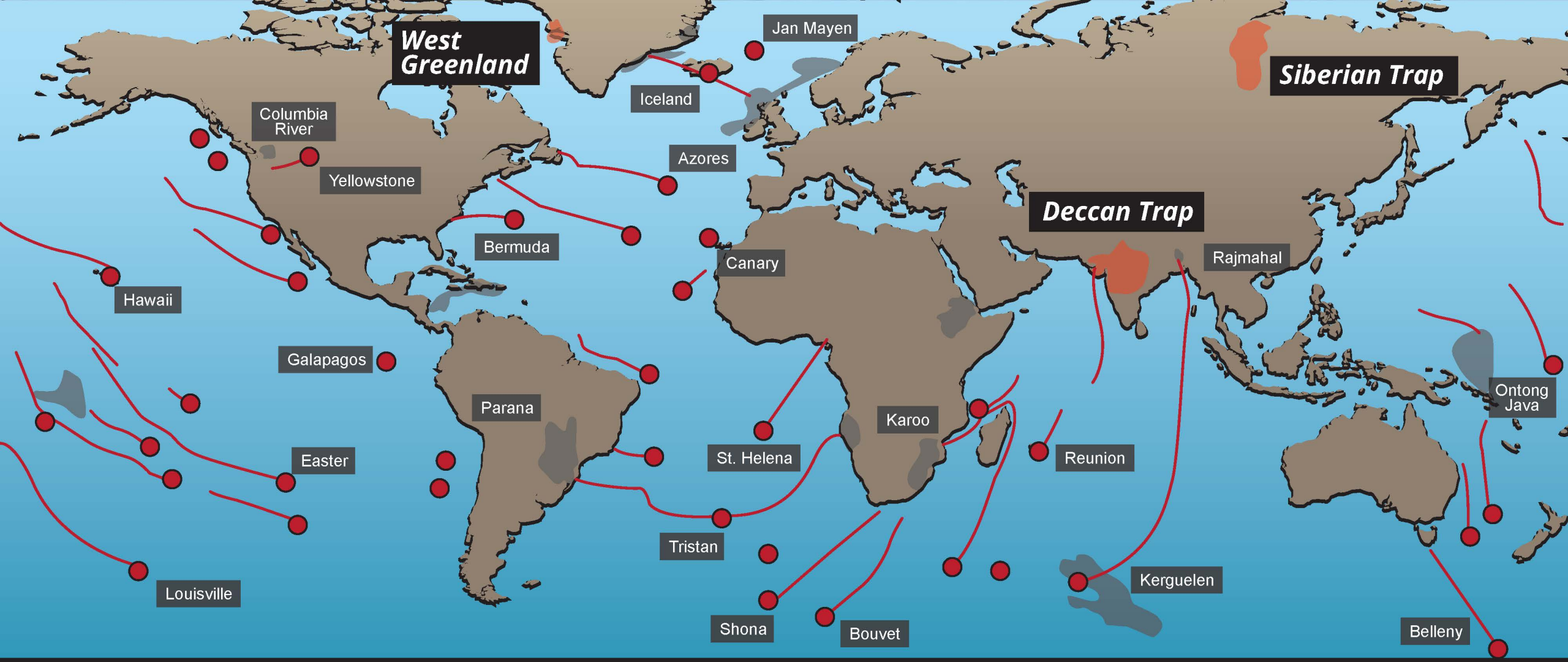


Chemostratigraphy of Continental Flood basalts: architecture, duration, and sulfur budget

Peter C. Lightfoot, PhD, PGeo

Adjunct Professor, Department of Earth Sciences, University of Western Ontario

Western

Lightfoot GEOSCIENCE

PCL: 1983

Deccan Trap at Mahabaleshwar, India: uninterrupted package of rather prosaic tholeiites

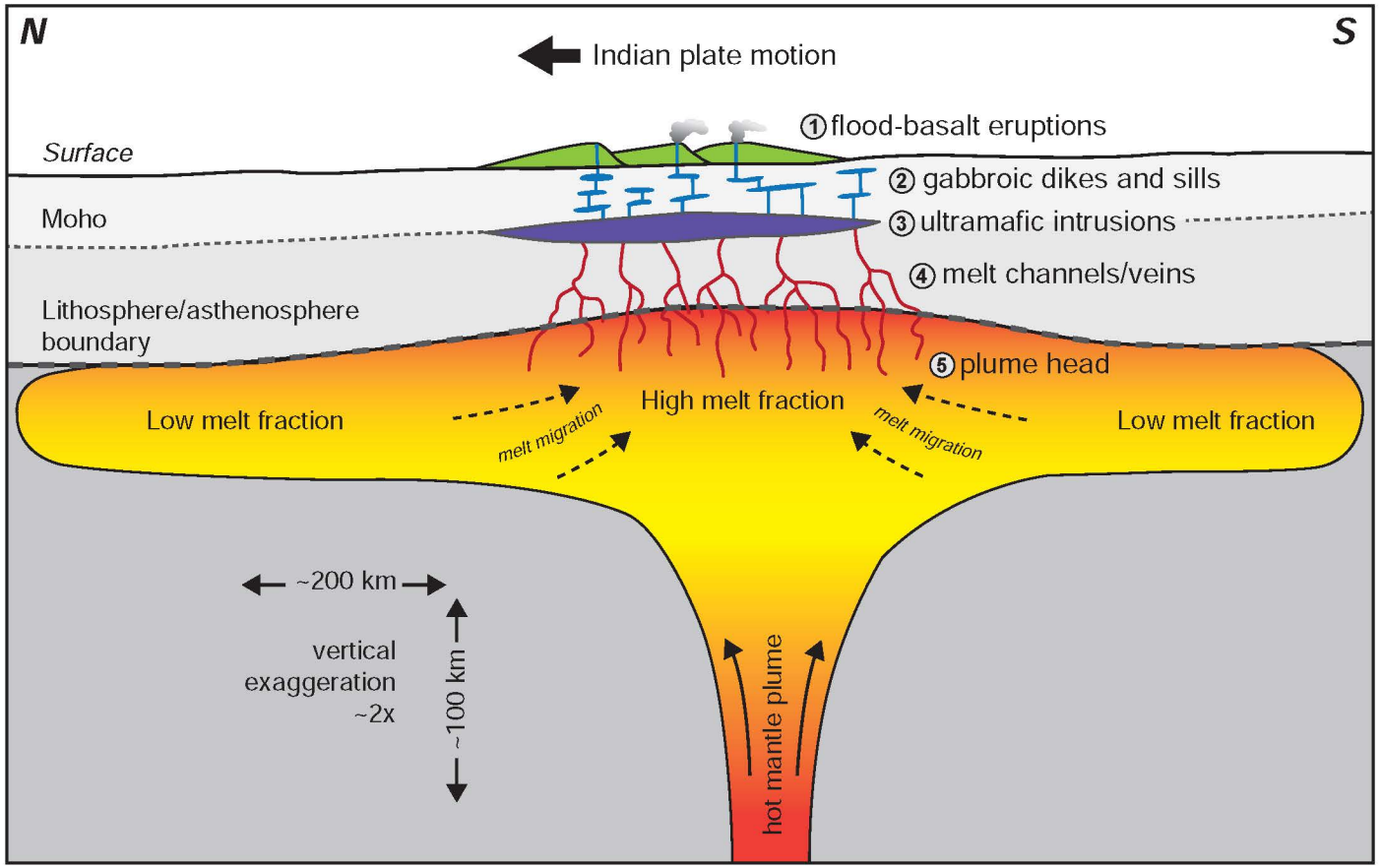
Anchors from stratigraphy

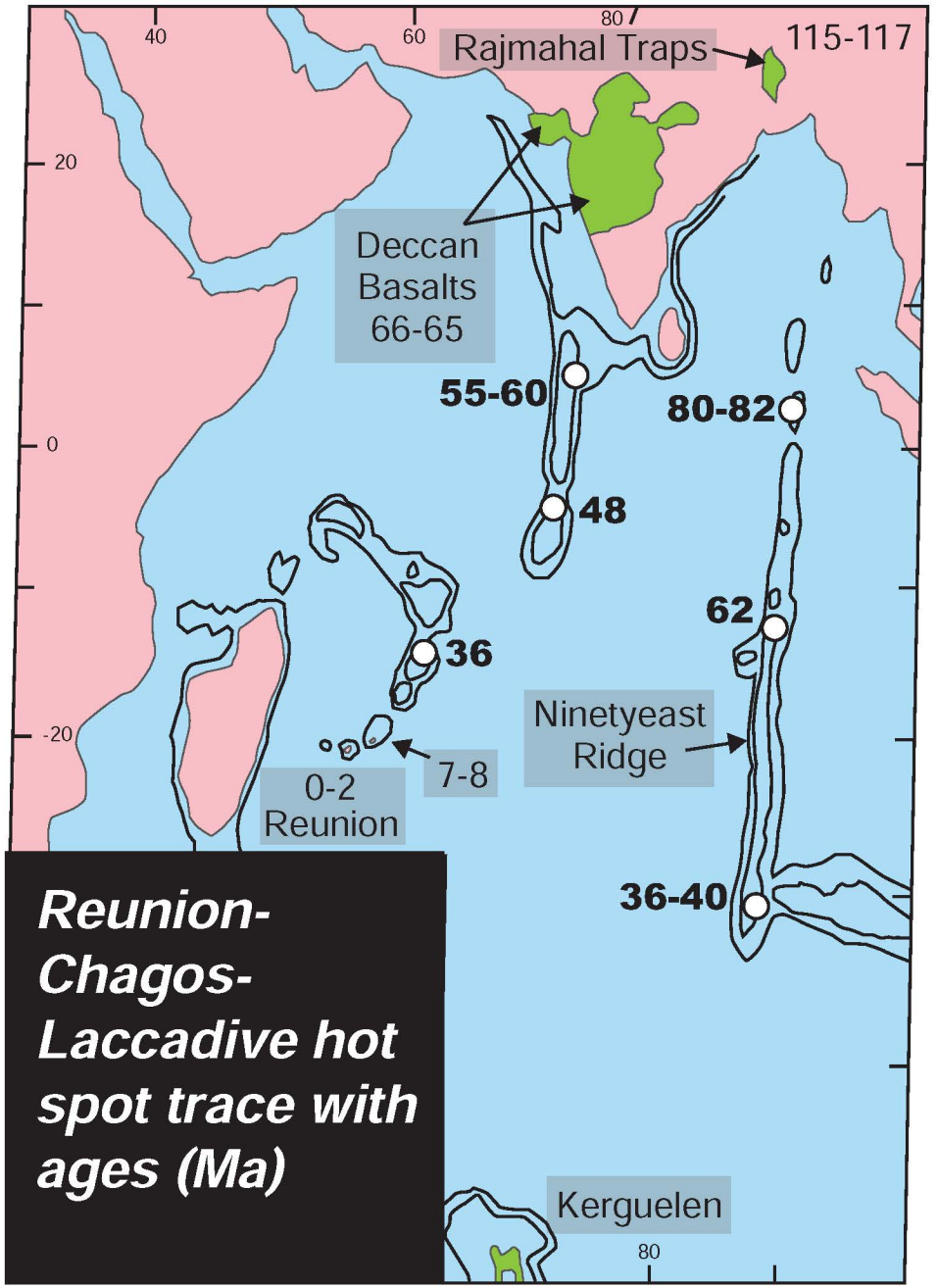
- Compositional diversity through time
- Correlation of volcanic packages *(chemostratigraphy)*
- Migration of volcanic center
- Duration of flood basalt event *(geochronology, magnetostratigraphy)*
- Rate of change in volume of magma erupted
- Degassing of magmas and sulfur budget
- Inform models for mass extinction
- Inform ore deposit models and exploration

This Presentation:	• *Deccan Trap*
	• *Siberian Trap*
	• *West Greenland*

Deccan Trap – tectonomagmatic setting

- ~65Ma position of Reunion hotspot *(Cox and Hawkesworth, 1984)*
- Antipodal to Chicxulub impact crater *(Richards et al., 2015)*
- Craton scale rift structures *(e.g. Brahmam and Negi, 1973)* possibly reactivated by magmatic event

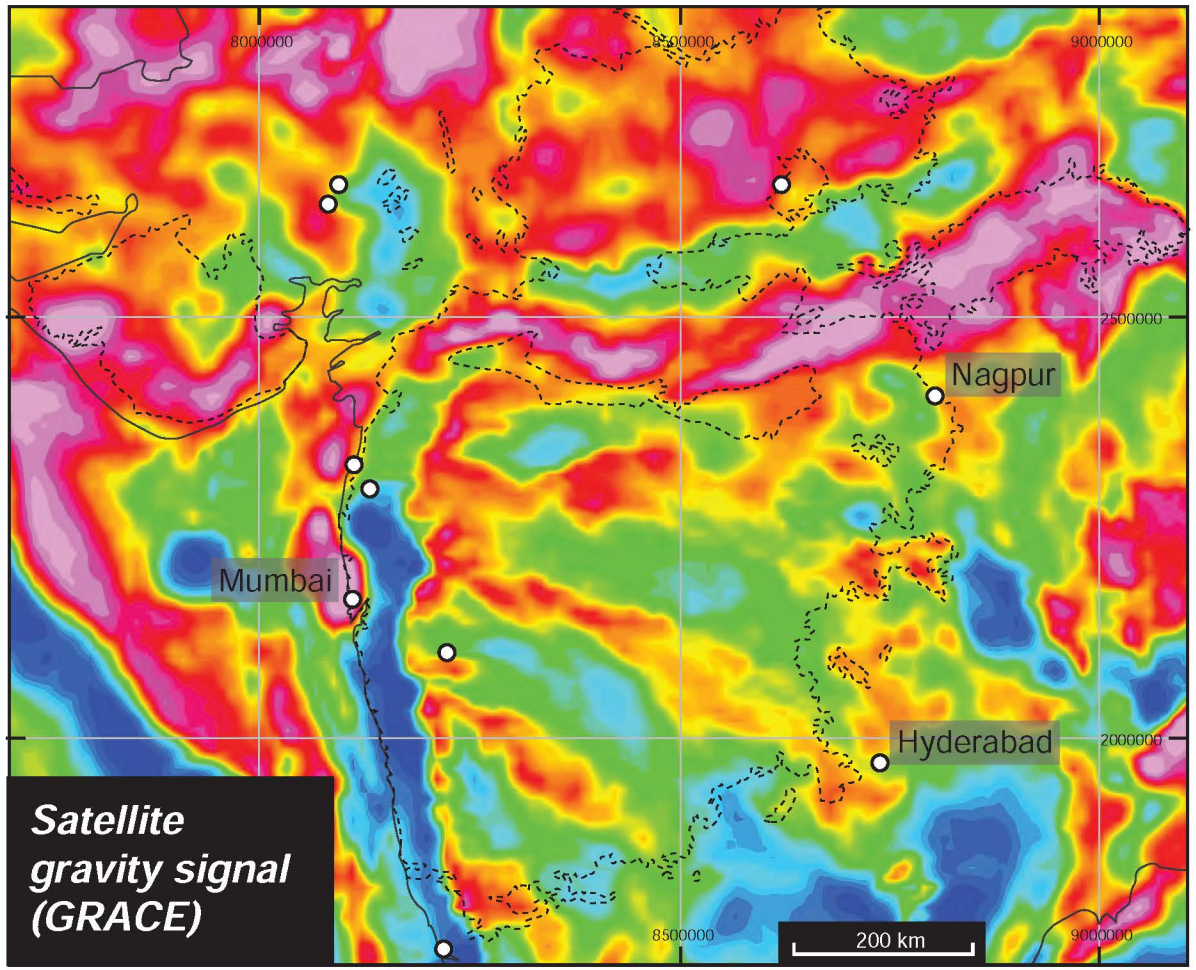




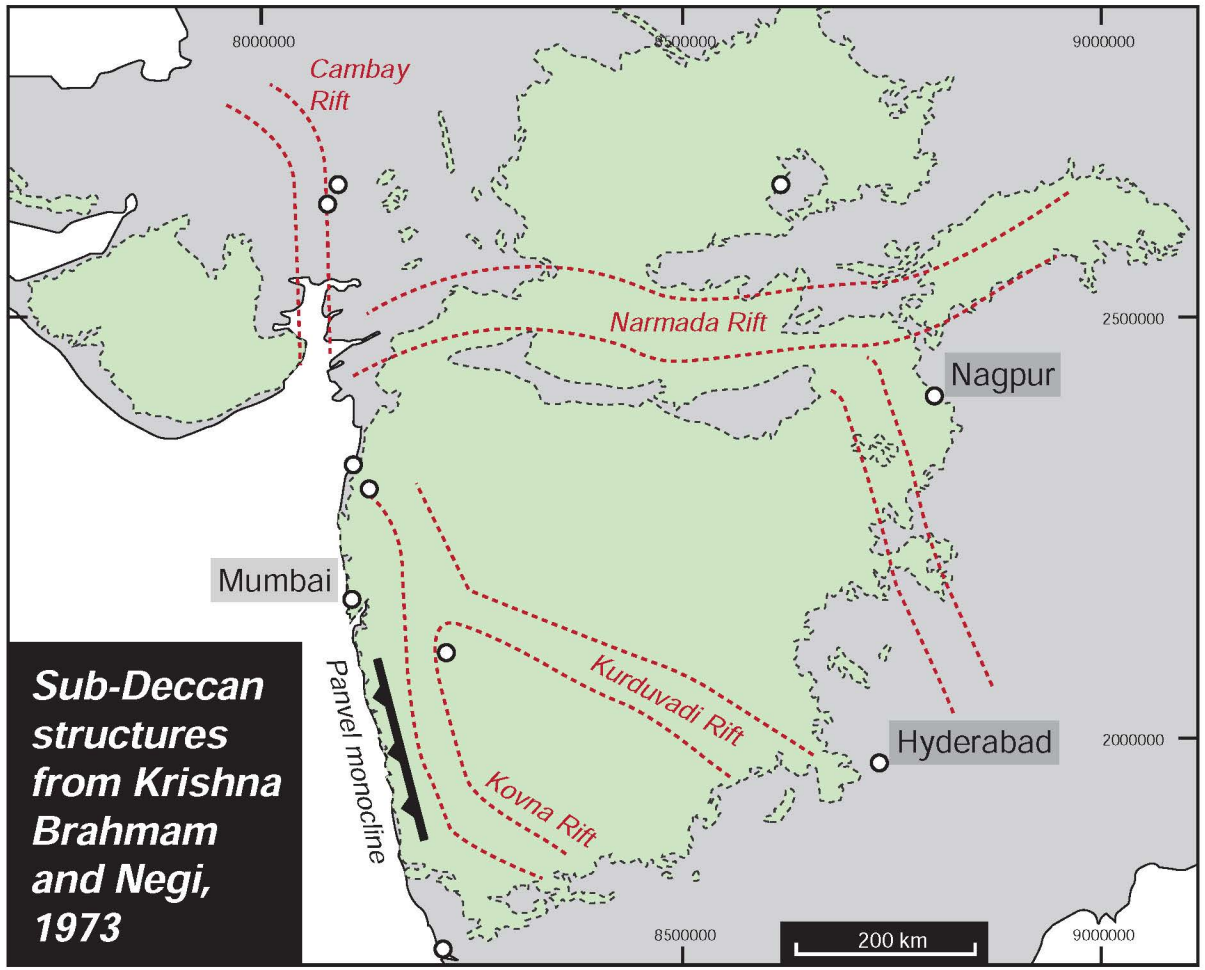
Reunion-Chagos-Laccadive hot spot trace with ages (Ma)

Deccan Trap – gravity, basalt distribution, and sub-volcanic rift structures

Basement and sedimentary rocks
Deccan Trap
Sub-volcanic rifts
Coastline

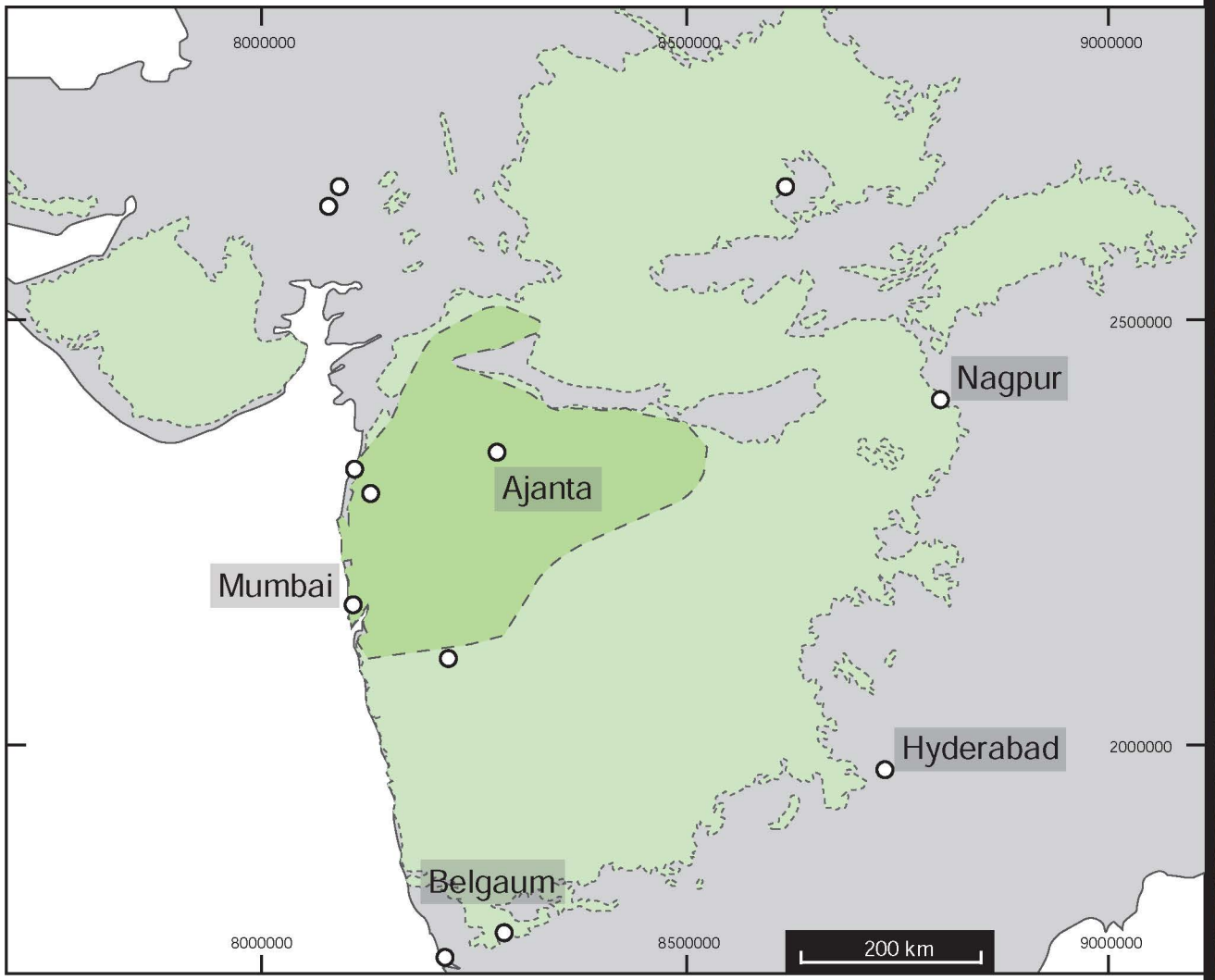


Satellite gravity signal (GRACE)



Sub-Deccan structures from Krishna Brahmam and Negi, 1973

Deccan Trap – types of basalt flow



Dominantly late simple type flows *(tholeiites)*
Dominantly early compound type flow *('picritic' olivine basalts)*
Basement and sedimentary rocks

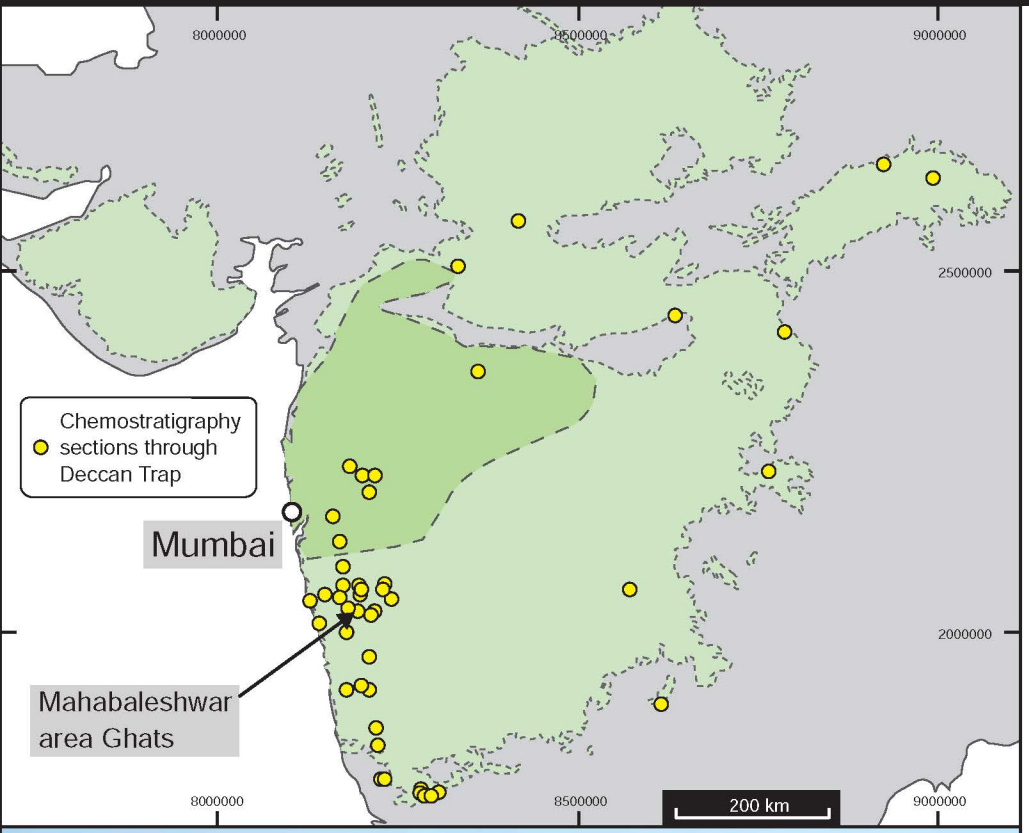
Simple type flows (Panhala Formation, Belgaum)

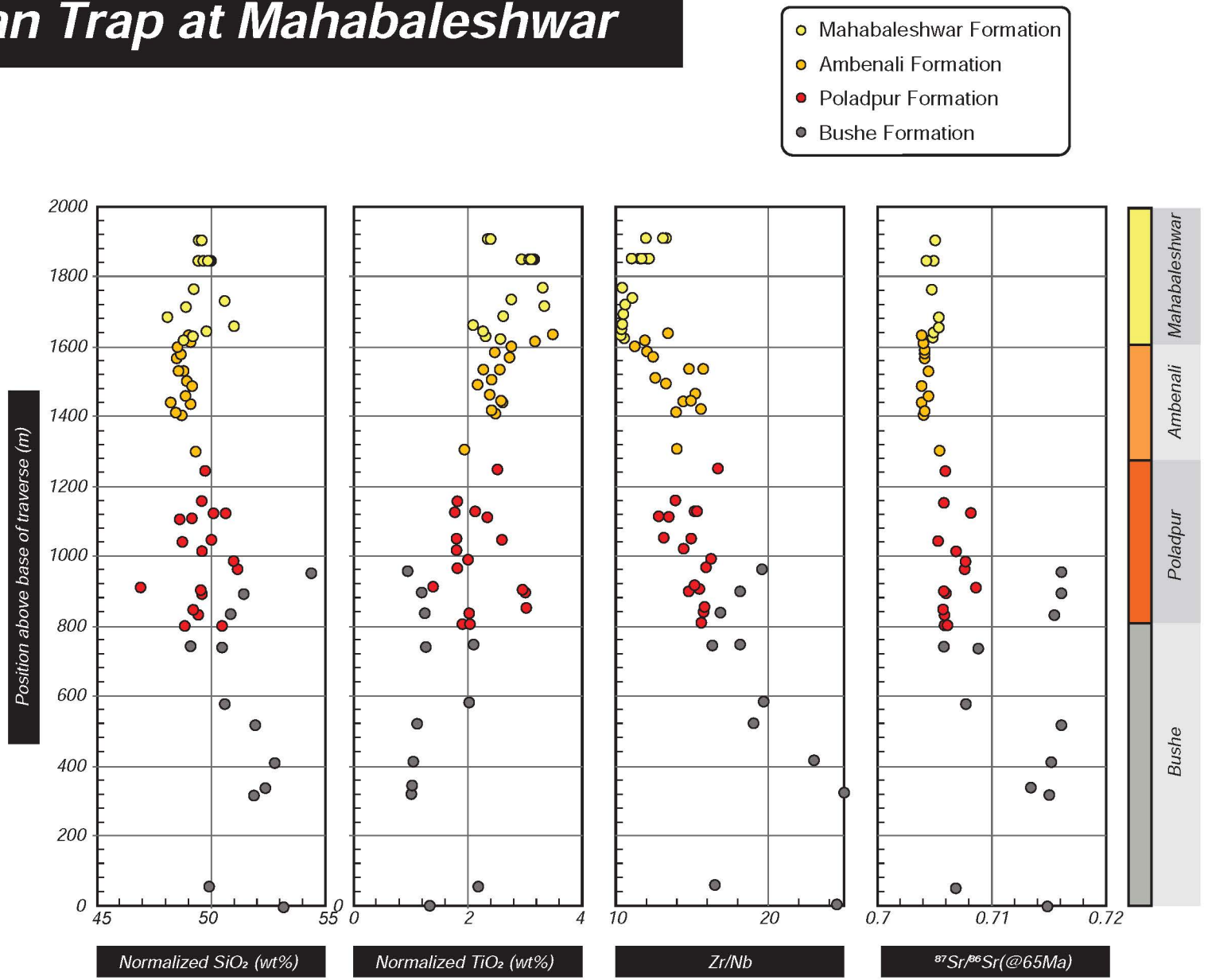
PCL: 1983

PCL: 2009

Compound type flows (Khandala Formation; Ajanta caves)

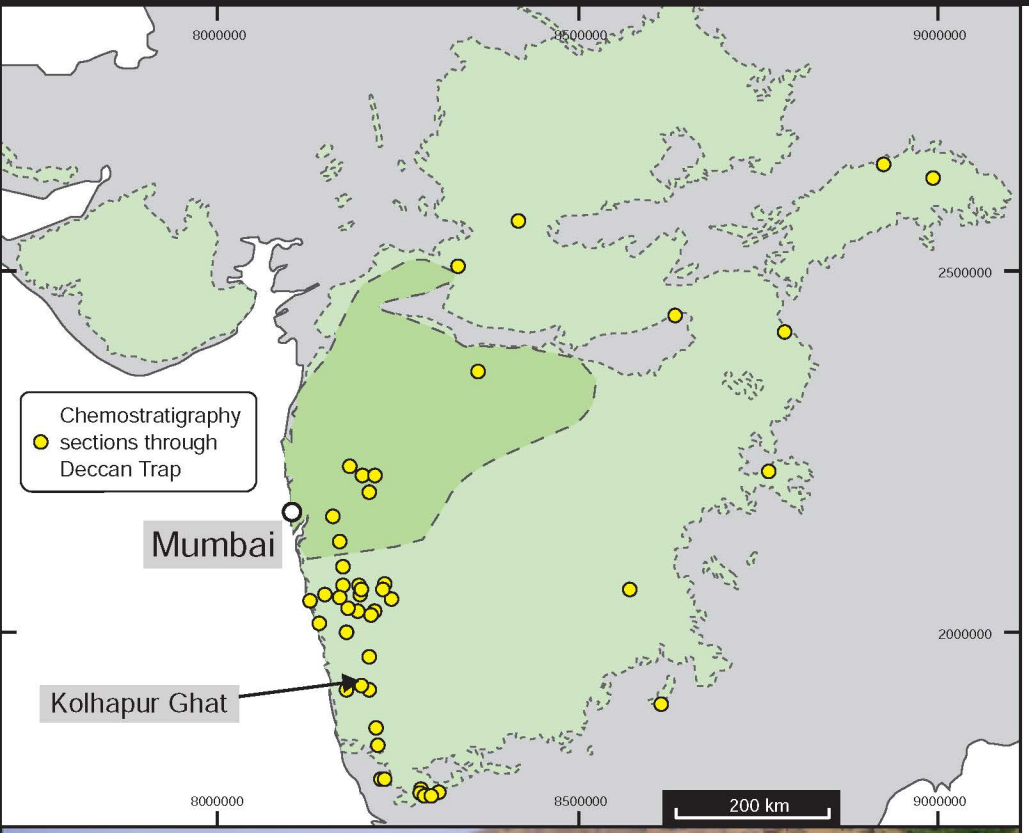
Chemostratigraphy of the Deccan Trap at Mahabaleshwar



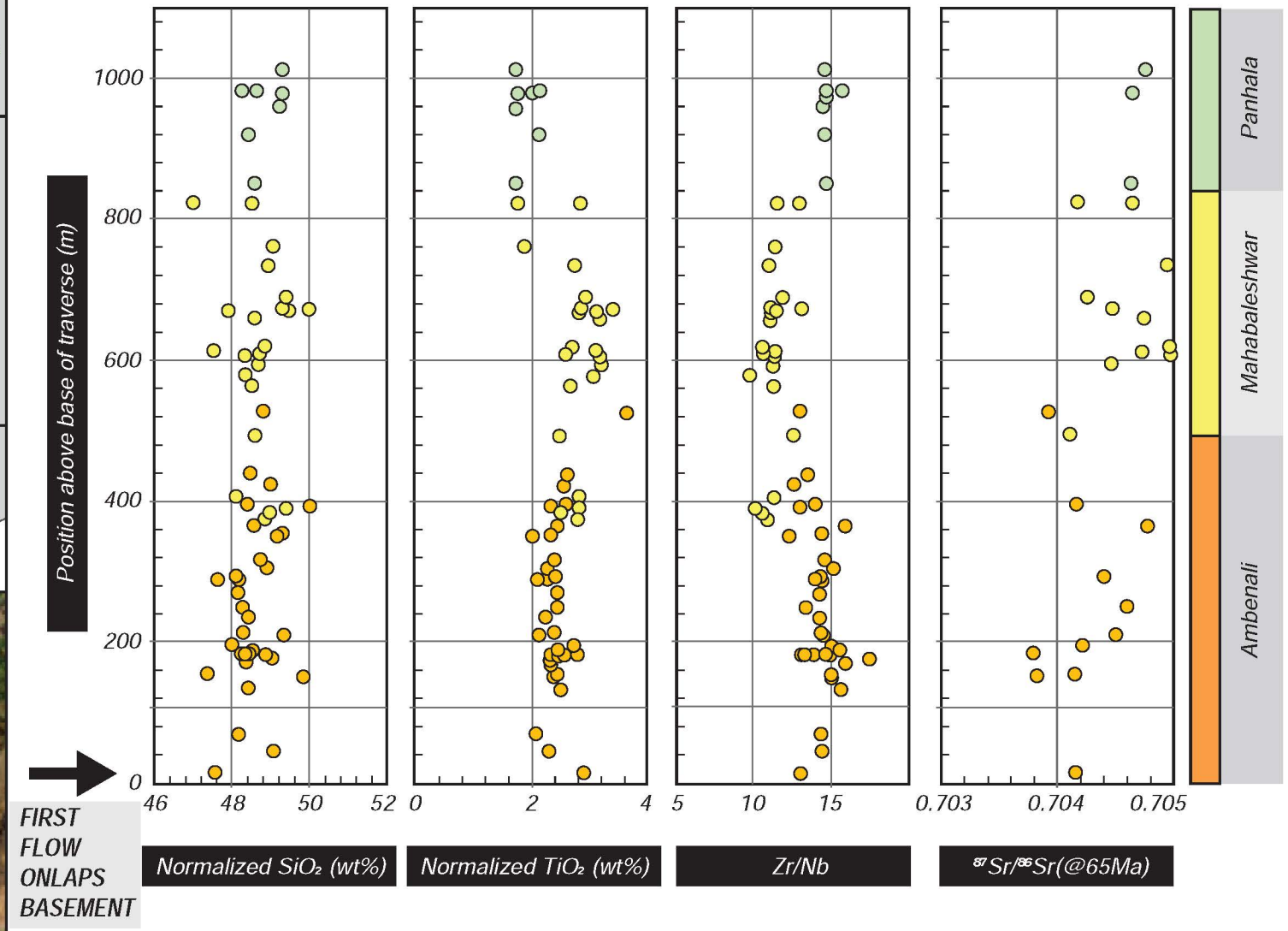


Cox and Hawkesworth, 1984, Mahoney et al., 1983; Lightfoot, 1985; Devey and Lightfoot, 1986; Lightfoot and Hawkesworth, 1987; Keays and Lightfoot, 2009

Chemostratigraphy of the Deccan Trap at Kolhapur

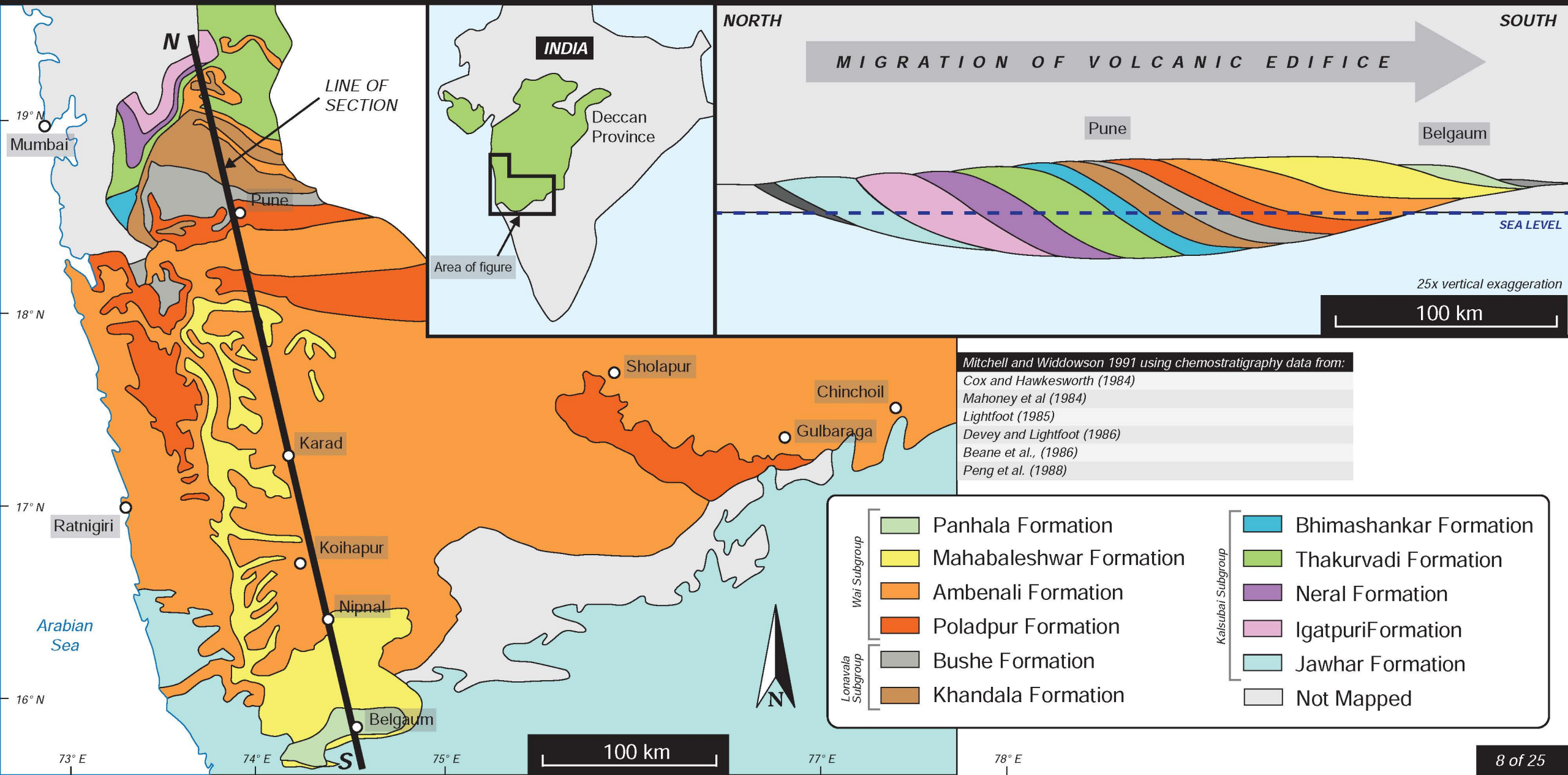


PCL:1983



Lightfoot, 1985

Geological map showing the stratigraphy of the Deccan Trap, and the progressive onlap of the basalts on to the basement towards the south

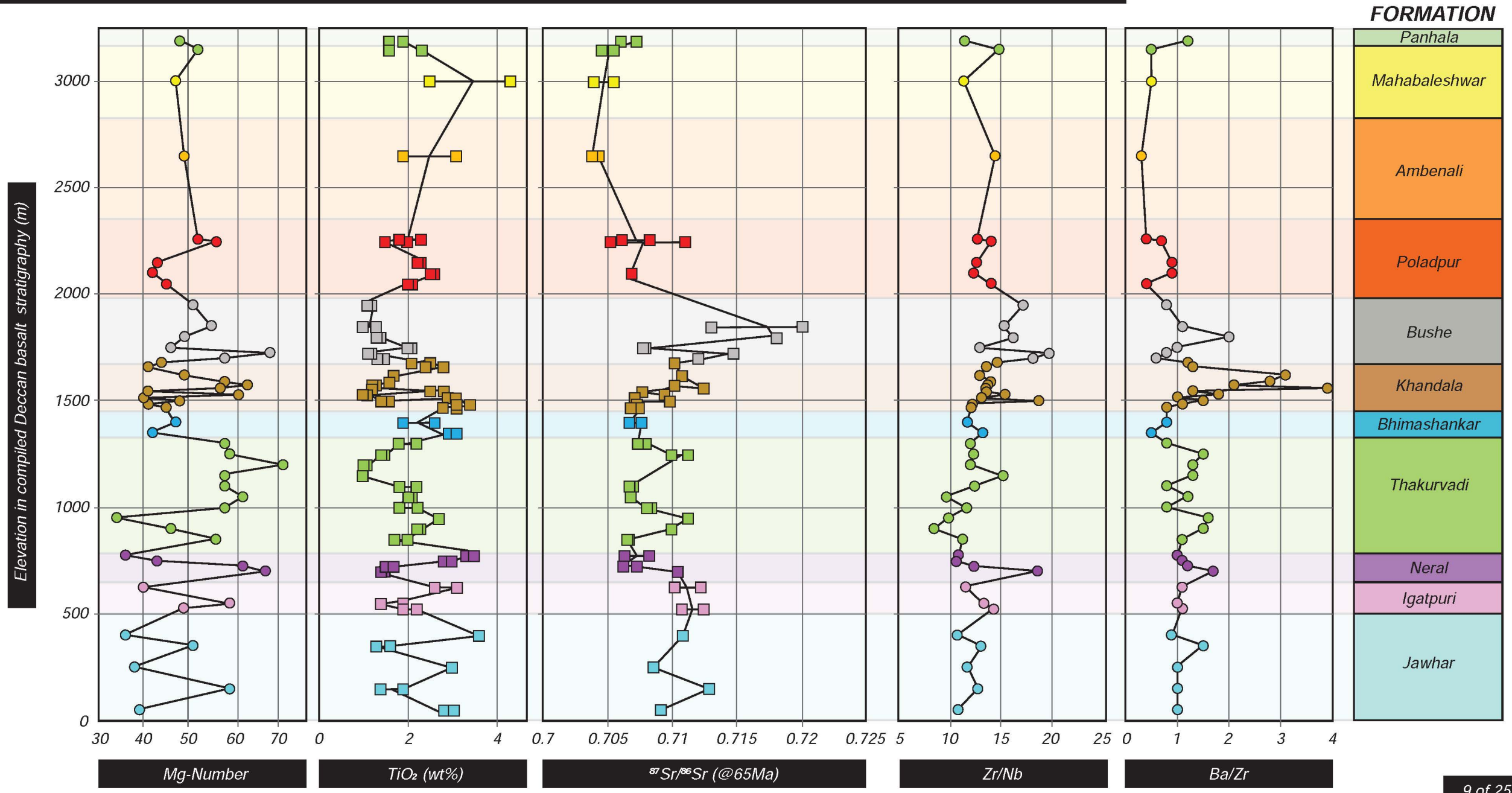


Mitchell and Widdowson 1991 using chemostratigraphy data from:
Cox and Hawkesworth (1984)
Mahoney et al (1984)
Lightfoot (1985)
Devey and Lightfoot (1986)
Beane et al., (1986)
Peng et al. (1988)

Wai Subgroup	Panhala Formation	
	Mahabaleshwar Formation	
	Ambenali Formation	
	Poladpur Formation	
Lonavala Subgroup	Bushe Formation	
	Khandala Formation	
Kalsubai Subgroup		Bhimashankar Formation
		Thakurvadi Formation
		Neral Formation
		IgatpuriFormation
		Jawhar Formation
		Not Mapped

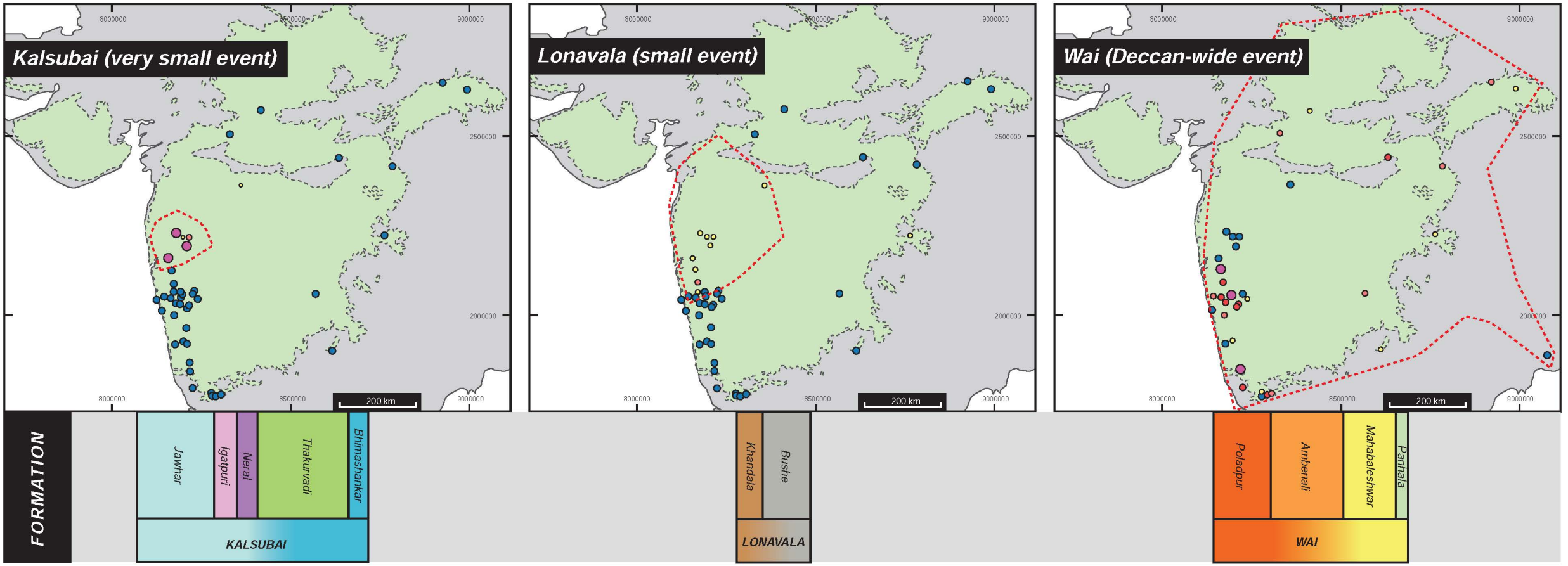
Geochemical signatures of Deccan Trap Formations

Modified from Peng et al. 1988



Distribution of Super-groups on scale of Deccan Trap

E R U P T I O N T I M E - L I N E

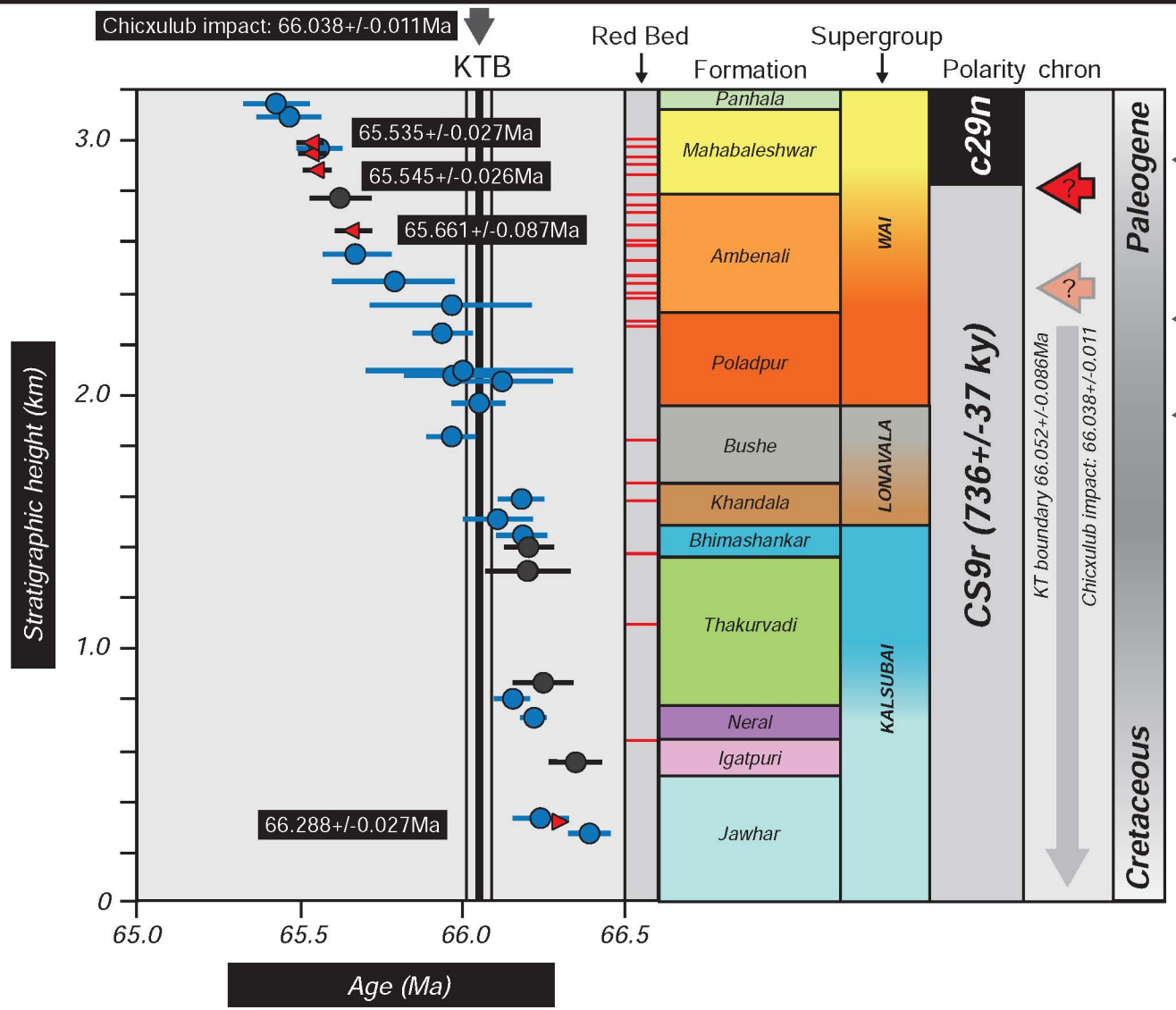


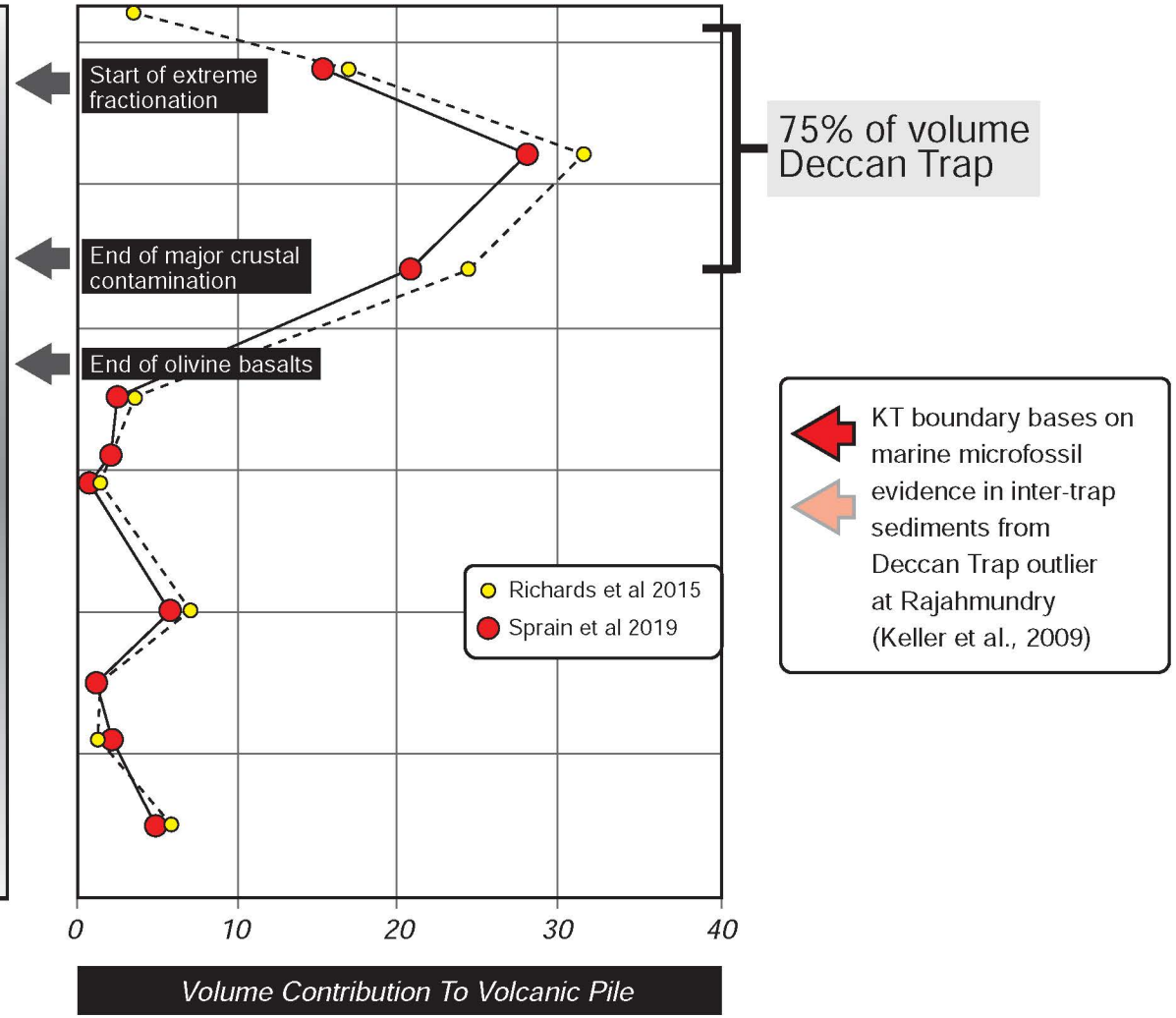
Minimum thickness (m)

- 0-100m
- >100-200m
- >200-300m
- >300-400m
- >400m

Minimum thickness estimates based on sections reported in:	
Cox and Hawkesworth (1984)	Mahoney et al. (2000)
Cox and Hawkesworth (1985)	Schobel et al. (2014)
Devey and Lightfoot (1986)	Vanderkluysen et al. (2011)
Beane et al (1986)	Verma and Khosla (2019)
Peng et al. (1994)	

Stratigraphic summary and eruptive history from $^{40}Ar/^{39}Ar$ plagioclase and zircon $^{238}U/^{206}Pb$ record >90% of Deccan Trap volume erupted in <1 million years



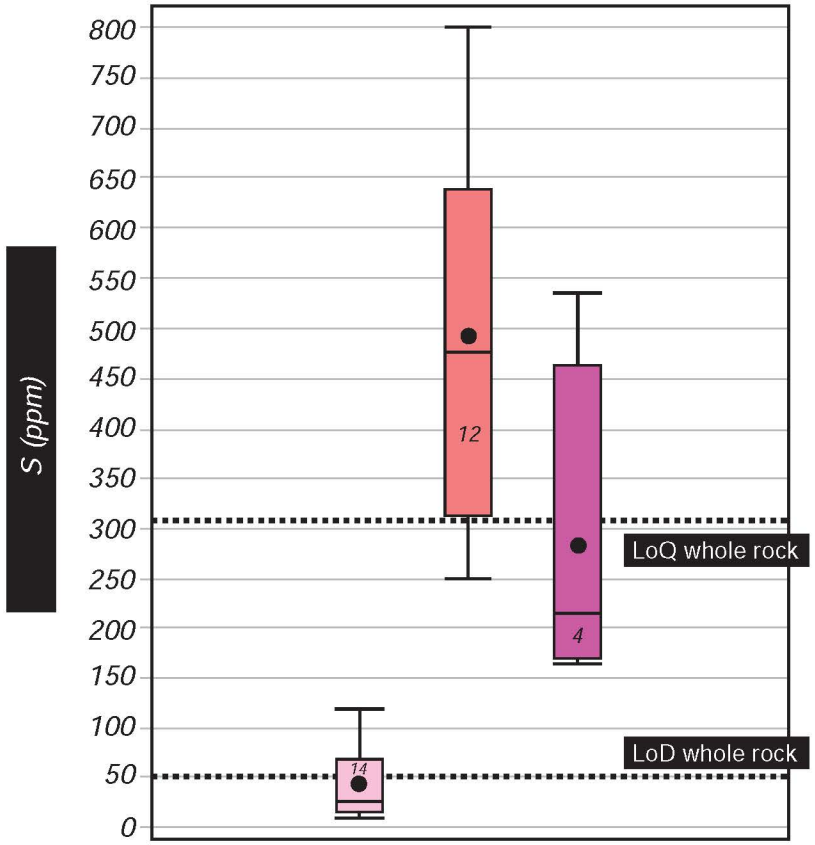


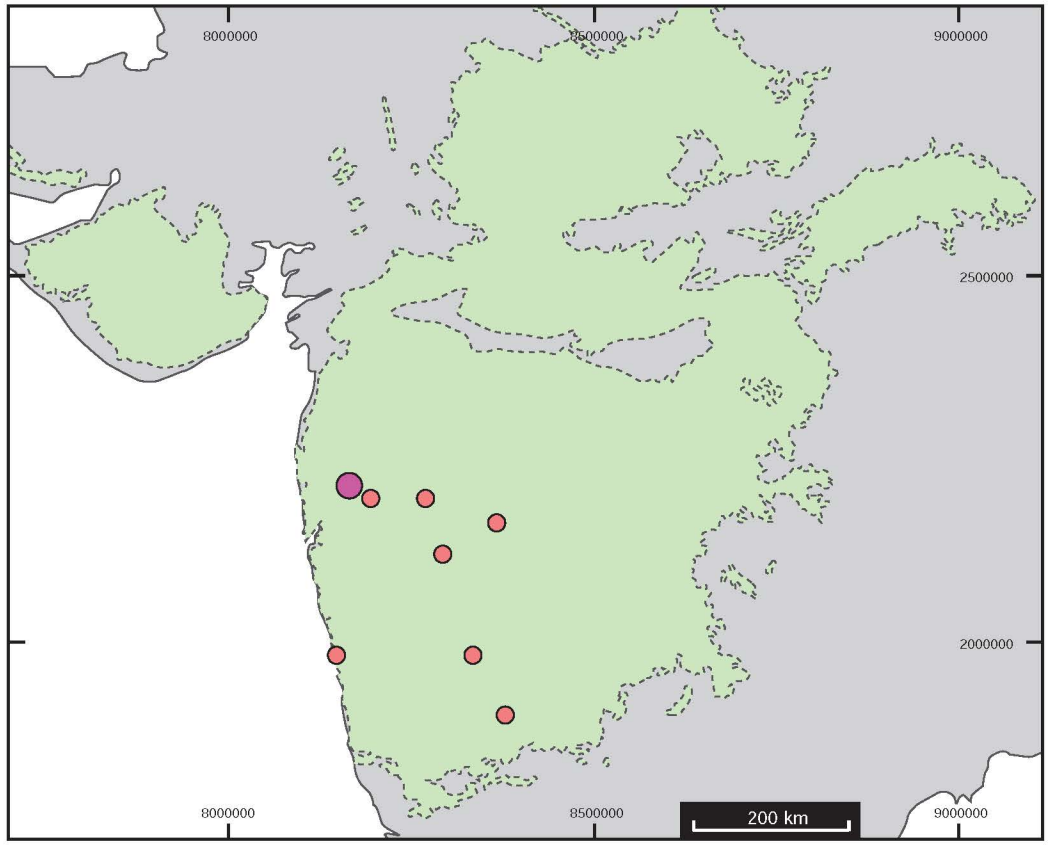
$^{40}Ar/^{39}Ar$ plagiclase: Renne et al. (2015)
$^{40}Ar/^{39}Ar$ plagiclase: Sprain et al. (2019)
$^{238}U/^{206}Pb$ zircon maximum age: Schoene et al. (2015)
$^{238}U/^{206}Pb$ zircon minimum age: Schoene et al. (2015)

Modified after Sprain et al., 2019;Schoene et al., 2015; Renne et al., 2015

Deccan sulfur budget

Very few analyses of basalt with available or reliable S concentrations
Equivocal sulfur mass balance





Formation	Wai Supergroup	
Volume estimate	km³	1,300,000
S in basalt	ppm	50
S in intrusion	ppm	500
SO_2 lost	ppm	899
Mass SO_2	Bmt	2,453
Mass SO_2	pa* (Mmt)	6

** 400,000 year duration of Wai event containing 75% of volume*

Global yearly anthropogenic:
SO_2= 115 Mmt (Smith et al., 2011)
CO_2=24 Bmt (USGS)

Global yearly volcanic:
SO_2= 18 Mmt (Textor et al., 2003)
CO_2 = 0.2 Bmt (USGS)

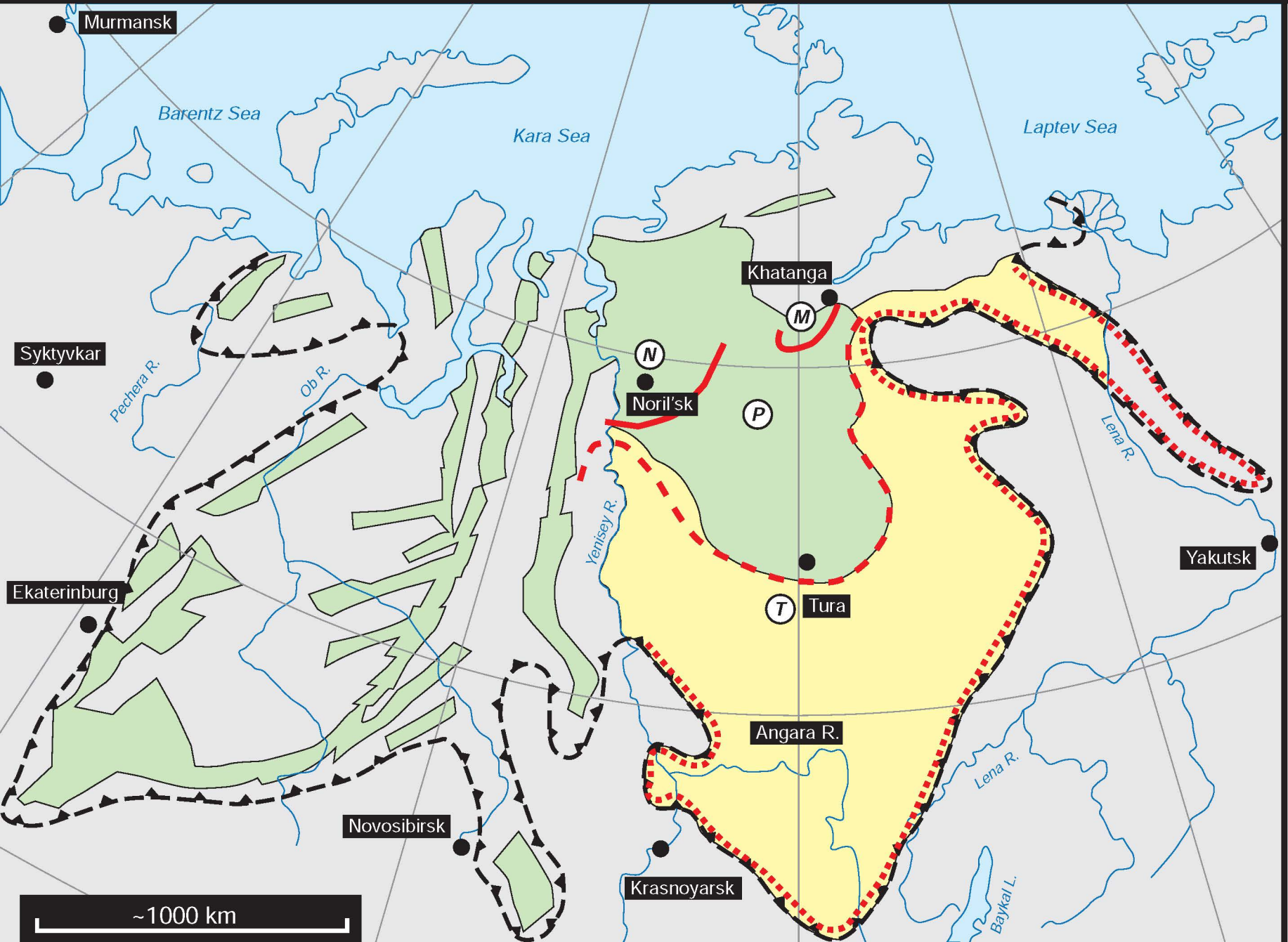
** 4.55 Tmt SO_2 (Self et al., 2008)*

Deccan Basalt (whole rock)
Deccan Basalt (glass)
Deccan diabase intrusion (whole rock)
Deccan Trap
Basement and sedimentary basin
Whole rock basalt sample locations (Crocket and Paul, 2004)
Glass and whole rock basalt sample location (Self et al., 2008)

LoD: A signal-to-noise ratio between 3:1 or 2:1 is generally considered acceptable for estimating the detection limit.

LoQ: The quantification(determination) limit of an individual analytical procedure is the lowest amount of analyte in a sample which can be quantitatively determined with suitable precision and accuracy.

Siberian trap magmatic event



- Basaltic lavas ~35% by volume
- Intrusions ~26% by volume
- Pyroclastic rocks ~39% by volume

Distribution of volcanic rocks

- Lavas
- Tuffs
- Approximate extent of intrusive rocks of Siberian Trap
- Approximate boundaries of the Siberian flood volcanic province
- Approximate boundaries between extensive, moderate, and sparse magmatic activity
- (N) Noril'sk area
- (M) Maymecha-Kotuy area
- (P) Putorana area
- (T) Nizhnyay Tunguska area

Siberian Trap basalts in the Noril'sk Region

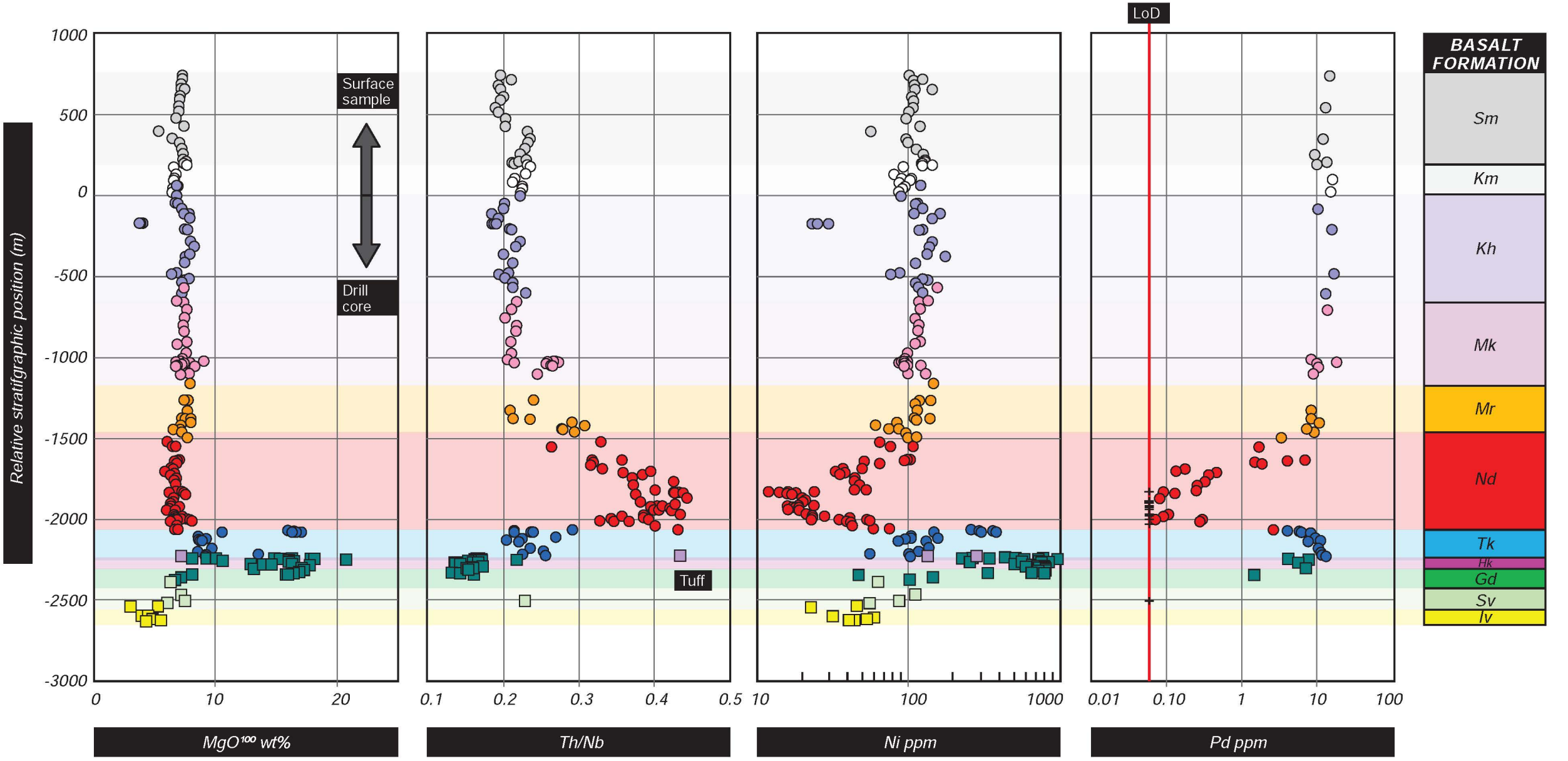

Valeri Fedorenko


PCL: 2004

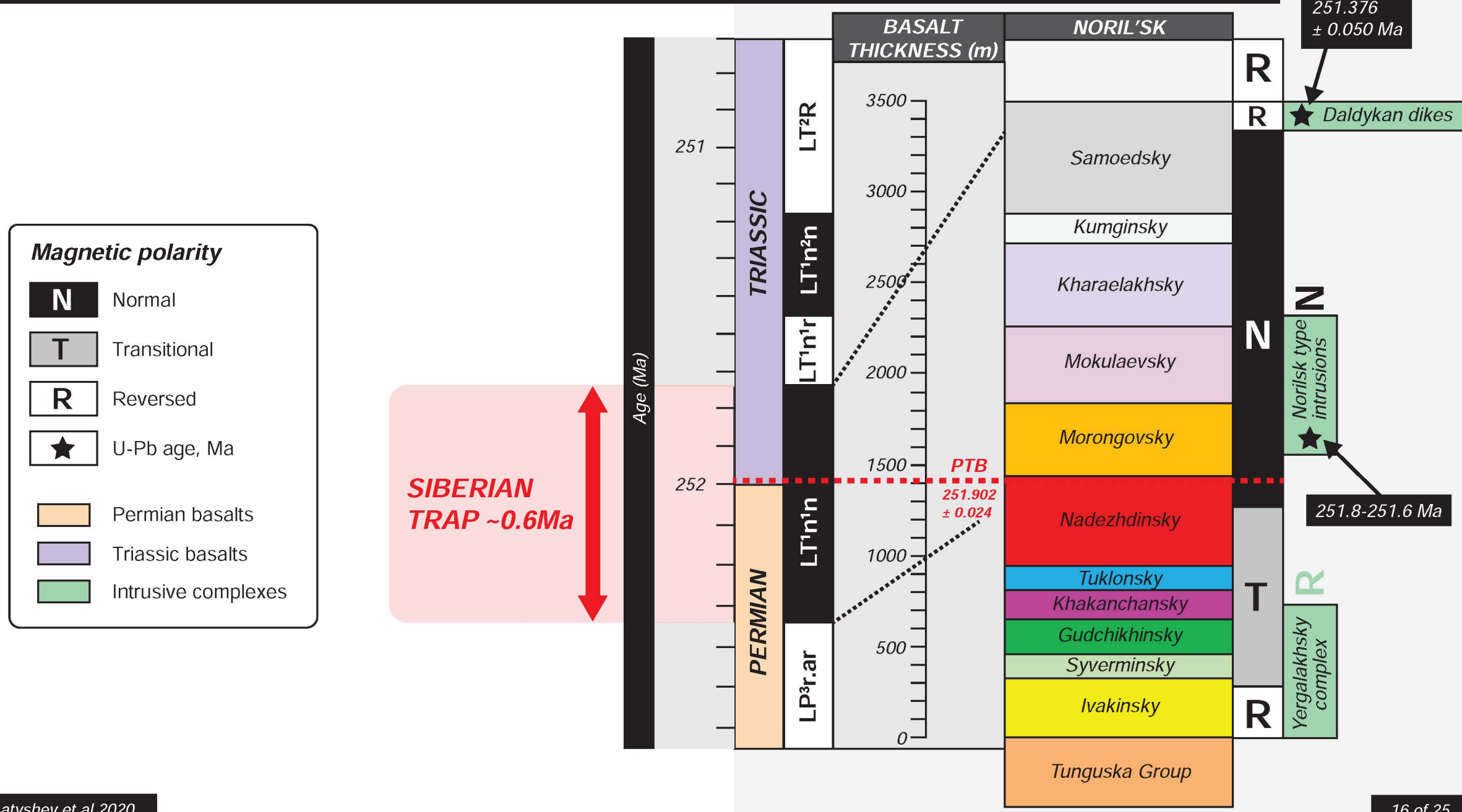

PCL: 2004


PCL: 2004

Siberian Trap basalts, Noril'sk Region: chemostratigraphy of basalts



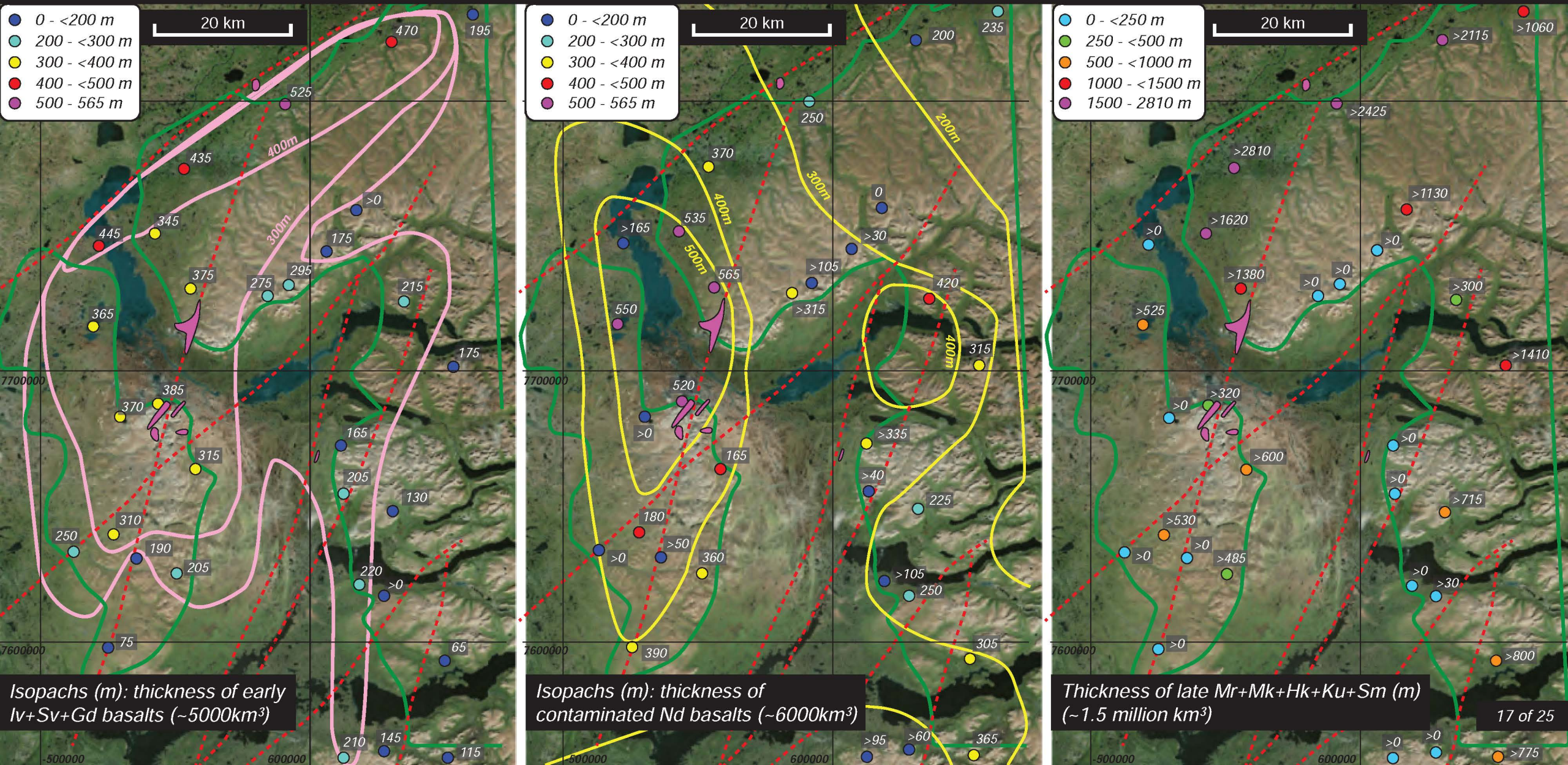
Duration of Siberian Trap magmatic event in the Noril'sk Region



Modified after Latyshev et al 2020

Noril'sk Region: migration of volcanic centers through time

EARLY TO LATE BASALTS



Isopachs (m): thickness of early Iv+Sv+Gd basalts (~5000km³)

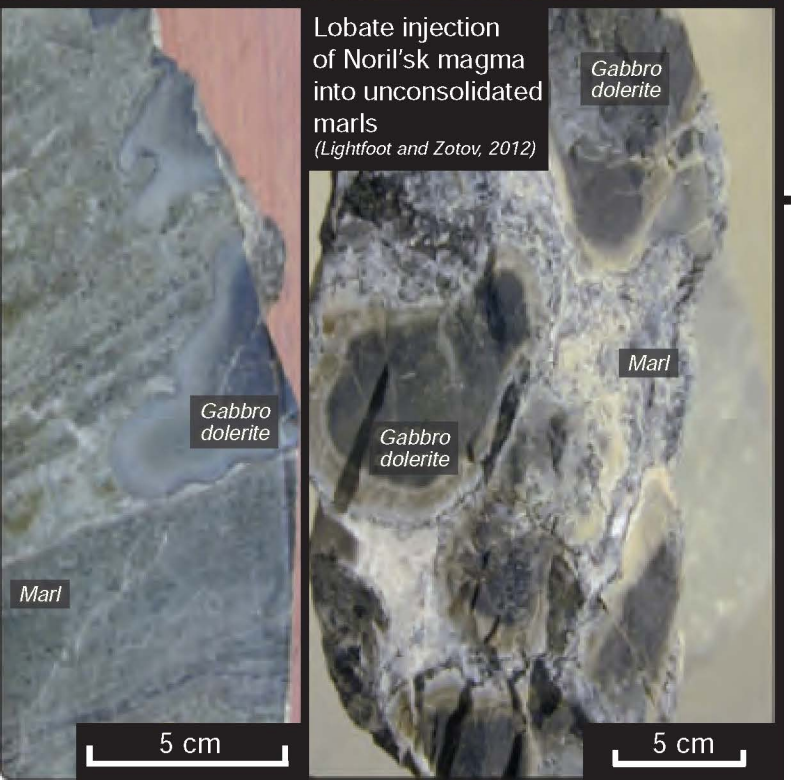
Isopachs (m): thickness of contaminated Nd basalts (~6000km³)

Thickness of late Mr+Mk+Hk+Ku+Sm (m) (~1.5 million km³)

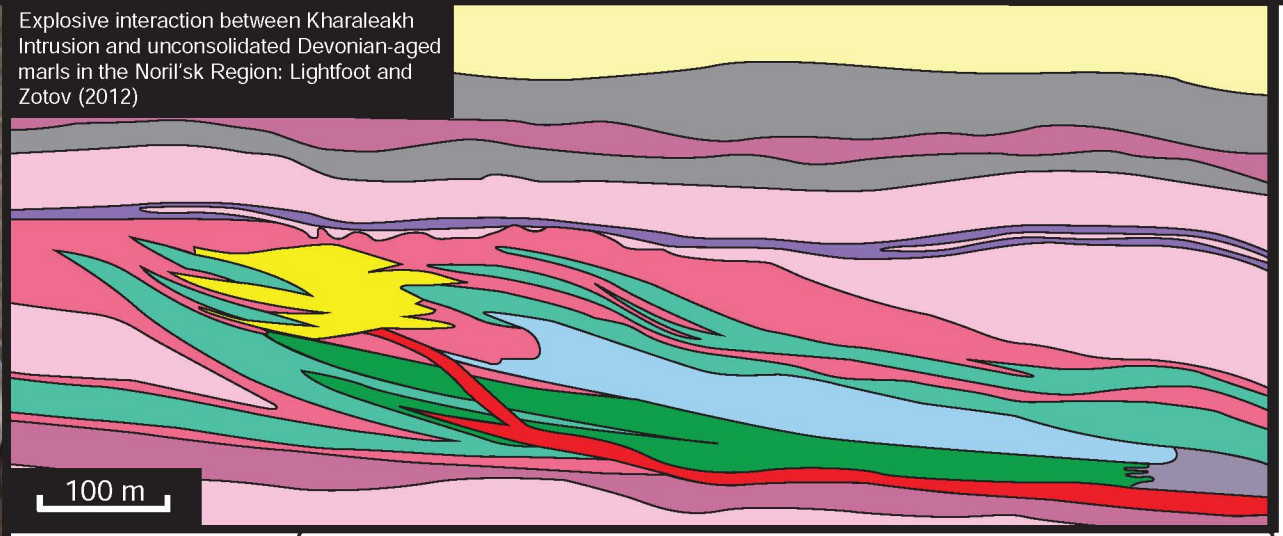
Explosive interaction between sills and unconsolidated sedimentary rock

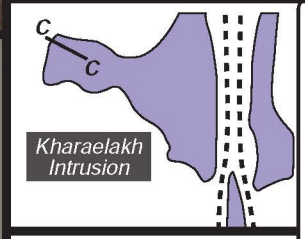
Talnakh: footwall breccia Lightfoot and Zotov (2012)

Lobate injection of Noril'sk magma into unconsolidated marls
(Lightfoot and Zotov, 2012)

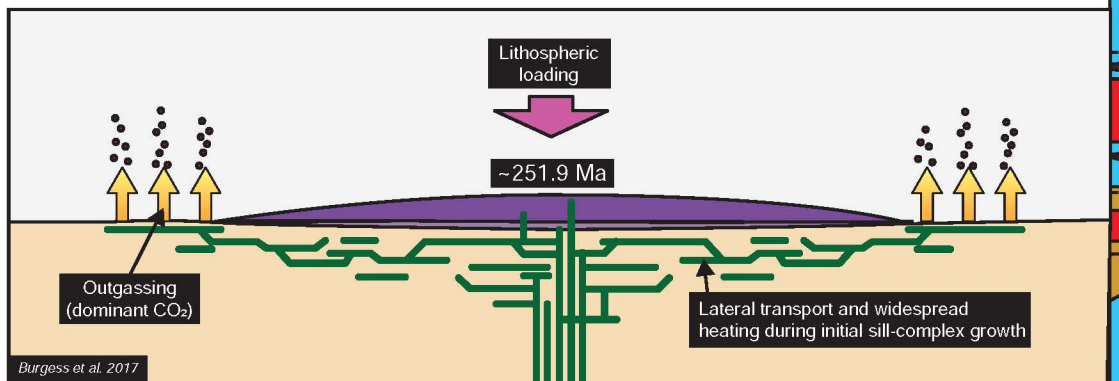


Explosive interaction between Kharaleakh Intrusion and unconsolidated Devonian-aged marls in the Noril'sk Region: Lightfoot and Zotov (2012)

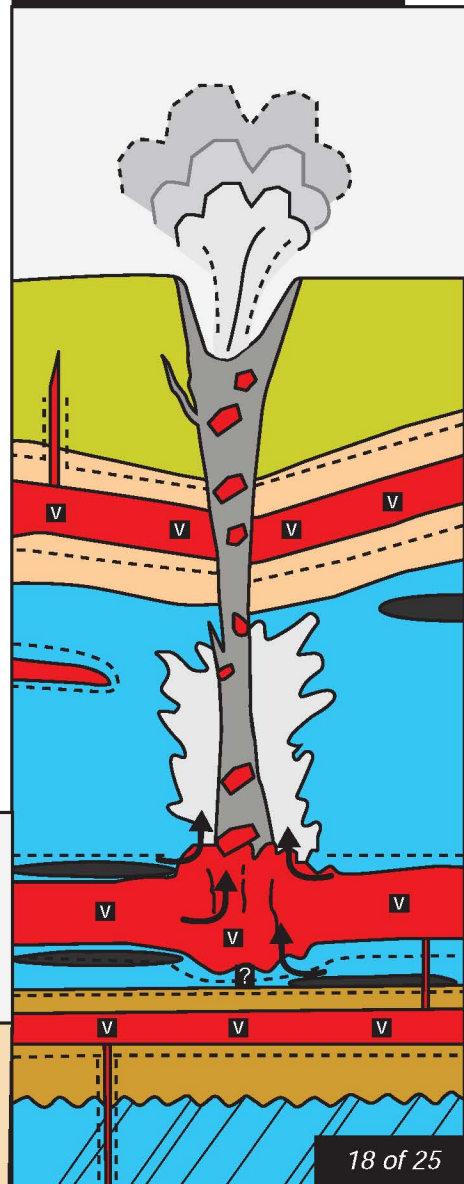




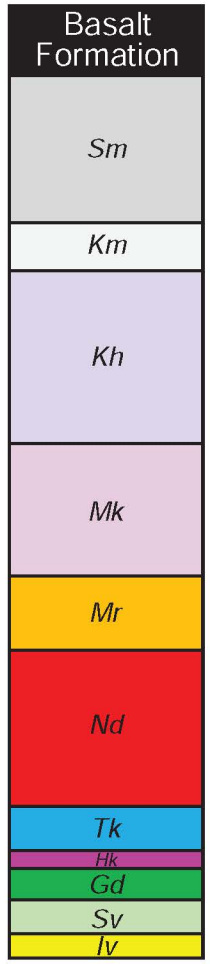
- Sandstone
- Dolomite and limestone
- Dolomite, anhydrite, and mari
- Argillite and marl
- Ti-augite dolerite
- Massive contact sulfide
- Cuprous breccia sulfide
- Olivine-free and olivine-bearing gabbrodolerite
- Troctolite
- Disseminated sulfide in taxitic gabbrodolerite
- Disseminated sulfide in picritic gabbrodolerite
- Pyroxene-garnet and pyroxene hornfels with calcite and anhydrite inclusions



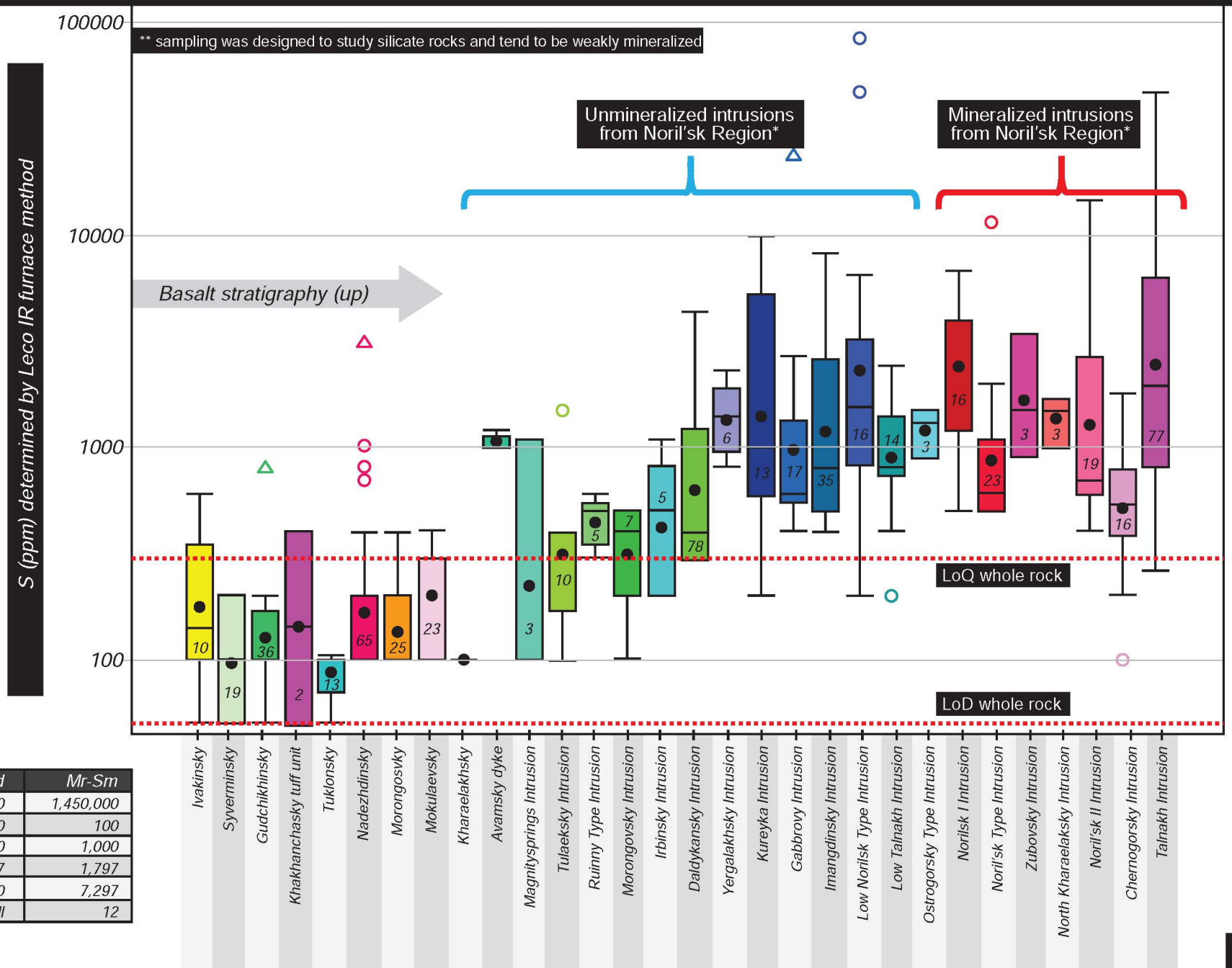
Explosive interaction between sills and unconsolidated Cambrian-aged sediments in the Tunguska Basin: Svensen et al (2009)



Siberian Trap basalts: sulfur budget



See Svensen et al. (2009) and Fristad et al. (2017) for sediment-sourced volatiles linked to sub-volcanic intrusions

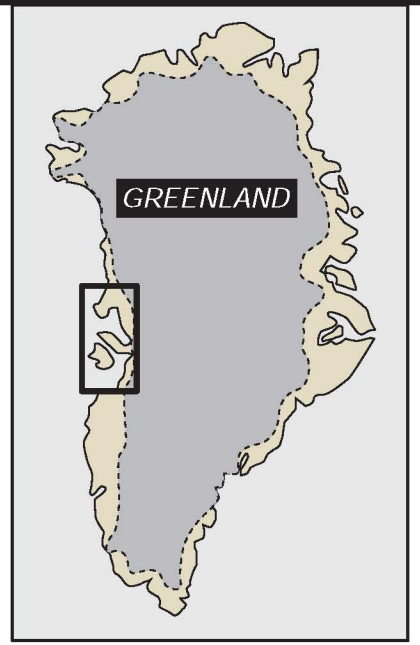


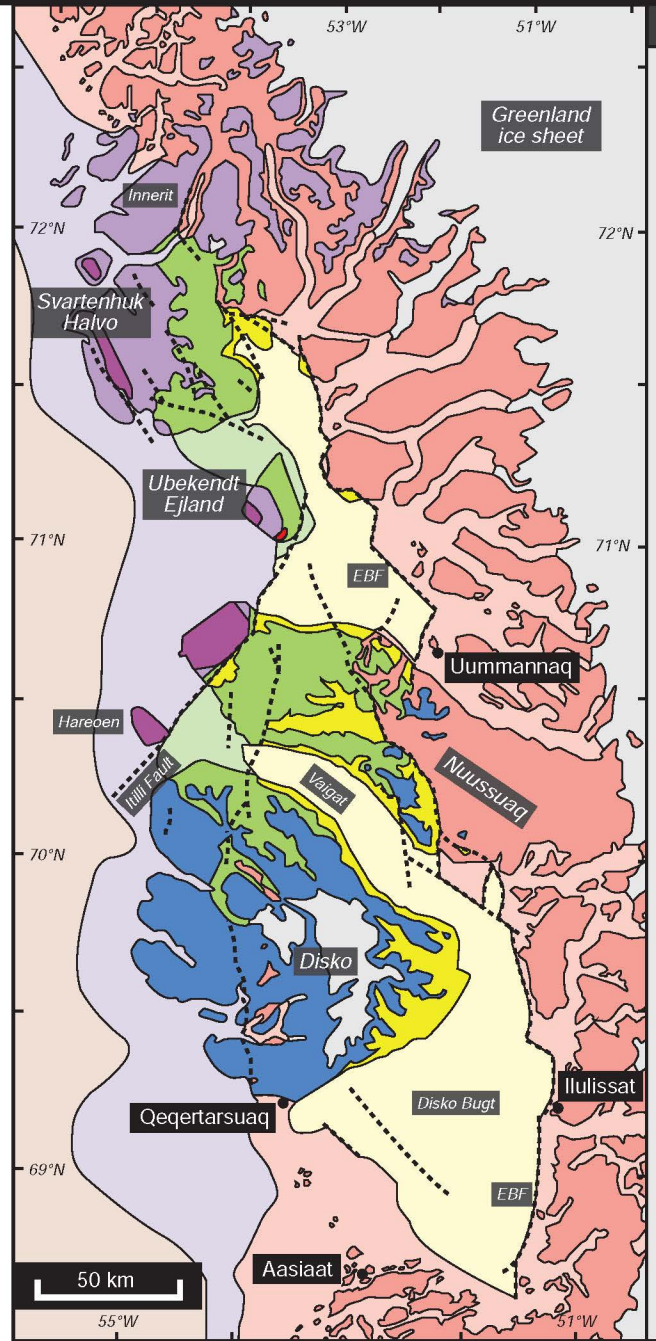
Mass balance

Formation		Iv-Sv-Gd	Tk	Nd	Mr-Sm
Volume estim	km³	5,500	5,000	6,000	1,450,000
S in basalt	ppm	100	100	100	100
S in intrusion	ppm	1,000	1,000	1,000	1,000
SO_2 lost	ppm	1,797	1,797	1,797	1,797
Mass SO_2	Bmt	28	25	30	7,297
Mass SO_2	pa* (Mmt)	small	small	small	12

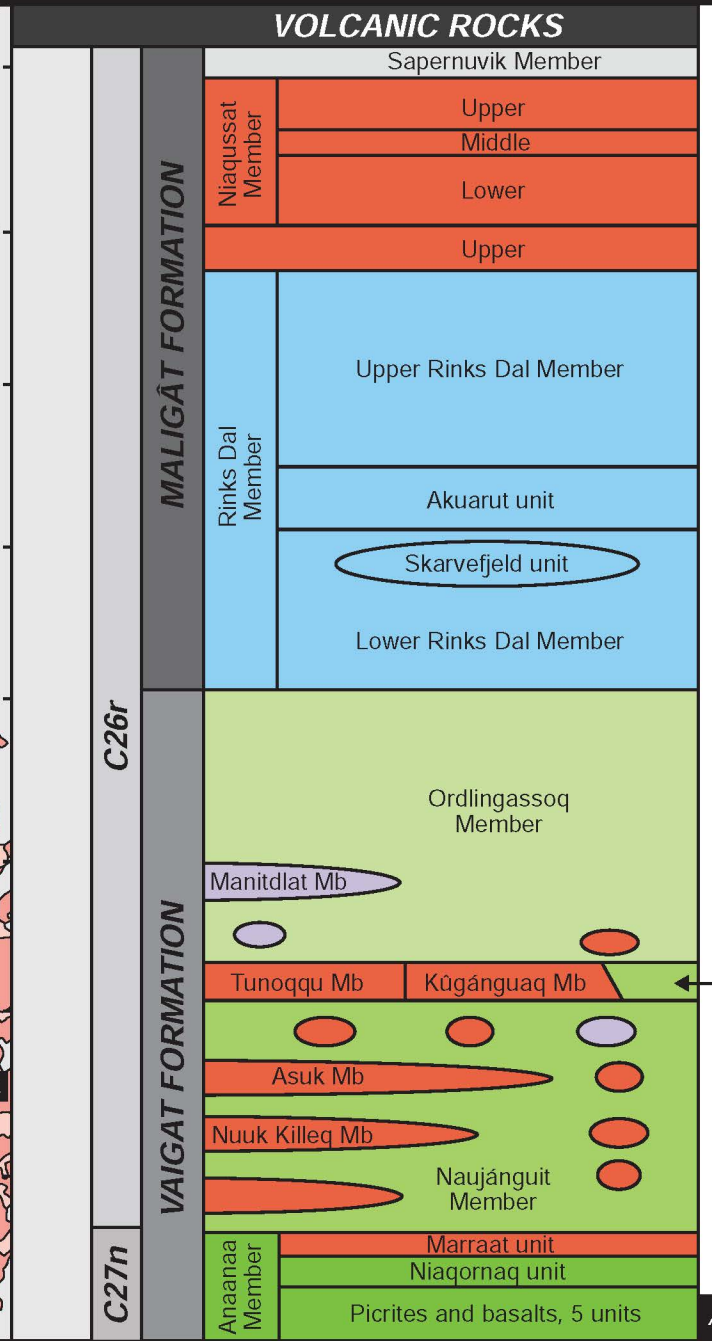
+ 600,000 year duration of Mr-Sm

West Greenland Flood Basalt Province





- Neogene sedimentary rock
- Offshore basalts
- Naqerloq Formation
- Svartenhuk Formation
- Maligât Formation
- Vaigat Formation
- Paleocene-Campanian
- Sedimentary rock
- Precambrian basement
- Fault

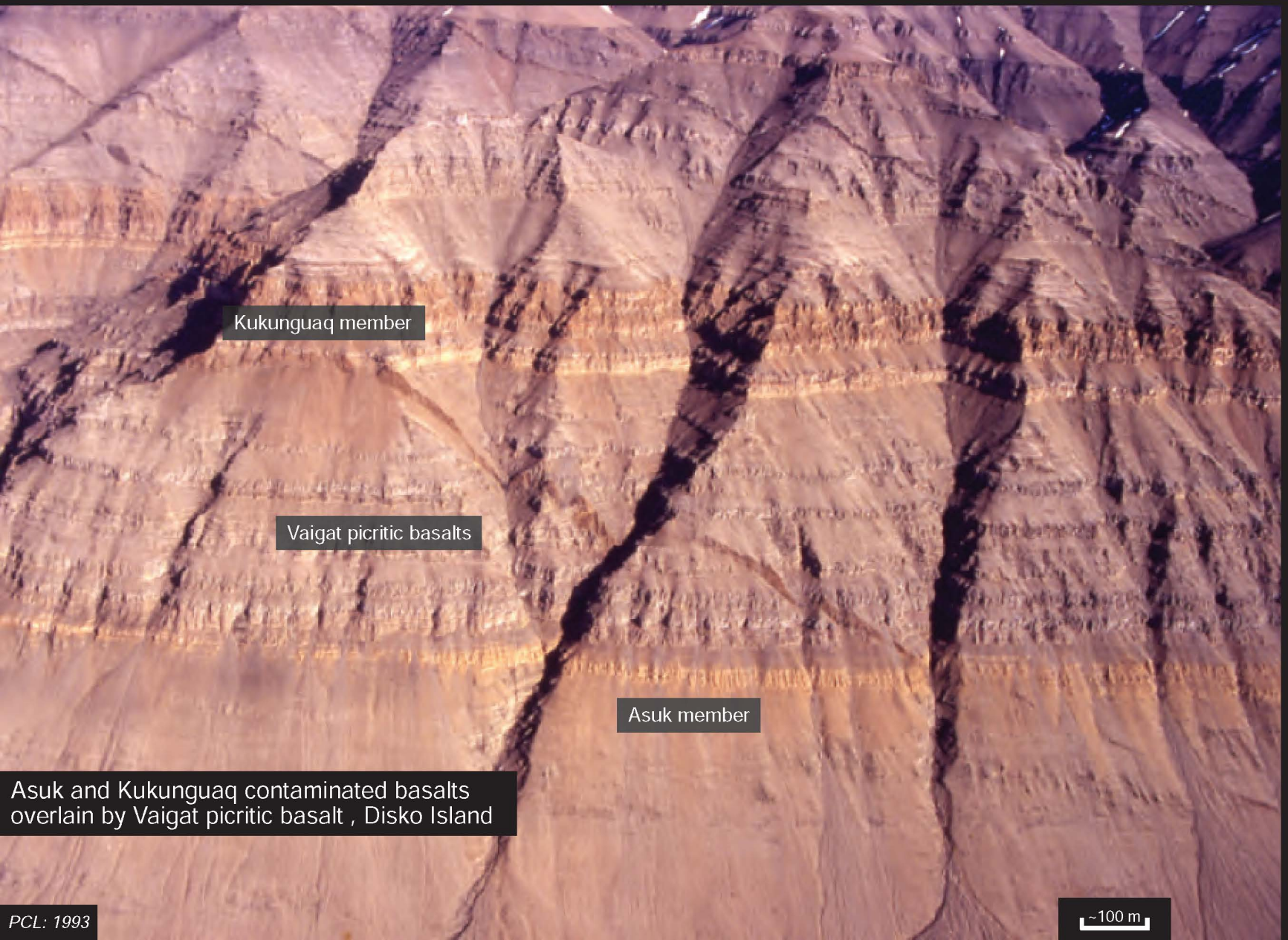


Disko Island basalt stratigraphy

- Tholeiitic basalts
- Contaminated basalt
- Picritic basalts

After Pedersen et al., 2018

Stratigraphy of volcanic rocks: easy to pick out contaminated basalt units in picritic basalts on Disko Island



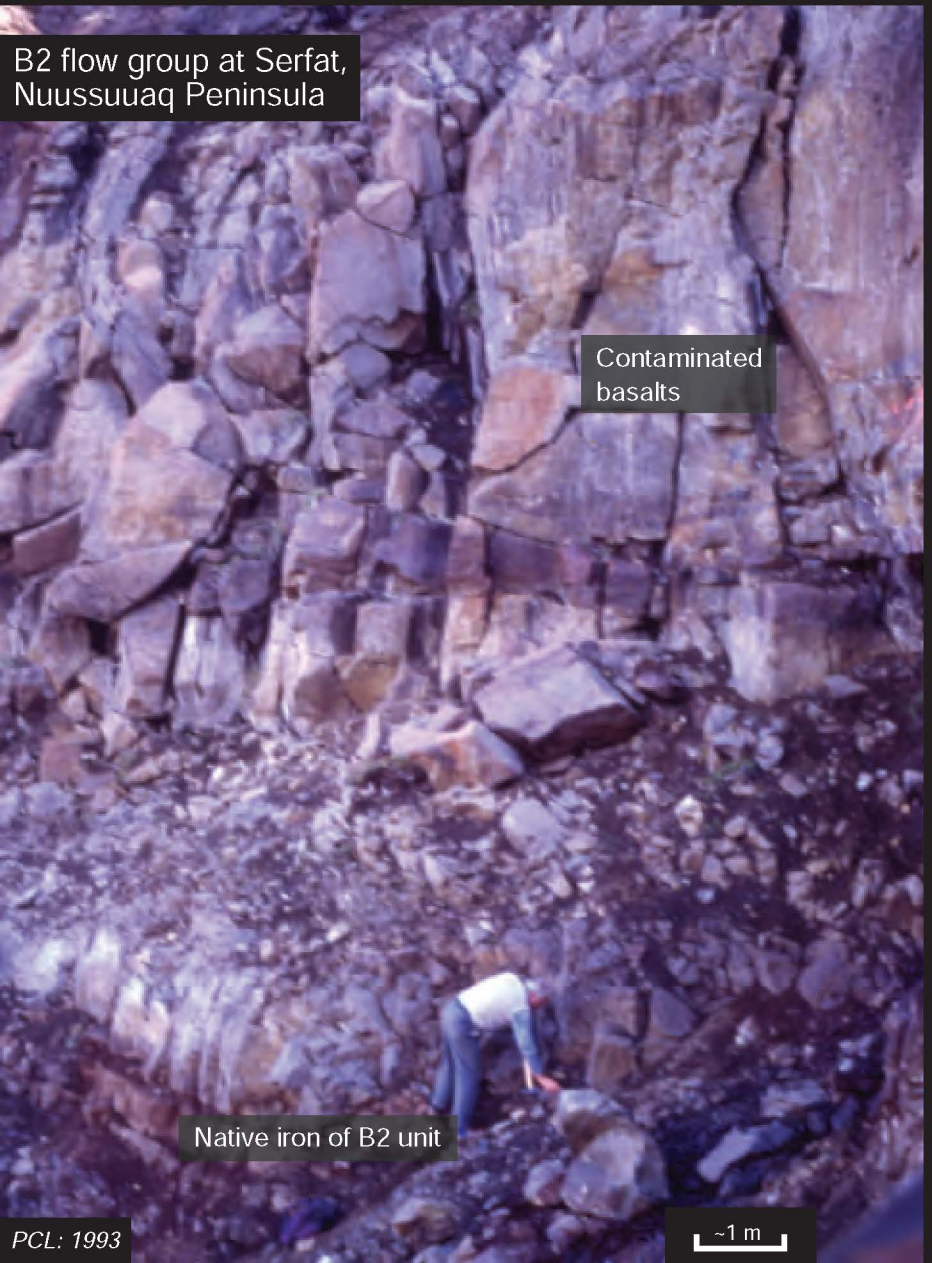
Asuk and Kukunguaq contaminated basalts overlain by Vaigat picritic basalt , Disko Island

PCL: 1993

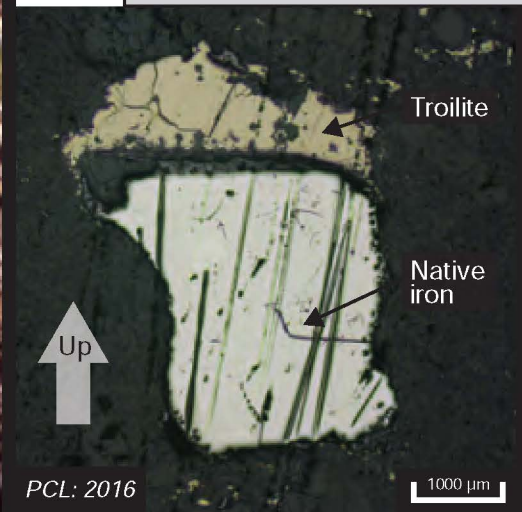
Maligât Formation tholeiitic basalts, Disko Island

PCL: 1993

Native iron occurrences commonly associated with contaminated basalt units; vesicles are often bituminous

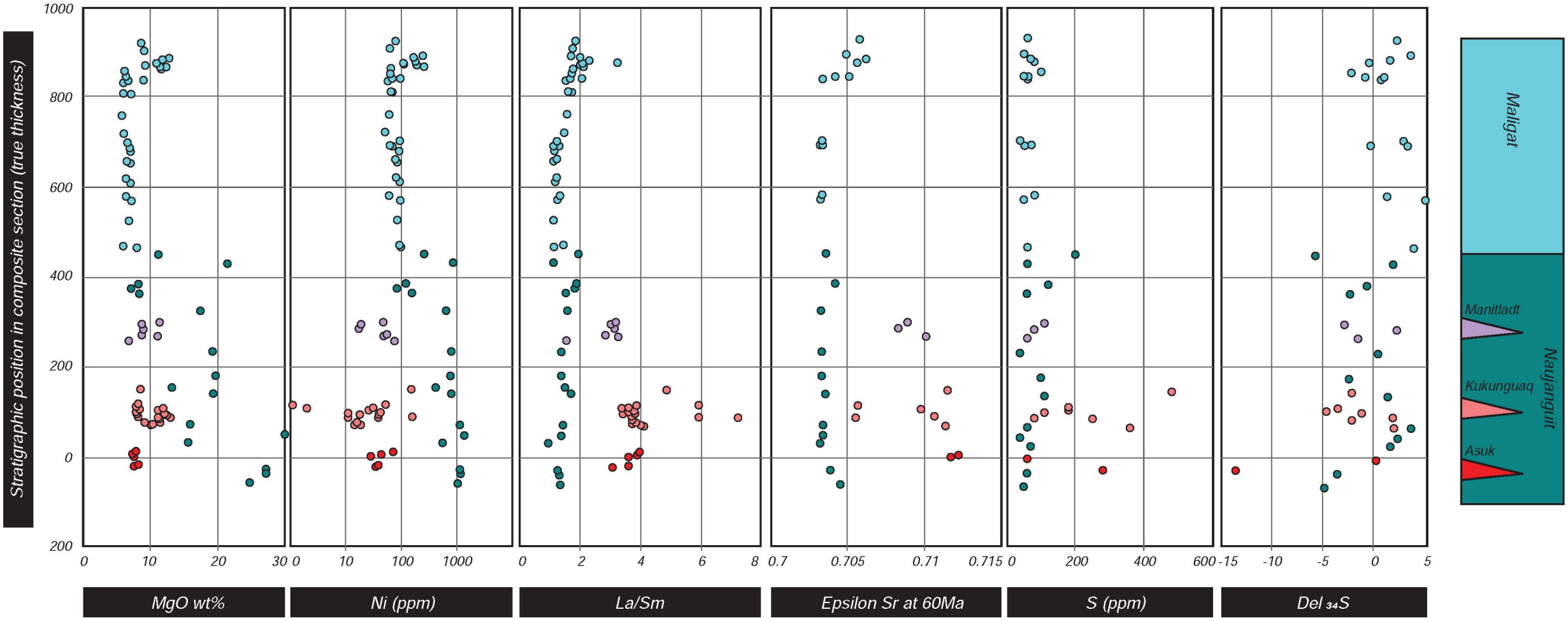


Locality	Stordal	Uiffaq
Year of find	1985	1870
Weight, tons	10	25
Estimated mode, vol. %		
Iron	60	43
Cohenite $(Fe, Ni, Co)_3C$	7	54
Troilite	30-40	3
Schreibersite $(Fe,Ni)_3P$	0	Trace
Silicate glass	0.1	0
Chromite	0.01	0
Wüstite: FeO	Trace	?
Calculated chemical composition, wt%		
Fe	80	91.6
Co	0.4	0.5
Ni	2	1.8
Cu	0.1	0.16
C	0.5	3.62
P	0.4	0.15
S	10-15	1.09
O	Trace	0.97



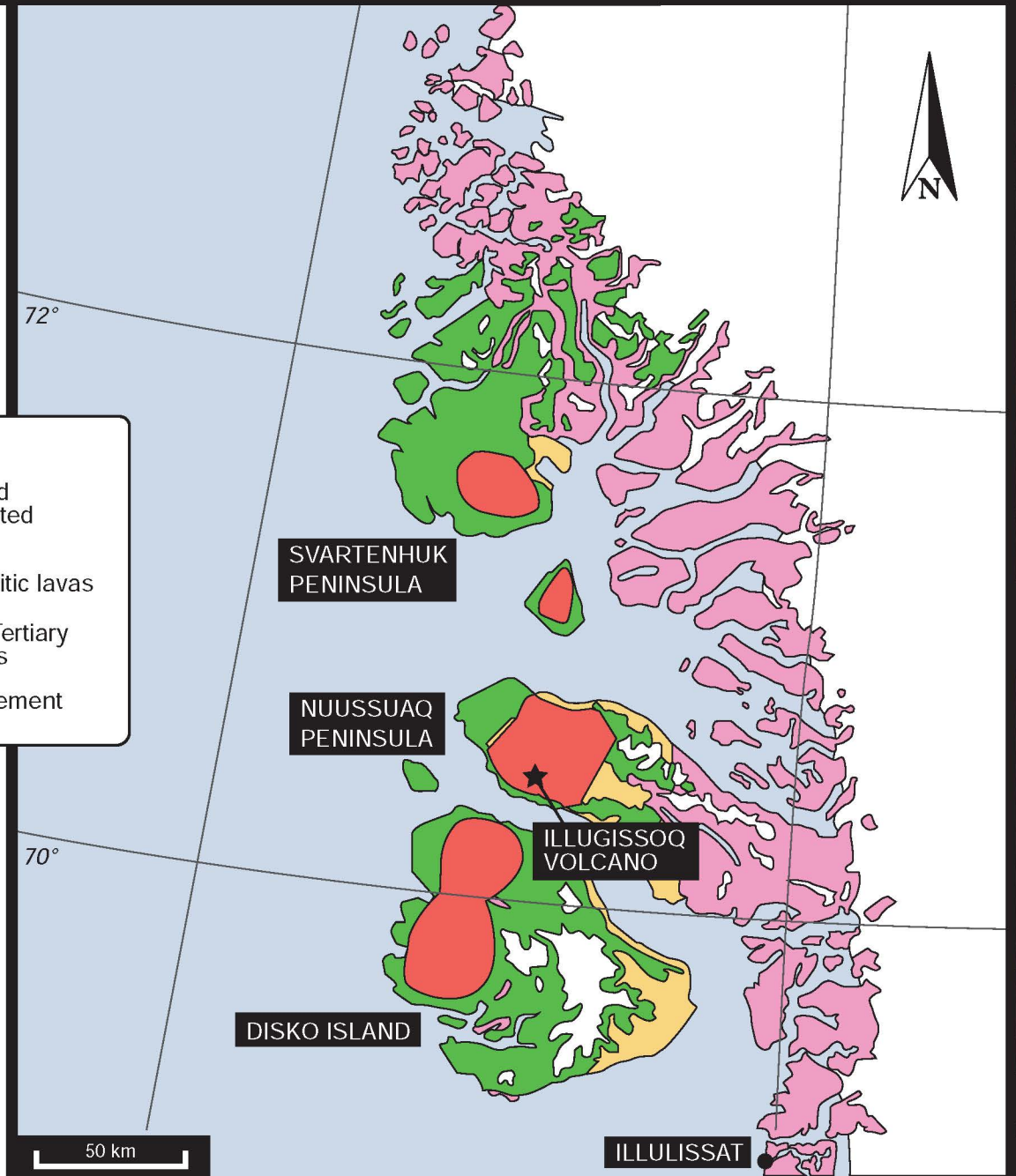
Native iron-troilite bleb with geopetal structures, contaminated vesicular tholeiite of B2 unit, Nuussuaq Peninsula

Chemostratigraphy: composite sections on Disko Island



Data sources:
Lightfoot et al. (1997)
Lightfoot and Hawkesworth (1997)
Grinenko et al. (1996)

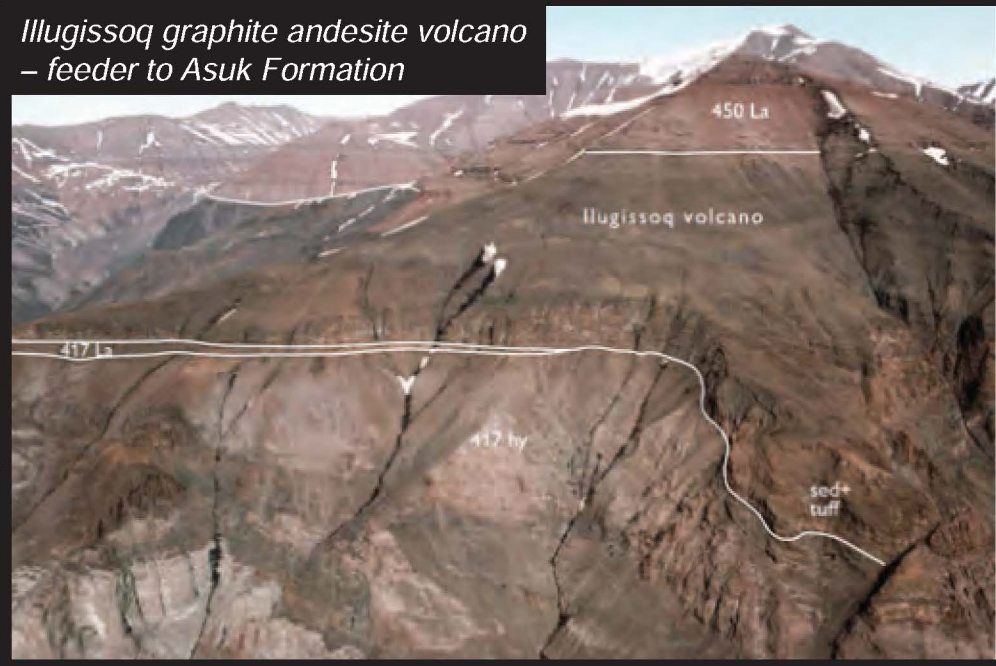
Scale of Tertiary volcanic centers in West Greenland



- Ice cap
- Contaminated and Ni-Cu-PGE-depleted volcanic centers
- Tholeiitic and picritic lavas
- Cretaceous and Tertiary sedimentary rocks
- Precambrian basement

Keays and Lightfoot, 2006

Illugissoq graphite andesite volcano – feeder to Asuk Formation

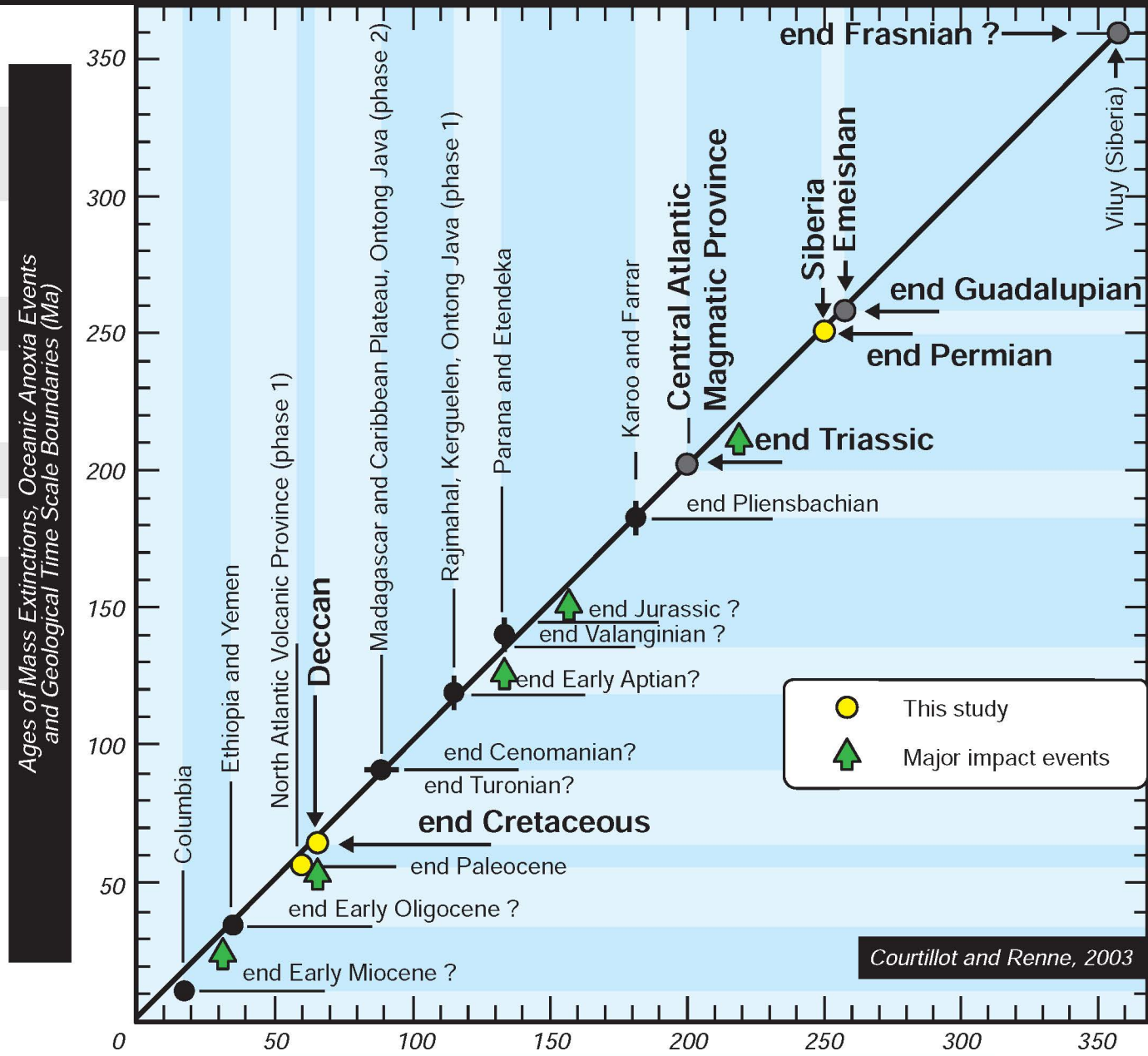


Vesicle filled with bitumen from Asuk Formation

Pedersen et al. 2017

Summary

- Chemostratigraphy records compositional diversity through time for more than just mantle and deep crustal processes
- Correlation of volcanic packages help to map migration of depocenters
- Duration and rate of change of magmatism can be mapped
- Degassing of magmas and sulfur budget for lavas – higher quality data required
- CFB atmospheric SO_2 models are not catastrophic
- Impact enhanced volcanism possible, but not required
- Magmatism through unconsolidated S-rich sedimentary rocks may influence SO_2 budget *(as well as magmatic sulfide ore deposits)*



Thank you to those who influenced my research on flood basalts

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Tony Green
Chris Hawkesworth
Reid Keays
Rogerio Monteiro
Tony Naldrett
Ashok Rao
Ed Ripley
Sam Sethna
Igor Zotov

Western

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Graphic Design: Alex J. Gagnon www.alexjgagnon.ca

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