Earth's Mantle evolution through the time

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In the Beginning

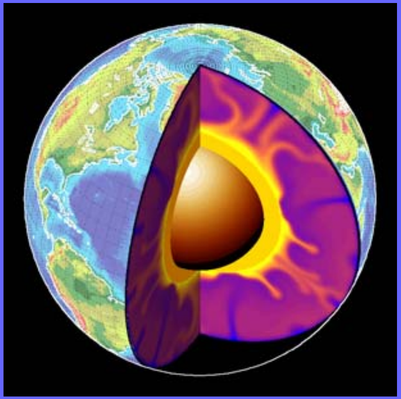
magma ocean

Core

< 10 Ma

Bulk Silicate Earth

10-30 Ma



Undifferentiated Earth

End of terrestrial accreation

Today

Hadean Eon 3.8-4.6 byBP **Archean Eon 2.5-3.8 byBP**

International Stratigraphic Commission, 2007

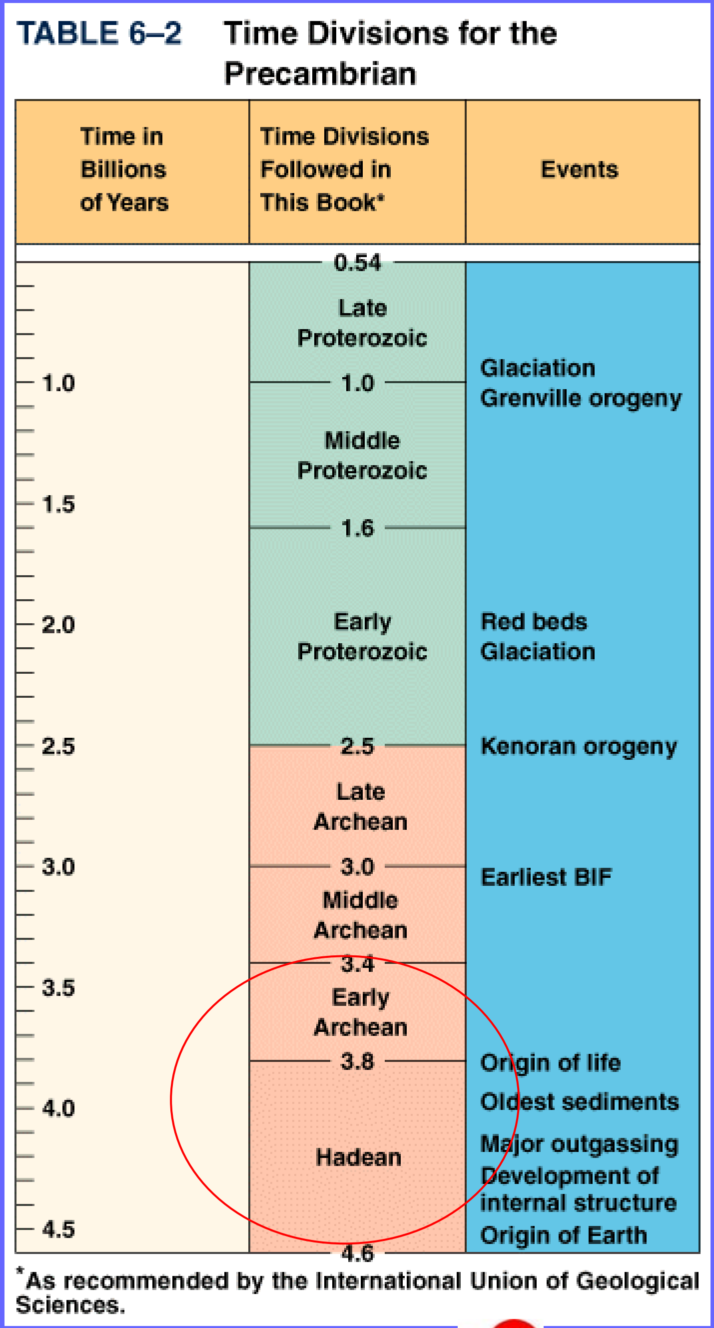


TABLE 6–2 Time Divisions for the Precambrian

Time in Billions of Years	Time Divisions Followed in This Book*	Events
	0.54	
	Late Proterozoic	
1.0	1.0	Glaciation Grenville orogeny
	Middle Proterozoic	
1.5		
	1.6	
2.0	Early Proterozoic	Red beds Glaciation
2.5	2.5	Kenoran orogeny
	Late Archean	
3.0	3.0	Earliest BIF
	Middle Archean	
	3.4	
3.5	Early Archean	
	3.8	Origin of life
4.0		Oldest sediments
	Hadean	Major outgassing Development of internal structure
4.5		Origin of Earth
	4.6	

*As recommended by the International Union of Geological Sciences.

Proterozoic Eon 0.54-2.5 byBP

Archean Eon 2.5-3.8 byBP

Hadean Eon 3.8-4.6 byBP

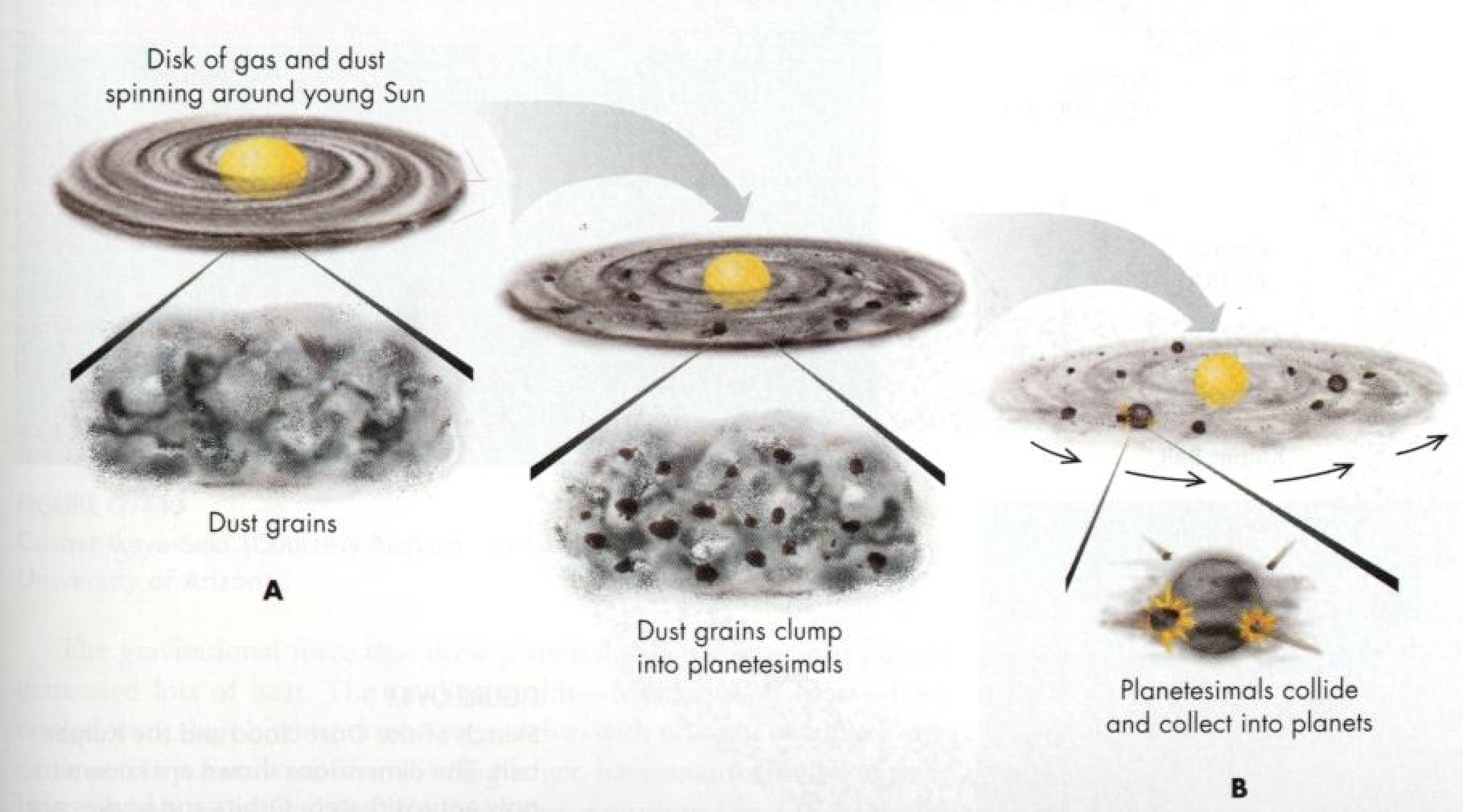
THE PRIMORDIAL EARTH

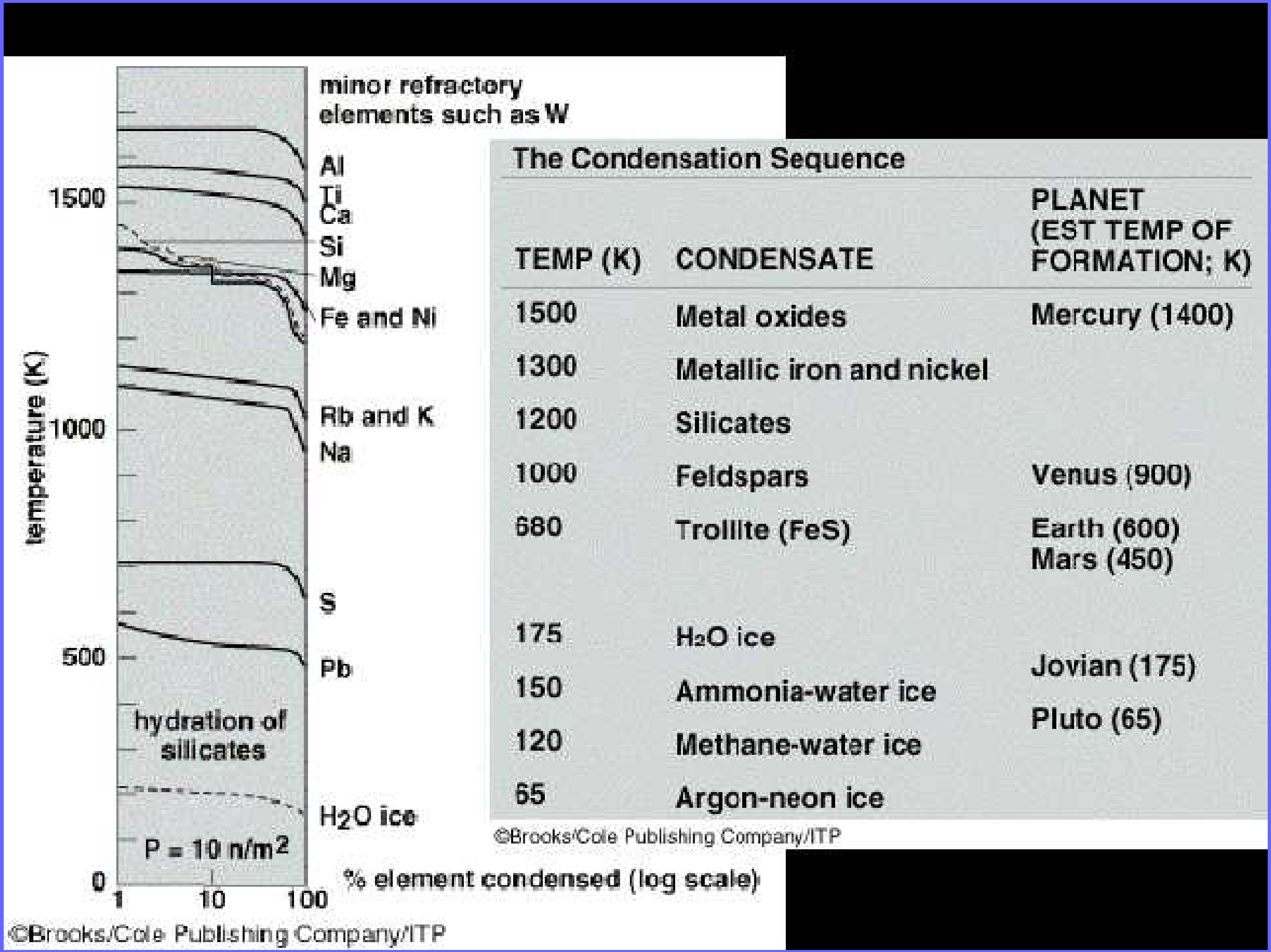
Hadean and Archean Eons

Accretion and Differentiation

Origin of the Earth's Internal Layering

Earth formed by accretion of dust and larger particles of metals and silicates.


Disk of gas and dust spinning around young Sun
Dust grains
A
Dust grains clump into planetesimals
Planetesimals collide and collect into planets
B



The Condensation Sequence

TEMP (K)	CONDENSATE	PLANET (EST TEMP OF FORMATION; K)
1500	Metal oxides	Mercury (1400)
1300	Metallic iron and nickel	
1200	Silicates	
1000	Feldspars	Venus (900)
680	Troilite (FeS)	Earth (600) Mars (450)
175	H_2O ice	Jovian (175)
150	Ammonia-water ice	Pluto (65)
120	Methane-water ice	
65	Argon-neon ice	

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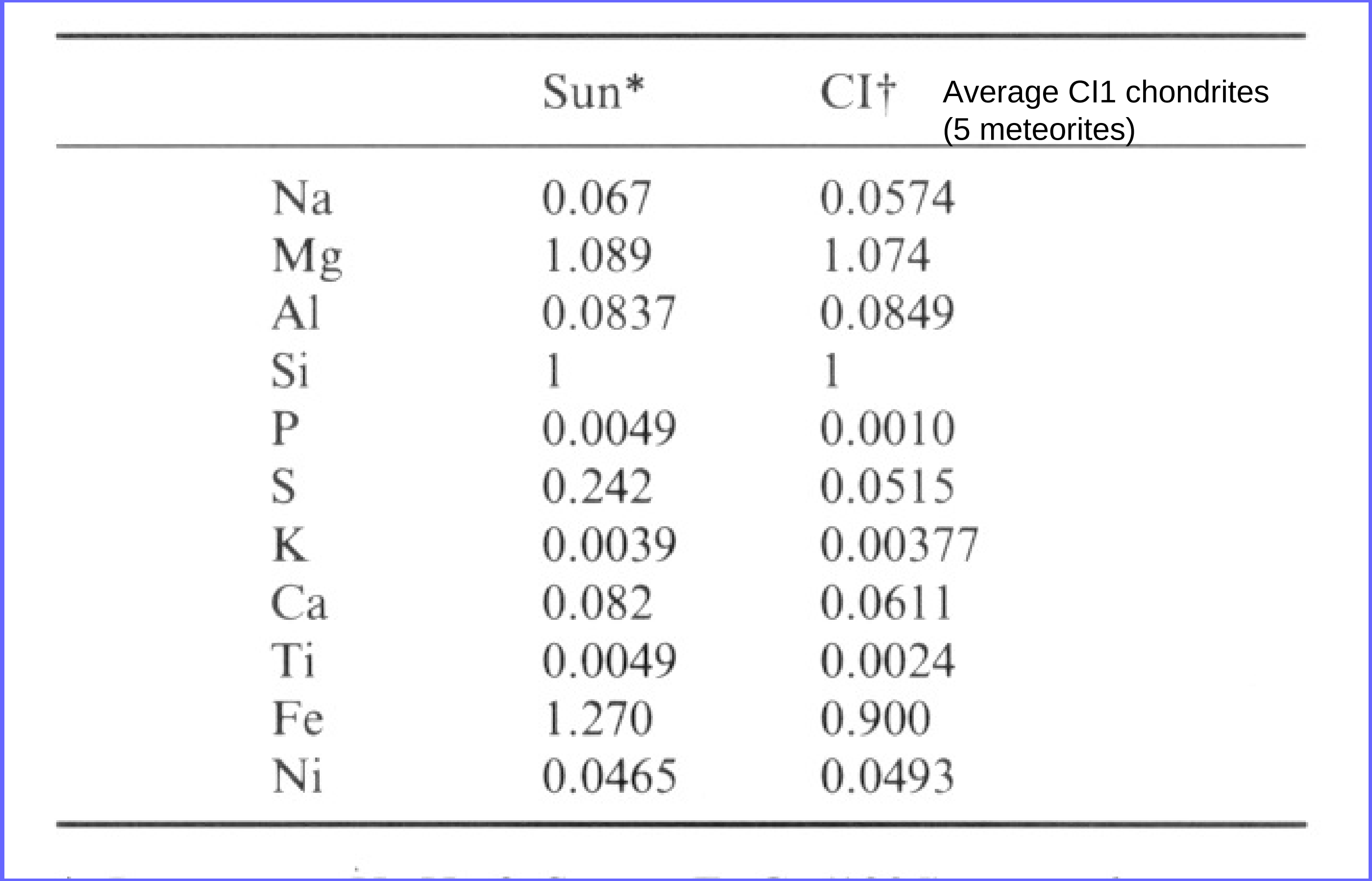
Planetary Materials Reviews in Mineralogy n.36 (1998)

Vaporization and **condensation** of silicate phases under the condition of primitive solar nebula are the key processes responsible for the very early formation of pyroxenes and olivines in the undifferentiated bodies (**chondrites**).

Starting minerals	Products
hibonite	corundum +vapor (C)
enstatite	fosterite + vapor (C, Mo, W)
spinel	corundum + vapor (C)
akermanite	larnite (Ca_2SiO_4)+ vapor (C)
olivine s.s.$(Mg, Fe)_2SiO_4$	more magnesian olivine + vapor (Mo, C)
plagioclase ss / diopside ss	non stechiometric calcic pl/ enstatite +vapor (C)



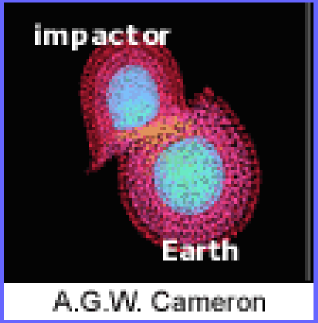
	Sun*	CI†
Na	0.067	0.0574
Mg	1.089	1.074
Al	0.0837	0.0849
Si	1	1
P	0.0049	0.0010
S	0.242	0.0515
K	0.0039	0.00377
Ca	0.082	0.0611
Ti	0.0049	0.0024
Fe	1.270	0.900
Ni	0.0465	0.0493

Average CI1 chondrites
(5 meteorites)

Table from Lunine, 1999

CI1 carbonaceous chondrites. These meteorites contain "heavy elements“-hight T condensated (i.e., elements other than hydrogen and helium)- in nearly the same abundances as in the Sun, which means that they are essentially unaltered since they were formed at about the same time as the solar system itself, some 4.6 billion years ago.

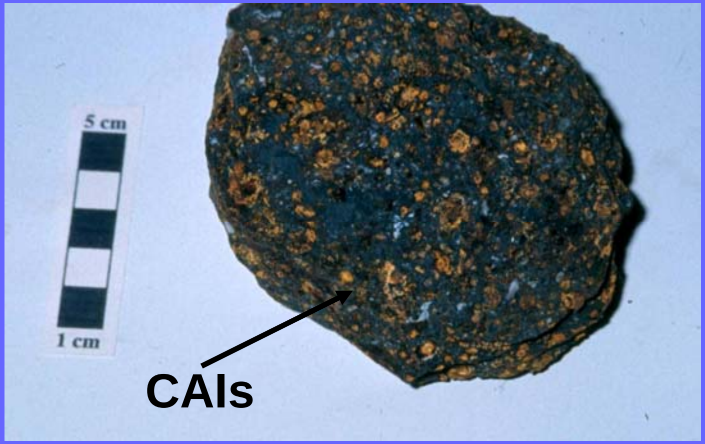
As observed in many carbonaceous chondrites (**CI and CV**), roughly 20/% of the silicate portion is constituted by enstatites and Ca-rich pyroxenes (O'Neill & Palme 1998, Brearly & Jones, 1998).



Ivuna meteorite, CI1

Fragment (10gr) property Natural History Museum of London

Vigarano meteorite, CV3

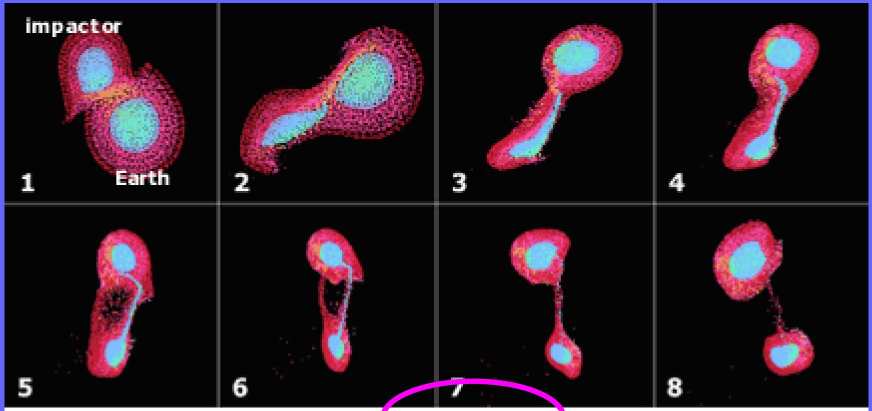


CAIs

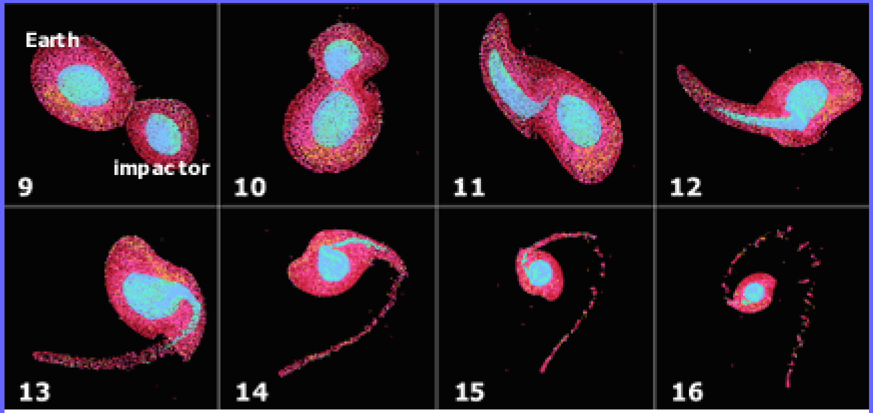
Fragment (2.4 gr) property Dip. Scienze Terra, Università di Ferrara

Origin of the Earth and Moon, 1998, LPI Contribution No. 957, Lunar and Planetary Institute, Houston.

"Although not proven to everyone's satisfaction, the giant impact hypothesis explains a lot about the Earth and Moon. Combined with our current understanding of accretion, it leads to a dynamic and somewhat terrifying picture of the first few hundred million years for both bodies. **The formation of the planets was a violent process**. Huge rocky planetary embryos smashed into one another, forming oceans of magma surrounded by white-hot silicate atmospheres. Between the huge impacts, Earth's **magma oceans probably cooled rapidly, perhaps in only a few years or decades**. One such impact flung enough rocky stuff into orbit to form the Moon, which began its existence largely molten. Earth continued to be bombarded, forming new magma oceans. The impact rate declined and a stable crust formed on the Earth."



(Courtesy of A. G. W. Cameron, Harvard College Observatory.)



(Courtesy of A. G. W. Cameron, Harvard College Observatory.)

Hartmann & Davis, 1975, Icarus
Cameron & Ward 1976 Proc. Lunar Planet. Sci. Conf 7th,

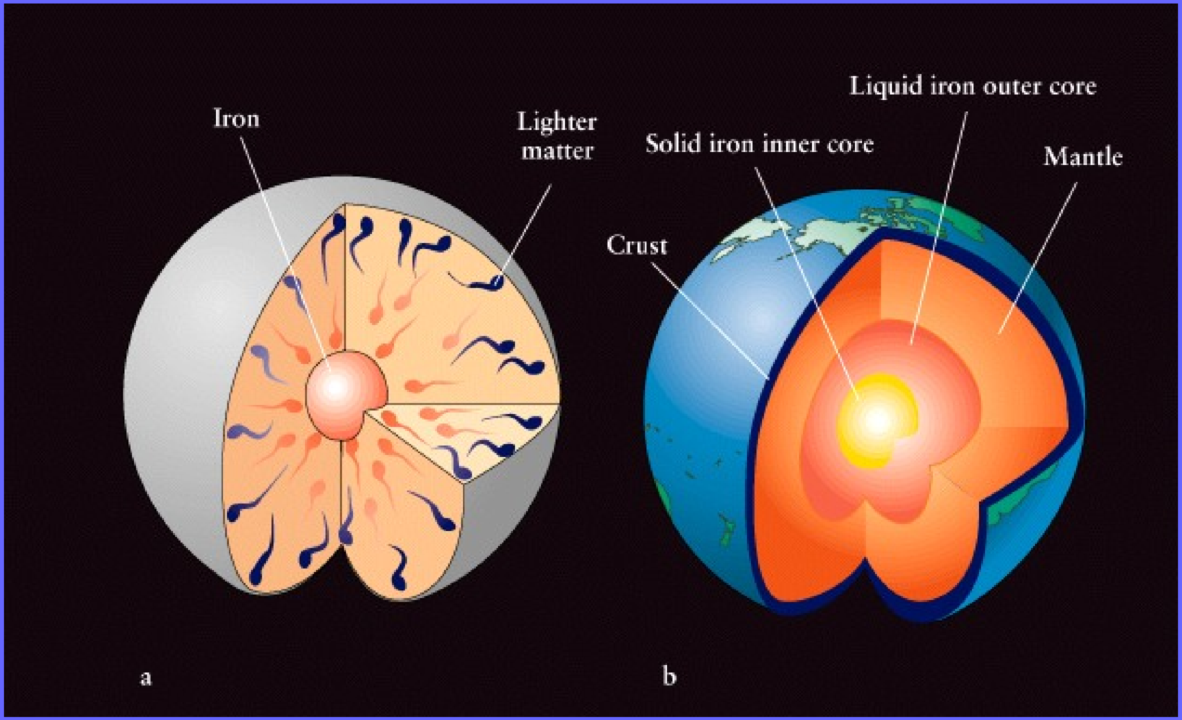
THE PRIMORDIAL EARTH

Hadean and Archean Eons

Accretion and Differentiation

Origin of the Earth's Internal Layering

Differentiation is the result of heating and at least partial melting.



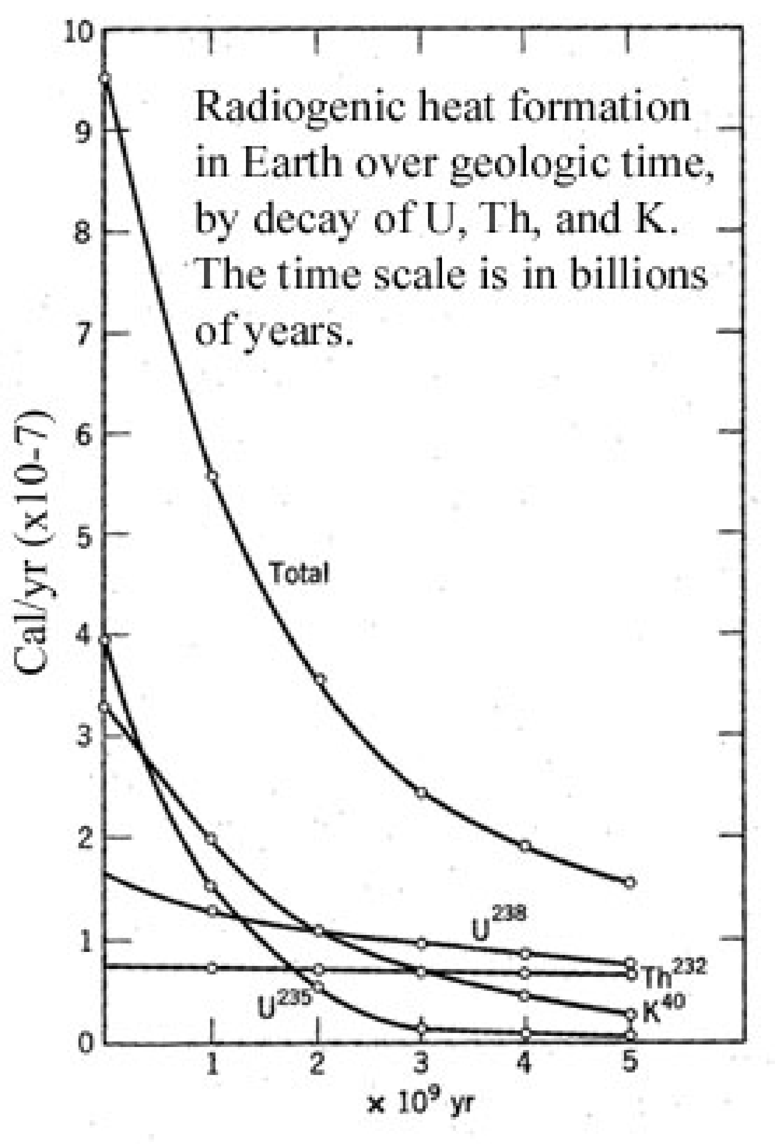
THE PRIMORDIAL EARTH

Hadean and Archean Eons

Accretion and Differentiation

Source(s) of heat for melting?

3. Radioactive decay



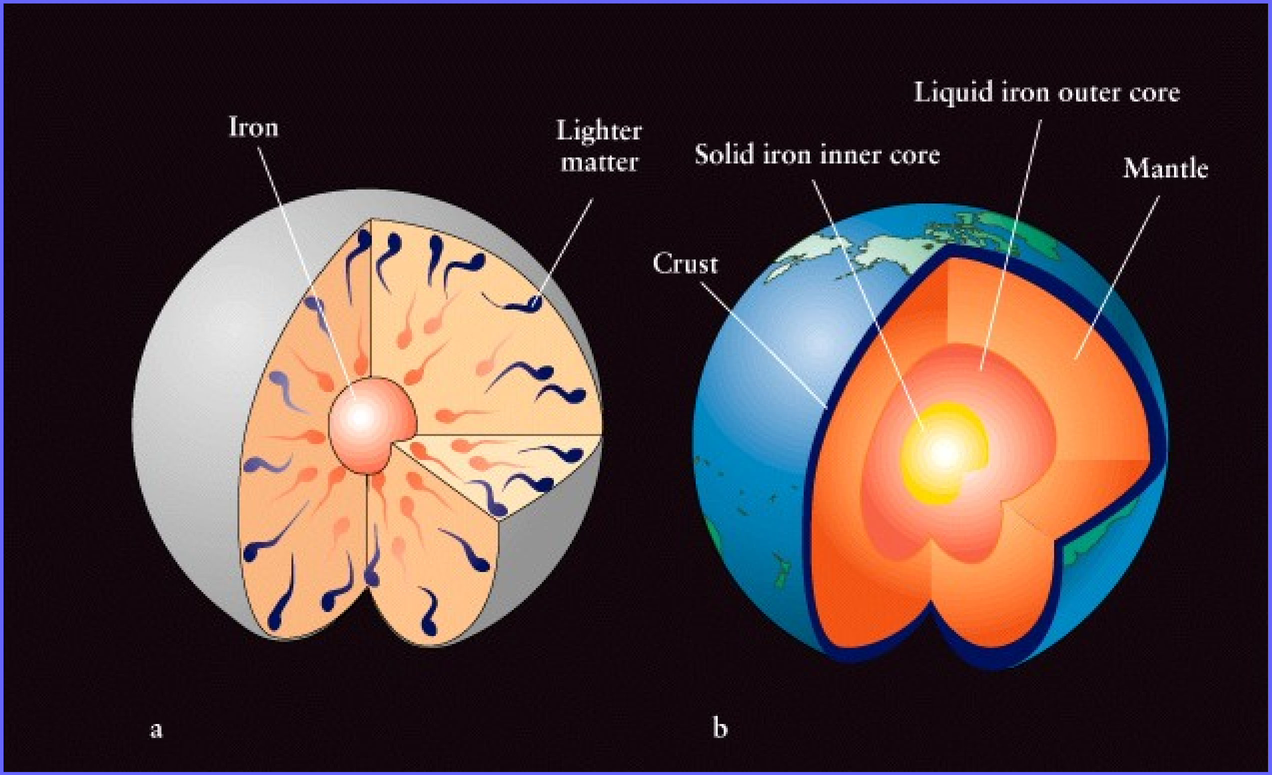
THE PRIMORDIAL EARTH

Hadean and Archean Eons

Accretion and Differentiation

Origin of the Earth's Internal Layering

Iron and nickel sink to form core (lower T melting)



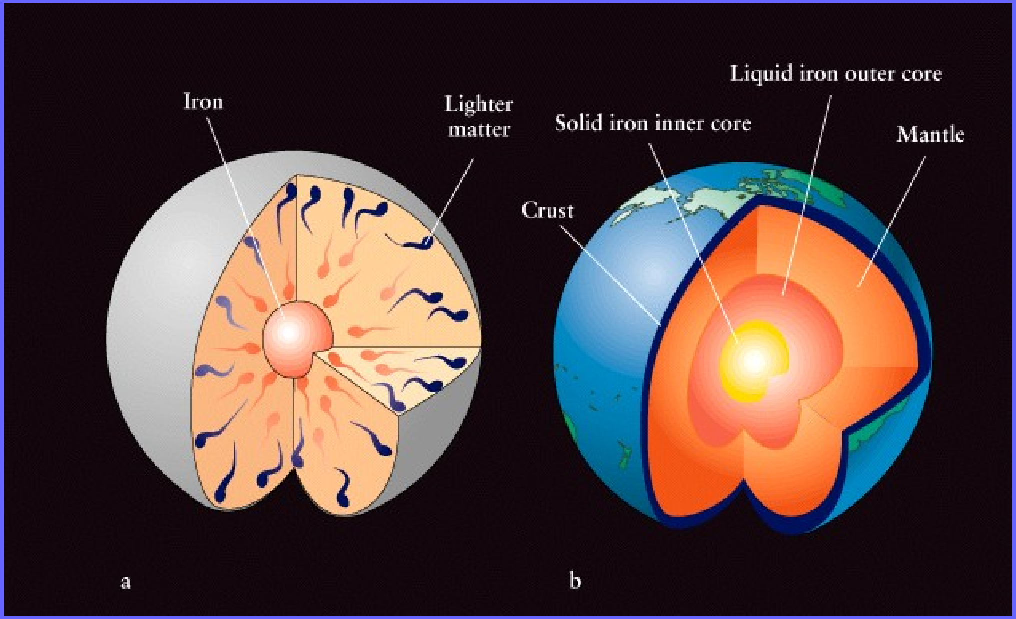
THE PRIMORDIAL EARTH

Hadean and Archean Eons

Accretion and Differentiation

Origin of the Earth's Internal Layering

Less dense material (silicon and oxygen mixed with remaining iron and other metals) forms mantle and lighter crust (primarily silicon and oxygen).



Bulk Silicate Earth

Chondritic model
vs
pyrolite model

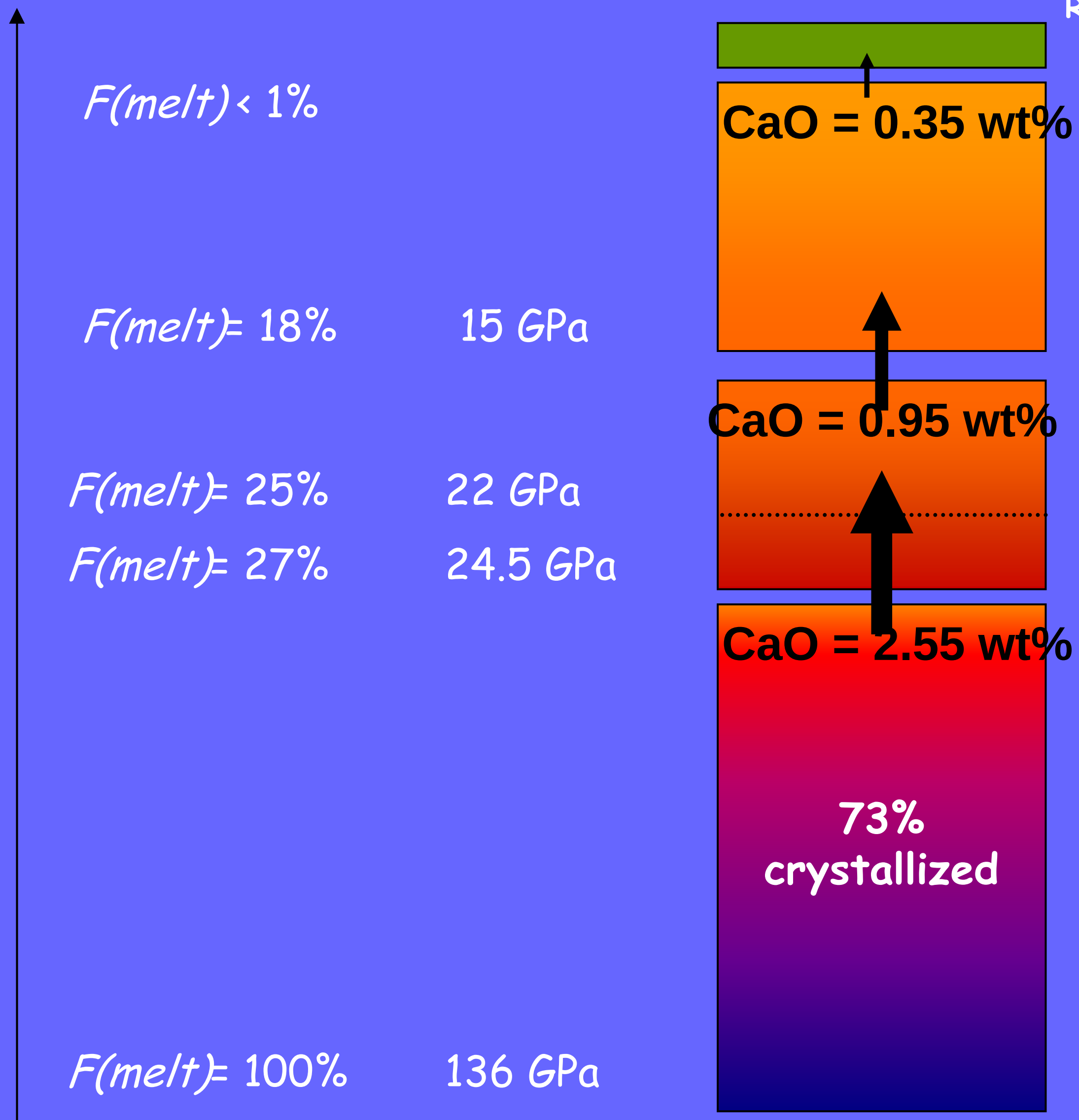
Major element composition model of BSE

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
MgO	36.77	38.1	38.3	36.8	35.5	37.8	37.8	37.77
Al2O3	4.49	3.3	4.0	4.1	4.8	4.06	4.4	4.09
SiO2	45.5	45.1	45.1	45.6	46.2	46.0	45.0	46.12
CaO	3.65	3.1	3.5	3.5	4.4	3.27	3.5	3.23
Feot	8.10	8.0	7.8	7.5	7.7		8.1	7.49
Total	98.41	97.6	98.7	97.5	98.6		98.8	98.7
RLE/Mg	1.21	1.02	1.03-1.14	1.1-1.4	1.3-1.5	1.06-1.07	1.17	1.05-1.08
Mgv	0.89	0.895	0.897	0.897	0.891		0.893	0.90

(1) O'Neill & Palme, 2003
(2) Ringwood , 1979
(3) Jagoutz et al., 1979
(4) Wänke et al., 1984
(5) Palme & Nichel, 1985
(6) Hart & Zindler, 1986
(7) McDonough & Sun, 1995
(8) Allègre et al., 1995

The major element composition trends from oceanic and off-craton subcontinental lithosphere intersect at an **Mg#** of about 0.893, indicating a common fertile lherzolite protolith.

Model for the crystallization of a terrestrial magma ocean (Caro et al., 2005, Wood et al., 2006)



(30-60 My)

Sequence of crystallization

Residual melt (protocrust)

F(melt) < 1%

CaO = 0.35 wt%

Uppermost mantle

5-7 wt% cpx

57% ol, 14% gt, 29% cpx

F(melt)= 18% 15 GPa

CaO = 0.95 wt%

Upper transition zone

57% Ring, 43% Maj

F(melt)= 25% 22 GPa

Lower transition zone

F(melt)= 27% 24.5 GPa

57% Ring, 38% Maj, 5% CaPv

CaO = 2.55 wt%

73% crystallized

Lower manle

79-75% MgPv

16% FP

5-9% CaPv

F(melt)= 100% 136 GPa

BSE phase proportions

CaO = 3.5 wt%

(based on Sm, Nd, Lu and Hf mineral/melt partition coefficients)

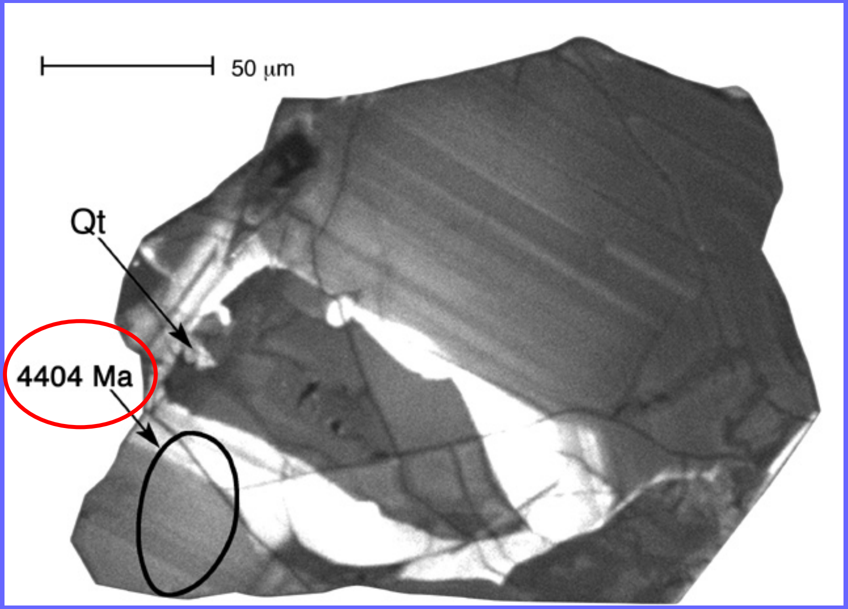
THE PRIMORDIAL EARTH

Hadean and Archean Eons

The Hadean Crust … from magma ocean

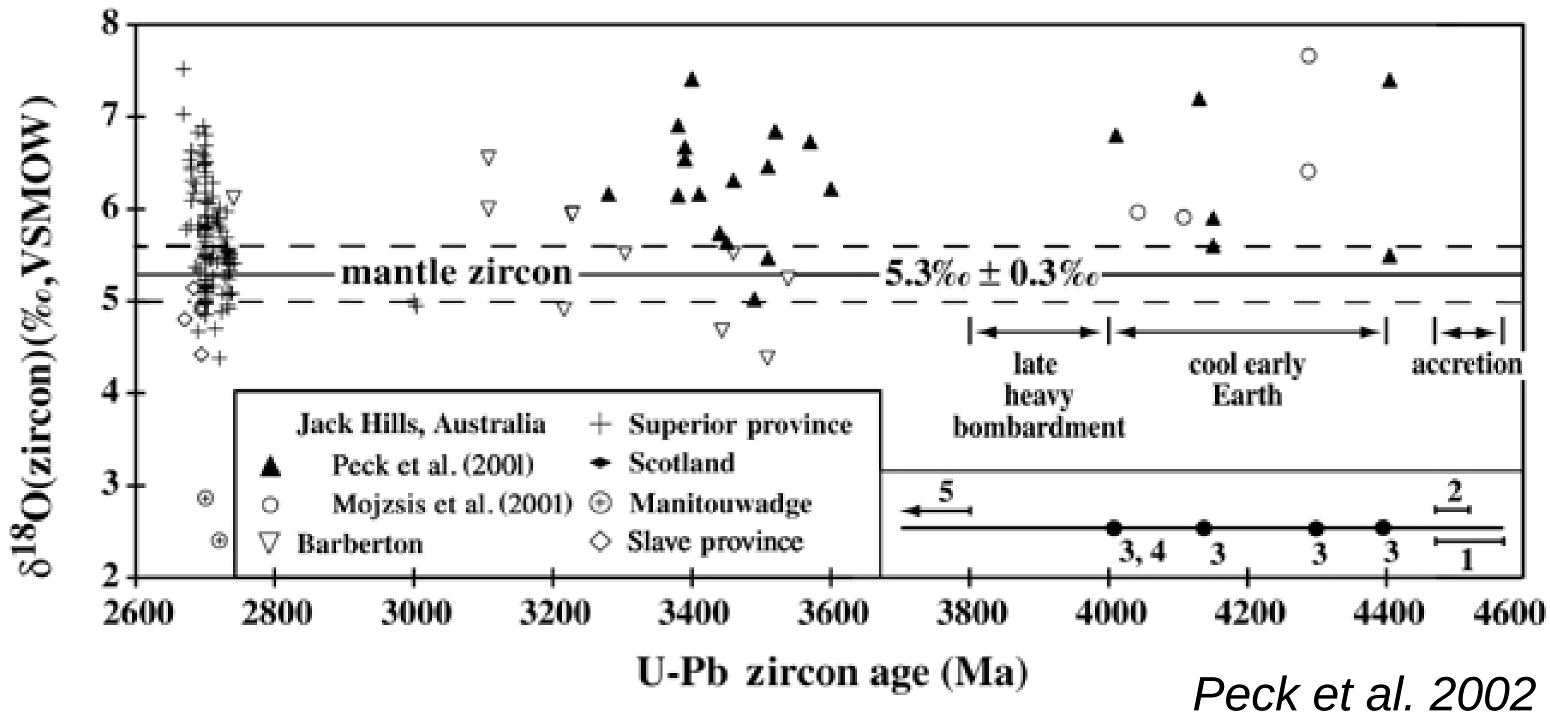
Outcrop of the oldest known sample of the Earth, a 4.4 Ga detrital zircon (sample W74) in the Jack Hills metaconglomerate, Eranondoo Hill, Jack Hills, Western Australia.

S.A Wilde (Curtin University) unpublished photograph



Recent studies have shown that Ti content in zircons in the oldest sample are consistent with crystallization temperature of 700°C, indistinguishable from present day zircon growth temperature in hydrous granitoids (Peck et al., 2001, 2002; Watson & Harrison, 2005, Ushikubo et al., 2008).

THE PRIMORDIAL EARTH
Hadean and Archean Eons

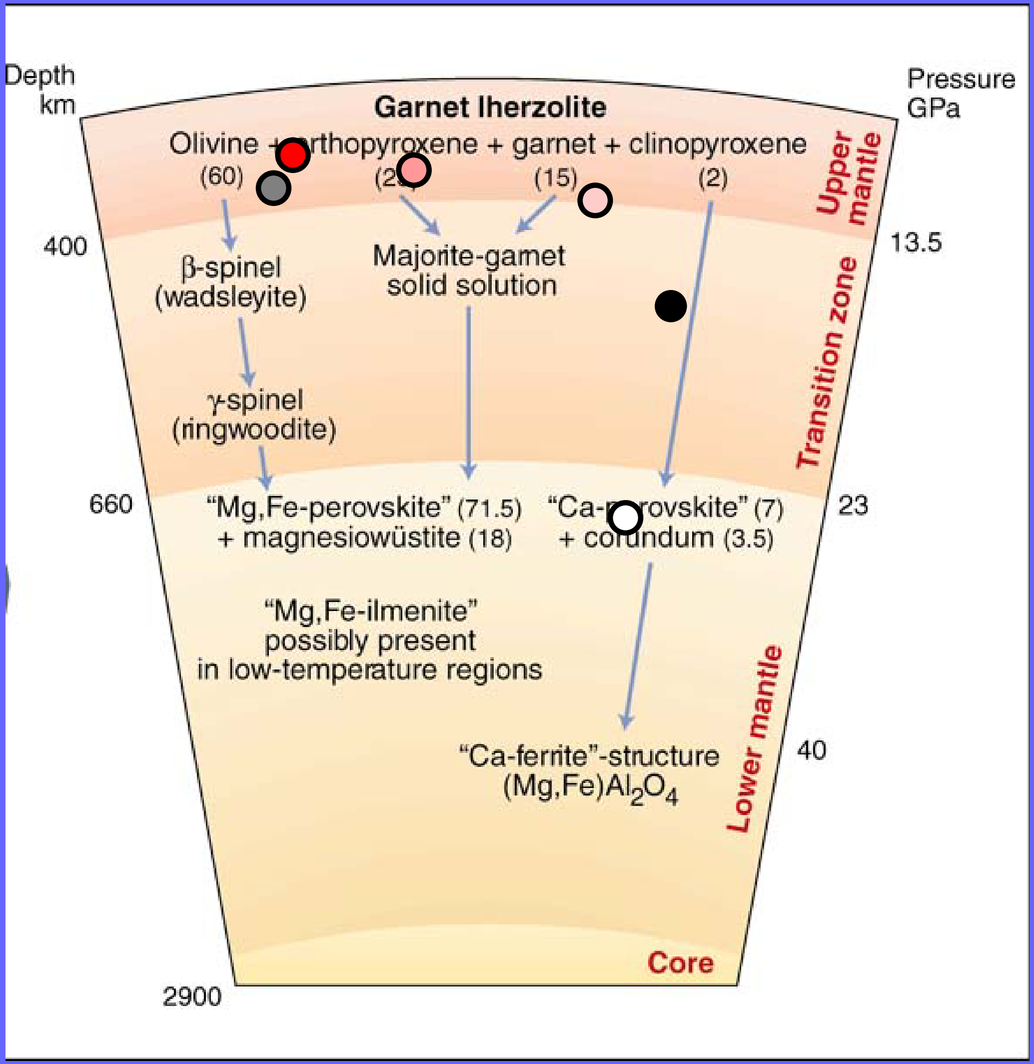


Peck et al. 2002

Crystallization age (U-Pb) and oxygen isotope ratio (δ^{18}O) for Archean magmatic zircons. Distribution of magmatic δ18O values does not change throughout the Archean. Most magmas had a primitive δ^{18}O value similar to that in the mantle today ("mantle zircon"), but some zircon values are as high as 7.5‰. High-δ^{18}O zircons and host magmas resulted from melting of protoliths that were altered by interaction with liquid water at low temperatures near surface of Earth

Timeline (inset, lower right) shows: (1) accretion of the Earth, (2) formation of the Moon and the Earth’s core, (3) minimum age of liquid water based on high δ^{18}O zircon, (4) Acasta gneiss, and (5) Isua metasedimentary rocks. (Valley et al. 2002)

From the Archean…

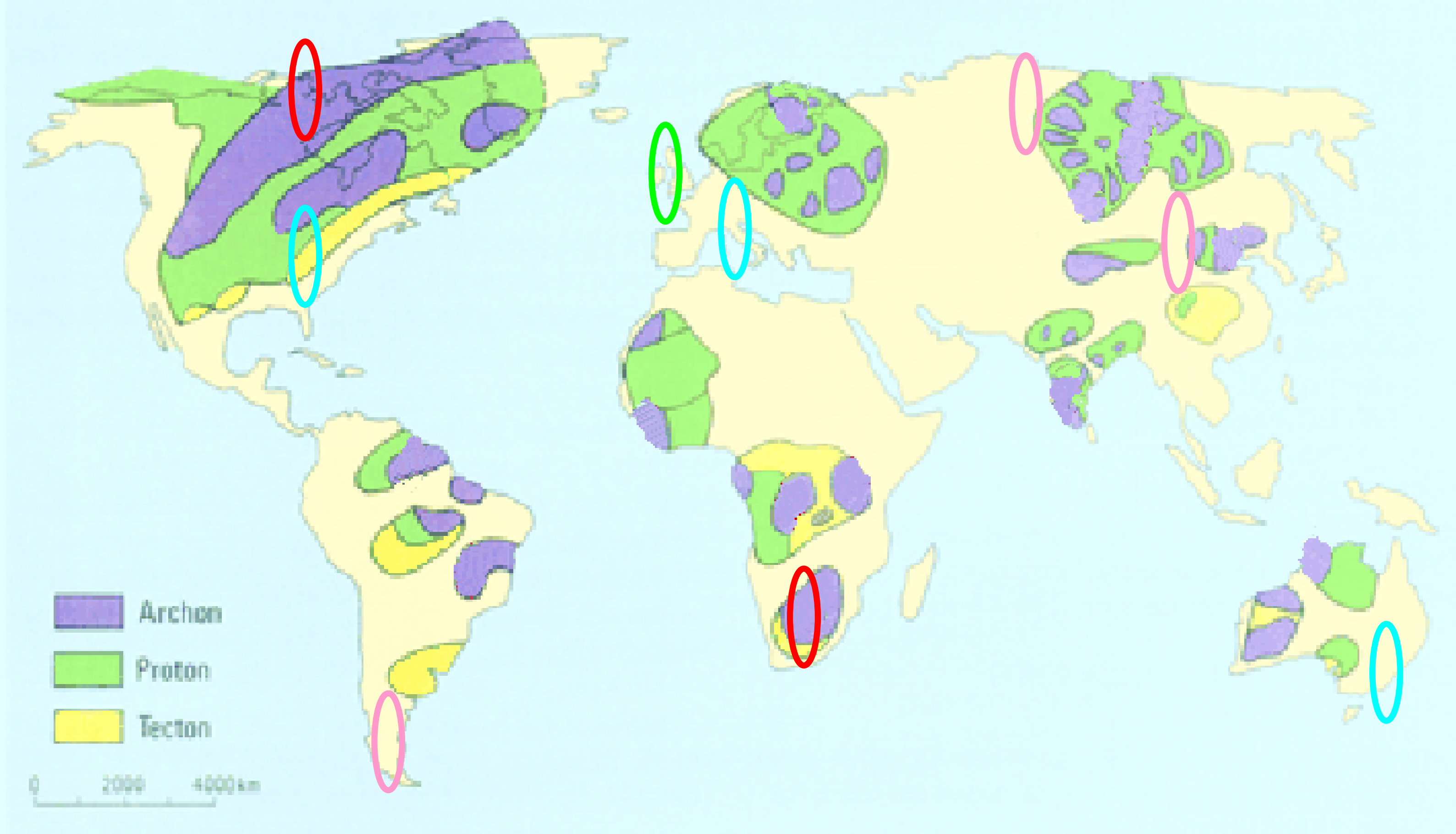


● ● **Mantle xenoliths**

○ ● **Diamond Peridotitic inclusions**

○ **Single mineral inclusions in diamonds (Ferropericlase, Mg-Si perovskite, magnesiowustite)**

Globe Map showing the locations of clinopyroxene considered in the study

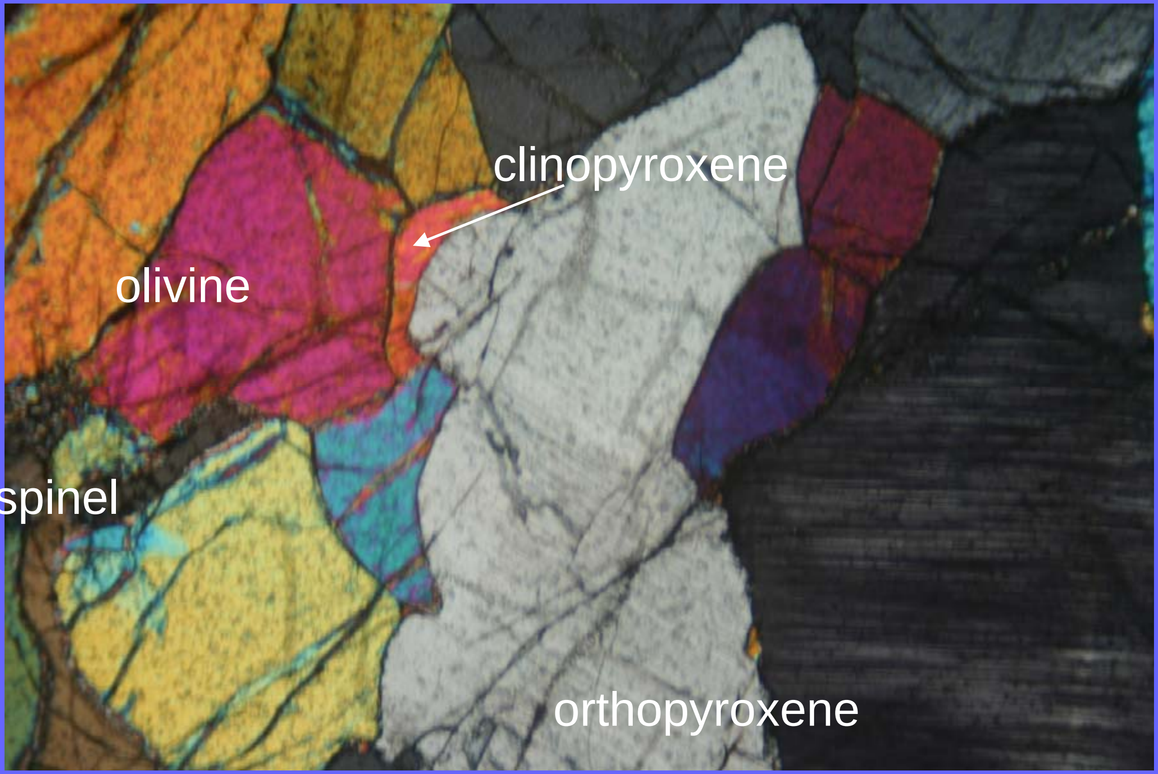


Global distribution of continental cratons different in age as indicated in the fields. Age provinces: Archons, >2.5 Ga; Protons, 2.5 to 1.0 Ga; and Tectons, <1 Ga. (From Haggerty, 1999).

SubContinental Lithospheric Mantle

SCLM

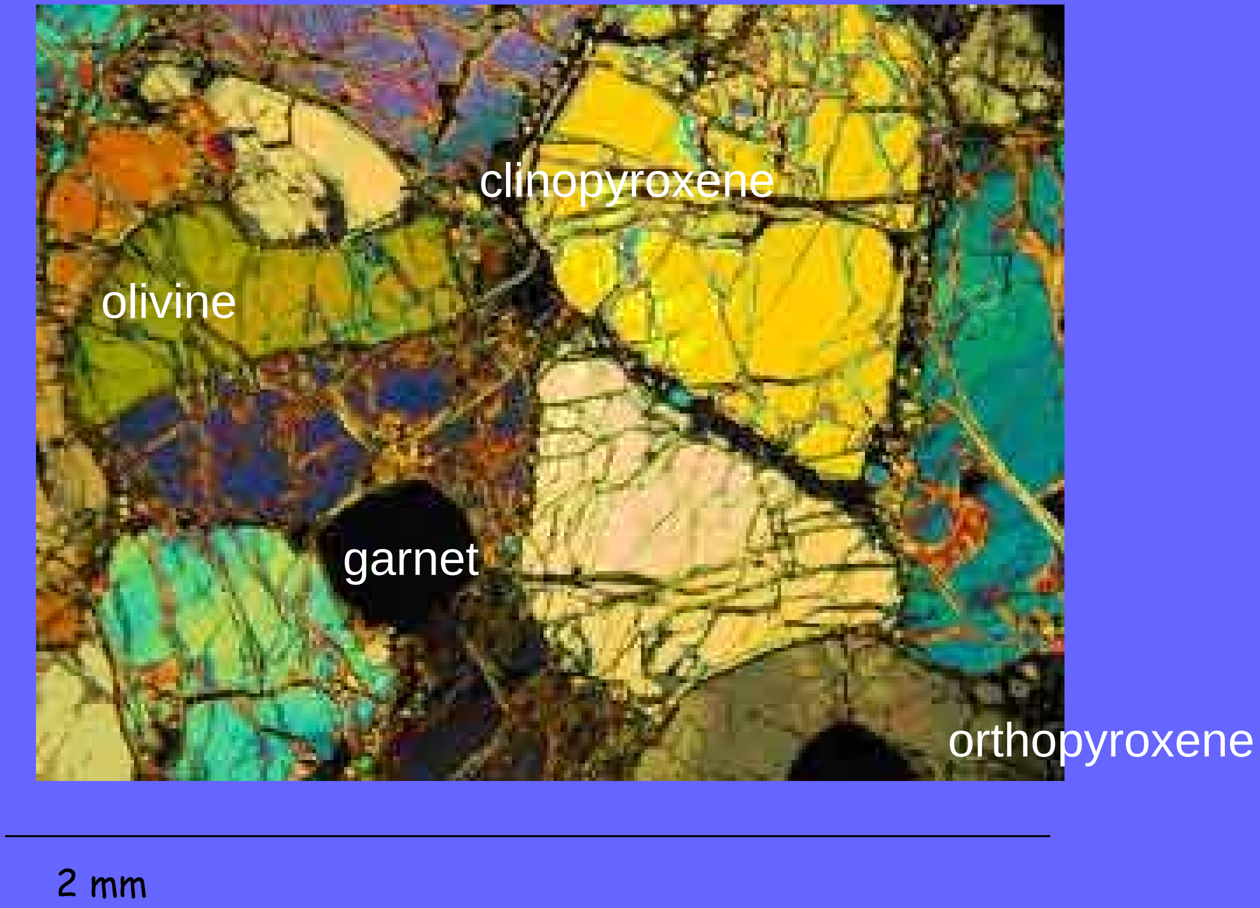
Upper mantle peridotite



2 mm

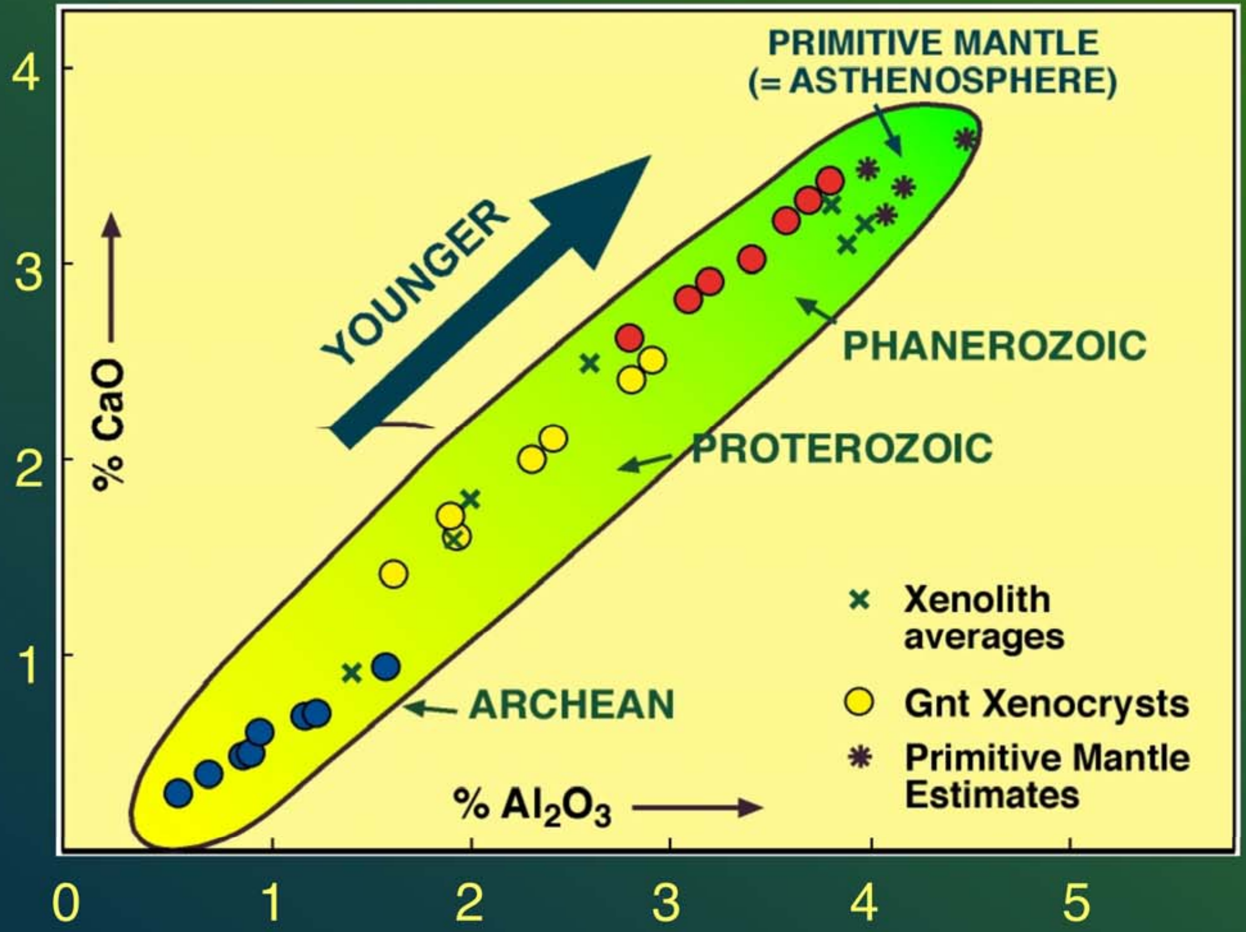
Primary protogranular texture

Upper mantle peridotite



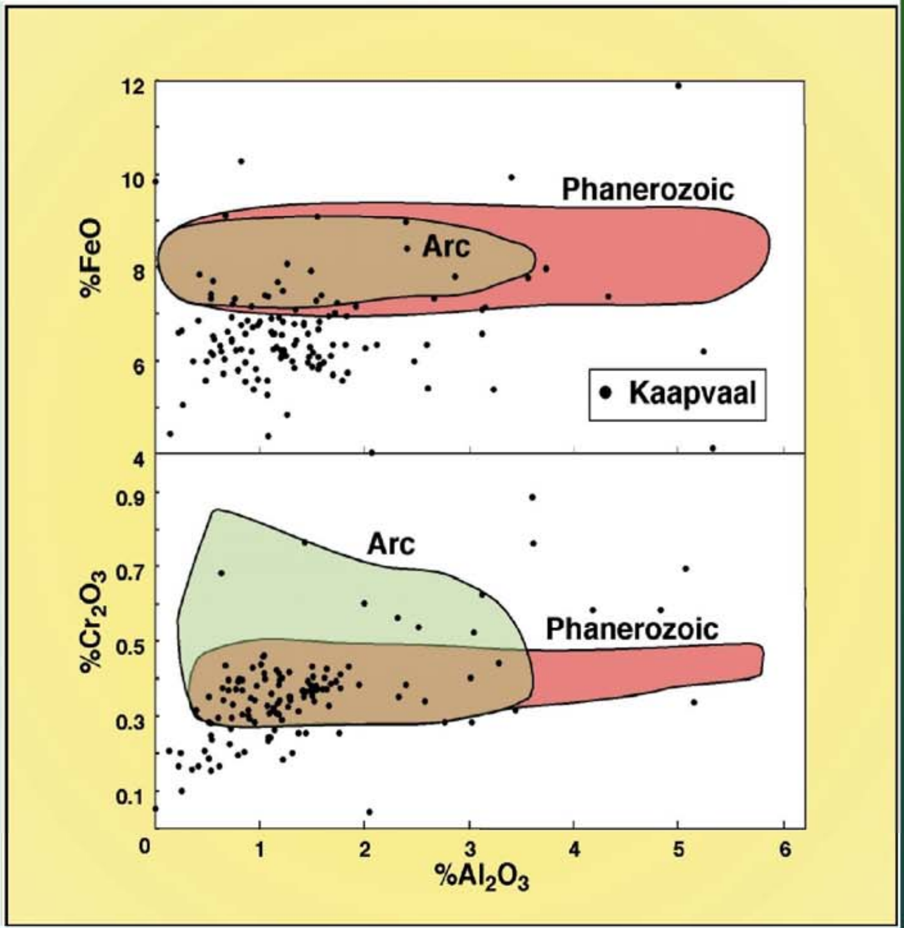
Primary protogranular texture

Secular change in SCLM composition



Courtesy of S. O'Reilly

Archean SCLM is *not* subducted oceanic lithosphere



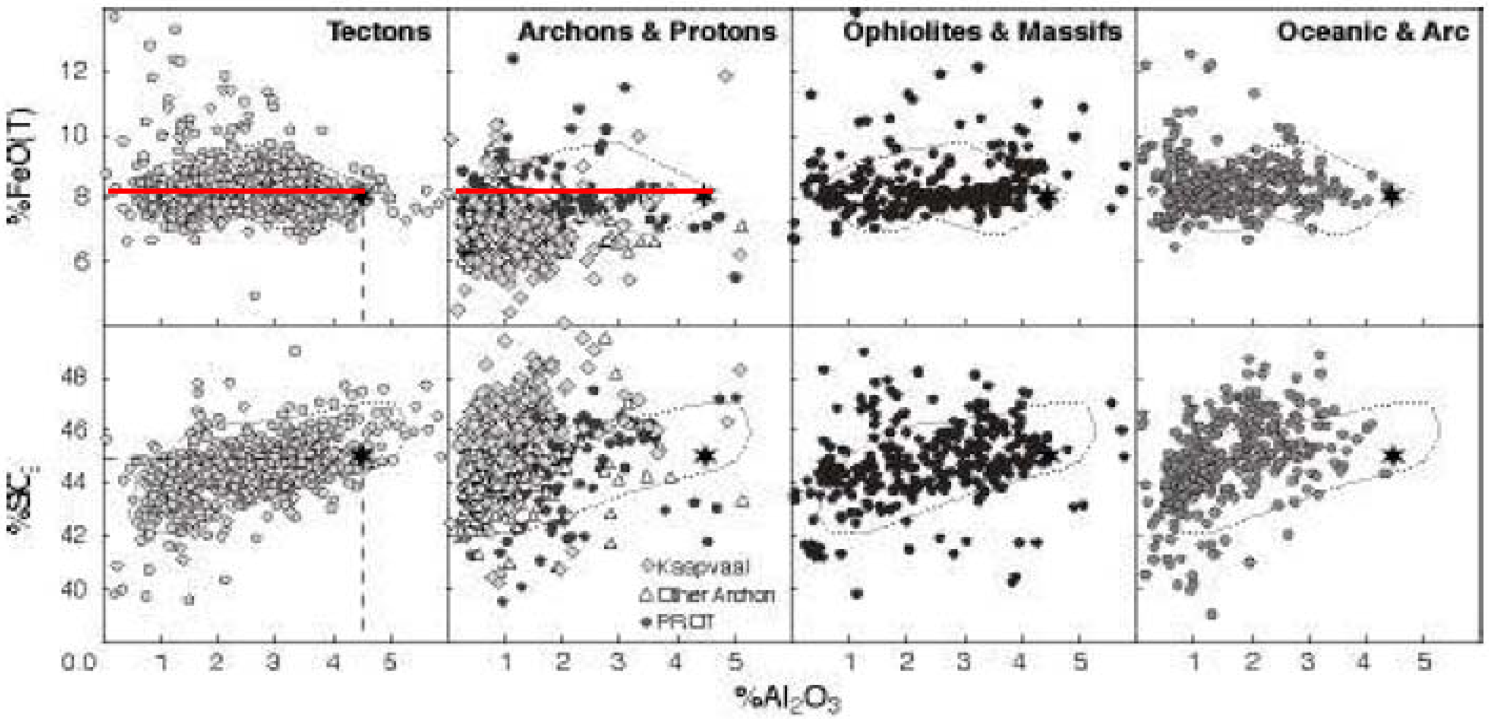
Modern oceanic and arc peridotites: Fe and Cr constant or rise as Al drops (increasing melt depletion)

Archean SCLM: Fe and Cr decrease with Al (especially at high degrees of depletion)

Implication: no garnet or spinel present during melt extraction - no buffer

High Pressure Process?

Courtesy of S. O'Reilly



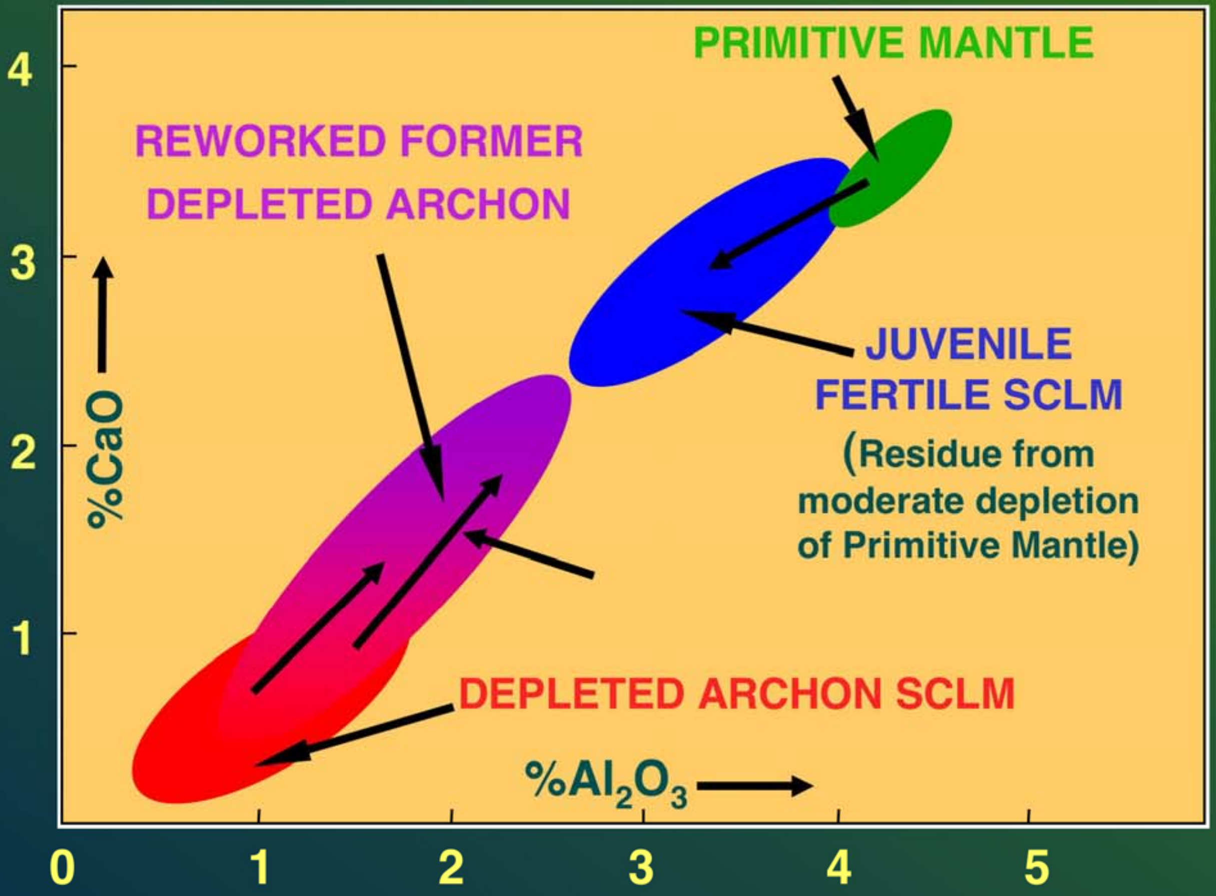
Griffin et al., 2009

Fe is buffered in opx/melt : from fertile lherzolites to most residual harzburgite/dunites of only **0.8 wt%**

cpx/melt: from fertile lherzolites to most residual harzburgite/dunites of only **0.5 wt%**

On the other hand, olivine looses easily iron passing from ~10.0-10.5 wt% in the most fertile to ~7.0 wt% in the most depleted modern peridotites (**up to 3% wt**).

Secular change in SCLM?
Really two trends

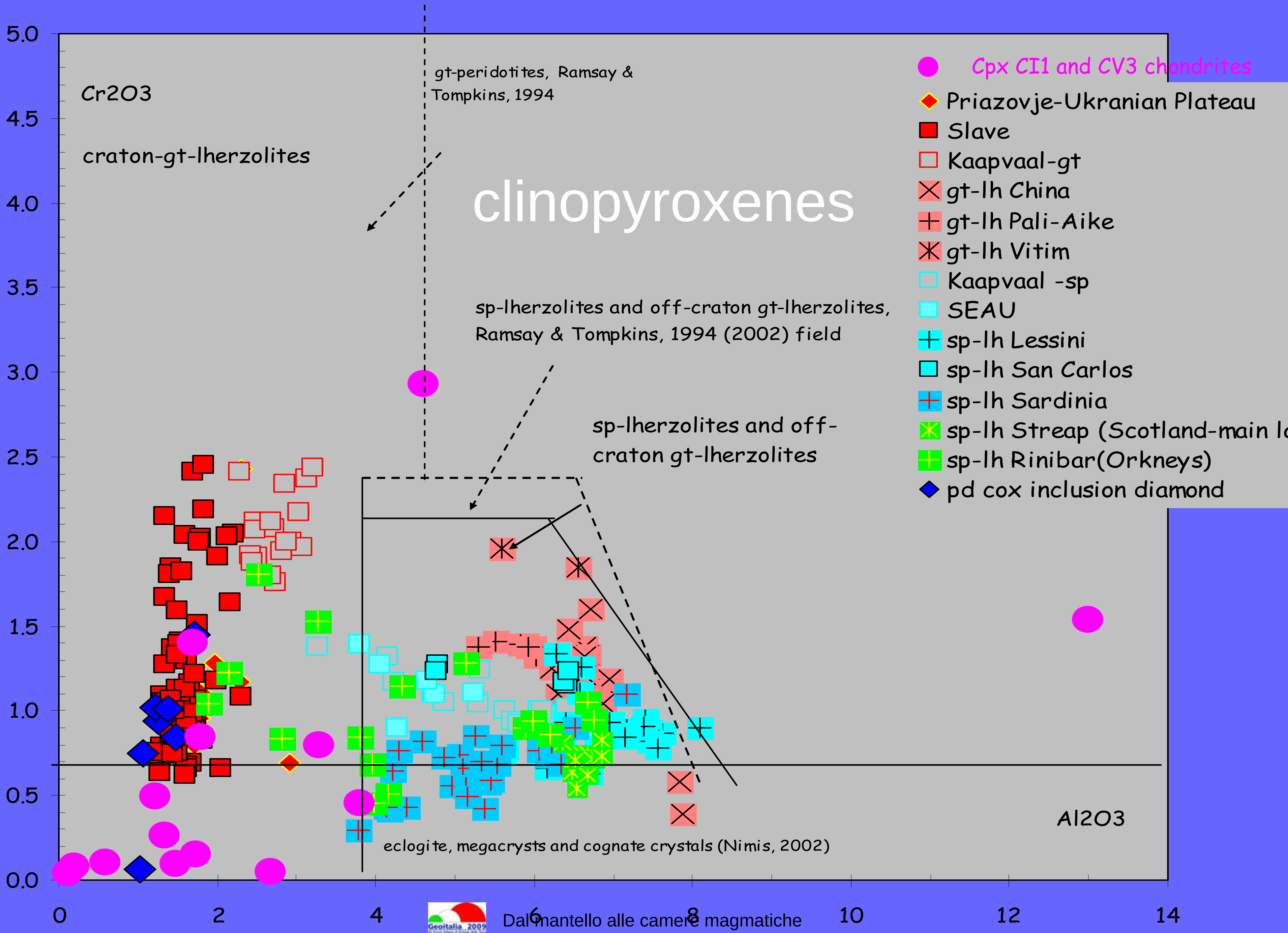


EMAW Ferrara 2007

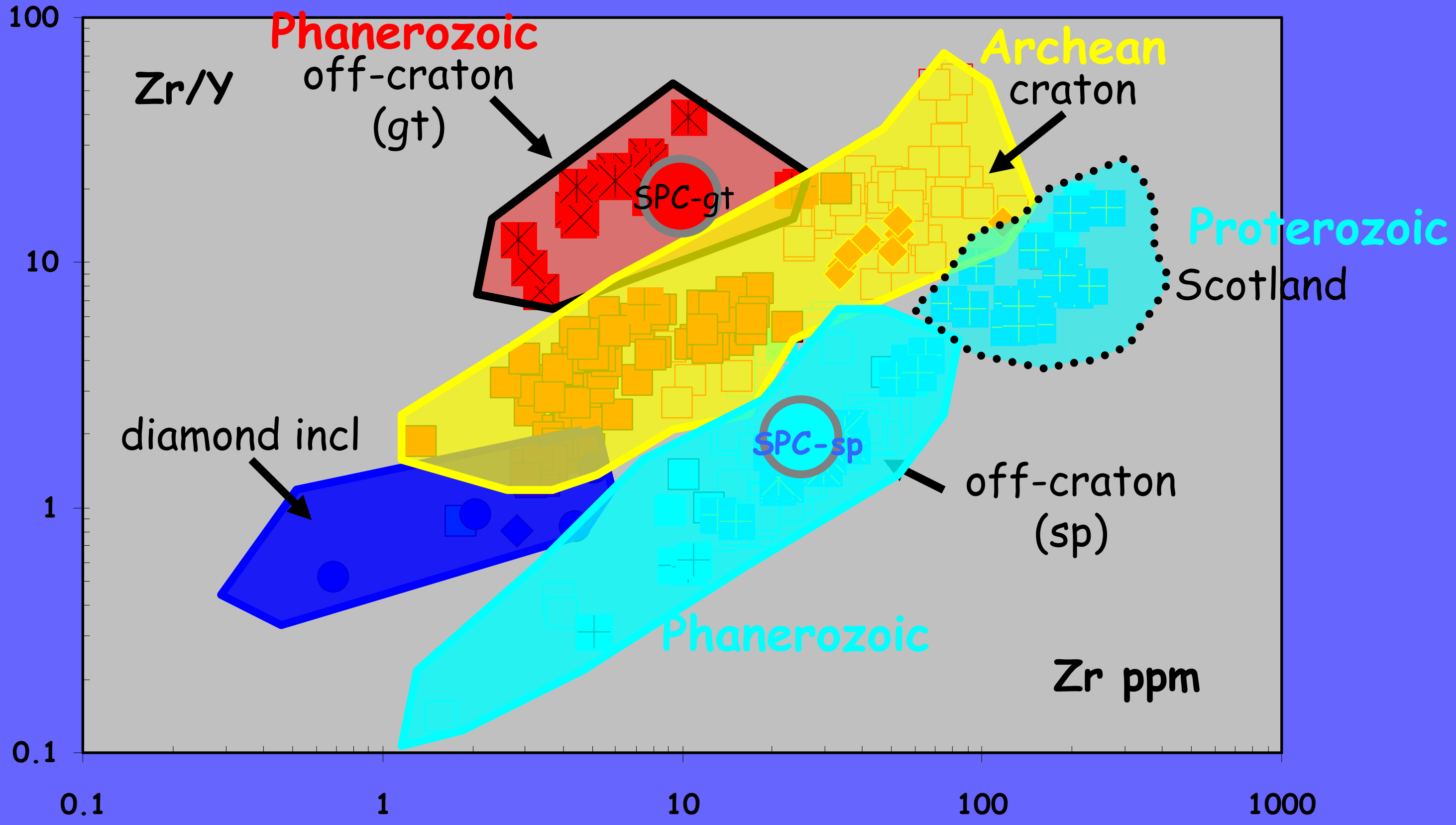
Dal mantello alle camere magmatiche

Courtesy of S. O'Reilly

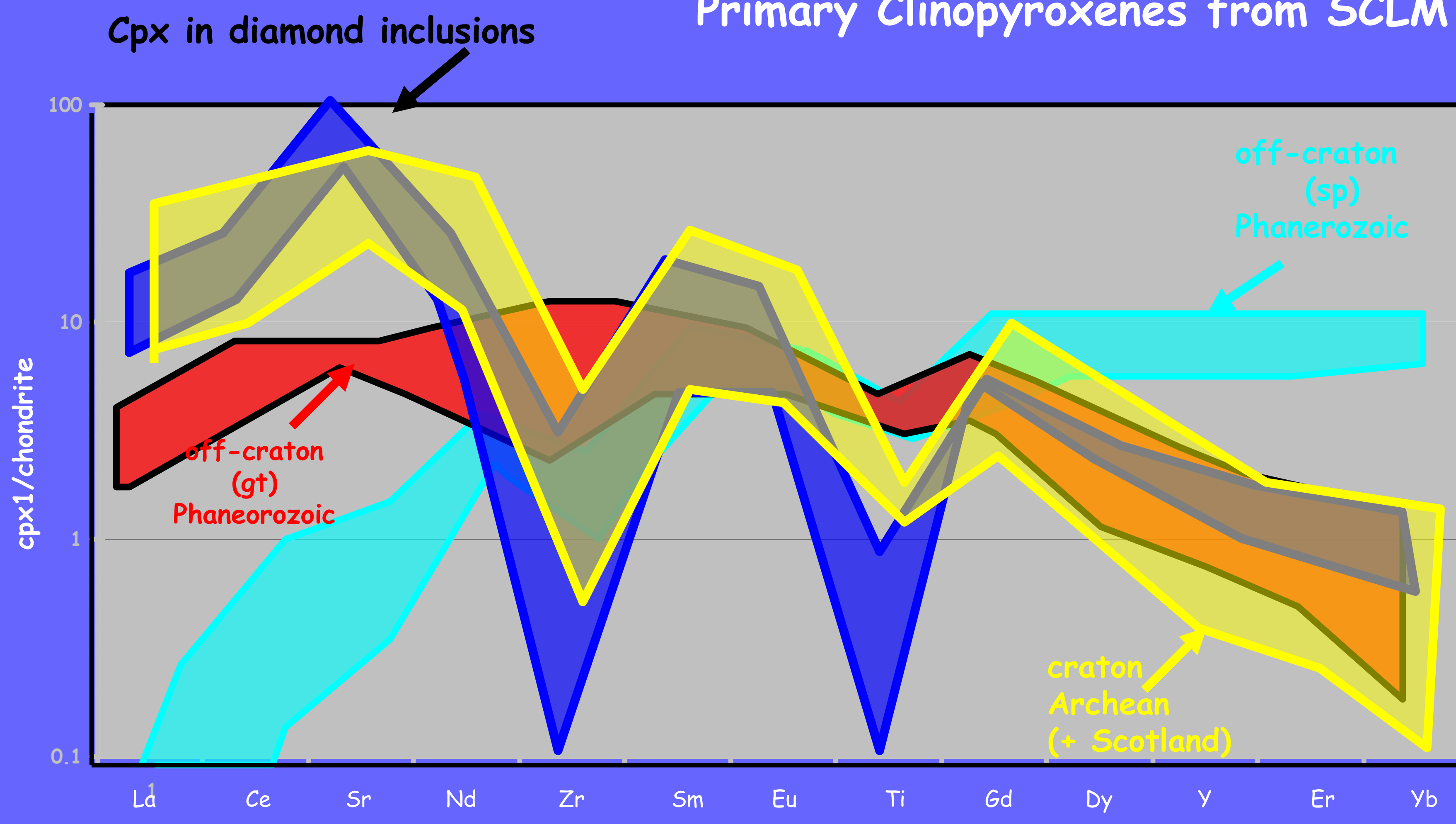
clinopyroxenes



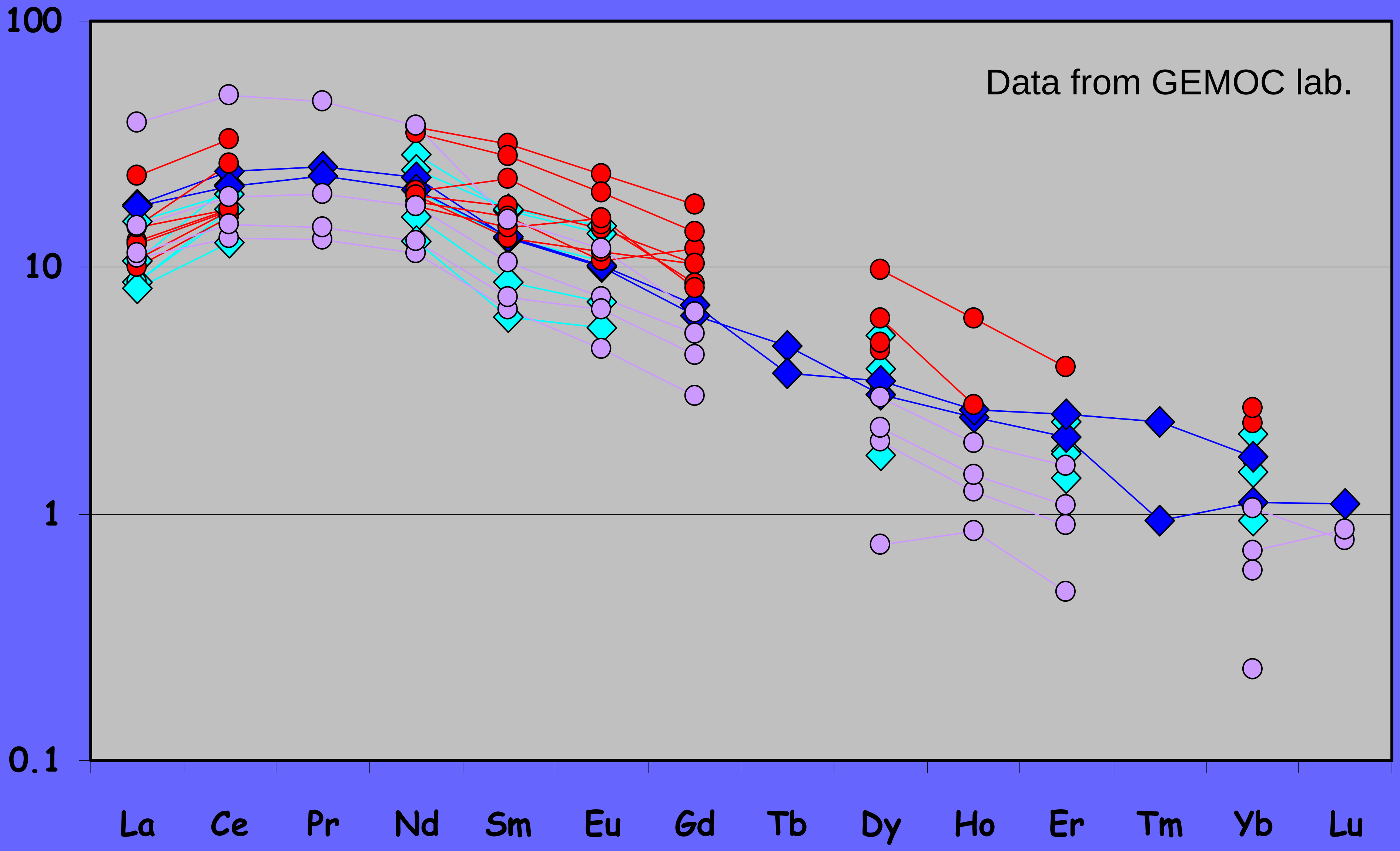
Primary clinopyroxenes



Primary Clinopyroxenes from SCLM



cpx in diamond peridotitic inclusions



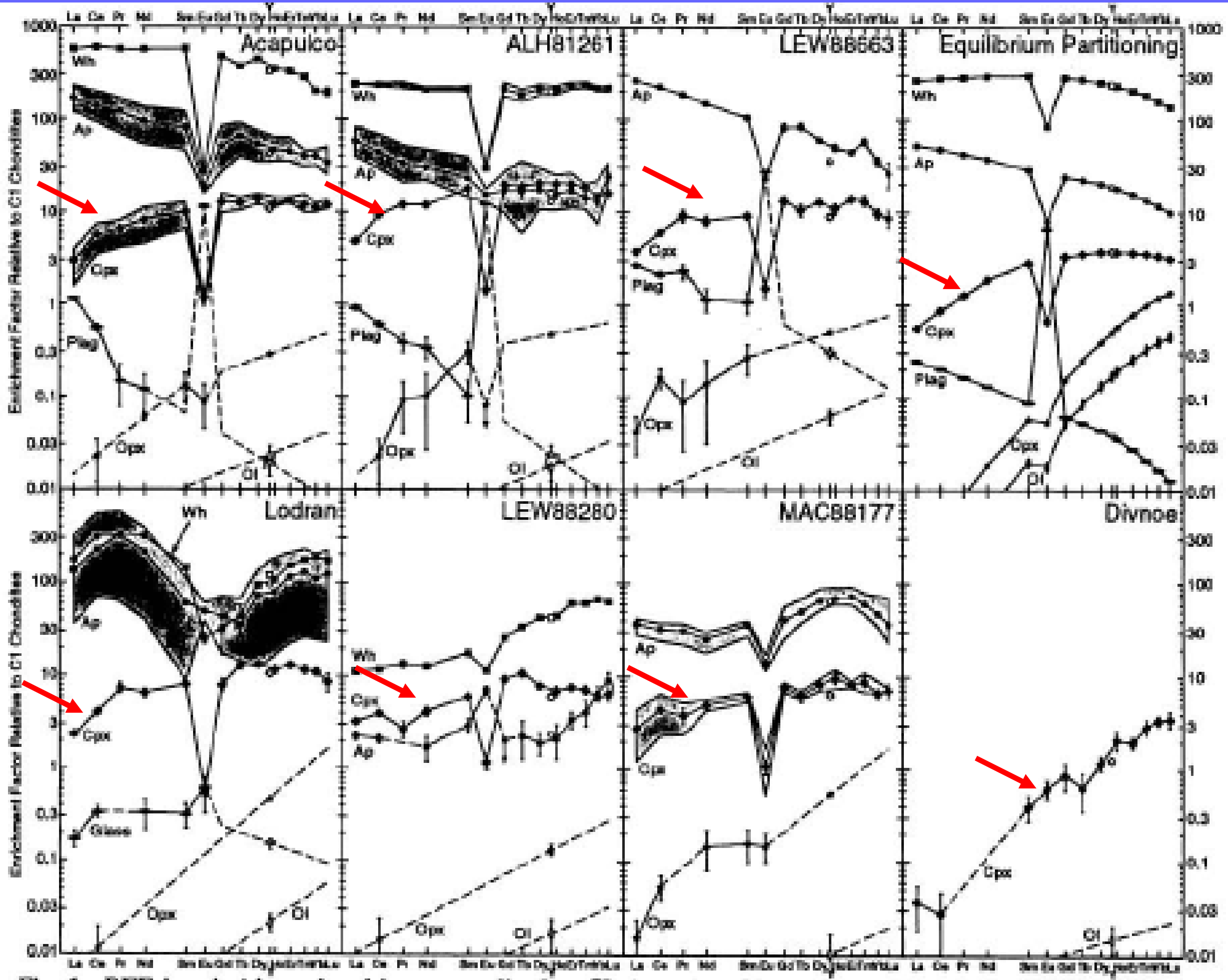
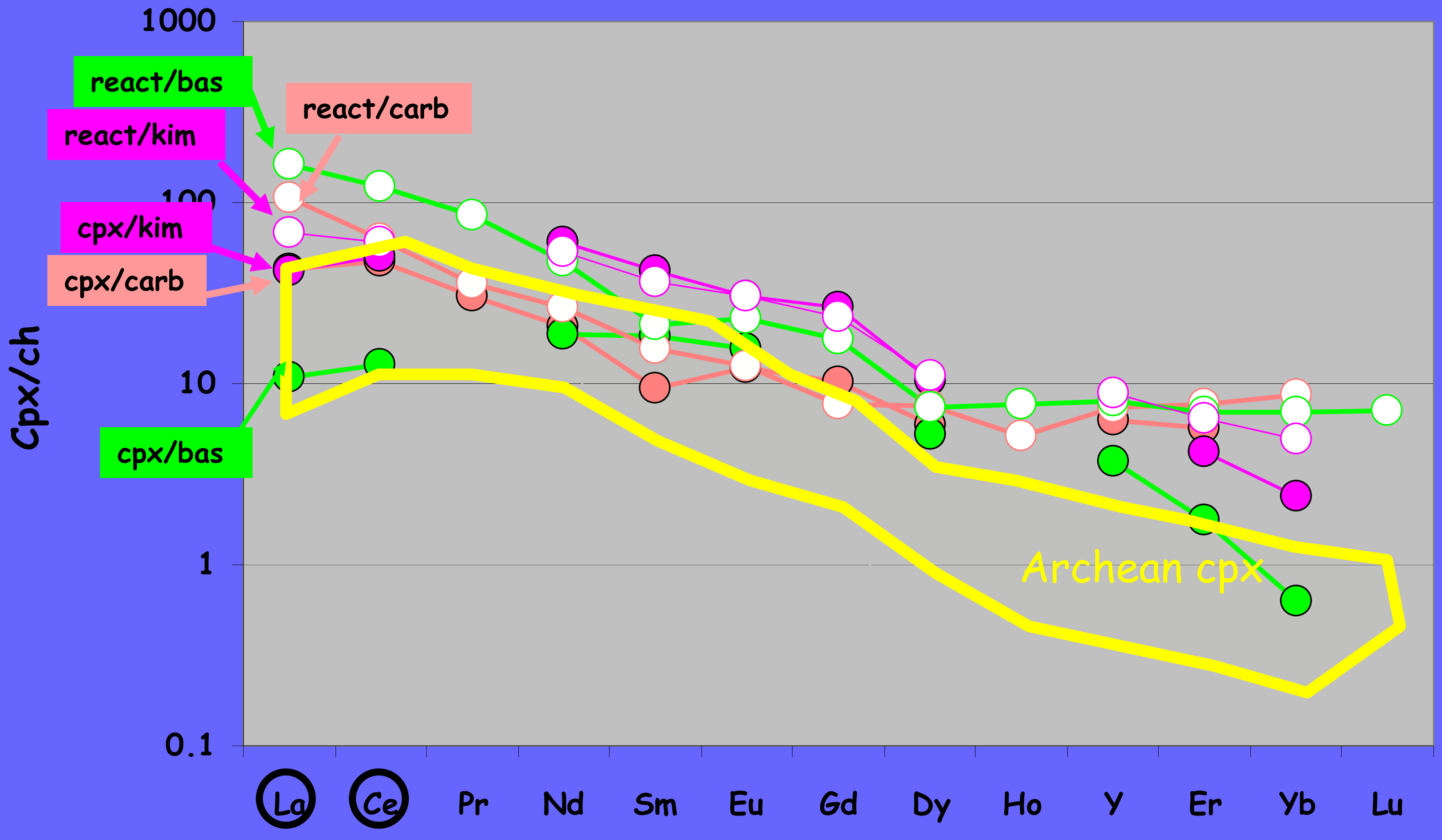


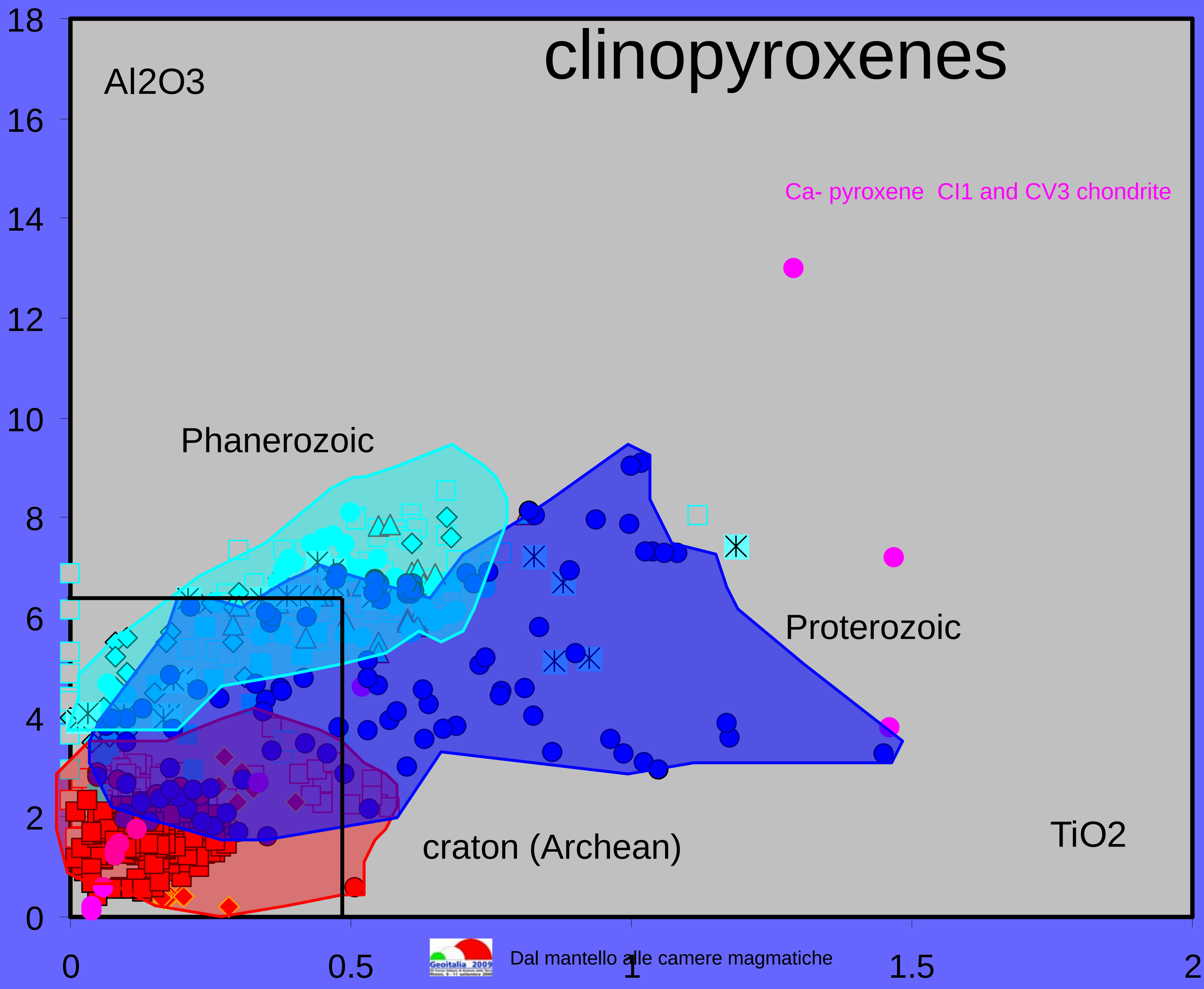
Fig. 1. REE in primitive achondrites, normalized to CI chondrites. Uncertainties are based on counting statistics and are ±1σ; upper limits are <2σ.

Davis et al., 1996

Crystallized cpx *vs* reacted cpx



clinopyroxenes



Clinopyroxene (and garnet) in the Earth upper mantle does not, in fact, derive from the segregation as liquidus phase during the early stages of cooling of the magma ocean: it is, probably, a metasomatic (modal) product of a subsequent enrichment of the lithospheric mantle due to the efficient recycling of the very early terrestrial crust (or, alternatively, by the circulation of ultra-hot mantle plumes).

the Earth’s Mantle up to Archean period seems “isolated” and independent in the evolution with respect to (Proterozoic) and Phanerozoic periods.

Data on short lived radionuclides (i.e. 26Al and 60Fe; Wood et al., 2006) and Lu/Hf and Sm/Nd isotopic systematics (Boyet & Carson, 2005; Caro et al., 2005)