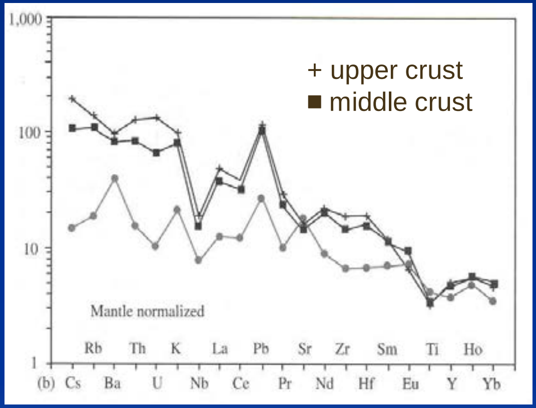
Features of continental crust

Continental crust growths magmatically,
constitutes only 0.6% of the silicate Earth,
has an average andesitic composition,
is highly differentiated and buoyant

Enriched in incompatible components compared to primeval chondritic composition, i.e.:
→ Important reservoir for many of the scarce elements (ore deposits)

Other features: negative anomalies for Nb and Ta and high Pb contents, low Nb/U…



Treatise on Geochemistry, Vol 3: The Crust

Old average age: ~2 Ga
→ Archean magmatism contributed greatly to the formation of the continental crust

Earth has considerably cooled since its formation
→ rates and processes of magma generation (plume-related versus arc-related) and crust formation have changed

Continental crust

Early crust was destroyed more rapidly than younger crust – why?

-- rifting

-- delamination or subduction

-- erosion

-- meteorite bombardment

-- covering by younger sediments

Crustal growth events

The most dramatic shift in the generation of continental crust began ~2.7 by ago. This crust formation period was followed by additions of continental crust at:

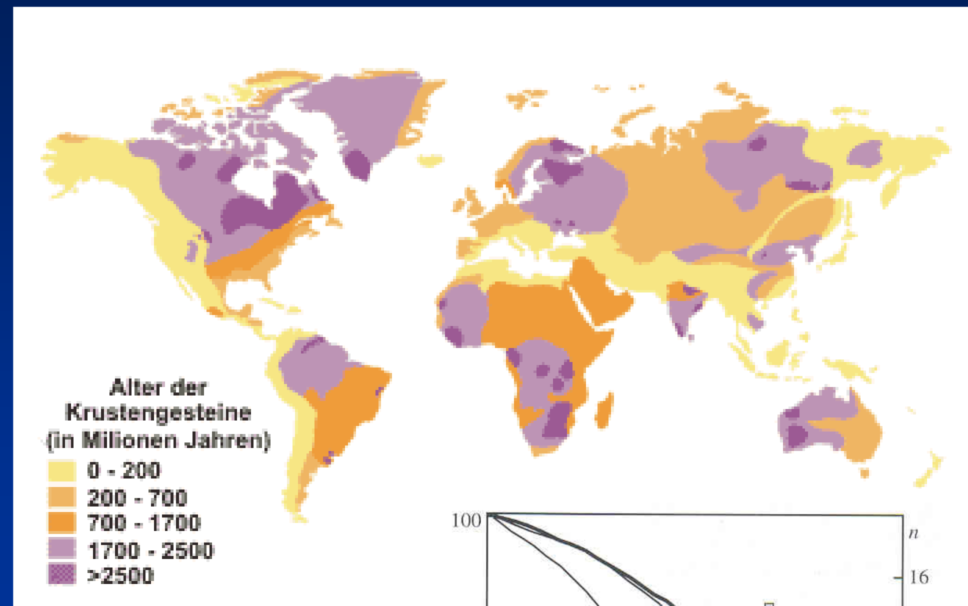
~1.9 by
~1.2 by
0.5 – 0.3 by

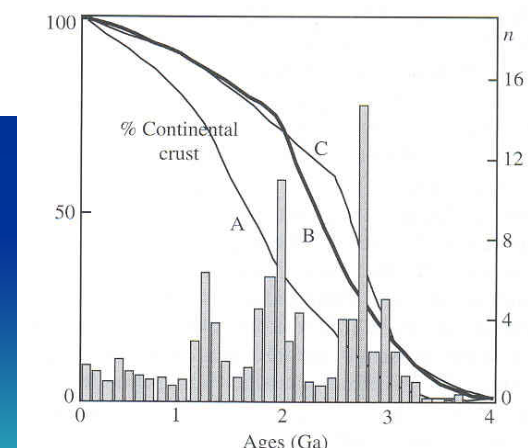
Large crustal volumes formed during short time periods

Global episodicity explained by:

1. Supercontinent cycle hypothesis

a) Break apart of supercontinent
b) Higher subduction rates
c) Formation of new continental crust





Crustal growth events

The most dramatic shift in the generation of continental crust began ~2.7 by ago. This crust formation period was followed by additions of continental crust at:

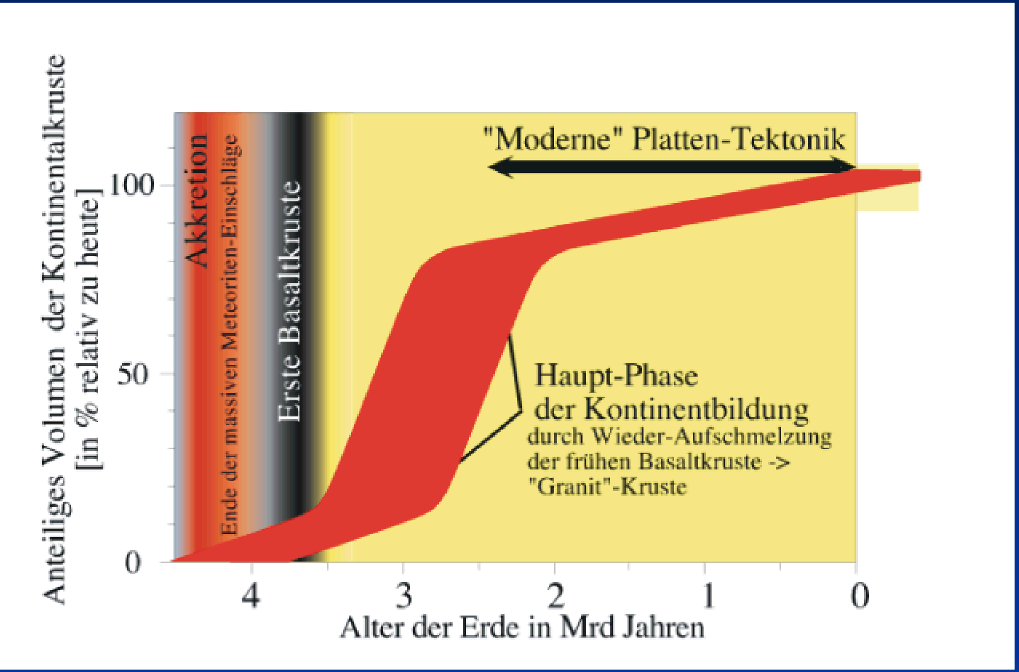
~1.9 by
~1.2 by
0.5 – 0.3 by

Large crustal volumes formed during short time periods

Global episodicity explained by:

1. Supercontinent cycle hypothesis

a) Break apart of supercontinent
b) Higher subduction rates
c) Formation of new continental crust



Continental crust

Why nonlinear or episodic growth?

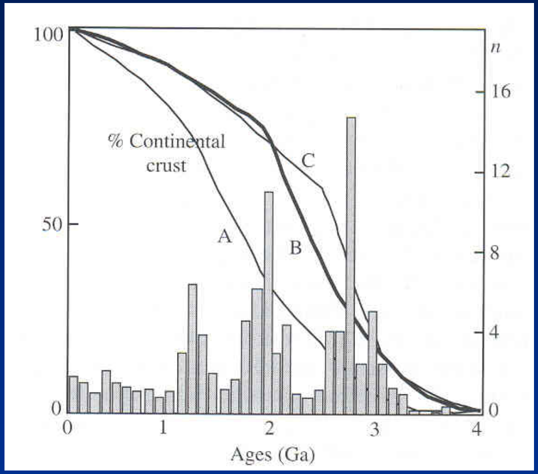
2. Superplume hypothesis

-- breackup of plates/continents followed by enhanced subduction

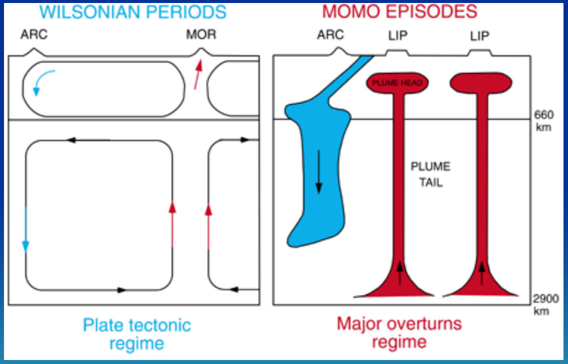
-- catastrophic turnover events in the mantle (MOMOs)

-- crust formation dominated by major thermal pulses associated with superplumes

Distribution of U-Pb ages from juvenile crust



Data source: Treatise on Geochemistry, Vol 3: The Crust



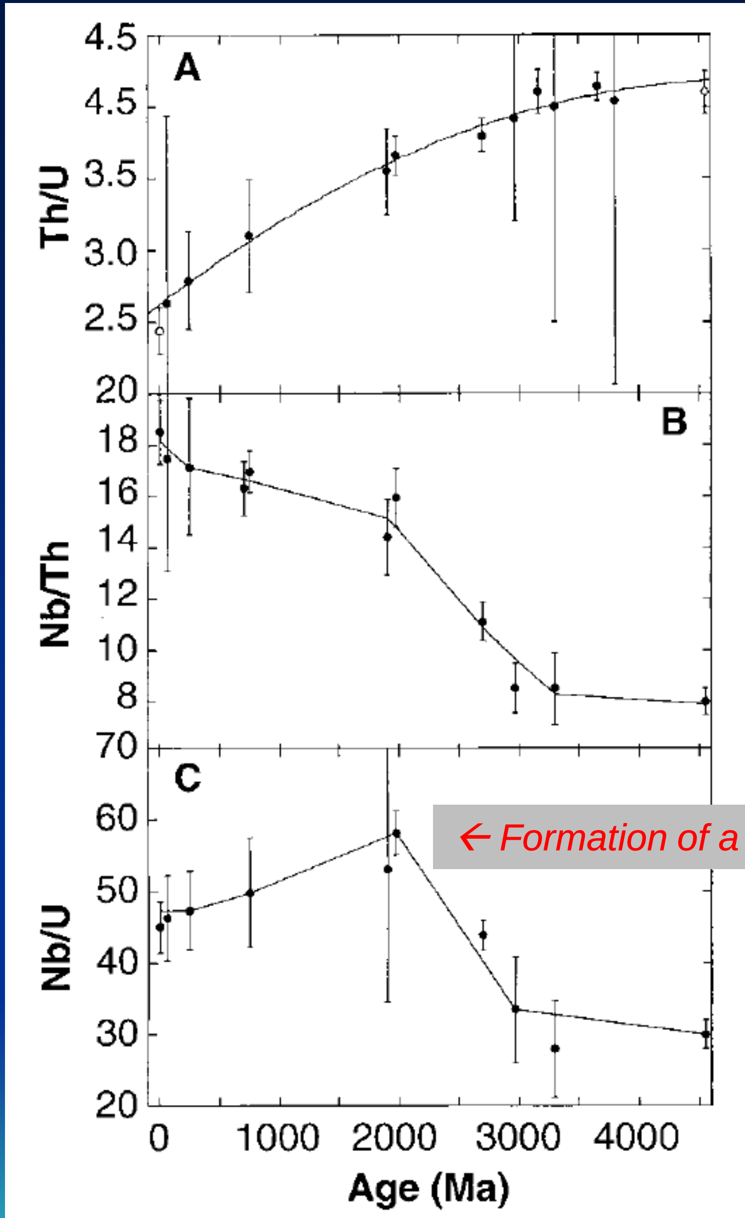
Stein & Hofmann (1994)

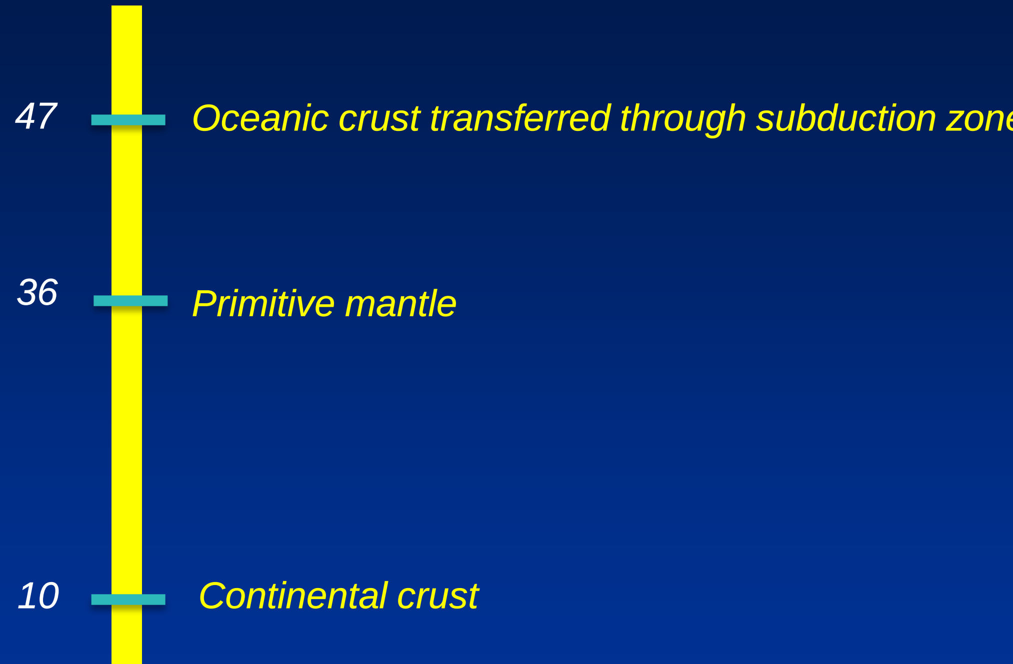
Table 1. Compilation of Th, U, and Nb data for depleted mantle–derived rocks (error = 1 SD). ε_{Nd} expresses the fractional difference between the initial $^{143}Nd/^{144}Nd$ ratio of the rocks and the corresponding value of this ratio in the chondritic uniform reservoir at the time of crystallization of the rocks, expressed in units of 10^4. Fm., formation.

Age (Ma)	Rock type	Location	ε_{Nd}	Th/U ± SD	Nb/U ± SD	Nb/Th ± SD	Data source
0	E-MORB	East Pacific	~10	2.44 ± 0.16	45.07 ± 3.55	18.5 ± 1.25	(7)
30–90	MORB	Indian, Pacific	~9	2.63 ± 1.31	46.35 ± 5.9	17.50 ± 4.42	(19)
240	Pillow basalt	Pioneer Fm.		2.79 ± 0.34	47.35 ± 5.52	17.16 ± 2.66	(20)
700	Basalt	Avalon arc	~4.7			16.33 ± 1.05	(21)
750	Meta-basalt	Ogcheon belt	~4.5			17.69 ± 3.9	(22)
750	Basalt dyke	Tilemsi belt		3.38 ± 0.49	55.32 ± 12.01	16.45 ± 3.51	(23)
750	Basalt	Gabal-Gerf	~8	2.83 ± 0.63	44.44 ± 11.73	16.11 ± 2.00	(24)
750	Gabbro	Gabal-Gerf				17.63 ± 2.86	(24)
750	Average*			3.10 ± 0.39	49.88 ± 7.69	16.97 ± 0.81	(22–24)
1900	Basalt	Flin-Flon	~4	3.34 ± 0.41	52.99 ± 18.43	14.48 ± 2.99	(25)
1900	Basalt	Flin-Flon		3.77 ± 0.25			(26)
1900	Basalt	Flin-Flon				12.77 ± 3.89	(27)
1900	Basalt dyke	Joruma				15.35 ± 3.23	(28)
1900	Pillow lava	Joruma				13.67 ± 3.54	(28)
1900	Average*			3.55 ± 0.3	52.99 ± 18.43	14.40 ± 1.50	(25–28)
1980	Basalt	Onega	~3	3.66 ± 0.14	58.26 ± 3.08	15.94 ± 1.13	(17)
2700	Spinifex komatiite	Abitibi	2.5	4.17 ± 1.10	47.80 ± 6.37	11.96 ± 2.59	(29)
2700	Komatiite + basalt	Abitibi		3.94 ± 0.97	46.82 ± 15.41	11.93 ± 2.61	(30)
2710	Komatiite + basalt	Abitibi				11.14 ± 1.33	(31)
2710	Basalt, borehole1	Lunnon Fm.	~2.5	3.75 ± 0.15	43.87 ± 2.71	11.72 ± 0.97	(1)
2710	Basalt, borehole 2	Lunnon Fm.		3.86 ± 0.20	39.61 ± 6.09	10.23 ± 1.28	(1)
2720	Komatiite + basalt	Abitibi	~3			11.82 ± 1.75	(32)
2730	Mafic + ultramafic	Superior		4.58 ± 1.22	43.99 ± 10.56	9.74 ± 1.52	(33)
2700	Average*			3.80 ± 0.12	43.80 ± 2.20	11.11 ± 0.79	(1, 29–33)
2970	Basalt + komatiite	Superior		3.92 ± 0.72	33.45 ± 7.41	8.51 ± 0.96	(34)
3170	Basalt + komatiite	Barberton		4.11 ± 0.15			(35)
~3300	Basalt	Pilbara				8.92 ± 3.94	(36)
~3300	Spinifex komatiite	Barberton	~2	5.55 ± 0.90	48.21 ± 14.12	8.79 ± 2.63	(29)
~3300	Komatiite	Barberton		2.59 ± 0.61	21.75 ± 7.83	8.29 ± 1.87	(5)
3300	Average*			4.00 ± 1.50	28.00 ± 6.70	8.50 ± 1.40	(5, 29, 36)
3650	Tonalite	SW-Greenland	1	4.14 ± 0.10			(37)
3800	Meta-komatiite	Labrador		4.04 ± 1.98			(38)

*Averages are of all preceding data with the same age. The 2700 average is from data at 2700, 2710, 2720, and 2730 Ma.

Nb/U ratio

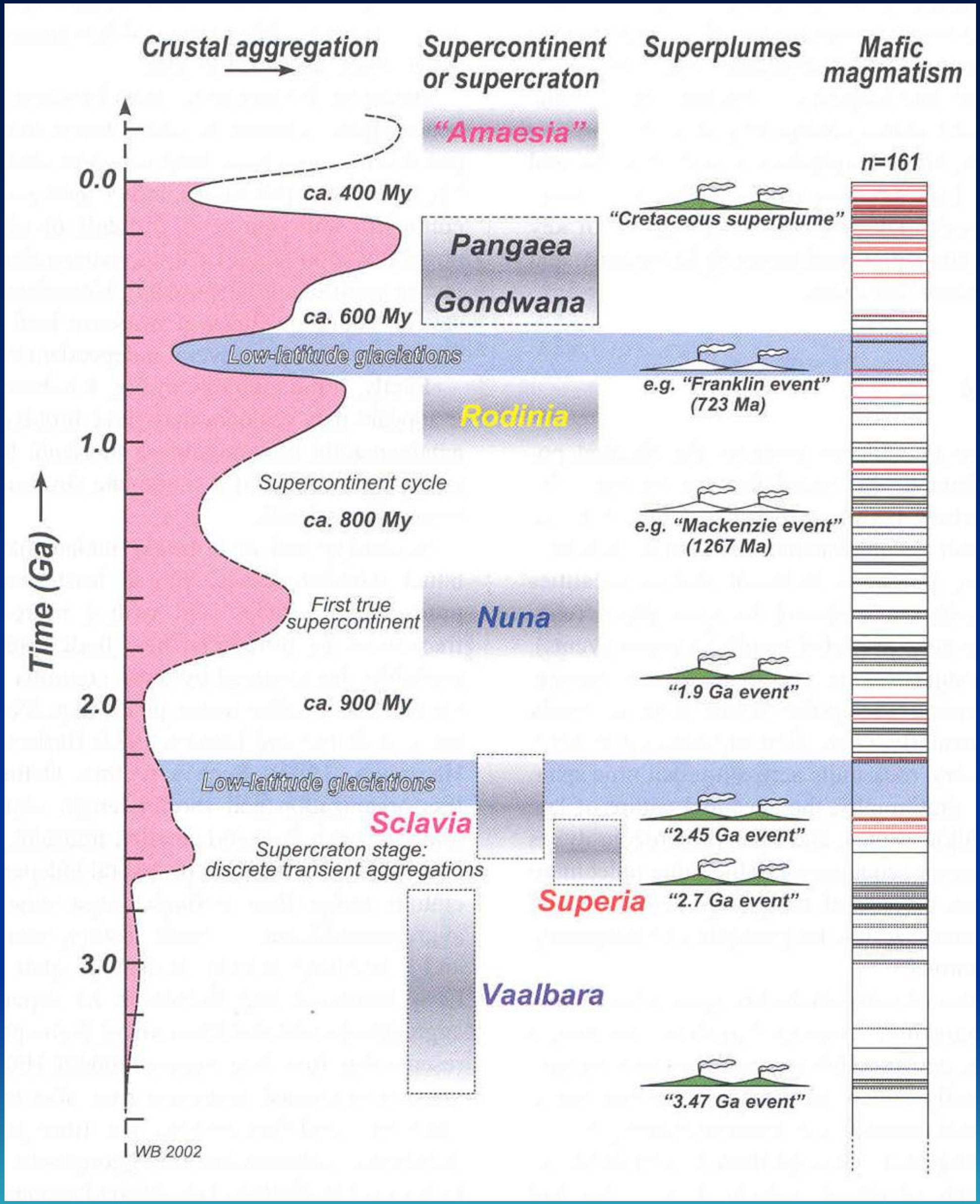




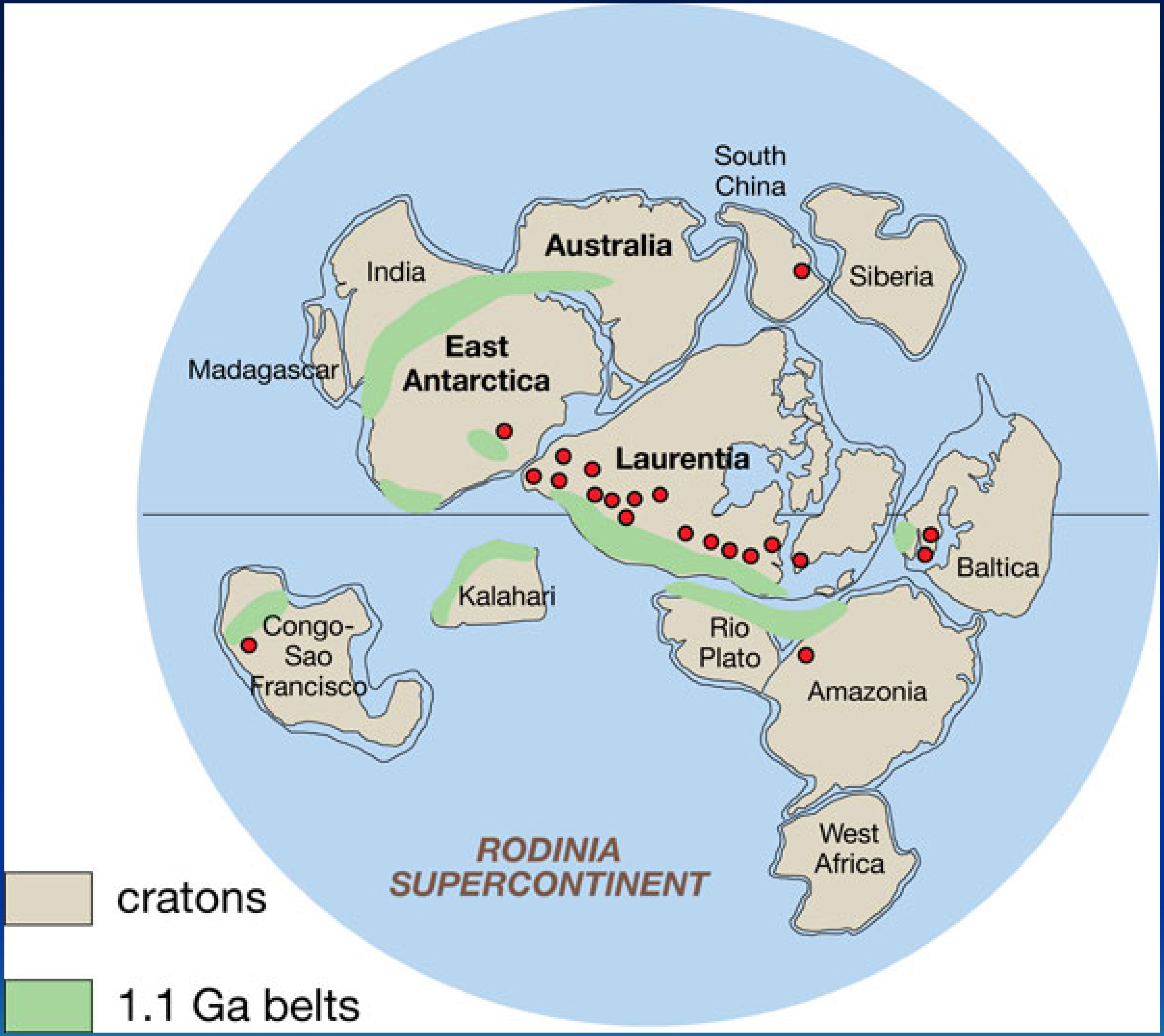
← *Formation of a globally oxidising atmosphere and hydrosphere*

Collerson & Kamber
Science 283, 1999

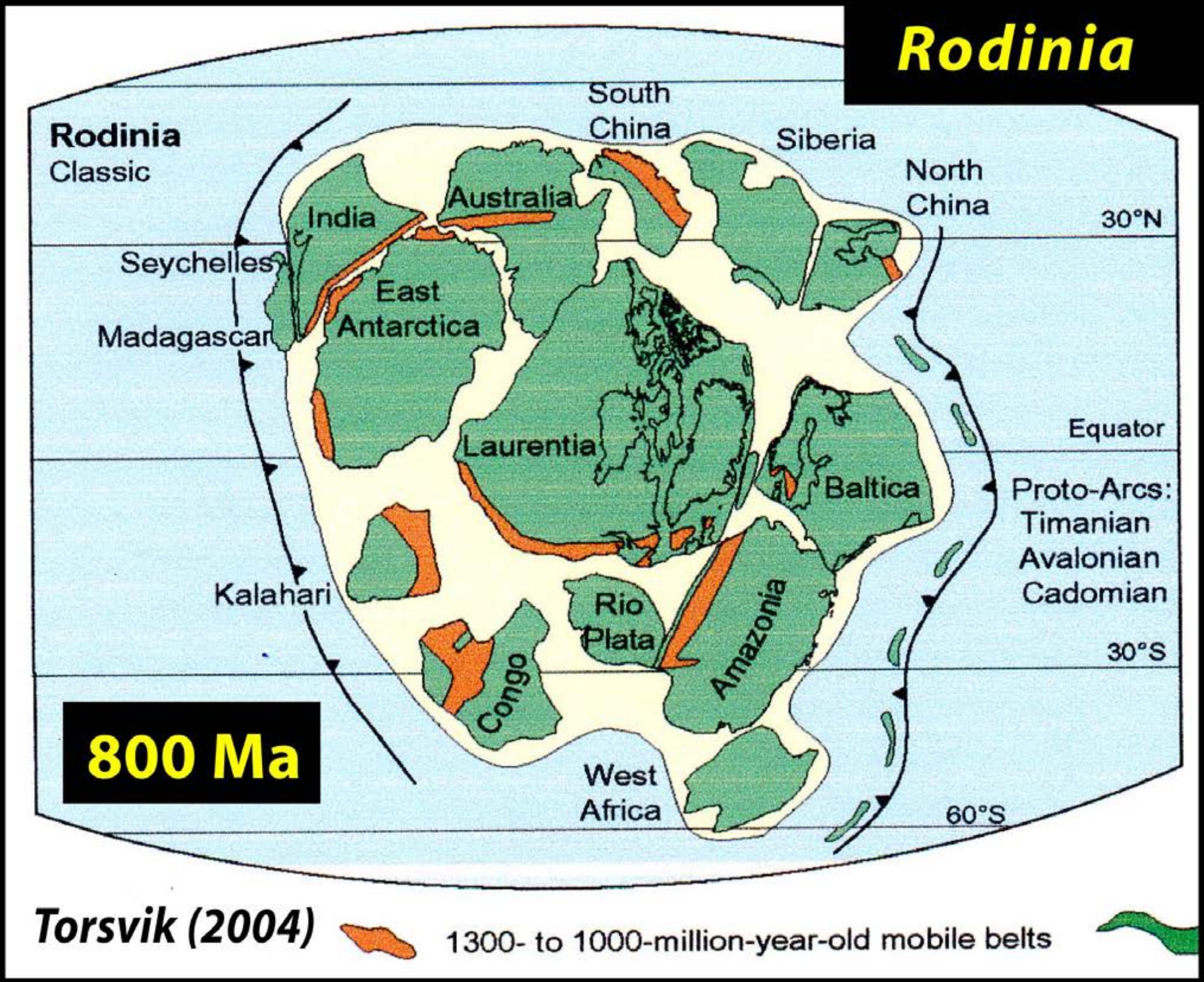
Crustal growth and supercratons



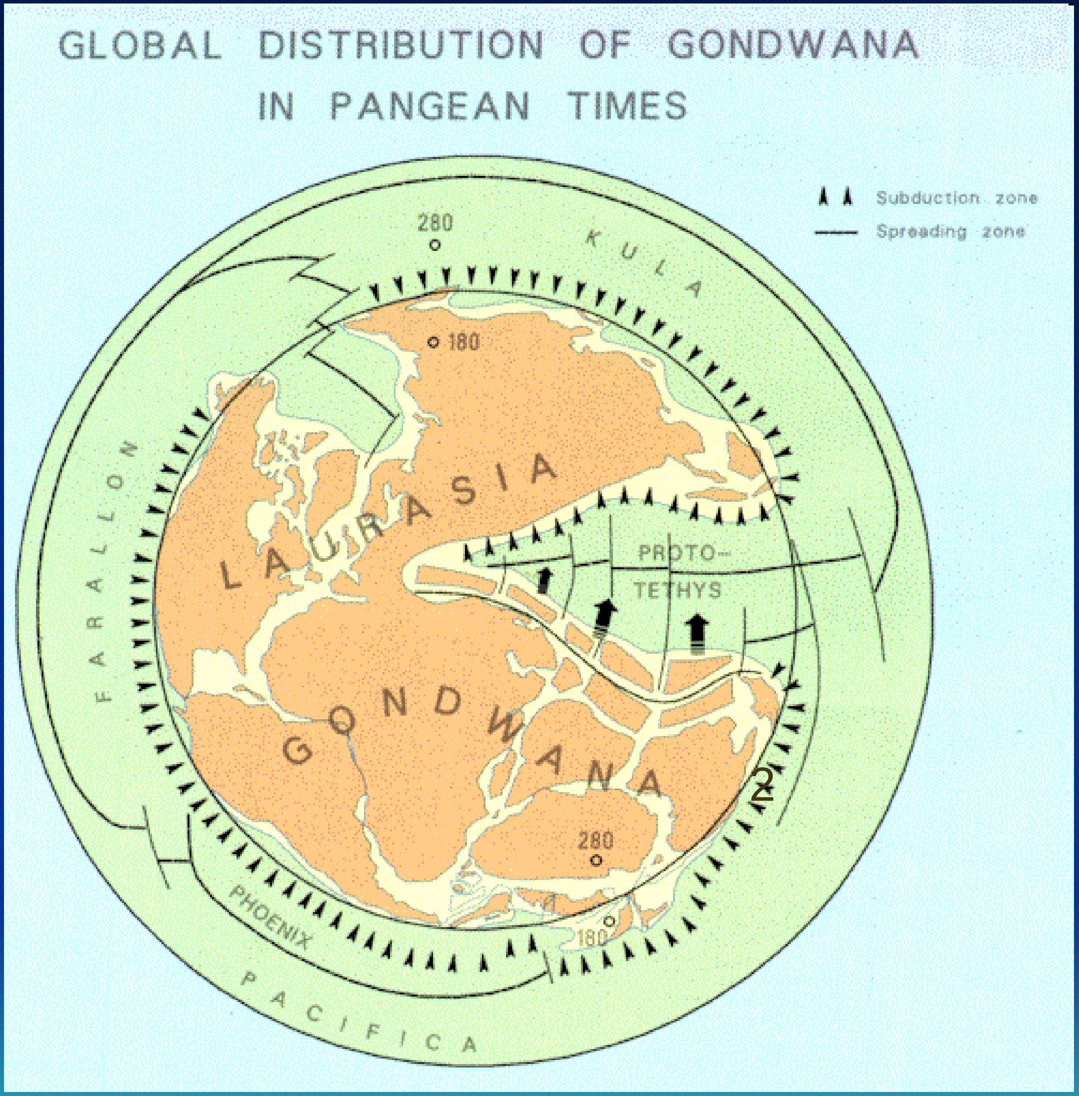
Bleeker: Lithos 71, 2003



Reconstruction of Rodinia for 750 Ma. Grenville orogenic belts of 1.1 Ga age highlighted in green


Rodinia
Rodinia
Classic
South
China
Siberia
North
China
30°N
Australia
India
Seychelles
East
Antarctica
Madagascar
Laurentia
Equator
Baltica
Proto-Arcs:
Timanian
Avalonian
Cadomian
Kalahari
Rio
Plata
Amazonia
30°S
Congo
800 Ma
West
Africa
60°S
Torsvik (2004)
1300- to 1000-million-year-old mobile belts

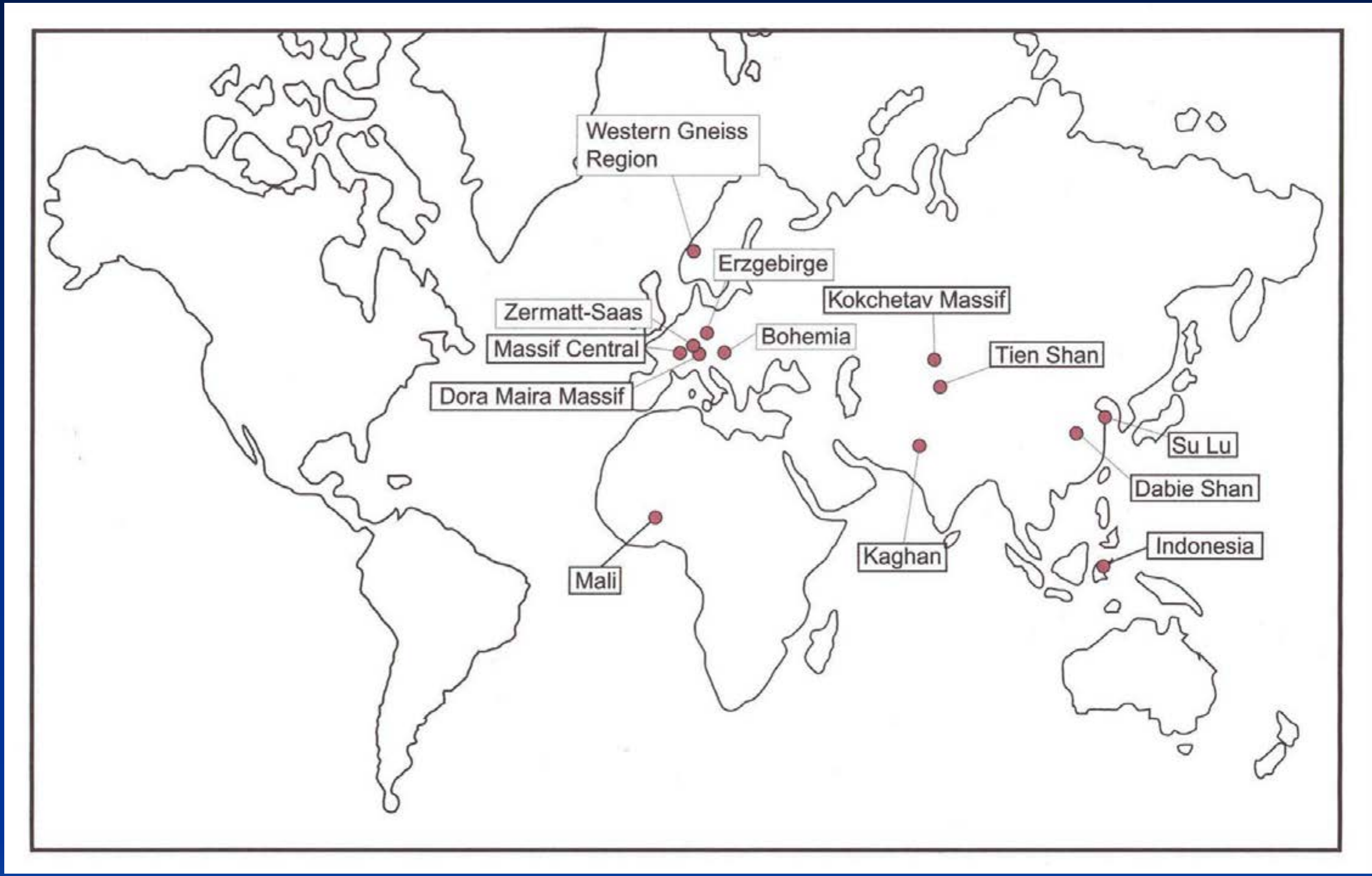
Gondwana - Pangaea



1

Continental crust subduction and UHP metamorphism

Subduction of continental crust into the mantle as a consequence of continent-continent collision (Dabie-Sulu, Kokchetav)



Localities of confirmed occurrences of coesite and/or diamond in crustal rocks (after Carswell 2000, Lardeaux et al. 1999).

The Archean crust
summary

During the Archean oceanic crust was being rapidly cycled by possibly ~100 separate crustal plates.

The Archean crust was composed of a mixture of basalt/komatiites (high-Mg basalts) and sodium-rich granites (TTG's – Tonalites, Trondhjemites, Granodiorites) → bimodal composition.

Crustal growth proceeded in an episodic fashion.

Widespread melting at this time formed much of the TTG's that constitutes much of the Archean crust.

Crust formation through Earth history

Basaltic crust generated by partial melting of mantle peridotite
1st. crust formation step – separation of basaltic rocks from the mantle

This crust was locally hydrated and transferred (in greater depth) into amphibolite/eclogite

Melting of basaltic crust during (1) subduction and/or (2) magmatic underplating (high heat flow) → generation of tonalites, trondhjemites and (differentiated) granodiorites
2nd. crust formation step – stratification into more evolved upper crust and mafic residual lower crust

Melting of TTG‘s and of sedimentary rocks → granite production and enrichment of SiO_2, Na_2O und K_2O
3rd. crust formation step – evolved modern continental crust

Archean crust

Rocks from many Archean terranes are **bimodal** in their silica distribution

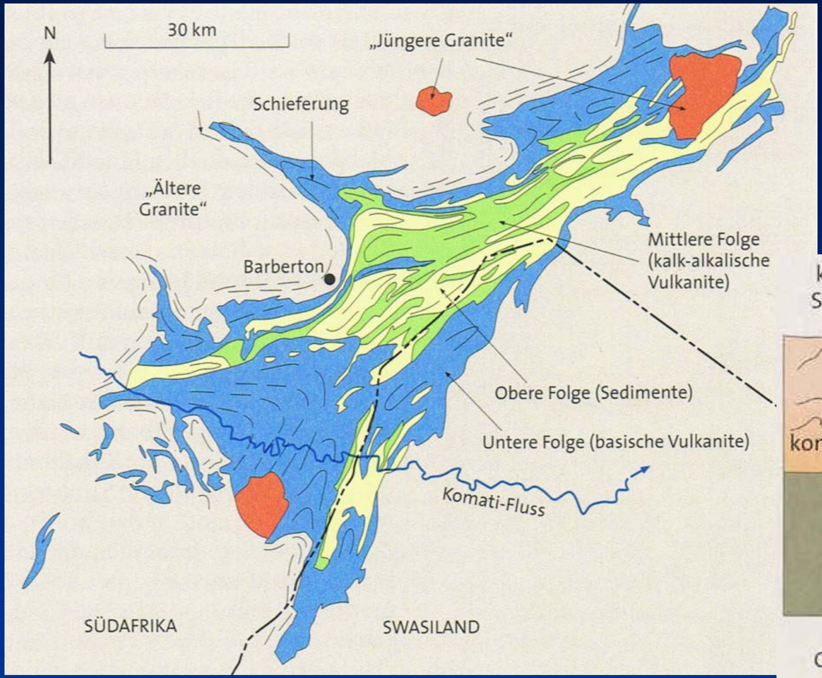
1) High-magnesium basalts
2) Felsic TTG‘s

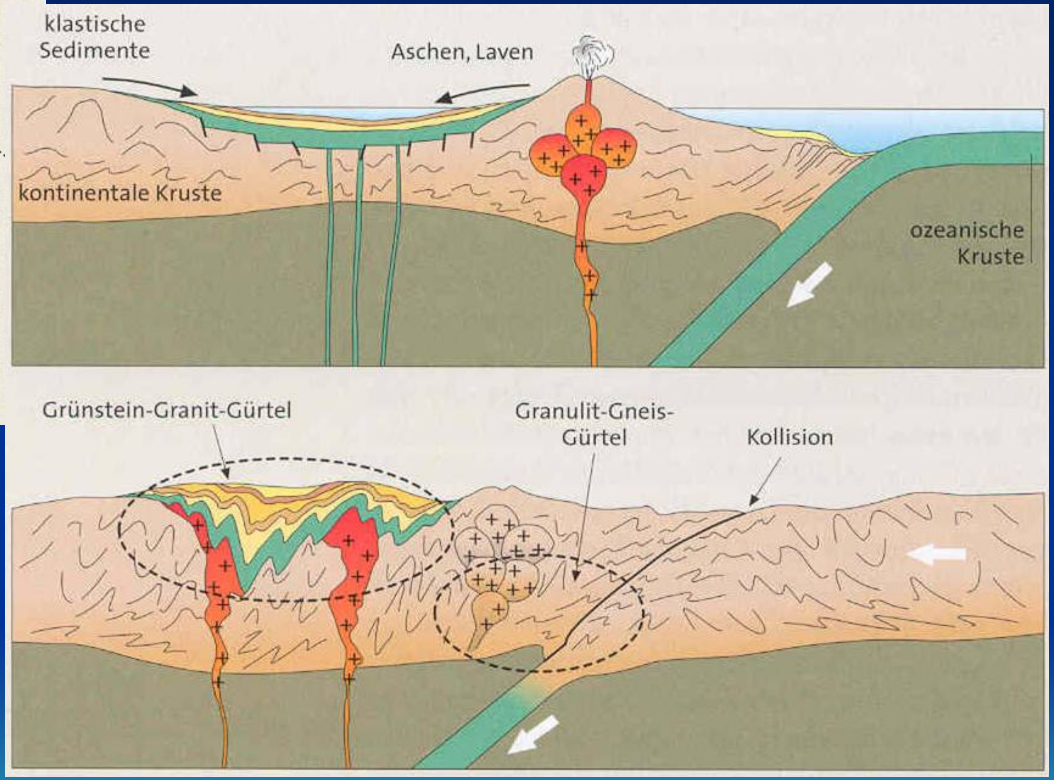
Bimodal compositions also in continental flood basalt provinces but:
at subduction zones bimodal suites are rather rare

→ Different tectonic „engines“ controlling crustal generation and evolution

TTG’s and Greenstone belts

TTGs & Greenstone belts





Frisch und Meschede (2005): Plattentektonik

Petrogenetic model for Archean TTG’s

Tectonic setting:

Melting in the subducted slab or
in underplated basalt (i.e., at the base of thickened crust)

TTG‘s are chemically analogous to modern adakites.
Adakites are confined to arc settings and are attributed to melting of the downgoing slab

Many TTG‘s and adakites have higher MgO and Ni than experimental melts from basalts

Slab melts must migrate through mantle wedge en route to the crust

→ Interaction of TTG magma with peridotite in the mantle wedge

Petrogenetic model for Archean TTG's

Secular changes in TTG composition

TTG composition between 4.0 and 2.5 Ga:

Evolve to progessively higher Mg# and Ni

→ greater assimilation of mantle peridotite

Explanation: increasing depth of slab melting as the Earth cooled

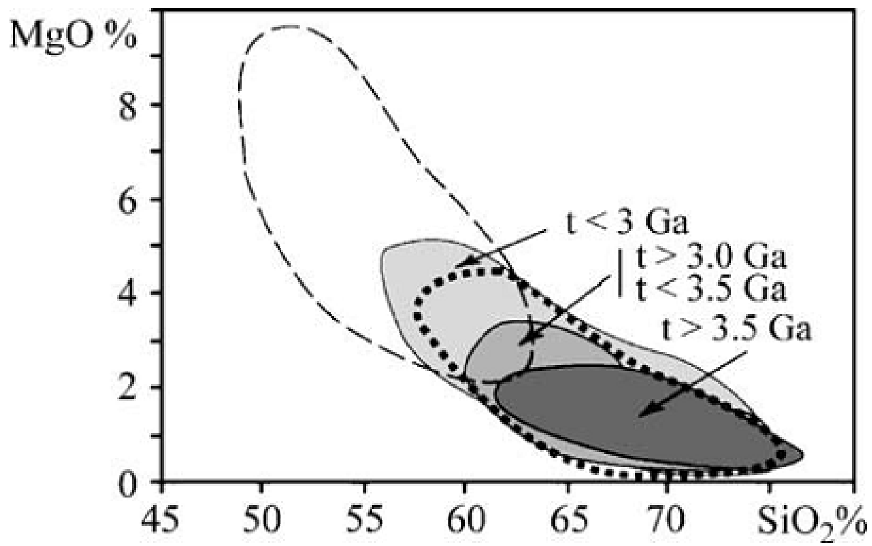


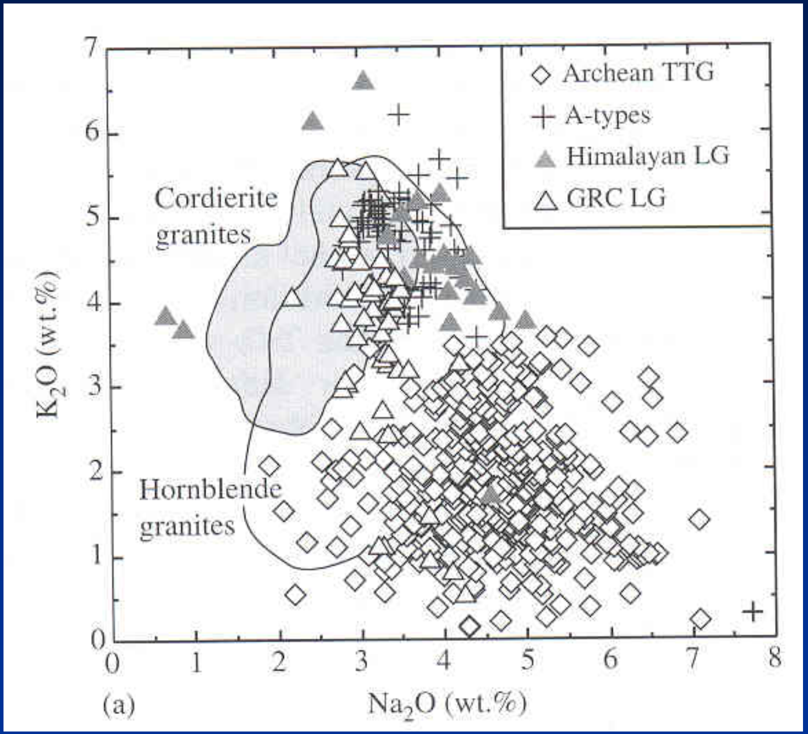
Fig. 10. MgO vs. SiO_2 diagram comparing composition of TTGs at different times (grey fields) with modern HSA (heavy dotted lined field) and LSA (light dotted lined field). A close analogy exists only between TTG younger than 3.0 Ga and HSA.

Martin et al. (2005) Lithos

Archean TTG's

Different from Proterozoic and younger plutonic rocks

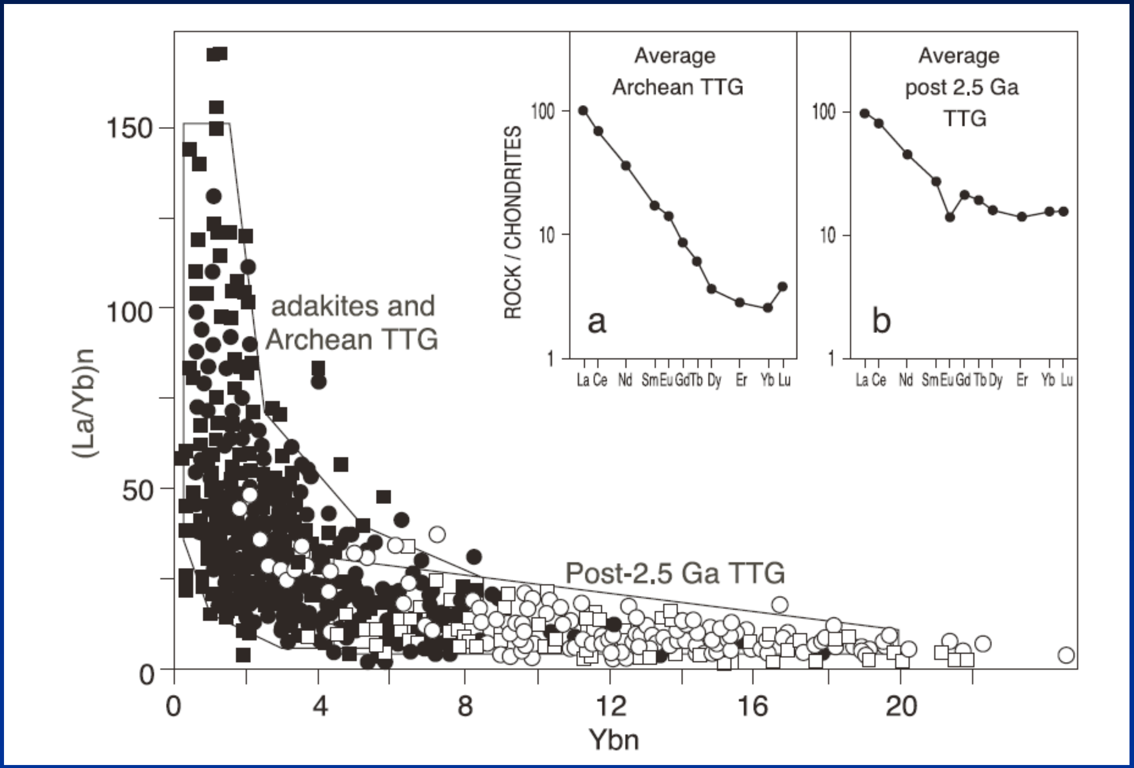
High Na_2O and Al_2O_3, low K_2O



Data source: Treatise on Geochemistry, Vol 3: The Crust

Archean TTG's

steep REE pattern, depleted HREE, Y and Sc high Sr, no negative Eu-anomaly



Derived from (meta)basaltic source rocks at depth below the stability field of plagioclase (> 40 km) in equilibrium with residual garnet (to account for low HREE)

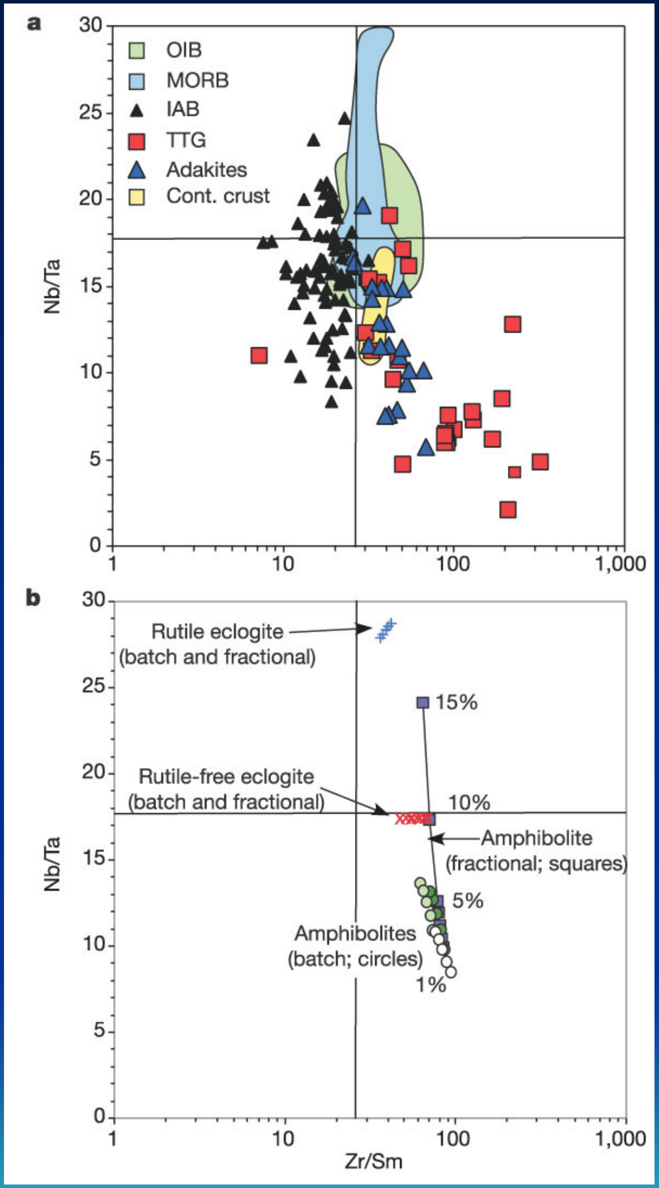
Composition of ancient and modern continental crust

Bulk Archean crust is more felsic than post-Archean crust! – why?

Most magmas of post-Archean subduction zones are derived from the mantle wedge rather than the downgoing slab

Petrogenetic model for Archean TTG’s

Experimental work suggests melting of low magnesium amphibolite, rather than eclogite



Foley et al. (2002) Nature 417: p.837

Modern crust

Modern Earth's crust has a bulk andesitic composition:
~61% SiO_2
Mg number (Mg#, molar Mg/(Mg + Fe)) is ~ 55

more differentiated than any magma in equilibrium with the upper mantle
But: modern crust is stratified

<u>Crustal growth by:</u>

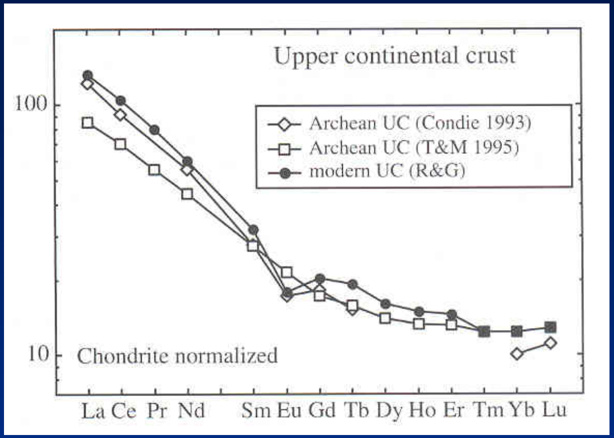
-- tectonic accretion of island arcs or oceanic plateaus i.e., addition of basalt. The basalts are ultimately reprocessed into felsic continental crust by intracrustal differentiation (fractional crystallization, remelting, weathering and erosion, etc.)

→ crust formation takes place in several stages

Upper continental crust

-- enriched in light REE
-- Eu-anomaly
-- flat heavy REE

This is different from TTG's but similar to most post-Archean granitic rocks → fundamental role of such granites in shaping the compositional structure of the crust



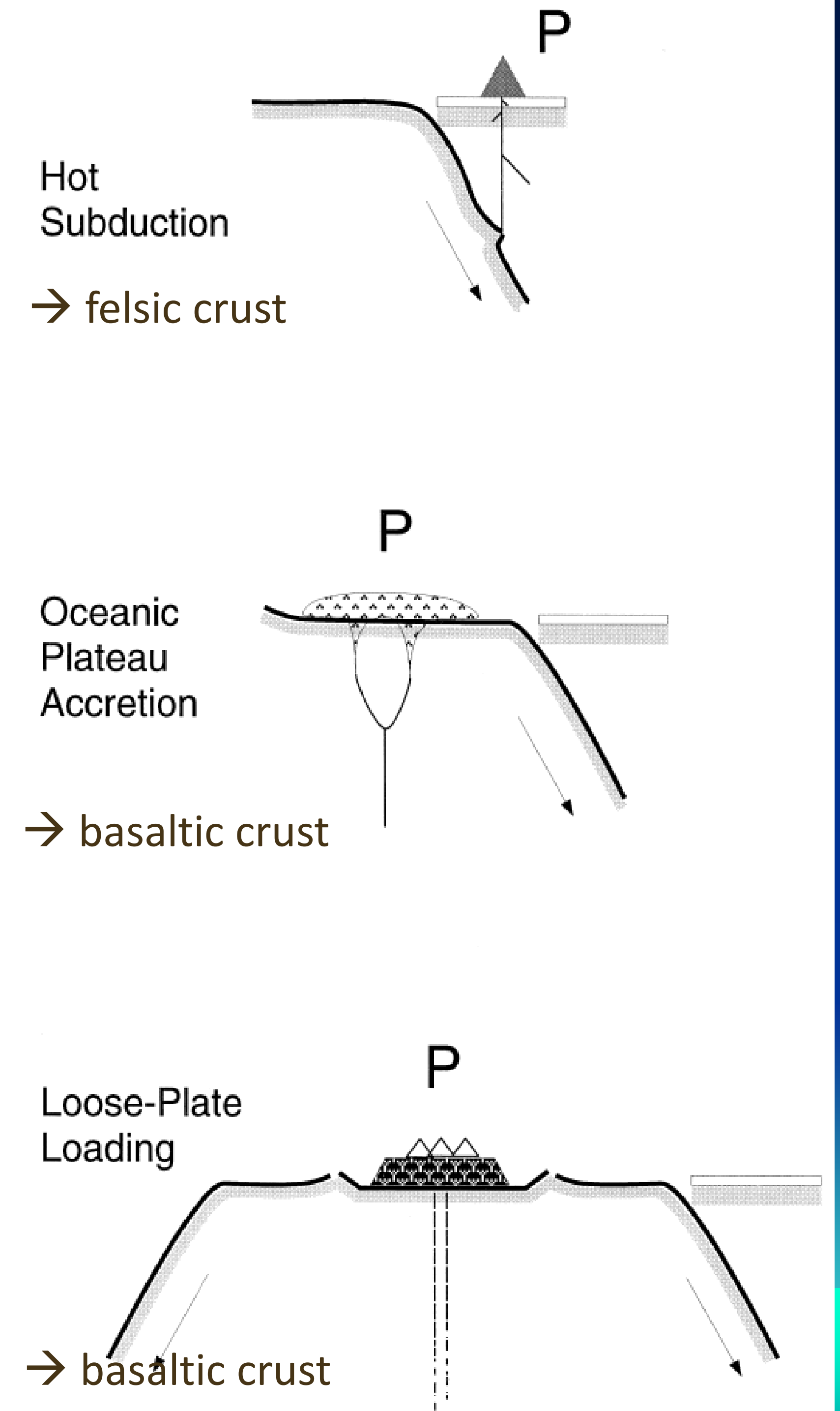
Treatise on Geochemistry, Vol 3: The Crust

Eu (like Sr) accommodated in plagioclase, and thus is sensitive to intracrustal differentiation processes

Can granitic plutons represent new crust? – yes, by

-- fractional crystallization of basaltic liquid
-- mixing between crustal and mantle-derived magmas
-- partial melting of young, mantle-derived mafic protoliths in the crust

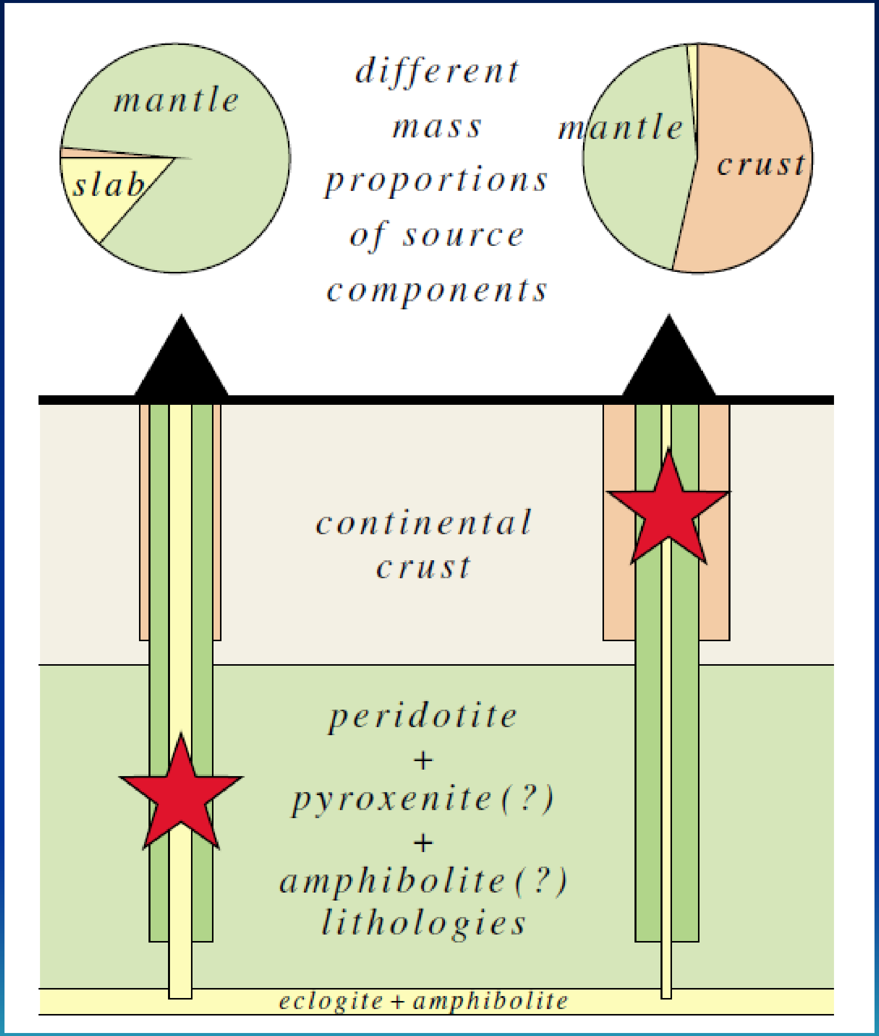
Growth of continental crust



Albarede (1998) Tectonophysics 296

Making continental crust

"Andesite model" & Orogenic andesites

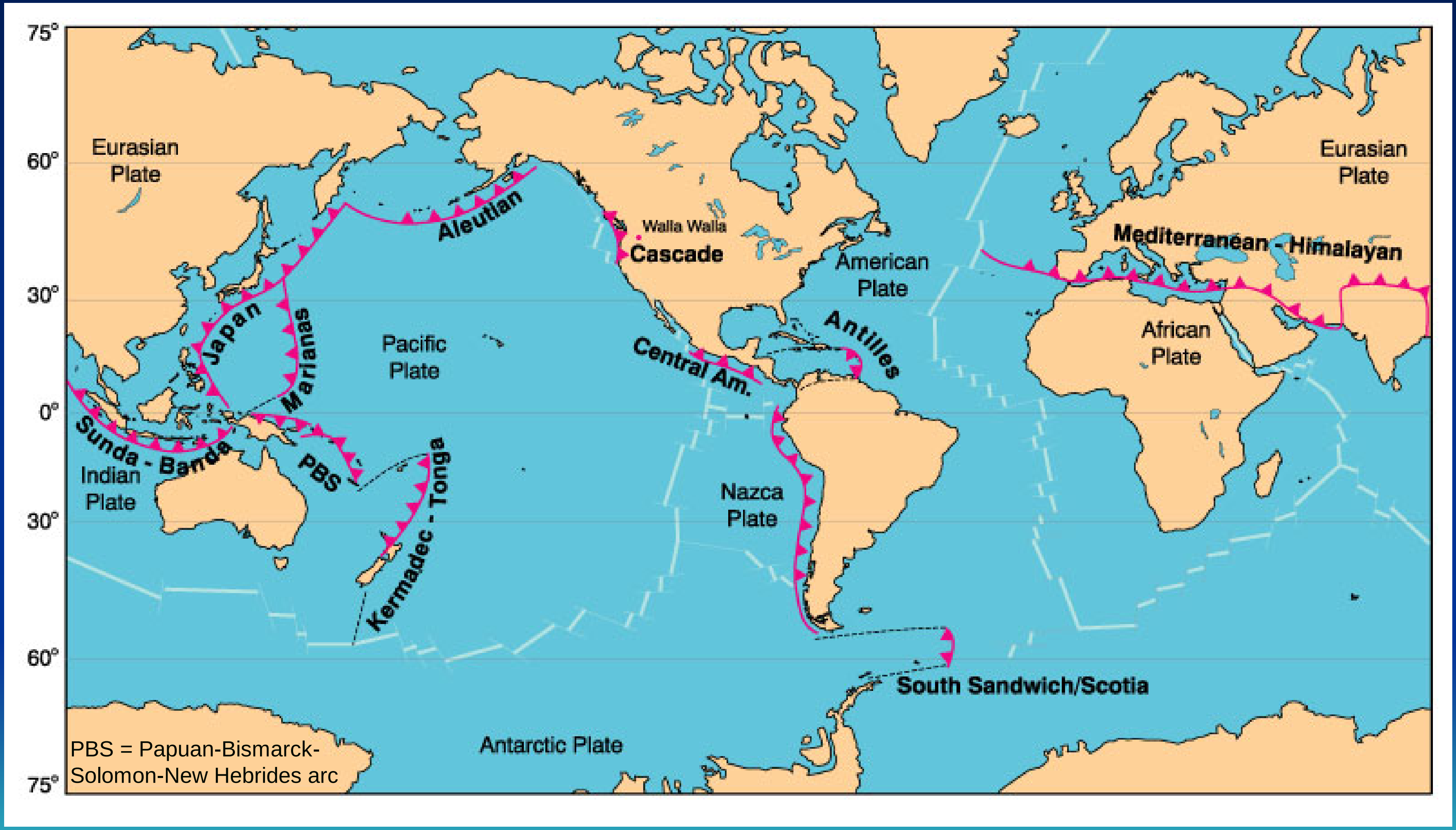


andesites form following hybridization of slab and mantle components in the subarc mantle

andesites evolve from parental arc basalts in the upper plate crust

Gomez-Tuena et al. 2013

Circum Pacific margins: Ocean-ocean subduction → Island Arc → arc accretion



Wilson (1989)

Growth of continents – Circum Pacific margins

Accretion-collision tectonics

Lateral accretion at subduction zones has played a major role in the growth and evolution of the Circum Pacific margins.

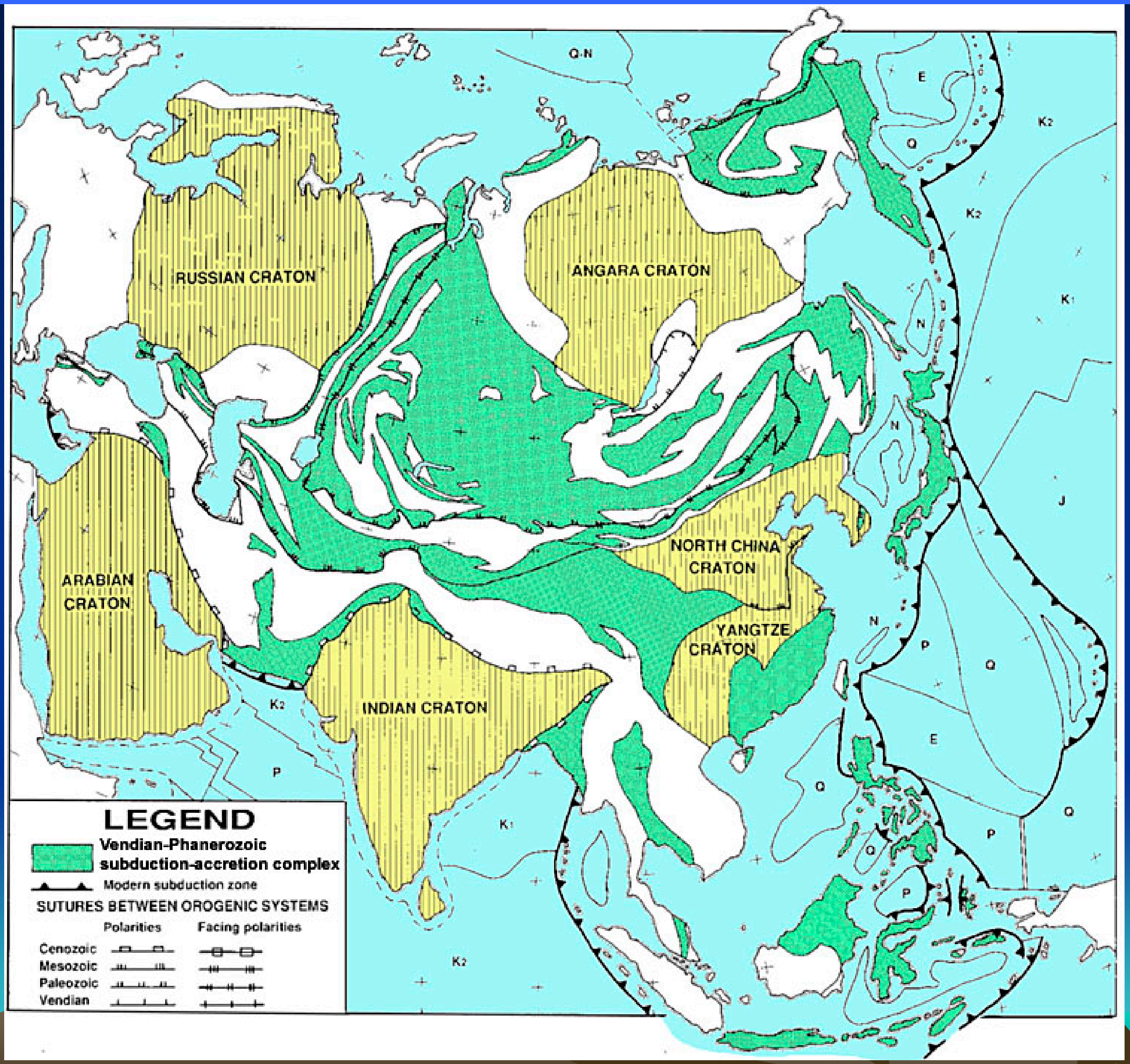
More than 200 terranes have been recognized in the Cordillera in Western North America.

Most of these terranes added during the Mesozoic and Cenozoic

continental margin was extended by as much as 800 km.

accreted terranes represent fragments of continents, oceanic plateaus, or portions of arc systems

Crustal grow in Asia by subduction-accretion processes



Cratons welded together by a range of orogenic systems (from oldest to youngest): Altaids, Manchurides, Tethysides, Nipponides

Sengör and Natal'in, 1996: The tectonic evolution of Asia