The nature of Tombstone Plutonic Suite rocks at Scheelite Dome, Tintina Gold Province: Evidence for an enriched mantle contribution.

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Magmatic-hydrothermal systems have long been recognized for their critical role in the generation of many ore deposit types. Examples of such deposits include tin and tungsten deposits related to felsic intrusions (Taylor, 1979), the spectrum of Cu±Mo±Au porphyry deposits (Titley and Bean, 1981; Sillitoe, 2000), and gold deposits related to alkaline magmatism (Muller and Groves, 1995; Jensen and Barton, 2000). Additionally, strong links have been demonstrated between porphyry systems and high-sulphidation epithermal systems (Hedenquist et al., 1998; Cooke and Simmons, 2000), and some workers have invoked an association of iron-oxide-copper-gold deposits with anorogenic alkaline magmatism (Hauck, 1990; Mutschler and Mooney, 1993; Groves and Vielreicher, 2001).

Although a wide range of gold deposit types have an intrusion-related affinity as outlined above, the term 'intrusion-related' has recently been adopted to recognize a specific class of gold deposits (Sillitoe, 1991; Sillitoe and Thompson, 1998; Thompson et al., 1999; Lang et al., 2000; Lang and Baker, 2001). In the literature this deposit class is typically described as: 1) being associated with metaluminous, sub-alkalic intrusions of intermediate to felsic composition that are weakly to moderately reduced; 2) forming inboard of recognized continental magmatic arcs in areas otherwise known for Sn and W mineralisation; 3) associated with variable enrichments of As, Bi, Mo, Sb, Te, and W; and 4) characterized by aqueous-carbonic hydrothermal fluids (Thompson et al., 1999; Lang et al., 2000). A large proportion of data on which this model is based has come from examples in the Tintina Gold Province (TGP), located in the Cordilleran Orogen of both Alaska and the Yukon Territory.

The TGP is a broad geographical expanse across the central Yukon and Alaska, that comprises numerous gold camps and districts that formed at different stages in the evolution of the Jura-Cretaceous orogen (Hart et al., 2002). Significant deposits include Donlin Creek (12.3 Moz), Pogo (5.8 Moz), Fort Knox (5.4 Moz), Dublin Gulch (4.1 Moz), Brewery Creek (0.85 Moz), and True North (0.79 Moz). The province encompasses a wide variety of gold deposits, including orogenic lode-style deposits, epithermal gold deposits, extensive placer-gold deposits, and the recently recognized class of intrusion-related gold deposits (Goldfarb et al., 2000; Hart et al., 2002). Gold mineralisation took place following deformation and metamorphism associated with the collision of exotic terranes and North America, and continued subduction of the Farallon plate under the Cordilleran margin, and in many areas, was co-eval with the emplacement of calc-alkaline plutons (Goldfarb et al., 2000).

Within the TGP, gold deposits that bear the strongest spatial and temporal relationships to intrusive rocks are those associated with the 92 Ma Tombstone Plutonic Suite (*TPS*). The TPS forms a narrow WNW-trending belt that extends for 550 km across the central Yukon, with a continuation in the Fairbanks district of east-central Alaska that was offset by latest Cretaceous to Tertiary displacement along the Tintina Fault. It is the youngest and most northerly (cratonward) of a series of mid-Cretaceous plutonic suites in the Northern Cordillera. Intrusions were emplaced into weakly metamorphosed latest-Proterozoic to Palaeozoic metasedimentary rocks of the Selwyn Basin. Magmatism occurred in a post-collisional setting that followed the waning of mid-Cretaceous subduction. The TPS is characterized by numerous isolated magmatic centres that feature either a number of intrusions of varying composition, a multiphase composite pluton, or a single pluton. Individual intrusions are rarely larger than 5 km in length. Intrusions are calc-alkaline to alkalic, predominantly I-type, and mostly intermediate to felsic, with calc-alkaline lamprophyres also common in many locations. Although both magnetite- and ilmenite-bearing intrusions occur, titanite-bearing intrusions are dominant, suggesting an oxidation state intermediate between magnetite- and ilmenite-series intrusions.

Scheelite Dome is located in the central Yukon, and features a variety of tungsten and gold mineralization styles hosted in, and adjacent to, a TPS magmatic center. In contrast to other renowned systems associated with TPS magmatism, the majority of mineralization at Scheelite Dome is hosted in hornfelsed metasedimentary strata, rather than TPS intrusive rocks. Soil and stream sediment sampling during initial exploration for primary gold occurrences in the 1990's identified an extensive (approximately 10 x 3 km) gold-in-soil anomaly (>20 ppb Au). Within the anomaly, primary gold occurrences are hosted in a variety of reduced skarns, potassic (biotite) alteration, and quartz veins. A TPS pluton that is approximately 5 x 2 km crops out to the immediate north of the anomaly. The pluton is dominated by an early quartz-monzonite phase. Felsic, intermediate, and mafic dikes are emplaced into both the quartz-monzonite and metasedimentary strata to the immediate south, coincident with the location of the gold-in-soil anomaly. The quartz-monzonite is weakly porphyritic with potassium feldspar megacrysts, and mafic phenocrysts of clinopyroxene, biotite, and minor hornblende. Intermediate dykes are alkalic, with a greater abundance of clinopyroxene and biotite. Mafic dykes include both spessartite and minette lamprophyres. Spessartites are amphibole rich (actinolitic hornblende) with resorbed Cr-diopside phenocrysts. Minnettes contain phlogopite and Al-Ti-Cr-rich augite phenocrysts (Mg# >85). Granite dikes are porphyritic with clinopyroxene, hornblende, biotite and potassium feldspar phenocrysts, in a fine-grained matrix of quartz, plagioclase and potassium feldspar. Subordinate aplite and pegmatite dikes occur within the main quartz-monzonite. Collectively, the intrusive rocks form a spectrum of compositions from granite to lamprophyre (excluding aplitic phases). Determining the relative timing of emplacement is restricted by the limited exposure; however, the quartz-monzonite is clearly the earliest phase, crosscut by all others. Intermediate dikes were emplaced next, followed by granitic dikes. Lamprophyres mostly crosscut all other plutonic phases.

Uranium/Pb zircon and titanite dates for the quartz-monzonite yield an approximate age of 92 Ma, and $^{40}Ar/^{39}Ar$ dates for magmatic biotite from the quartz-monzonite yield an age of 92 Ma, whereas phlogopite from a minette that crosscuts both other intrusive phases and gold mineralization yields an age of 90 Ma (minimum age). This time interval is the window for both magmatism and gold and tungsten mineralization. Hydrothermal alteration overprints the quartz-monzonite, but has mutually crosscutting relationships with granite porphyry and lamprophyre dikes. $^{40}Ar/^{39}Ar$ dates of hydrothermal biotite from gold-bearing potassic alteration yield an age of 91.4 Ma., and hydrothermal biotite from a tungsten-rich quartz vein in the quartz-monzonite yields an age of 91.5 Ma, to confirm the co-eval timing of magmatism and hydrothermal activity.

Despite the compositional variation, all intrusive rock types have similar trace-element concentrations, and are strongly enriched in LILEs and LREE. Primitive mantle-normalized trace-element spider diagrams feature distinct negative Ti, Ta, and Nb anomalies. Intermediate to mafic phases contain elevated Cr concentrations (>100ppm), with spessartites containing >500 ppm Cr. Major-element variation diagrams show linear trends for FeO, MgO and CaO, with high variability for Al_2O_3, K_2O and Na_2O. Most intrusive rock types are weakly metaluminous, except for quartz-monzonites, which are weakly peraluminous. Titanite is common to all phases, ilmenite is rare, and magnetite is present in granite porphyry dykes. Most rocks have heavy $\delta^{18}O$ whole-rock values of 10-12.5*‰*, except some minette dykes, which have lower values of approximately 6-10*‰*. Additionally, all rocks have similar initial $^{87}Sr/^{86}Sr$ ratios of 0.711 – 0.713 and epsilon Nd values range from -8 to -11.5. An investigation of zircons in intermediate and felsic rocks using a high resolution ion microprobe, indicates that the irregular zircon cores, which have an inherited appearance, are mostly either isotopically reset to the age of magmatism, or they are earlier, partially-resorbed magmatic phases from the same event. This suggests that magma temperatures exceeded those estimated for zircon saturation at Scheelite Dome (780-800°C), as determined following the method outlined by Watson and Harrison (1983).

Mafic enclaves of predominantly augite-diopside, biotite (high Mg #) and apatite are common in intermediate dikes, and to a lesser extent in quartz-monzonites. Such material has compositional similarities to minettes, and could represent pockets of frozen, more primitive magma, or possible restite material from the source region. Clinopyroxene is present in all intrusive phases at Scheelite Dome, excluding aplite dykes. Granite porphyry dikes contain diopside (Mg # ~ 60) with rare resorbed Cr-diopside grains (Mg # > 90) that are rimmed by amhibole. Intermediate dykes commonly contain a variety of clinopyroxenes, with resorbed Al-Ti-Cr-rich augite that has Mg numbers in excess of 85 (similar composition to augite in minettes), Cr-Ti-poor augite that has Mg numbers from 65 - 75, and fine diopside amongst quartz and potassium feldspar that has Mg numbers of 60-65. Coronae of fine diopside grains around quartz are also common. Some intermediate dykes also contain unusual miarolitic cavities with concentric bands of quartz-potassium feldspar-carbonate, and diopside. The cavities contain primary low-salinity aqueous-carbonic fluid inclusions, which are very similar in bulk constituents to fluid inclusions identified in the gangue assemblages of ore specimens.

Tombstone plutonic suite rocks at Scheelite Dome cover a broad spectrum of compositions from mafic to felsic. Lamprophyres represent the mafic end member and are interpreted to be of a mantle origin, with their ultra-potassic nature, extreme enrichment of LREE and LILE's, and strongly radiogenic isotopic signature indicative of an enriched lithospheric mantle source. In contrast to minettes, all spessartites have heavier $\delta^{18}O$ whole-rock values (>10*‰*) that support greater crustal interaction. Felsic to intermediate phases all feature heavy $\delta^{18}O$ whole-rock values, radiogenic intial $^{87}Sr/^{86}Sr$ ratios, and apparent zircon inheritance, which all support a significant crustal component. However, similar radiogenic isotope signatures and similar trace element compositions across all intrusive phases, and the presence of primitive pyroxenes and mafic enclaves in more-evolved intrusive phases suggest strong genetic ties between the different plutonic phases. Collectively, the data support a model of localized crustal underplating by lamprophyric melts, with the influx of volatiles and heat promoting subsequent melting of the crust. The resultant felsic to intermediate melts have geochemical features indicative of a crustal component, but also have features common to the lamprophyres. Mafic magmatism continued with, and succeeded, felsic magmatism, resulting in intermediate dikes with strong petrographic and geochemical evidence for magma mingling.

Both field relationships and geochronology support a genetic relationship between gold (and tungsten) deposits at Scheelite Dome, and intrusive rocks of the TPS. The more evolved TPS magmas are similar to those more commonly associated with tungsten deposits (Candela, 1995), whereas the more primitive lamprophyric rocks are similar to alkaline rocks more commonly associated with some gold deposits (Muller and Groves, 1994; Jensen and Barton, 2000). In concert with the unusual setting for both gold mineralization and magmatism, TPS rocks can be considered anomalous: the product of a complex hybridized magma system that has both an enriched mantle and crustal component. Moreover, this study suggests that the this style of intrusion-related gold deposits may be derived from highly specific magma types that are not present in the normal fore-arc settings of the more common orogenic gold deposits (Groves et al., 2003).

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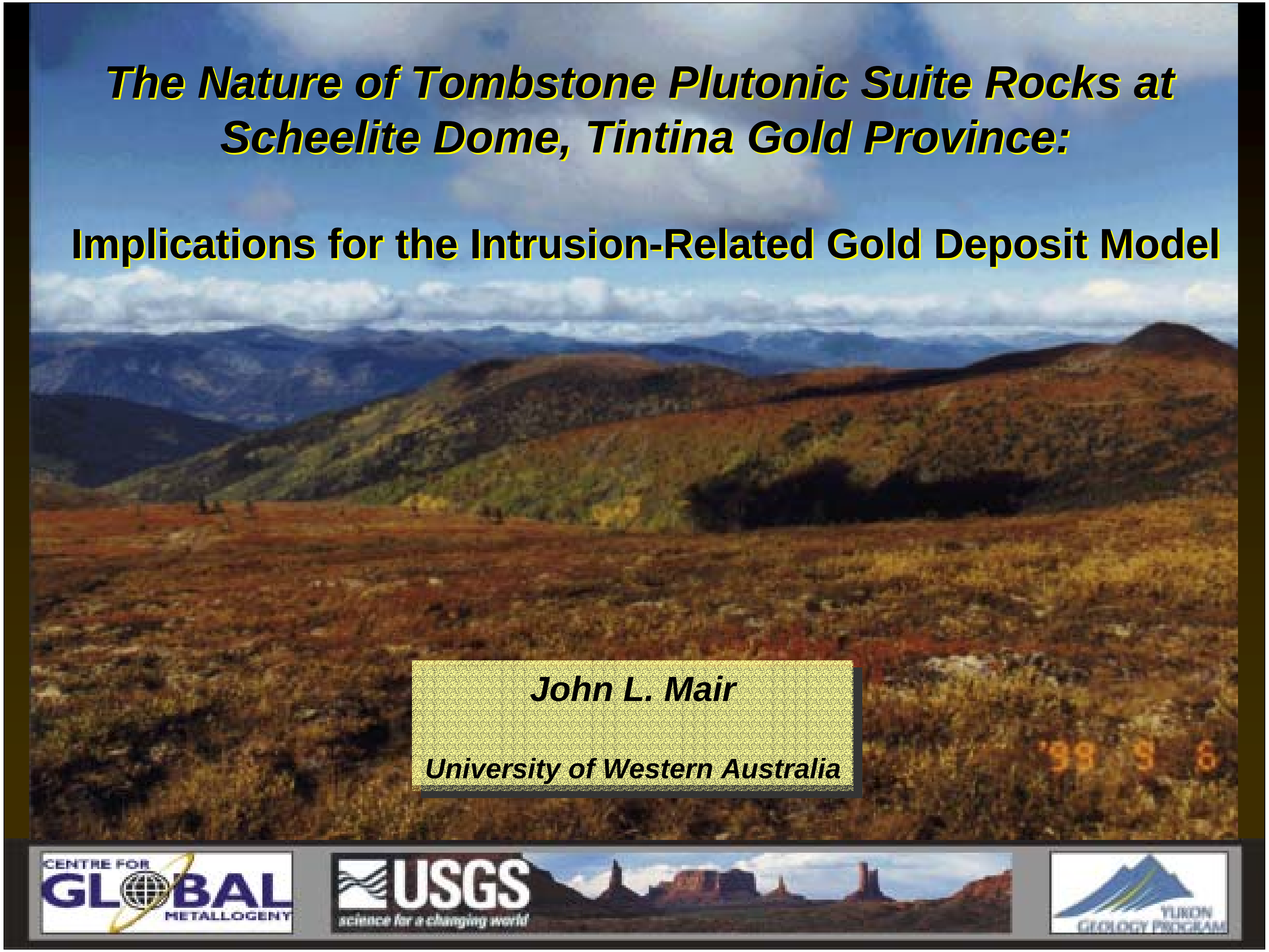
The Nature of Tombstone Plutonic Suite Rocks at Scheelite Dome, Tintina Gold Province:
Implications for the Intrusion-Related Gold Deposit Model
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Overview

- **The intrusion-related Au deposit model**
- **The *Tintina Gold Province***
- **The *Tombstone Plutonic Suite (TPS)***
- **Scheelite Dome**
    - ***Geology, mineralisation styles***
  - **TPS rocks**
    - ***Types, field relations, absolute timing***
    - ***Mineralogy, chemistry, textures***
    - ***Source***
- **Regional comparisons**
- **Implications for the *intrusion-related Au-deposit* model**

The Intrusion-Related Au Deposit Model

- **Magmatic-hydrothermal systems**
  - ***Porphyry – Cu, Mo, Au***
  - ***High sulfidation epithermal Au ???***
  - ***Sn & W skarns, greisens***
  - ***Gold deposits associated with alkaline magmatism***

- **And Now….. *“Intrusion-related gold”***
  - **Inboard of convergent plate boundaries**
  - **Magmatic provinces known for Sn and/or W**
  - **Metaluminous, sub-alkalic, weakly reduced intrusions**
  - **Au associated with Bi, Te, W, As +/- Mo, Sb**
  - **Aqueous-carbonic, low-salinity fluids**
  - **Sheeted vein complexes, replacements, skarns**

The Controversy

- **Despite numerous review-style papers – very little data exists….**
  - **Did the intrusions contribute fluids and metals exotic to the deposit environment, or are such components sourced from local country rocks??**
  - **If so…**
    - ***What is special about these intrusive rocks ?***
    - ***How are they generated ?***
    - ***In what kind of setting are they generated ?***
    - ***What tectonic history has an area undergone to be conducive to generating such magmas ?***
- **Existing data indicates such systems occur in convergent margin settings, and have similar hydrothermal characteristics to orogenic Au deposits**
  - **These factors have sparked contention and confusion**


The Tintina Gold Province
North America
ARCTIC OCEAN
Greenland (Denmark)
EUROPE
Arctic Circle
80° N
60° N
Bering Sea
Beaufort Sea
Baffin Bay
Alaska (U.S.)
Tintina Province
Labrador Sea
Canada
Hudson Bay
Canadian Shield
Great Plains
Rocky Mts.
Coast Ranges
Colorado Mineral Belt
Carlin
0 1,000 Miles
0 1,000 Kilometers
180°
Hawaii (U.S.)
PACIFIC OCEAN
0° Equator
160° W
120° W
40° N
20° W
Tropic of Cancer
20° N
Bermuda (U.K.)
40° W
Gulf of Mexico
Mexico
CARIBBEAN
Cuba
Haiti
Puerto Rico (U.S.)
Jamaica
Dominican Republic
Belize
Honduras
Guatemala
El Salvador
Nicaragua
Costa Rica
Panama
SOUTH AMERICA
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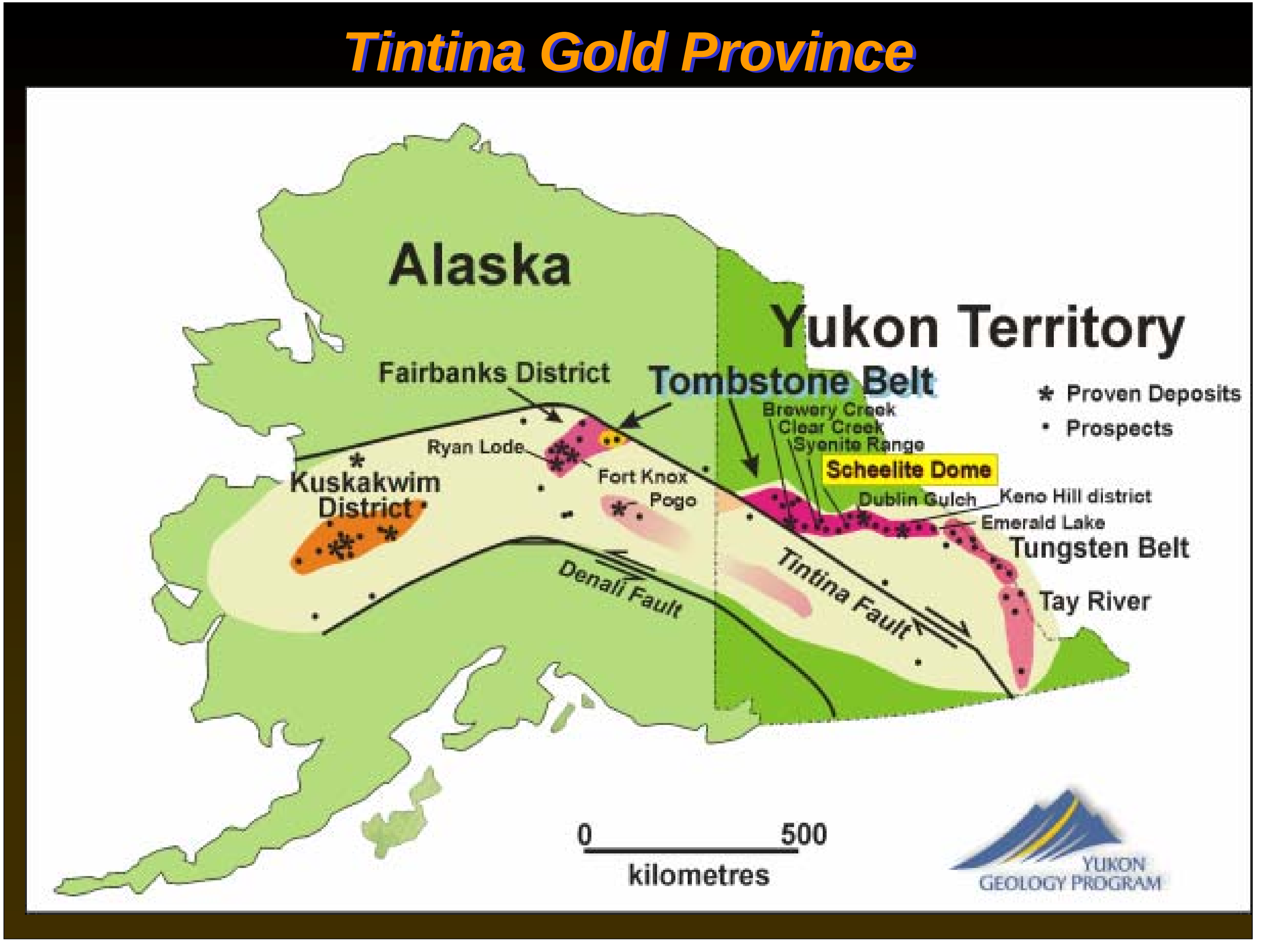
Tintina Gold Province
Alaska
Yukon Territory
Fairbanks District
Tombstone Belt
Ryan Lode
Fort Knox
Pogo
Kuskakwim
District
Brewery Creek
Clear Creek
Syenite Range
Scheelite Dome
Dublin Gulch
Keno Hill district
Emerald Lake
Tungsten Belt
Tay River
Denali Fault
Tintina Fault
* Proven Deposits
• Prospects
0
500
kilometres
YUKON
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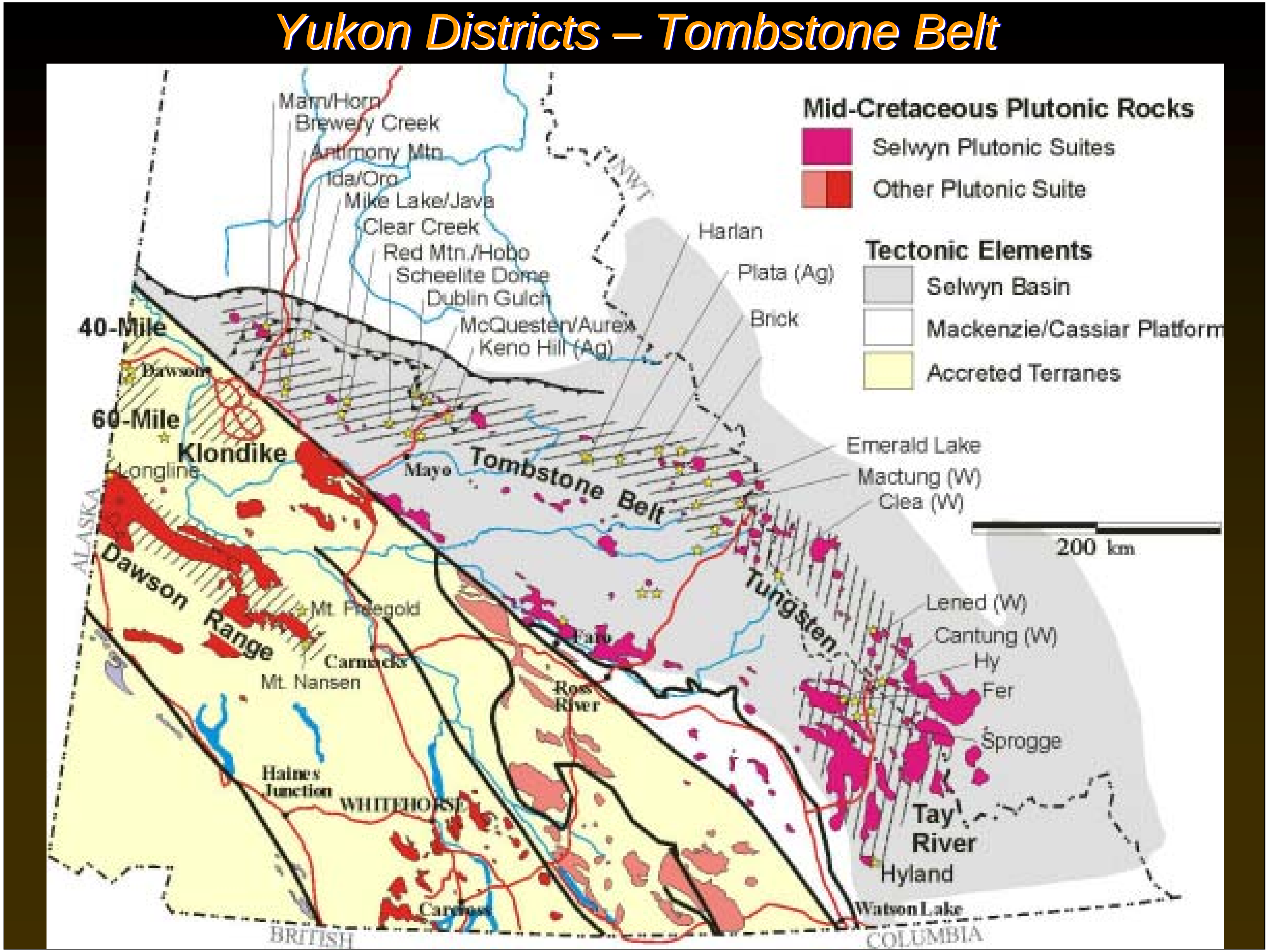
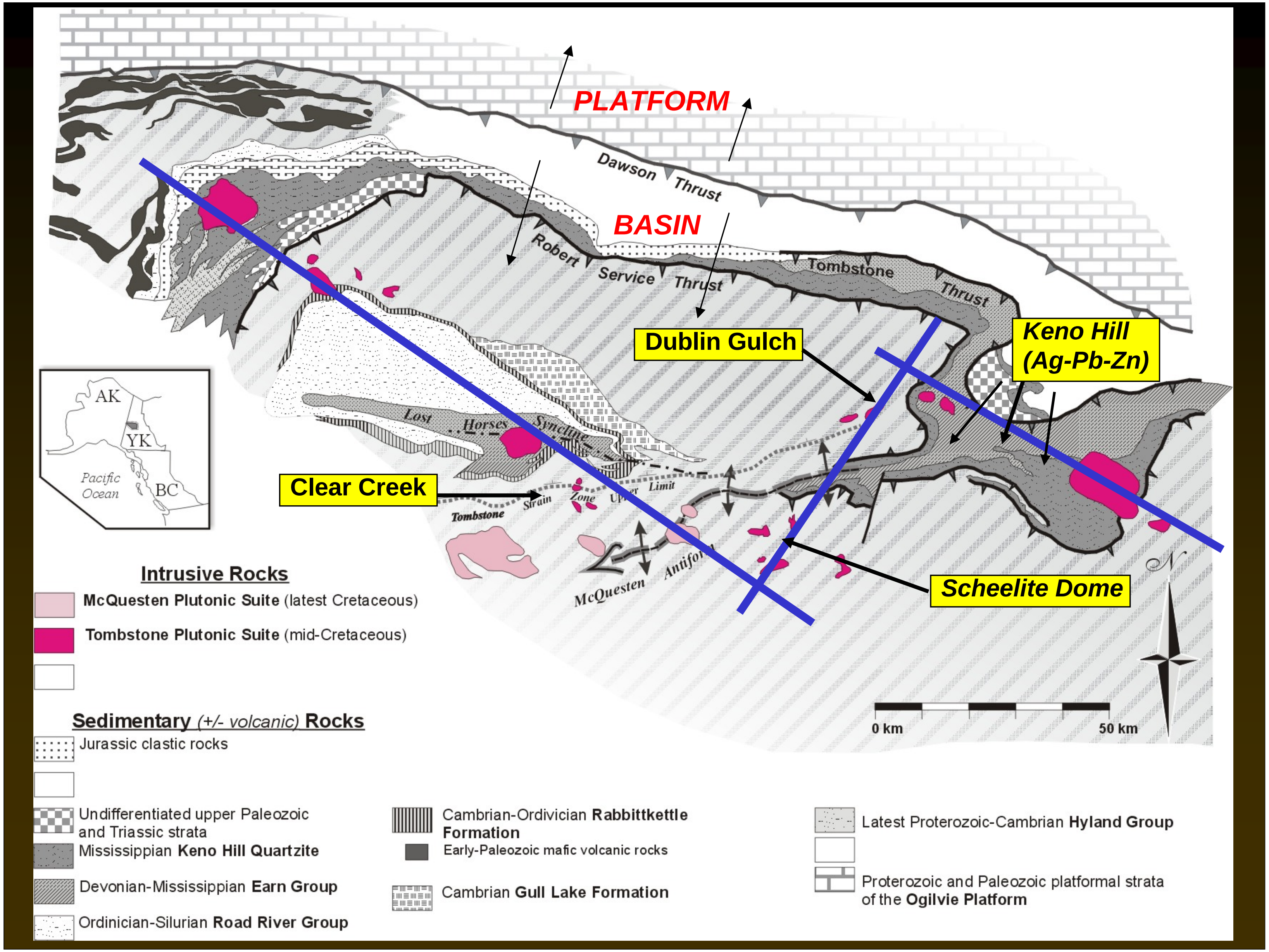
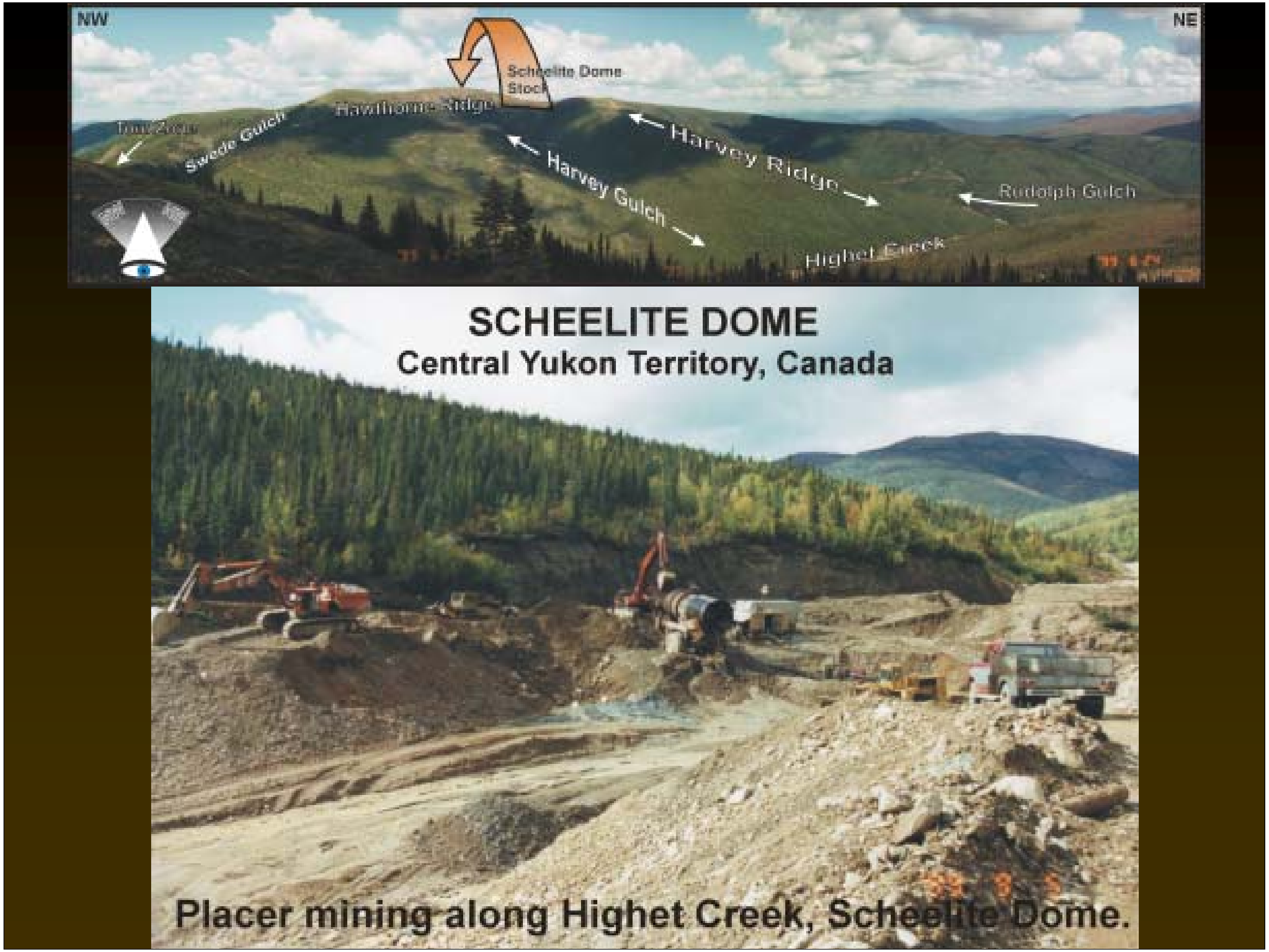

Yukon Districts – Tombstone Belt
Mid-Cretaceous Plutonic Rocks
Selwyn Plutonic Suites
Other Plutonic Suite
Tectonic Elements
Selwyn Basin
Mackenzie/Cassiar Platform
Accreted Terranes
Marn/Horn
Brewery Creek
Antimony Mtn
Ida/Oro
Mike Lake/Java
Clear Creek
Red Mtn./Hobo
Scheelite Dome
Dublin Gulch
McQuesten/Aurex
Keno Hill (Ag)
Harlan
Plata (Ag)
Brick
Emerald Lake
Mactung (W)
Clea (W)
200 km
Lened (W)
Cantung (W)
Hy
Fer
Sprogge
Tay River
Hyland
Watson Lake
NWT
40-Mile
Dawson
60-Mile
Klondike
Longline
Mayo
Tombstone Belt
Tungsten
Dawson Range
Mt. Freegold
Carmacks
Mt. Nansen
Faro
Ross River
Haines Junction
WHITEHORSE
ALASKA
BRITISH
COLUMBIA

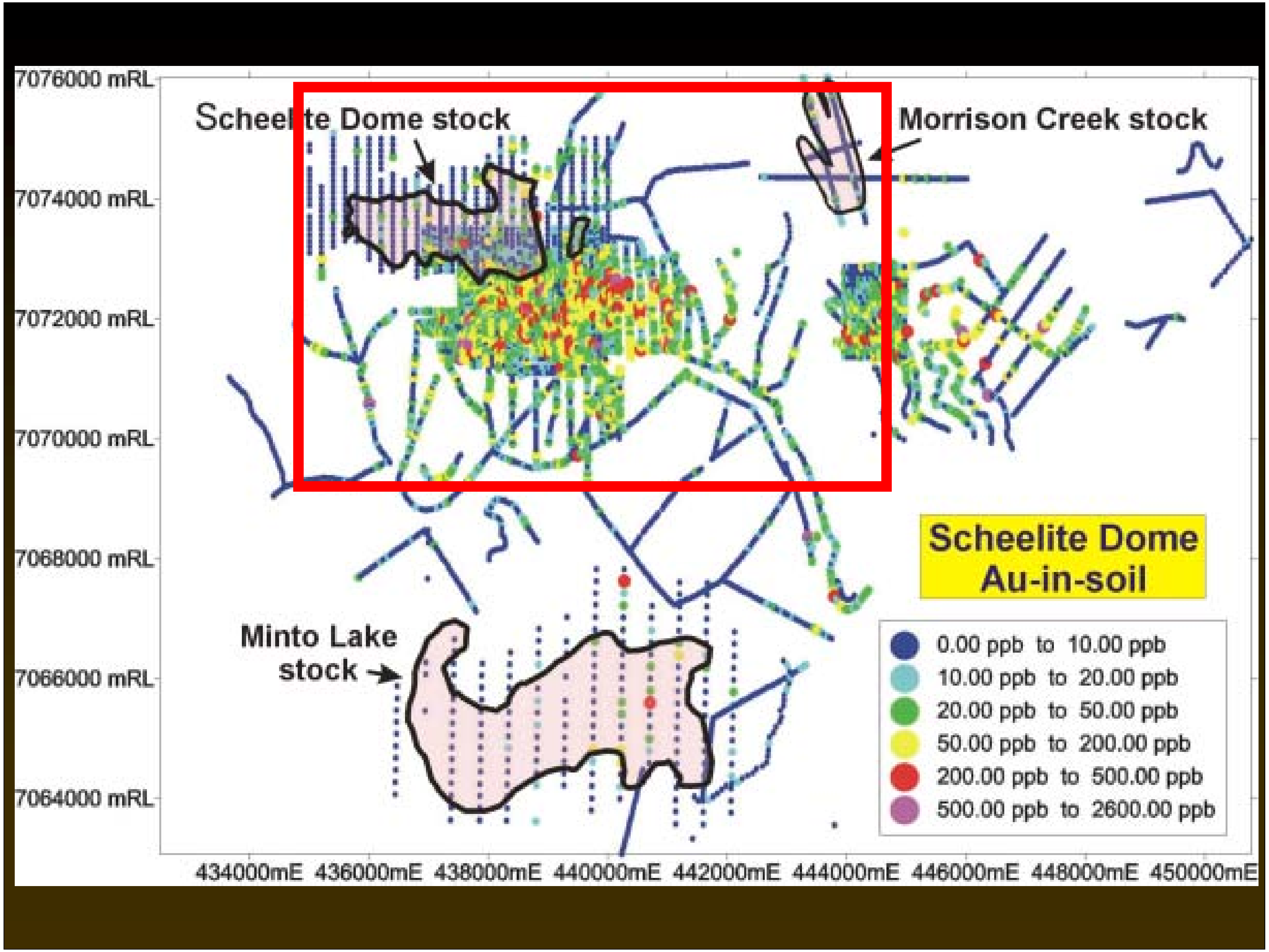
Yukon Districts – Tombstone Belt

Tombstone Plutonic Suite:

- **Youngest, and most inboard *(cratonward)* of mid-K plutonic suites**
- **Isolated intrusive centres that comprise compositionally diverse intrusions.**
- **Individual intrusions rarely > 5 km in exposed length**
- **Calc-alkaline to alkalic, felsic to mafic (felsic dominated)**
- **Weakly oxidised to weakly reduced (titanite-bearing)**
- **Associated with W and Au (± Te, Bi, As) deposits**


PLATFORM
BASIN
Dawson Thrust
Robert Service Thrust
Tombstone Thrust
Dublin Gulch
Keno Hill (Ag-Pb-Zn)
Clear Creek
Scheelite Dome
Lost Horses Syncline
Tombstone Strain Zone
Upper Limit
McQuesten Antiform
AK
YK
BC
Pacific Ocean
0 km
50 km
Intrusive Rocks
McQuesten Plutonic Suite (latest Cretaceous)
Tombstone Plutonic Suite (mid-Cretaceous)
Sedimentary (+/- volcanic) Rocks
Jurassic clastic rocks
Undifferentiated upper Paleozoic and Triassic strata
Mississippian Keno Hill Quartzite
Devonian-Mississippian Earn Group
Ordinician-Silurian Road River Group
Cambrian-Ordivician Rabbittkettle Formation
Early-Paleozoic mafic volcanic rocks
Cambrian Gull Lake Formation
Latest Proterozoic-Cambrian Hyland Group
Proterozoic and Paleozoic platformal strata of the Ogilvie Platform


NW
NE
Scheelite Dome
Stock
Hawthorne Ridge
Swede Gulch
Harvey Ridge
Harvey Gulch
Rudolph Gulch
Highet Creek
SCHEELITE DOME
Central Yukon Territory, Canada
Placer mining along Highet Creek, Scheelite Dome.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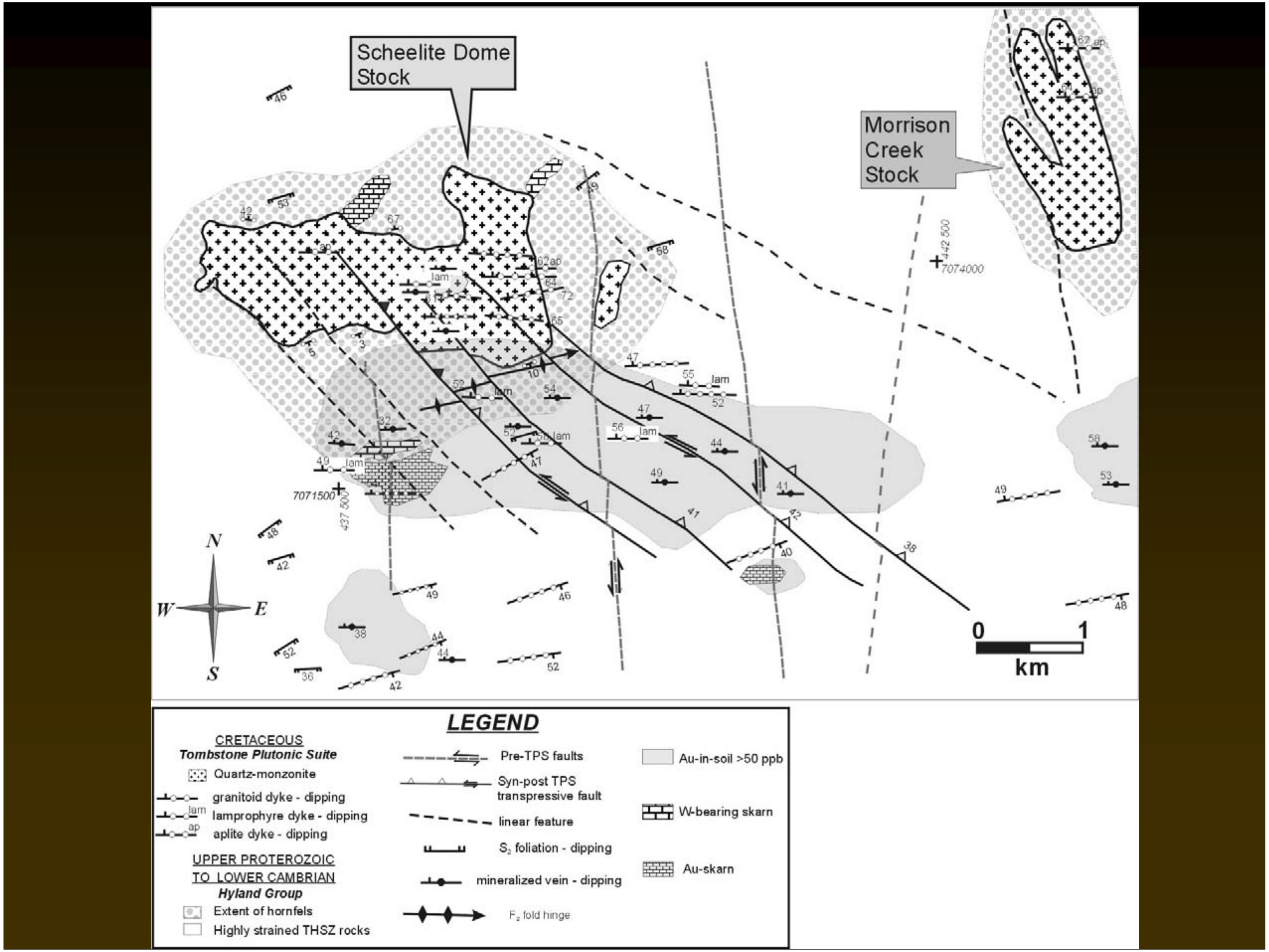
7072000 mRL
7070000 mRL
7068000 mRL
7066000 mRL
7064000 mRL
434000mE 436000mE 438000mE 440000mE 442000mE 444000mE 446000mE 448000mE 450000mE
Scheelite Dome stock
Morrison Creek stock
Minto Lake stock
Scheelite Dome Au-in-soil
0.00 ppb to 10.00 ppb
10.00 ppb to 20.00 ppb
20.00 ppb to 50.00 ppb
50.00 ppb to 200.00 ppb
200.00 ppb to 500.00 ppb
500.00 ppb to 2600.00 ppb


Scheelite Dome Stock
Morrison Creek Stock
N
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W
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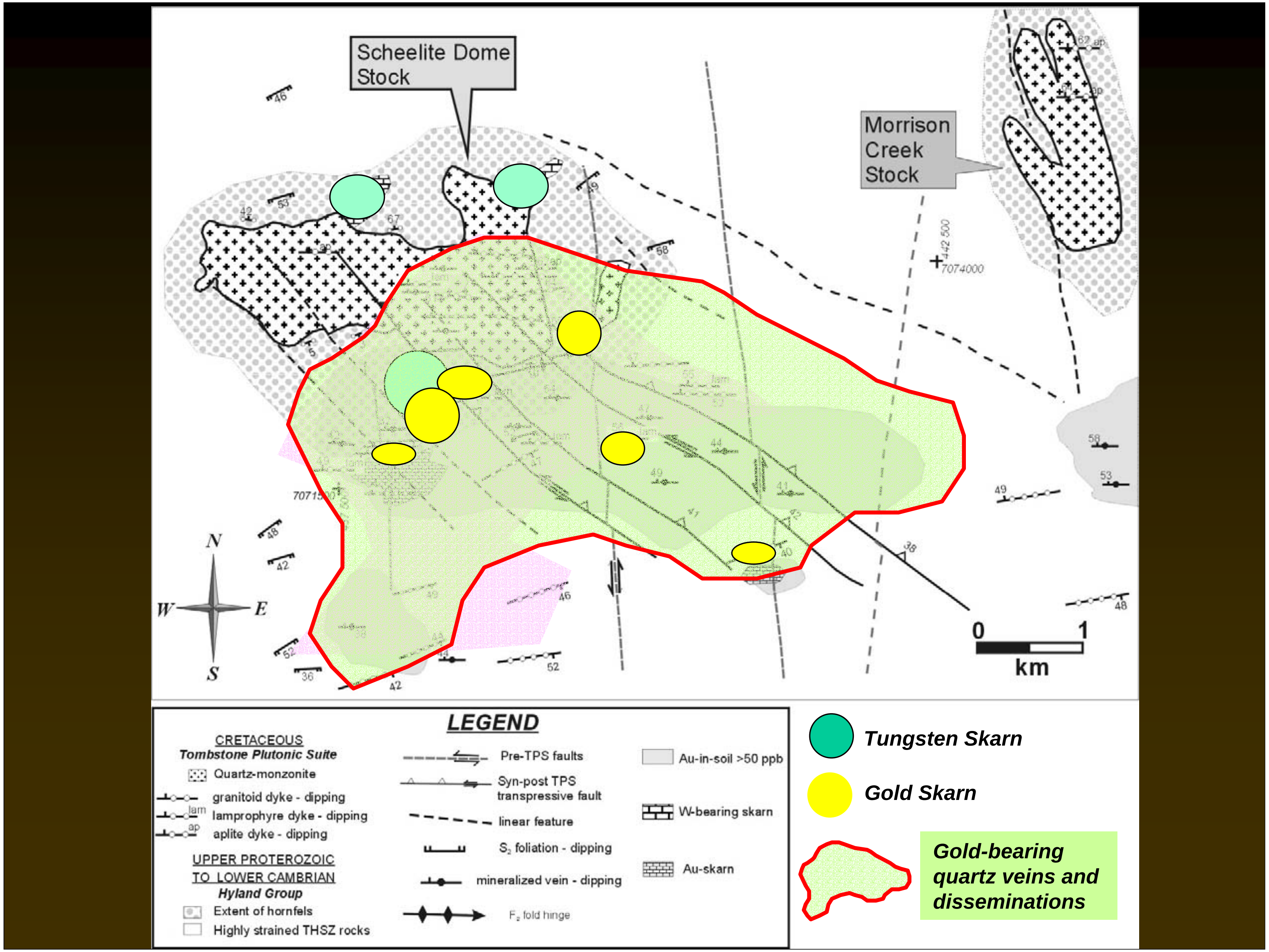
1
km
LEGEND
CRETACEOUS
Tombstone Plutonic Suite
Quartz-monzonite
granitoid dyke - dipping
lamprophyre dyke - dipping
aplite dyke - dipping
UPPER PROTEROZOIC TO LOWER CAMBRIAN
Hyland Group
Extent of hornfels
Highly strained THSZ rocks
Pre-TPS faults
Syn-post TPS transpressive fault
linear feature
S2 foliation - dipping
mineralized vein - dipping
F2 fold hinge
Au-in-soil >50 ppb
W-bearing skarn
Au-skarn


Scheelite Dome Stock
Morrison Creek Stock
N
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LEGEND
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linear feature
S2 foliation - dipping
mineralized vein - dipping
F2 fold hinge
Au-in-soil >50 ppb
W-bearing skarn
Au-skarn
Tungsten Skarn
Gold Skarn
Gold-bearing quartz veins and disseminations


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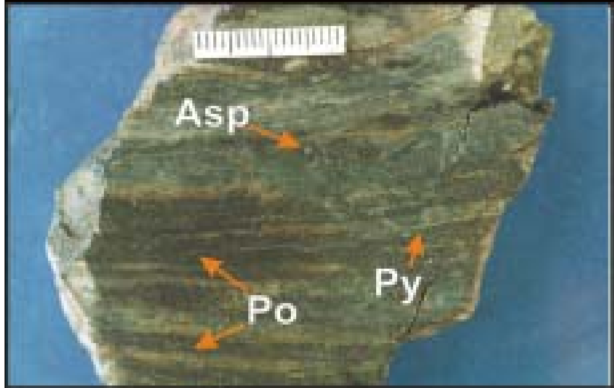
High temperature pervasive mineralisation



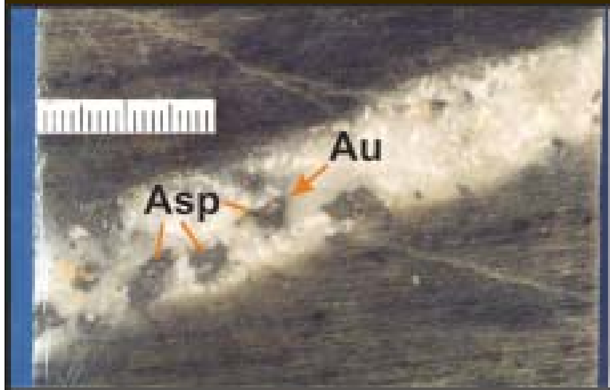
ELEMENT	*FA-4*
Mo	4
Cu	*3927*
Pb	7
Zn	52
Ag	5
As	3367
Sb	36
Bi	*426*
W	*161*
Au	*17*
Te	*12*

Au - skarn
Diopside-plagioclase gangue

ELEMENT	*TZL-1*
Mo	6
Cu	72
Pb	85
Zn	37
Ag	11
As	*99999*
Sb	208
Bi	*3961*
W	*4153*
Au	*152*
Te	*110*

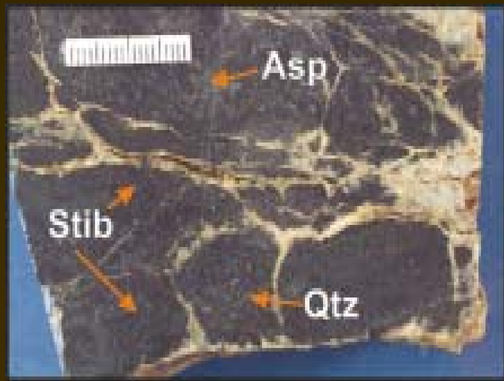
Potassic alteration
Phlogopite gangue

Vein-hosted mineralization *(medium temperature)*



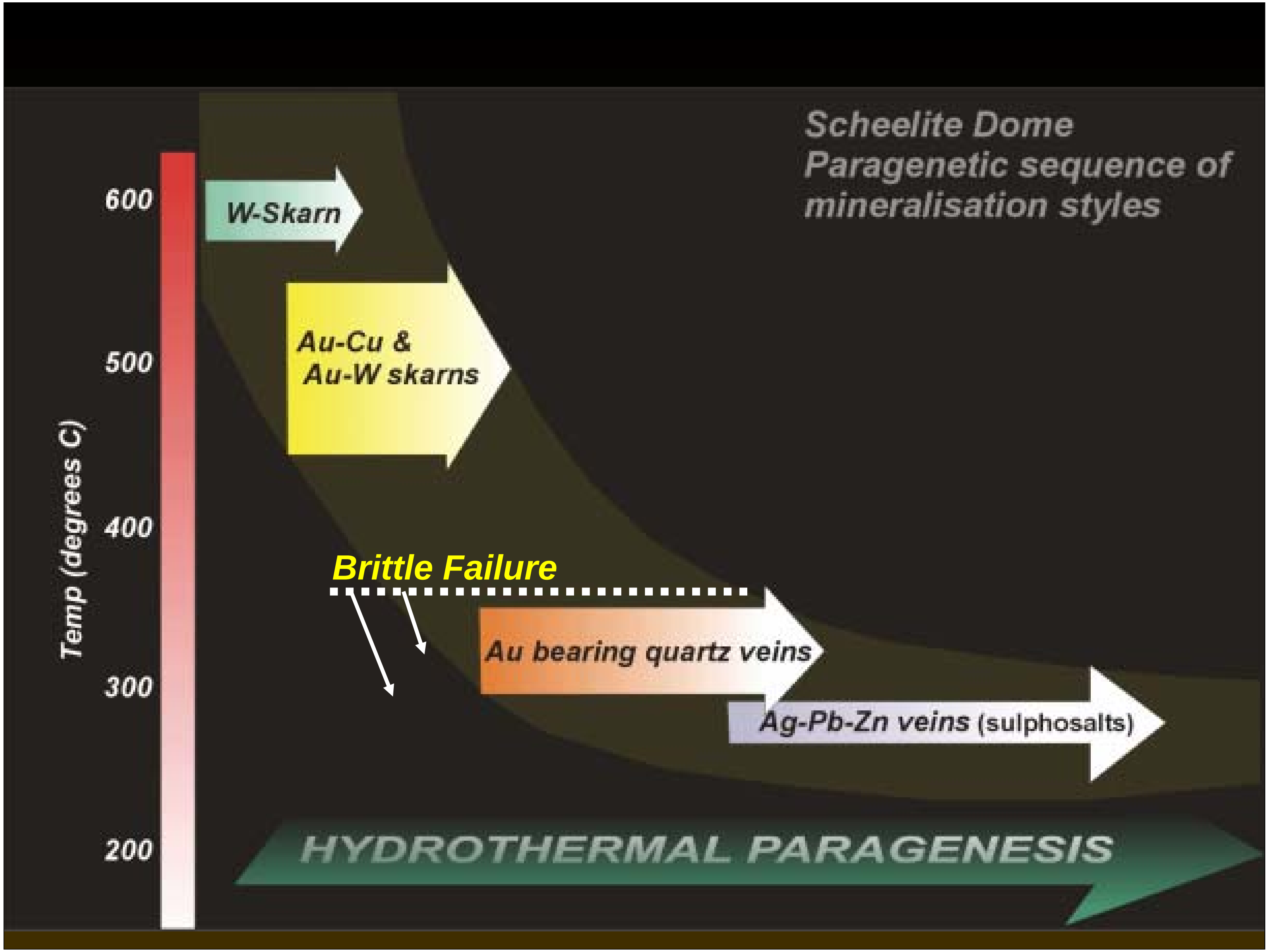
ELEMENT	*SH11-78*
Mo	2
Cu	46
Pb	125
Zn	82
Ag	11
As	*35867*
Sb	84
Bi	*27*
W	< 2
Au	*60*
Te	4

Tension vein



ELEMENT	*1H*
Mo	2
Cu	*1865*
Pb	*21040*
Zn	*173*
Ag	*288*
As	14883
Sb	*20431*
Bi	24
W	3
Au	*2*
Te	0

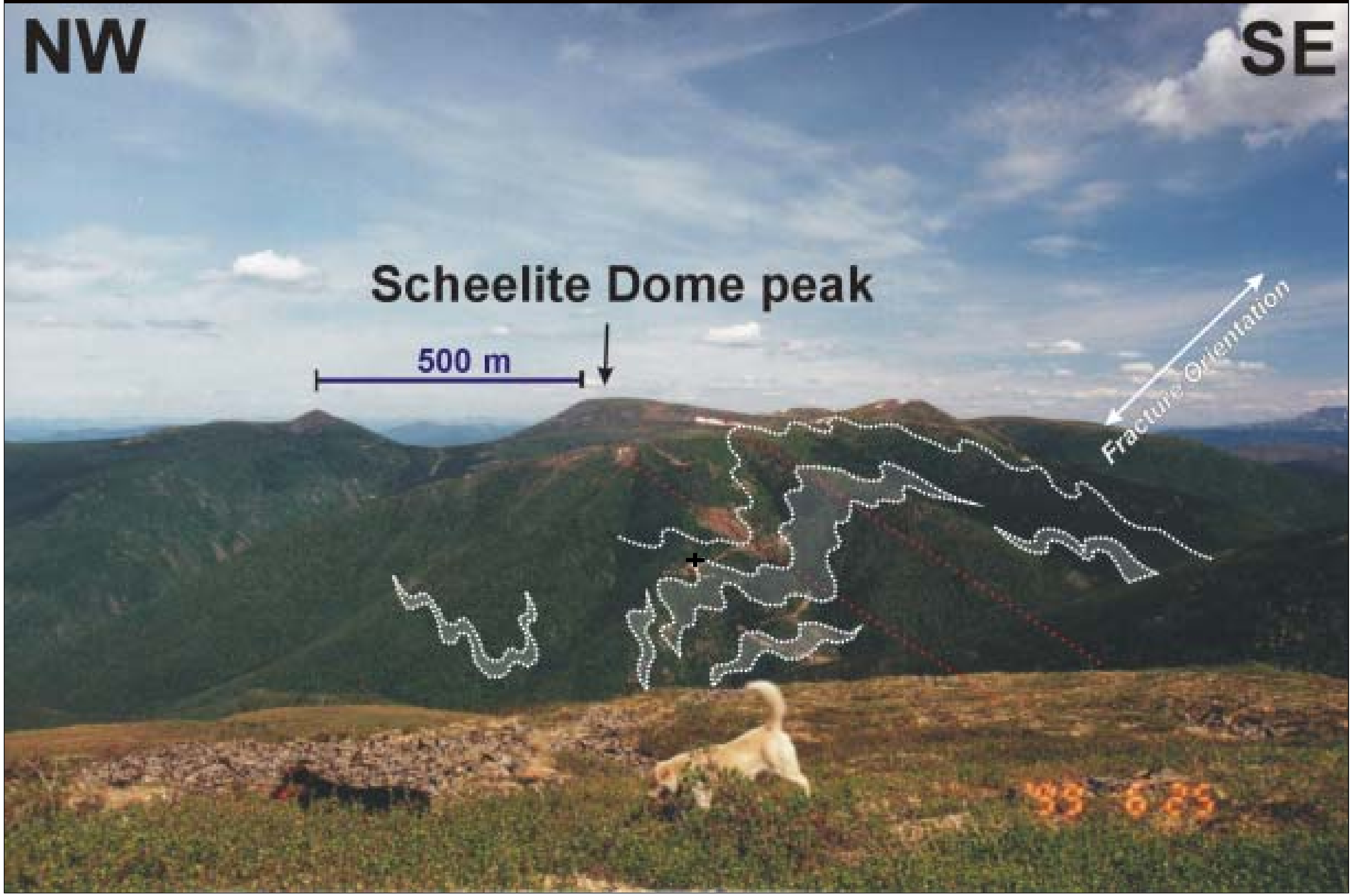
Fault vein


Scheelite Dome
Paragenetic sequence of
mineralisation styles
Temp (degrees C)
600
500
400
300
200
W-Skarn
Au-Cu &
Au-W skarns
Brittle Failure
Au bearing quartz veins
Ag-Pb-Zn veins (sulphosalts)
HYDROTHERMAL PARAGENESIS

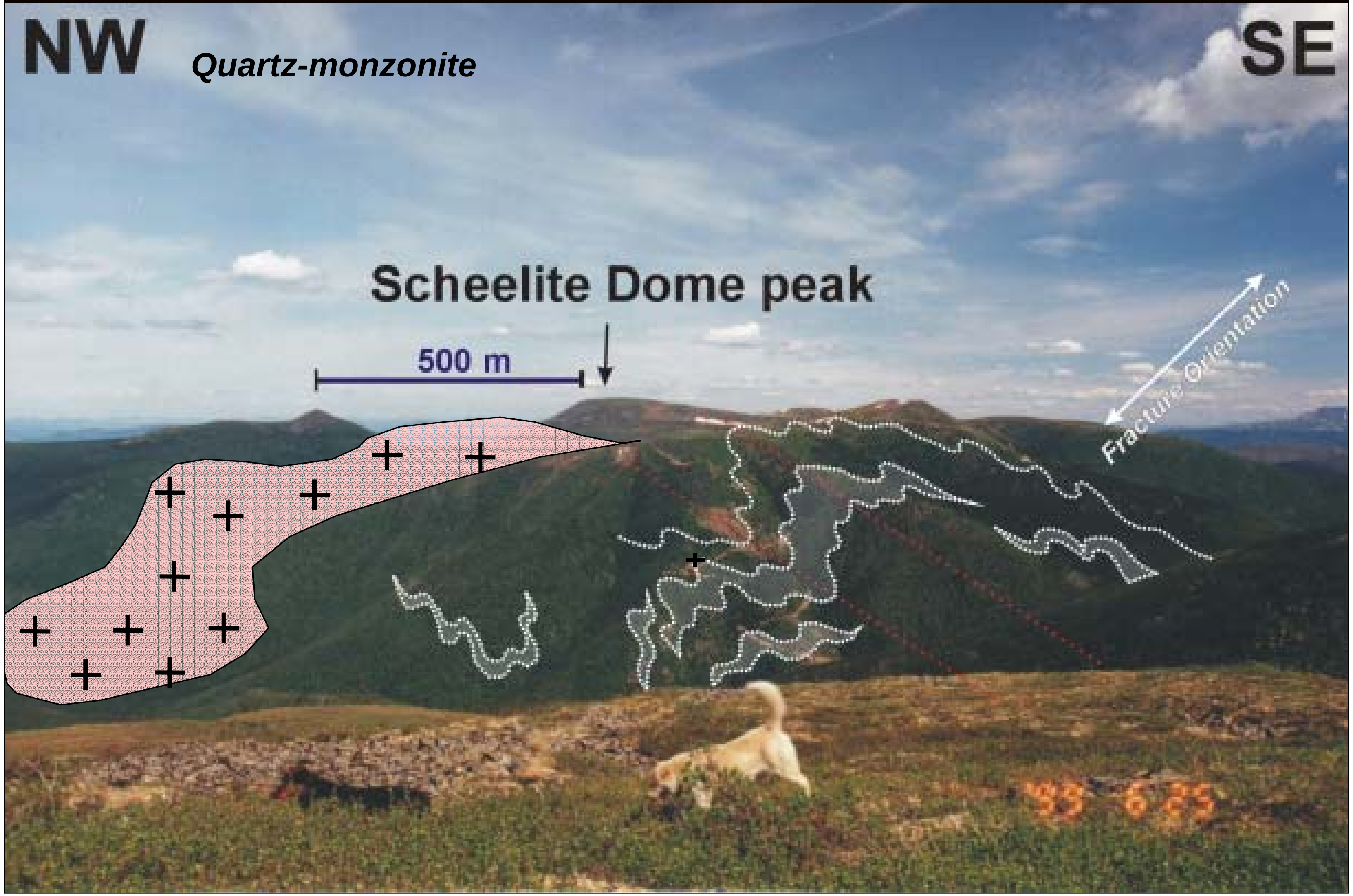
Tombstone Plutonic Suite Rocks at Scheelite Dome

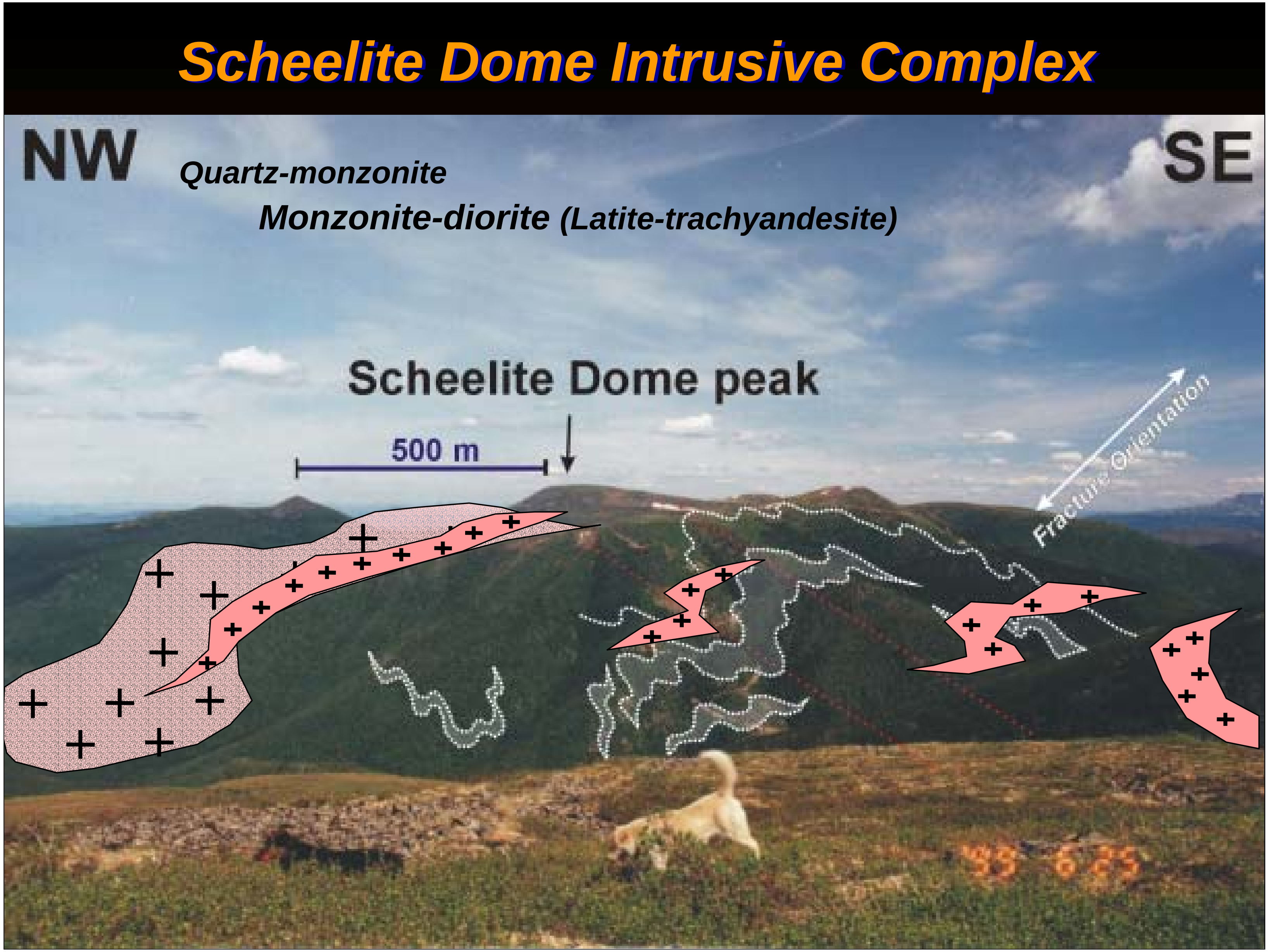
- Variety of stocks and dykes crosscut collision-related deformation fabrics (*post collisional*)
- Emplaced at approximately 6-8 km depth
- Ambient geotherm ~ 250° C or less
- Compositionally diverse
  - *Granite to lamprophyre*

Scheelite Dome Intrusive Complex

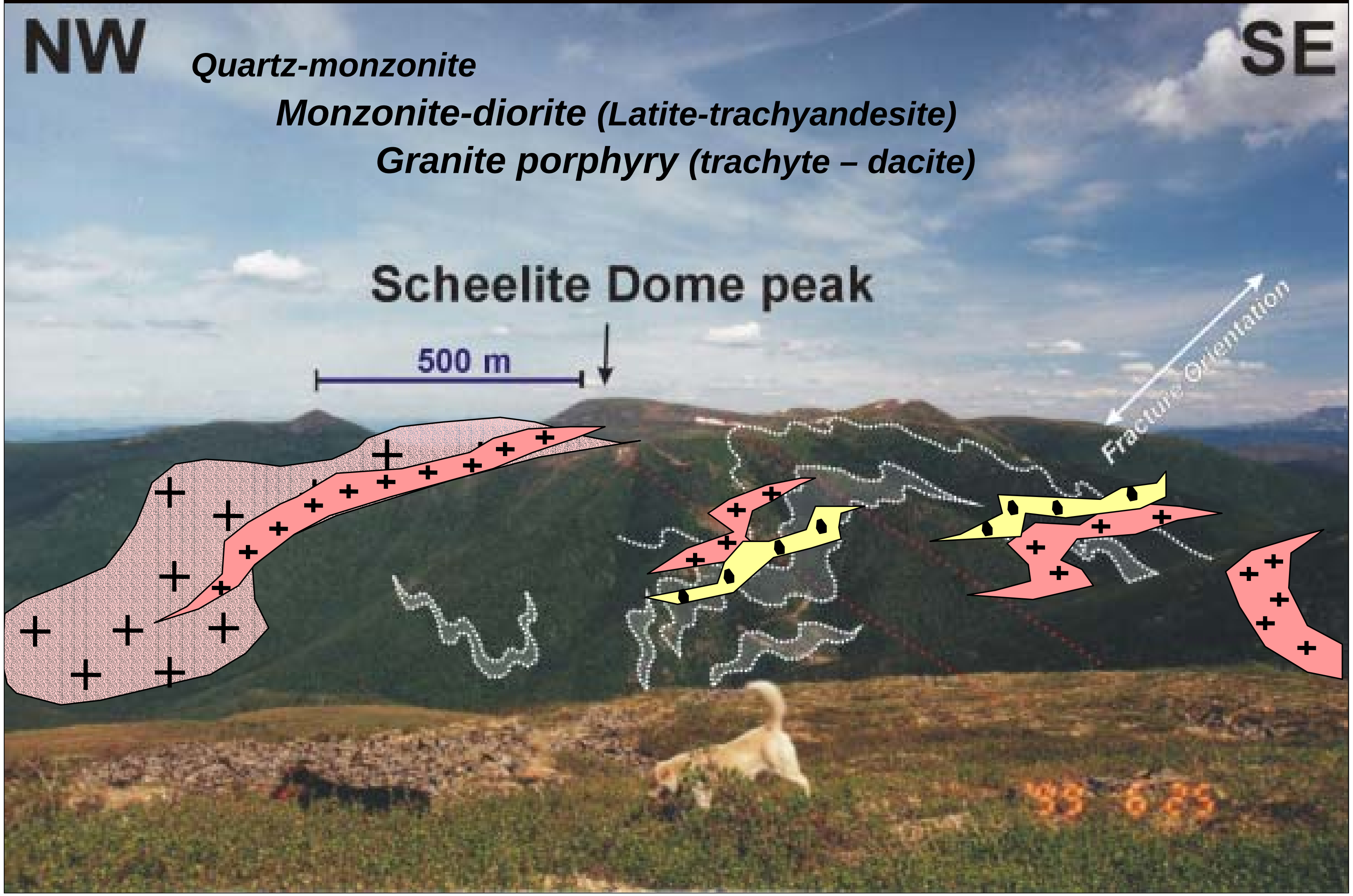


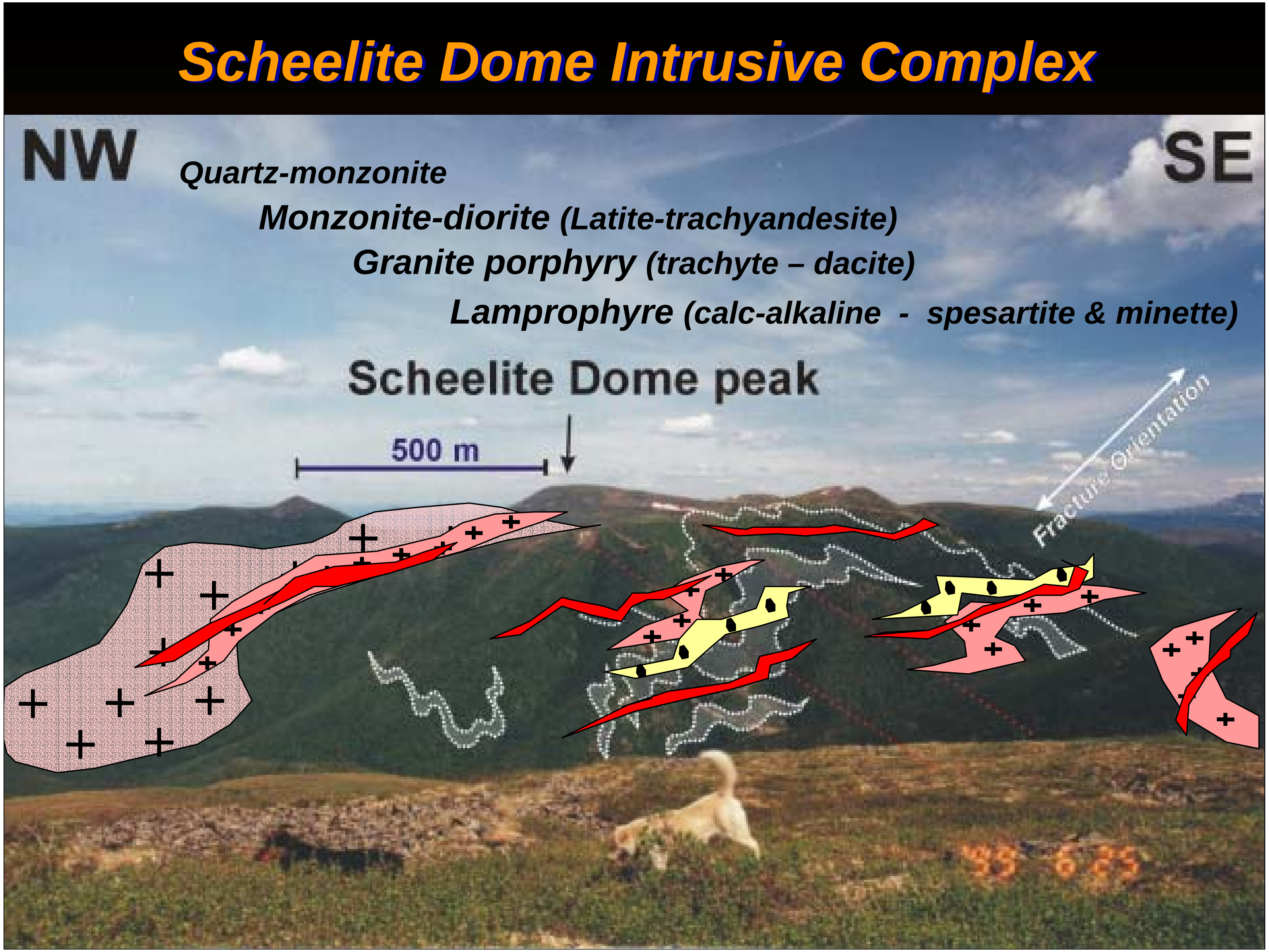
Scheelite Dome Intrusive Complex

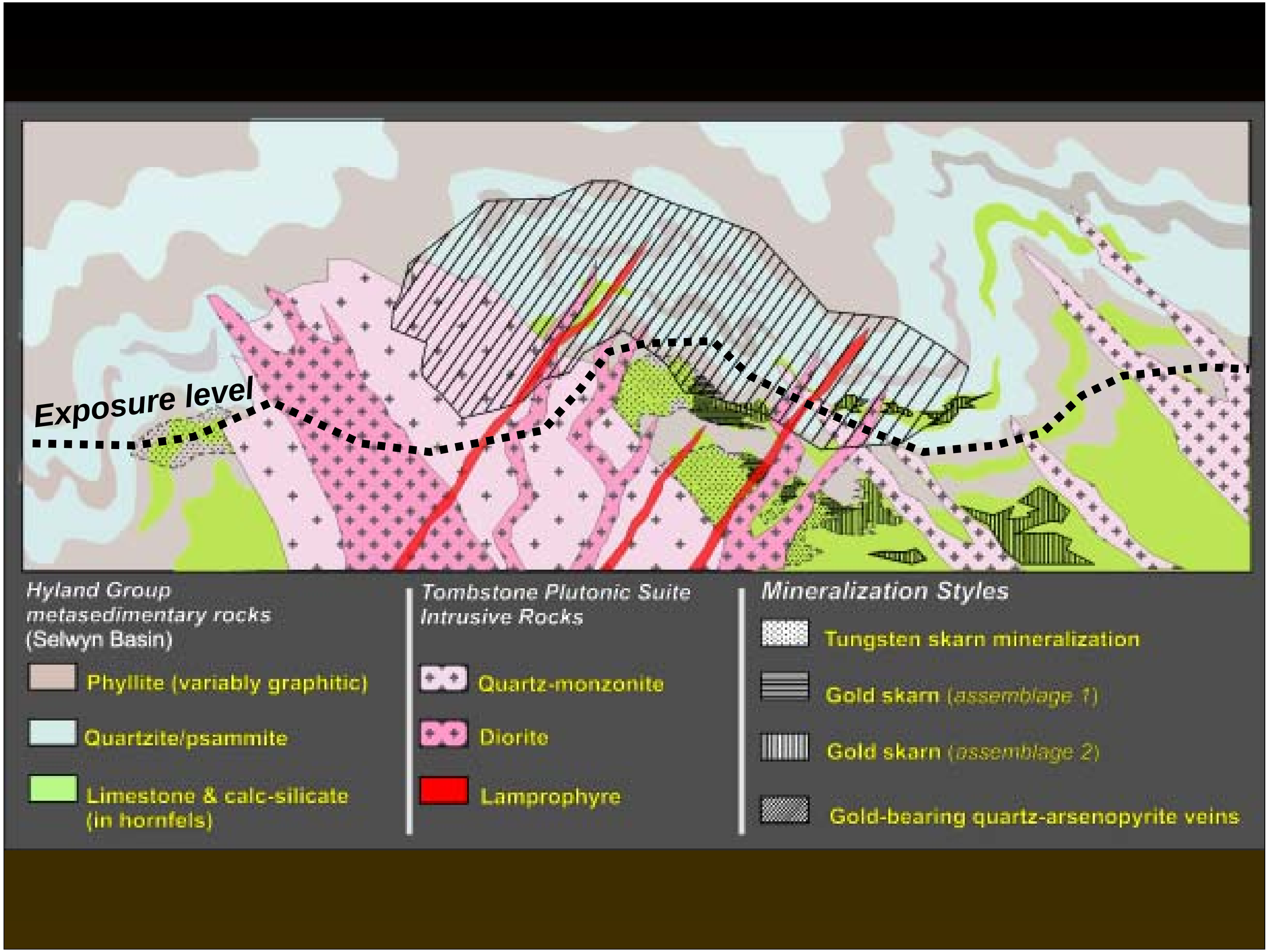



Scheelite Dome Intrusive Complex
NW
SE
Quartz-monzonite
Monzonite-diorite (Latite-trachyandesite)
Scheelite Dome peak
500 m
Fracture Orientation

Scheelite Dome Intrusive Complex

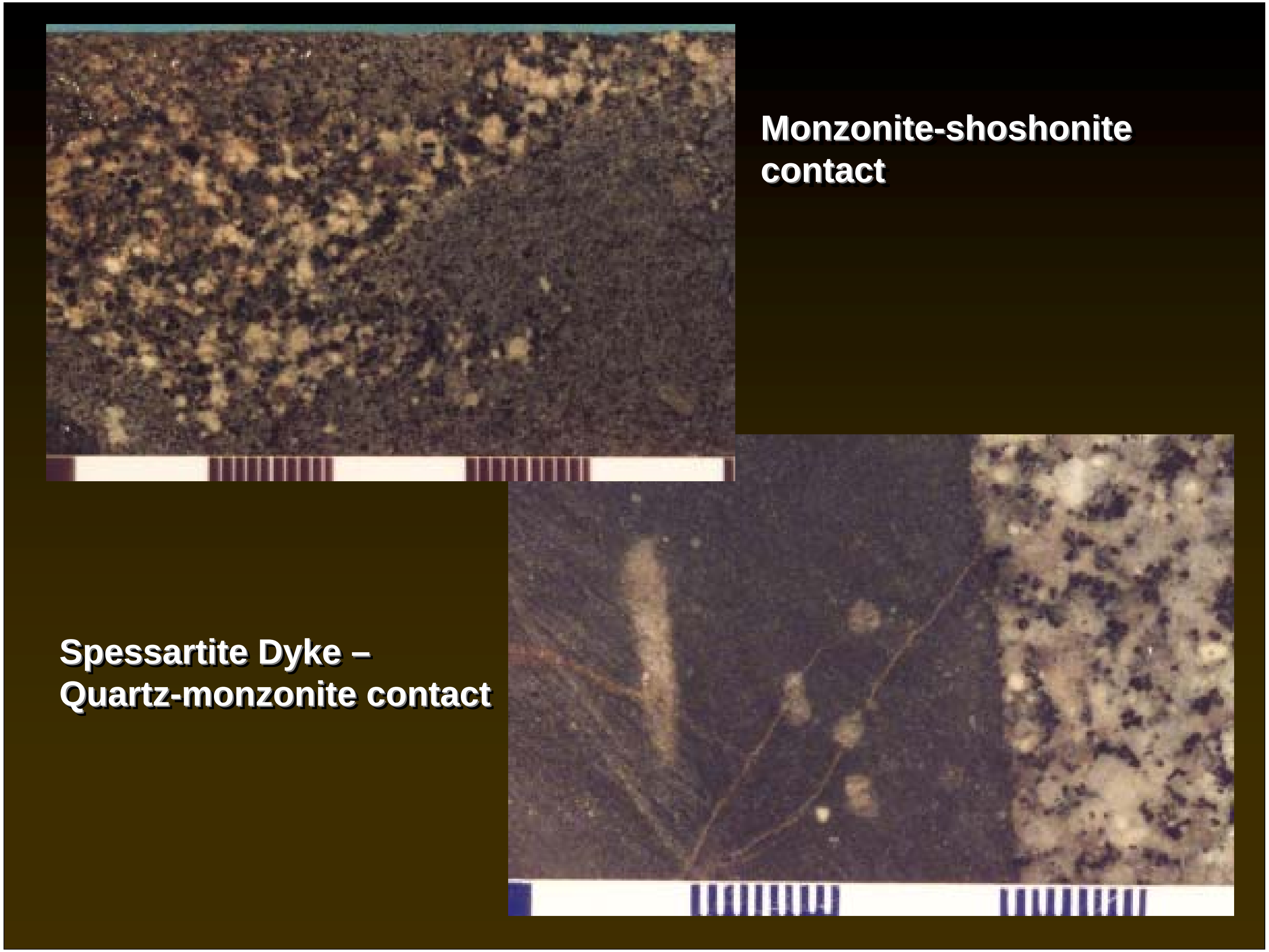


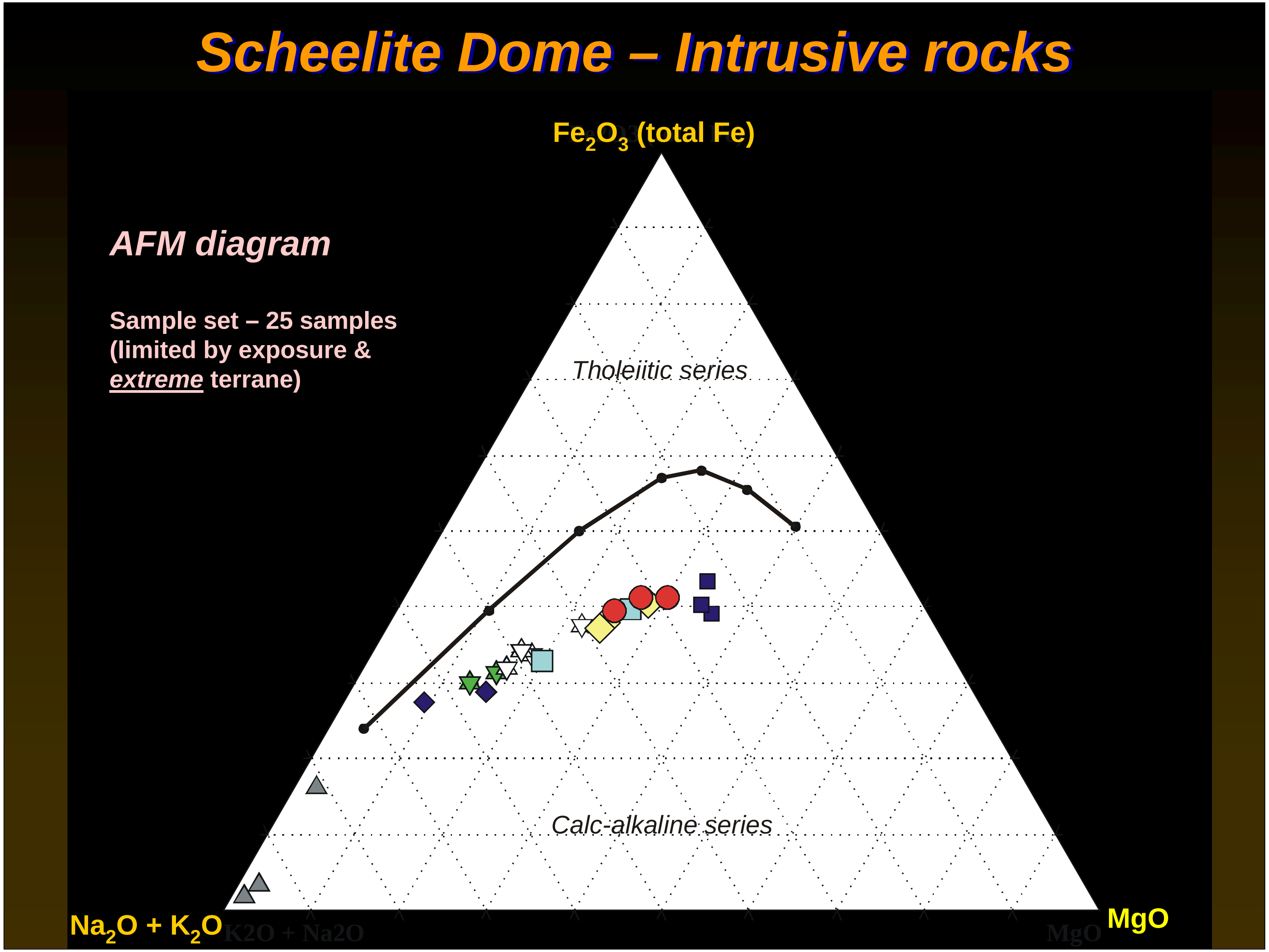

Scheelite Dome Intrusive Complex
NW
SE
Quartz-monzonite
Monzonite-diorite (Latite-trachyandesite)
Granite porphyry (trachyte – dacite)
Lamprophyre (calc-alkaline - spesartite & minette)
Scheelite Dome peak
500 m
Fracture Orientation

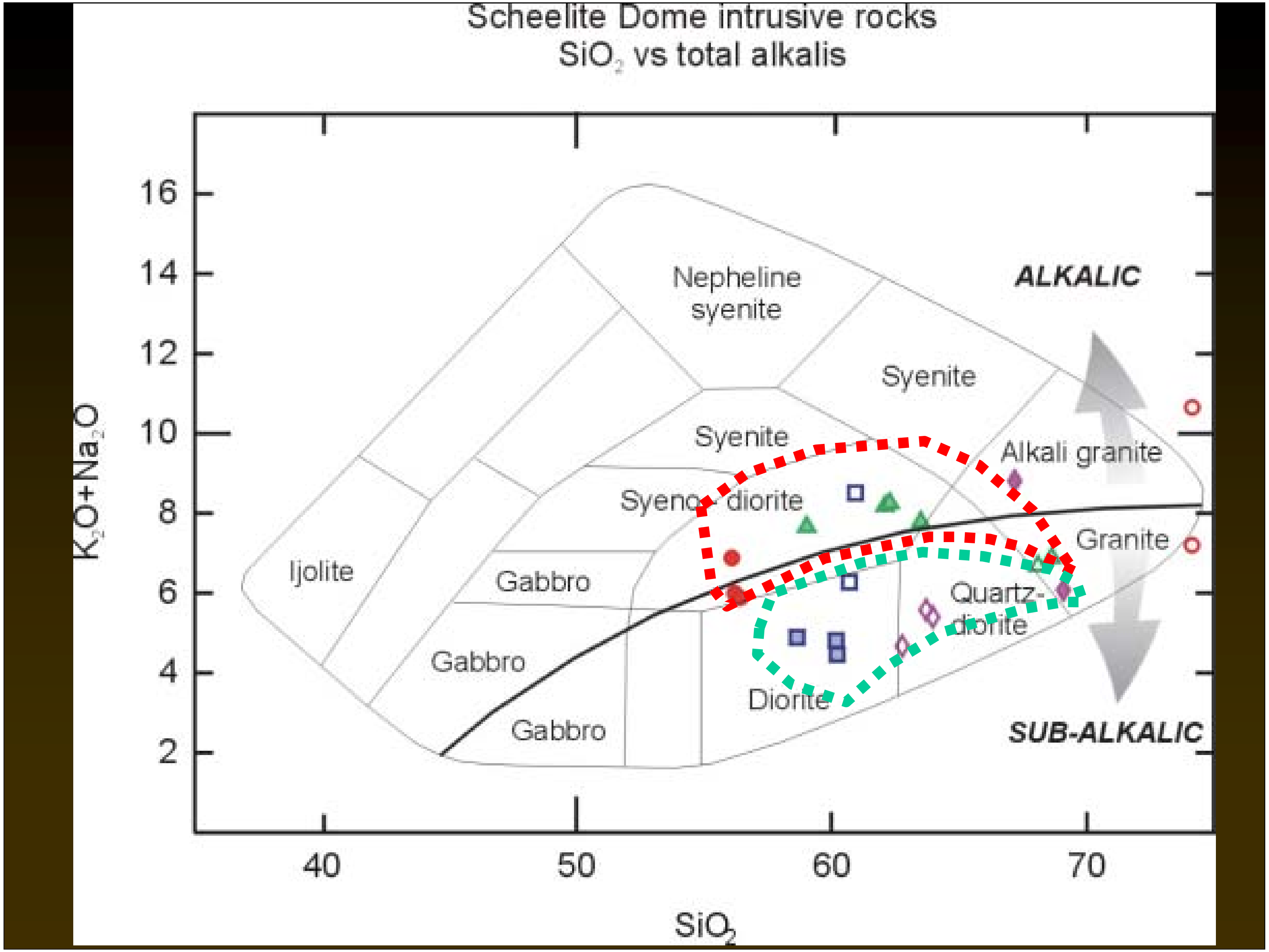

Exposure level
Hyland Group metasedimentary rocks (Selwyn Basin)
Phyllite (variably graphitic)
Quartzite/psammite
Limestone & calc-silicate (in hornfels)
Tombstone Plutonic Suite Intrusive Rocks
Quartz-monzonite
Diorite
Lamprophyre
Mineralization Styles
Tungsten skarn mineralization
Gold skarn (assemblage 1)
Gold skarn (assemblage 2)
Gold-bearing quartz-arsenopyrite veins

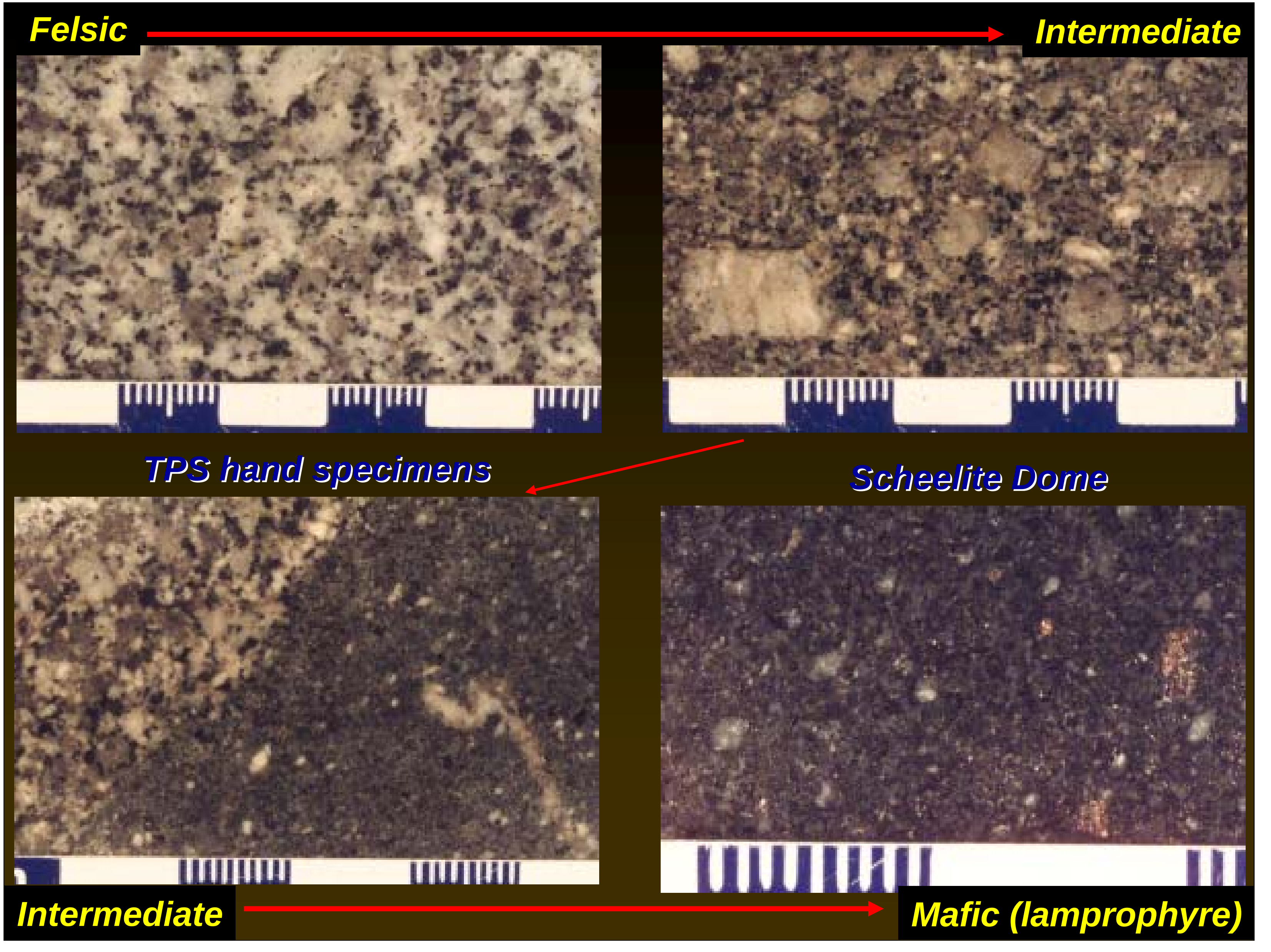
Timing Constraints

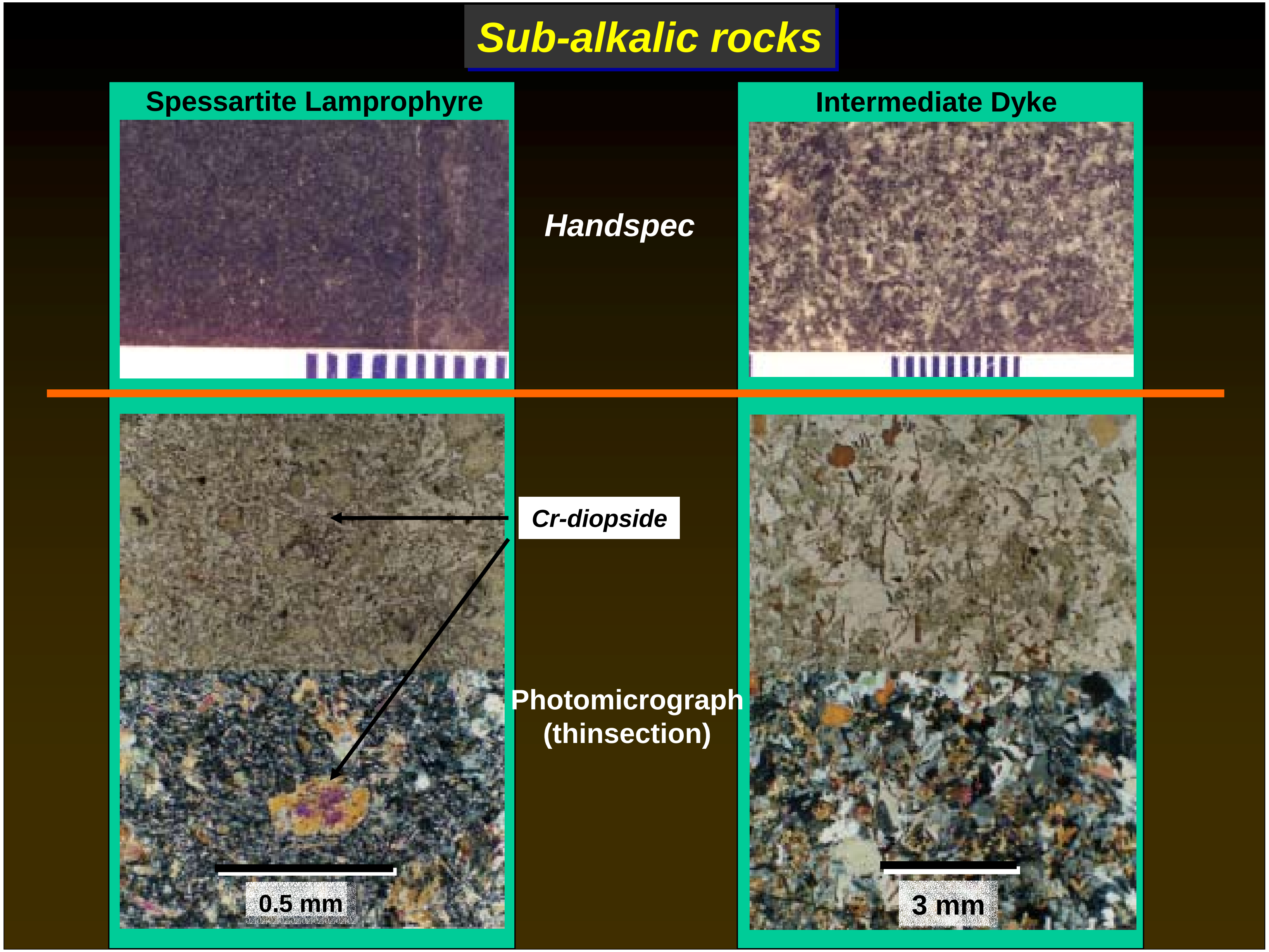
- ***RELATIVE:***
- **Qtz-monzonite cut by all other intrusive phases and hydrothermal assemblages**
- **Monzonite/latite and diorite/trachyandesite dykes emplaced next**
- **Lamprophyre and granite porphyry dykes feature mutually cross cutting relationships with mineralised hydrothermal assemblages**
- ***ABSOLUTE:***
- **Qtz-monzonite – Emplaced @ ~ 92.5 Ma (U/Pb & Ar/Ar)**
  - **Hydrothermal assemblages (Au & W) – 91.5 Ma (Ar/Ar)**
  - **Late minette dyke (x cuts both mineralisation and intrusive rocks) – 91 Ma (Ar/Ar)**

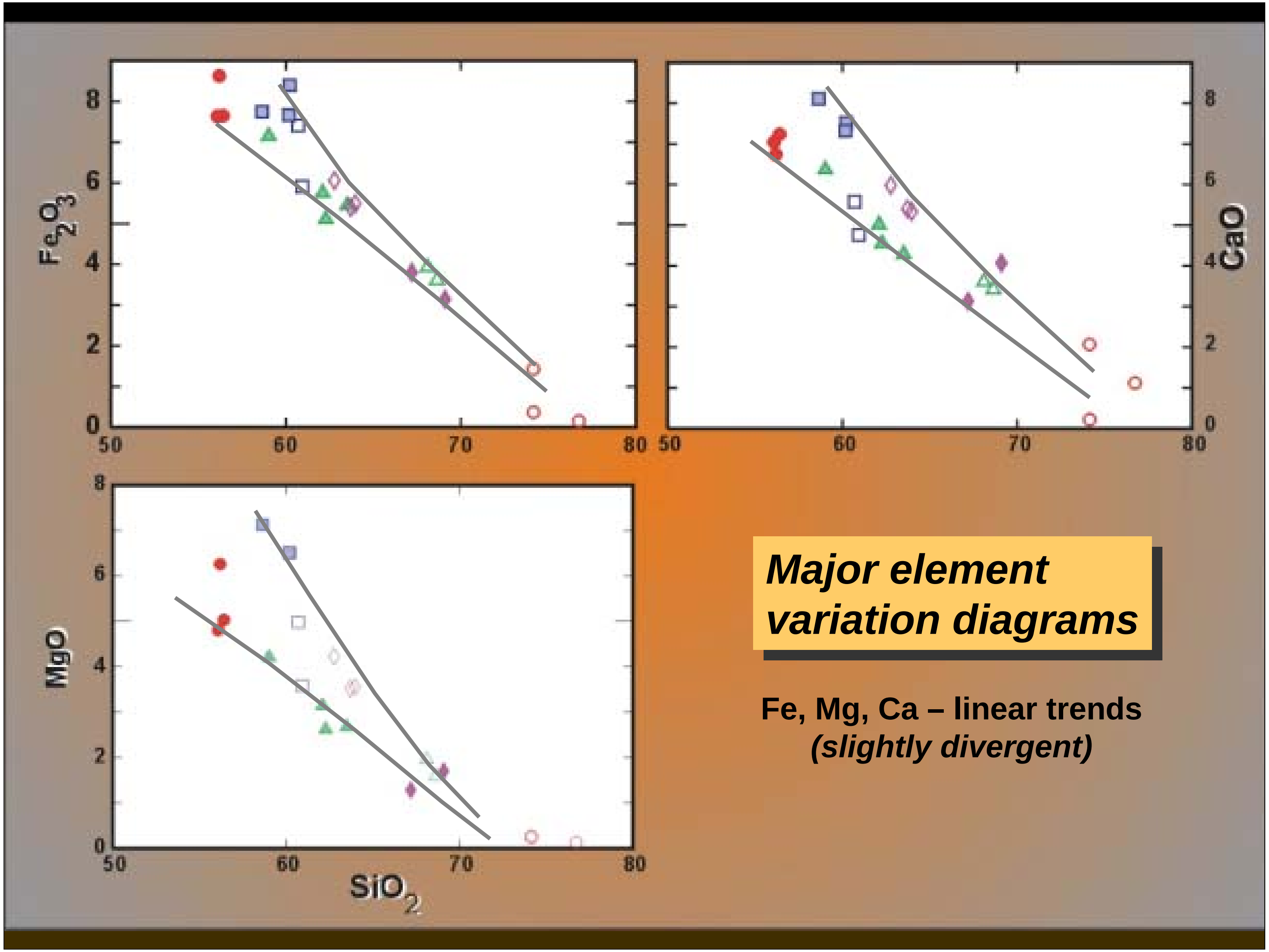

Monzonite-shoshonite contact
Spessartite Dyke – Quartz-monzonite contact


Scheelite Dome – Intrusive rocks
AFM diagram
Sample set – 25 samples
(limited by exposure &
extreme terrane)
Fe2O3 (total Fe)
Tholeiitic series
Calc-alkaline series
Na2O + K2O
MgO

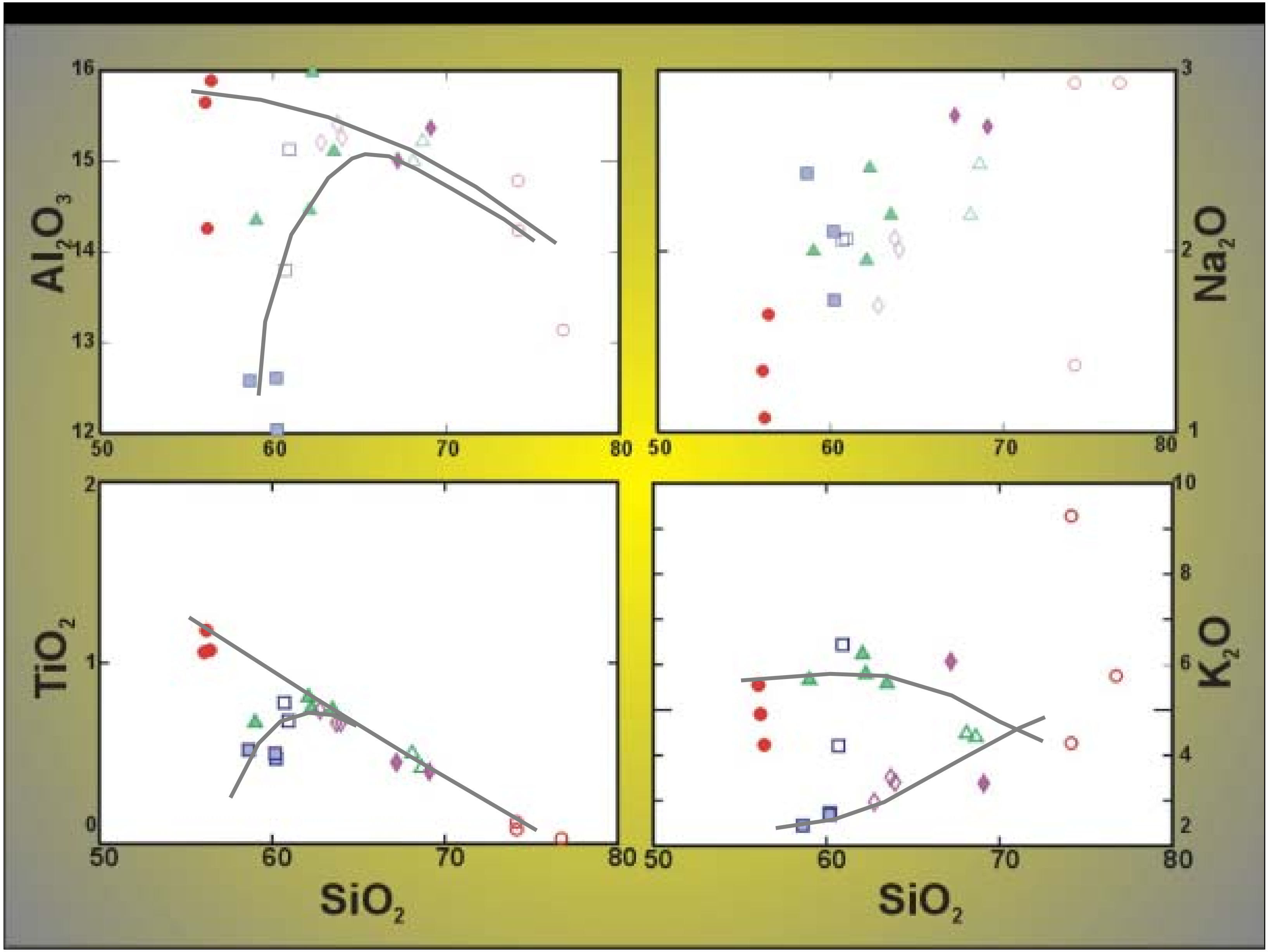

Scheelite Dome intrusive rocks
SiO2 vs total alkalis
16
14
12
10
8
6
4
2
K2O+Na2O
40
50
60
70
SiO2
Nepheline syenite
Syenite
Syenite
Syeno-diorite
Ijolite
Gabbro
Gabbro
Gabbro
Diorite
Quartz-diorite
Alkali granite
Granite
ALKALIC
SUB-ALKALIC


Felsic
Intermediate
TPS hand specimens
Scheelite Dome
Intermediate
Mafic (lamprophyre)

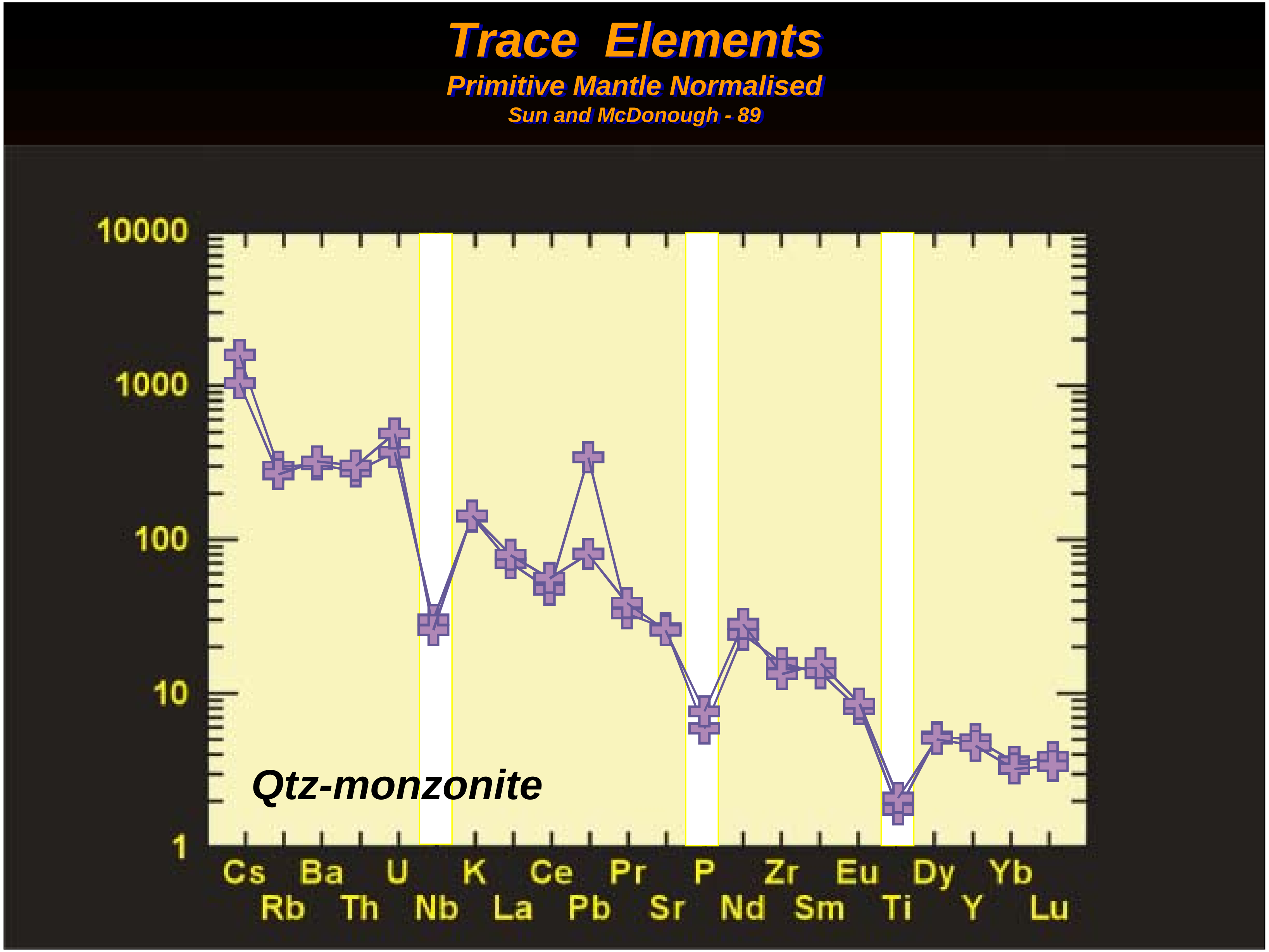

Sub-alkalic rocks
Spessartite Lamprophyre
Intermediate Dyke
Handspec
Cr-diopside
Photomicrograph
(thinsection)
0.5 mm
3 mm

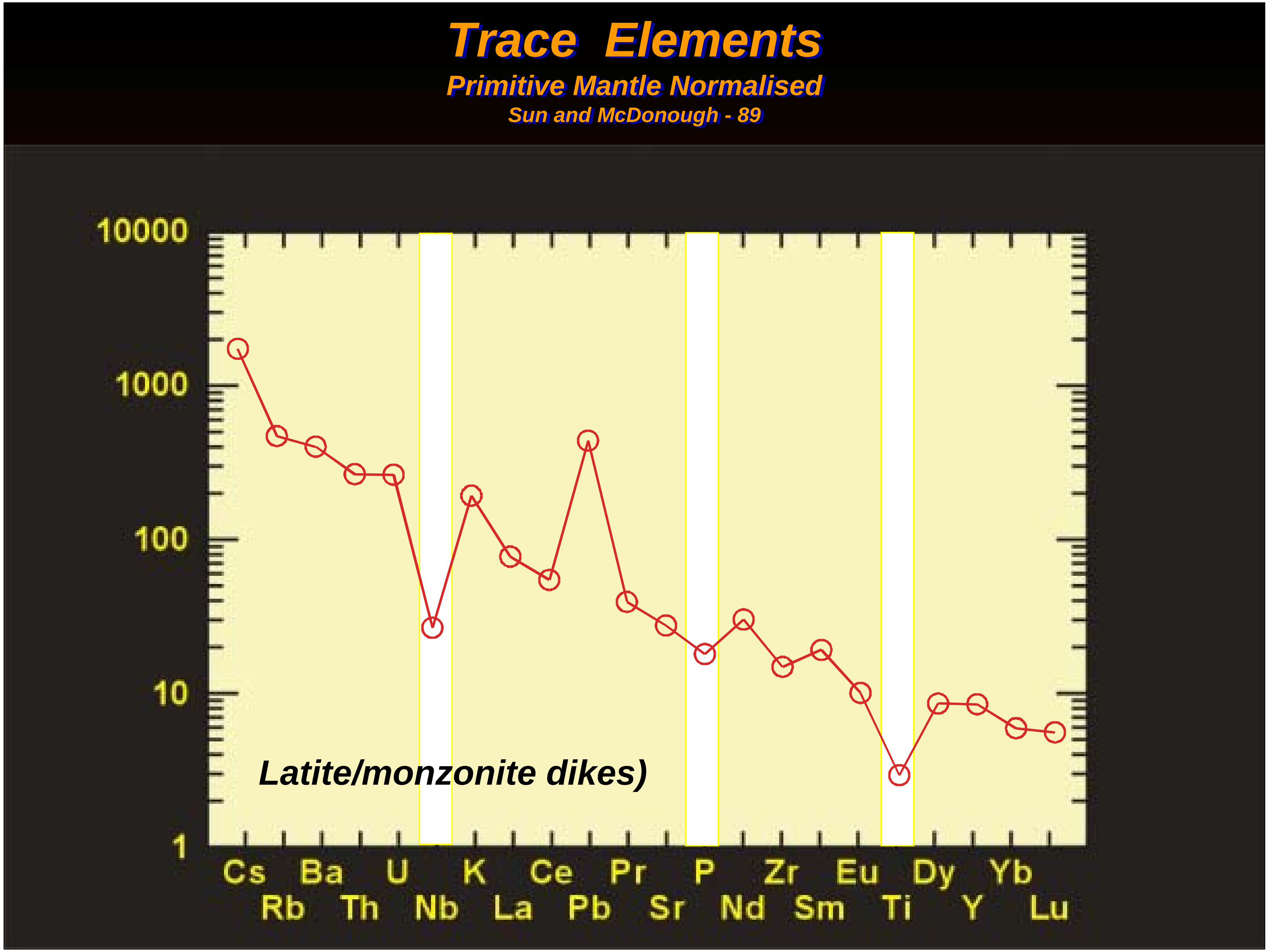


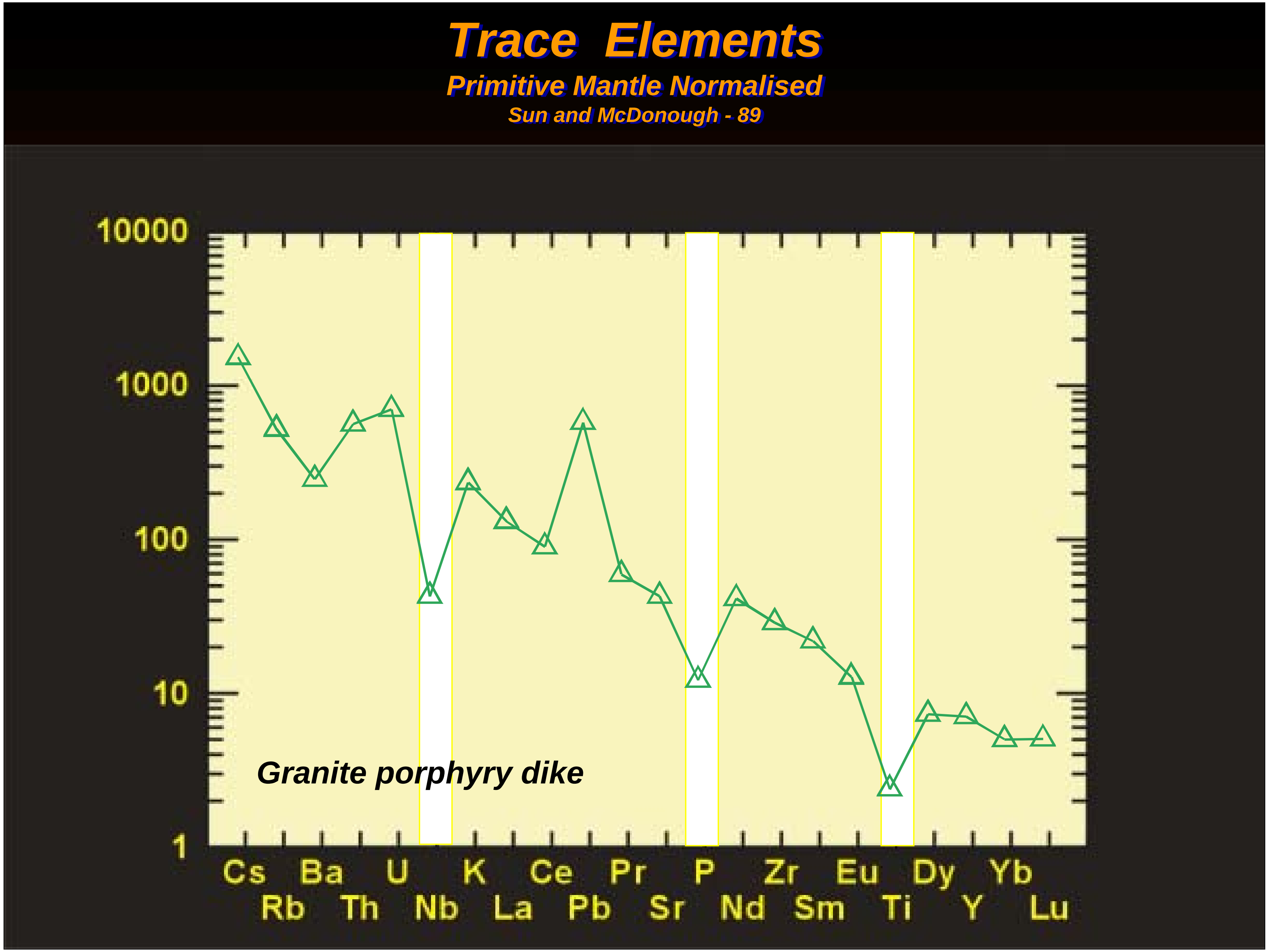
Fe2O3
CaO
MgO
SiO2
0 2 4 6 8
50 60 70 80
Major element variation diagrams
Fe, Mg, Ca – linear trends
(slightly divergent)

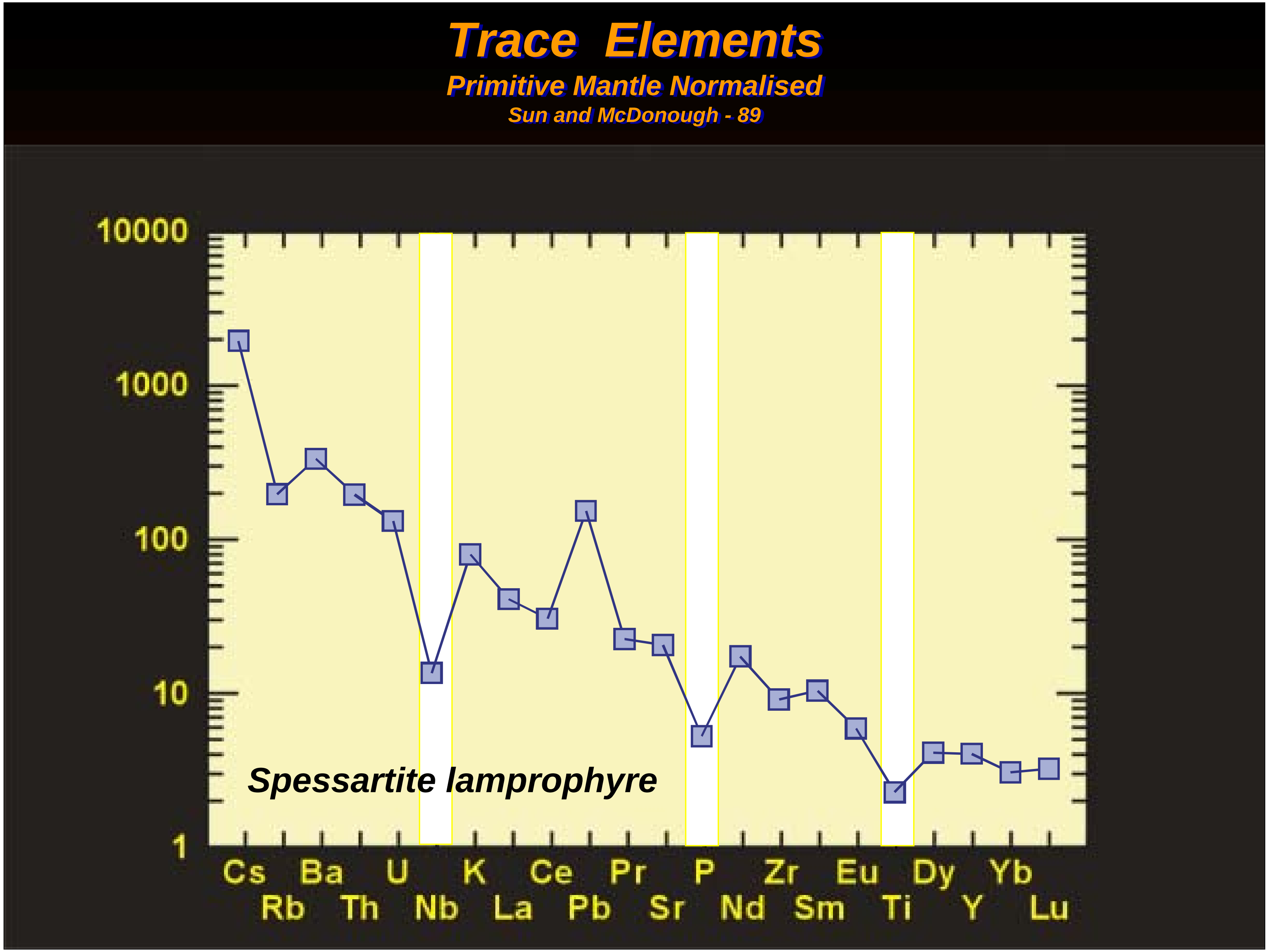


Al_2O_3
Na_2O
TiO_2
K_2O
SiO_2
SiO_2

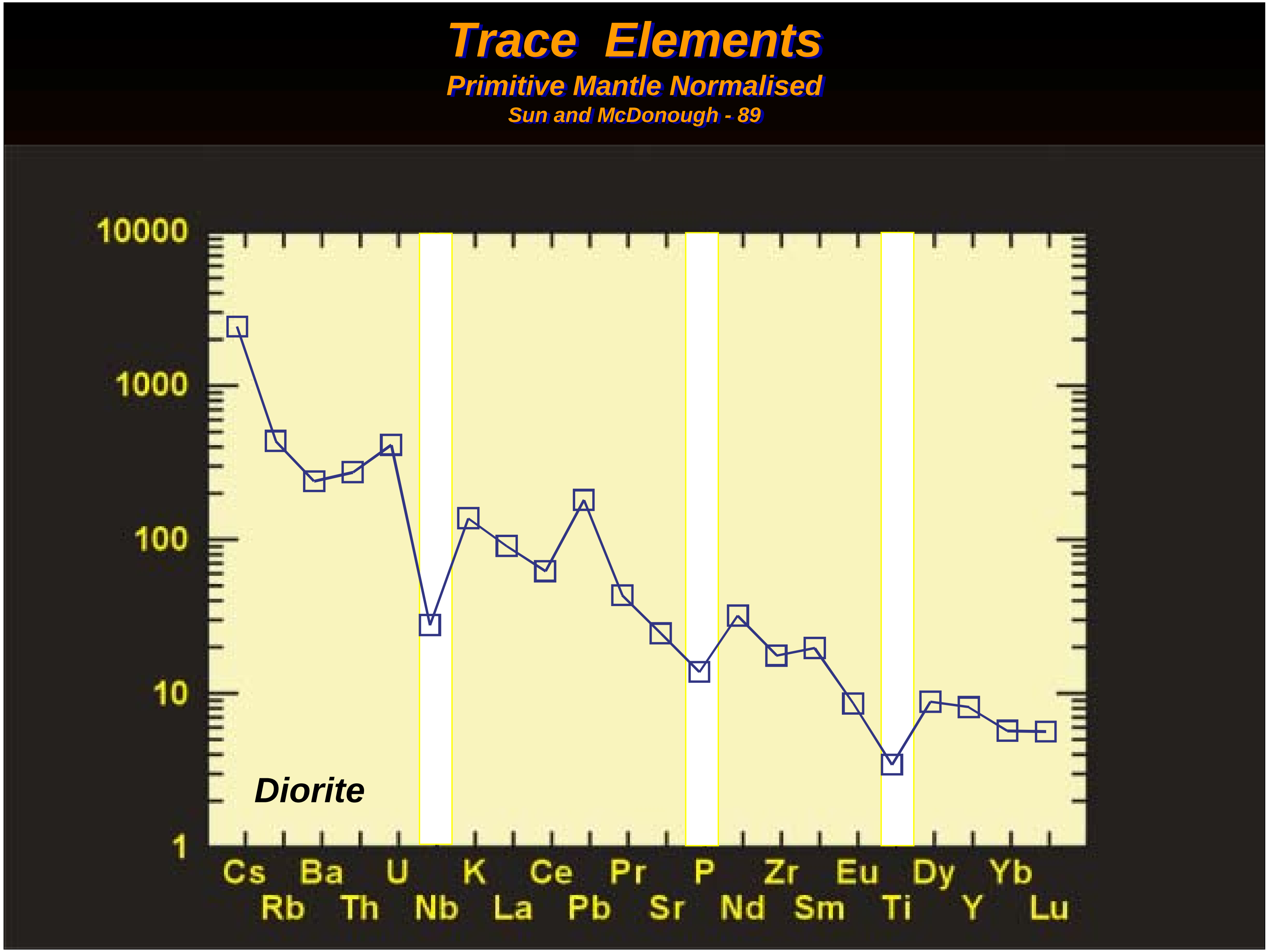

Trace Elements
Primitive Mantle Normalised
Sun and McDonough - 89
10000
1000
100
10
1
Qtz-monzonite
Cs Ba U K Ce Pr P Zr Eu Dy Yb
Rb Th Nb La Pb Sr Nd Sm Ti Y Lu

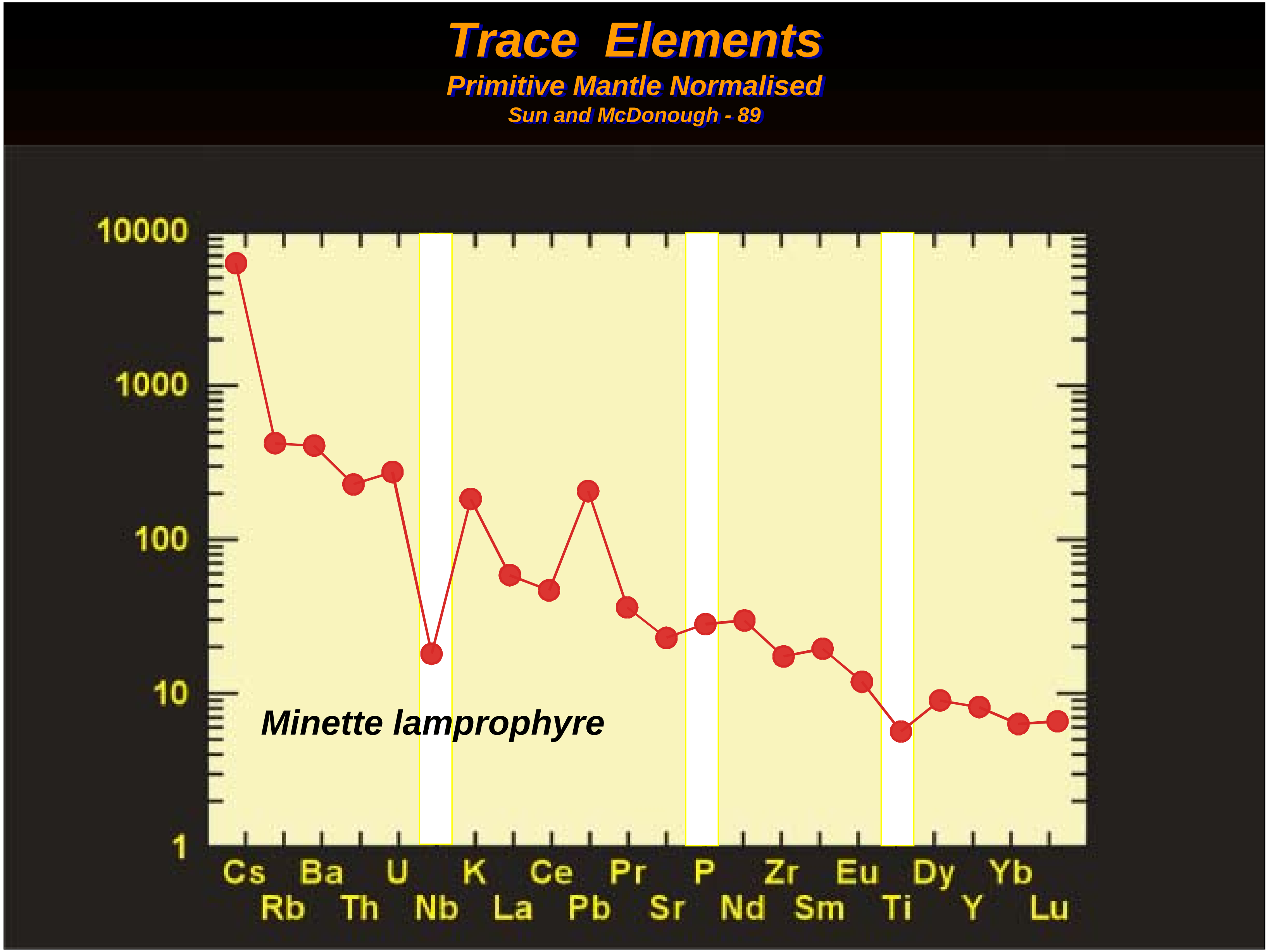

Trace Elements
Primitive Mantle Normalised
Sun and McDonough - 89
10000
1000
100
10
1
Latite/monzonite dikes)
Cs Ba U K Ce Pr P Zr Eu Dy Yb
Rb Th Nb La Pb Sr Nd Sm Ti Y Lu

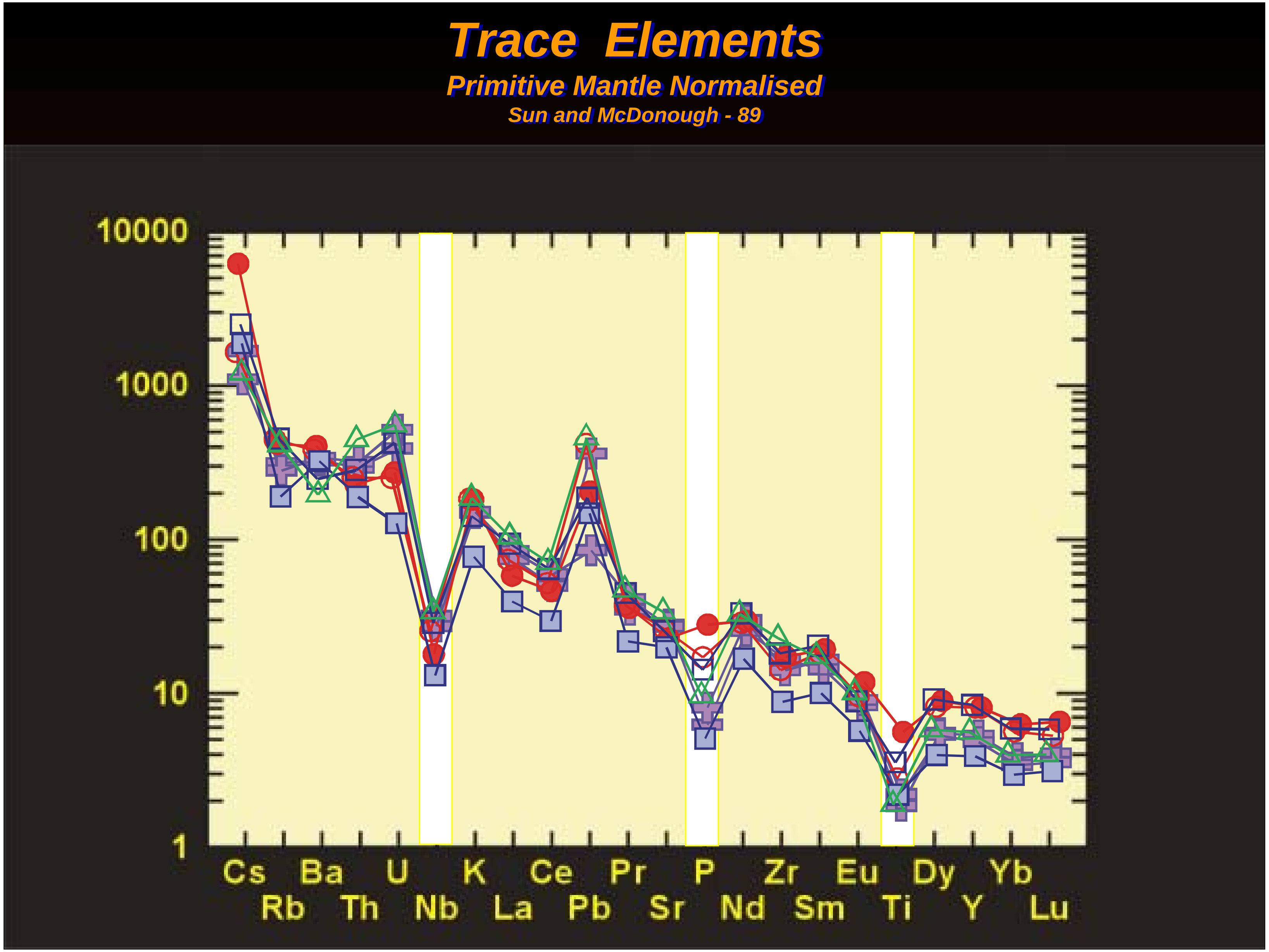

Trace Elements
Primitive Mantle Normalised
Sun and McDonough - 89
10000
1000
100
10
1
Granite porphyry dike
Cs Ba U K Ce Pr P Zr Eu Dy Yb
Rb Th Nb La Pb Sr Nd Sm Ti Y Lu

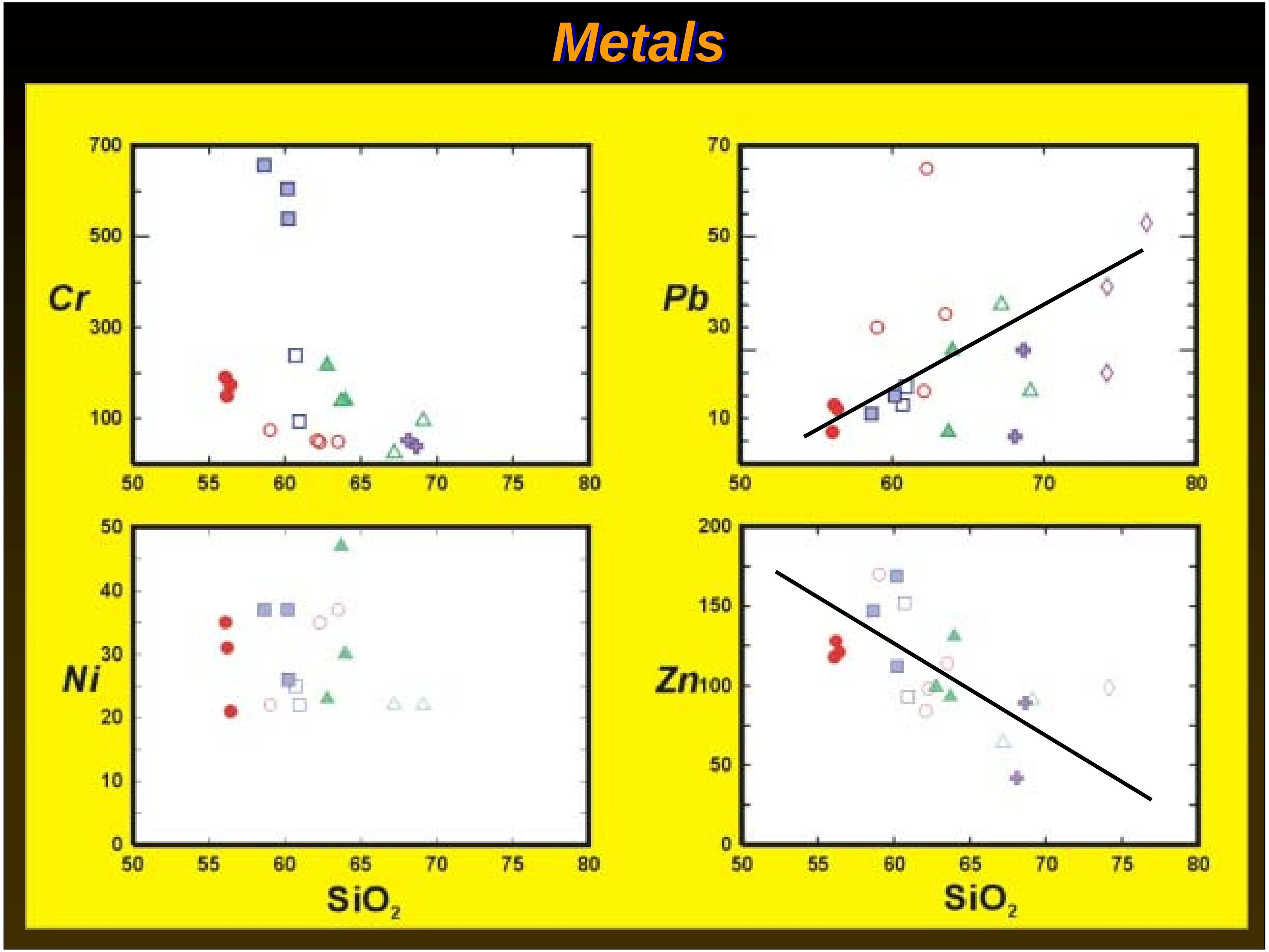


Trace Elements
Primitive Mantle Normalised
Sun and McDonough - 89
10000
1000
100
10
1
Spessartite lamprophyre
Cs Ba U K Ce Pr P Zr Eu Dy Yb
Rb Th Nb La Pb Sr Nd Sm Ti Y Lu


Trace Elements
Primitive Mantle Normalised
Sun and McDonough - 89
10000
1000
100
10
1
Diorite
Cs Ba U K Ce Pr P Zr Eu Dy Yb
Rb Th Nb La Pb Sr Nd Sm Ti Y Lu

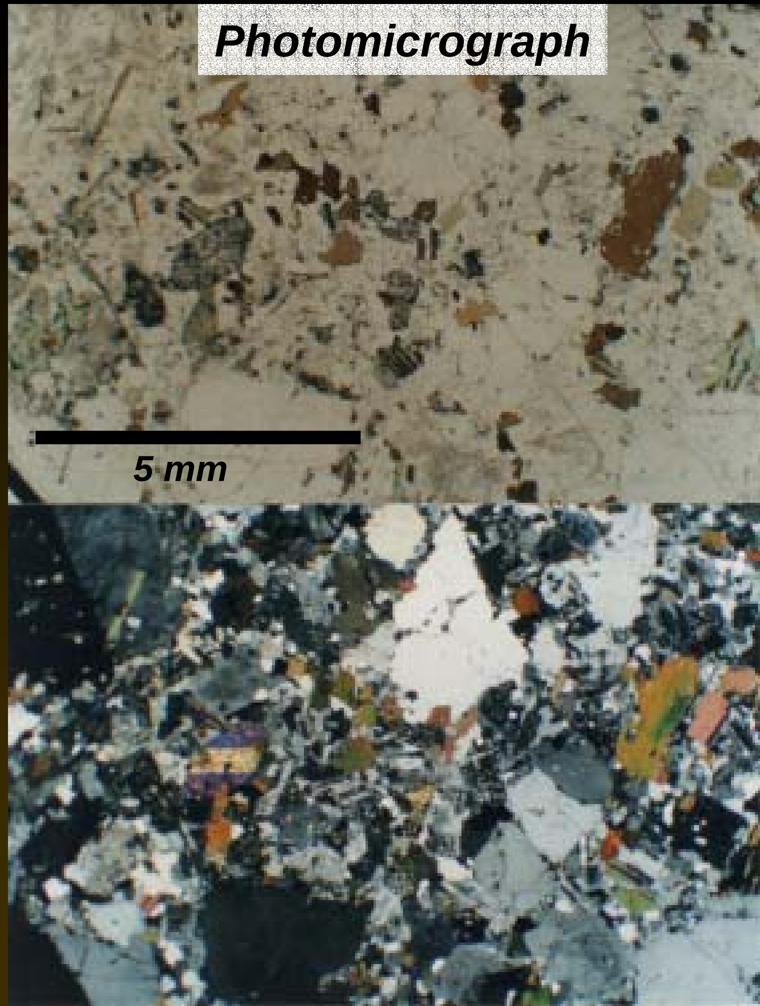

Trace Elements
Primitive Mantle Normalised
Sun and McDonough - 89
10000
1000
100
10
1
Minette lamprophyre
Cs
Ba
U
K
Ce
Pr
P
Zr
Eu
Dy
Yb
Rb
Th
Nb
La
Pb
Sr
Nd
Sm
Ti
Y
Lu


Trace Elements
Primitive Mantle Normalised
Sun and McDonough - 89
10000
1000
100
10
1
Cs
Rb
Ba
Th
U
Nb
K
La
Ce
Pb
Pr
Sr
P
Nd
Zr
Sm
Eu
Ti
Dy
Y
Yb
Lu


Metals
Cr
700
500
300
100
50
55
60
65
70
75
80
Pb
70
50
30
10
50
60
70
80
Ni
50
40
30
20
10
0
50
55
60
65
70
75
80
SiO2
Zn
200
150
100
50
0
50
55
60
65
70
75
80
SiO2

Mineralogy

- All intrusive phases (excluding aplites) contain cpx, biotite, variable amphibole, allanite, titanite and apatite
- Alkalic phases contain mostly cpx and biotite, with only minor amphibole
- Sub-alkalic phases (spessartites, diorites, granite porphyry dikes) contain greater abundance of amphibole



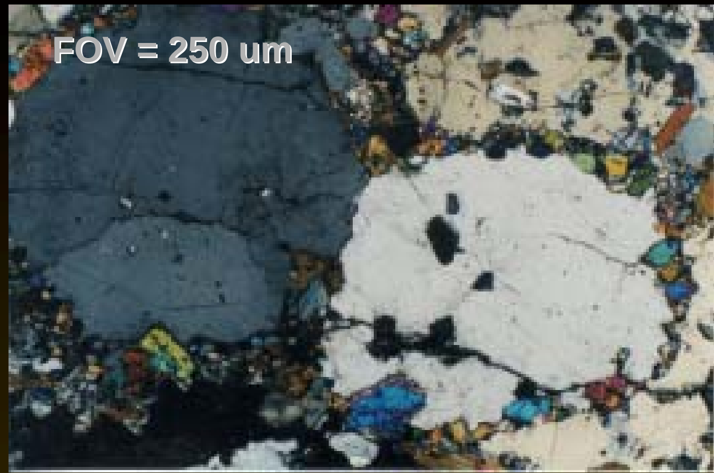
Early Qtz-monzonite

Weak to moderately porphyritic

Cpx, biotite, minor amphibole plagioclase, K-spar, qtz, titanite

Allanite, zircon, apatite, Magnetite, illmenite

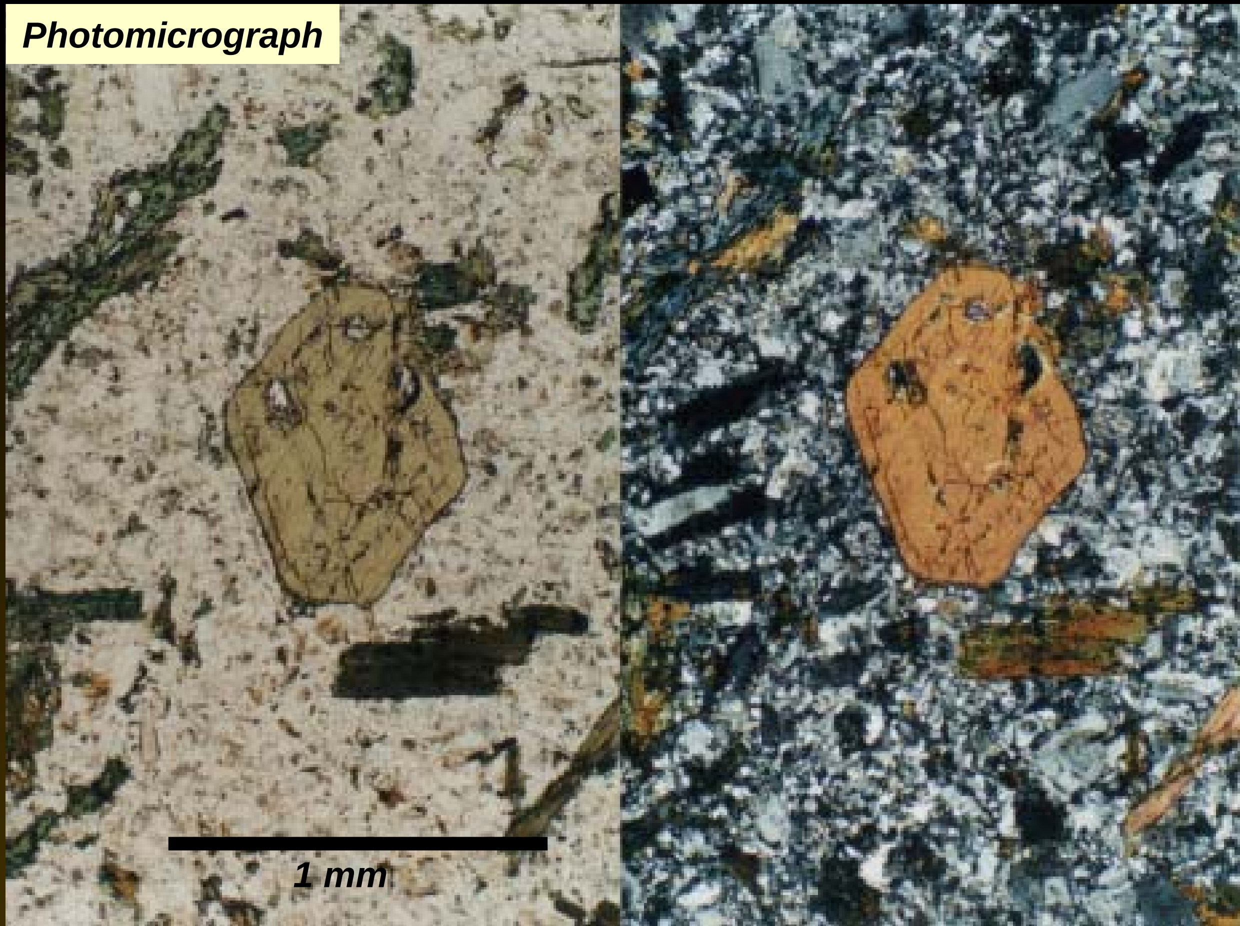
Monzonite/latite
(Photomicrograph)

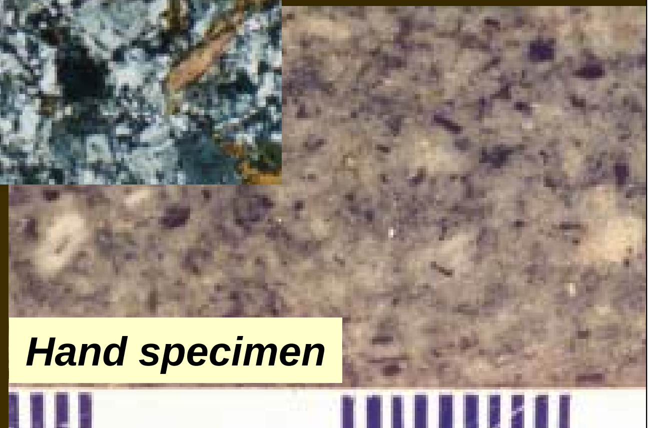


Quartz occelli
(clinopyroxene rimming quartz)

Textures:

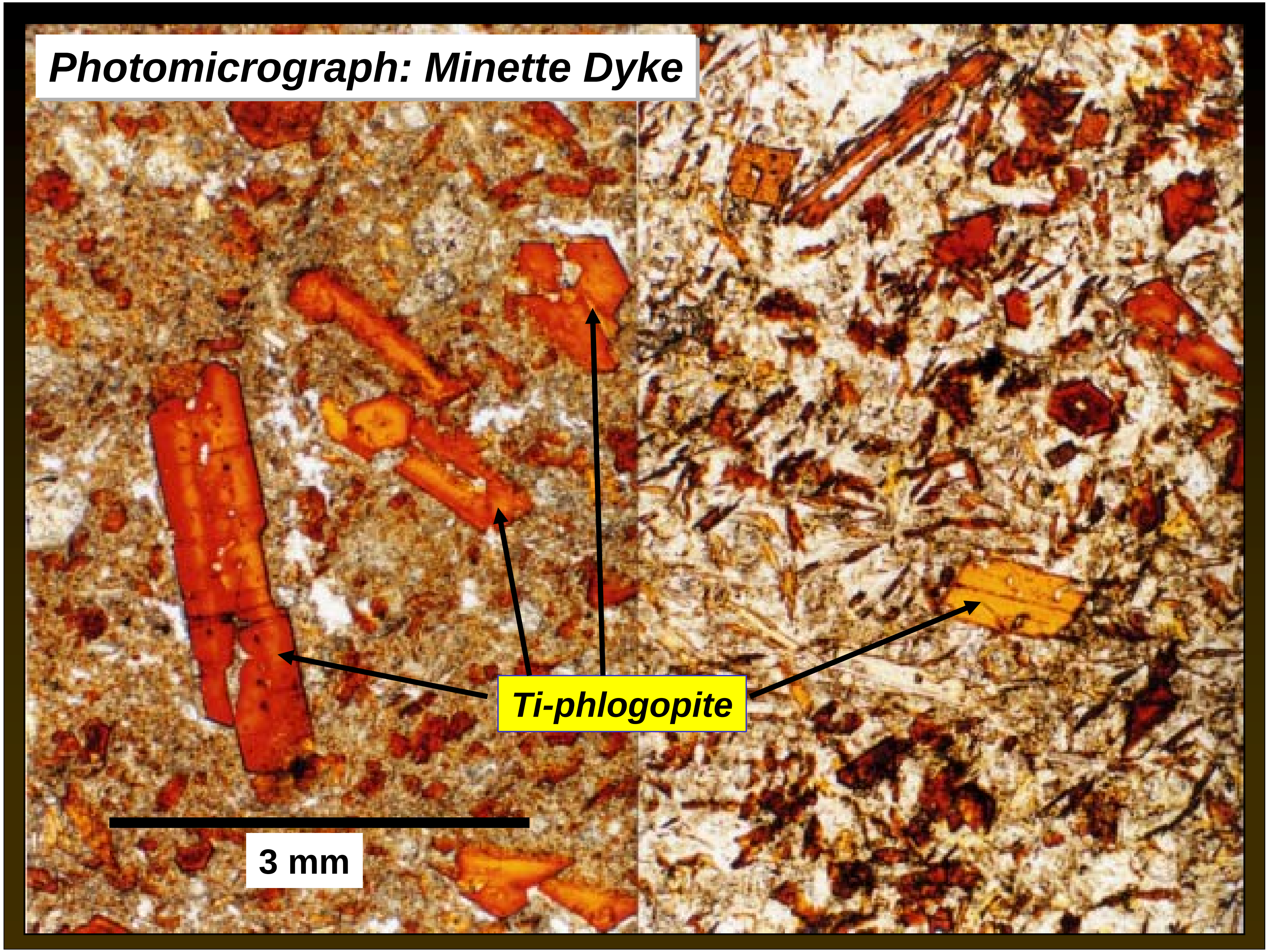
- **Weak to moderately porphyritic**
- **2 generations of cpx growth**
- **Cpx coronae around quartz**
- **Fine grained cpx in silica rich areas**
- **Evidence of quenching, mixing**

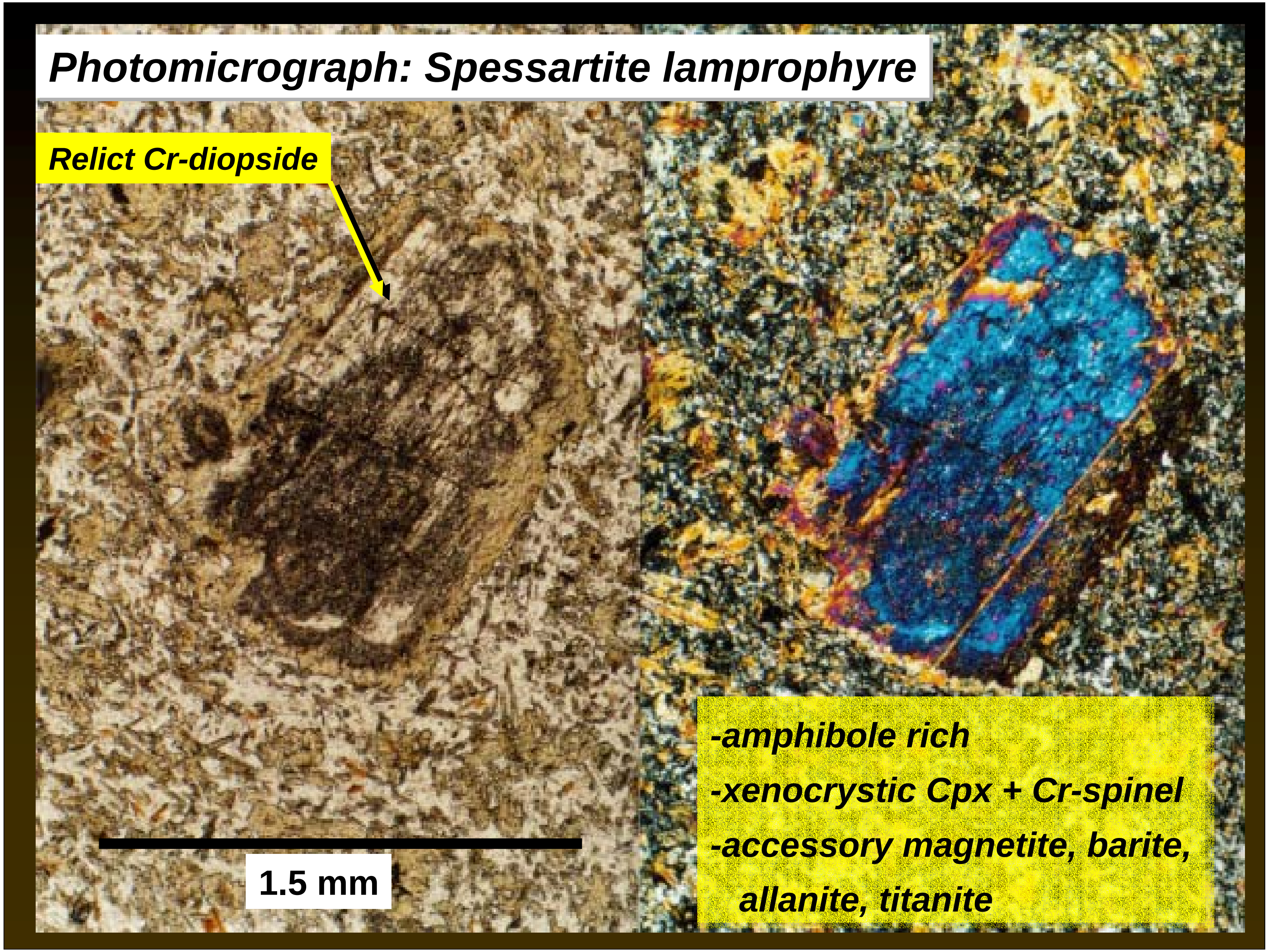


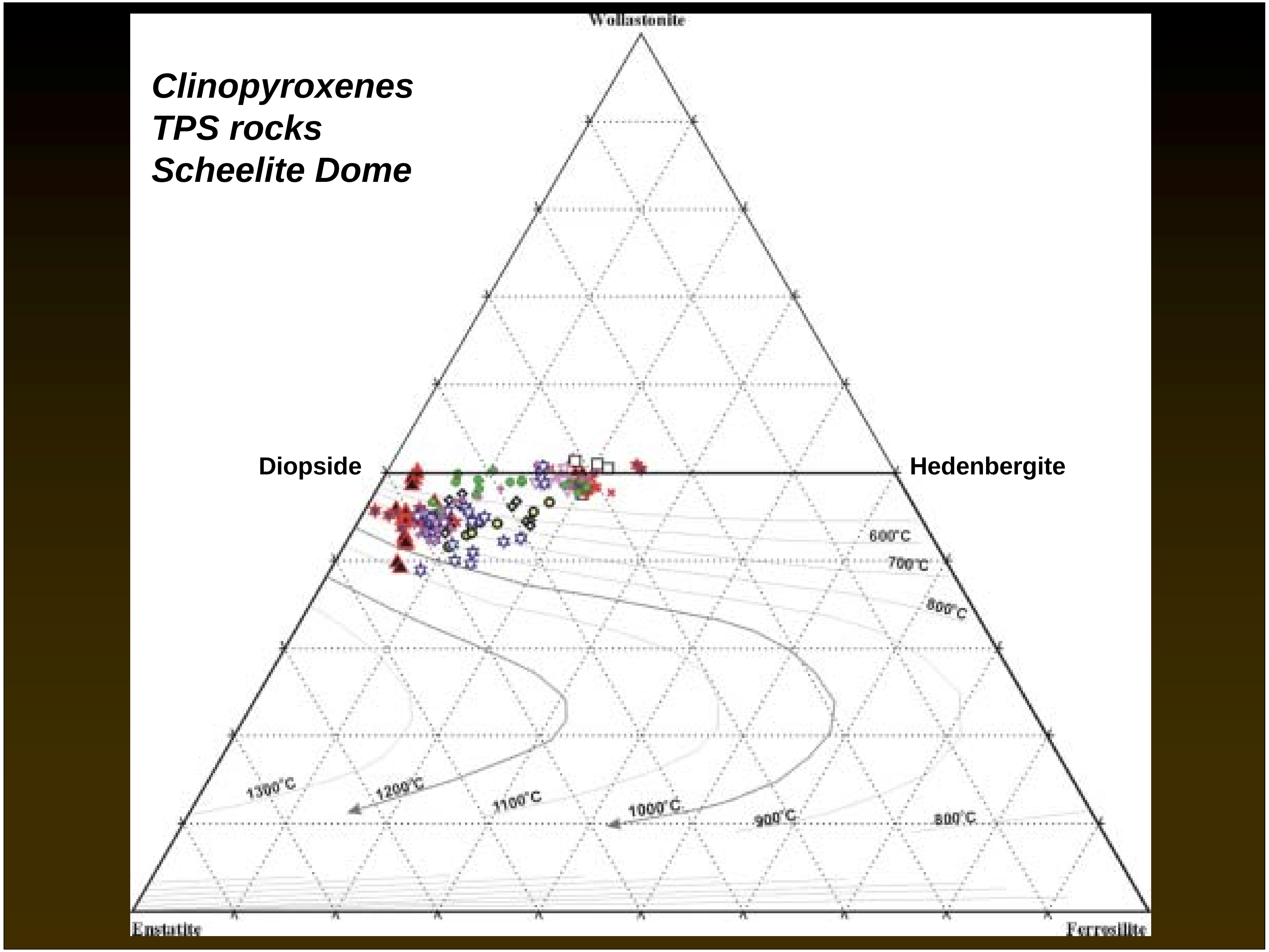


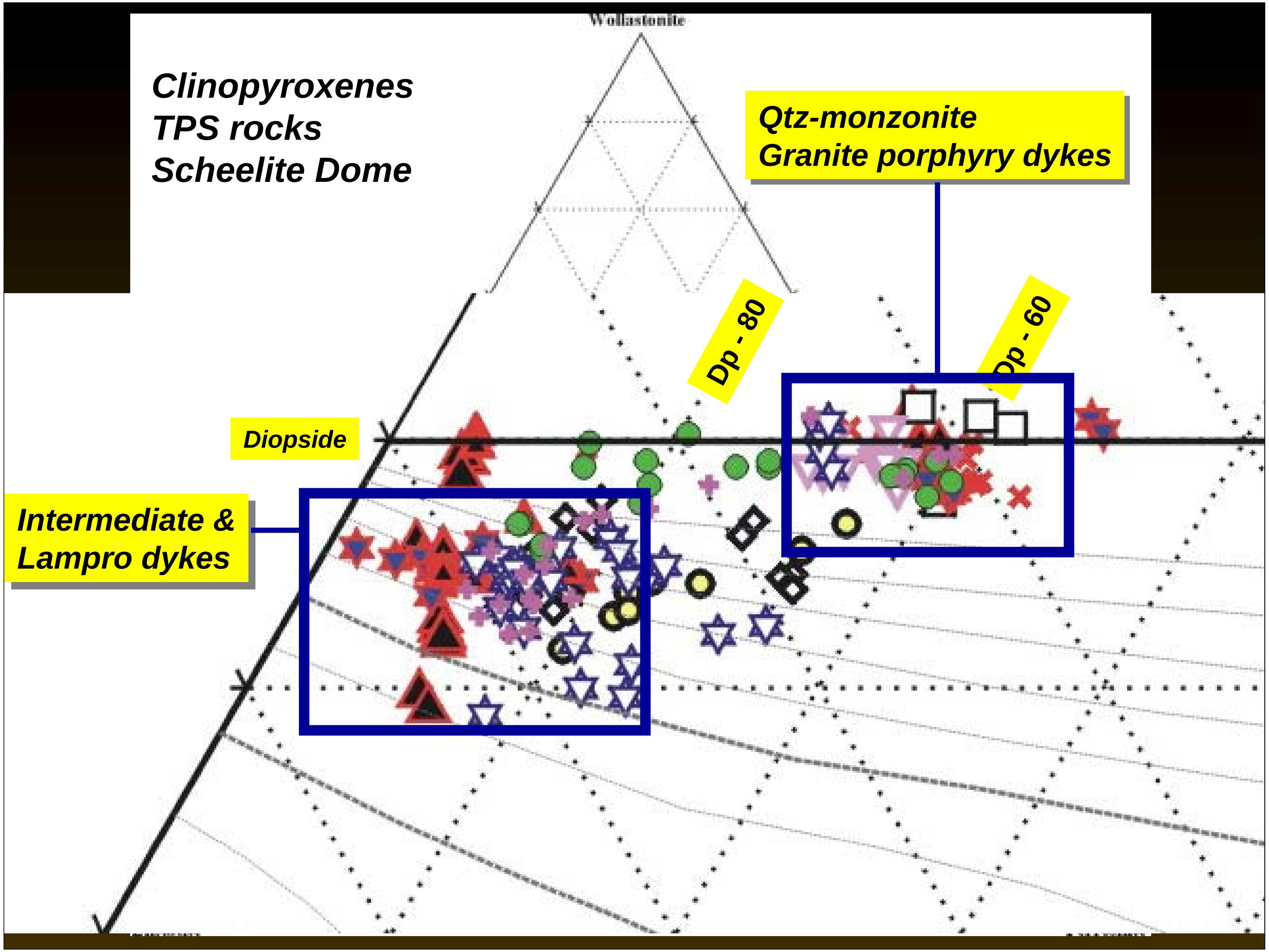
Granite Porphyry Dykes

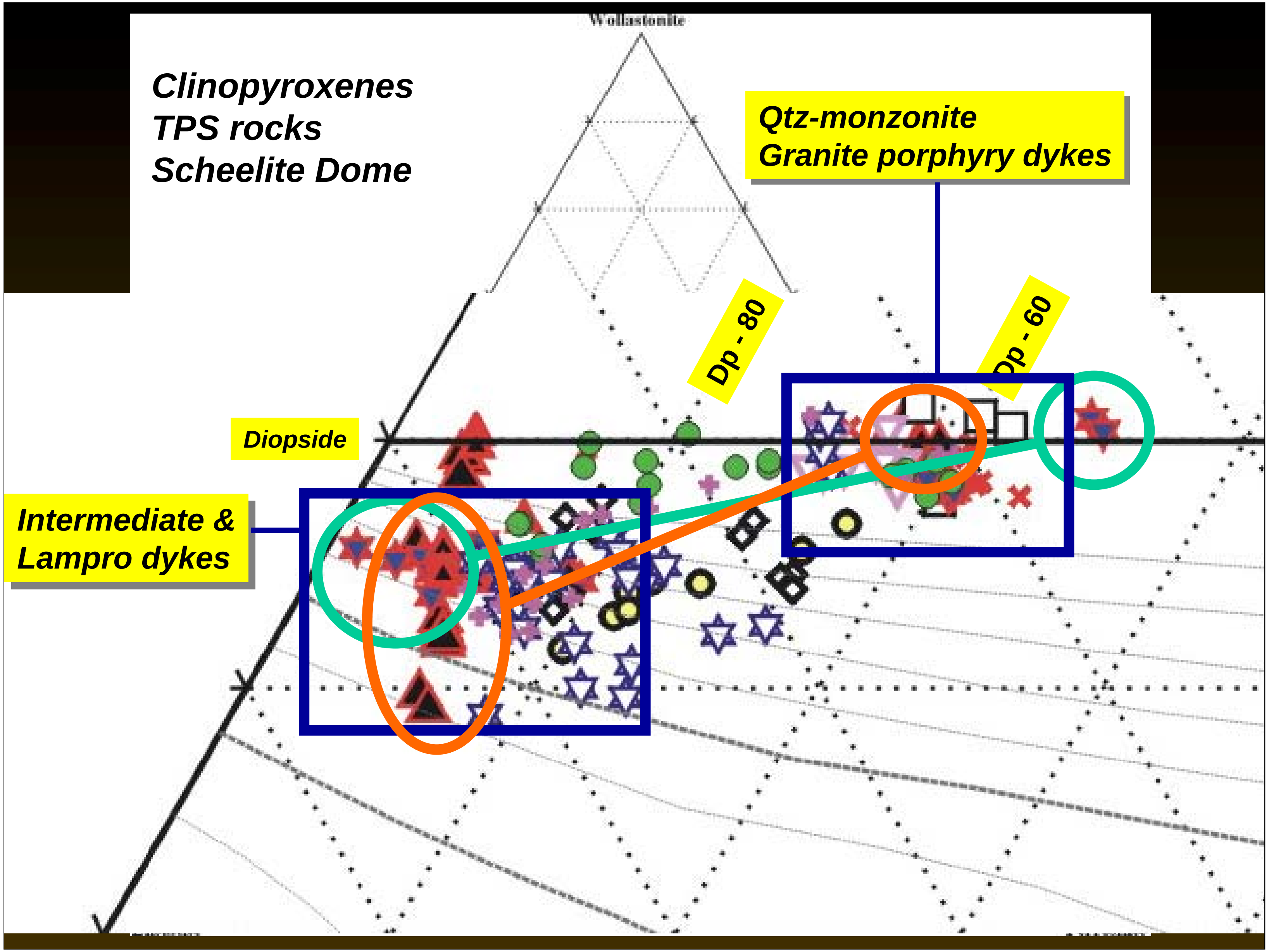
Hornblende phenocrysts indicate >4% H_2O


Photomicrograph: Minette Dyke
Ti-phlogopite
3 mm

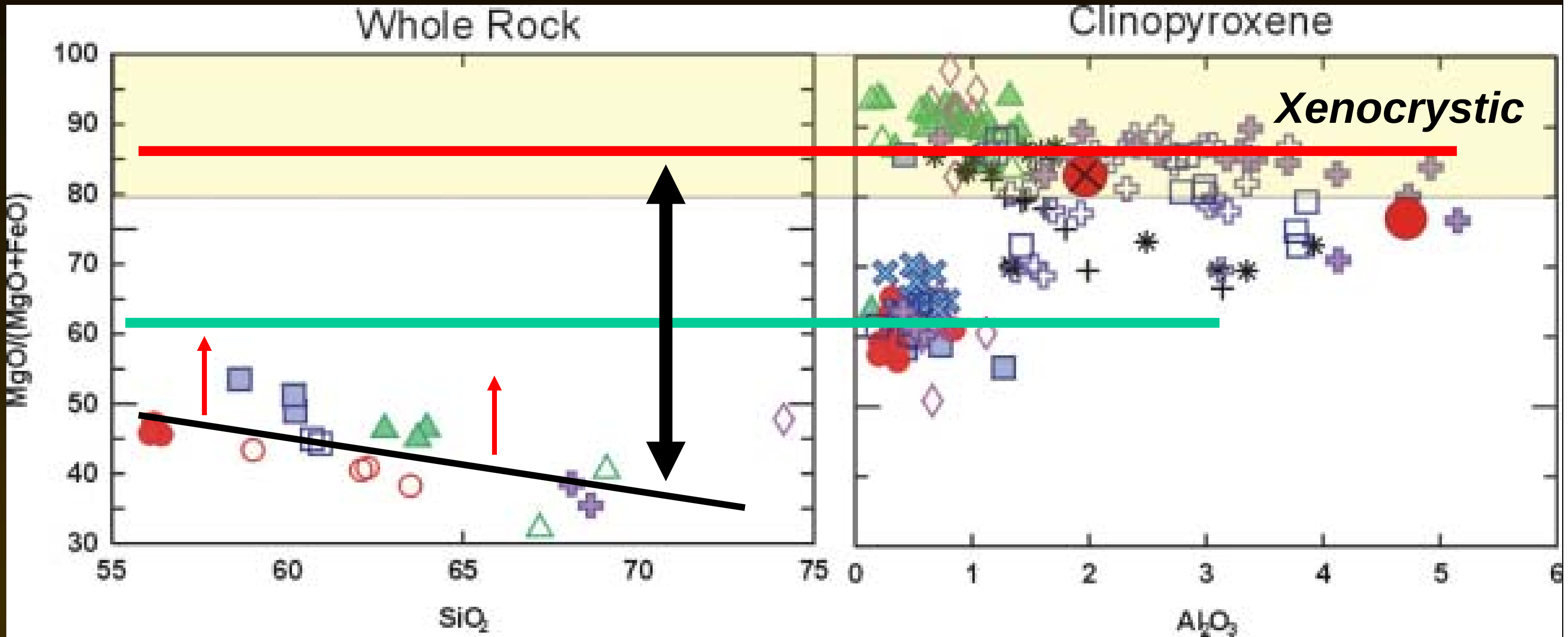

Photomicrograph: Spessartite lamprophyre
Relict Cr-diopside
1.5 mm
-amphibole rich
-xenocrystic Cpx + Cr-spinel
-accessory magnetite, barite,
allanite, titanite


Wollastonite
Clinopyroxenes
TPS rocks
Scheelite Dome
Diopside
Hedenbergite
600°C
700°C
800°C
1300°C
1200°C
1100°C
1000°C
900°C
800°C
Enstatite
Ferrosilite

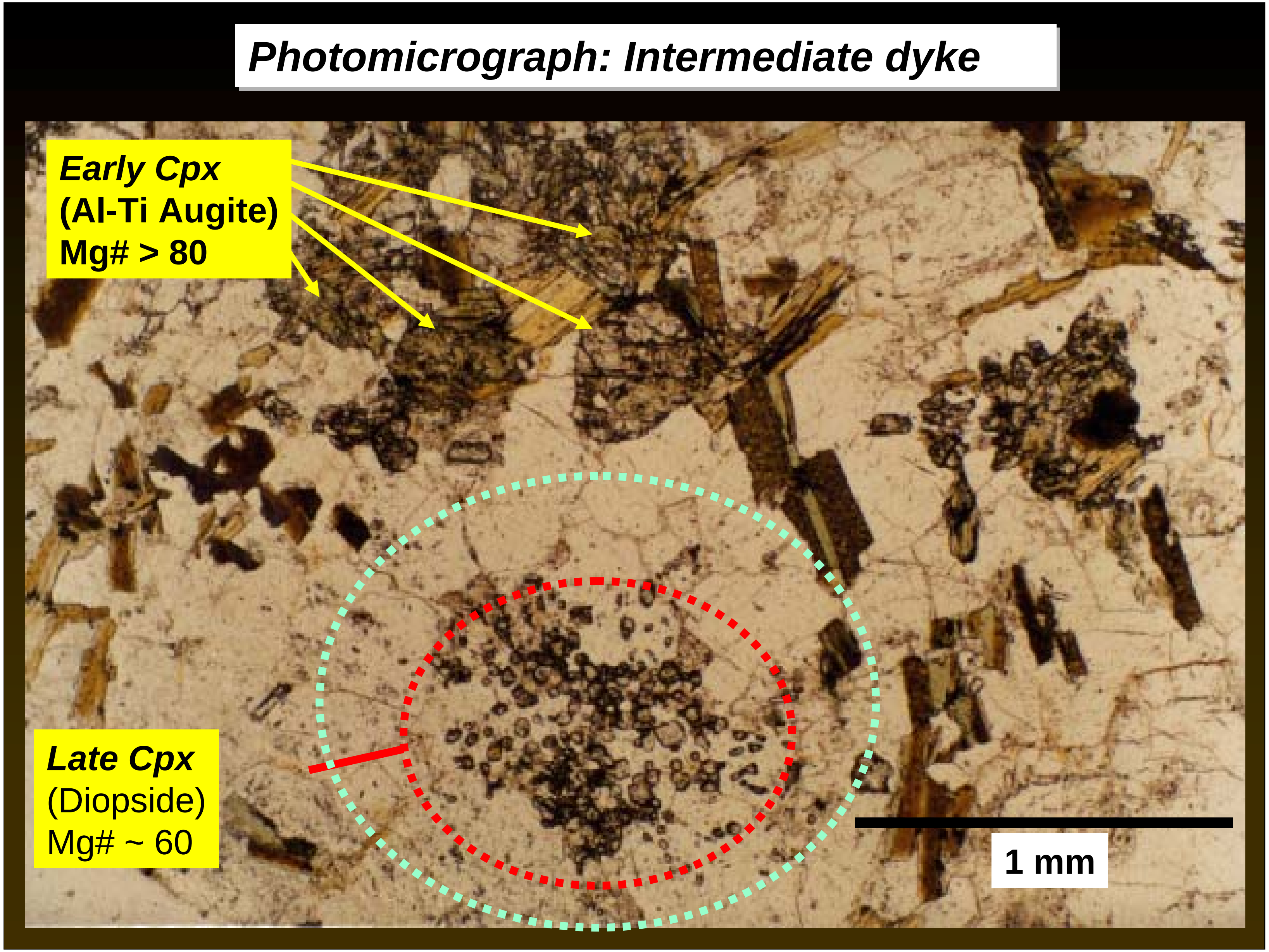

Wollastonite
Clinopyroxenes
TPS rocks
Scheelite Dome
Qtz-monzonite
Granite porphyry dykes
Dp - 80
Dp - 60
Diopside
Intermediate &
Lampro dykes

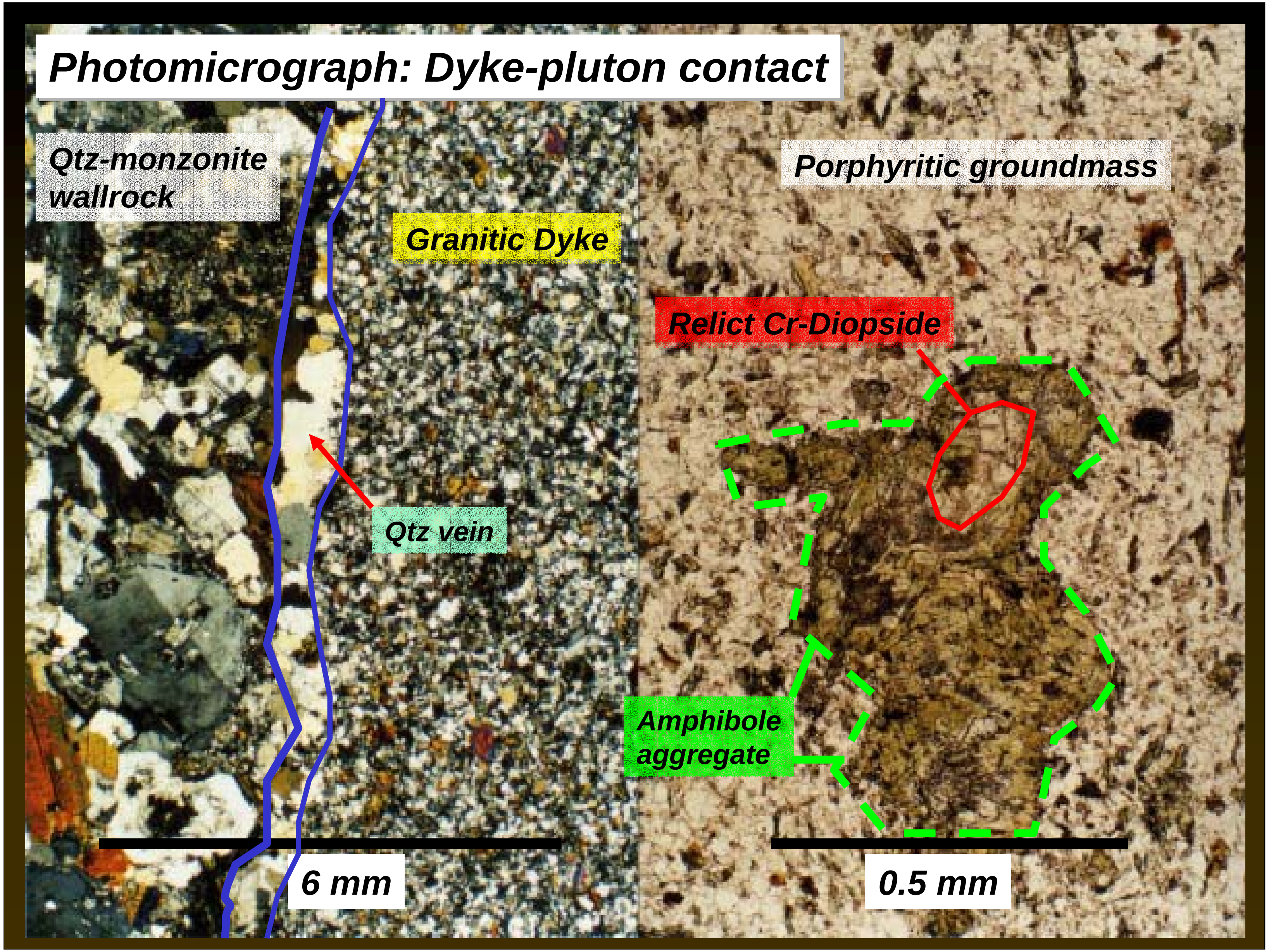

Wollastonite
Clinopyroxenes
TPS rocks
Scheelite Dome
Qtz-monzonite
Granite porphyry dykes
Dp - 80
Dp - 60
Diopside
Intermediate &
Lampro dykes

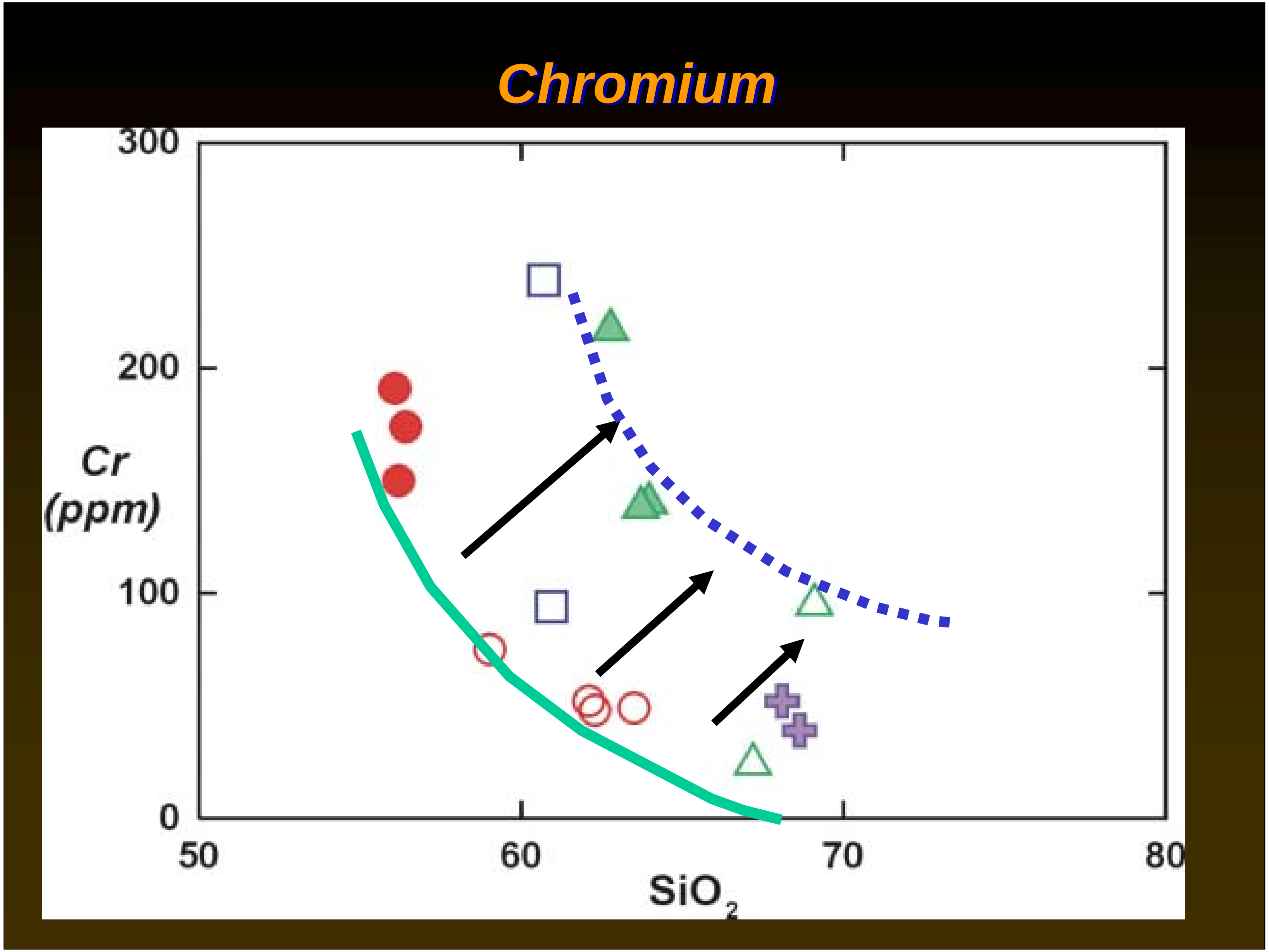
Whole rock Mg no. vs Cpx Mg no.

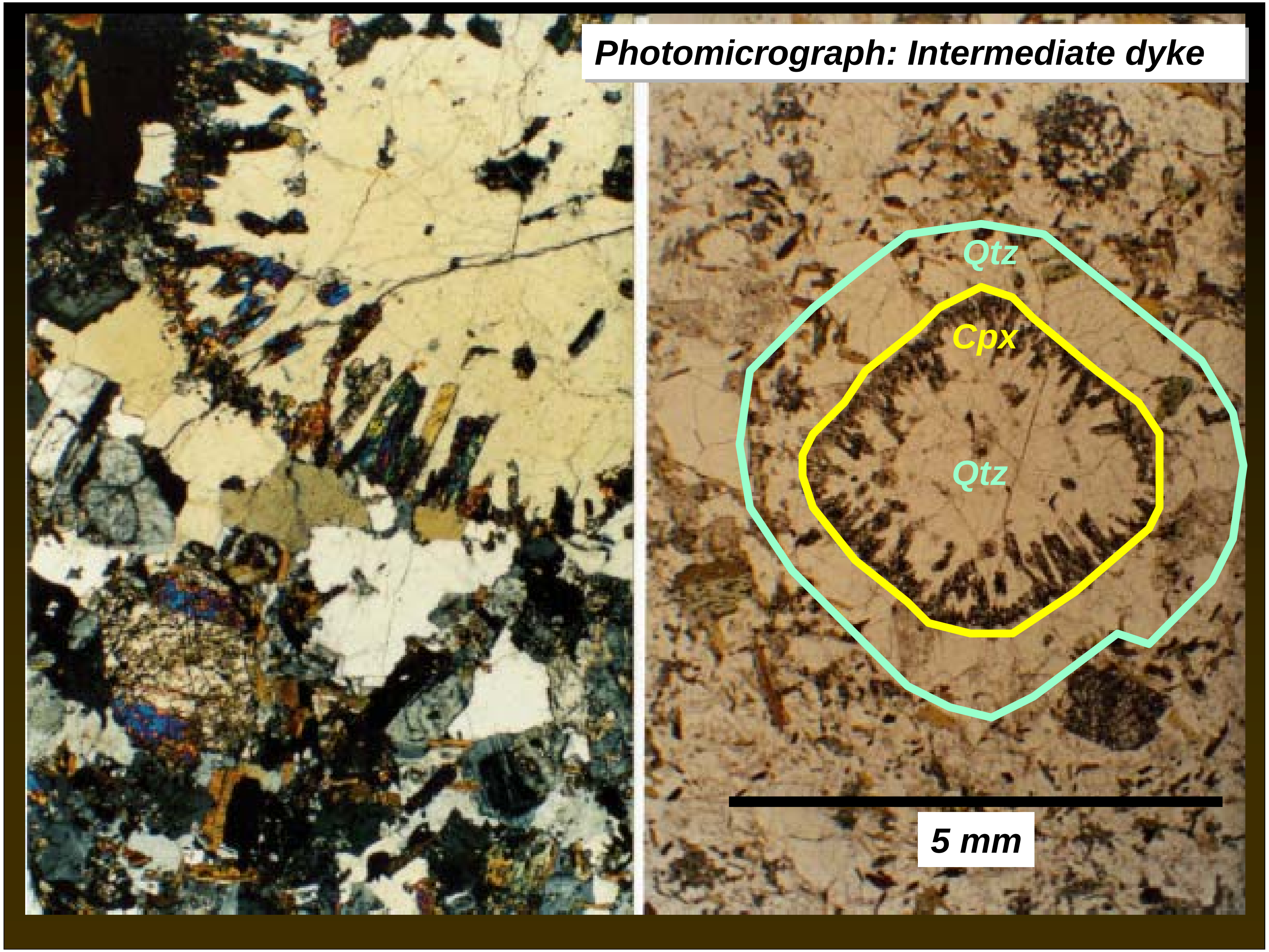


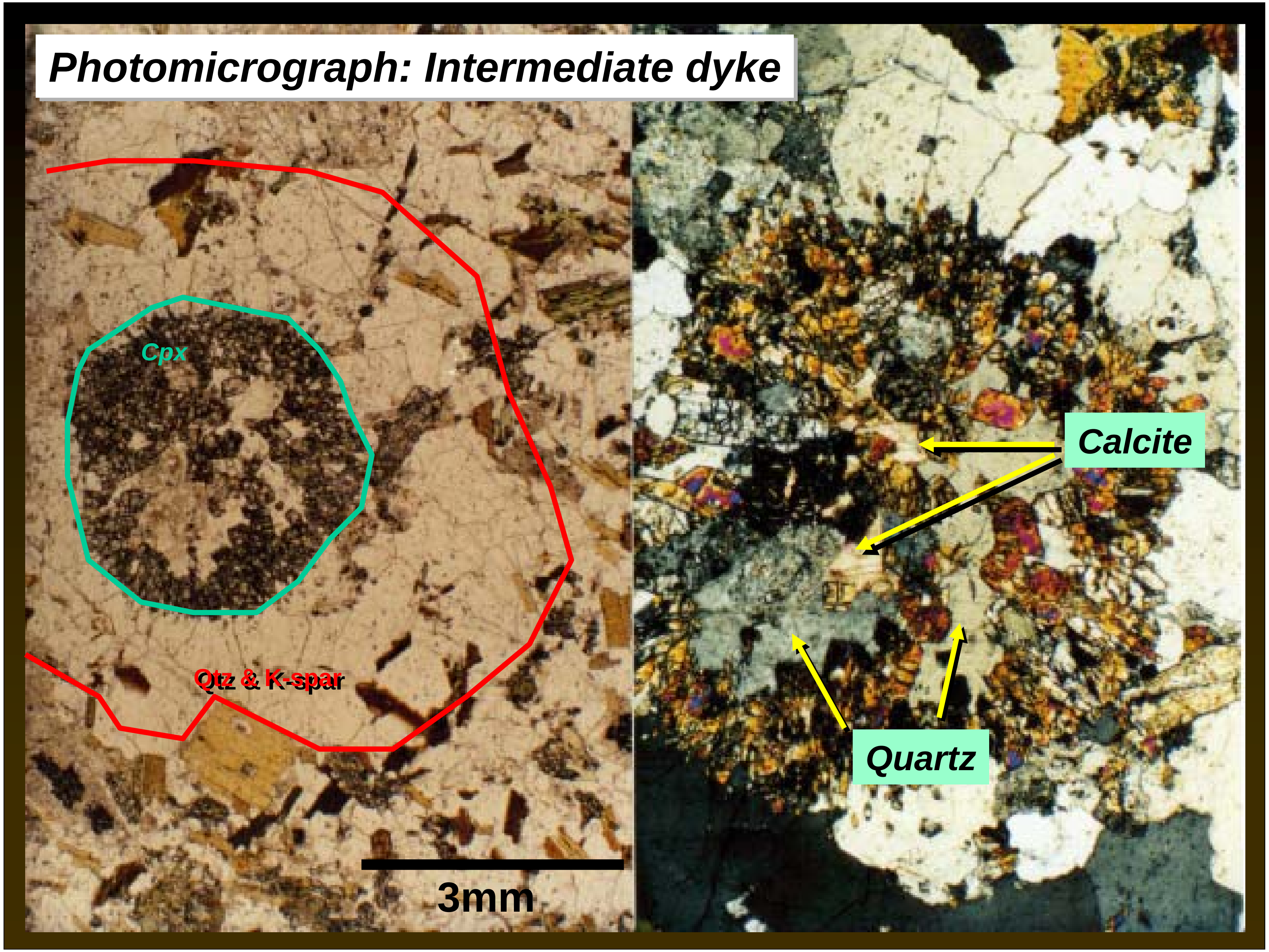
Clinopyroxenes are compositionally equivalent with those described in mantle xenolith studies: that is they equilibrated with mantle rocks in a high P-T setting


Photomicrograph: Intermediate dyke
Early Cpx
(Al-Ti Augite)
Mg# > 80
Late Cpx
(Diopside)
Mg# ~ 60
1 mm

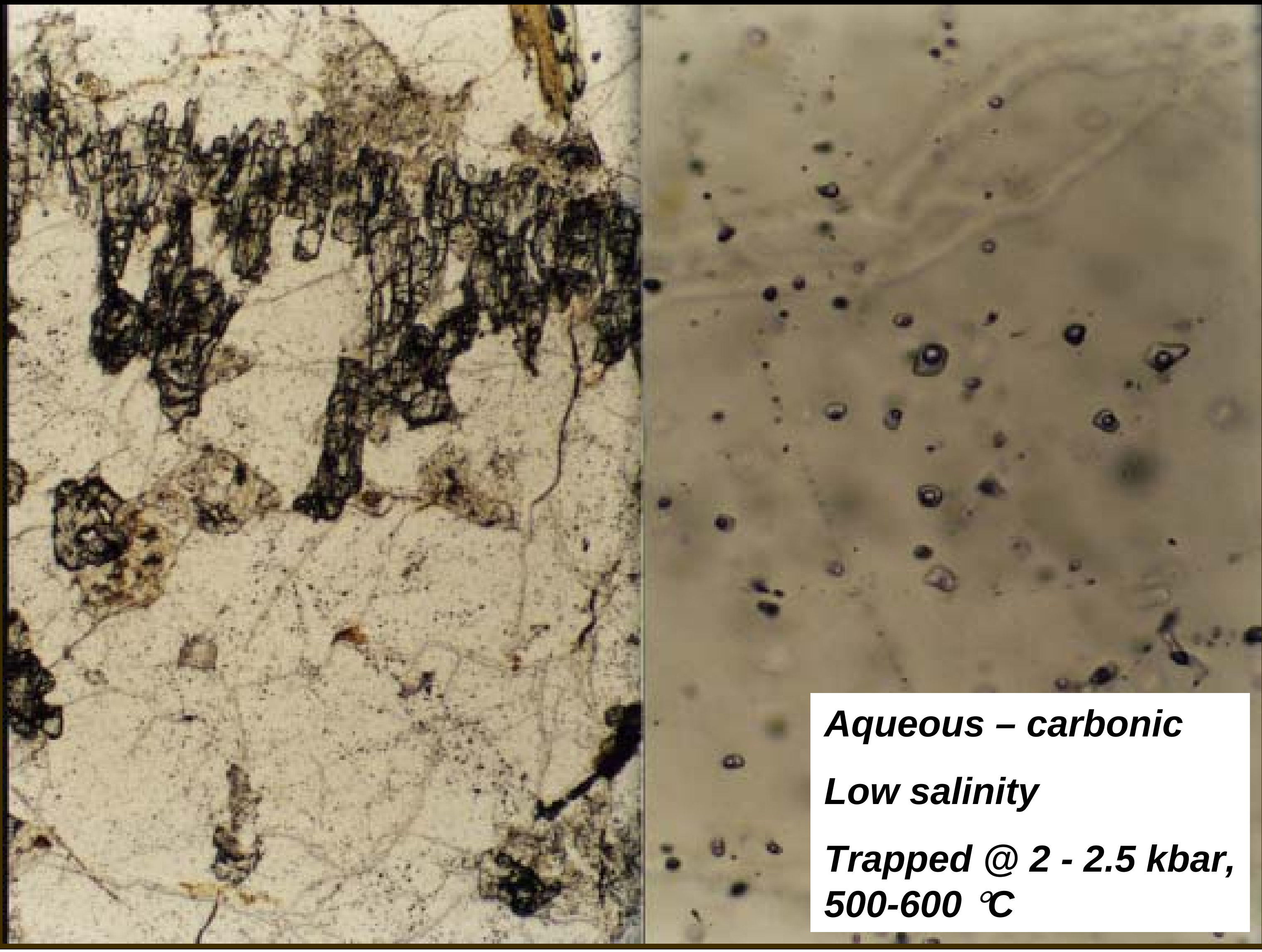

Photomicrograph: Dyke-pluton contact
Qtz-monzonite wallrock
Granitic Dyke
Porphyritic groundmass
Relict Cr-Diopside
Qtz vein
Amphibole aggregate
6 mm
0.5 mm


Chromium
300
200
100
0
Cr
(ppm)
50
60
70
80
SiO2


Photomicrograph: Intermediate dyke
Qtz
Cpx
Qtz
5 mm


Photomicrograph: Intermediate dyke
Cpx
Qtz & K-spar
3mm
Calcite
Quartz

Magmatic Fluid Inclusions

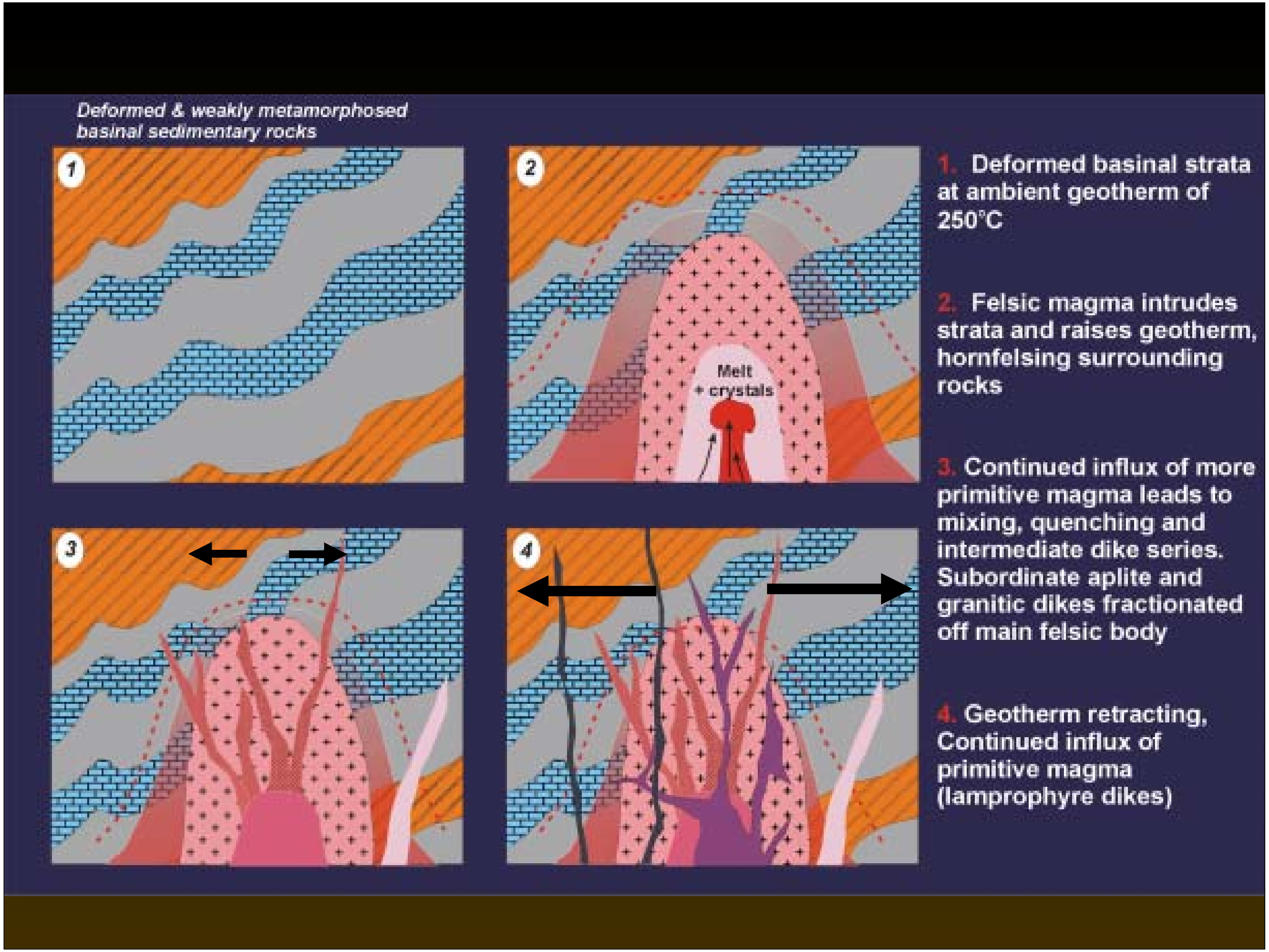


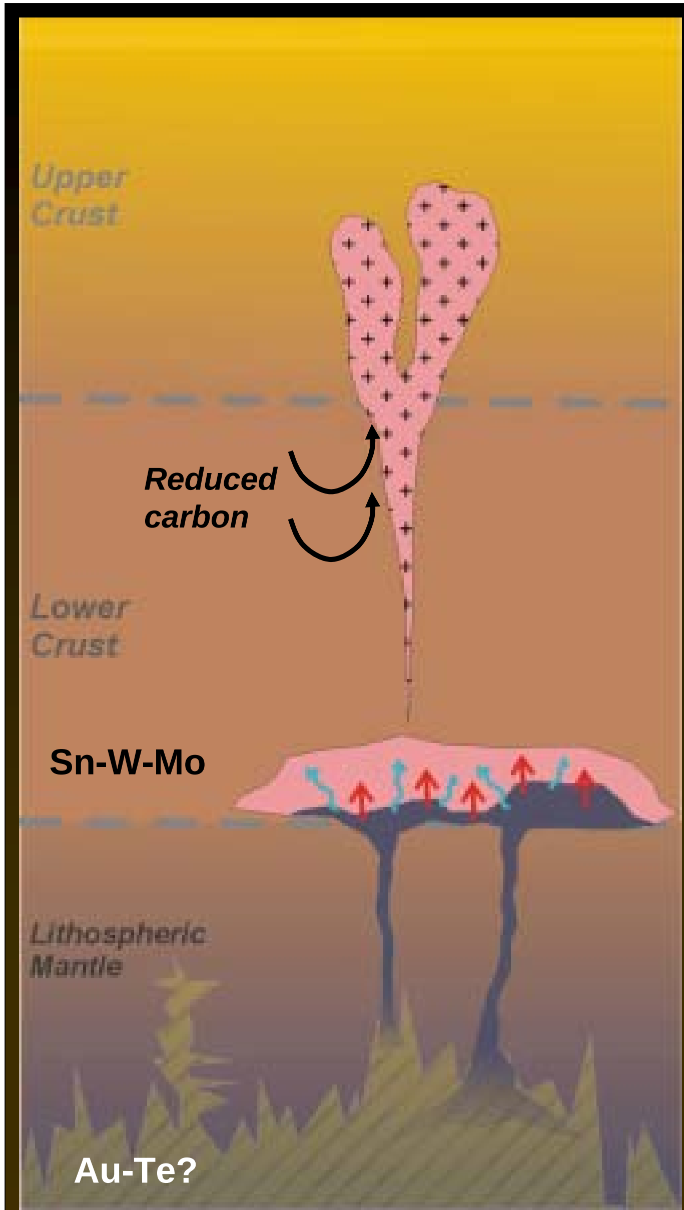
Isotopic Constraints

- Oxygen (*whole rock & selected minerals*) 10.5 – 12.5 ‰ $\delta^{18}O$
  - Except minettes 6 – 12 ‰ $\delta^{18}O$
- All intrusions highly radiogenic (initial Sr >0.71)
  - Most ~ 0.712 - 0.713
- All intrusions feature εNd -8 to –11
- All intrusions feature $^{206}Pb/^{204}Pb$ ~ 19.5 & $^{207}Pb/^{204}Pb$ ~ 15.6 – 15.8

Source Components

- **Lithospheric mantle source for lamprophyres (*EM II* isotopic signature)**
  - ***Minettes* – modally metasomatised source region – phlogopite clinopyroxenite ??**
  - ***Spessartites* – lower modal % of metasomatic phases – retains "depleted major element signature – < Ti, Al, Fe, > Mg, Cr"**
- **Sialic crustal material**
  - **Inherited zircons (Proterozoic to Late Archaean – where cores *have not* been reset)**
  - **Heavy $\delta^{18}O$**
  - **Reduced – marine siliciclasitc rocks**


Deformed & weakly metamorphosed basinal sedimentary rocks
1
2
Melt + crystals
3
4
1. Deformed basinal strata at ambient geotherm of 250°C
2. Felsic magma intrudes strata and raises geotherm, hornfelsing surrounding rocks
3. Continued influx of more primitive magma leads to mixing, quenching and intermediate dike series. Subordinate aplite and granitic dikes fractionated off main felsic body
4. Geotherm retracting, Continued influx of primitive magma (lamprophyre dikes)

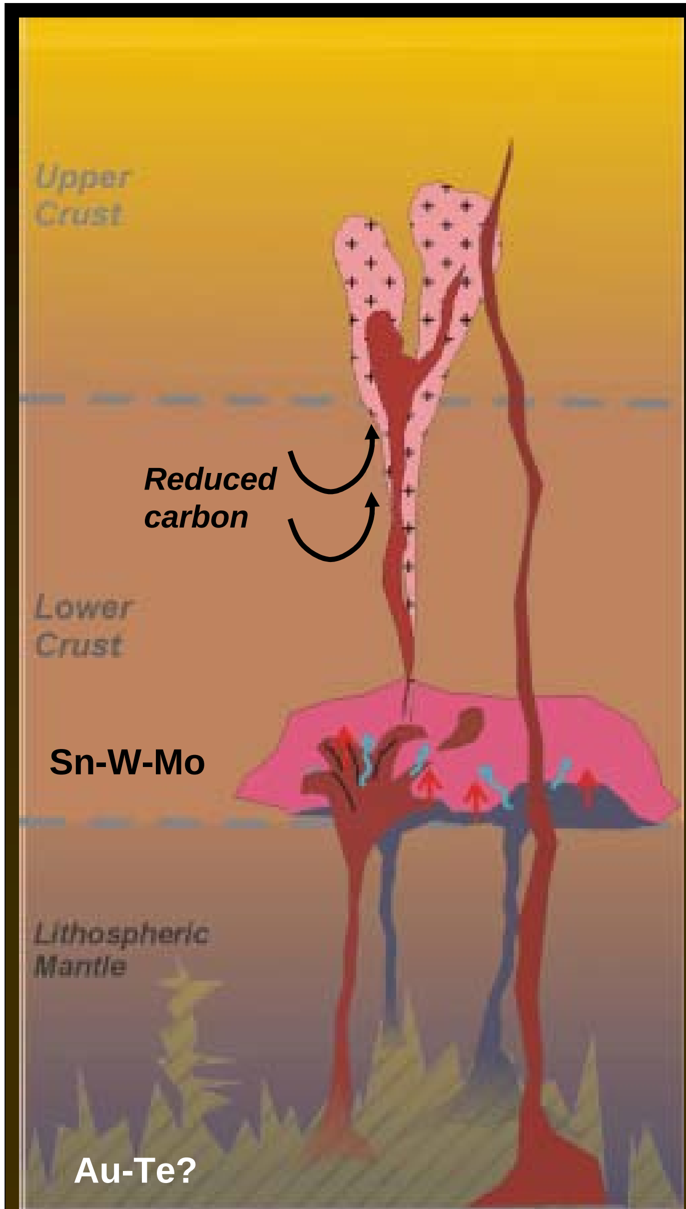


Schematic Lithospheric Section

•Post-collision and subduction processes

Volatile-rich mafic, alkalic melts from metasomatised upper mantle contribute heat and volatiles to the lower crust, to promote melting.

Felsic crustal melts of lower density than mafic melt



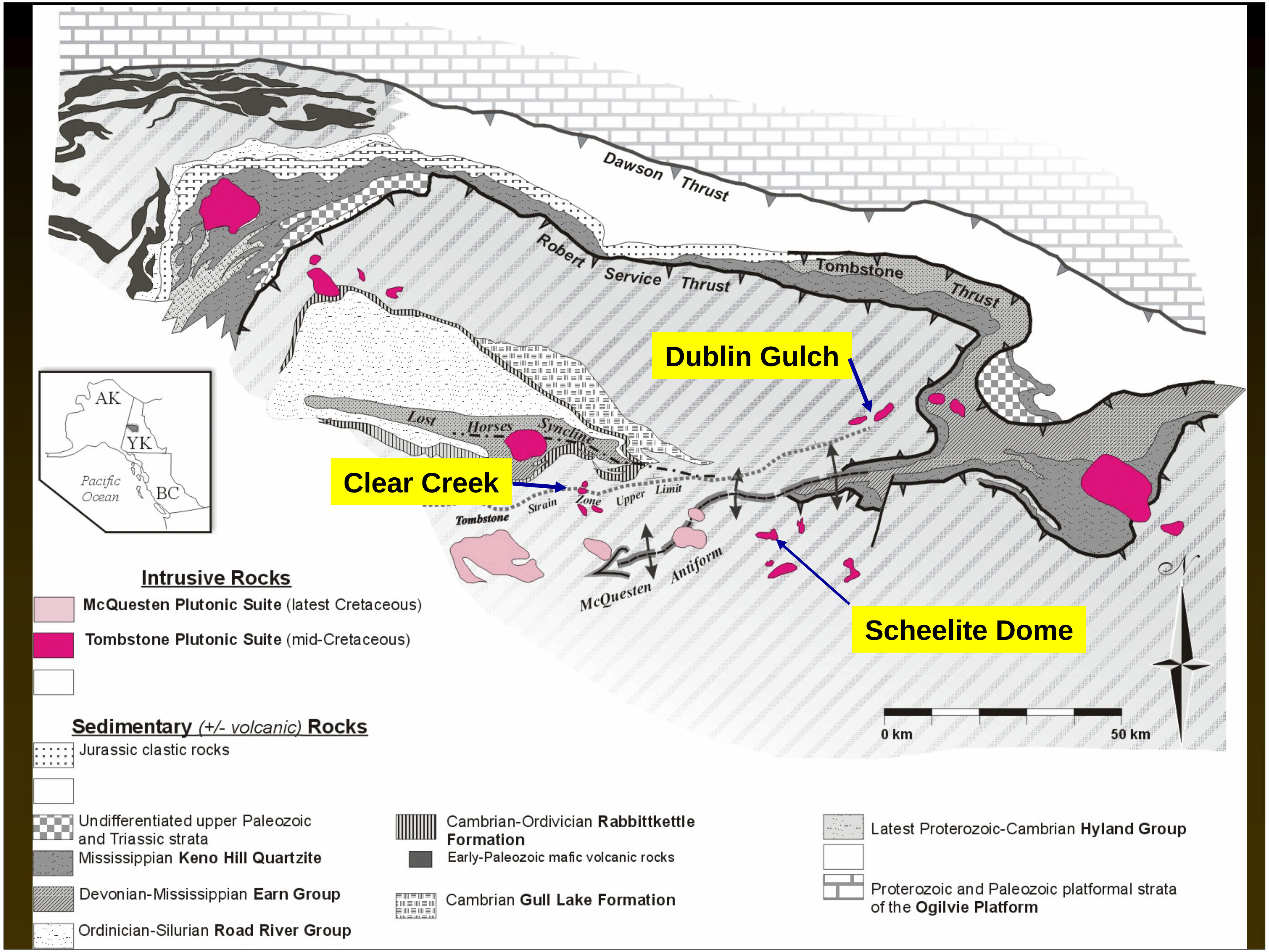
Schematic Lithospheric Section

- Post-collision and subduction processes

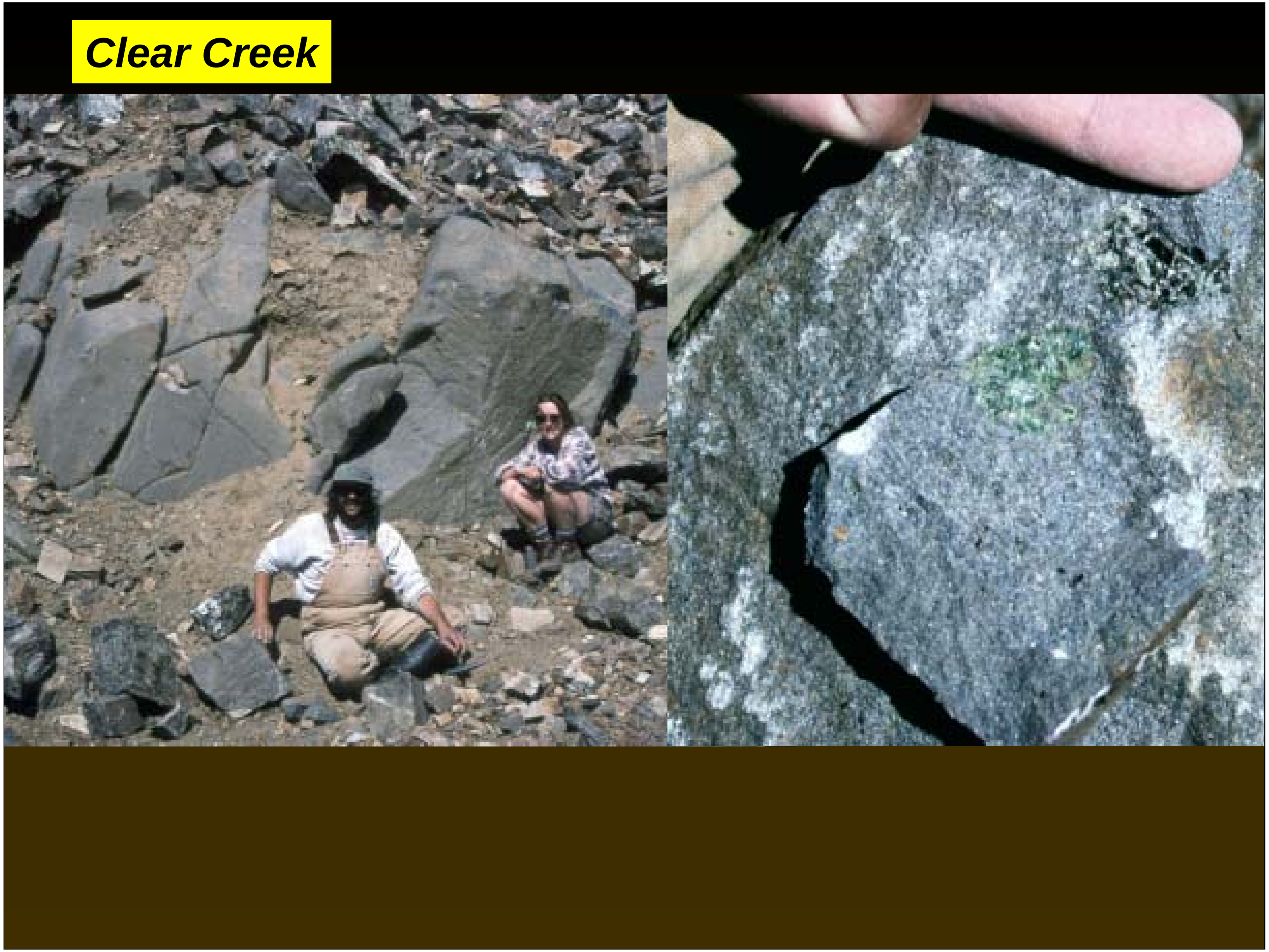
Volatile-rich mafic, alkalic melts from metasomatised upper mantle contribute heat and volatiles to the lower crust, to promote melting.

Felsic crustal melts of lower density than mafic melt

Influx of mafic magma continues, with progressively less crustal contamination



Dawson Thrust
Robert Service Thrust
Tombstone Thrust
Dublin Gulch
Lost Horses Syncline
Clear Creek
Tombstone Strain Zone
Upper Limit
McQuesten Antiform
Scheelite Dome
AK
YK
BC
Pacific Ocean
0 km
50 km
Intrusive Rocks
McQuesten Plutonic Suite (latest Cretaceous)
Tombstone Plutonic Suite (mid-Cretaceous)
Sedimentary (+/- volcanic) Rocks
Jurassic clastic rocks
Undifferentiated upper Paleozoic and Triassic strata
Mississippian Keno Hill Quartzite
Devonian-Mississippian Earn Group
Ordinician-Silurian Road River Group
Cambrian-Ordivician Rabbittkettle Formation
Early-Paleozoic mafic volcanic rocks
Cambrian Gull Lake Formation
Latest Proterozoic-Cambrian Hyland Group
Proterozoic and Paleozoic platformal strata of the Ogilvie Platform

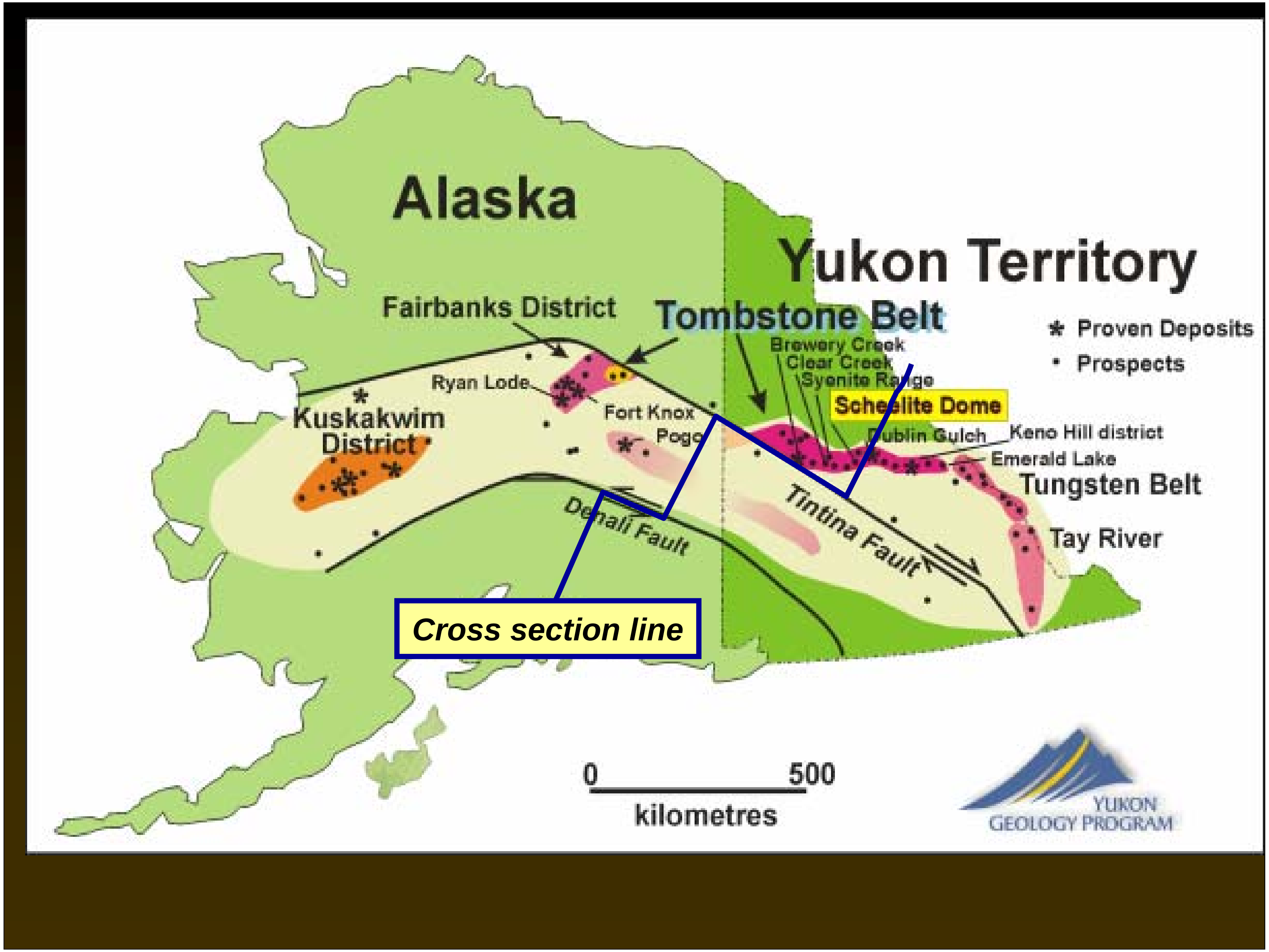

Clear Creek

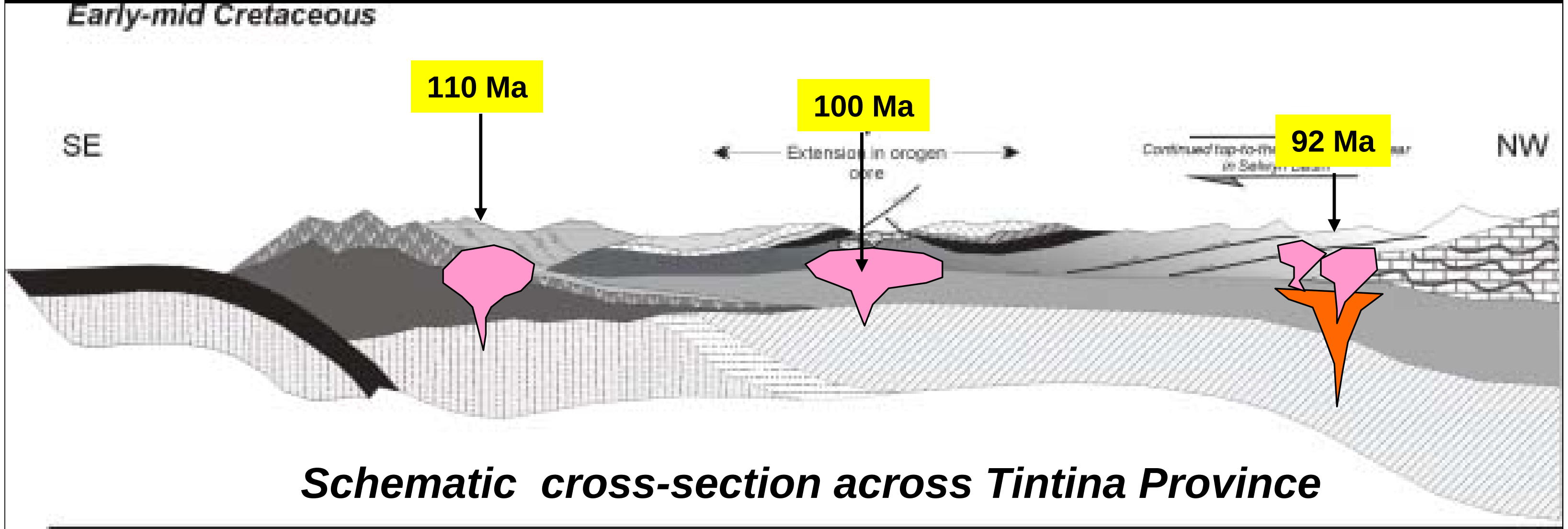

Dublin Gulch
(hybrid monzonite dike)
Abundant quartz
Cr-diopside
Ti-phlogopite

Summary - Tombstone Plutonic Suite
Scheelite Dome

- **Hybridised magma system emplaced at ~ 92 Ma in a post-collisional setting**
  - **Felsic to mafic (lamprophyric)**
- **Metaluminous to weakly peraluminous**
- **Weakly *oxidised* to weakly *reduced* (titanite bearing)**
- **Sub-alkalic to alkalic,**
- **Magmas can be considered *hot* – reset zircon cores, cpx dominant mafic phase**

- ***Regional Associations***
- **Au-rich systems associated with a component of alkalic magmatism**
- **All occur in a post-collisional to weakly extensional setting**
- **All occur inboard (cratonward) of accreted terranes, over old lithosphere**
- ***Ultimately are TPS-related systems another sub-variety of Au-deposits related to enriched alkalic magmatism ??***


Alaska
Yukon Territory
Fairbanks District
Tombstone Belt
Brewery Creek
Clear Creek
Syenite Range
Scheelite Dome
Dublin Gulch
Keno Hill district
Emerald Lake
Tungsten Belt
Tay River
Ryan Lode
Fort Knox
Pogo
Kuskakwim District
Denali Fault
Tintina Fault
Proven Deposits
Prospects
Cross section line
0
500
kilometres
YUKON GEOLOGY PROGRAM

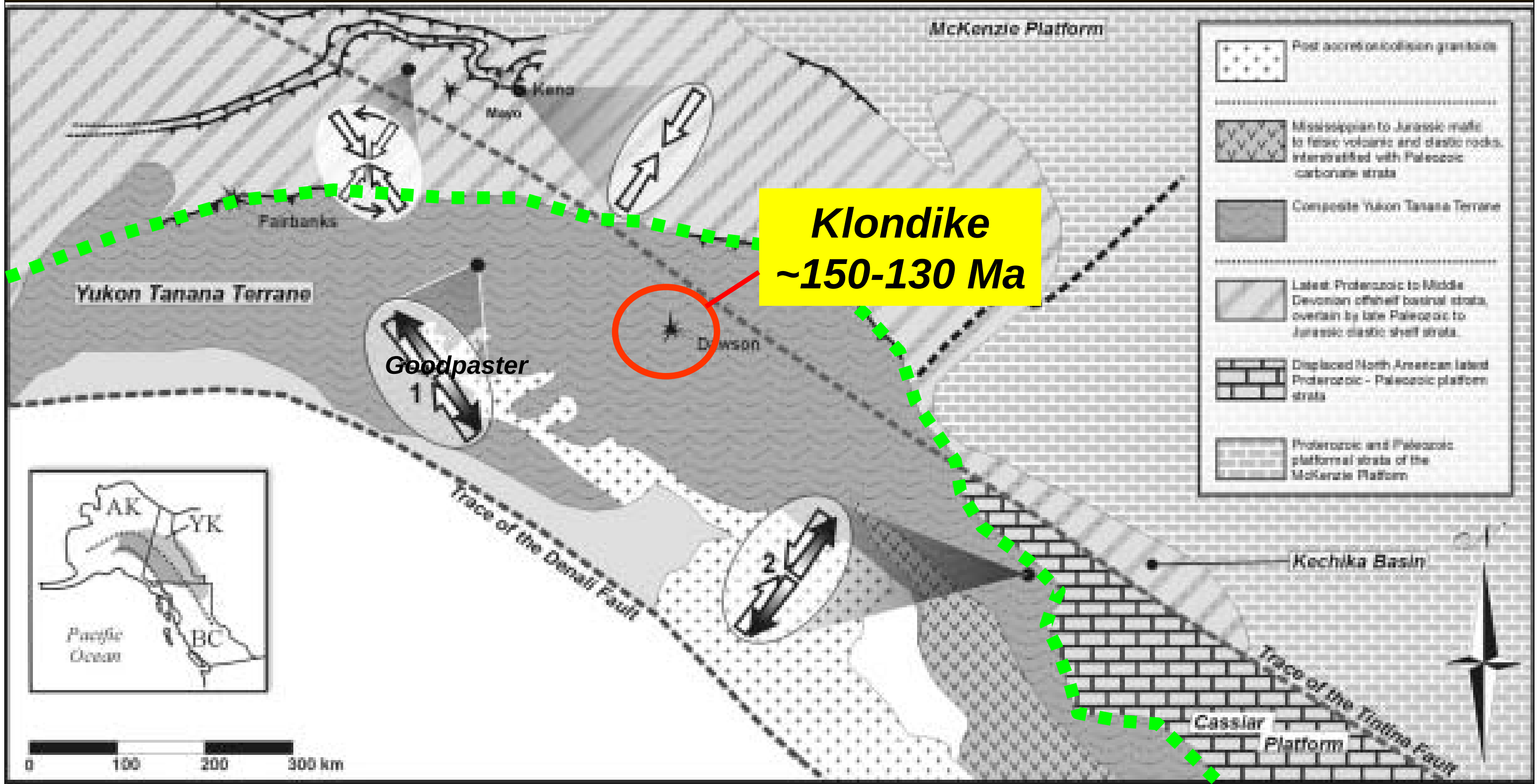


Schematic cross-section across Tintina Province

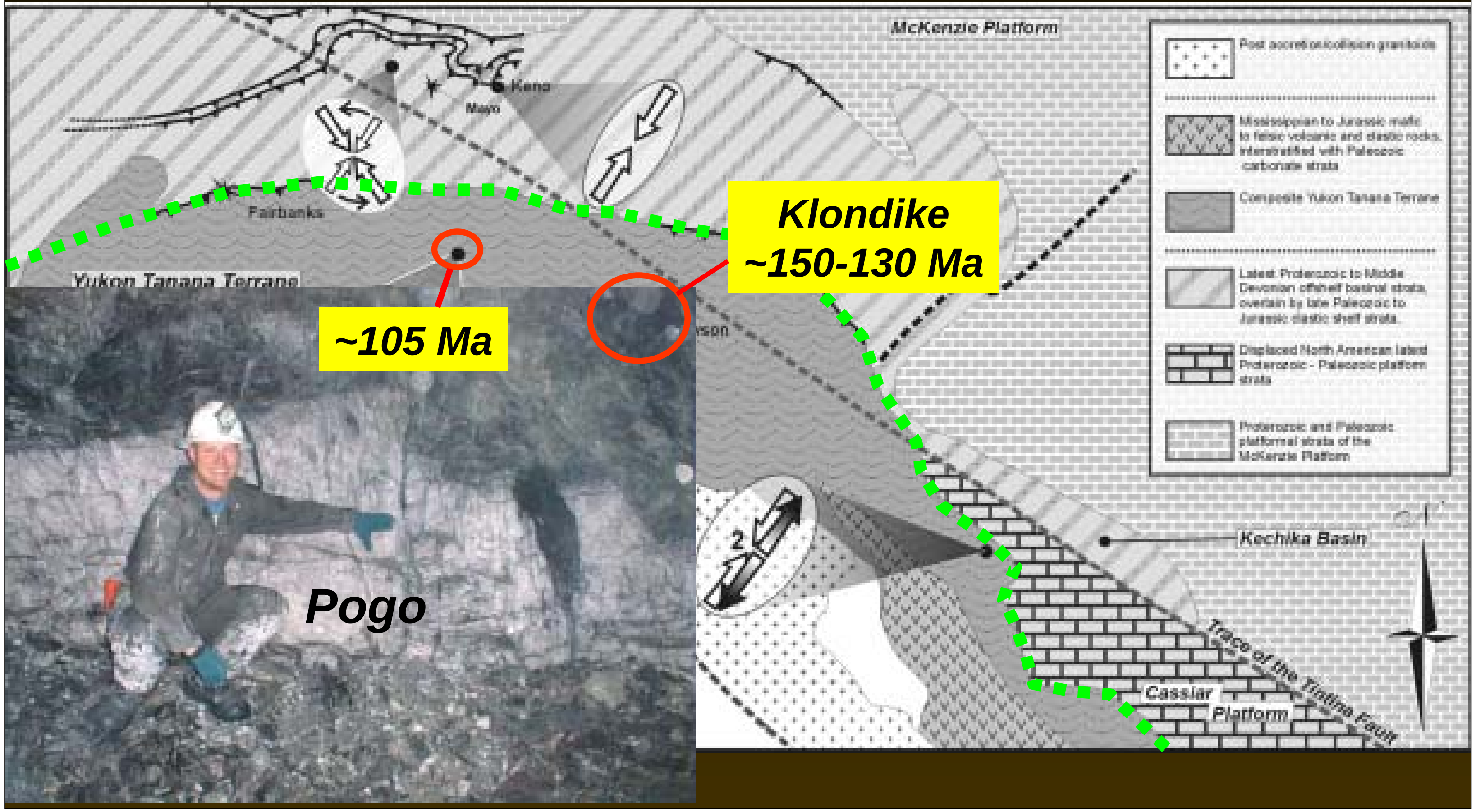
- ***TPS-style hybridised magmatism is restricted to inboard part of collisional orogen over old North American lithosphere***

- ***Such magmatism is not usually present in the accretionary and collisional belts that usually host orogenic lode-style Au deposits***

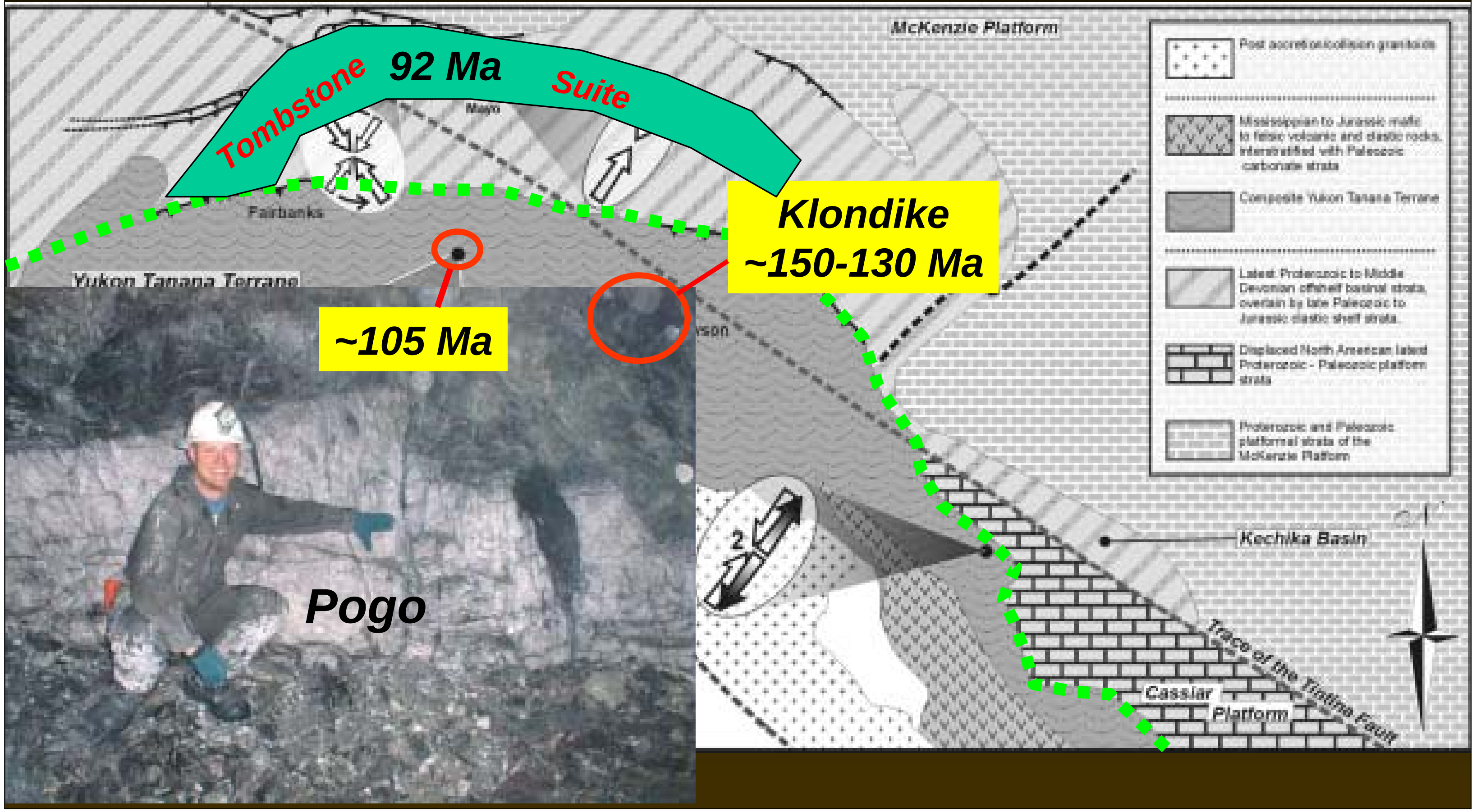
Summary – Tintina Province Timing



Summary – Tintina Province Timing



Summary – Tintina Province Timing



Conclusions:

- Hybridised mantle-crustal magma systems
- Mantle component – volatile-rich alkalic magmas
  - Sourced from metasomatised lithospheric mantle *(old refractory mantle enriched by metasomatic processes)*
- Melts are *weakly oxidised* to *weakly reduced*, mostly weakly metaluminous
- Associated hydrothermal systems are Au (+Te, Bi, As) and W rich (*in contrast to oxidised Cu-rich systems*)
- A variety of Au-rich magmatic hydrothermal systems related to volatile-rich alkalic magmatism