Mantle-lithosphere interactions and their role in the making of mineral systems

Franco Pirajno

Geological Survey of Western Australia;
Centre for Exploration Targeting,
University of Western Australia
The SCLM is subjected to metasomatism

Continental crust is the main host of mineral systems

Processes of mineral systems formation involve the SCLM and the asthenosphere

The SCLM has thicknesses of 350 ~250 to 350 km, beneath Archaean cratons and ~150 km beneath Phanerozoic terranes

The SCLM may be eroded/partially destroyed by thermal events (mantle plumes, delamination)

Thickened SCLM and continental crust, may become gravitationally unstable and delaminate into the asthenosphere

The SCLM is subjected to metasomatism
Magmatic-hydrothermal mineral systems: e.g. porphyry, skarns, epithermal, greisens, pegmatites, IOCG, REE in carbonatites and alkaline complexes

May form via partial melting of a metasomatised SCLM

The SCLM is subject to metasomatism either from subduction-derived volatiles (H$_2$O, Cl, H$_2$S, etc)

AND/OR

From volatiles (CO$_2$, F and Cl) released from upwelling asthenospheric melts or mantle plumes degassing
Sublithospheric isotopically heterogeneous mantle, with pods of HIMU and EM1 material

HIMU $\eta = \frac{^{238}U}{^{204}Pb}$ ratio of an Earth reservoir

EM1 enriched mantle with intermediate $\frac{^{87}Sr}{^{86}Sr}$ and low $\frac{^{206}Pb}{^{204}Pb}$
Slab break-off; upwelling of asthenospheric mantle
Distribution of selected mineral systems along major structures
Unaltered granite at right, flanked by strong foliation fabric with chloritic (1) and sericitic (2) alteration along Ti Tree shear zone.
Areas of hydrothermal alteration based on field observations combined with ASTER data analysis

Field and petrographic observations indicate phases of protracted hydrothermal activity within regional planar structures, particularly the Ti Tree Shear Zone;

Importantly, there is evidence that sericitic alteration OVERPRINTS the foliation fabric in the shear zone.
Late moly in quartz veinlets

Minnie Ck
Cu-Mo-W prospect

Early disseminated moly
Tentative sequence of events that led to the formation of the Minnie Springs intrusion-related mineral systems

(Re-Os dating, Pirajno, Mao JW, Du A, unpublished)
Gifford Creek ferrocarbonatites

Pirajno and González-Álvarez, GSWA Record 2013/12; and Pirajno et al. in prep
U-Pb age determination of apatite grains of Gifford Creek ferrocarbonatite by LA-ICP-MS (Wei Chen and Antonio Simonetti, Notre Dame University)
Known distribution of mafic-ultramafic and mafic rocks of the WLIP

Pirajno and Hoatson, 2013, OGR and Pirajno et al. in prep
Temporal association of carbonatites and LIPs, based on age distribution in selected provinces

From Ernst and Jowitt, Econ Geol, 2013; by courtesy of R. Ernst
Stratigraphic setting and interpreted geometry of the Abra mineralisation

Pirajno et al. 2010, IAGOD Congress Ext Abs and Pirajno et al. GSWA Report In prep)

Re-Os on pyrite = 1280-1284 Ma
Distribution of mineral systems along the Quarztite Well shear zone on a TMI (total magnetic intensity) image
Possible genetic model for the Abra polymetallic breccia pipe

Model based on Iberian Pyrite Belt (IPB); after Tornos (2006), OGR, v. 28,
Interpretation of seismic transect across the Gascoyne Province

After and details in
Johnson SP et al. 2013, Aus J E S, v. 60
1) Pegmatites and Quartz veins
   950 Ma

2) W skarns*

3) Intrusion-related Pb-Cu-Mo
   1770-975 Ma

(*) calc-silicate alteration (skarn) NOT associated with carbonate rocks
Nardoo W skarns, Gascoyne Province

187873 epidote-rich band overprinting a quartz polygonal aggregate

187878; actinolite sheafs replacing epidote + quartz assemblage

187869; garnet and epidote replacing polygonal quartz assemblage

187867; scheelite crystals
Skarn mineral system and stages of its formation:
1) isochemical, hornfels;
2) metasomatism, exo- and endo-skarn;
3) Retrograde stage

After Einaudi et al., 1981
The skarn alteration and associated mineralisation (usually W, Mo-W, Fe-P) affects rocks other than carbonates.

This calc-silicate alteration has regional extent and has no genetic relationship with spatially associated granitoids.

**How are these skarn formed?**

High-T, Low-P metamorphism associated with upwelling asthenospheric mantle along major strike-slip shear zones/sutures.
Altai orogen (NW China; Xinjiang Province), part of the Central Asian Orogenic Belt

Listwaenite outcrop, qtz stockworks

Skarn and listwaenite belt
Abagong “skarn” (Fe-P) deposits (black lines in Google Earth image)
Abagong skarns

A) Massive wollastonite skarn
B) Garnet-magnetite skarn
Skarn-type Hahaigang deposit of Gangdese metallogenic belt, unrelated to carbonate rocks and older (c. 63 Ma) than spatially associated granitoids (c. 57 Ma)

After Xiaofeng Li et al. (in press) OGR
Comparative cross-sections of southeastern and western Tibet at present day. Both sections are true scale, from MFT across the Himalayan orogenic wedge (MHT: Main Himalayan Thrust, STD: South Tibet Detachment), to Tibetan terranes (Lhasa and Qiangtang).
Au-Ag-Te epithermal and Cu-Au porphyry systems, related to partial melting of volatile- and incompatible elements-enriched lithospheric mantle

Lithospheric mantle fertilisation due to subduction metasomatism 50 Myrs ahead of the extensional regime that produced the magmas and associated mineral systems

Inset shows the Apuseni Mountains (AM), the current location of the Adriatic subduction front

S-wave tomographic images of the regional subsurface. Red stars mark the location of the Apuseni Mountains. Red lines on map views show location of depth sections directly below maps; numbers on the lines correspond to the distance across the transect in degrees.
• Rifts tend to form around cratonic margins, usually following weak zones of Proterozoic orogenic belts

• Crustal-scale ductile to brittle-ductile shear zones control the location of rift structures, magma emplacement and ore systems

• Long-lived shear zones and multiple ore-forming events

• Asthenospheric melts, rich in C, F, Cl and S penetrate the overlying SCLM, causing extensive metasomatism

• Metasomatised SCLM partially melts producing alkaline and carbonatitic magmas
Sequence of geodynamic events leading to multiple stages of metasomatism of SCLM

After Su BX et al., 2011, Gondwana Res, v. 20
Model depicting the formation of rift-related magmas (e. g. syenitic, carbonatites; A-type granites, rhyolites) enriched in high-field-strength elements and the rare earths

After Martin, 2006, Lithos. V. 91

Ph phonolite
C carbonatite
SG syenite, granite
N nephelinite
Modified after Lindenfeld et al., 2012, Tectonophysics 566-562: 95-104

Modified after Sibson et al., 1975, Geos Soc London; 131: 653-559
Tectono-magmatic evolution of EARS (African-Arabian sector) plume-rift systems

Note lithospheric uplift and developing crustal rifts, accompanied by varying degrees of SCLM metasomatism in different sectors of the EARS

From and by courtesy of Beccaluva et al., 2011, Geo Soc Am Sp Paper 478
Opposing model for the development of High-Ti and Low-Ti flood basalts of the 260 Ma Emeishan large igneous province; SW China

after Xiao, Pirajno, 2003, Acta Petr Sinica

after Xu JF, 2007, Geoch Cosmoch Acta, v. 71
Magmatic-temporal evolution of the Siberian SCLM, stages 1 and 2

**Stage 1:** Low-T (950-1100 °C) metasomatism

> 360 Ma

**Stage 2:** High-T (>1200 °C) metasomatism

~ 360 Ma

*Eruption of Pre-SFB Kimberlite pipes*

After and by courtesy of Howarth et al. 2013, Lithos
Magmatic-temporal evolution of the Siberian SCLM, stages 3 and 4

Stage 3: Extensive basaltic metasomatism
~250 Ma

SFB

Stage 4: Local kimberlite metasomatism
~160 Ma

Eruption of Post-SFB Kimberlite pipes

(SFB = Siberian flood basalts)

After and by courtesy of Howarth et al. 2013, Lithos,

See also: Griffin et al. 2013, Nature Geoscience
Metallogenic trend = ~ 1000-2000 km

Polymetallic systems
Porphyry; LS epithermal Au, Kimberlites, carbonatites

Ni-Cu-PGE; Fe-Ti-V

Translithospheric
Strike-slip

Lamprophyre
Dykes

Alkaline intrusions, A-type
Zoned Mafic-um intrusions

Traps, sills
Layered complexes

Crust & mantle lithosphere

Fertile lithosphere, variably metasomatised

Fertile lithosphere, variably metasomatised

Pirajno, 2010, J Geodynamics
Acknowledgments

Weronika Gorczyk (CET)
Tom Lenane (GSWA)
Murray Jones (GSWA)