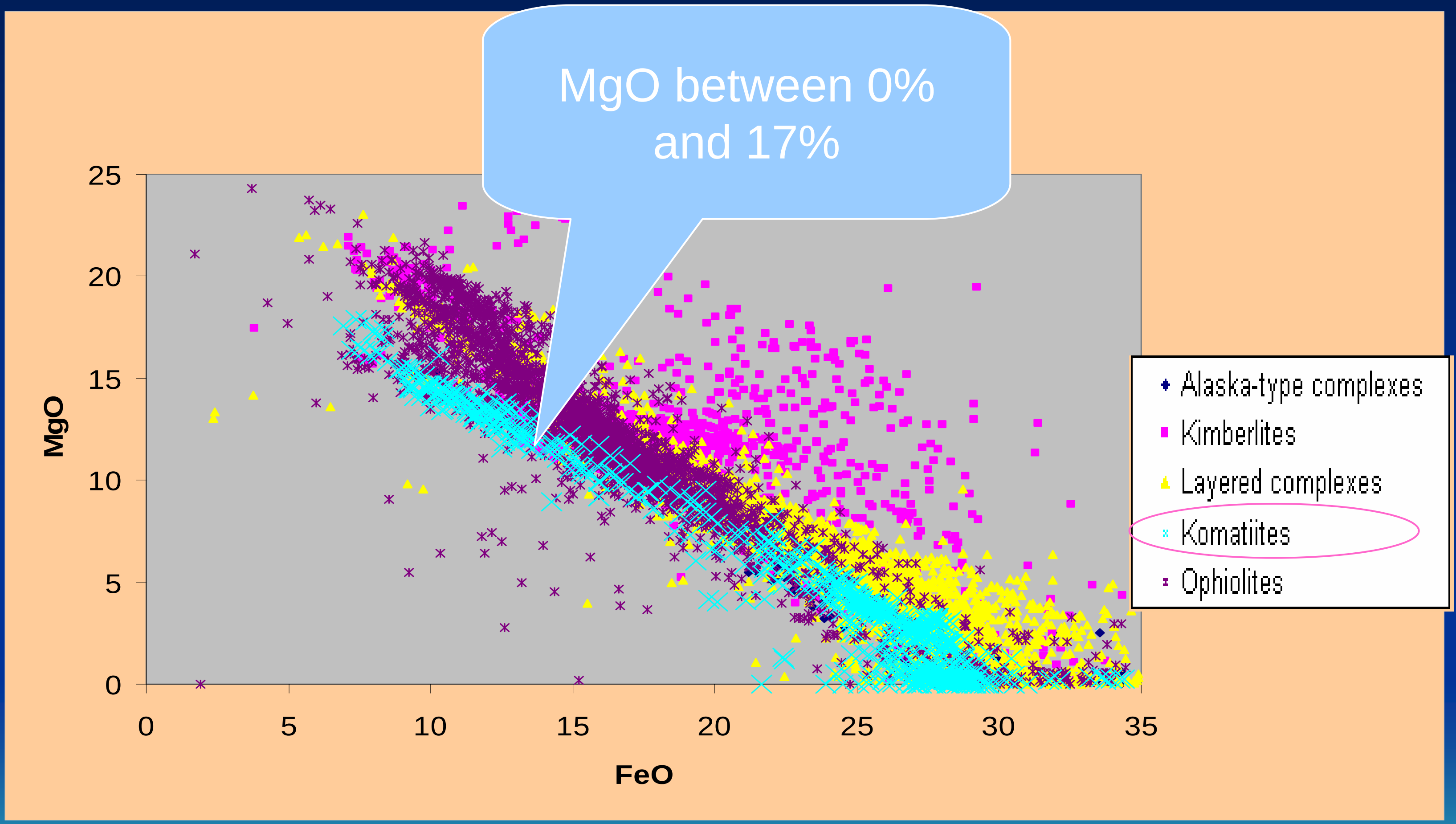
- Kimberlites
- Komatiites
- Ophiolites, peridotites
- Layered mafic complexes
- ‘Alaska’-type complexes



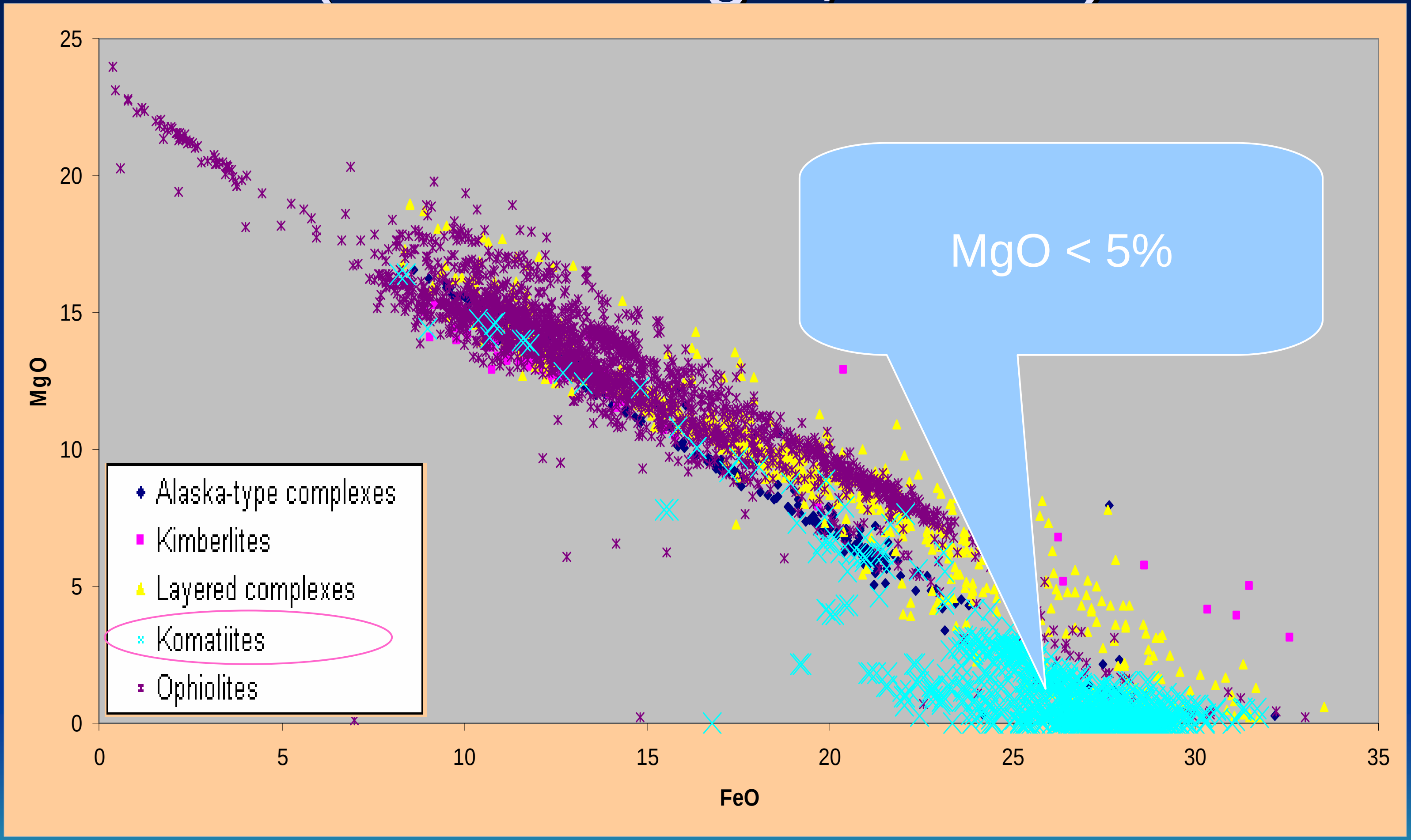
Komatiites (Fe_2O_3 *vs* Cr_2O3, Y-site)



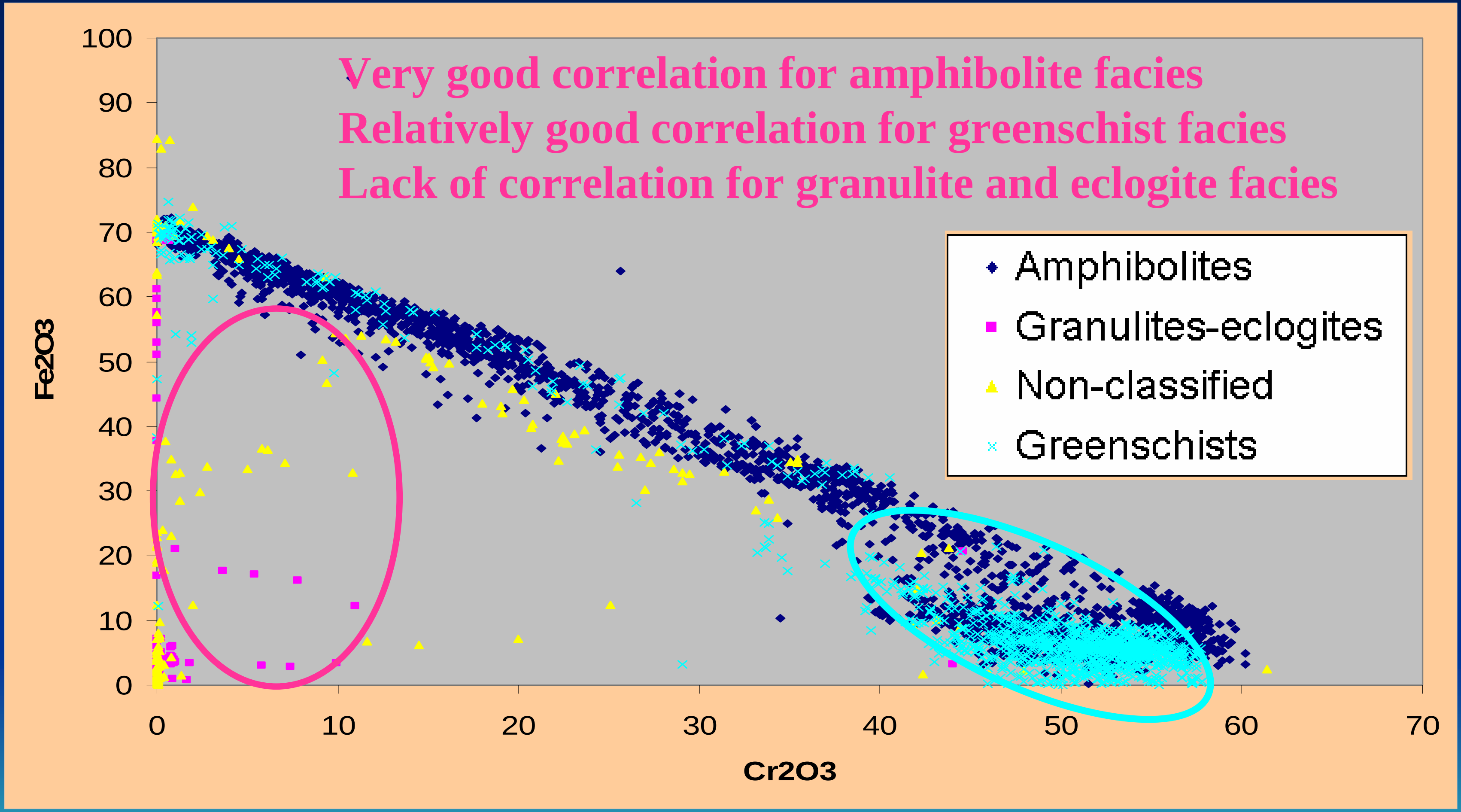
Barren komatiites (FeO *vs* MgO, X-site)



Mineralized komatiites (FeO *vs* MgO, X-site)



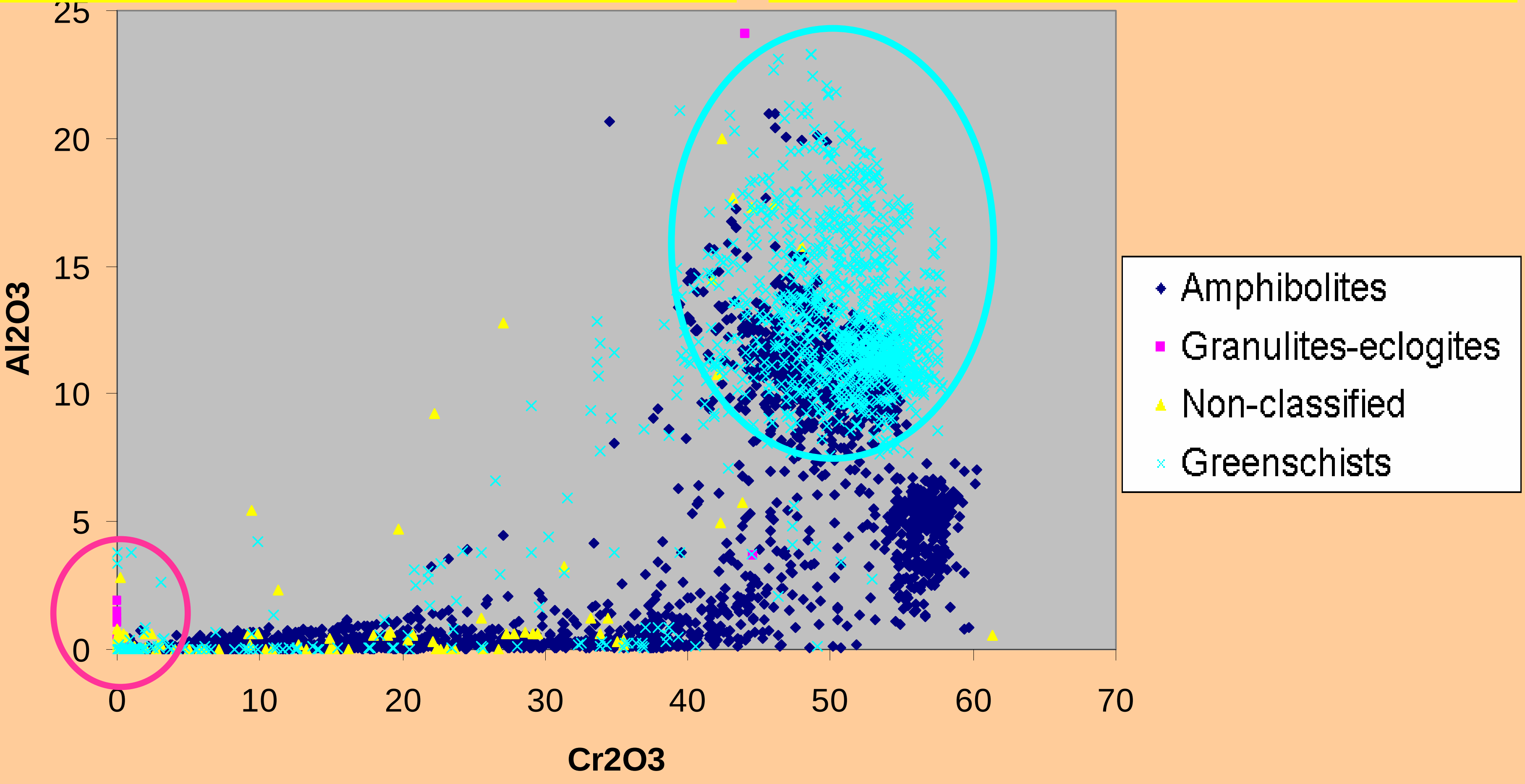
Metamorphic komatiites (Fe$_2$O$_3$ *vs* Cr$_2$O3, Y-site)



Metamorphic komatiites (Al_2O_3 *vs* Cr_2O3, Y-site)

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



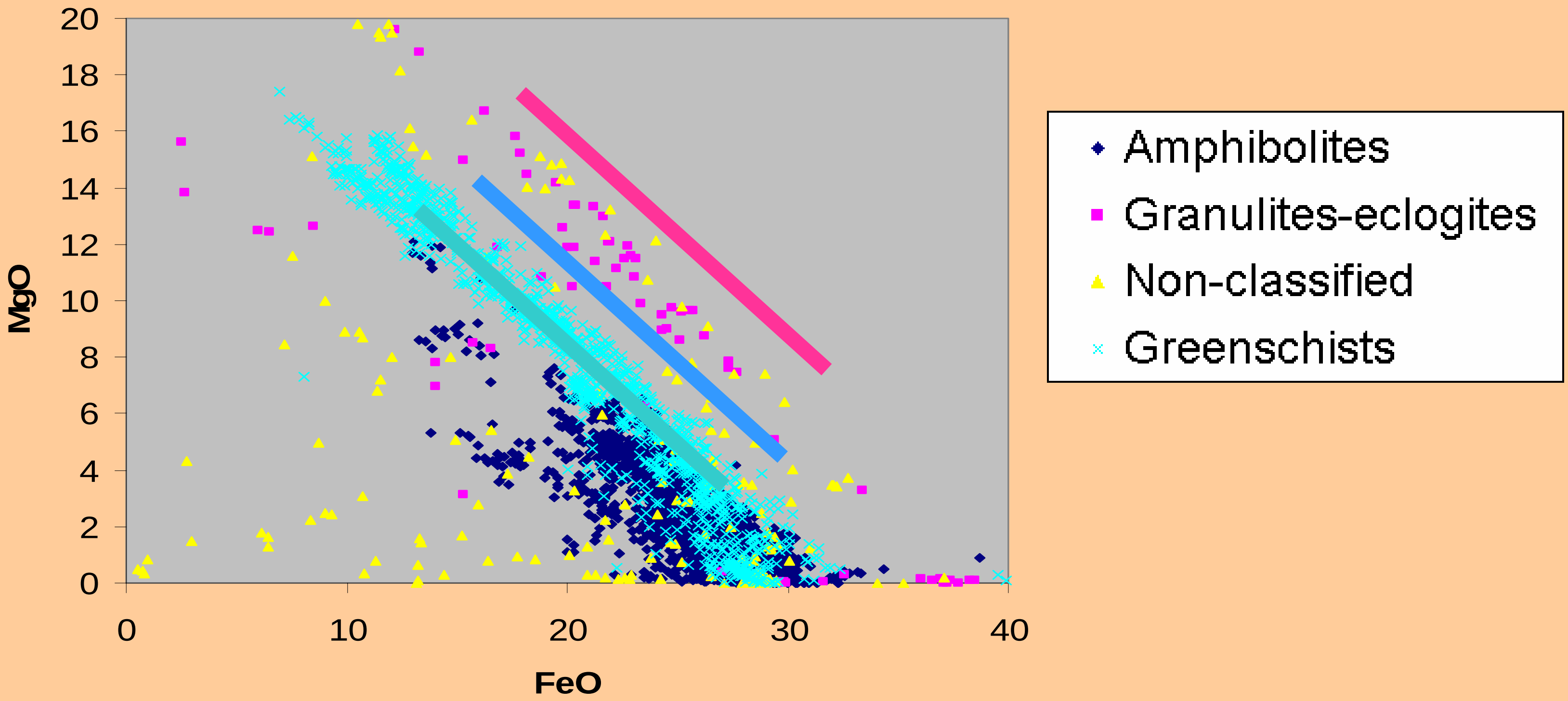
Metamorphic komatiites (MgO vs FeO, X-site)

Three tendencies:

Greenschist: regular Fe^{2+} replacement by Mg

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

Granulite – eclogite: increase in Mg and 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:

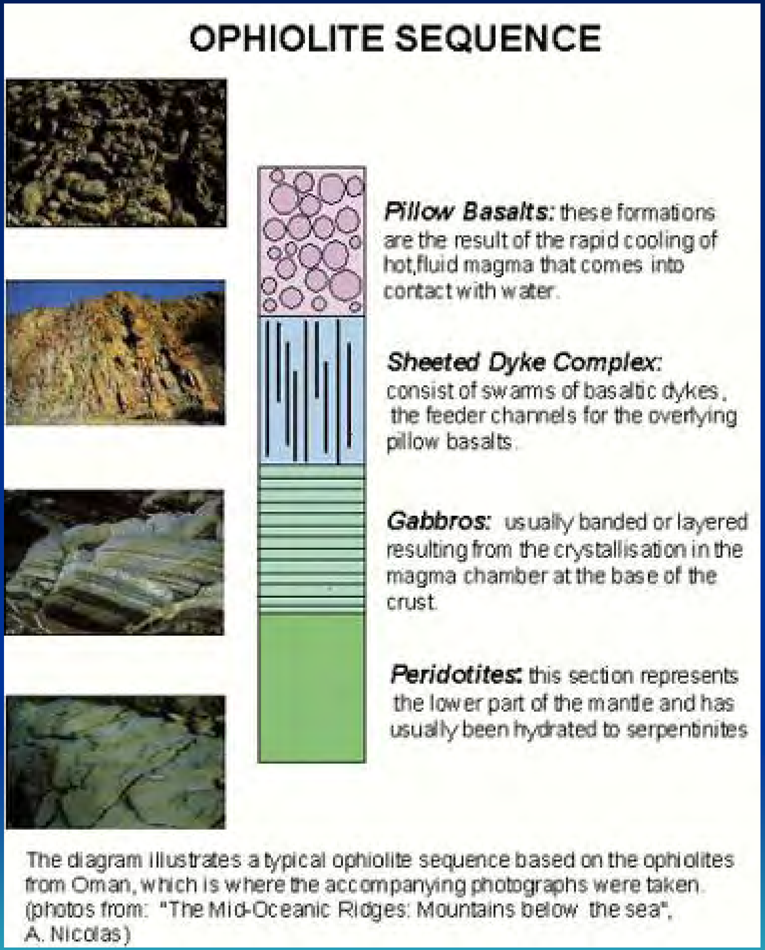
  Cr_2O_3 content decreases

  Al_2O_3 content decreases

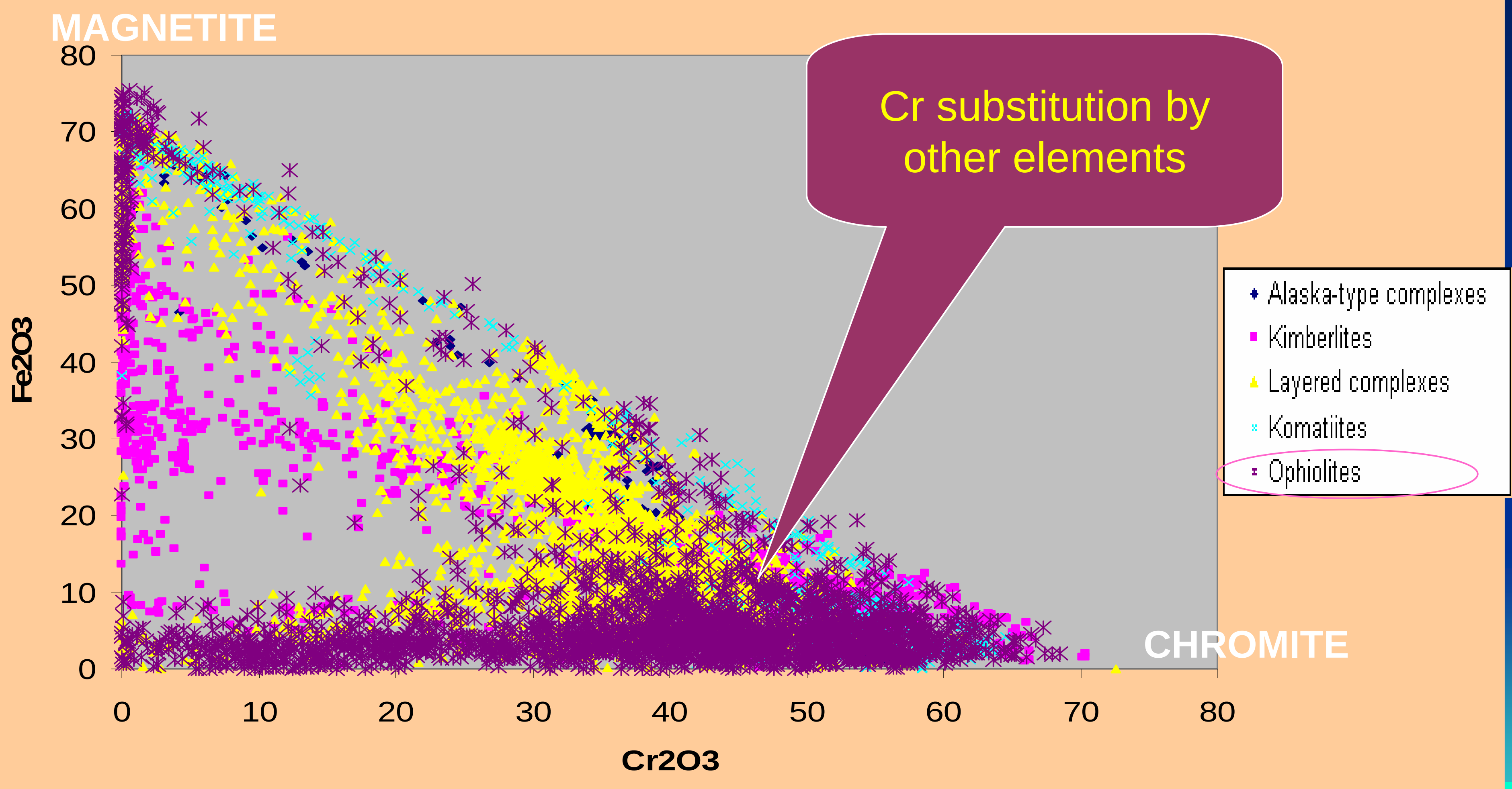
- Cr_2O_3 frequent replacement by Fe_2O_3 for the mineralized and barren komatiites probably reflects the metamorphic grade

Geological environments

- Kimberlites
- Komatiites
- Ophiolites, peridotites
- Layered mafic complexes
- 'Alaska'-type complexes

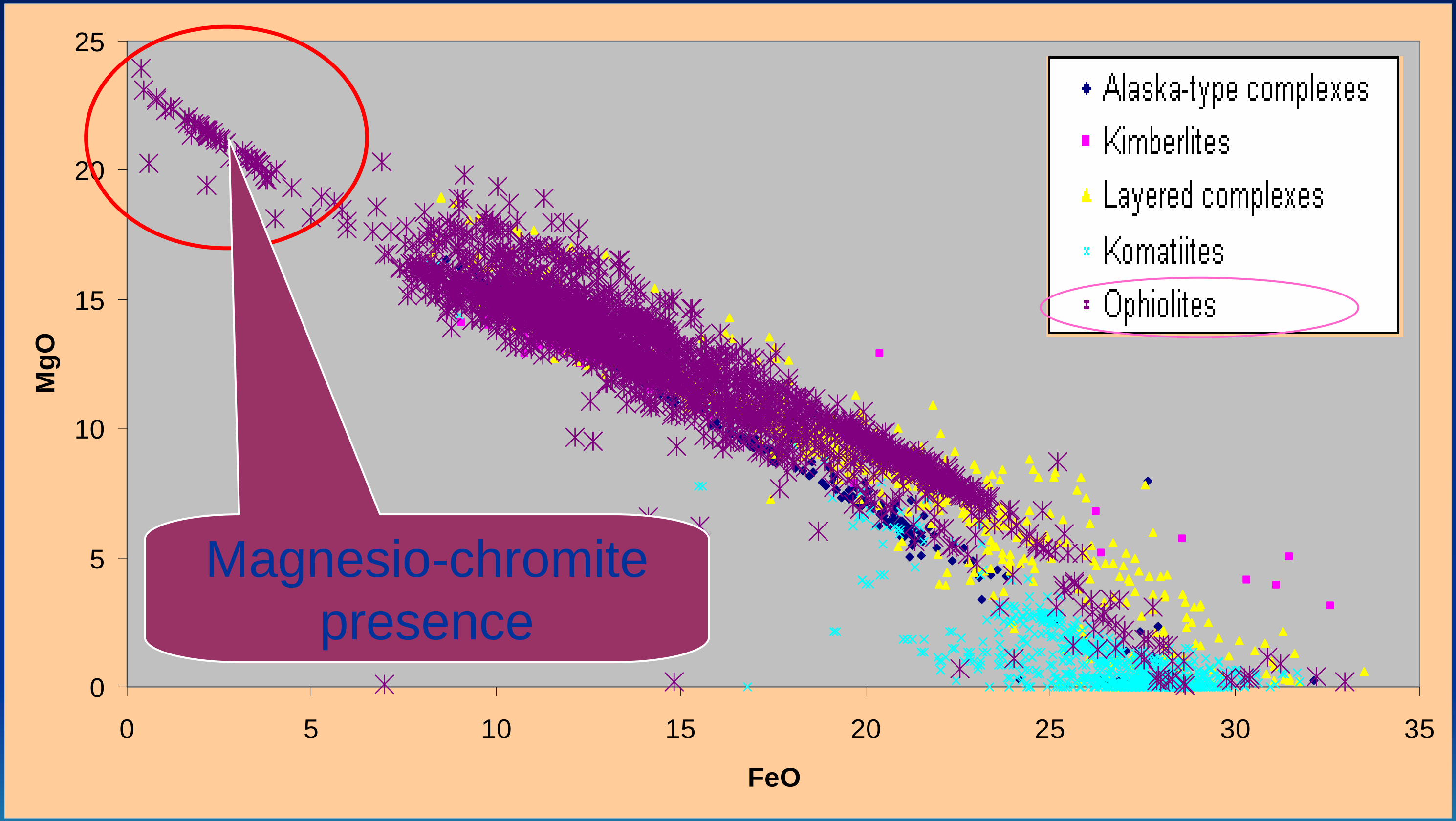


Barren ophiolites, peridotites
(Fe_2O_3 *vs* Cr_2O3, Y-site)



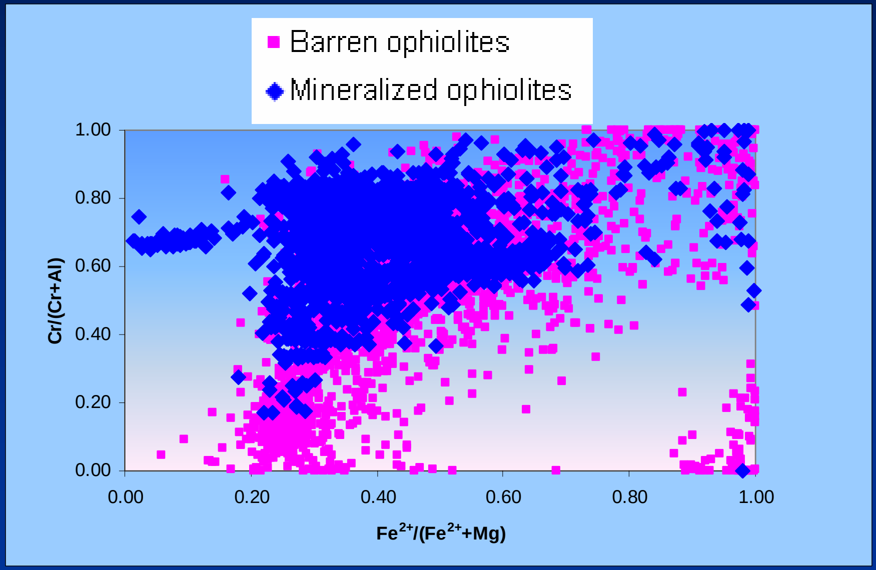
Mineralized ophiolites, peridotites

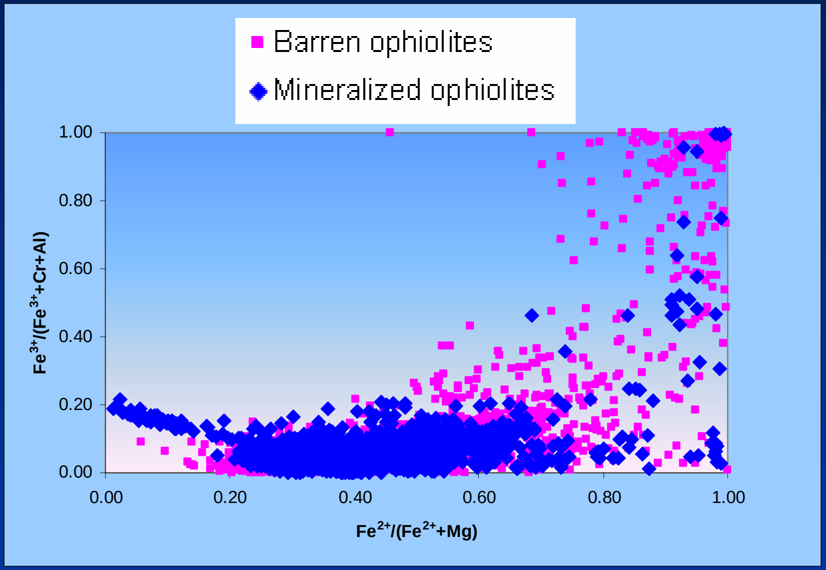
(MgO vs FeO, X-site)

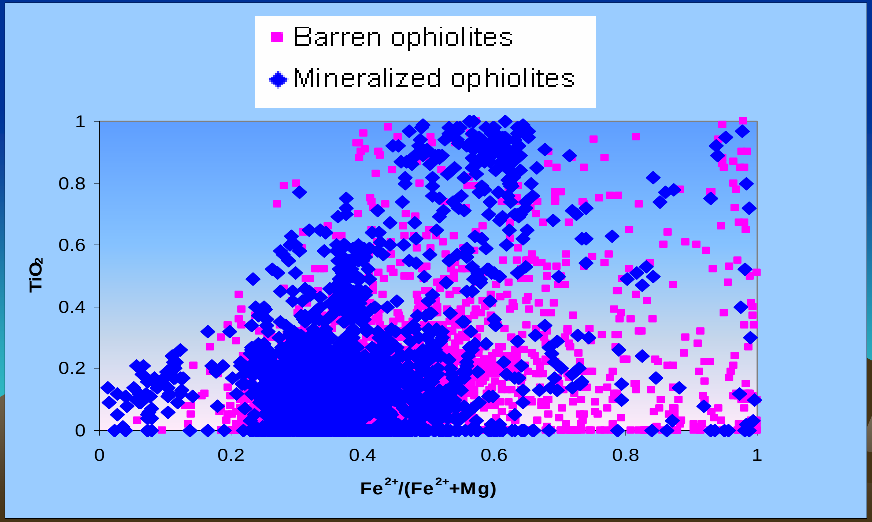


Ophiolites, peridotites (Cation ratios)

Mineralized n = 2272
Barren n = 3051







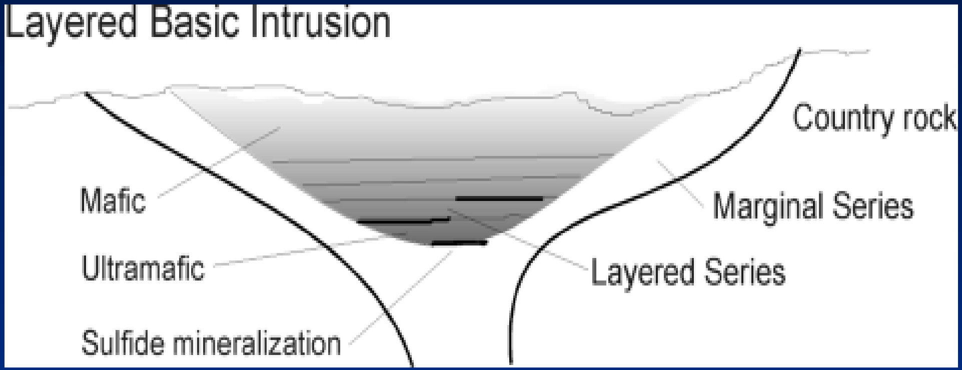
No significant differences between mineralized *vs* barren ophiolites

Ophiolites, peridotites

- **Positive criteria**
  - Magnesio-chromite presence
  - Chromite substitution by other Al_2O_3 -rich minerals such as spinel, gahnite and hercynite
  - Lack of Cr_2O_3 replacement by Fe_2O_3

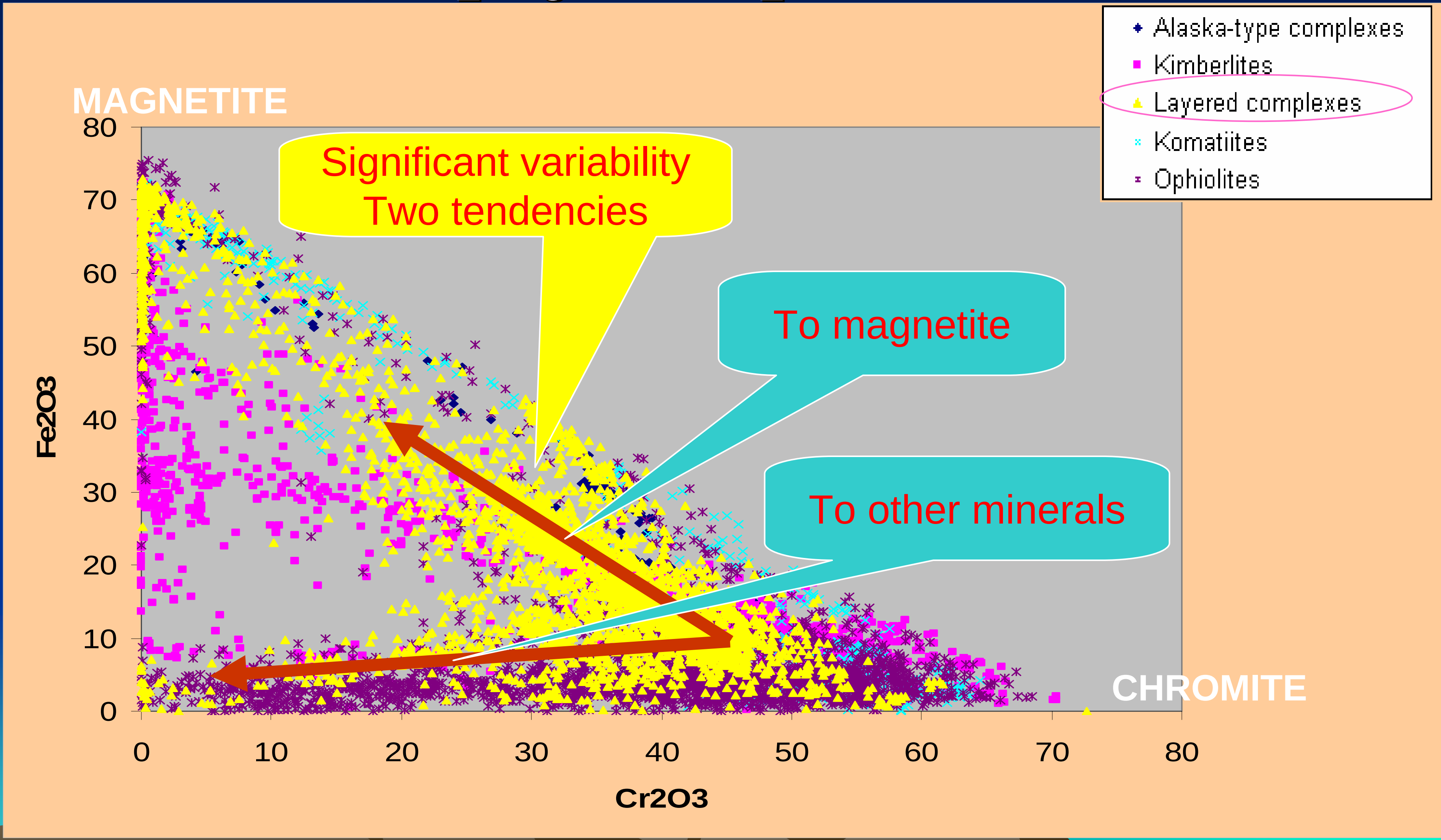
- **Negative criteria**
  - Cr_2O_3 replacement by Fe_2O_3

Geological environments

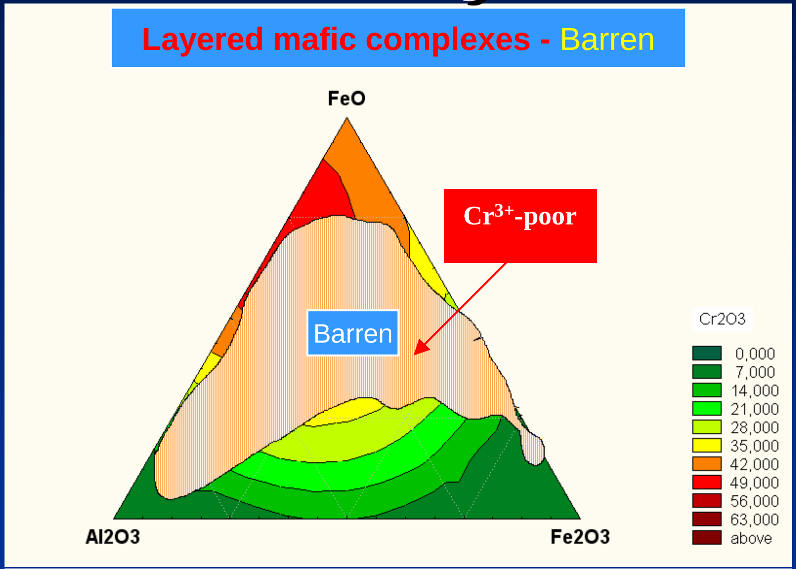


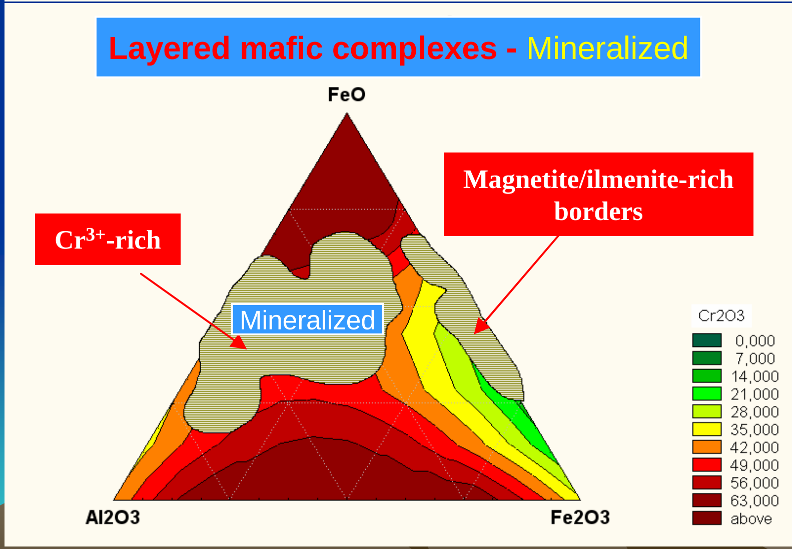
- Kimberlites
- Komatiites
- Ophiolites, peridotites
- Layered mafic complexes
- ‘Alaska’-type complexes

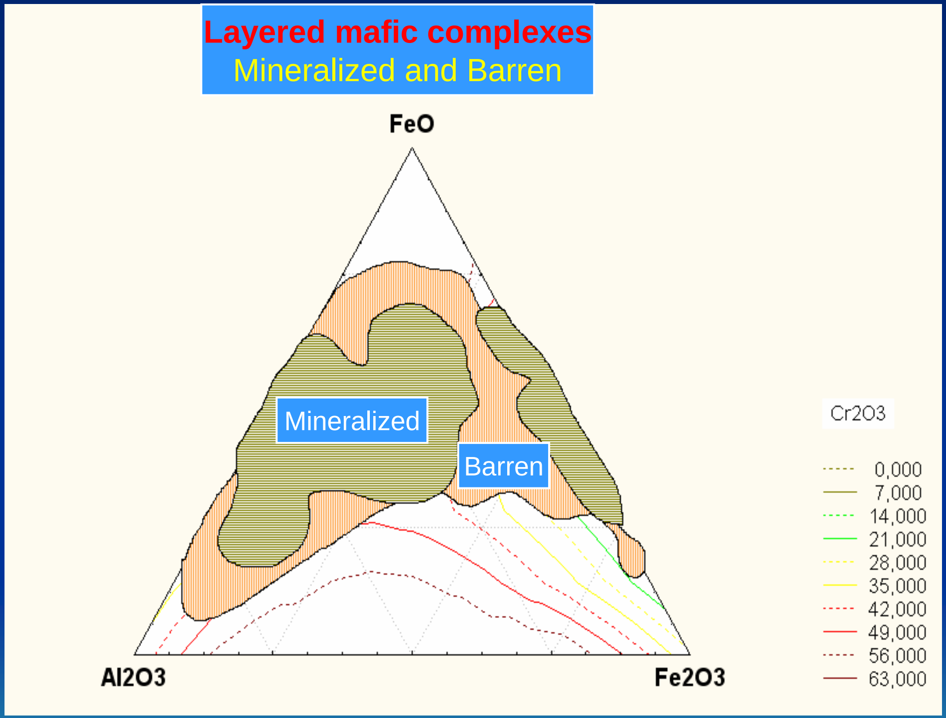
Layered mafic complexes
(Fe_2O_3 *vs* Cr_2O3, Y-site)



Layered mafic complexes

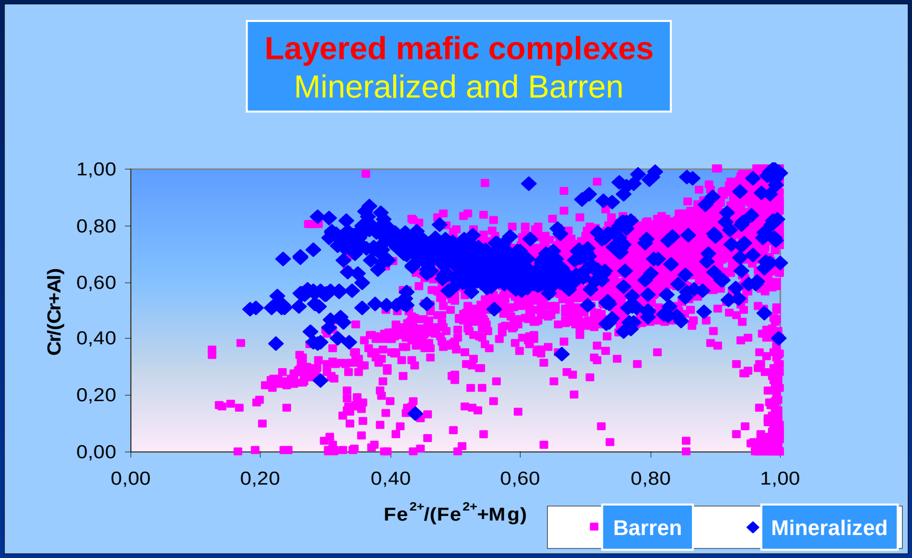


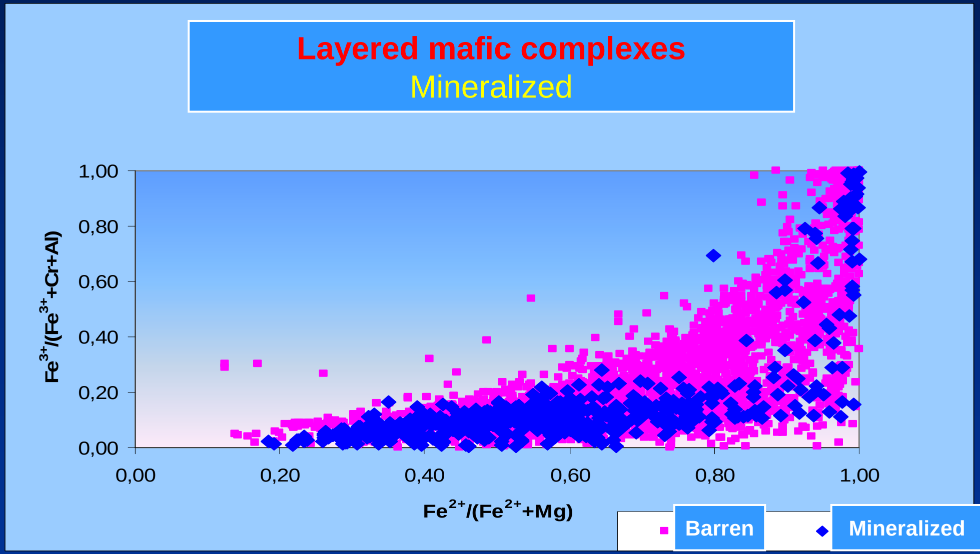


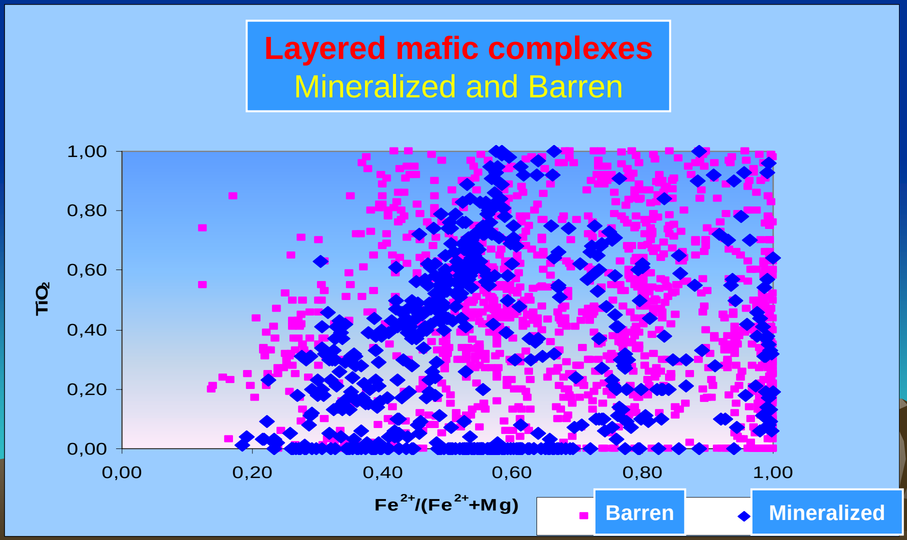


Layered mafic complexes

Mineralized n = 646
Barren n = 3260

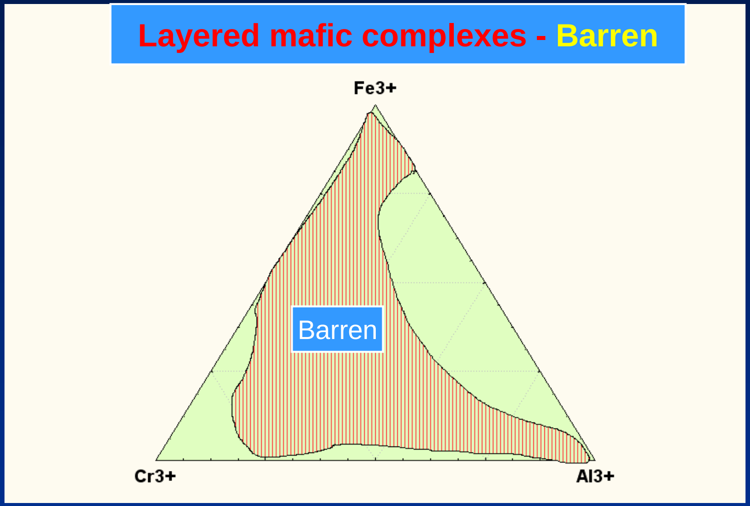


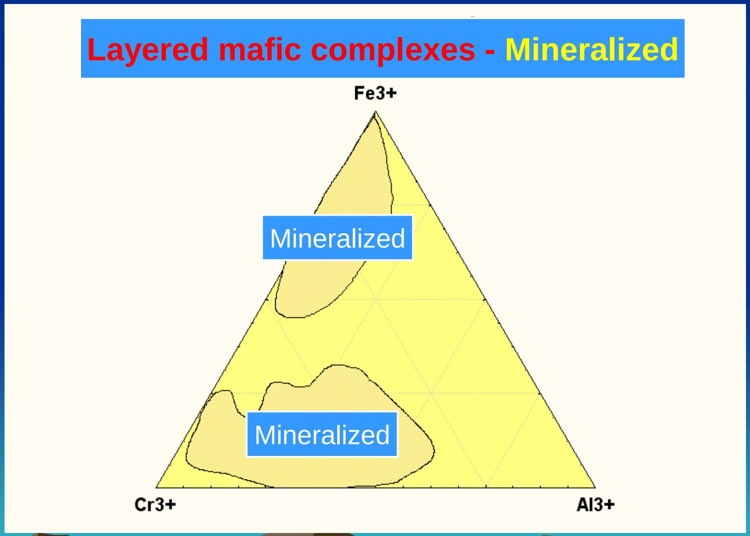


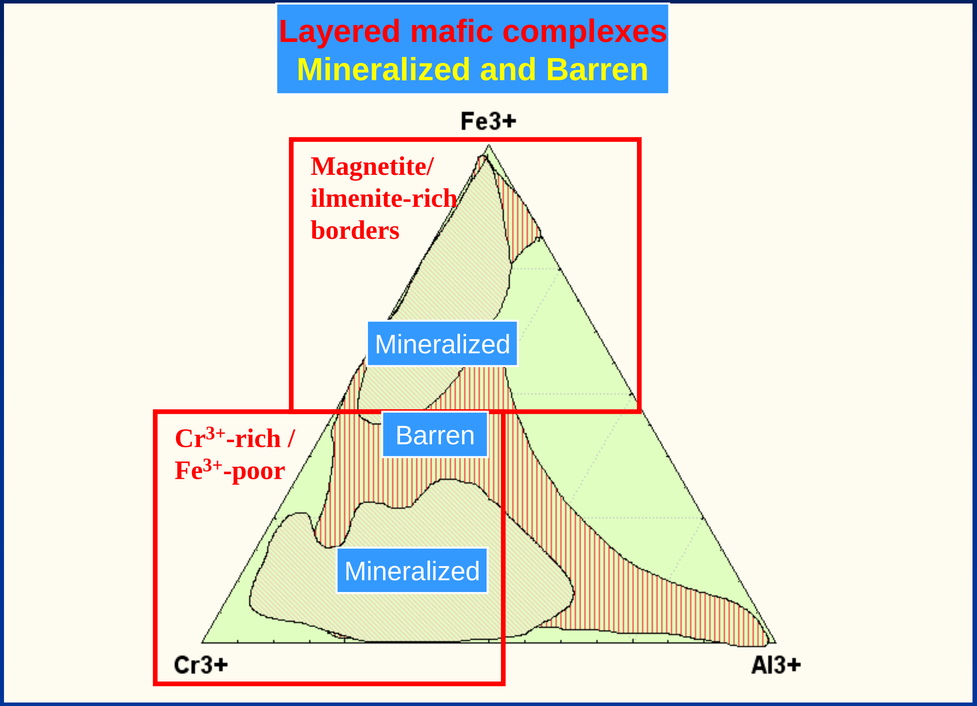


No significant differences between chromites of mineralized *vs* barren complexes

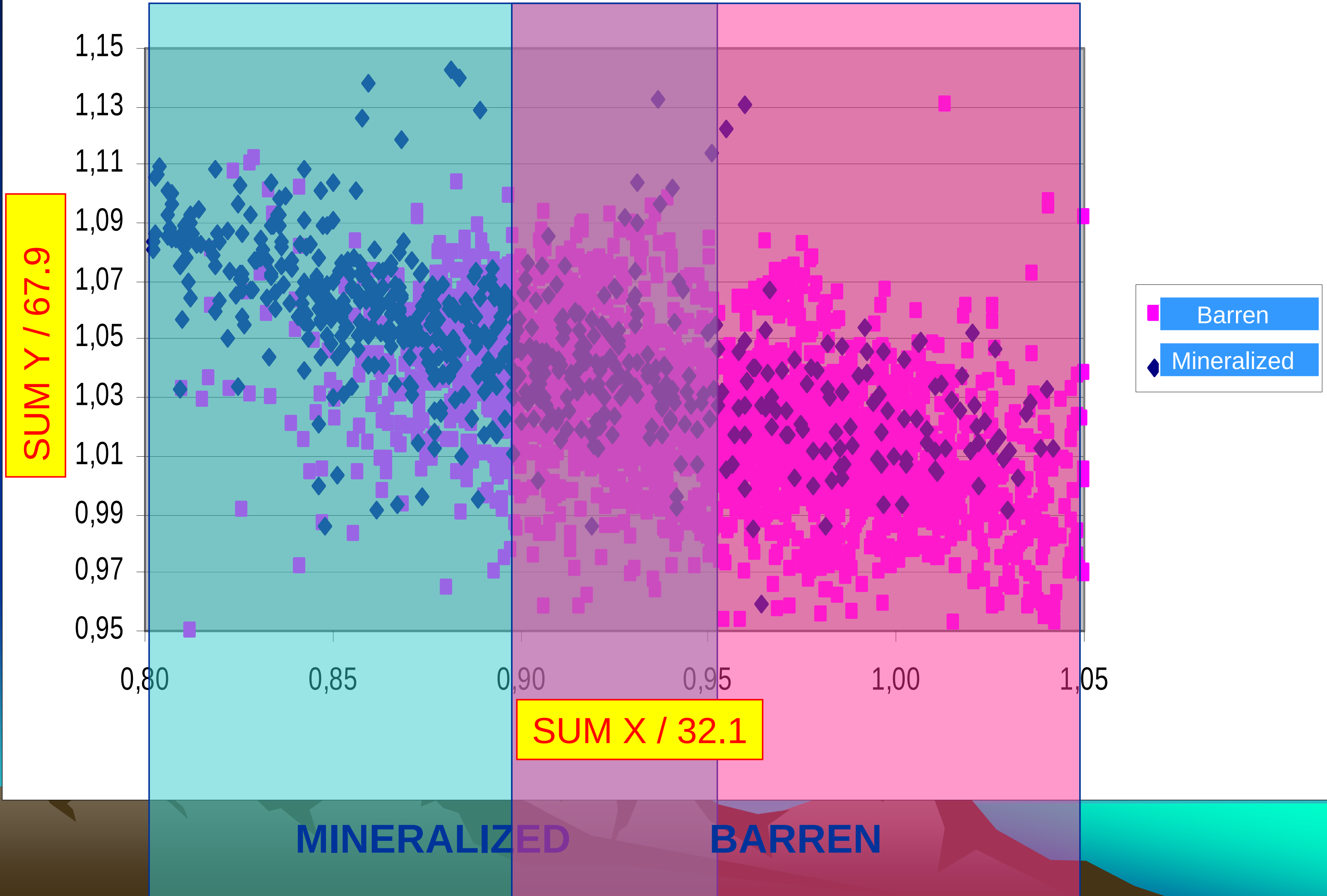
Layered mafic complexes







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



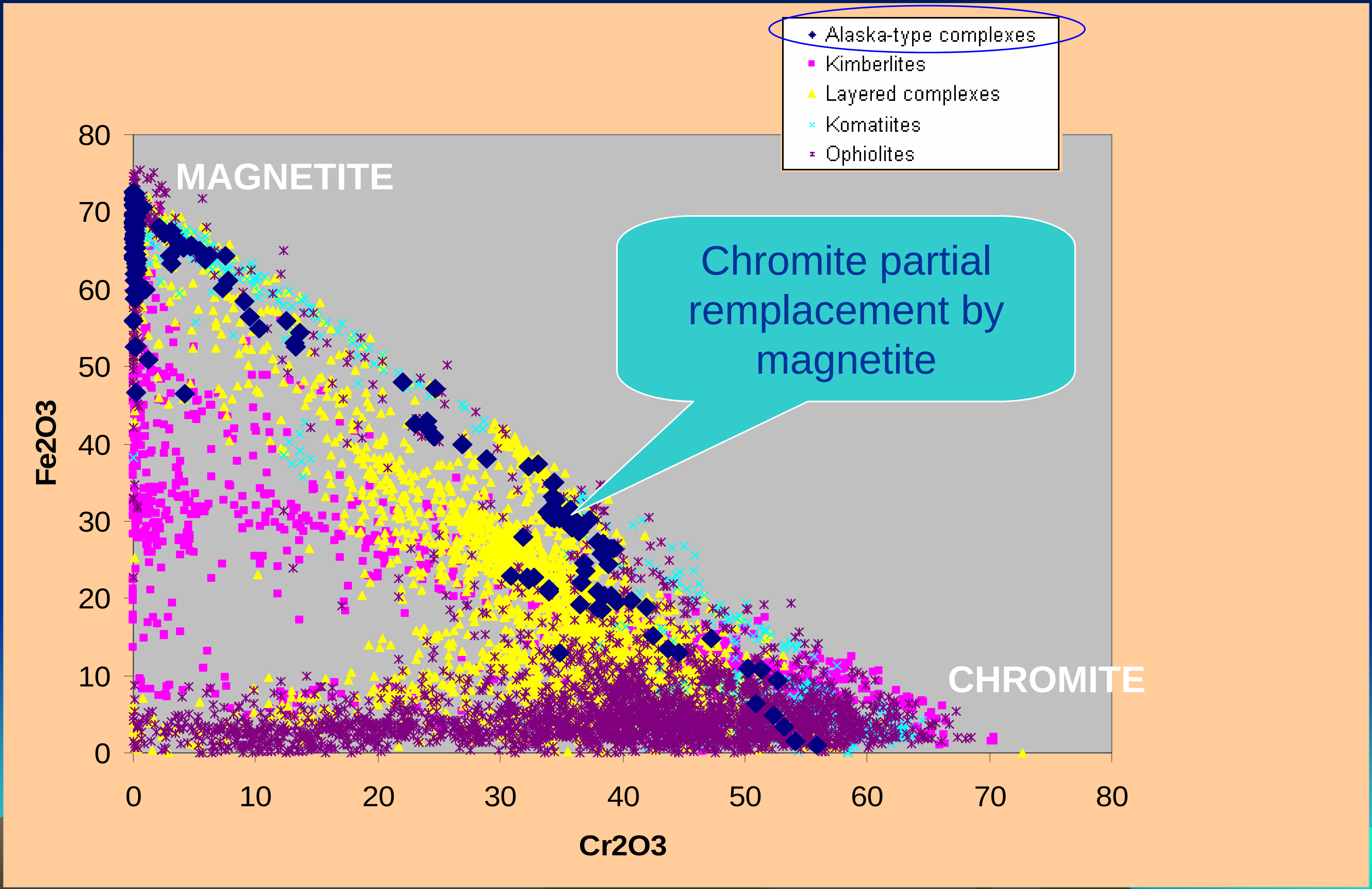
Layered mafic complexes

- Positive
  - Cr_2O3 partial substitution by Fe_2O_3
- Negative
  - Cr_2O3 partial substitution by Al_2O_3
  - Chromite substitution by other minerals such as spinel, gahnite and hercynite

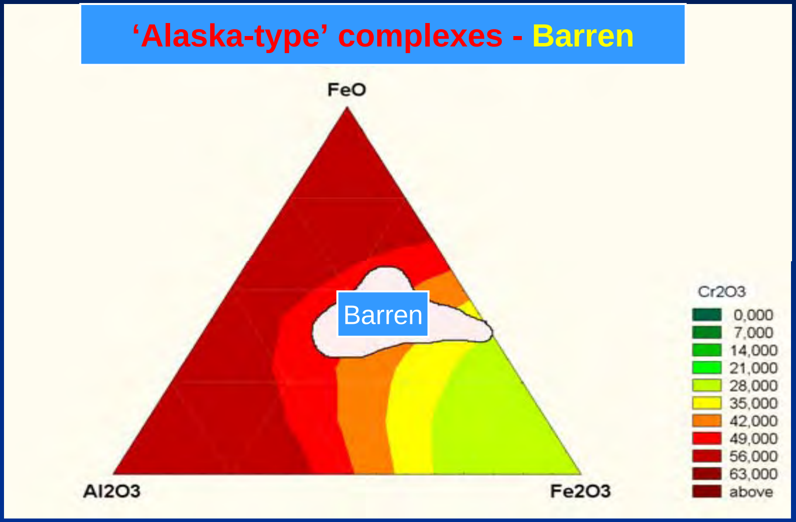
Geological environments

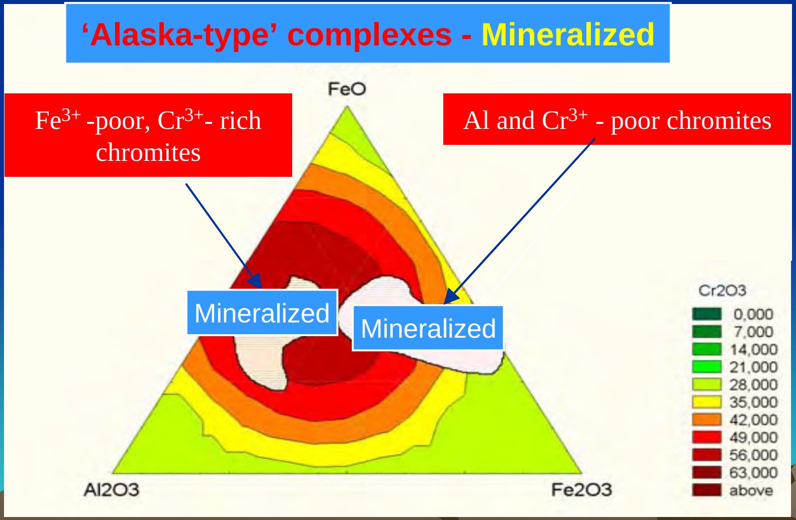
- Kimberlites
- Komatiites
- Ophiolites, peridotites
- Layered mafic complexes
- ‘Alaska-type’ ultramafic complexes

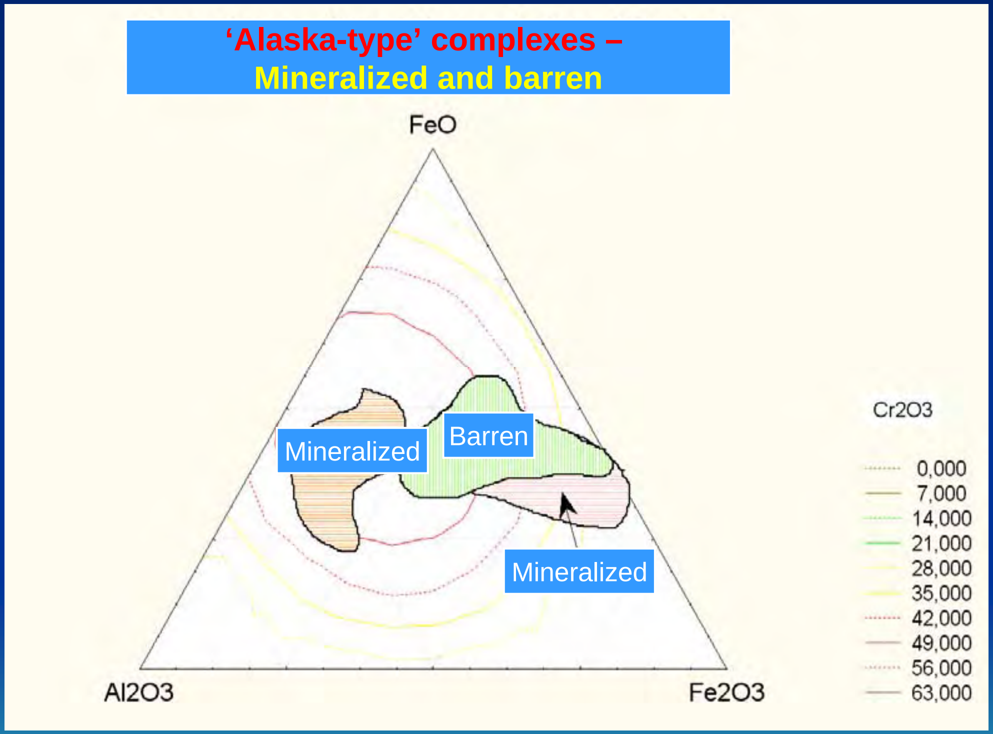
‘Alaska-type’ ultramafic complexes



‘Alaska-type’ ultramafic complexes



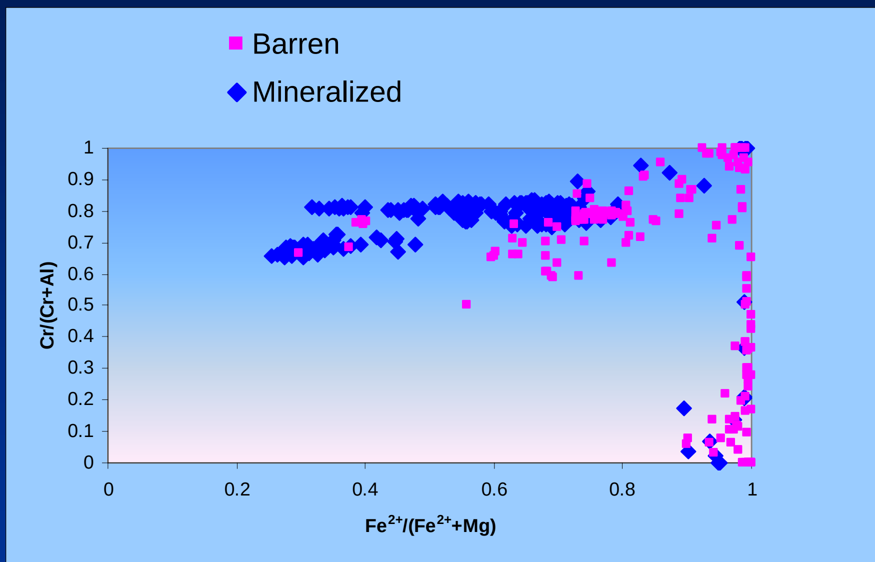


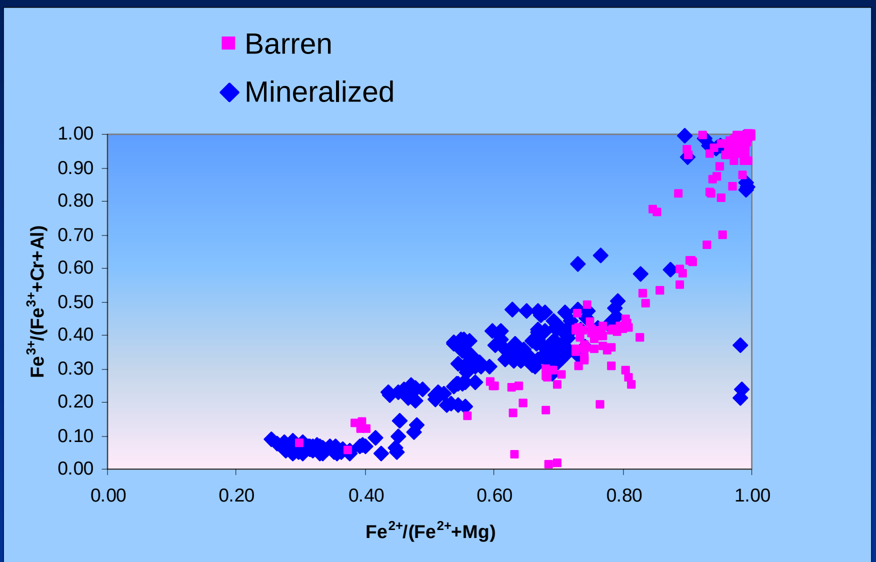


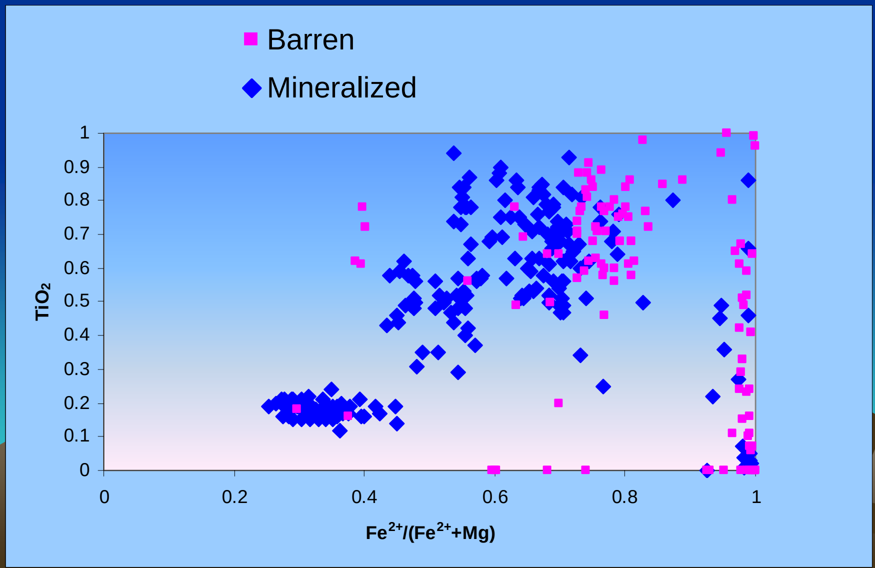
→ **No significant difference**

‘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

… exploration tools…

- **Presence or absence of oxide substitution in Y-site;**
- **Fe^{2+} replacement by 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

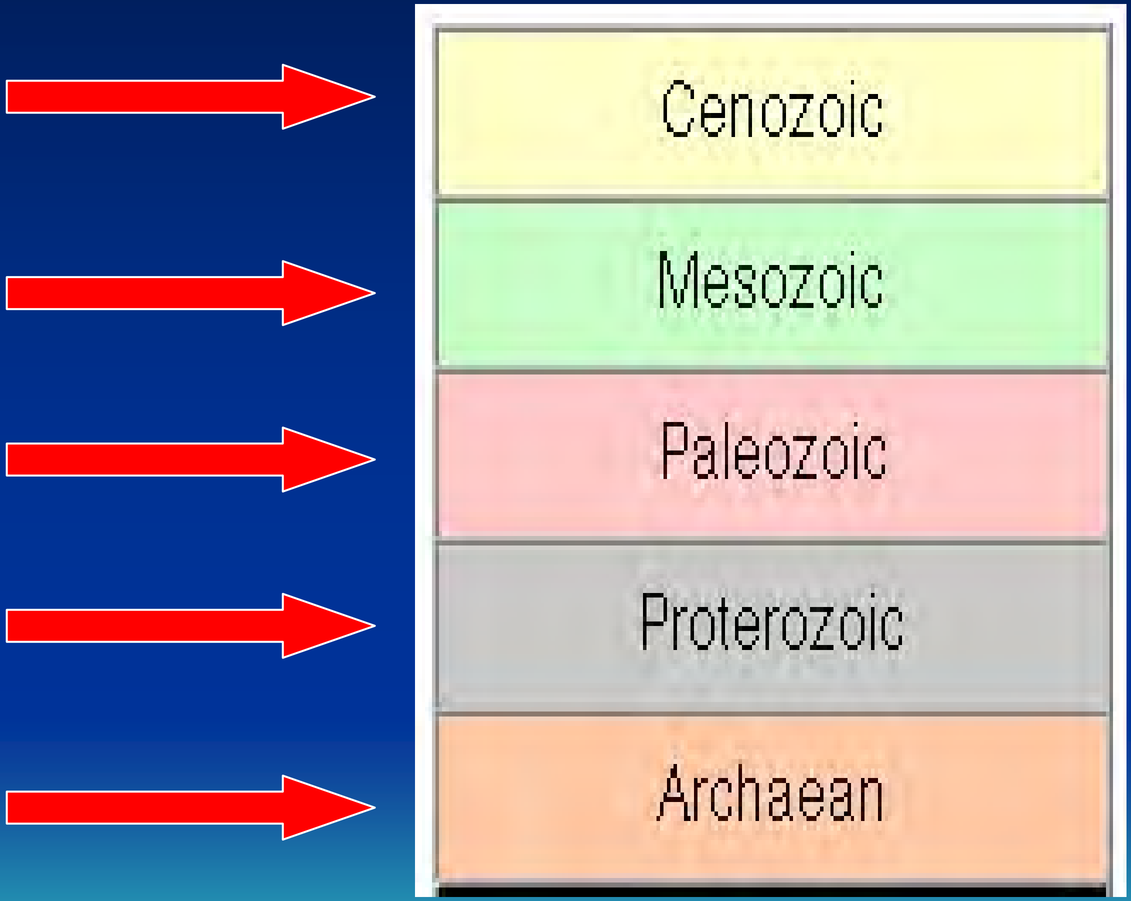
Methodology

- **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



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

Unmetamorphosed

Metamorphic facies divided in:

Greenschists

Greenschists– Amphibolites

Amphibolites

Amphibolites – Granulites

Granulites

Tourmaline classification

Species	(X)	(Y_3)	(Z_6)	T_6O_{18}	$(BO_3)_3$	V_3	W
Alkali tourmaline							
Elbaite	Na	$Li_{1.5}Al_{1.5}$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Dravite	Na	Mg_3	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Chromdravite	Na	Mg_3	Cr_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Schorl	Na	Fe^{2+}_3	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Olenite	Na	Al_3	Al_6	Si_6O_{18}	$(BO_3)_3$	O_3	(OH)
"Hydoxy-buergerite"	Na	Fe^{3+}_3	Al_6	Si_6O_{18}	$(BO_3)_3$	O_3	(OH)
"Fluor-elbaite"	Na	$Li_{1.5}Al_{1.5}$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
"Fluor-dravite"	Na	Mg_3	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
"Fluor-chromdravite"	Na	Mg_3	Cr_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
"Fluor-schorl"	Na	Fe^{2+}_3	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
"Fluor-olenite"	Na	Al_3	Al_6	Si_6O_{18}	$(BO_3)_3$	O_3	F
Buergerite	Na	Fe^{3+}_3	Al_6	Si_6O_{18}	$(BO_3)_3$	O_3	F
"Oxy-elbaite"	Na	$LiAl_2$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Oxy-dravite"	Na	$MgAl_2$	$MgAl_5$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
Povondraite	Na	Fe^{3+}_3	$Mg_2Fe^{3+}_4$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Oxy-schorl"	Na	$Fe^{2+}Al_2$	$Fe^{2+}Al_5$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Oxy-chromdravite"	Na	$MgCr_2$	$MgCr_5$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Mn-dravite"	Na	Mn^{2+}_3	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
"Oxy-Mn-dravite"	Na	Mn^{2+}_2Al	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"V-dravite"	Na	V^{3+}_3	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
"Oxy-V-dravite"	Na	$V^{3+}Al_2$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
Calcic tourmaline							
"Hydroxy-liddicoatite"	Ca	Li_2Al	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
"Hydroxy-uvite"	Ca	Mg_3	$MgAl_5$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
"Hydroxy-feruvite"	Ca	Fe^{2+}_3	$MgAl_5$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Liddicoatite	Ca	Li_2Al	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
Uvite	Ca	Mg_3	$MgAl_5$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
Feruvite	Ca	Fe^{2+}_3	$MgAl_5$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
"Oxy-liddicoatite"	Ca	$Li_{1.5}Al_{1.5}$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Oxy-uvite"	Ca	$MgAl_2$	Mg_2Al_4	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Ferri-feruvite"	Ca	$MgFe^{3+}_2$	$Mg_2Fe^{3+}_4$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Oxy-feruvite"	Ca	$Fe^{2+}Al_2$	Mg_2Al_4	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Ferri-feruvite"	Ca	$Fe^{2+}Fe^{3+}_2$	$Mg_2Fe^{3+}_4$	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
X-site vacant tourmaline							
Rossmanite	□	$LiAl_2$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
"Mg-foitite"	□	Mg_2Al	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
Foitite	□	Fe^{2+}_2Al	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
"Fluor-rossmanite"	□	$LiAl_2$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
"Fluor-Mg-foitite"	□	Mg_2Al	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
"Fluor-foitite"	□	Fe^{2+}_2Al	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	F
"Oxy-rossmanite"	□	$Li_{0.5}Al_{2.5}$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Oxy-Mg-foitite"	□	$MgAl_2$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Oxy-Mg-ferri-foitite"	□	$MgFe^{3+}_2$	Fe^{3+}_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Oxy-foitite"	□	$Fe^{2+}Al_2$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Oxy-ferri-foitite"	□	$Fe^{2+}Fe^{3+}_2$	Fe^{3+}_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O
"Mn-foitite"	□	Mn^{2+}_2Al	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	(OH)
"Oxy-Mn-foitite"	□	$Mn^{2+}Al_2$	Al_6	Si_6O_{18}	$(BO_3)_3$	$(OH)_3$	O

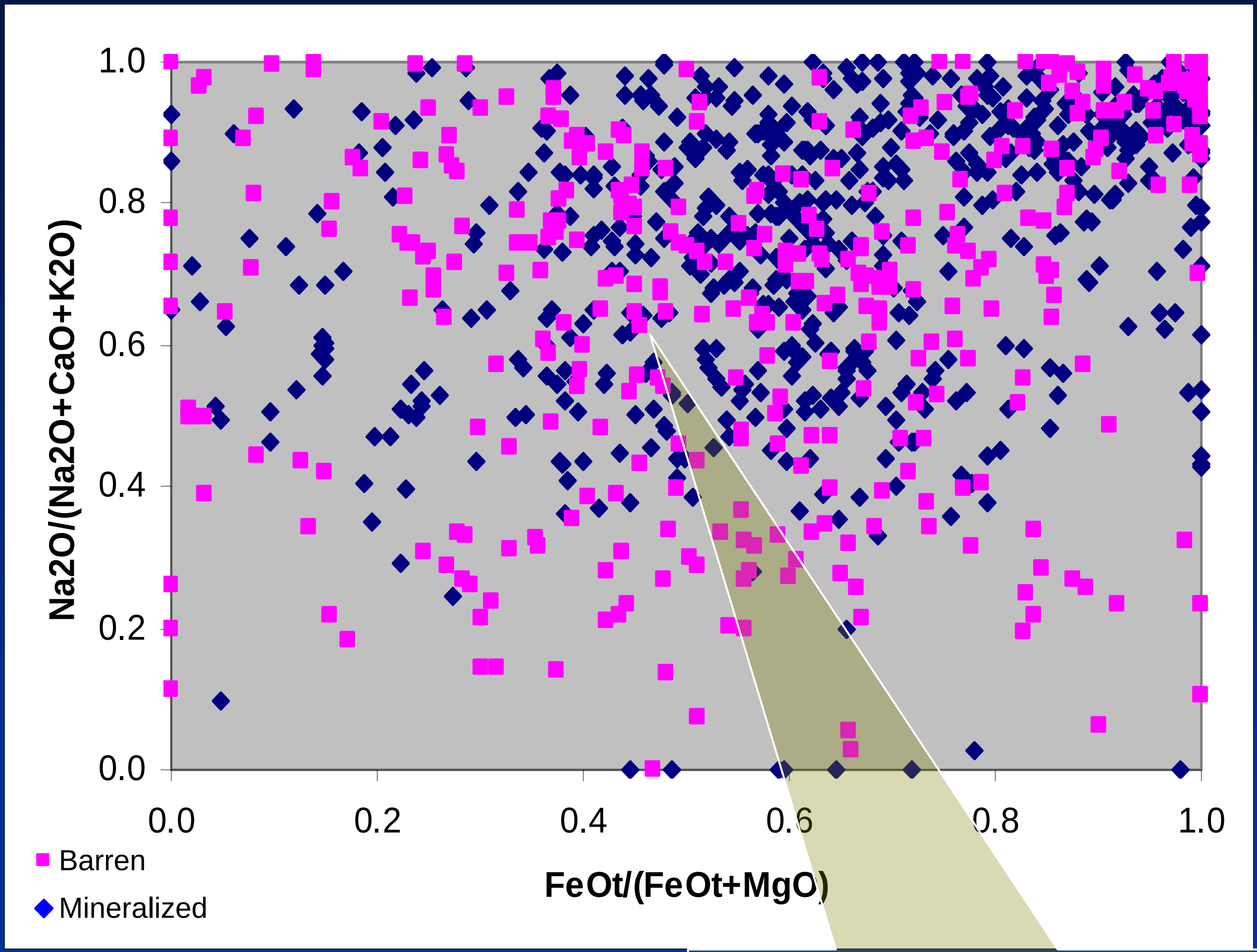
Three main groups:

1. Na-rich tourmaline
2. Ca-rich tourmaline
3. X-site vacant tourmaline

Factors that influence tourmaline composition

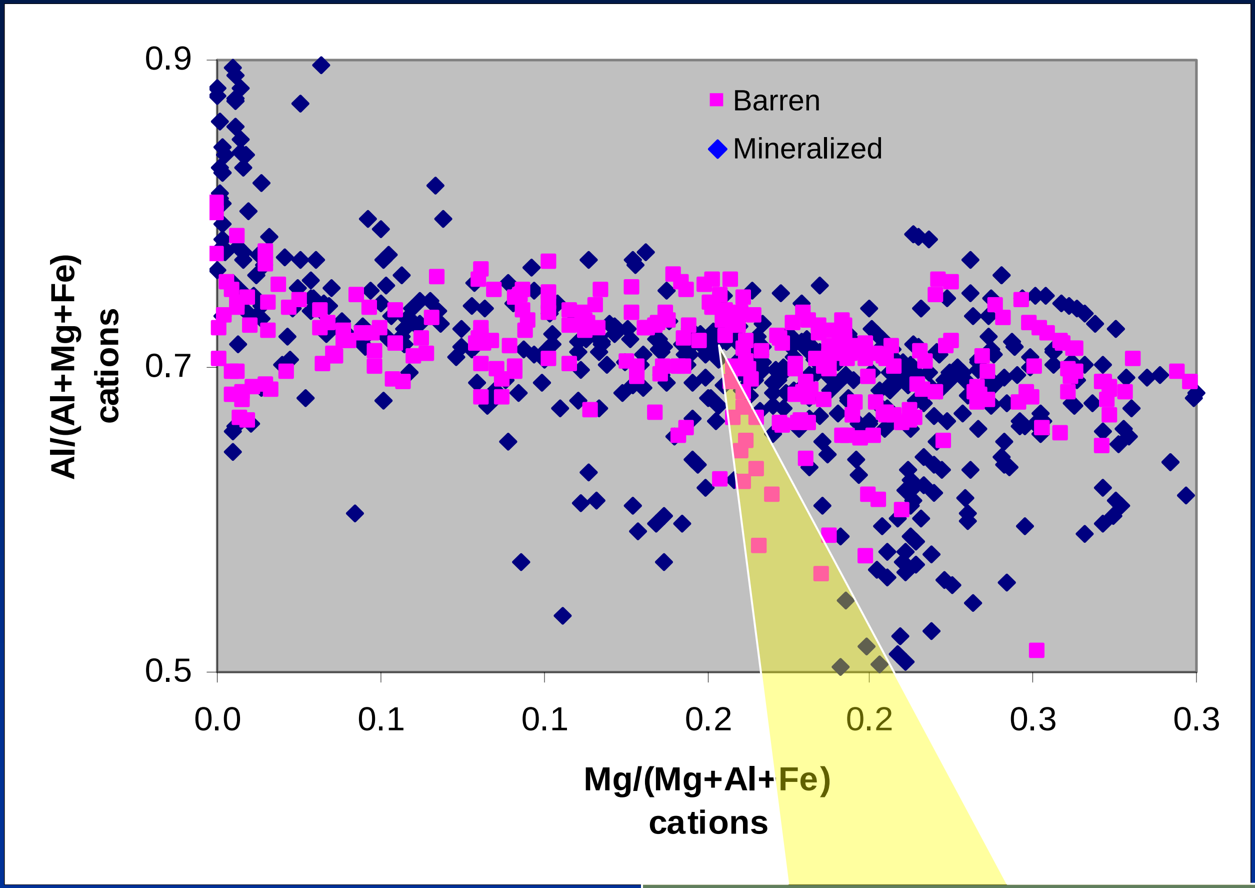
- Bore concentration
- Metasomatism
- Petrographic composition of host lithology
- Leach processes of the host lithology
- Temperature

Tourmaline – mineralized *vs* barren (alkali *vs* Fe#)



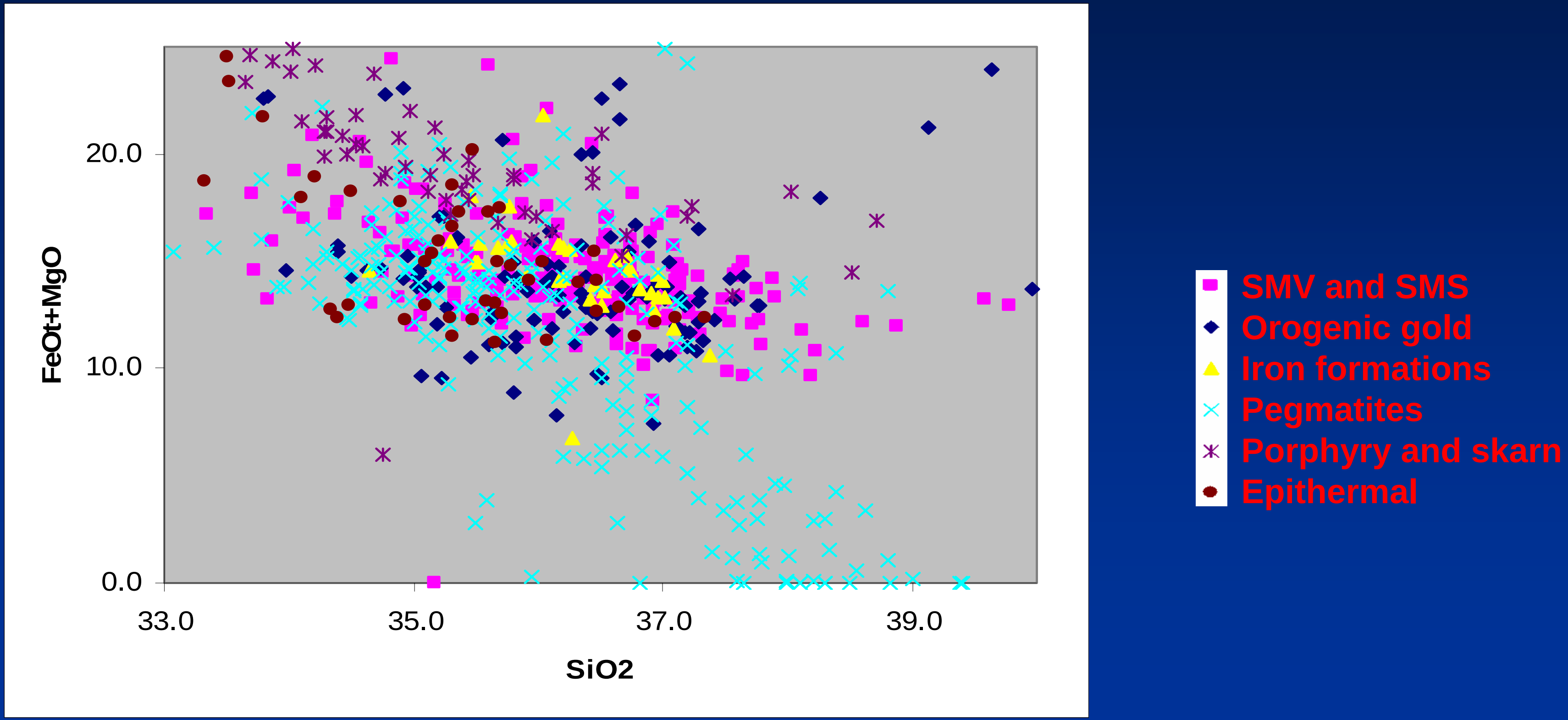
No difference between tourmaline chemical composition associated to mineralized *vs* barren rocks

Tourmaline – mineralized *vs* barren (cation ratios)



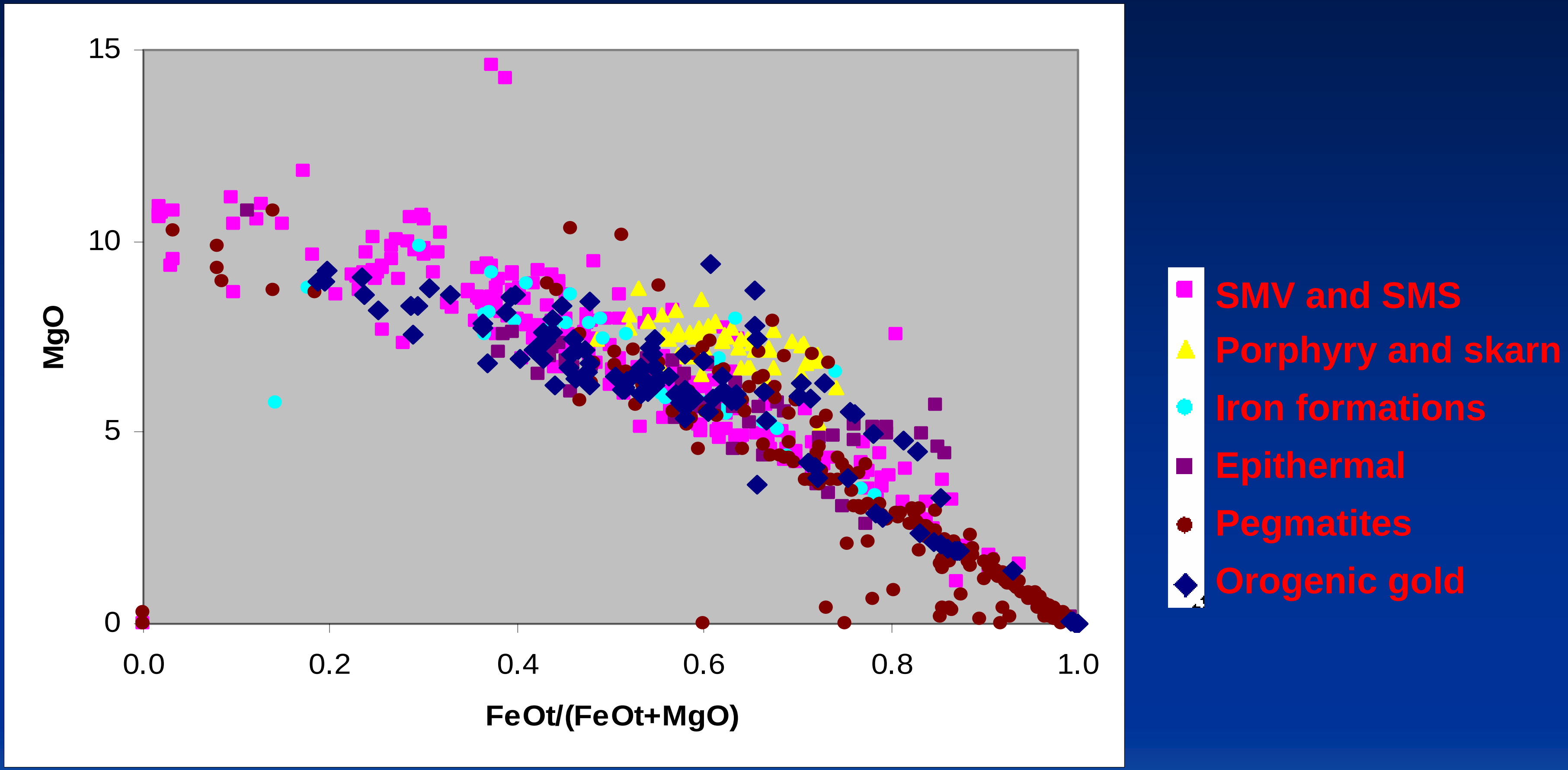
No difference between tourmaline chemical composition associated to mineralized *vs* barren rocks

Tourmaline – Deposit type [(FeO+MgO) *vs* 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

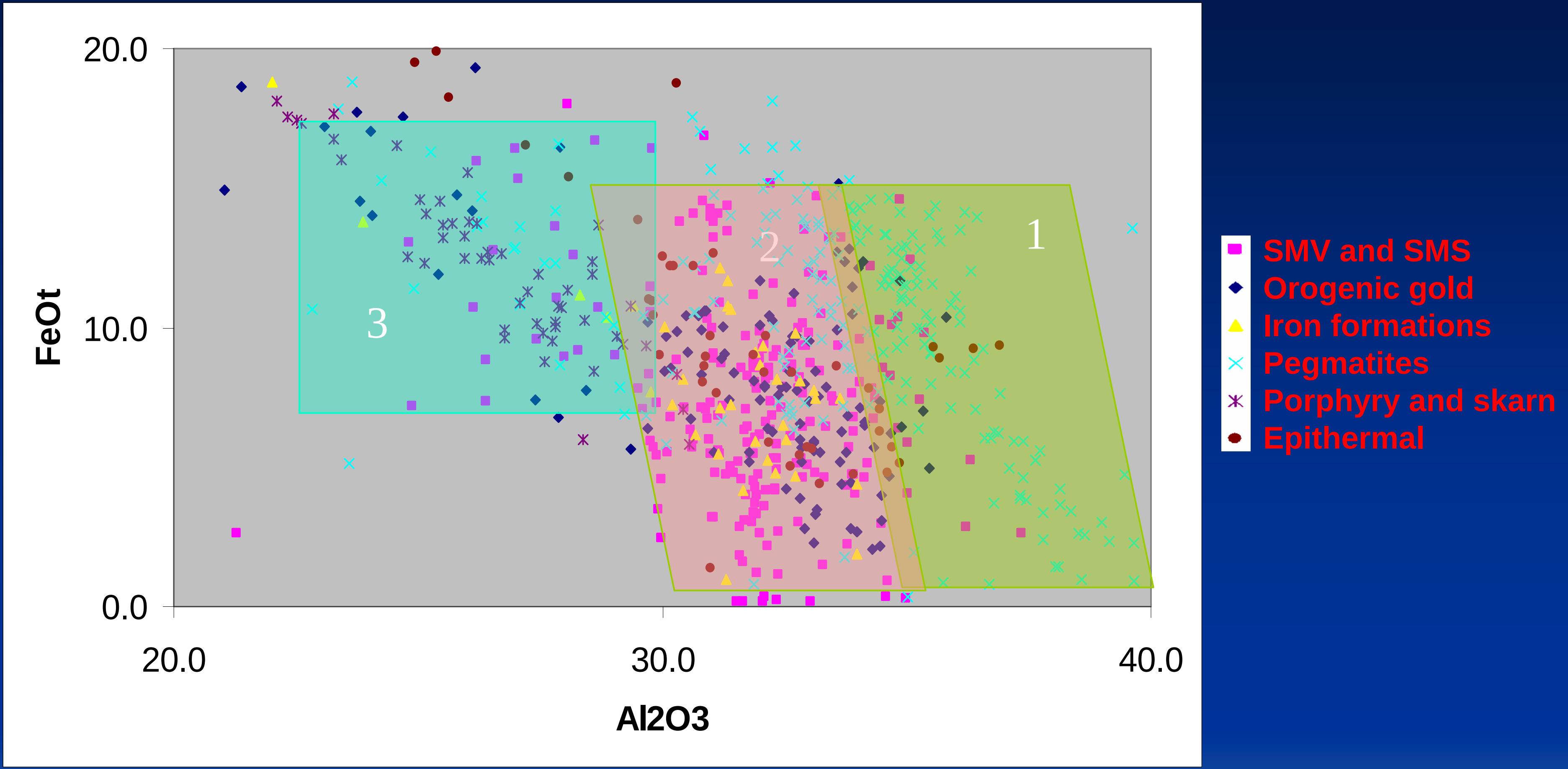
Tourmaline – Deposit type
(MgO vs Fe#)



- Good correlation between Mg et Fe# for all deposit types

- Significant variability of pegmatites and massive sulfides

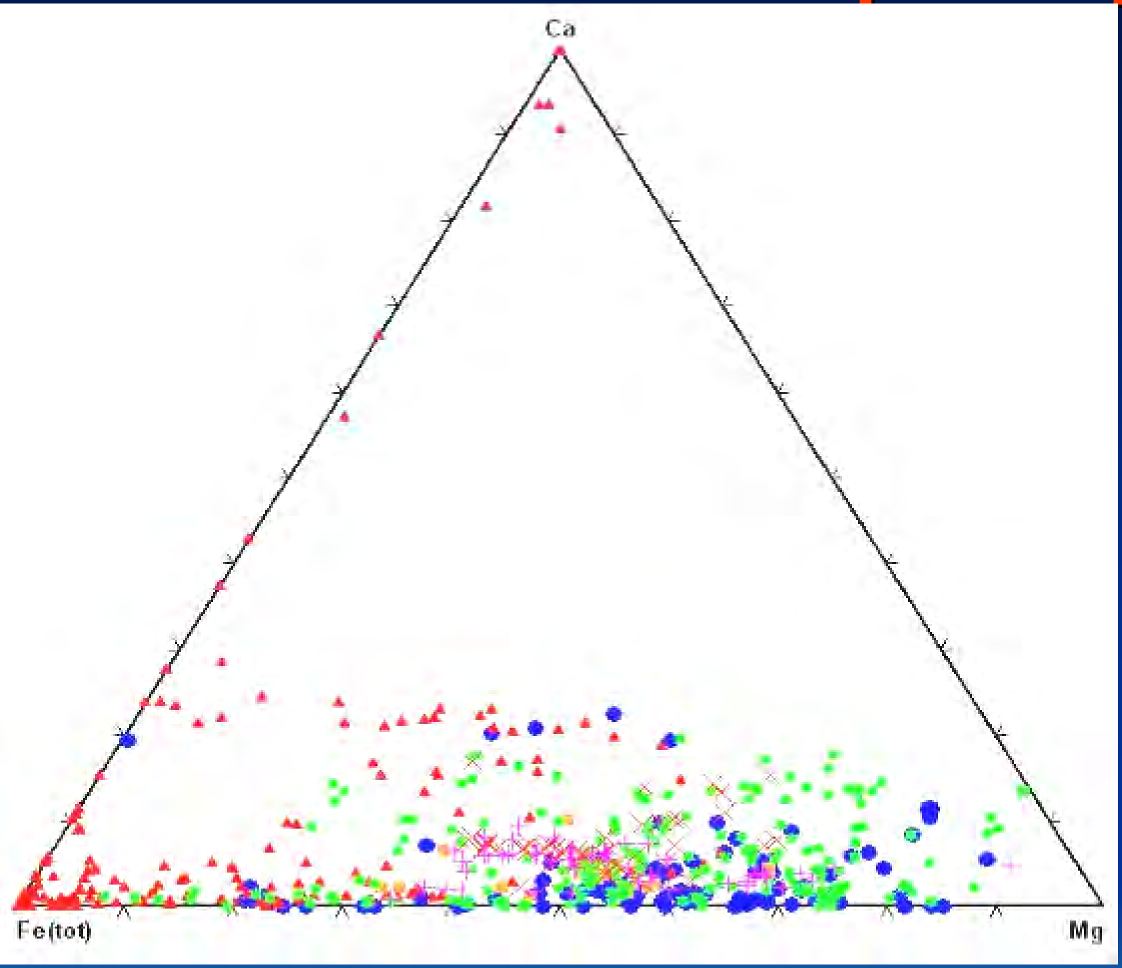
Tourmaline – Deposit type (FeO_t *vs* Al_2O_3)



- 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

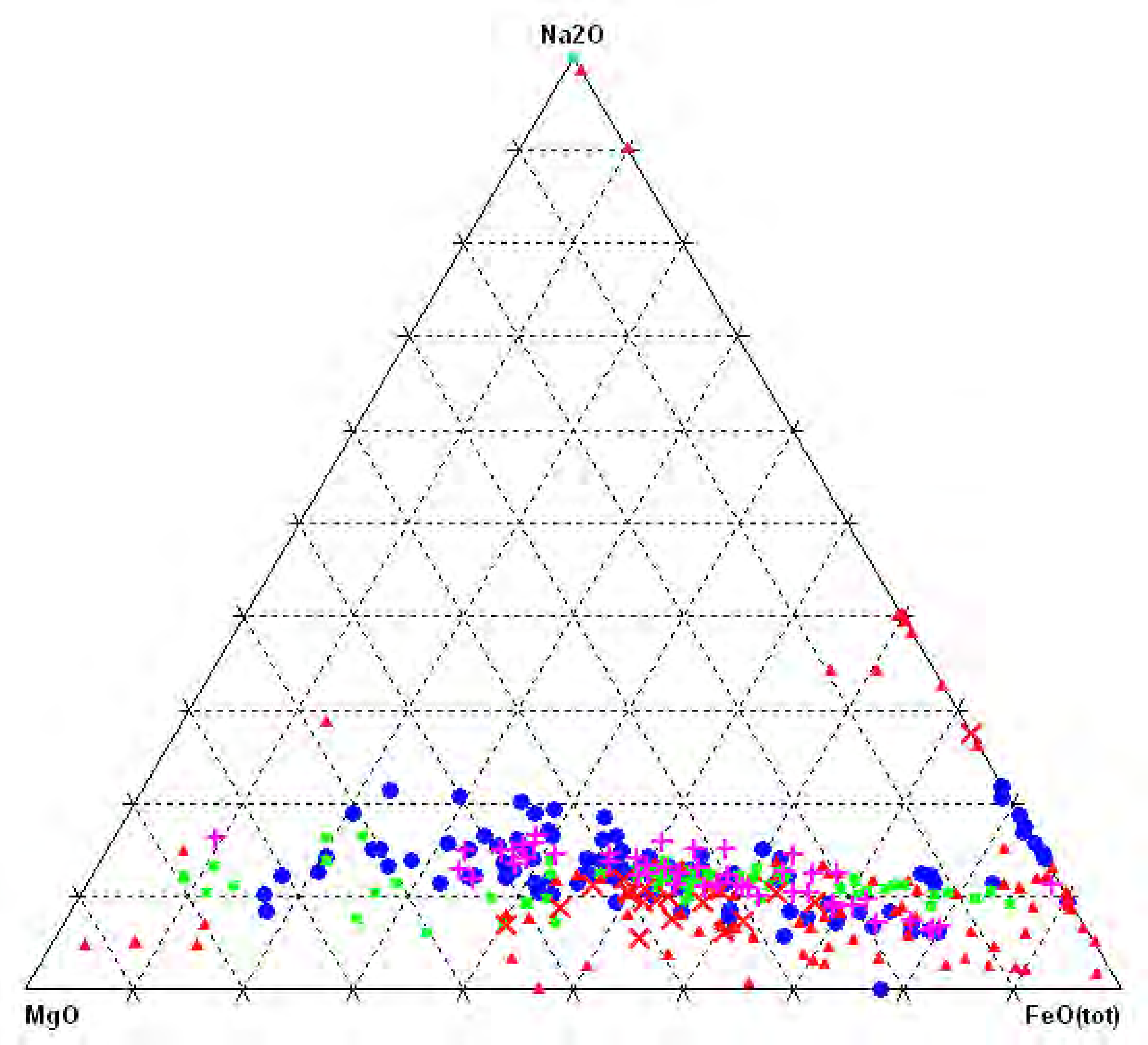
Tourmaline – Deposit type (Fe-Mg-Ca)



- Orogenic gold
- SMV and SMS
- Iron formations
- Porphyry and skarn
- Epithermal
- Pegmatites

- 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

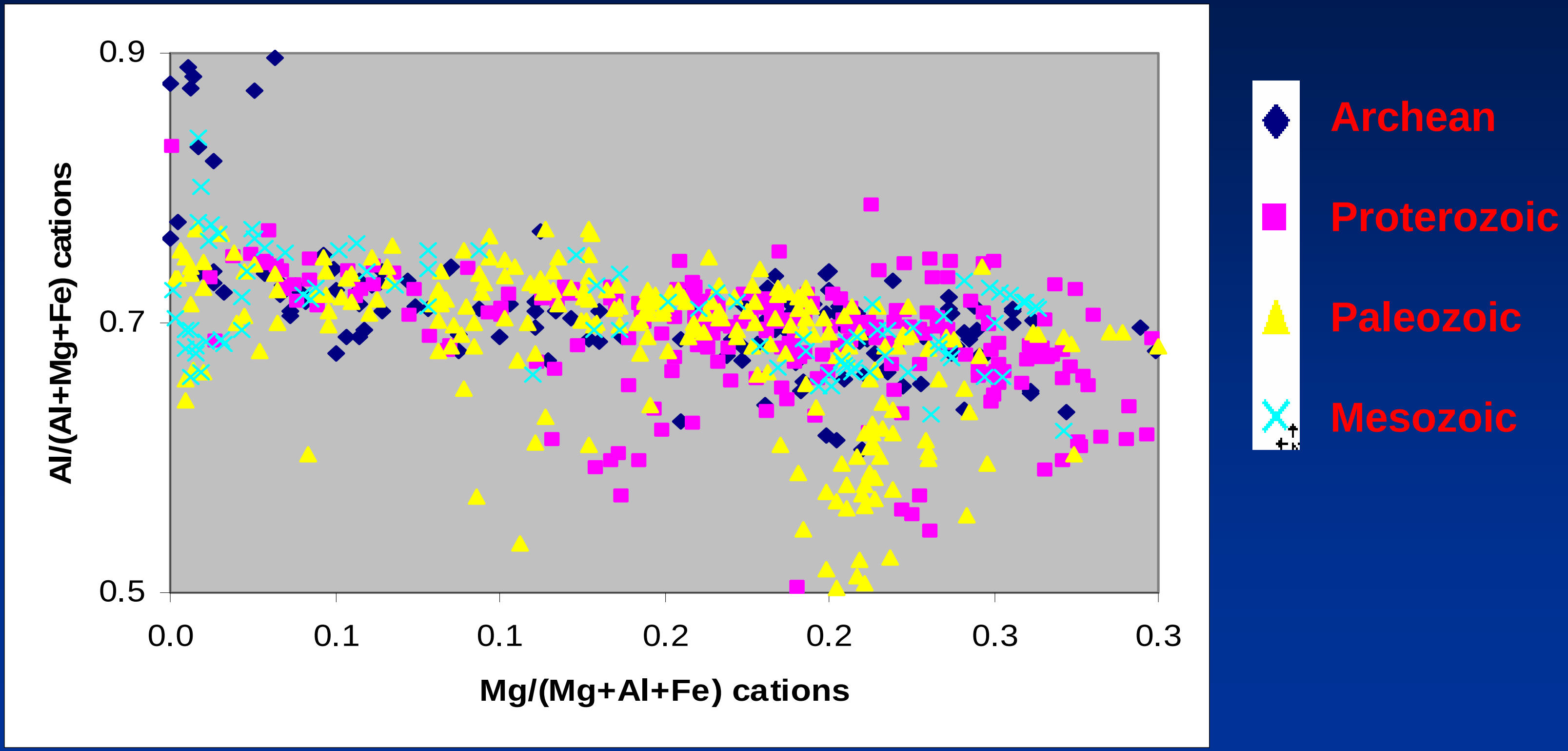
Tourmaline – Deposit type (FeO_t-MgO-Na_2O)



- 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

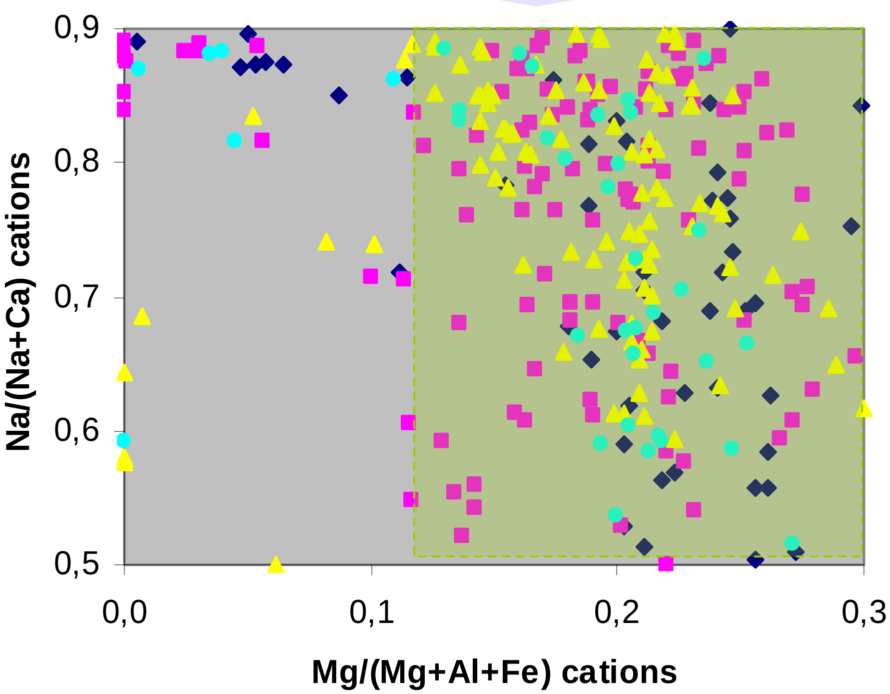


Chemical composition doesn't vary with tourmaline deposition age

High chemical variability of the Mg/(Mg+Al+Fe) ratio applies to all tourmalines, regardless of age

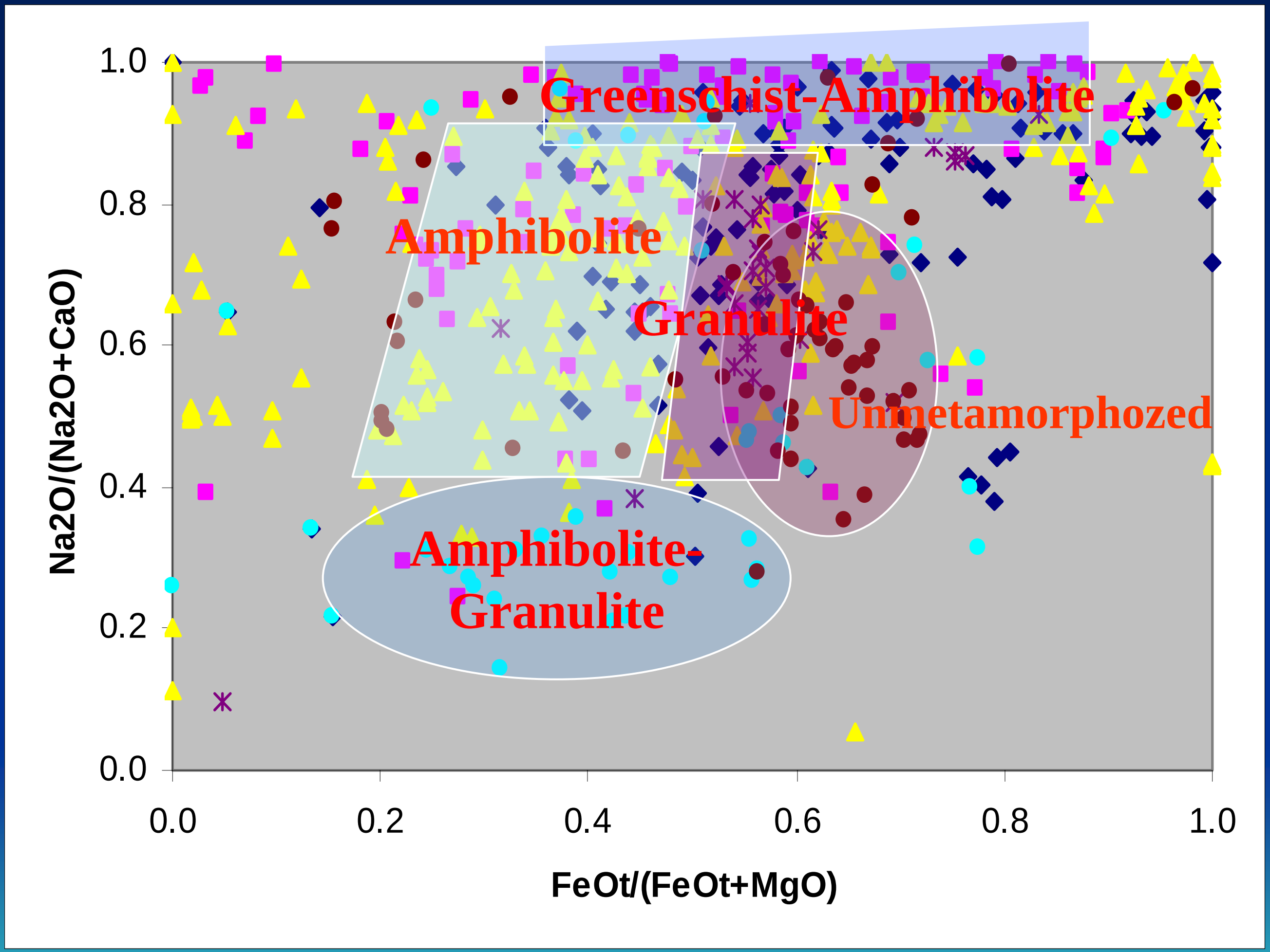
Tourmaline – Chemical composition *vs* Age

Significant variability of alkali metal ratios



Chemical composition (cations) doesn't vary with the tourmaline deposition age

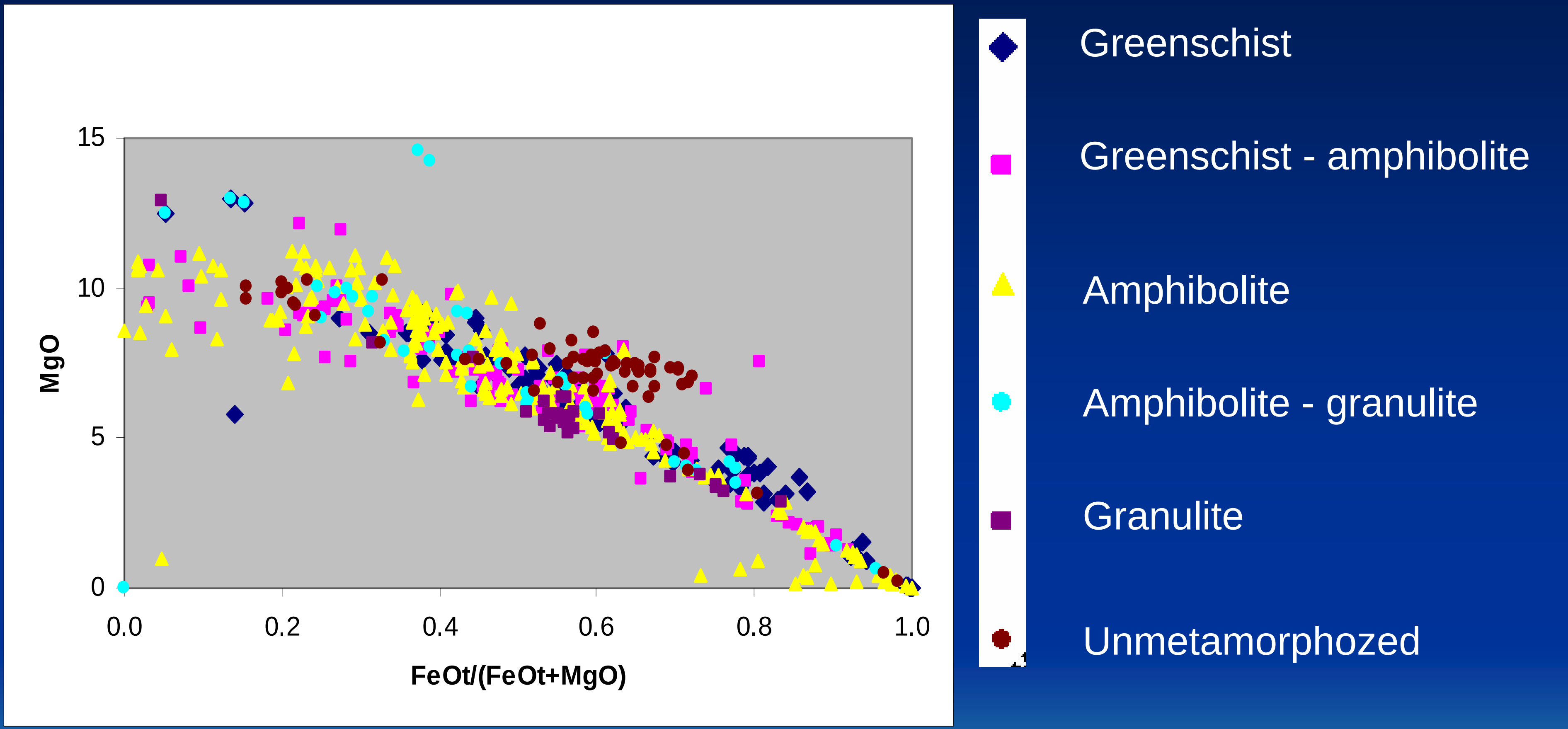
Tourmaline – metamorphic facies



- Greenschist
- Greenschist – amphibolite
- Amphibolite
- Amphibolite – granulite
- Granulite
- Unmetamorphozed

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