Archean SCLM: What do we (think) we know?

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What is the Sub-Continental Lithospheric Mantle (SCLM)?

- Non-convecting uppermost mantle formed
  - as partial melting residues
  - by cooling of upwelling asthenosphere
  - by plume accretion to existing lithosphere

- Depleted in basaltic components, then *overprinted by metasomatic processes* -- geochemically complex

- Base of depleted SCLM = Lithosphere-Asthenosphere Boundary (LAB) -- recognisable chemically, ?seismically

- Temperature at LAB ≈ 1200-1300 °C
What do we need to know about the Archean SCLM?

- Age – relative to crust, etc. One hit, or a long process?
- Composition – bulk; stratification?
- Origin – subduction, or what?
- Why/how is it different from younger SCLM?
- Tectonic effects – what changed once we had an SCLM, and why?
How old is the SCLM? 
Re-Os dating of mantle sulfides

Individual sulfide grains in peridotite xenoliths

- Few >3.5 Ga
- Major peak ~3.0 Ga -- formation of most Archon SCLM?
- Later peaks = metasomatic events?

A unique period in Earth history!
In-situ Re-Os Dating
Mantle sulfides, Kaapvaal Craton

Each terrane carried its own “root” into craton assembly

Oldest ages in each terrane = oldest crustal ages

Other peaks = ages of known events (including suturing)
Sulfides in Xenoliths: S. Africa

Southern Africa
(N=94)
W. Kaapvaal Craton
N. Lesotho

Relative Probability

T(RD), Ga

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5

Goldschmidt 2012
Sulfides in Xenoliths: Siberia

Udachnaya, Siberia
(N=130)

All sulfides enclosed in olivine -- fewer young ages

Main peak 2.7-3.2 Ga
Sulfides in Xenoliths: Siberia

- Udachnaya, Siberia (N=130)
- Internationalnaya (N=99)

Relative Probability vs. T(RD), Ga

Internationalnaya -- All sulfides enclosed in Gnt
-- Cause of age shift?

Main peak 2.4-3.0 Ga
No Hadean model ages - few >3.3 Ga

Major peak 2.7~3.0 Ga -- formation of most Archon SCLM?

Started at ≈ 3.5 Ga!

Later peaks = metasomatism events?

A unique period in Earth history!
$T_{RD}$ ages of high-Re/Os sulfide and alloy grains in mantle-derived xenoliths ($n=370$)

Whole-rock model ages = minimum values, because of mixing >1 sulfide generation – but overall agreement on the oldest $T_{RD}$

SCLM age = $3 \pm 0.5 \text{ Ga}$
How old is the SCLM?
PGE contents of komatiitic magmas

Variations in the PGE content of komatiites through time indicate that the mantle was homogenised between 3.5 and 3.0 Ga.

Consistent with stirring of the mantle by a burst of deep-sourced plumes between 3.5-3.0 Ga (Major Mantle Overturn)

(Maier et al., 2009)
Major changes in chemistry/origin of mafic rocks, and crustal dynamics, at 2.5 Ga ---
Major changes in chemistry/origin of mafic rocks, and crustal dynamics, at 2.5 Ga ----

Or by 3 Ga?
SCLM -- An Archean Genesis

Early Earth
- no stable SCLM
- little preserved crust

Archean (3.6-3.0 Ga)?
- mantle overturns form stable SCLM
- some subduction?

Present Day
- subduction
- steady-state recycling
- no stable SCLM formed
Secular change in SCLM composition

Samples
Xenoliths and
- Kimberlites
- Lamproites
- Basalts

Progressively less depletion through time?
Sampling the Archean SCLM

- Xenolith Suites in Kimberlites
  - 85% of analyses from Kimberley mines (huge dumps)
  - Completely dominated by garnet lherzolites
    - Pretty, can do P-T, etc etc
    - High Si/Mg (opx-rich)
    - Now obvious these are metasomatically refertilised!

- Xenolith suites in alkali basalts
  - Rare -- E. Greenland, Cape Verde Islands, W. USA

- Exposed massifs with Archean ages
  - Rare -- mainly Western Gneiss Region (Norway)
Archean SCLM’s unique Fe depletion -- a signature of high-P melting?

Young peridotites have FeO = 8±1% at any degree of depletion

Shallow melting processes.....

Most Archon SCLM lower-Fe

High-P melting!
Archean SCLM: Si enrichment (?)

Most Archon SCLM high-Mg#

High Si/Mg rare outside Kaapvaal Craton

Biased sample!
Seismic Tomography -- A problem with the models

Archon cores: thick, depleted, cool; high Vs

Can’t model with “typical Archean SCLM”

AND -- thick “typical” SCLM is too buoyant -- gives too low geoid and too high elevation
SCLM Control on Rifts and Alkaline Magmas

Cratonic margins act as focal point

Squares = Kimberlites
Stars = Carbonatites
Circles = Syenites
Polygons = Rifts

CCFS Perth 2013
Detailed Vs model
200±50 km

Fouche et al. 2004
+ kimberlites

Kimberlites cluster
around high-Vs domains
-- no samples of these depleted cores

Circles -- best xenolith - xenocryst suites:
sampling refertilised low-Vs SCLM

A biased sample!
Lherz(olite) -- Case study in mantle refertilisation

Harzburgite

Lherzolite/websterite

Le Roux et al., 2006
“Pristine” Archean SCLM: More depleted than we think?

- Western Norway: huge bodies of dunite/harzburgite
- Zones of garnet lherzolite ± eclogite
- Re-Os: dunites are Archean, lherzolites are Proterozoic
- Refertilisation process -- an analogue for most Archean SCLM?

Gusdal quarry and Ugelvik gnt peridotite, Norway
Western Gneiss Region (Norway) Dunites: Refertilisation to Lherzolite

Proterozoic refertilisation of Archean dunite/harzburgite:
add gnt + cpx; increase Al, Fe, Ca, Na; lower Mg#, Cr#
~ All trace elements (REE, Sr, Zr etc) also increased!
WGR Dunites -- Refertilisation to Lherzolites

- Dunites/harzburgites extremely depleted
- Lherzolite refertilisation trend mimics xenolith "depletion trend" -- *in reverse*
- Kaapvaal peridotite xenoliths = same trend
- Original Archean SCLM ≈ WGR dunite/harz?
Refertilisation affects all of the “diagnostic” or “robust” trace elements -

None can be used to argue for shallow melting processes
SCLM Compositions and Processes

2 processes:
1) Juvenile fertile SCLM = mafic melt extraction from PUM;
2) Enrichment of depleted Archon

- Reworked Archon (P/A, T/P/A)
- Fertile Juvenile Lithosphere (Residue after loss of mafic melt)
- Depleted Archon SCLM
- Asthenosphere (PUM)
- %CaO
- %Al₂O₃

Modification by interaction with melts and volatiles

E.g. Island arc mantle, oceanic lithosphere

Xian 2009
A More Depleted Archon SCLM
Tough, Buoyant and Still With Us

Griffin et al. 2009, J. Petrology 50
A More Realistic Archon SCLM Solves the Geoid/Elevation problem
Conclusions: Archean SCLM

- “Typical” Archean gnt Iherzolite is a metasomatic product -- cannot be used to model SCLM formation
- Primitive Archean SCLM is much more depleted than estimates from xenoliths -- inconsistent with shallow origin
- Most (all?) formed >3 Ga ago, by deep high-degree melting
- Archean lithosphere (lower crust and SCLM) is much more widespread laterally and vertically than previously thought
- Original volume of lithosphere formed in the Archean (>2.7 Ga) far greater than currently assumed -- ≥ 70%
- What about the Yilgarn? Only two small kimberlites – sampling fertile mantle – very poor and biased sample – over to geophysics!
Continental drift without subduction on a stagnant-lid planet
Comparisons between the Archaean Earth and Venus

Jean Bédard  (Geological Survey of Canada)
Lyal Harris  (Institut National de la Recherche Scientifique)

Bédard, Harris & Thurston, The hunting of the snArc (2013)
Precambrian Research 229:20-48
Harris & Bédard, Crustal evolution and deformation in a non-plate-tectonic Archaean Earth: Comparisons with Venus (2013)
Archean Earth and Early life, Springer (in press)
Why do people believe in Archaean Plate Tectonics?

1) Generation of **compressional fabrics** and assembly of Terranes requires horizontal tectonics... But does this **REQUIRE** Plate Tectonics?

2) Calc-Alkaline magmas with –Nb-Ta-Ti & +LILE anomalies. Do these require ARC(s)?
What Defines Plate Tectonics?

Seafloor Spreading

Subduction

Continental drift?
Do the Americas drift westward because of Plate Boundary Forces?

- Pacific Ocean
- 1-2 kilobars, to raise Andes
- 500 bars to maintain Altiplano
- SCLM
- 200 bars Ridge Push?
- Atlantic Ridge

If Ridge Push Raises Cordillera, why hasn’t Subduction Initiated?
(185 my oceanic crust)

Force Calculation from Russo & Silver 96, Geology
NO The Americas drift because of basal traction from mantle currents!

Husson et al 2012 EPSL
Unstable Stagnant Lid Planet

Stagnant Lid Convection Prevents Formation of Oceanic Lithospheric Mantle

Komatiites Above
Plume-Like Instabilities
Craton + SCLM Start to Form

Shallow Mantle (Tholeiites), No Systematic Chemical Evolution

Episodic mantle evolution?
If continents with deep lithospheric roots migrate due to mantle traction, subduction is not needed to explain terrane accretion & orogenesis!

Becker & Facenna, 2011, EPSL
Alvarez 2010, EPSL

So if the SCLM is of Archaean age, then Cratons would have started drifting in the Archaean!
Archaean Continental Drift
Causes accretion of buoyant oceanic
plateau type crust. Transient
tectonic relief feeds sedimentary belts

Archaean continental crust has no
relief (too soft)

Stagnant lid
Convection prevents
formation of
oceanic lithospheric
mantle = buoyant
Simatic lithosphere

Subcreted basalt
Melts = TTG
Restite + mantle
Remelt = SCLM

Mantle Traction
Hot metabasalt melts = TTG + Gt-Px restite

Eclogite-polluted Mantle Remelts = SCLM

MANTLE WIND

Heat

Polluted mantle

crustal drips melt & metasomatize mantle

Harris & Bédard (2013) in press
Summary: Linked Evolution of SCLM and continental crust

-- SCLM formed mainly 3.5-3.0 Ga – massive overturns, mixing – buoyant because of Fe removal

Provided basis for continents, “modern” plate tectonics (and Archean psuedo-plate tect.)

4-fold division of Archean (4.0-2.4 Ga)/Hadean?
and what *Don’t* we know?

- Real composition of high-Vs cratonic cores – fundamental to estimates of SCLM composition, origin(s)
- Sources/origins of metasomatic fluids – in any detail
- Sources of non-cratonic lithospheric mantle – relict vs new, residual vs refertilised,……..accreted plates?
- Nature/properties of mid-lithospheric discontinuity – is this how Archean SCLM gets thinned?
- Fate of Hadean lithosphere – stored at depth?
Thank You and Goodbye