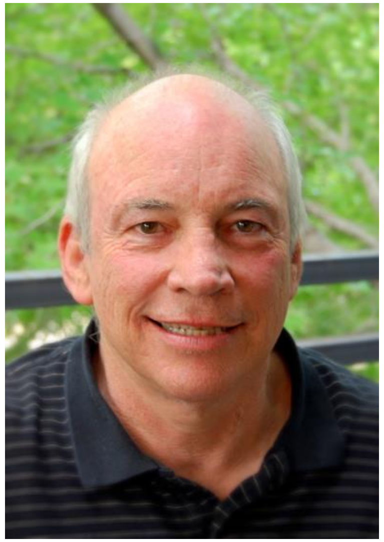
The Geodynamic Evolution of Iran

Robert J Stern (UT Dallas, USA)
Hadi Shafaii Moghadam (Damghan U, Iran)
Hossein Azizi (Kurdistan U, Iran)
Mortaza Pirouz (UTD, USA)
Walter Mooney (USGS, USA)



Stern

Moghadam

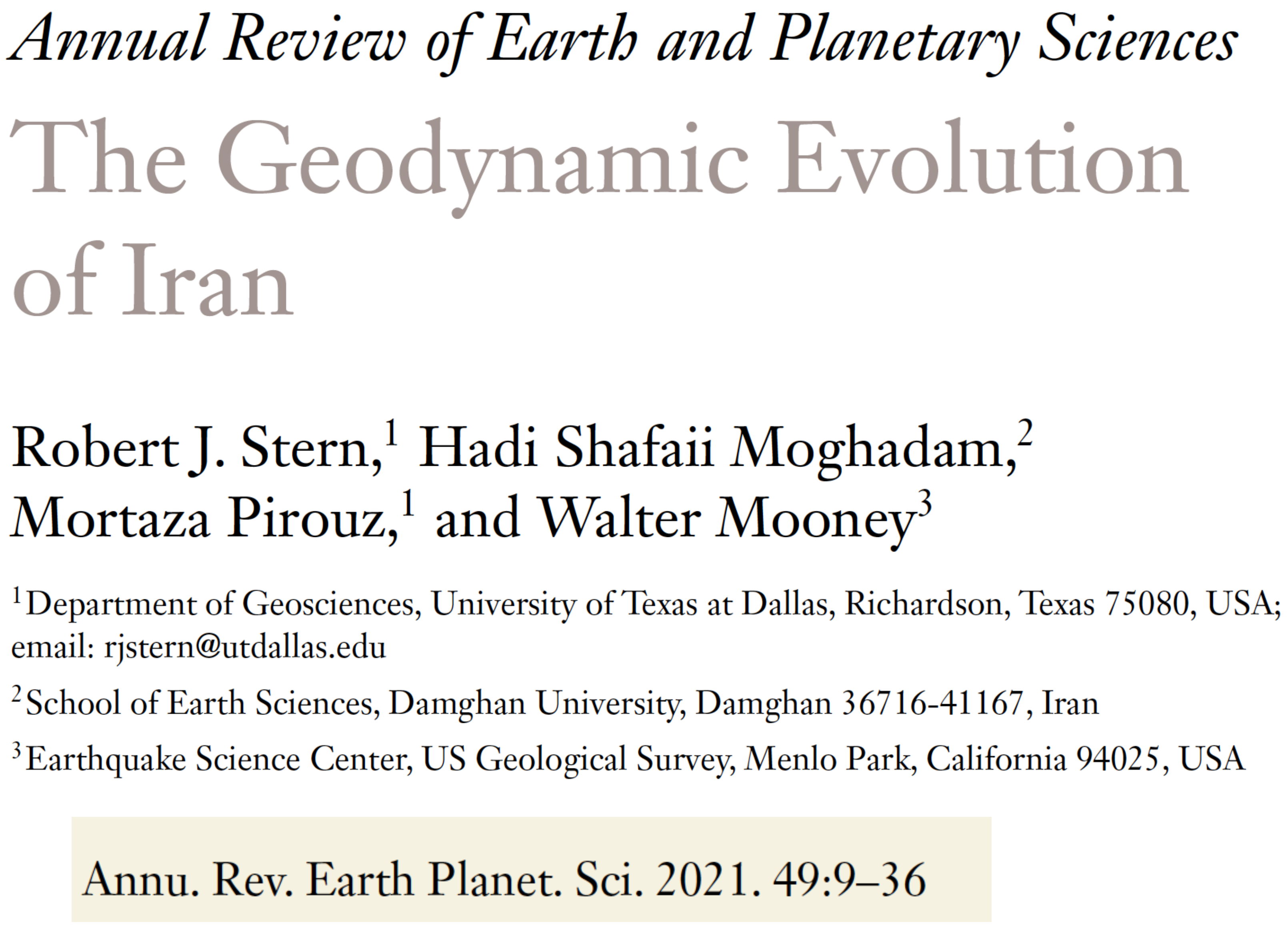
Azizi

Pirouz

Mooney

Iran is a Natural Geoscience Laboratory

- Study Cadomian rocks to understand how new continental crust forms
- Study Jurassic Sanandaj-Sirjan Zone rocks to understand the formation of continental rifts and volcanic passive margins
- Study Late Cretaceous ophiolites to understand how new subduction zones form
- Study Paleogene igneous rocks and associated sediments to understand extensional continental arcs
- Study Neogene igneous and sedimentary rocks and Zagros structure to understand early stages of continental collision



Annual Review of Earth and Planetary Sciences

The Geodynamic Evolution of Iran

Robert J. Stern,[1] Hadi Shafaii Moghadam,[2]
Mortaza Pirouz,[1] and Walter Mooney[3]

[1] Department of Geosciences, University of Texas at Dallas, Richardson, Texas 75080, USA;
email: rjstern@utdallas.edu

[2] School of Earth Sciences, Damghan University, Damghan 36716-41167, Iran

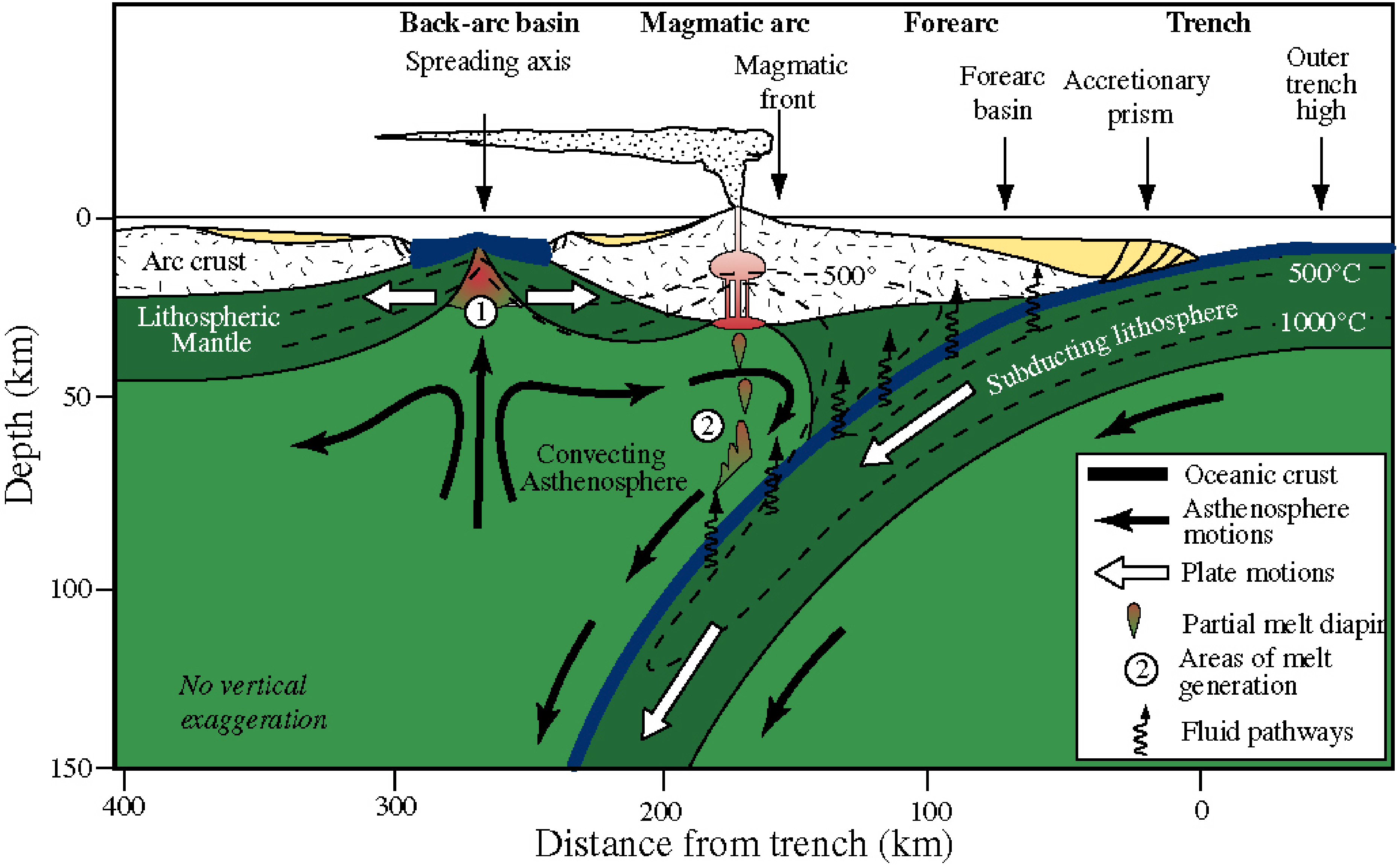
[3] Earthquake Science Center, US Geological Survey, Menlo Park, California 94025, USA

Annu. Rev. Earth Planet. Sci. 2021. 49:9–36

Can download from “robert j. stern phd publications”

Iran is a large country (~1.65 million km^2), more than 4 times the size of Japan, about 2.5 times the size of France, and more than twice the size of Texas.

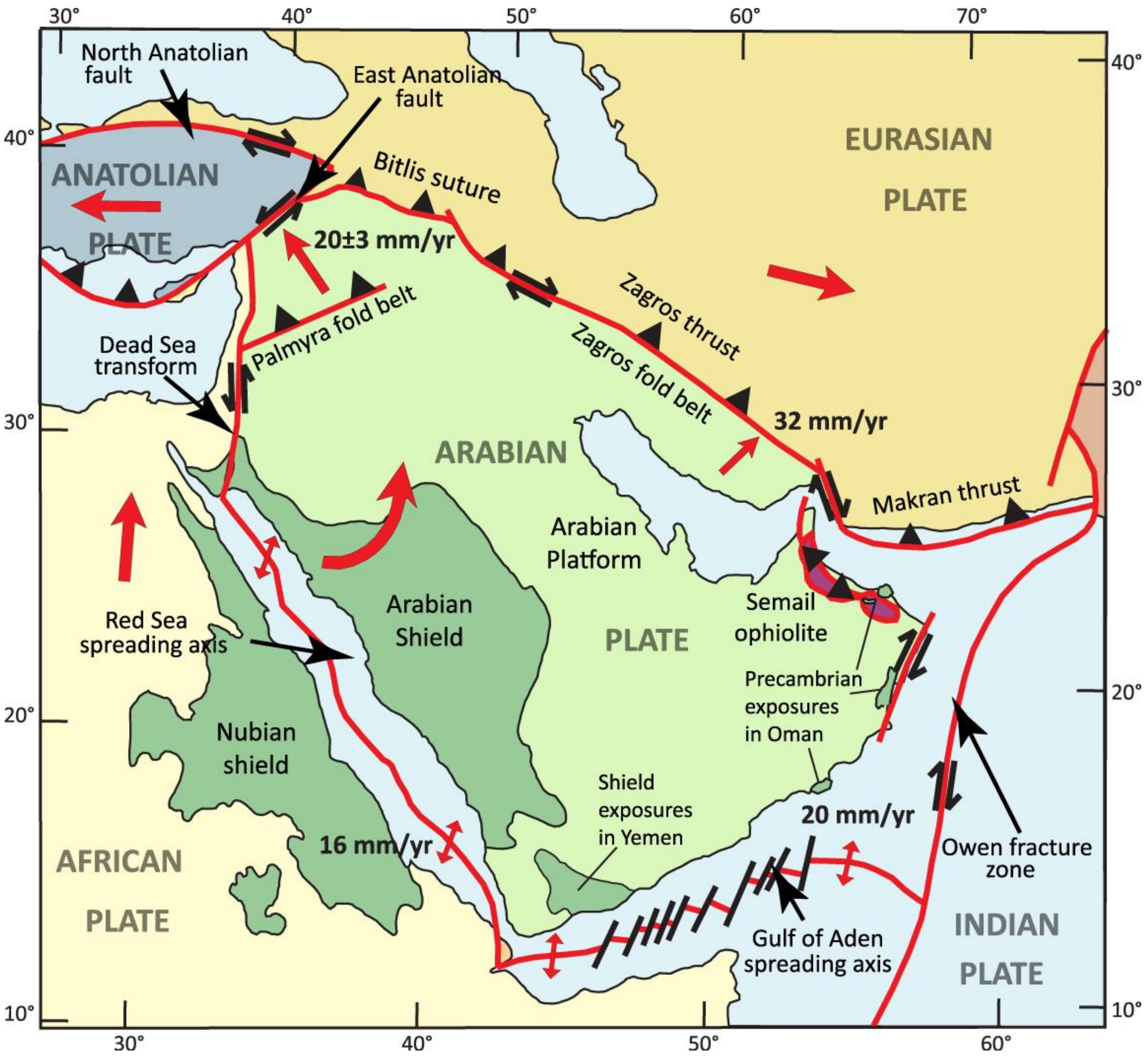
Today Iran lies on the upper plate of a convergent plate margin



Stern 2002

The Arabian plate was created by rifting from NE Africa ~25 Ma to form Red Sea

Red Sea rifting happened about the same time that Arabia-Iran collision began!



GPS shows convergence of Arabian plate with Eurasian plate

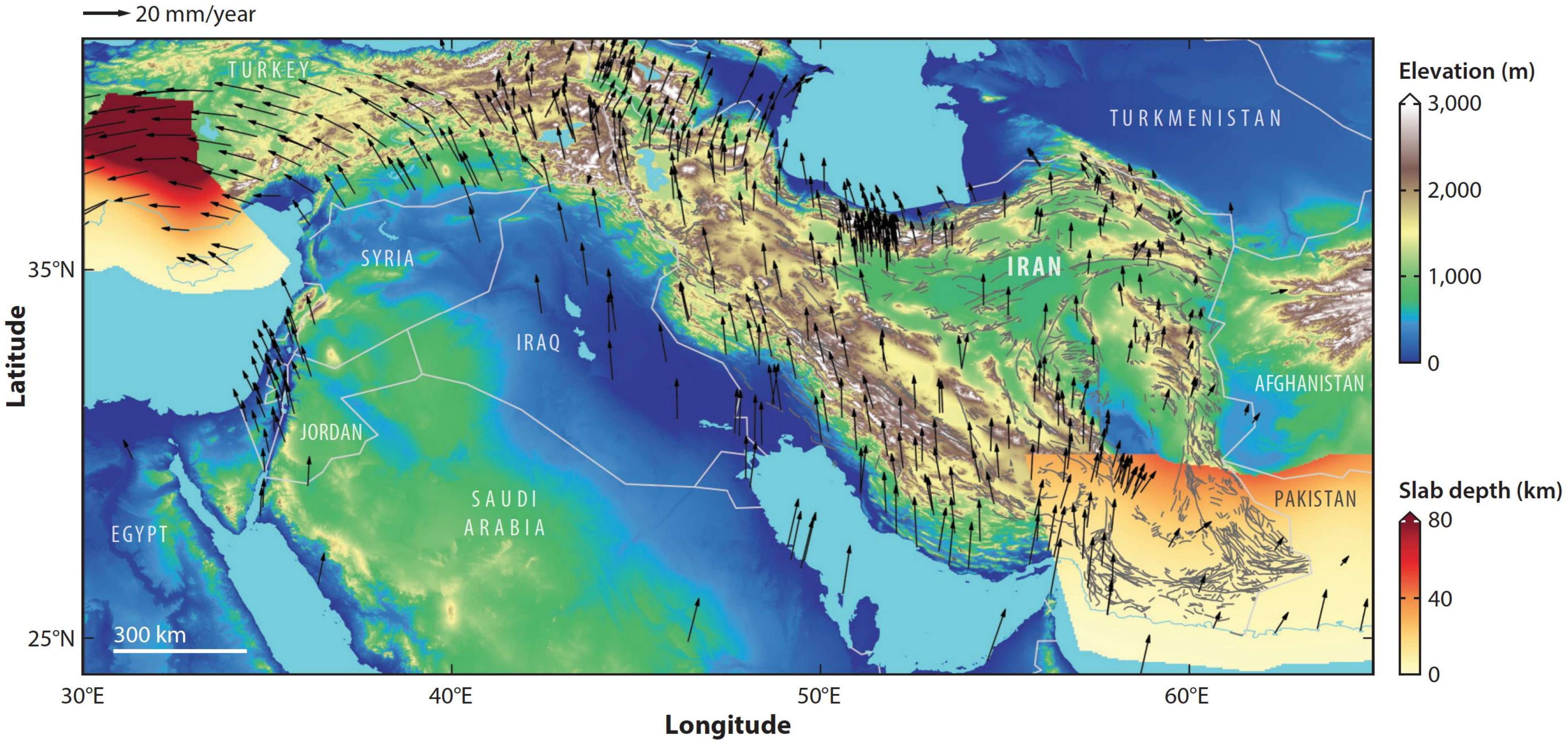
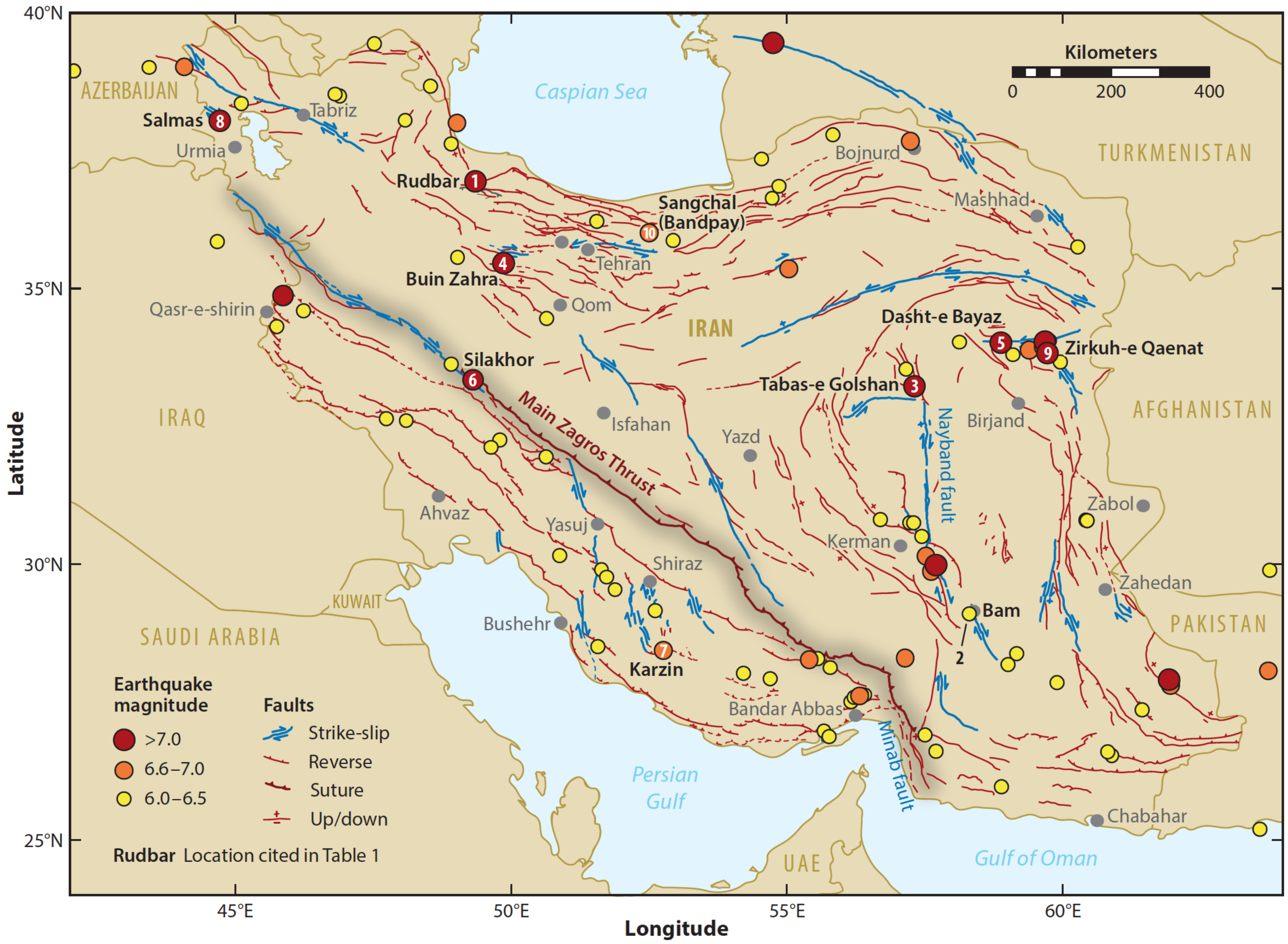


Figure 3

Neotectonic setting of Iran showing deformation of Iran and surrounding regions. Note regions that are underlain by subducted lithosphere of the African plate in the west and Arabian plate in the east (*yellow-orange* regions) and the intervening ~2,500 km where no subducting slab is imaged. Arrows are GPS velocities determined for Africa, Arabia, and Iran with respect to Eurasia. GPS data from Khorrami et al. (2019) and Blewitt et al. (2018). Sites used to construct the Eurasia plate model from supplementary table S2 of Altamimi et al. (2017). Geometry of subducted slab from Hayes et al. (2018). Elevation data from Jarvis et al. (2008).



Convergence causes upper plate deformation, faulting, and earthquakes. Active fault map and 1900–2019 epicenters of large earthquakes (>6.0 magnitude) in Iran. Numbers correspond to the deadliest 10 earthquakes from 1909 to 2003

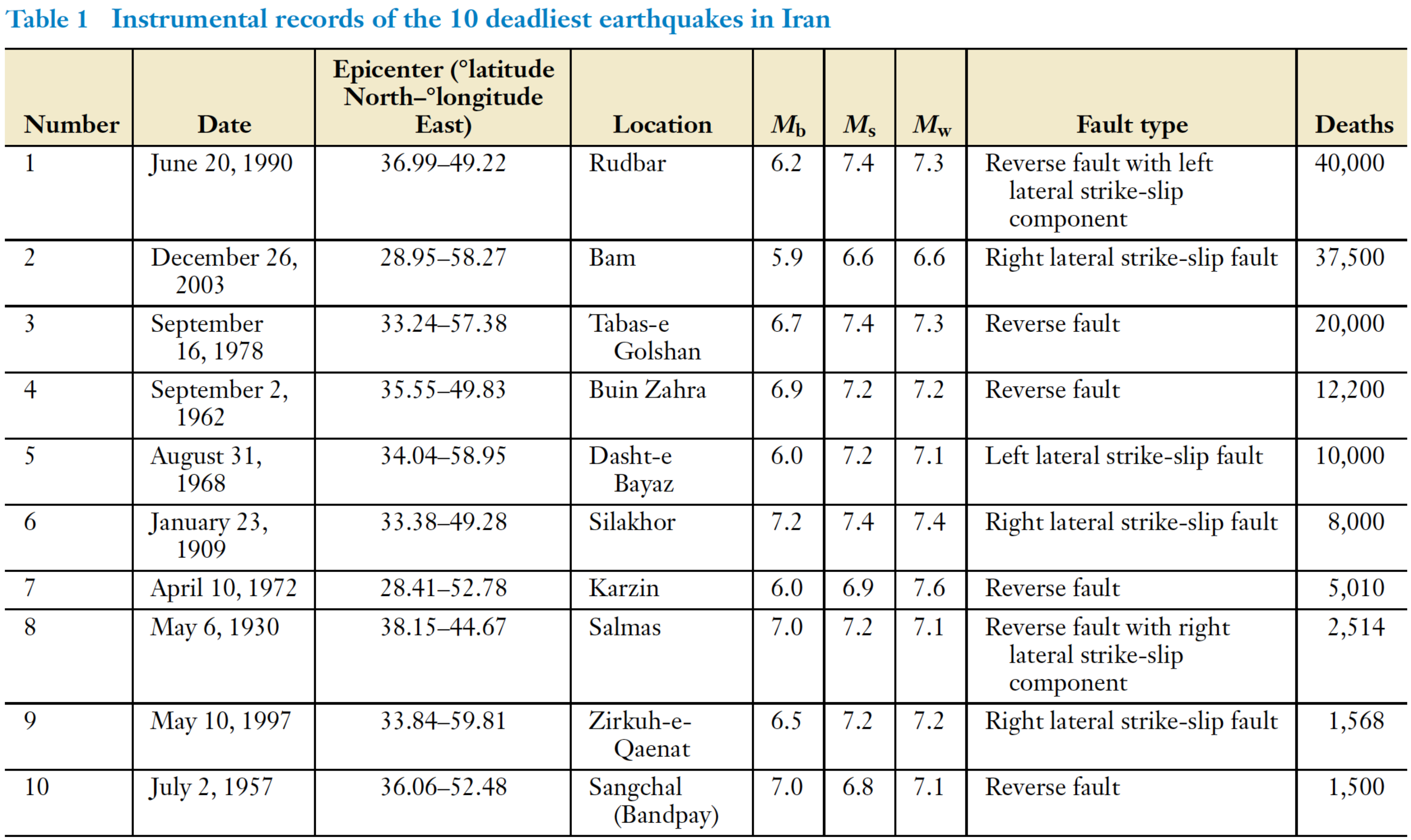
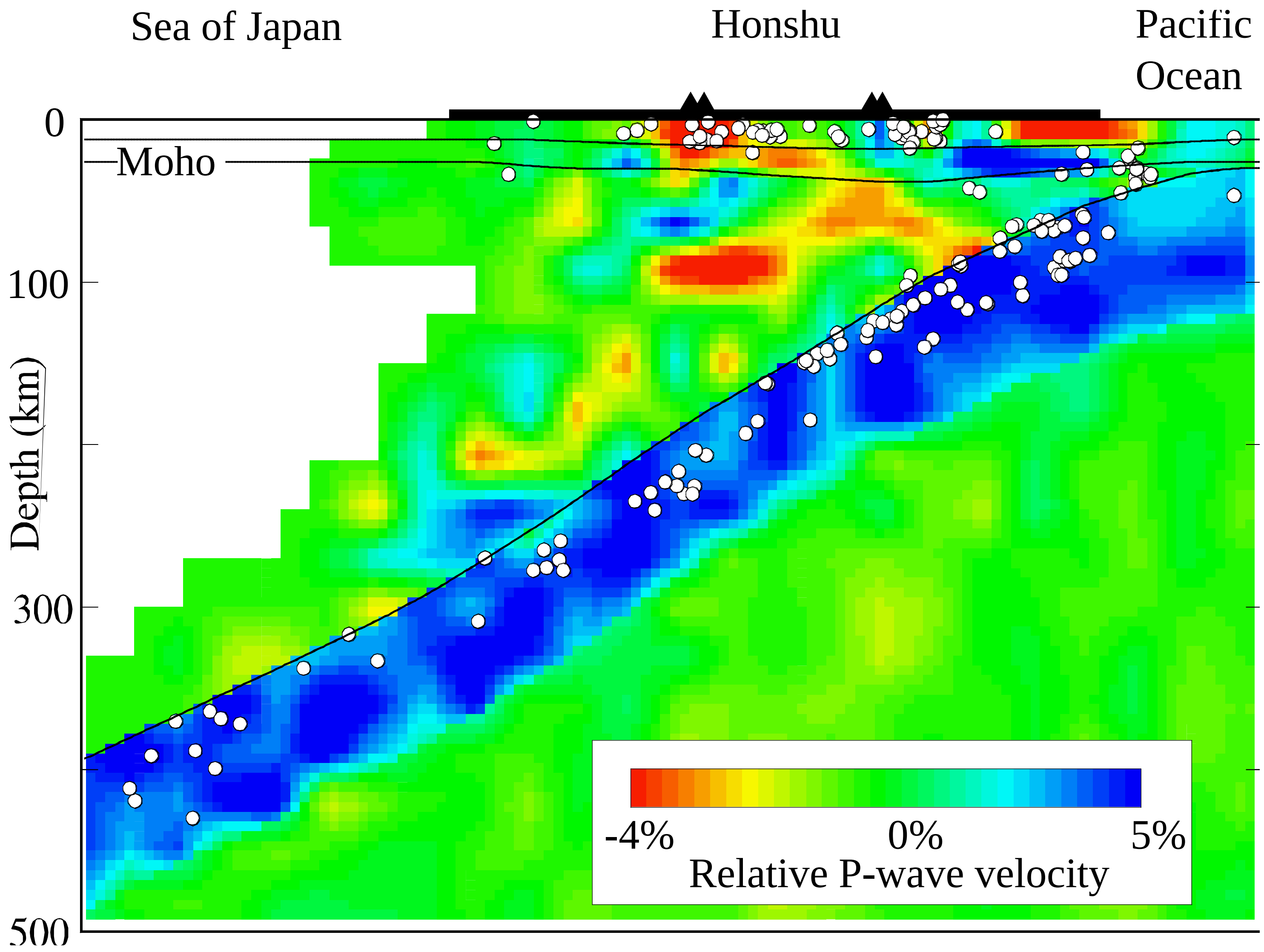


Table 1 Instrumental records of the 10 deadliest earthquakes in Iran

Number	Date	Epicenter (°latitude North–°longitude East)	Location	M_b	M_s	M_w	Fault type	Deaths
1	June 20, 1990	36.99–49.22	Rudbar	6.2	7.4	7.3	Reverse fault with left lateral strike-slip component	40,000
2	December 26, 2003	28.95–58.27	Bam	5.9	6.6	6.6	Right lateral strike-slip fault	37,500
3	September 16, 1978	33.24–57.38	Tabas-e Golshan	6.7	7.4	7.3	Reverse fault	20,000
4	September 2, 1962	35.55–49.83	Buin Zahra	6.9	7.2	7.2	Reverse fault	12,200
5	August 31, 1968	34.04–58.95	Dasht-e Bayaz	6.0	7.2	7.1	Left lateral strike-slip fault	10,000
6	January 23, 1909	33.38–49.28	Silakhor	7.2	7.4	7.4	Right lateral strike-slip fault	8,000
7	April 10, 1972	28.41–52.78	Karzin	6.0	6.9	7.6	Reverse fault	5,010
8	May 6, 1930	38.15–44.67	Salmas	7.0	7.2	7.1	Reverse fault with right lateral strike-slip component	2,514
9	May 10, 1997	33.84–59.81	Zirkuh-e-Qaenat	6.5	7.2	7.2	Right lateral strike-slip fault	1,568
10	July 2, 1957	36.06–52.48	Sangchal (Bandpay)	7.0	6.8	7.1	Reverse fault	1,500

Mb = body wave magnitude; Ms = surface wave magnitude; M_W = moment magnitude. Table modified from Berberian (2014).

Seismic tomography and earthquakes reveal a continuous subducted slab beneath most convergent plate margins but not beneath Iran!



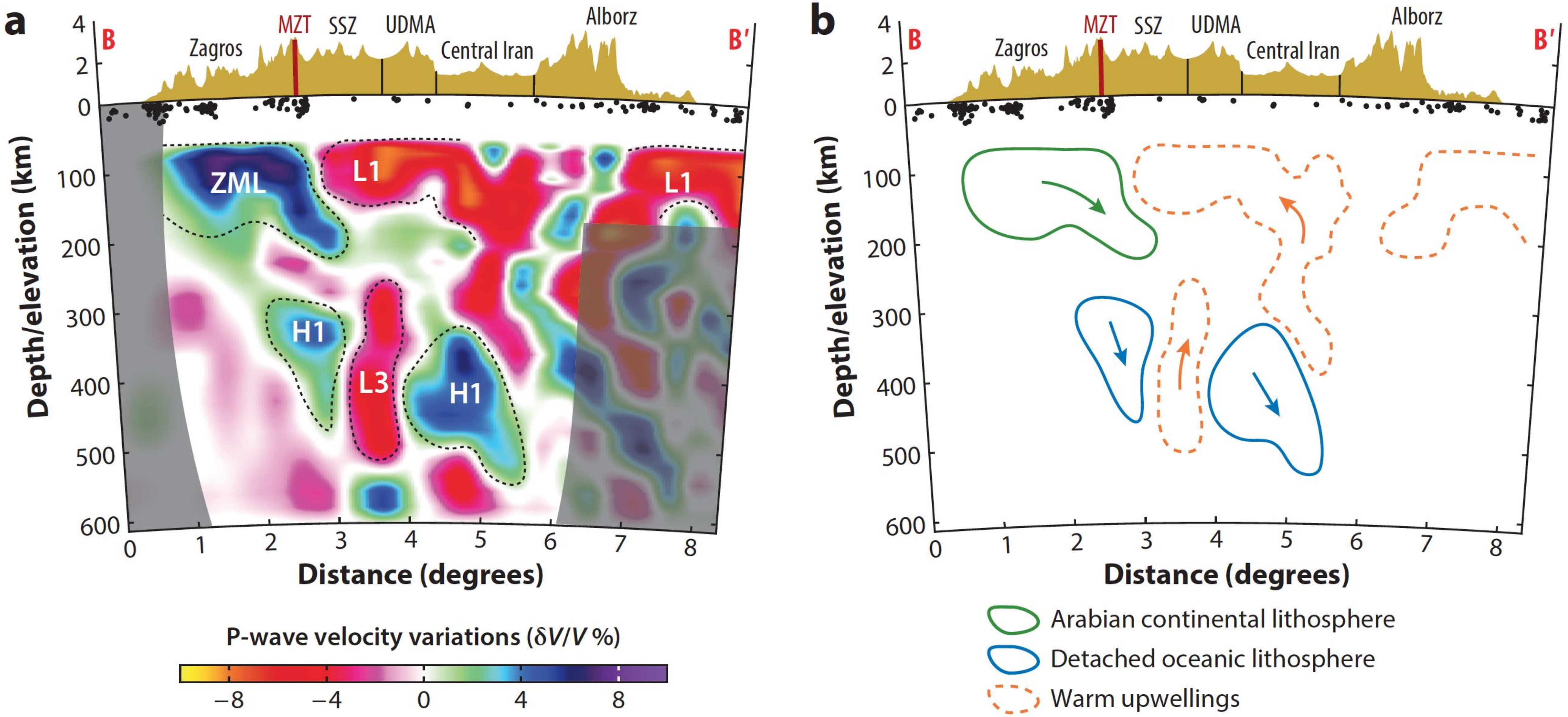
Blue areas have high Vp = **cold**

Red areas have low Vp = **hot**

Small circles show earthquakes

Zhao et al., 1994

What happened to the subducted slab beneath Iran?

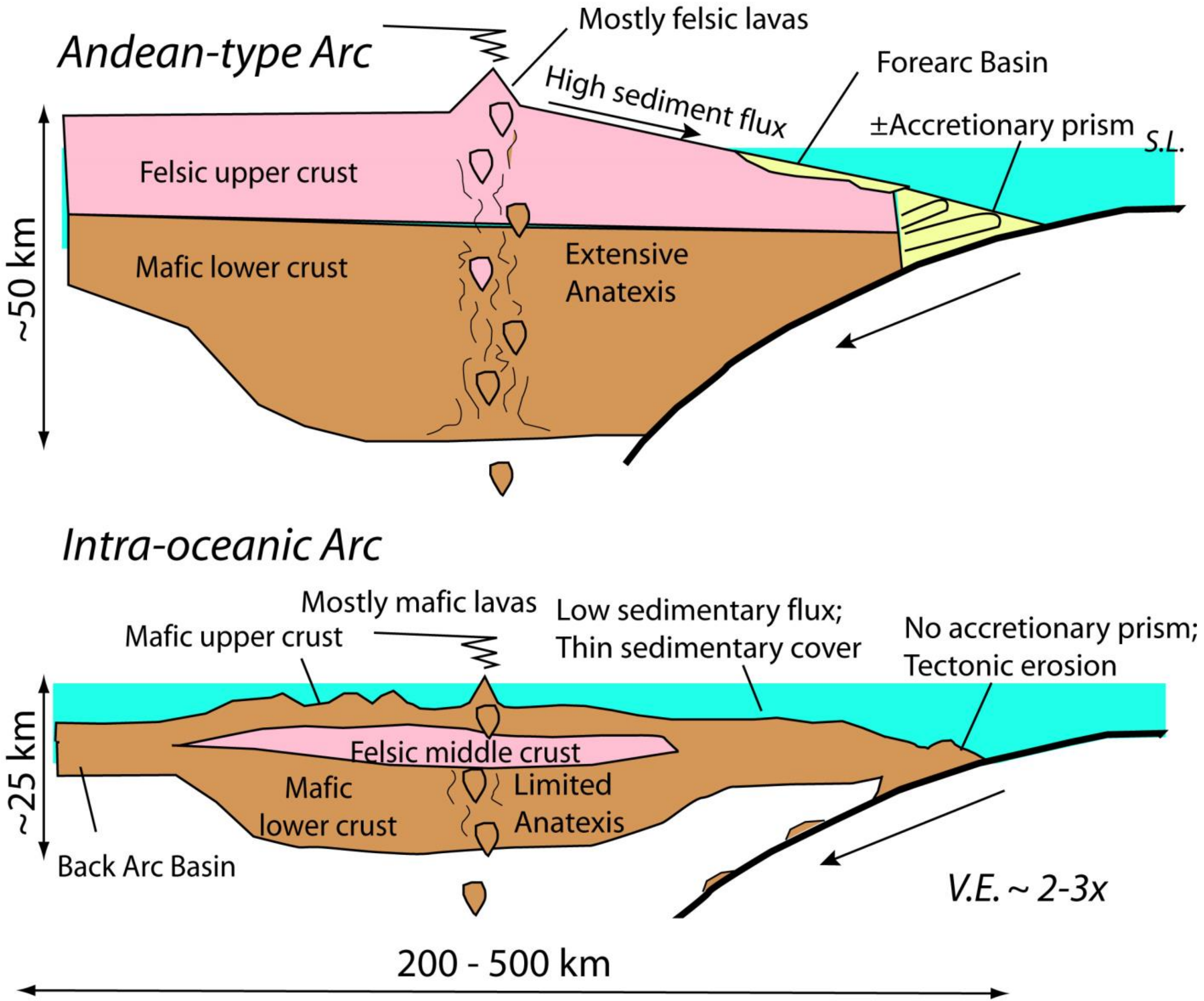


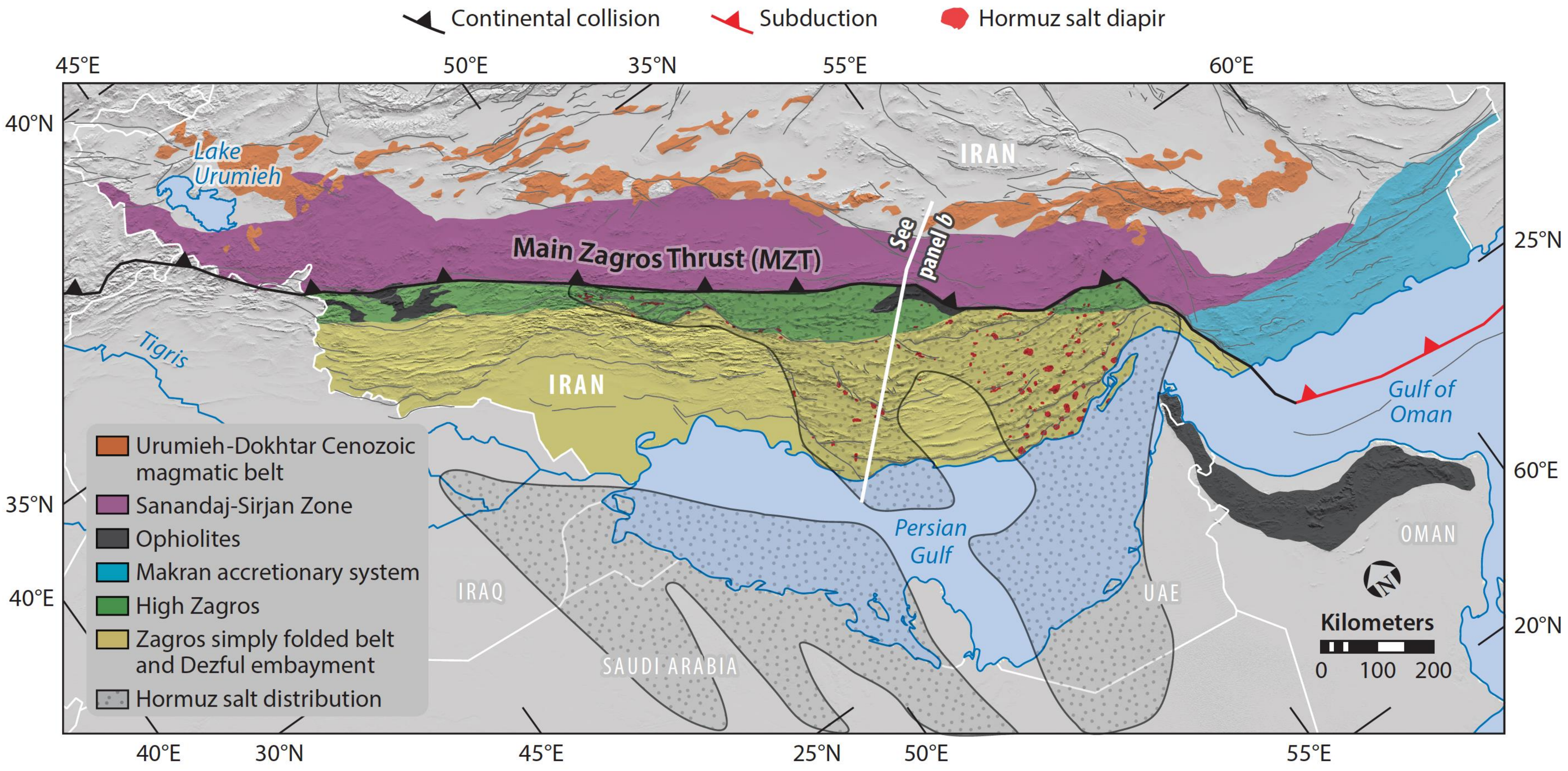
(*a*) P-wave seismic tomography cross sections across northern Iran from Iraq to the Alborz Mountains (Mahmoodabadi et al. 2019). The location is shown on **Figure 2**. Topography is indicated in light brown. (*b*) Interpretation of seismic tomography cross section. Subduction of the Zagros Mountains can be imaged to a depth of 200 km. Deeper high-seismic-velocity bodies, outlined with solid lines, may be detached slabs of oceanic lithosphere. Sinking dense material is compensated by upwelling warm mantle material with a low seismic velocity, outlined with dashed lines. Abbreviations: H1, mantle high-velocity zones; L1 and L3, mantle low-velocity zones 1 and 3; MZT, Main Zagros Thrust; SSZ, Sanandaj-Sirjan Zone; UDMA, Urumieh-Dokhtar magmatic arc; ZML, Zagros mantle lithosphere.

Iran is an excellent example of a Continental Arc System with an accretionary prism (Zagros Fold-and-Thrust Belt)

Continental arc: Easier to study and often associated with an accretionary prism

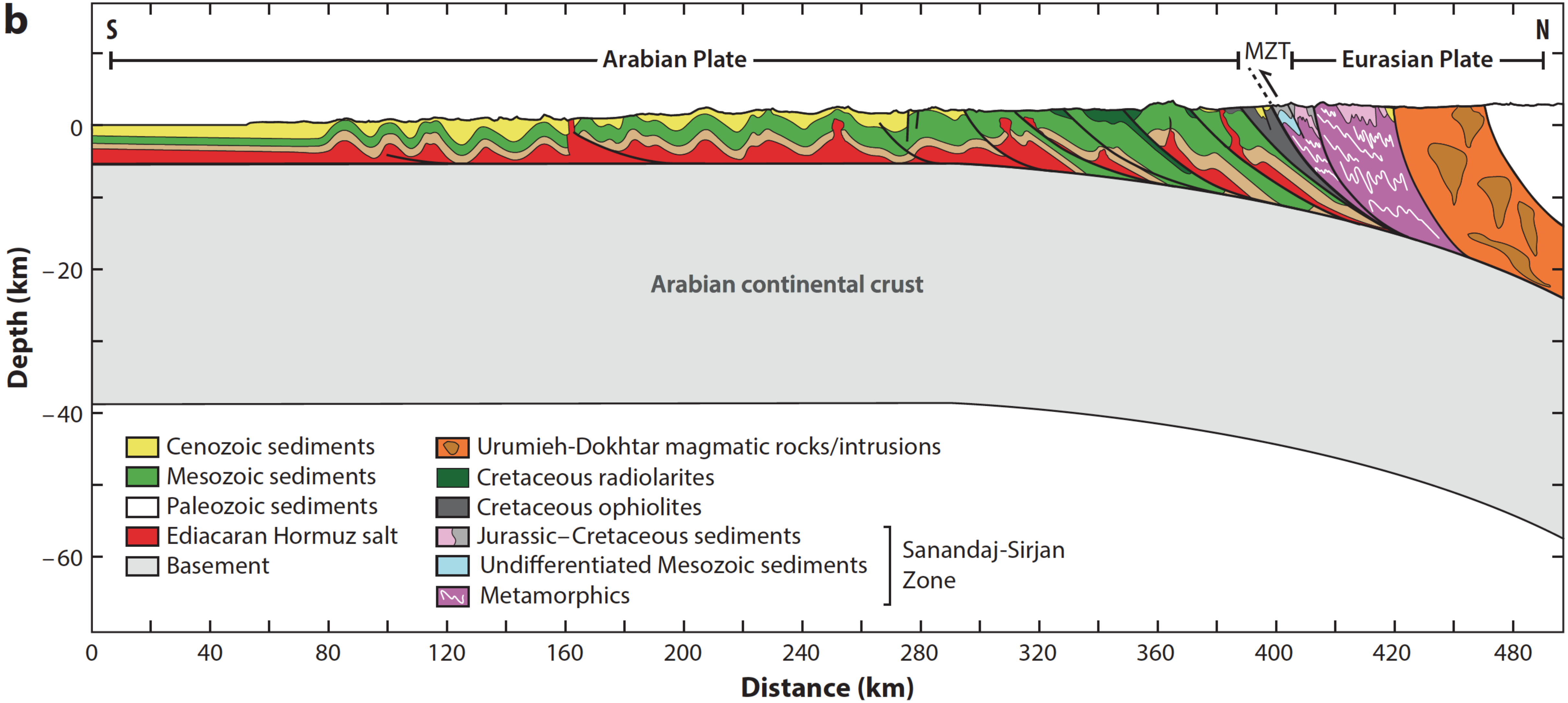
Oceanic Arc: Harder to study and generally lack an accretionary prism





Structural subdivisions along the edges of Arabia and Eurasia showing continental-continental collision zone changes to subduction toward the east in the Makran area.

The Zagros Fold-and-Thrust Belt is the Accretionary Prism of the Arabia-Iran Subduction/Collision Zone



Crustal scale cross section across the Zagros Fold-and-Thrust Belt. Data from Huber (1976) and Pirouz et al. (2017).

Crust and Lithosphere

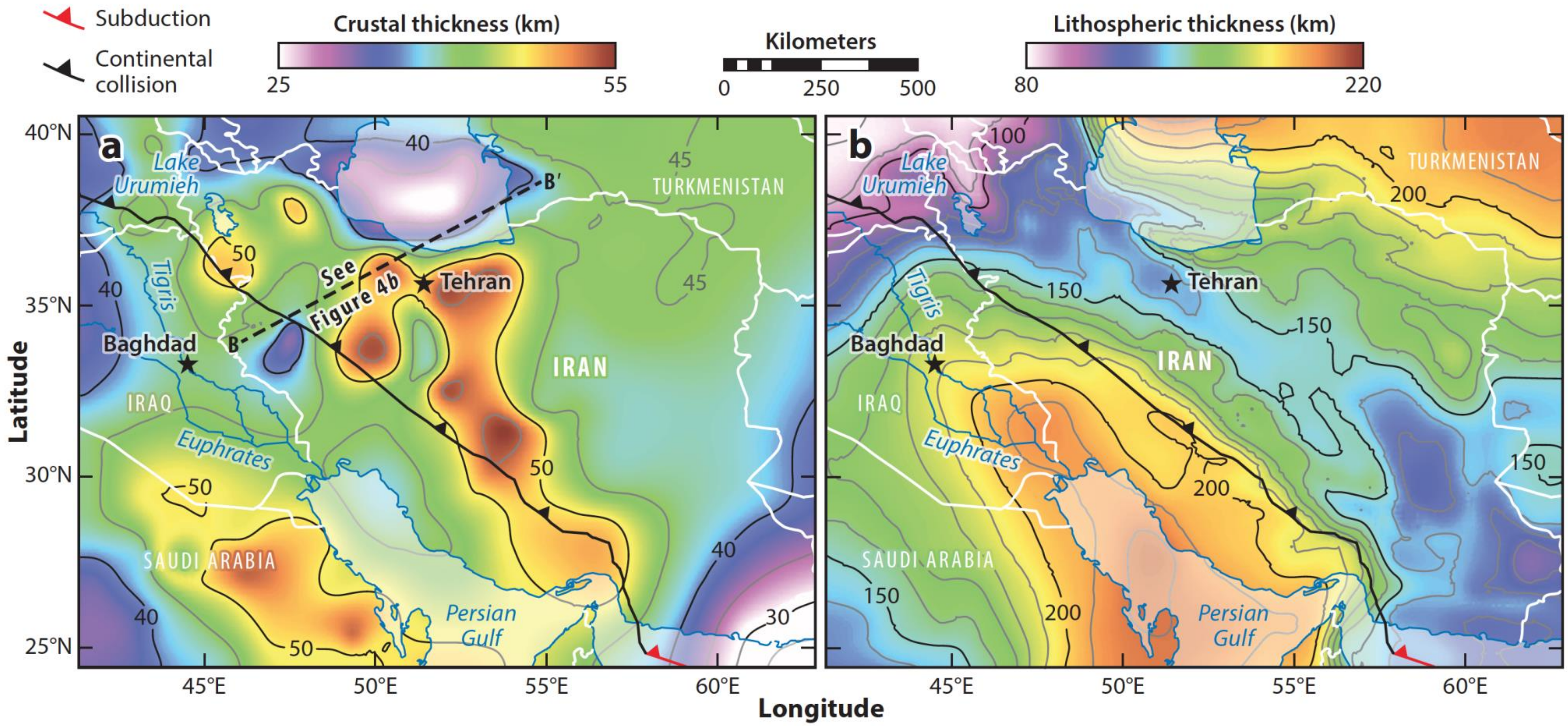
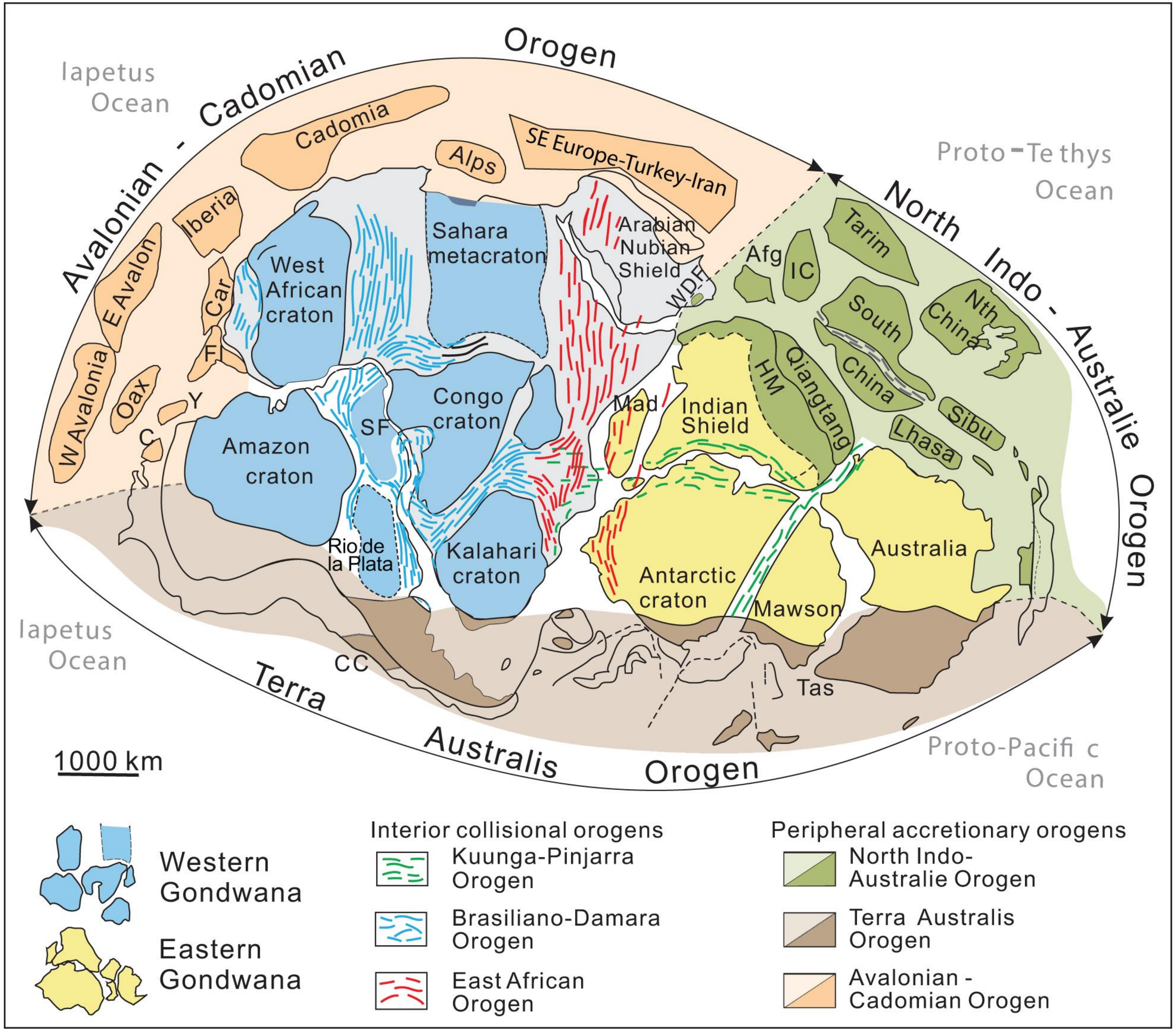


Figure 2

Crust and lithosphere thicknesses for Iran and surrounding regions. (*a*) Crustal thickness for Iran and neighboring regions based on seismic measurements. We estimate uncertainties in crustal thickness to be 20%, which is +/−8 km for 40-km-thick crust. Data from Prodehl & Mooney (2012) and Mooney (2015). The thick dashed black line shows the location of the tomographic section in **Figure 4**. (*b*) Lithospheric thickness determined by combining topography and the geoid beneath Arabia and Iran (Jiménez-Munt et al. 2012).

Six Key Events and Episodes in the Geologic Evolution of Iran

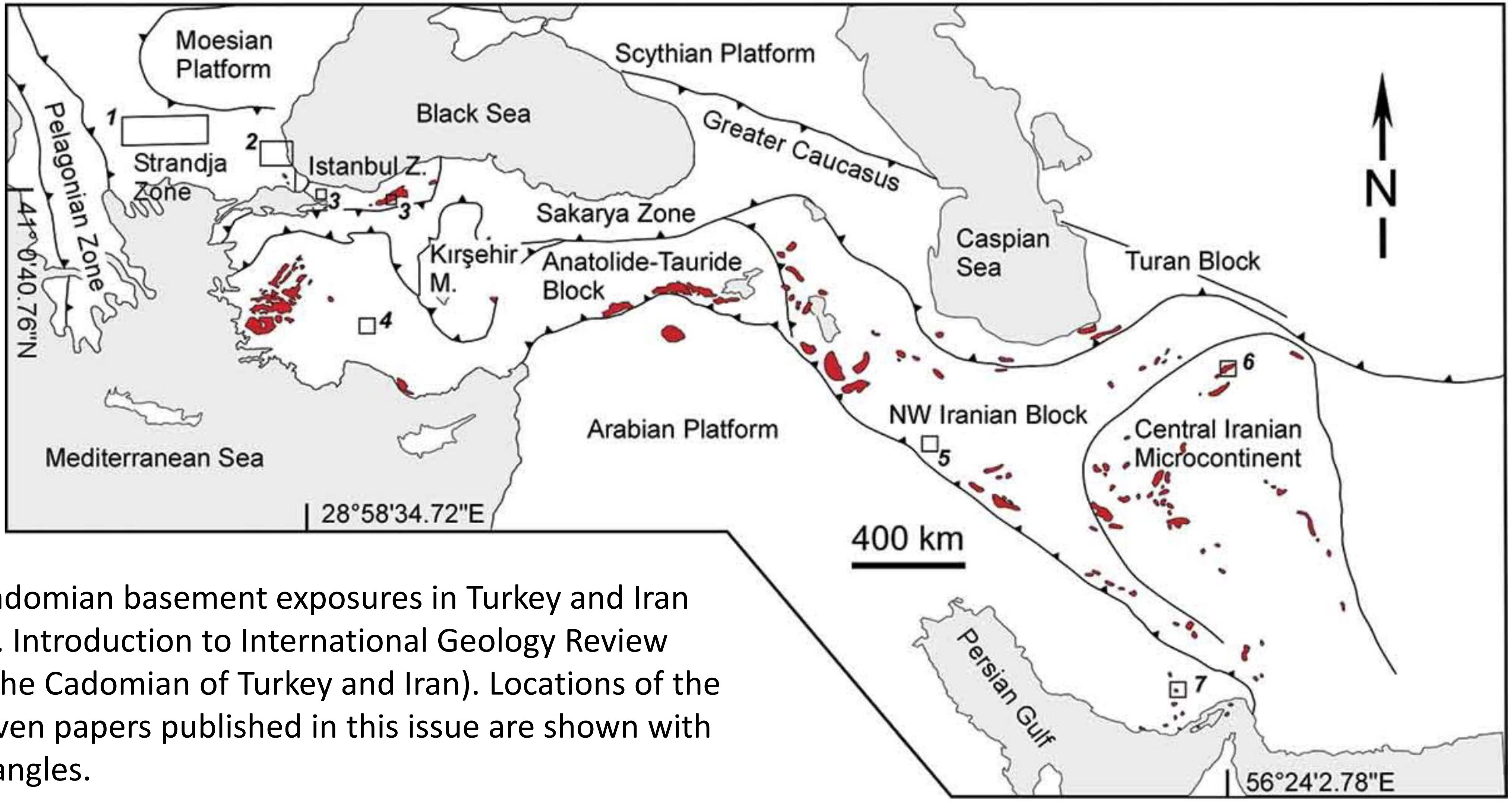
1. Cadomian (500-600 Ma) continental crust formation on the northern margin of Gondwana.
2. Paleozoic rifting from Gondwana and accretion to Eurasia in Permo-Triassic time.
3. Jurassic continental rifting to form the Sanadaj-Sirjan Zone.
4. Late Cretaceous Subduction Initiation.
5. Paleogene extensional convergent margin
6. Neogene collision with Arabia



Greater Gondwana or Pannotia ~550 Ma (during the Cadomian orogeny)

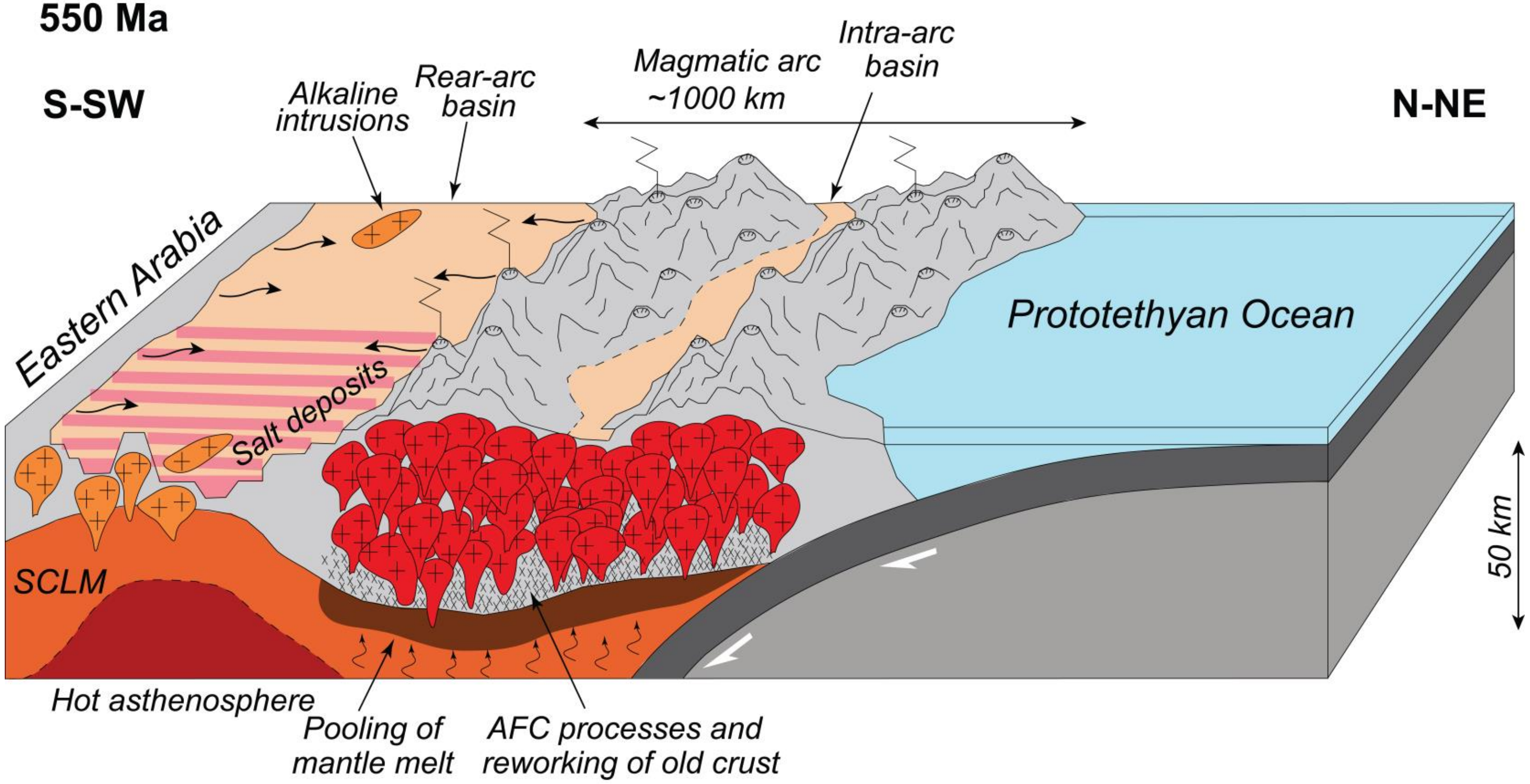
Cawood et al., 2021

Cadomian of SE Europe, Turkey, and Iran

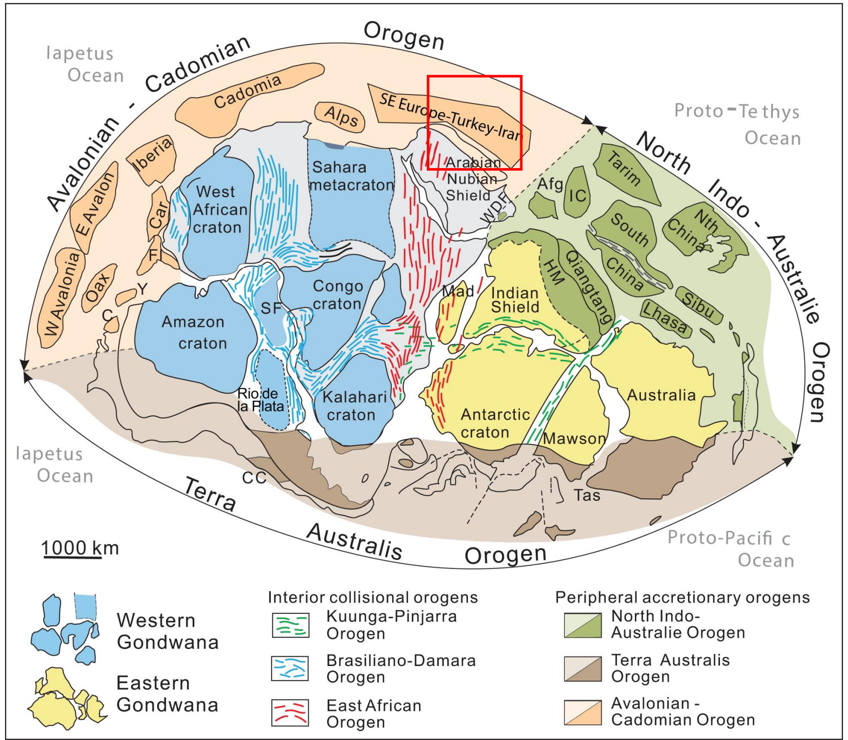


Distribution of Cadomian basement exposures in Turkey and Iran (from Topuz et al. Introduction to International Geology Review Special Issue on the Cadomian of Turkey and Iran). Locations of the study areas of seven papers published in this issue are shown with squares and rectangles.

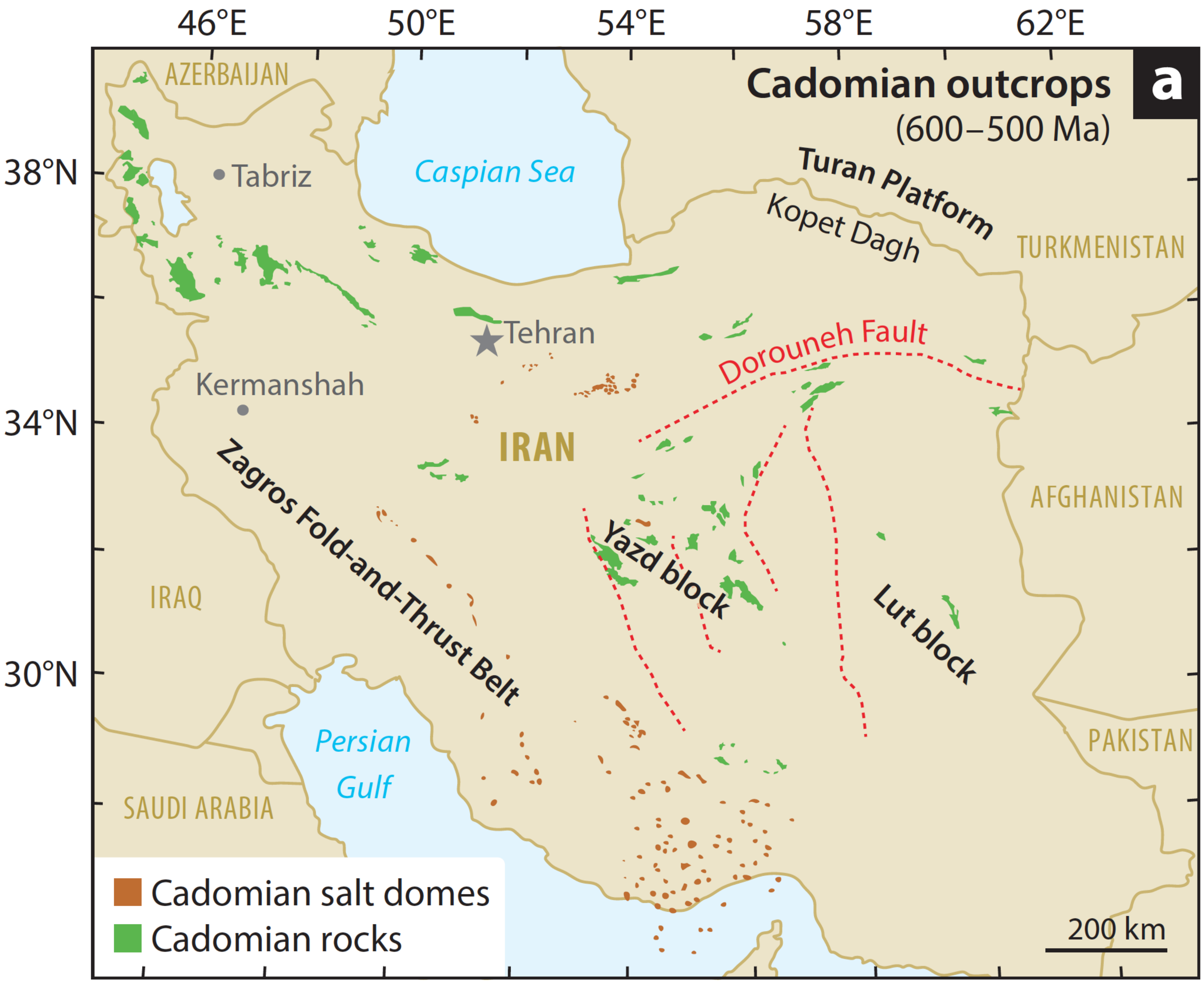
The Cadomian of Iran: A Continental Arc on the N margin of Greater Gondwana

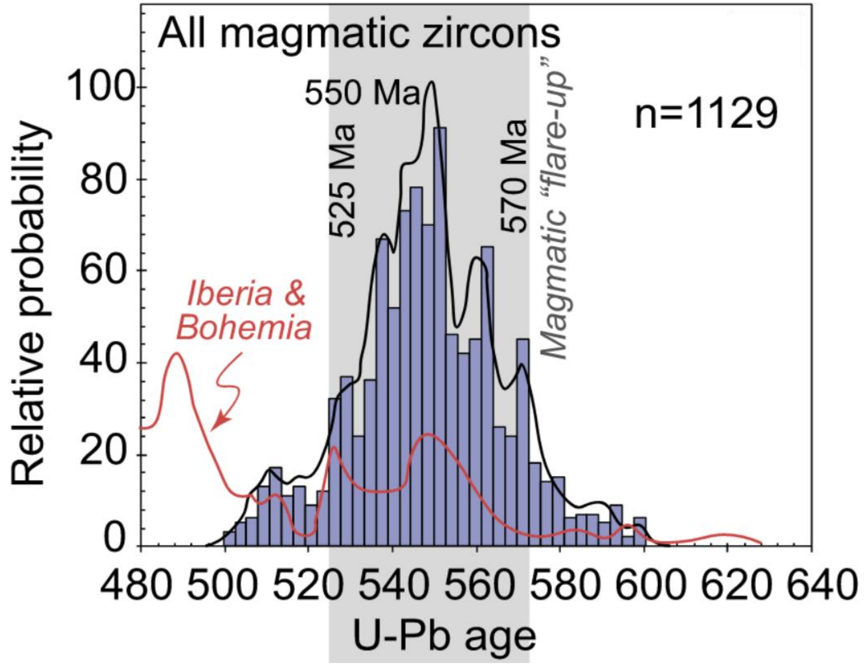


Where the continental crust of Iran mostly formed



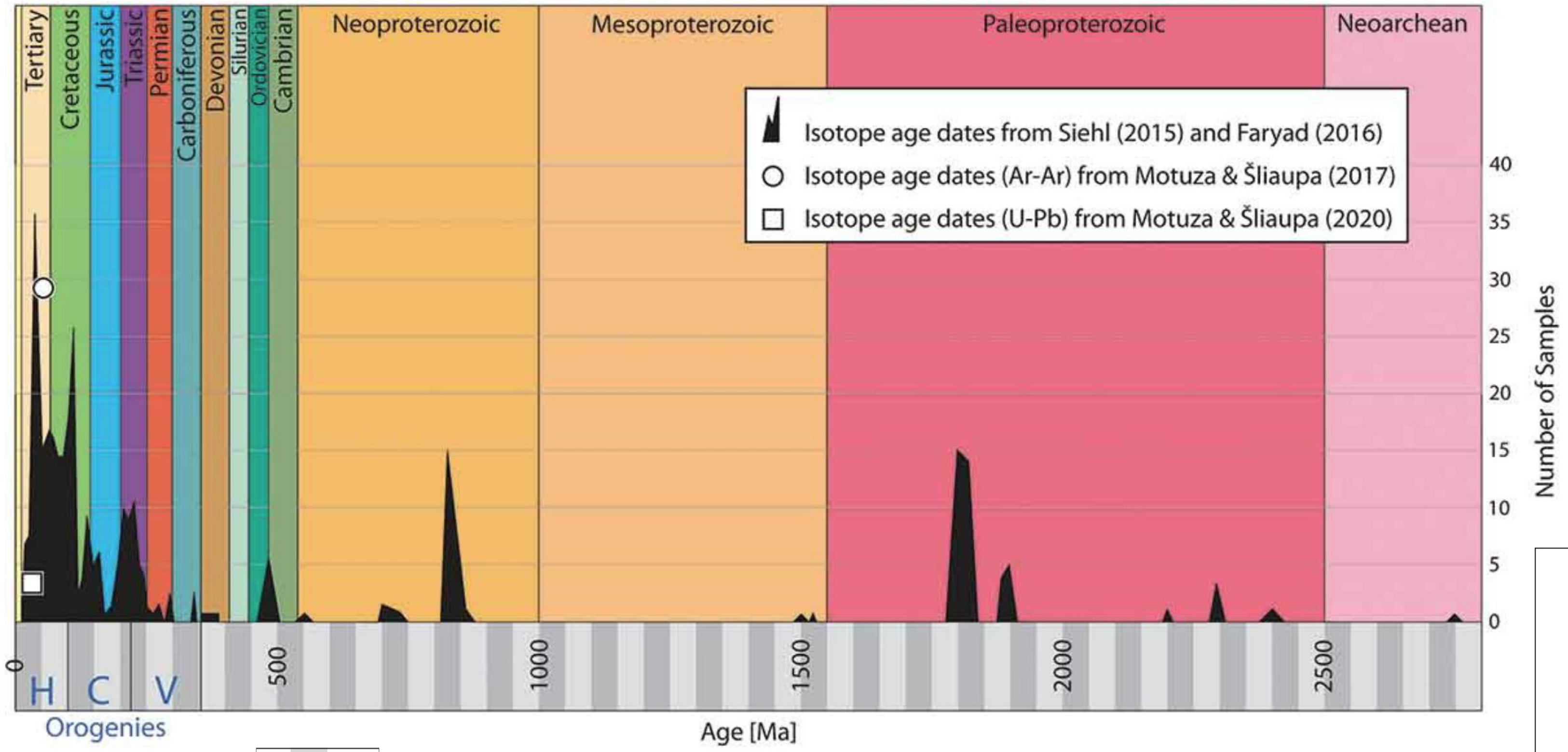
Cadomian (600-500 Ma) outcrops in Iran





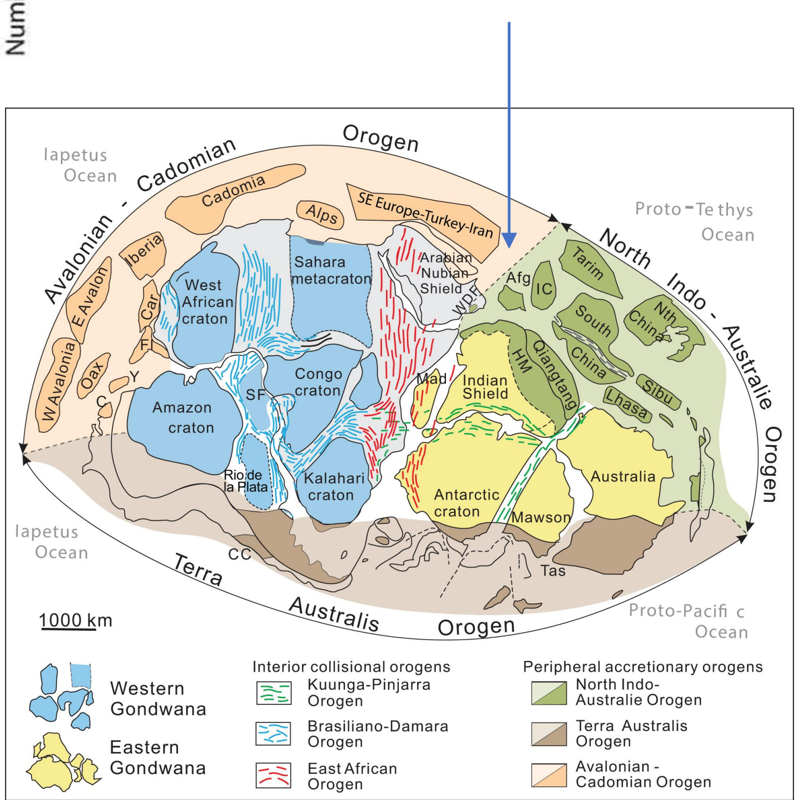
Moghadam et al., 2020

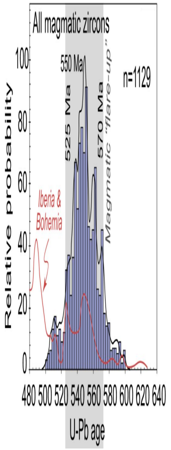
Continental crust of Turkey and Iran are very similar; crusts of Iran and Afghanistan are very different!



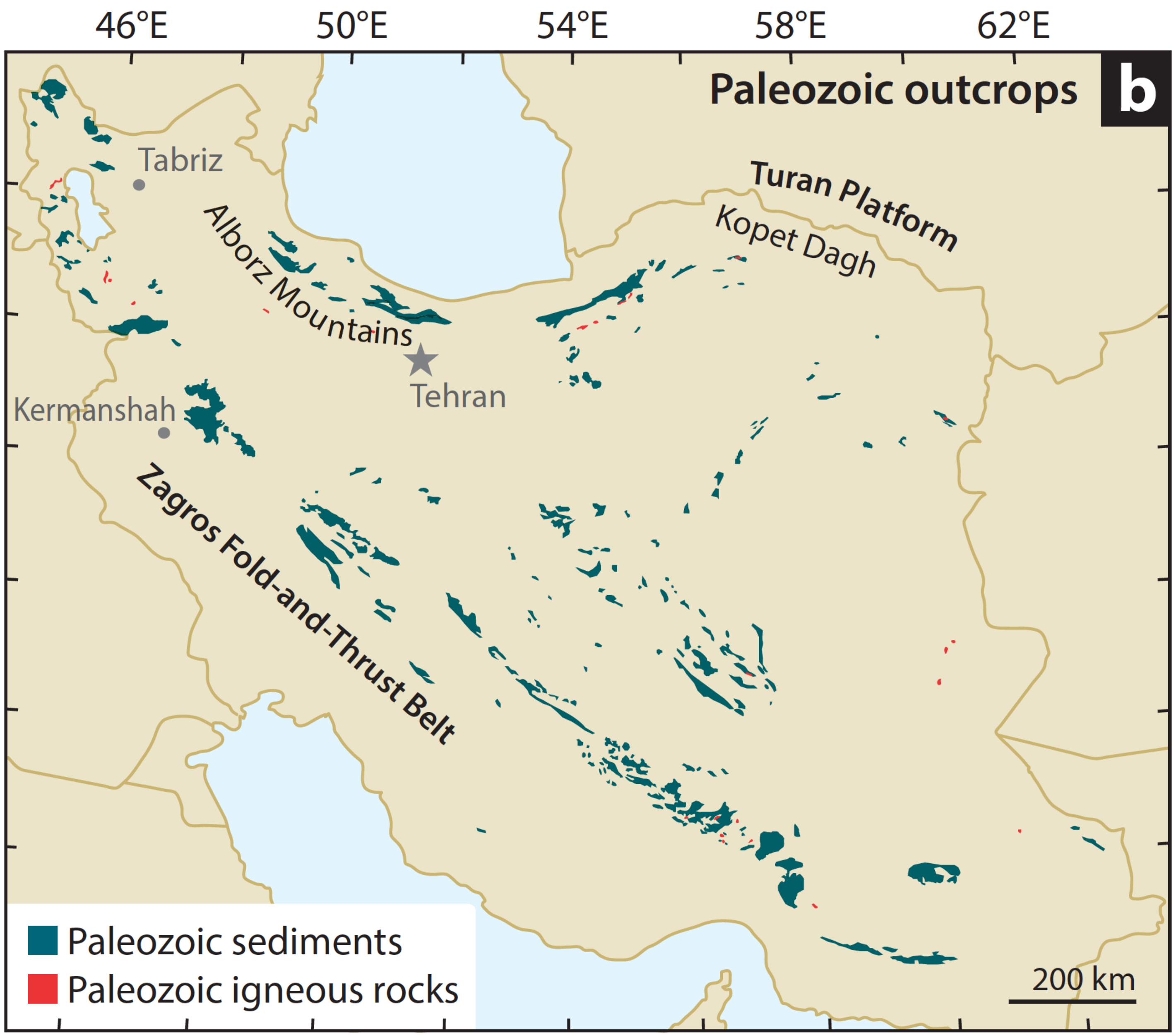
Afghanistan has very little Cadomian crust (Shroder et al., 2021)

This is an important crustal boundary!





Iran = dominantly Cadomian crust

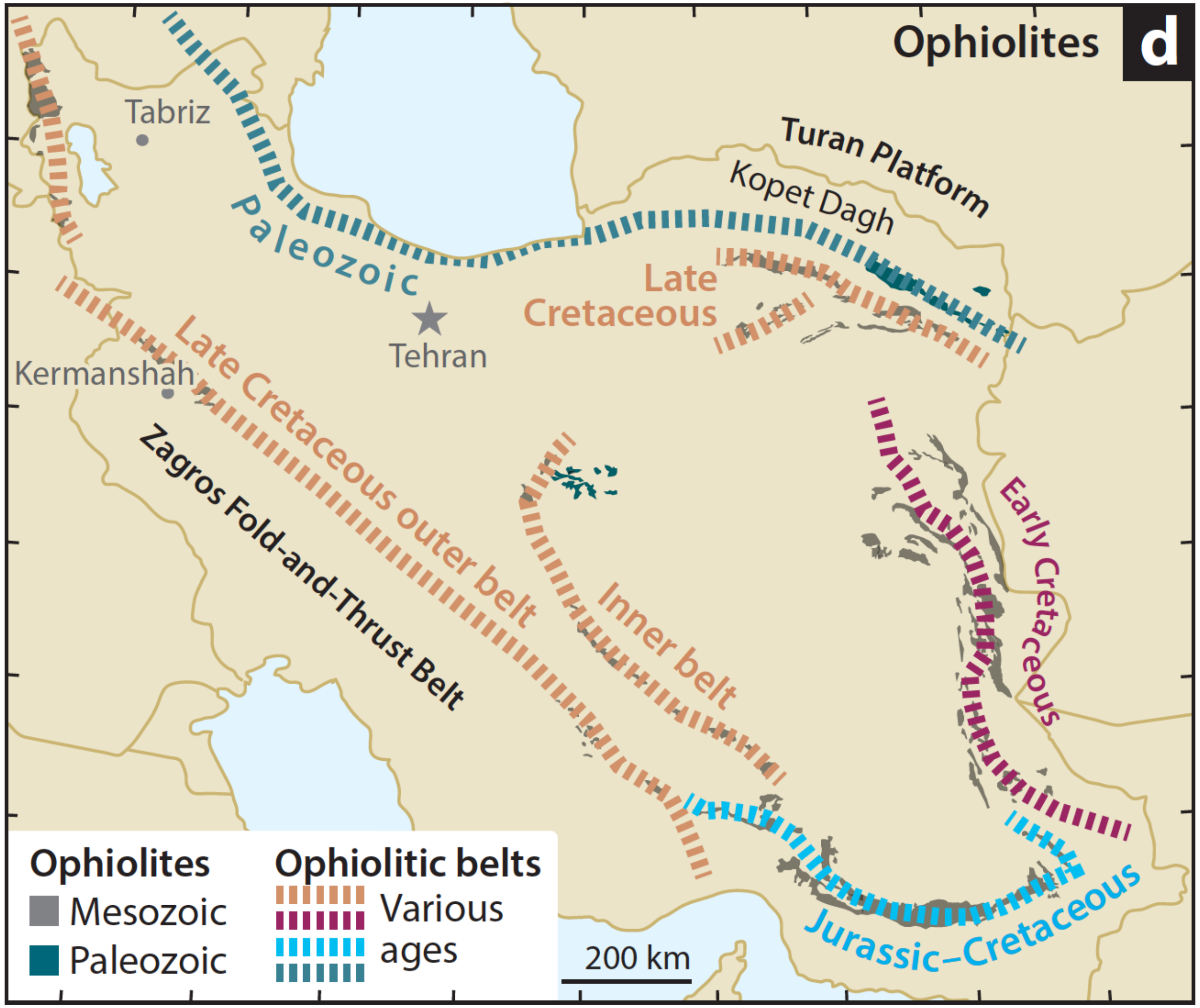


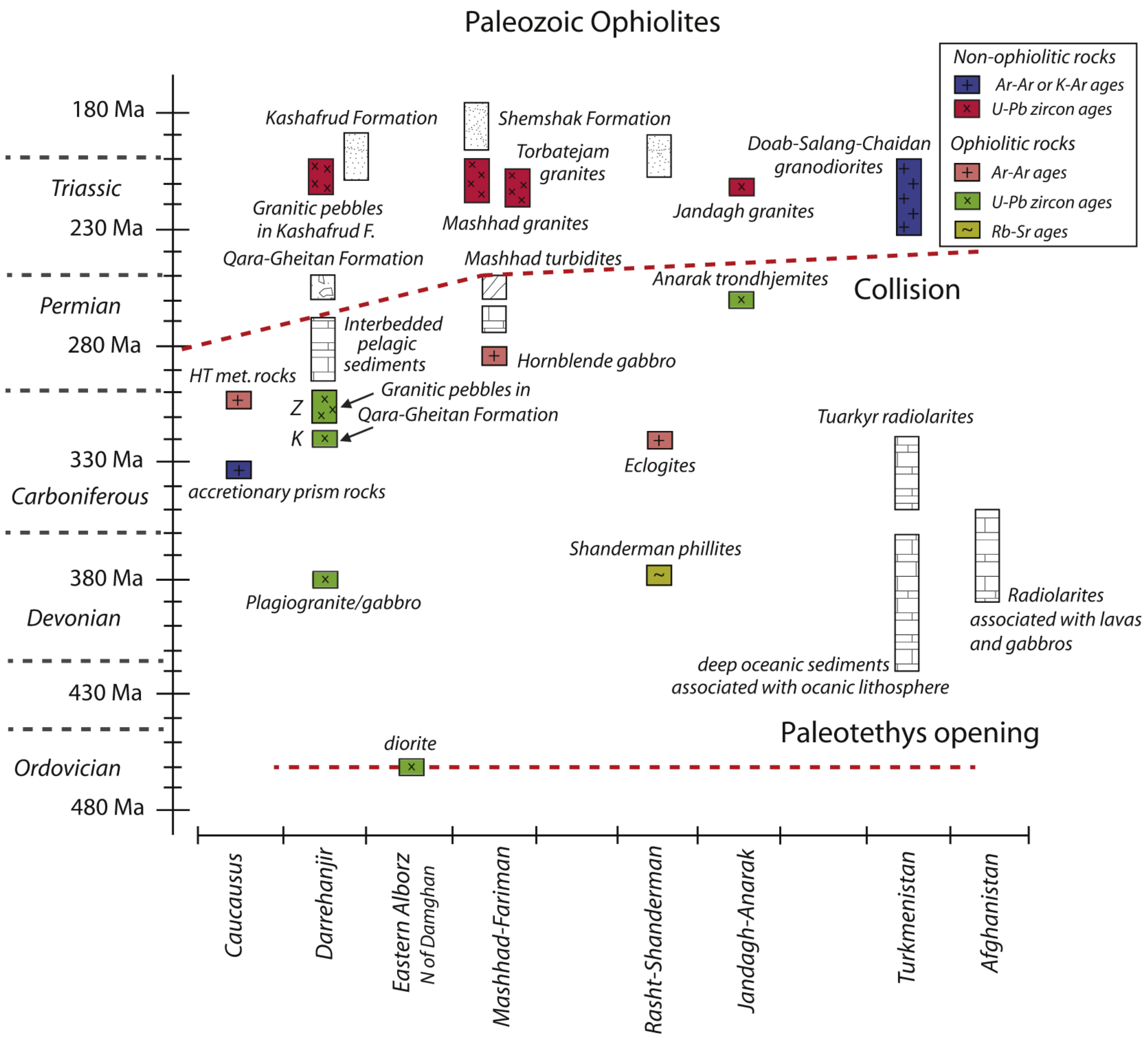
Paleozoic rocks of Iran

Total thickness of Ediacaran through Paleozoic sediments is remarkably constant across Iran, from 3 to 4 km thick (Stocklin, 1968).

This succession suggests that Iran mostly behaved as a marine platform during Paleozoic time.

Paleozoic Ophiolites of N. Iran show where and when Iran was sutured to Eurasia

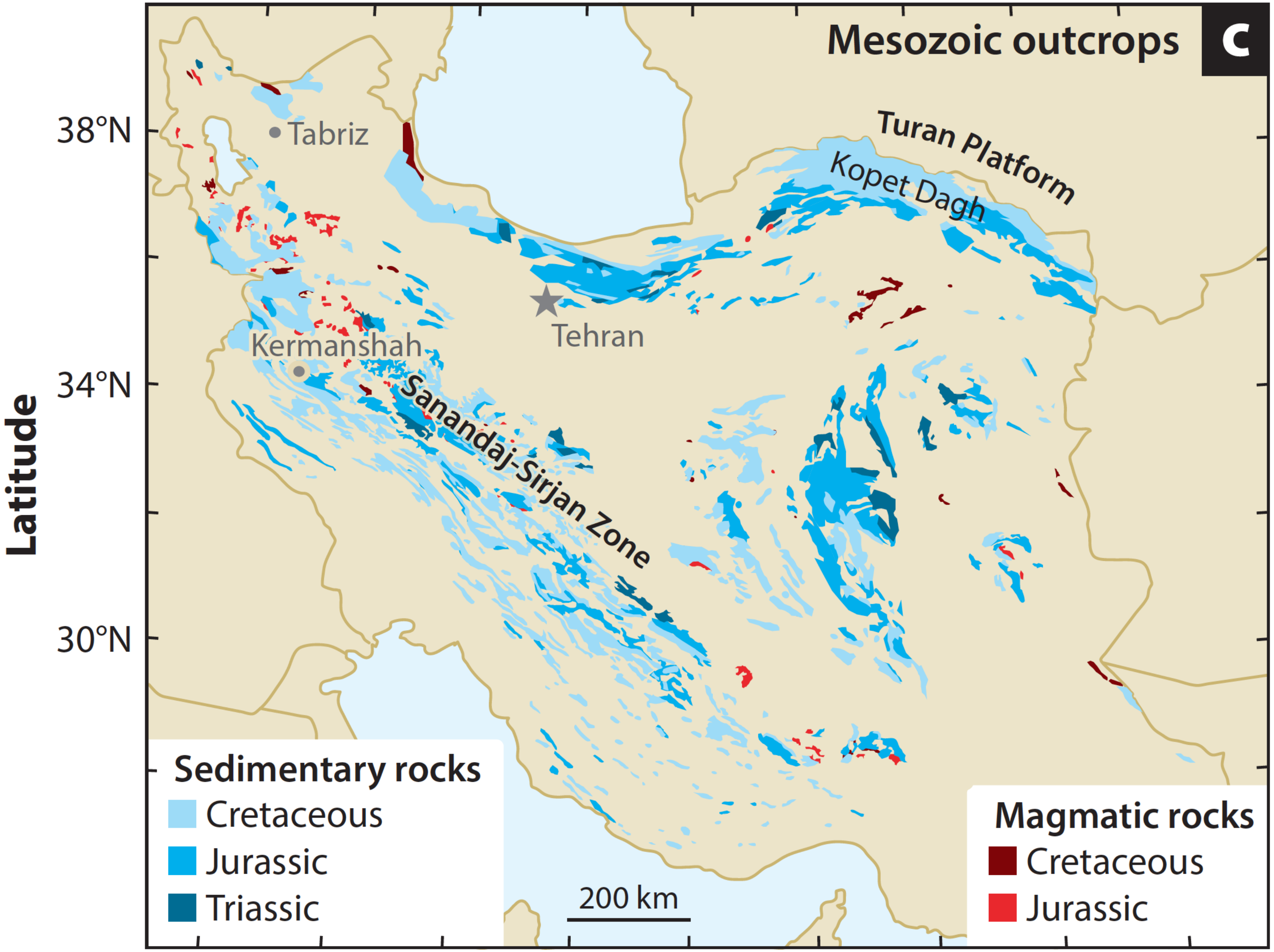




Simplified chart showing the ages of magmatic and sedimentary sequences that constrain ages of Iranian Paleozoic ophiolites; greenish area inside dashed lines are ophiolite ages.

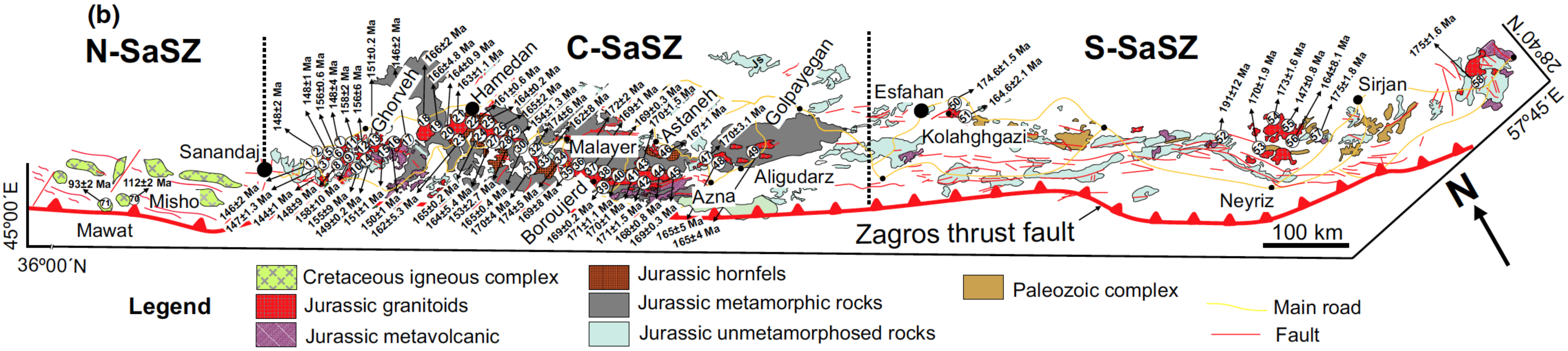
Moghadam and Stern, 2014

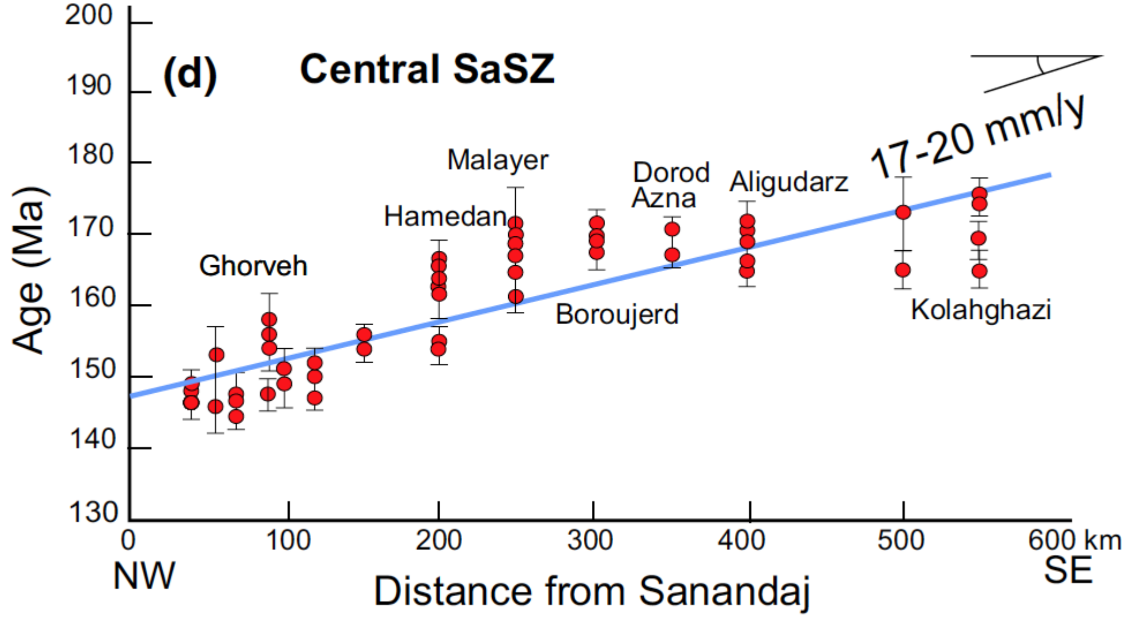
Mesozoic Rocks of Iran



The Sanandaj-Sirjan Zone is especially interesting!

Sanandaj-Sirjan Zone (SaSZ)

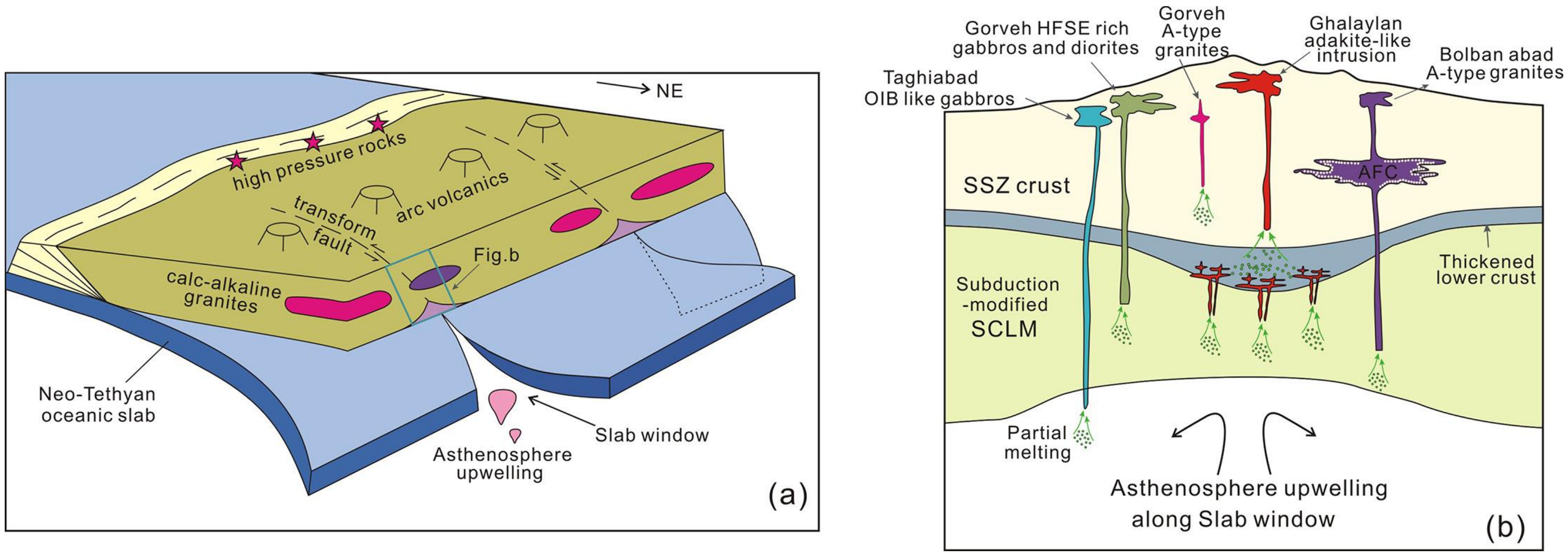




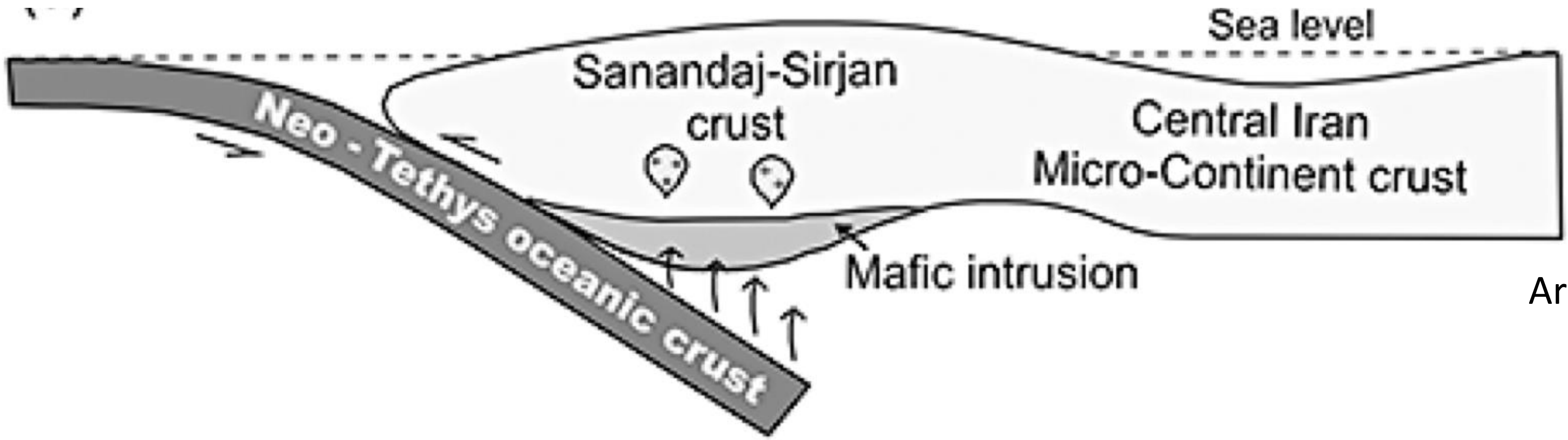
NW migration of magmatism is inconsistent with a magmatic arc. It is expected for a mantle plume or a propagating rift.

Azizi and Stern, 2019

The Sanandaj-Sirjan Zone is often depicted as an arc above a Jurassic subduction zone

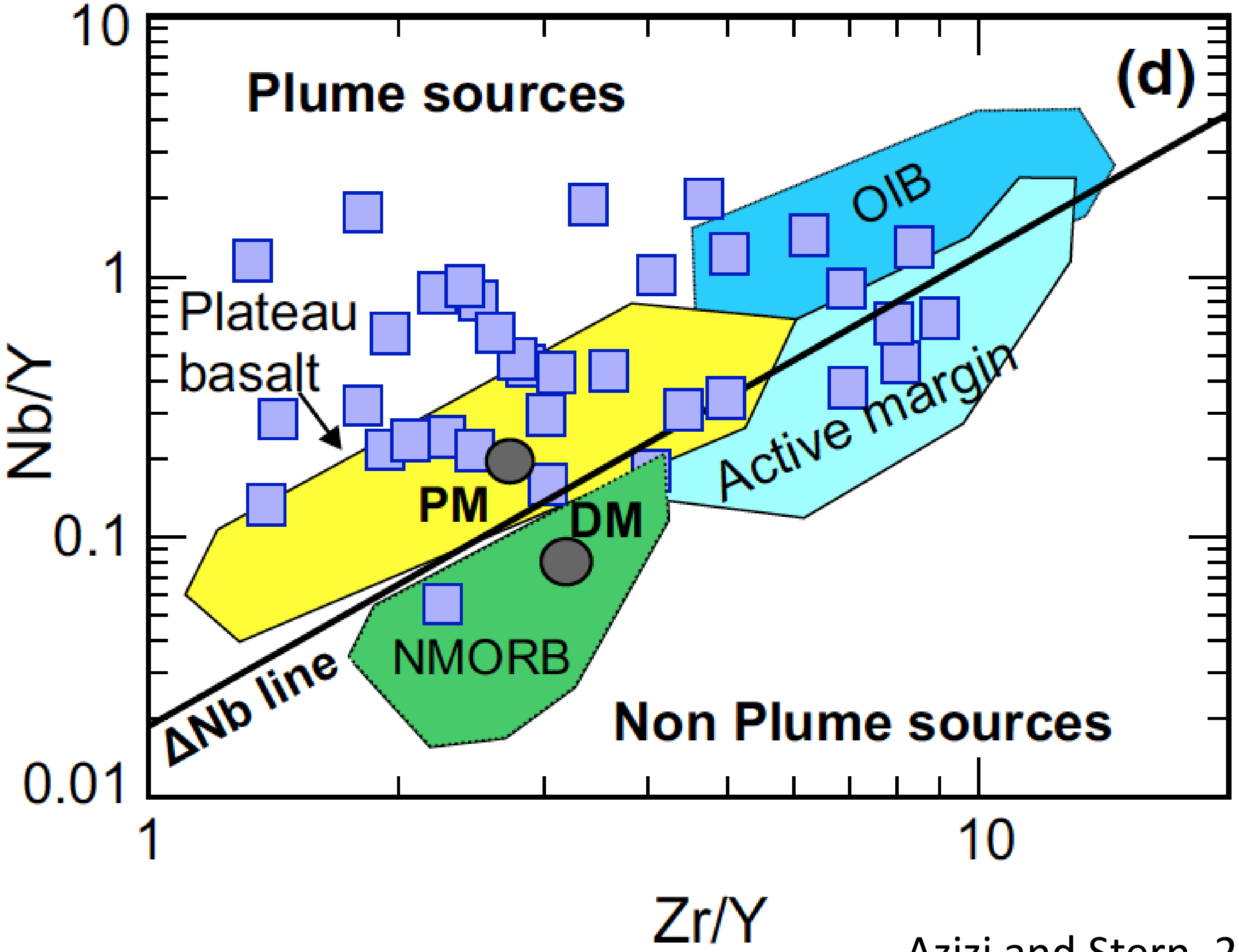


Zhang et al., 2018

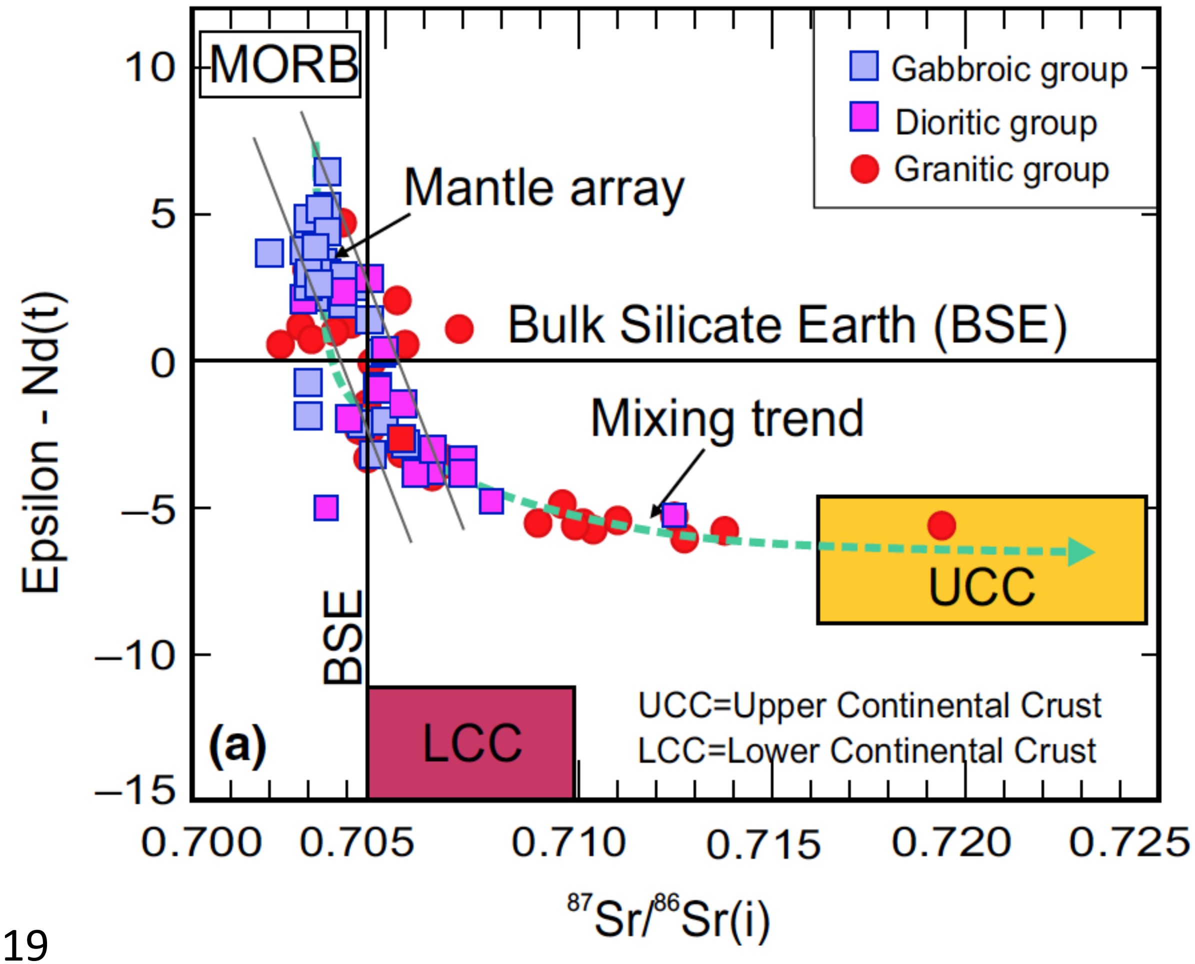


Arfania and Shahiari, 2009

SaSZ Mafic Igneous rocks are not arc-like. Related to plume and rift sources

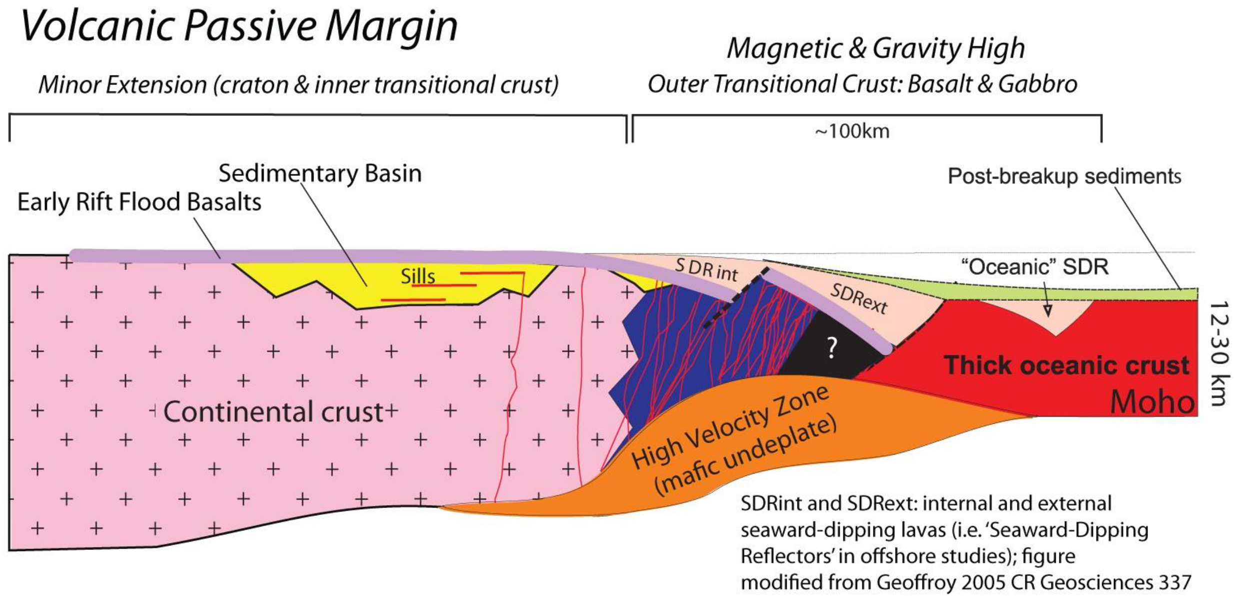


SaSZ Felsic Igneous rocks are strongly contaminated by Iran continental crust



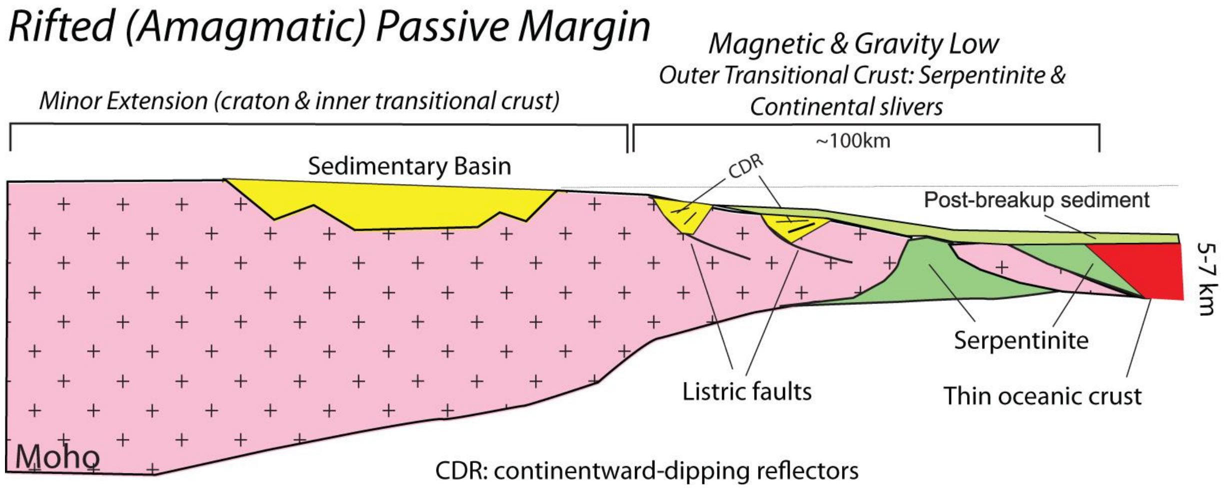
Azizi and Stern, 2019

Two endmember types of Rifted Continental Margins: Volcanic margins and Nonvolcanic margins. Based on nature of **Transitional Crust**



SDRint and SDRext: internal and external seaward-dipping lavas (i.e. 'Seaward-Dipping Reflectors' in offshore studies); figure modified from Geoffroy 2005 CR Geosciences 337

Volcanic margins;
aka VRM
SaSZ may be a VRM!

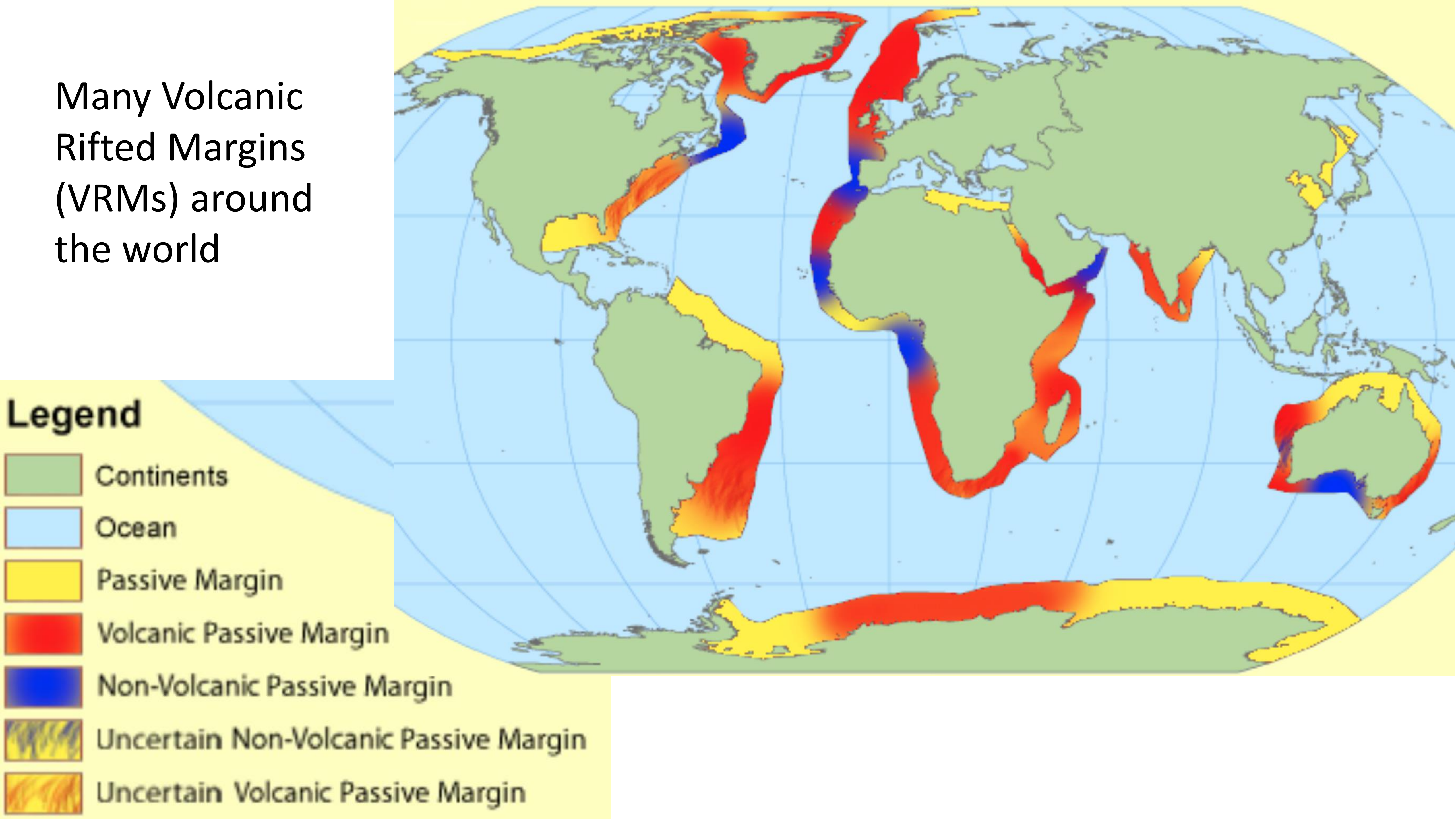


CDR: continentward-dipping reflectors

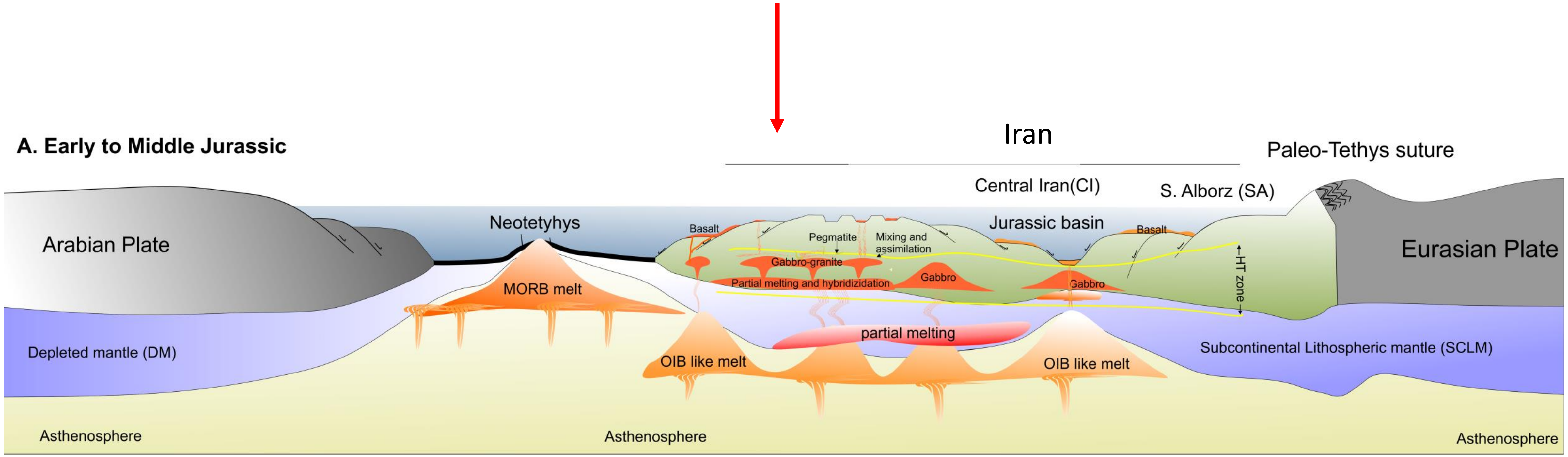
Nonvolcanic margins;
aka RPM

As we have seen, these will form and evolve differently.
Most rifted continental margins are volcanic.

Many Volcanic Rifted Margins (VRMs) around the world

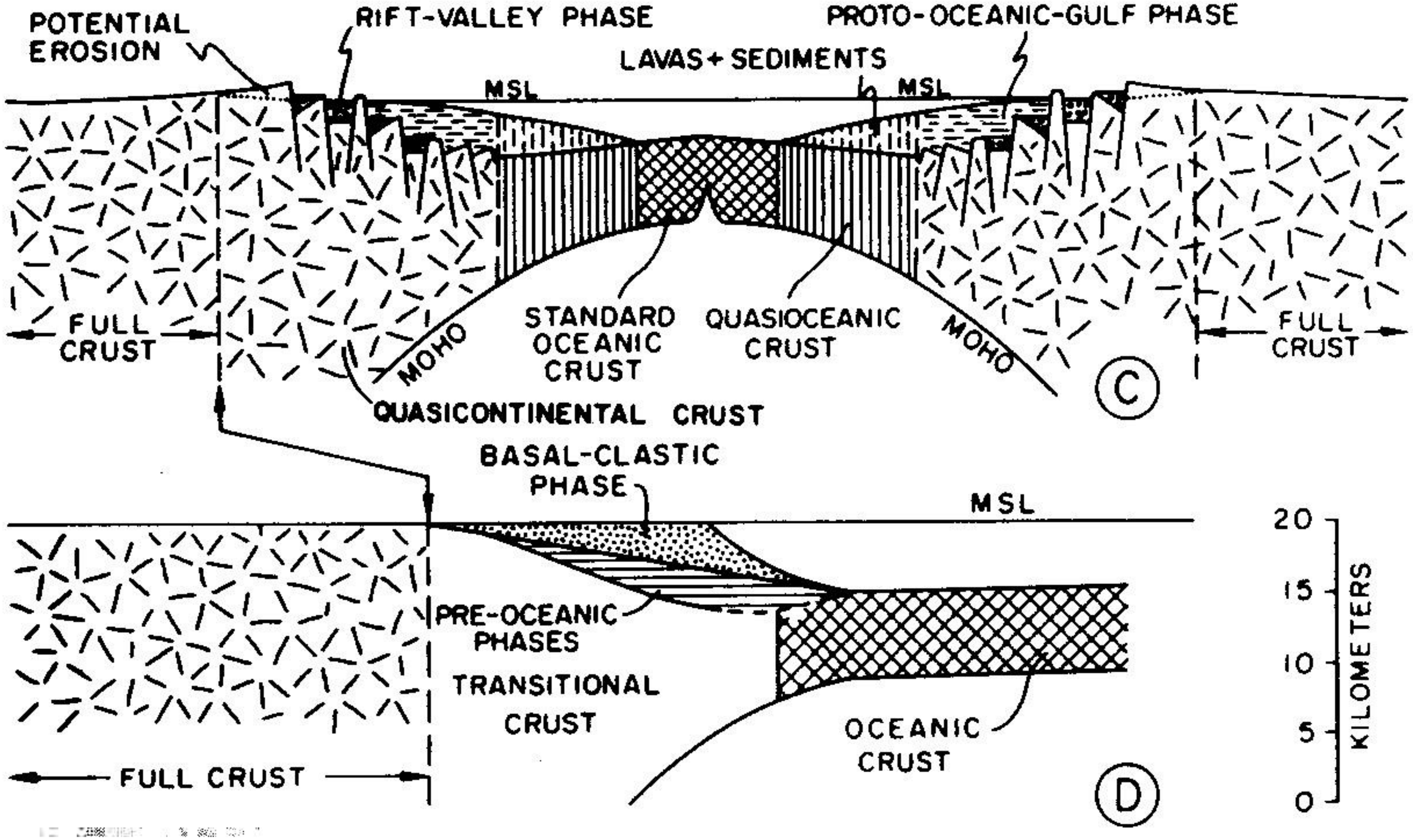


The SaSZ as a Jurassic VRM

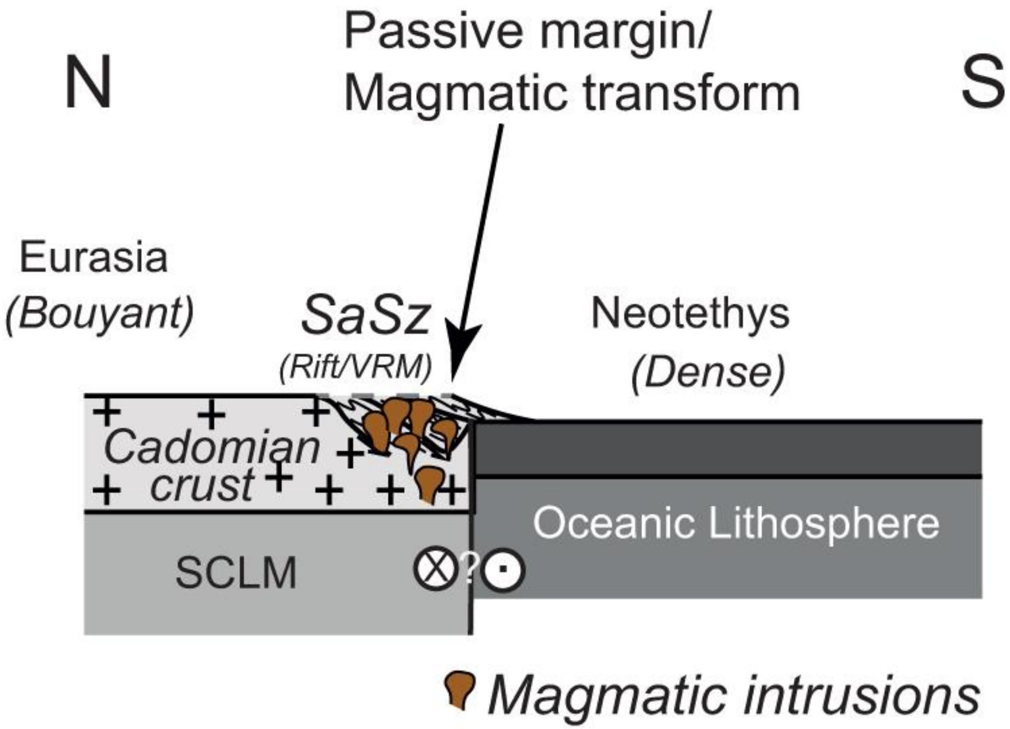


Related to the Opening of NeoTethys

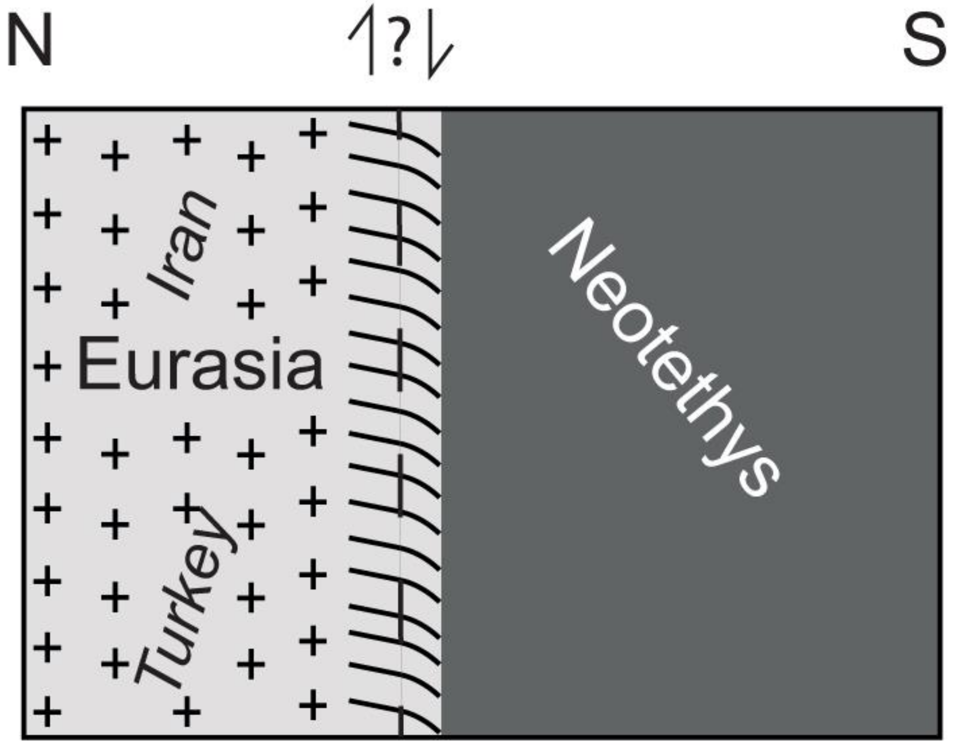
SW margin of Iran evolved as a passive continental margin until mid-Cretaceous (~100 Ma)



~150 Ma (Late Jurassic)



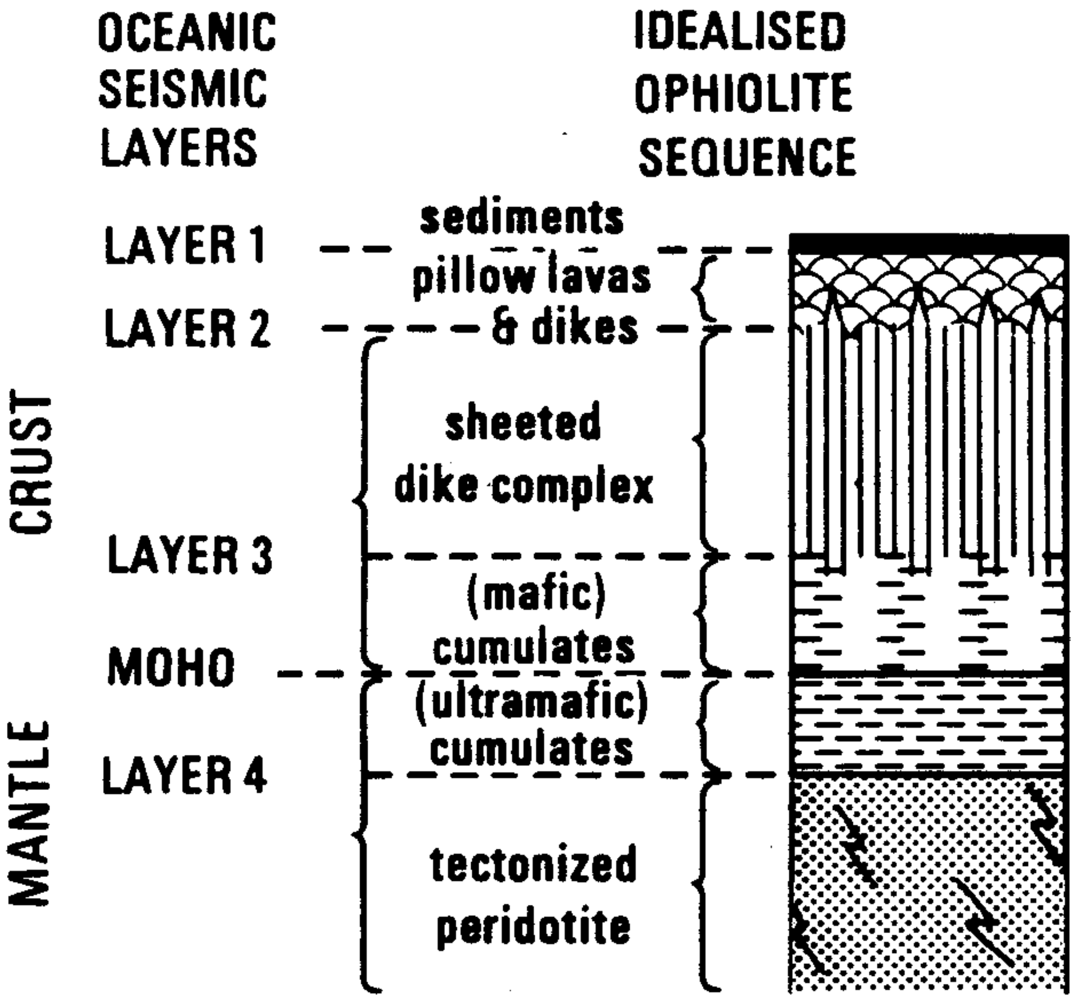
CrossSection



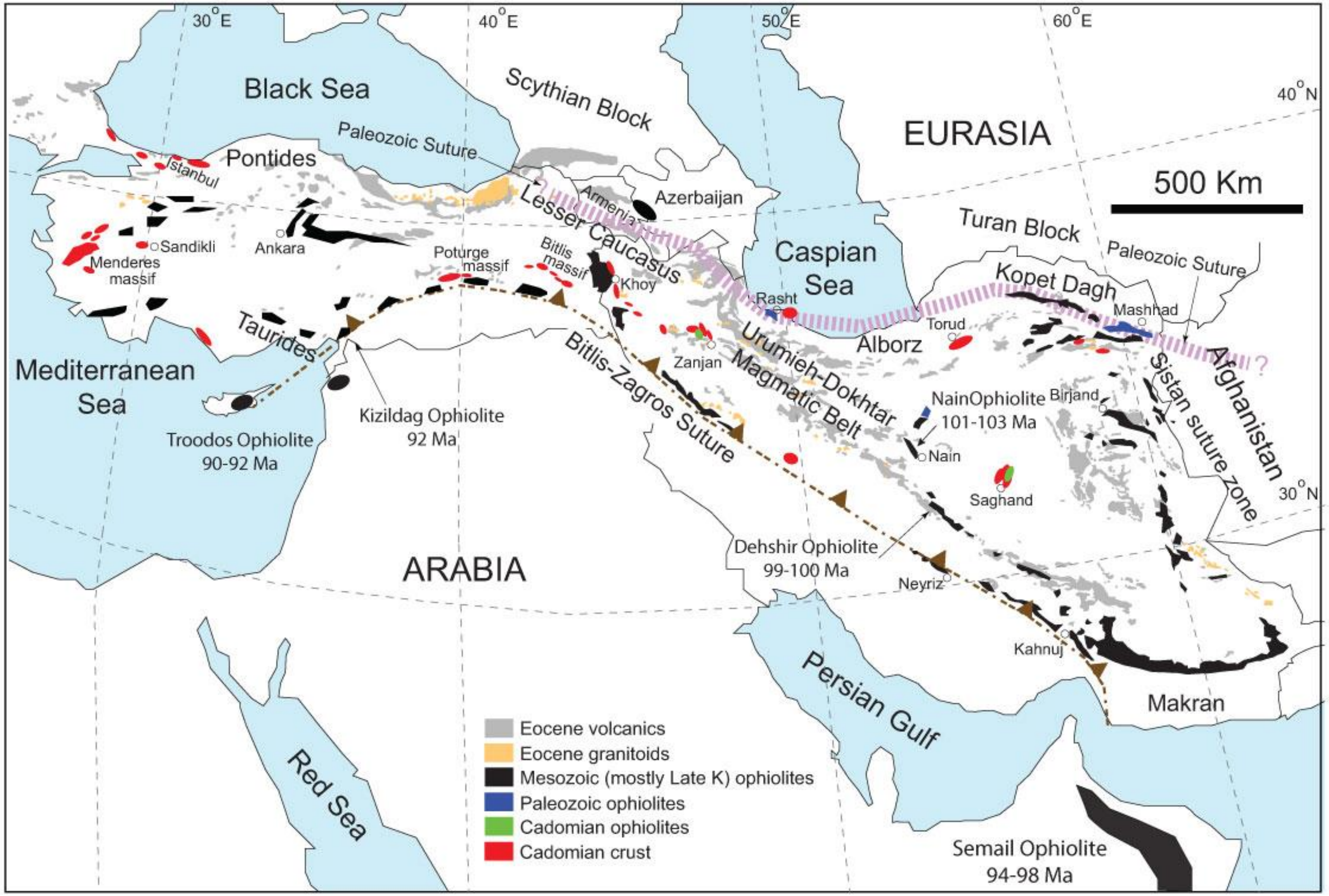
Map View

Ophiolites: fragments of oceanic lithosphere

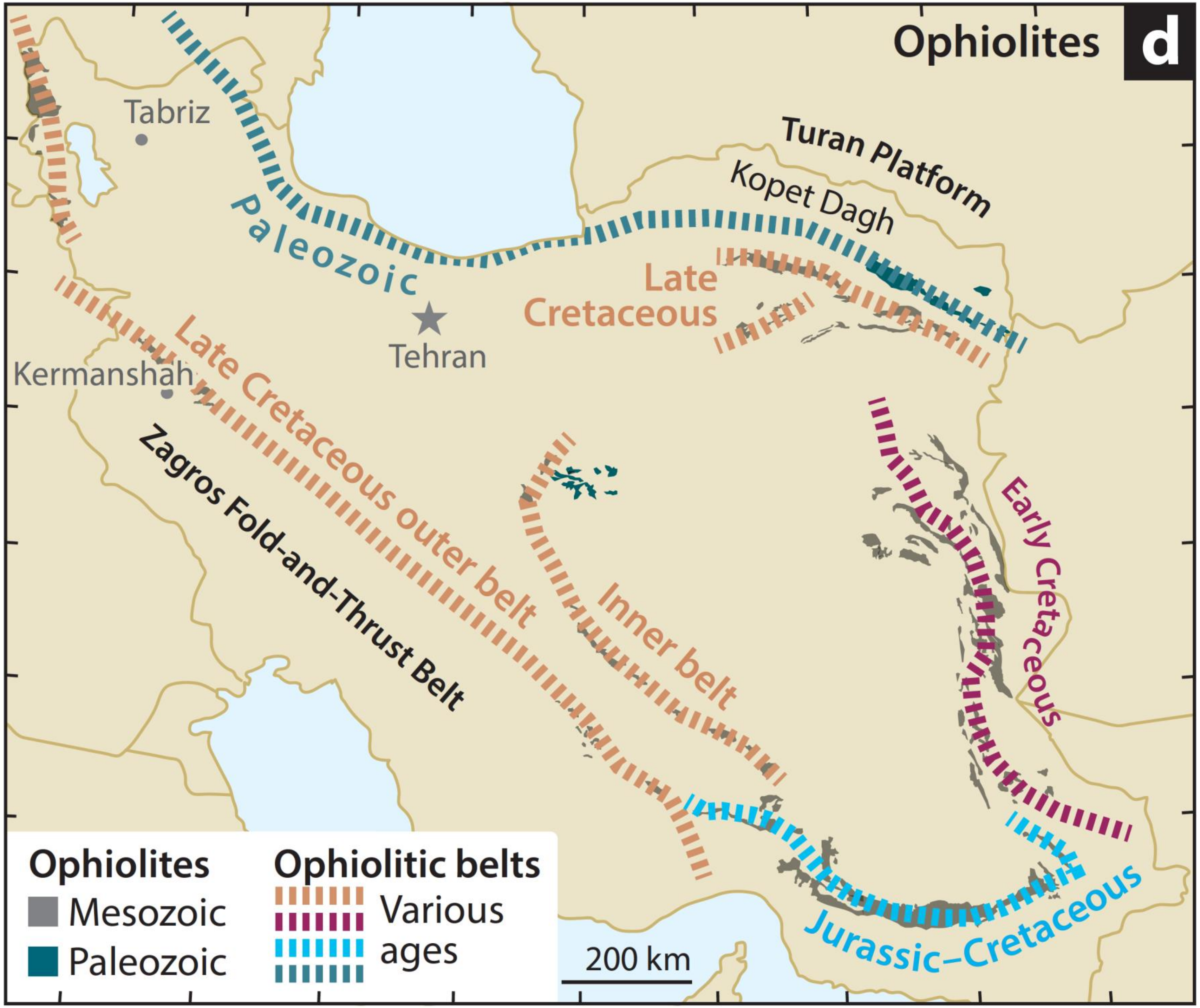
- Ophiolites are argued to be fragments of oceanic lithosphere
- Most (including the abundant Late Cretaceous ophiolites of Iran) form during formation of new subduction zones (subduction initiation, SI)



U-Pb zircon ages for Late Cretaceous "Subduction Initiation" ophiolites along the Bitlis-Zagros suture

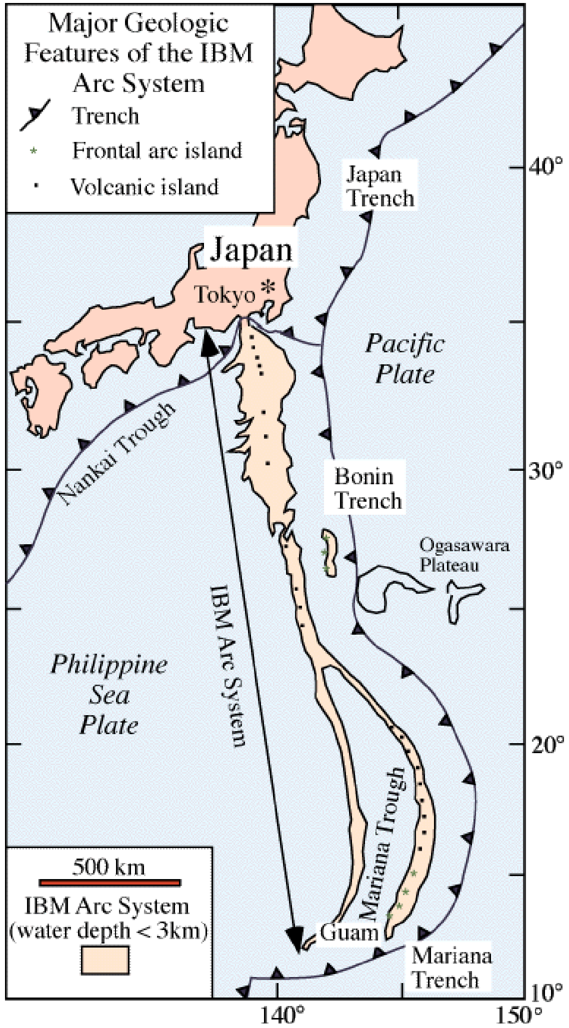


Moghadam et al., 2013



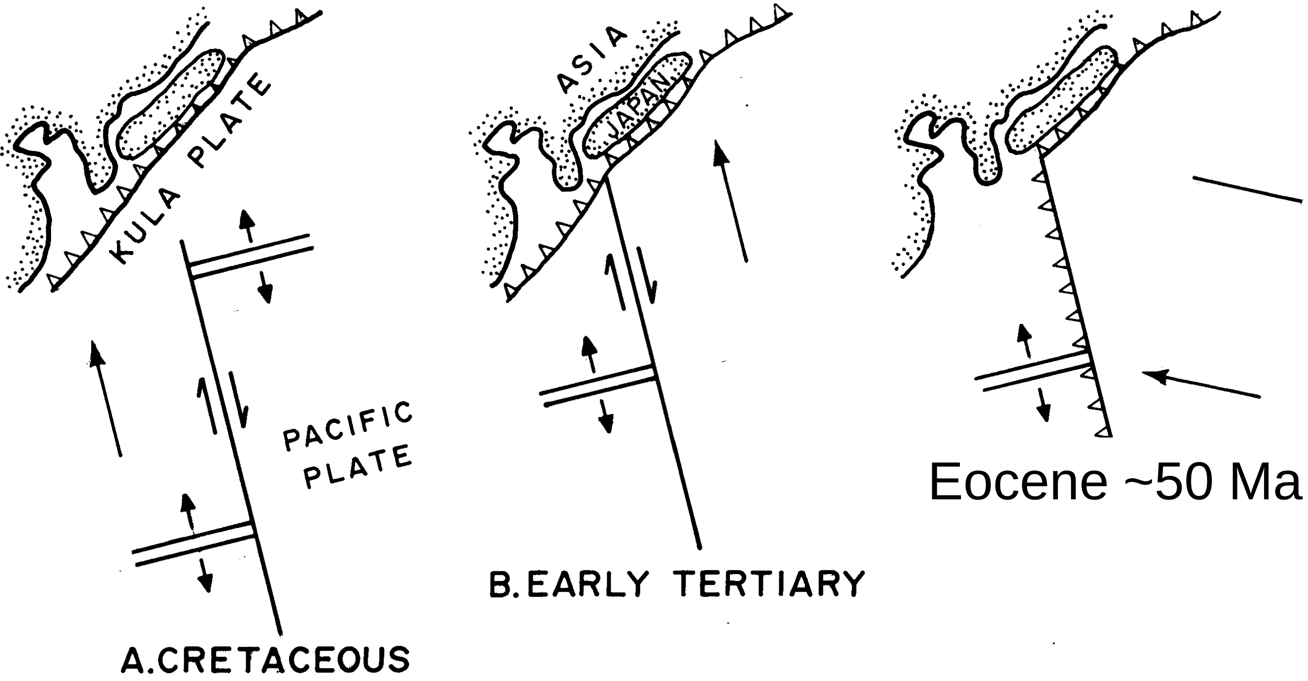
Ophiolites of Iran

Izu-Bonin-Mariana (IBM) arc system in the Western Pacific south of Japan



The crust of the IBM forearc formed when subduction began ~50 Ma

Transform margin collapse (Uyeda & Ben Avraham model)

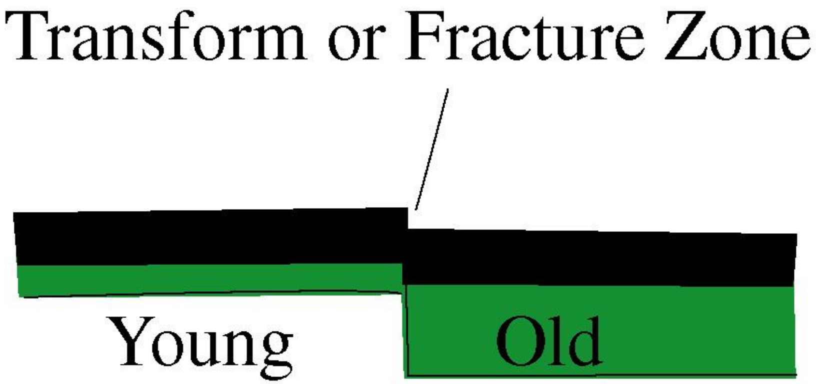


Eocene ~50 Ma

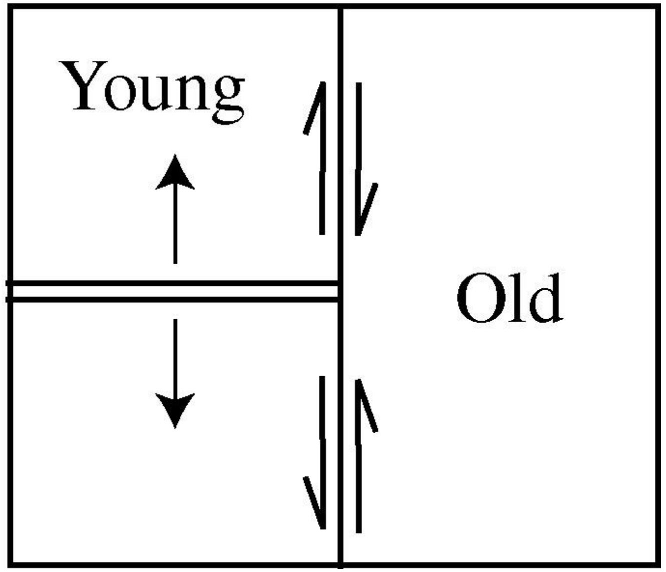
How did IBM subduction zone form?

1. Exploitation of Lithospheric Weakness (fracture zone or transform fault) separating old, dense oceanic lithosphere and young, buoyant oceanic lithosphere

Section



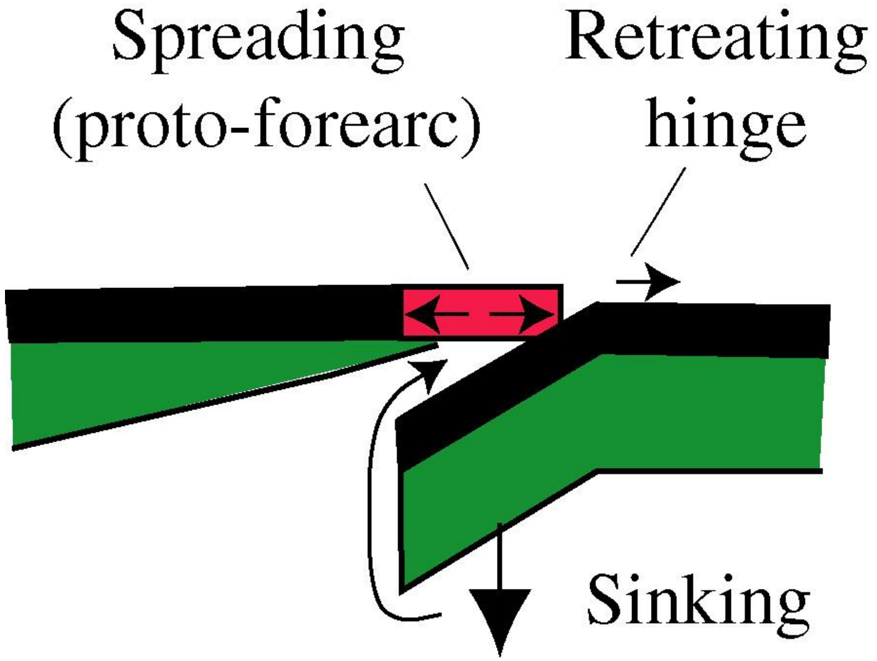
Map View



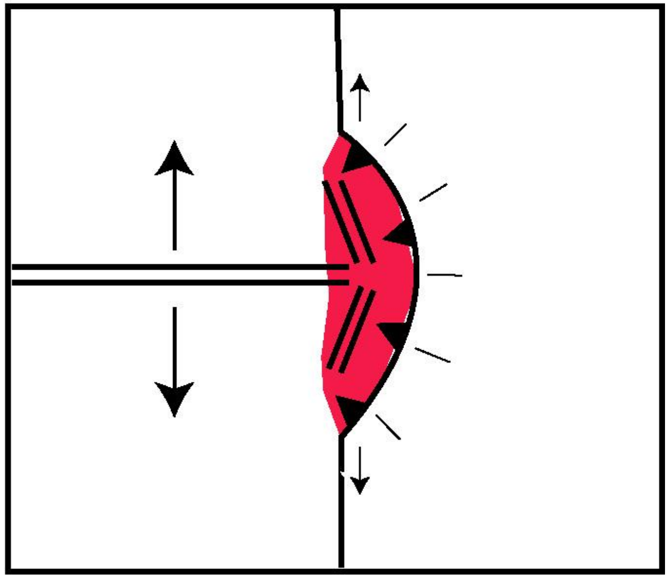
How did IBM Subduction Zone form?

2. Lithospheric Collapse & Formation of Infant Arc (proto-forearc*) by seafloor spreading

Section



Map View



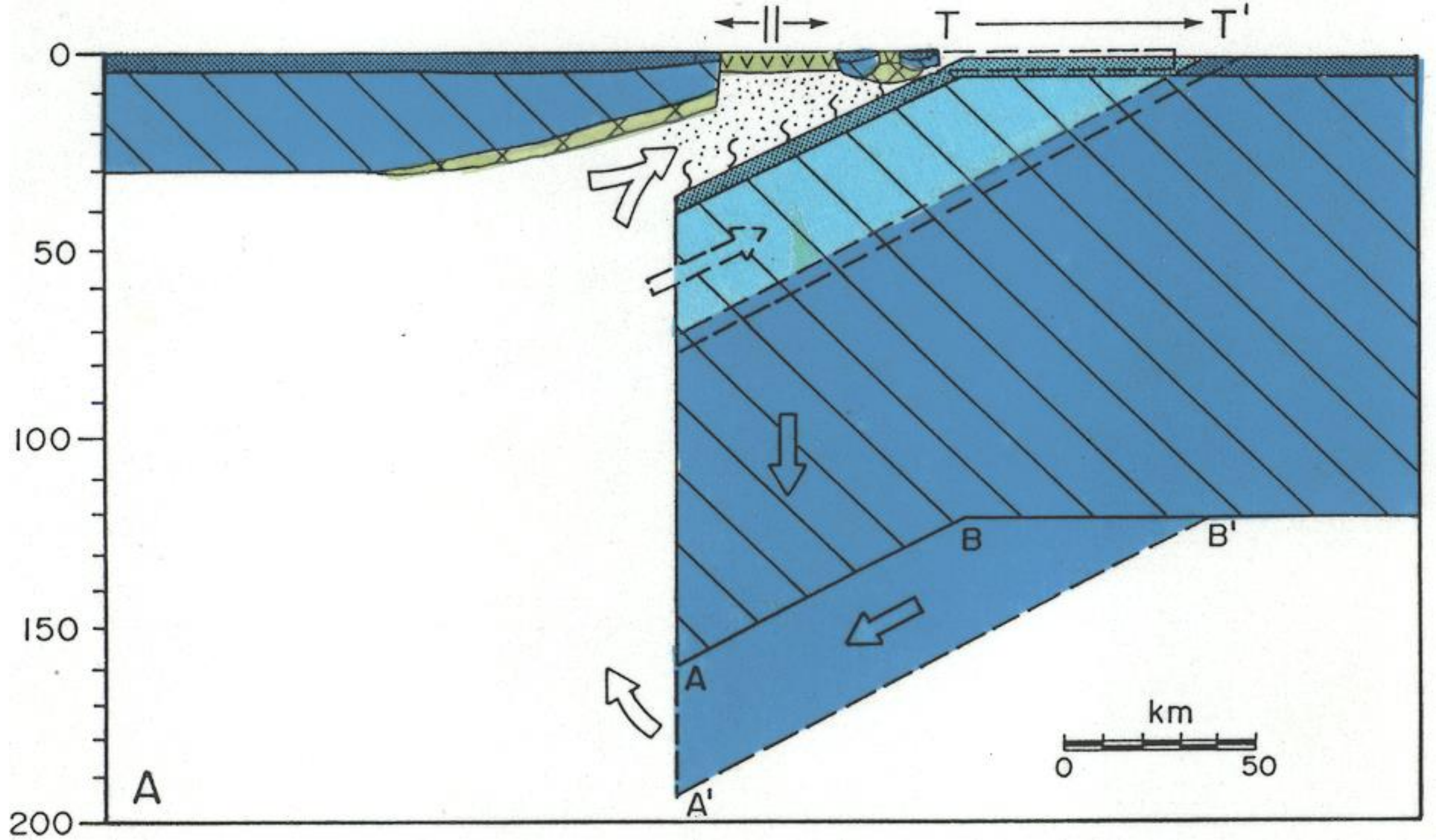
*Nursery of most ophiolites

How did IBM subduction zone form?

3. Proto-forearc widened by seafloor spreading as lithospheric subsidence continued

spreading

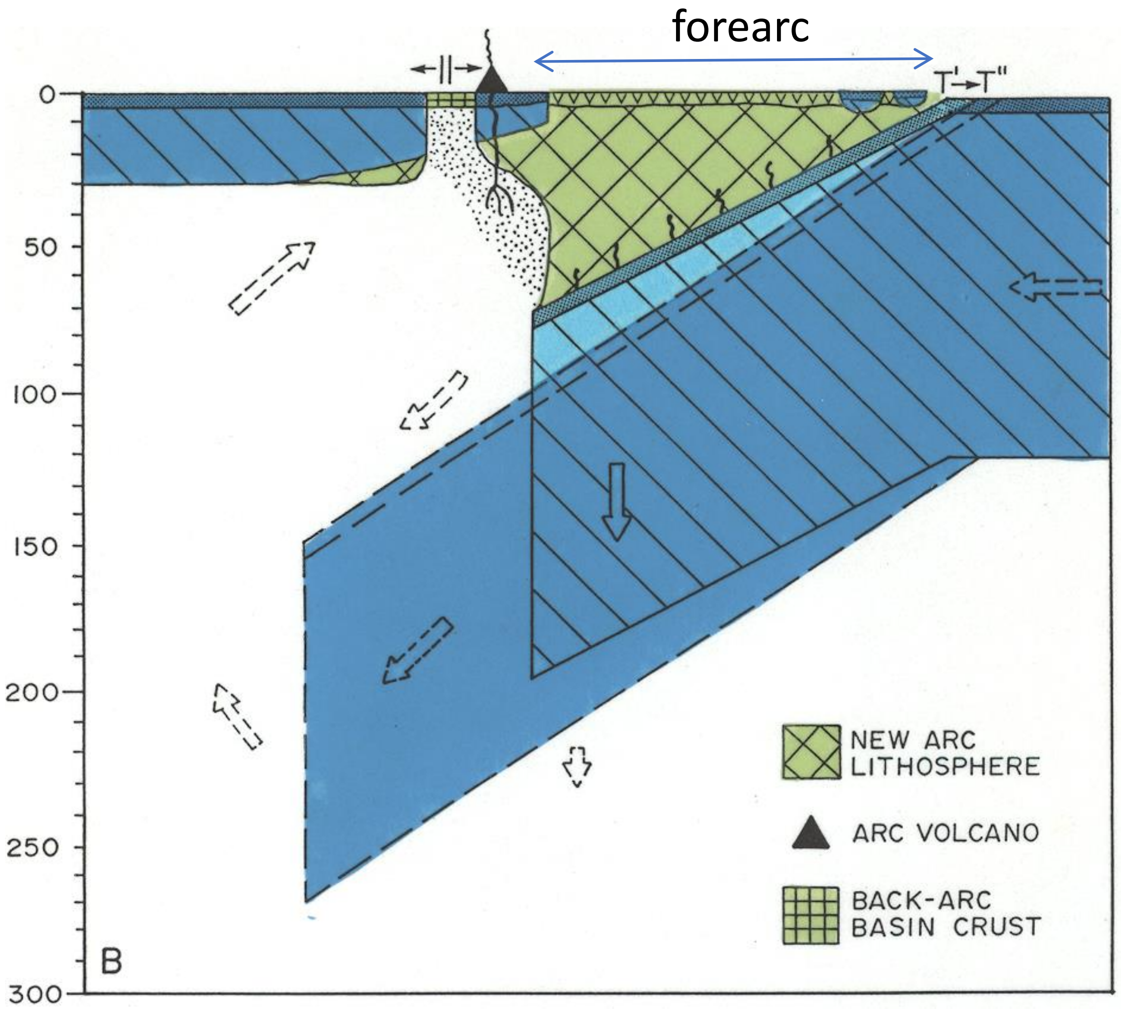
Trench rollback



Lithospheric subsidence and trench rollback drew in more asthensophere

How did IBM subduction zone form?

4. Forearc cools soon after true subduction (down-dip motion of plate) begins



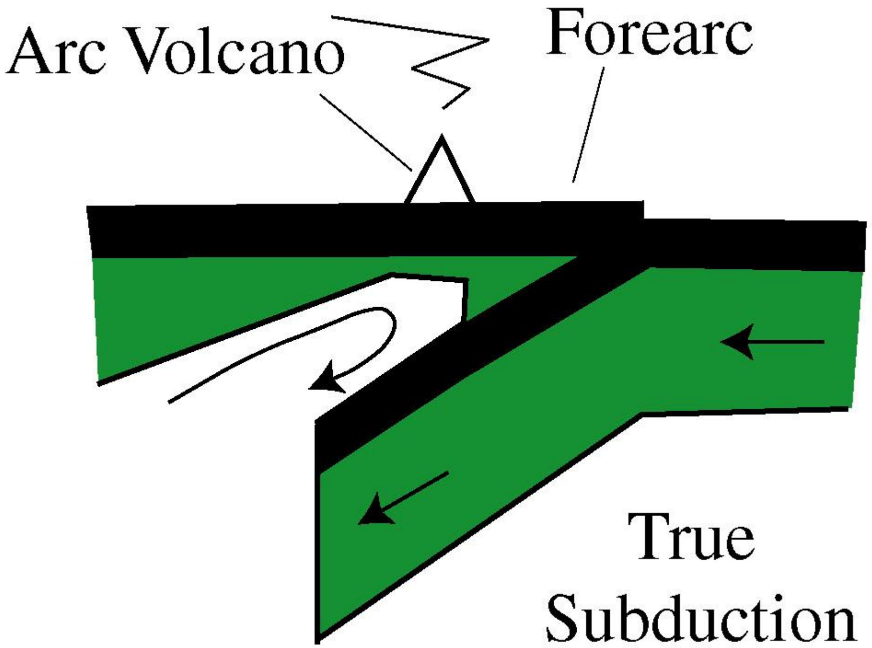
Lithospheric subsidence evolves to down-dip motion and true subduction

Mature arc system begins as forearc cools

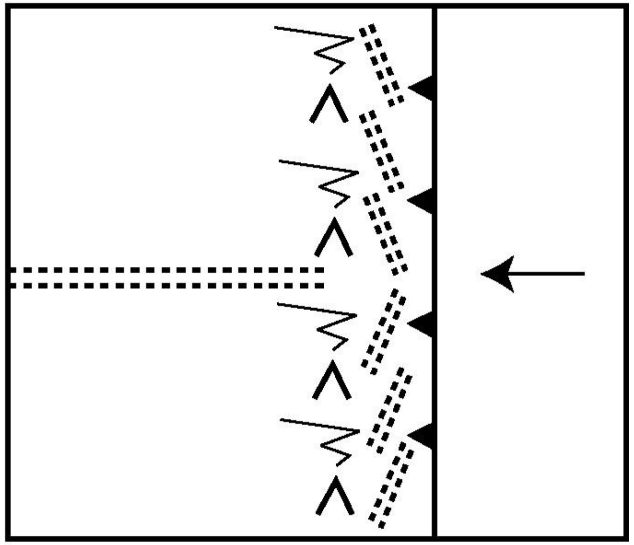
Stern & Bloomer 1992

E. Mature Subduction Zone

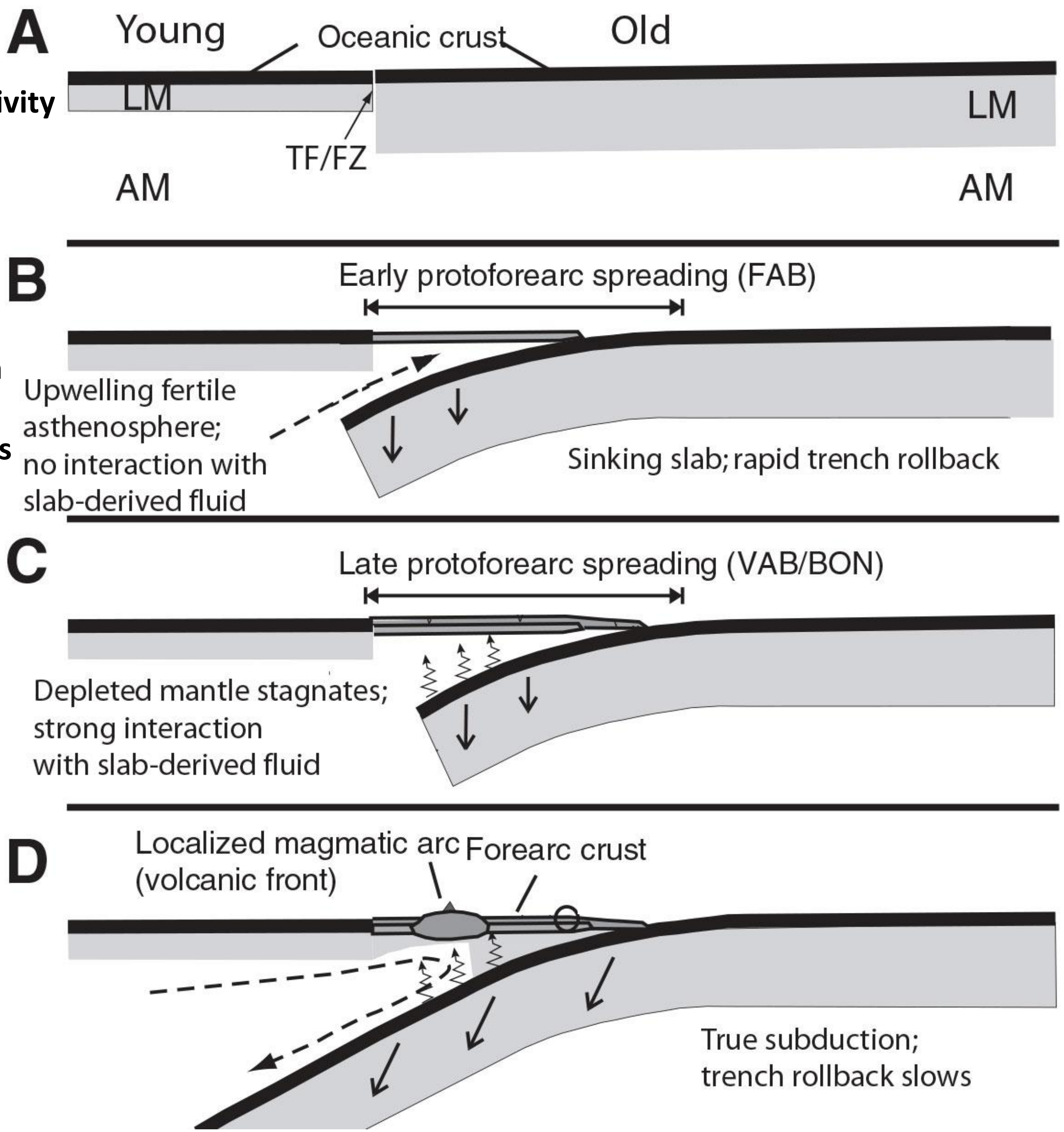
Section



Map View



Geochemical implications of lithospheric collapse SI model



No igneous activity

No Forearc igneous activity

Decompression melting; MORB-like melts (FAB)

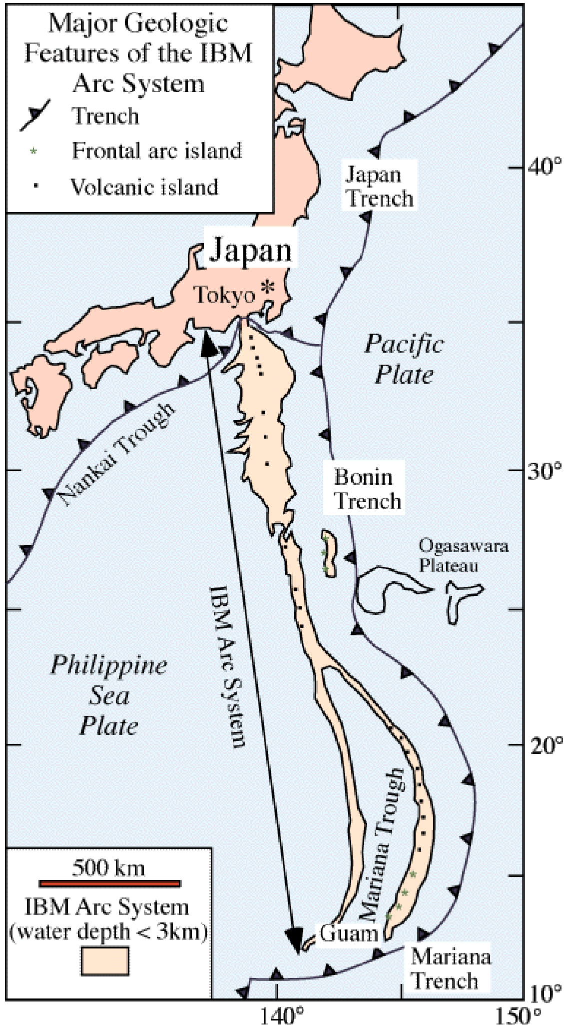
Forearc igneous activity (ophiolite formation)

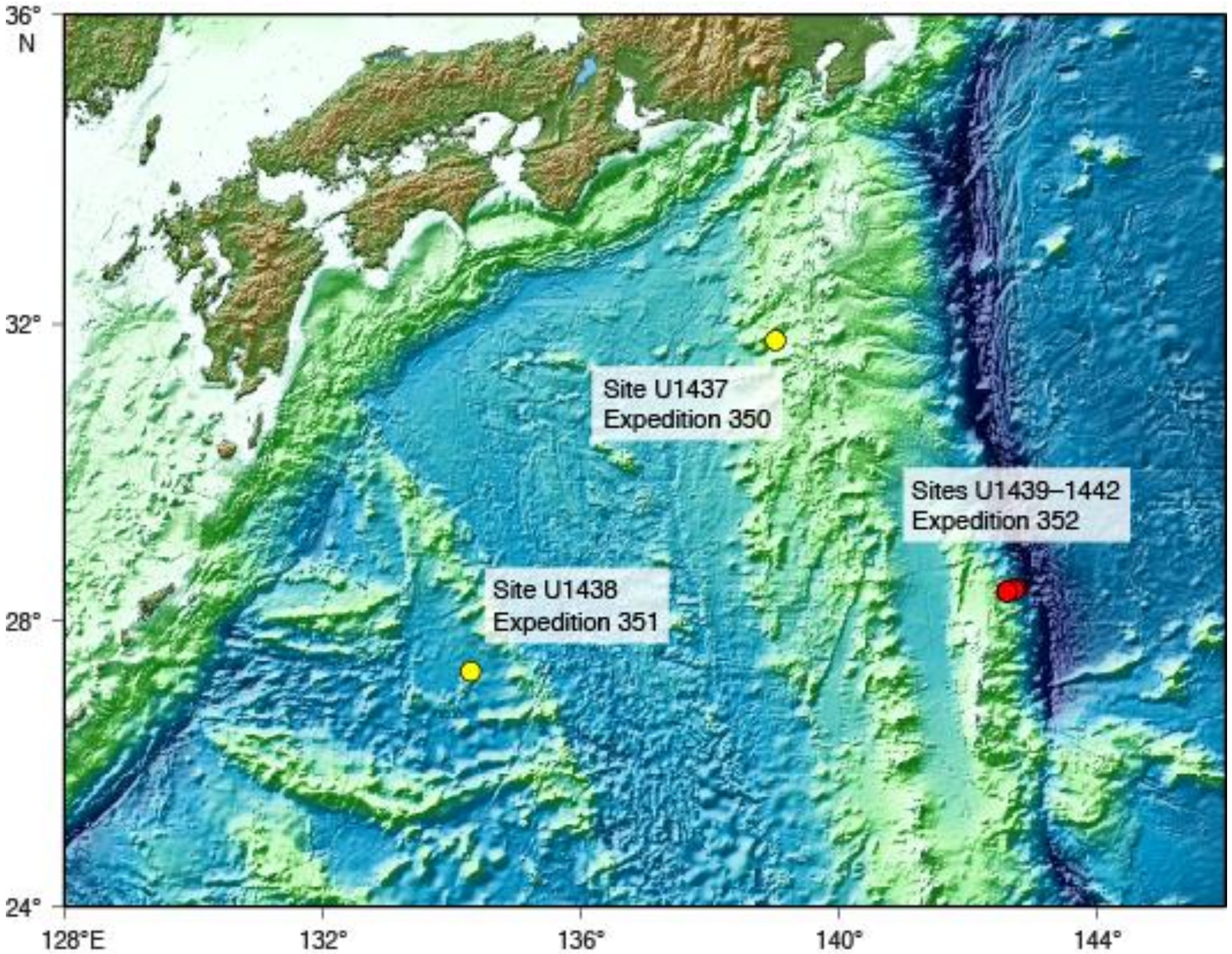
Flux melting (boninites and VAB)

Normal subduction and arc magmatic activity

No Forearc igneous activity

Test the Subduction Initiation model by drilling into forearc crust” IODP Drill Site 350 in the Izu forearc





IODP USIO

Expedition 352: Izu-Bonin-Mariana Forearc

30 July–29 September 2014

Co-Chief Scientists

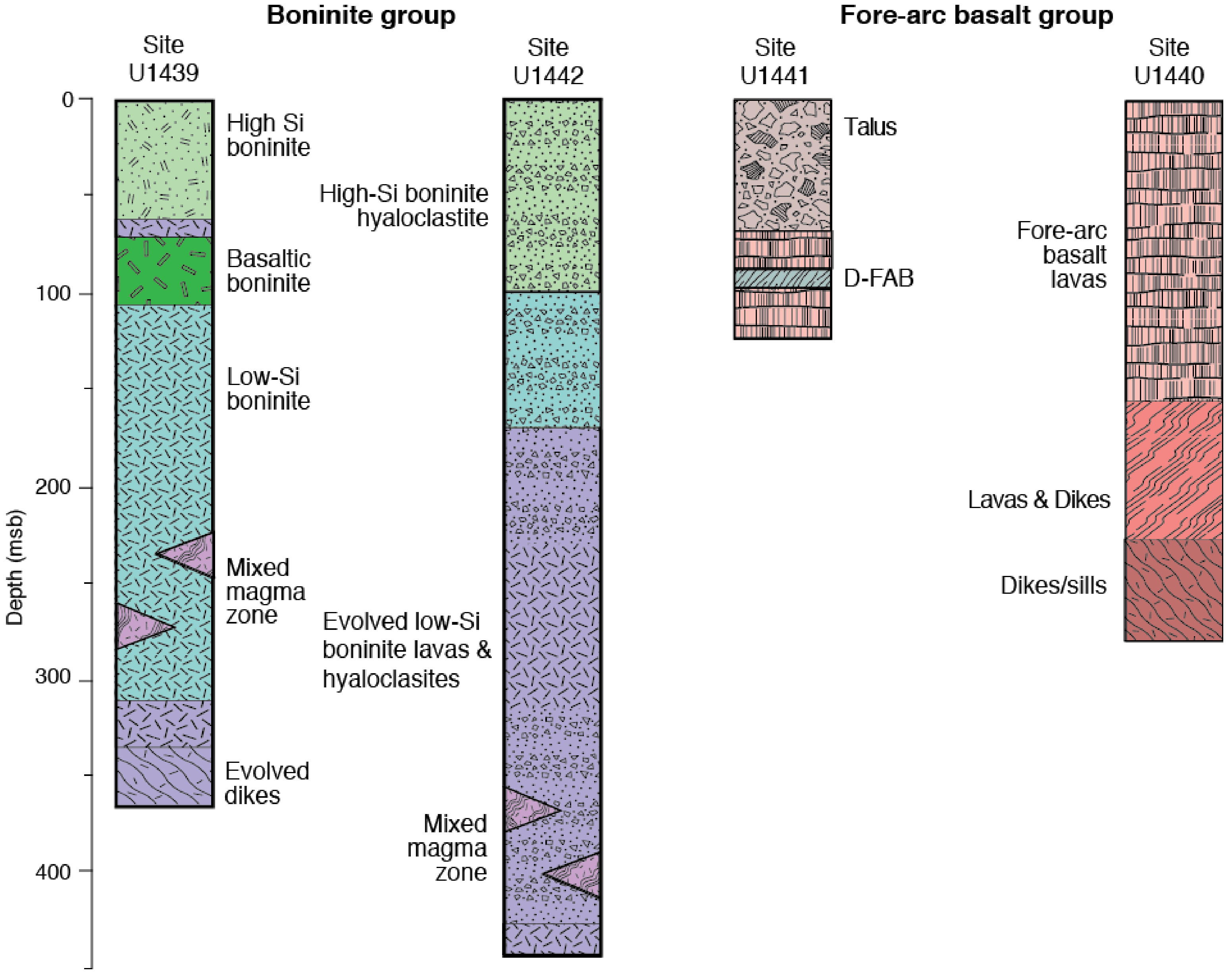
Julian Pearce　　Mark Reagan

Scientists

Renat Almeev, Aaron J. Avery, Claire Carvallo, Timothy Chapman, Gail L. Christeson, Eric C. Ferré, Marguerite Godard, Daniel E. Heaton, Maria Kirchenbaur, Walter Kurz, Steffen Kutterolf, Hongyan Li, Yibing Li, Katsuyoshi Michibayashi, Sally Morgan, Wendy R. Nelson, Julie Prytulak, Marie Python, Alastair H.F. Robertson, Jeffrey G. Ryan, William W. Sager, Tetsuya Sakuyama, John W. Shervais, Kenji Shimizu, Scott A. Whattam

IODP
INTERNATIONAL OCEAN DISCOVERY PROGRAM

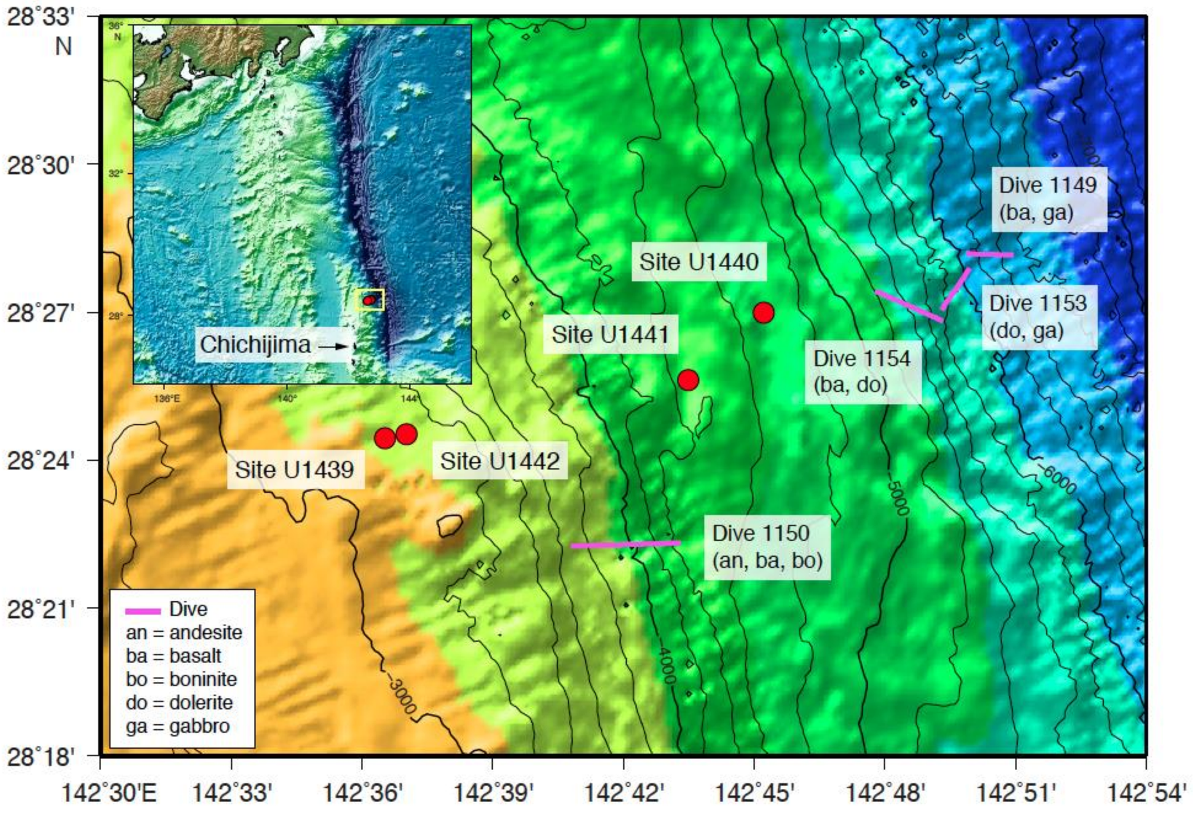
IODP 352 Lithostratigraphy

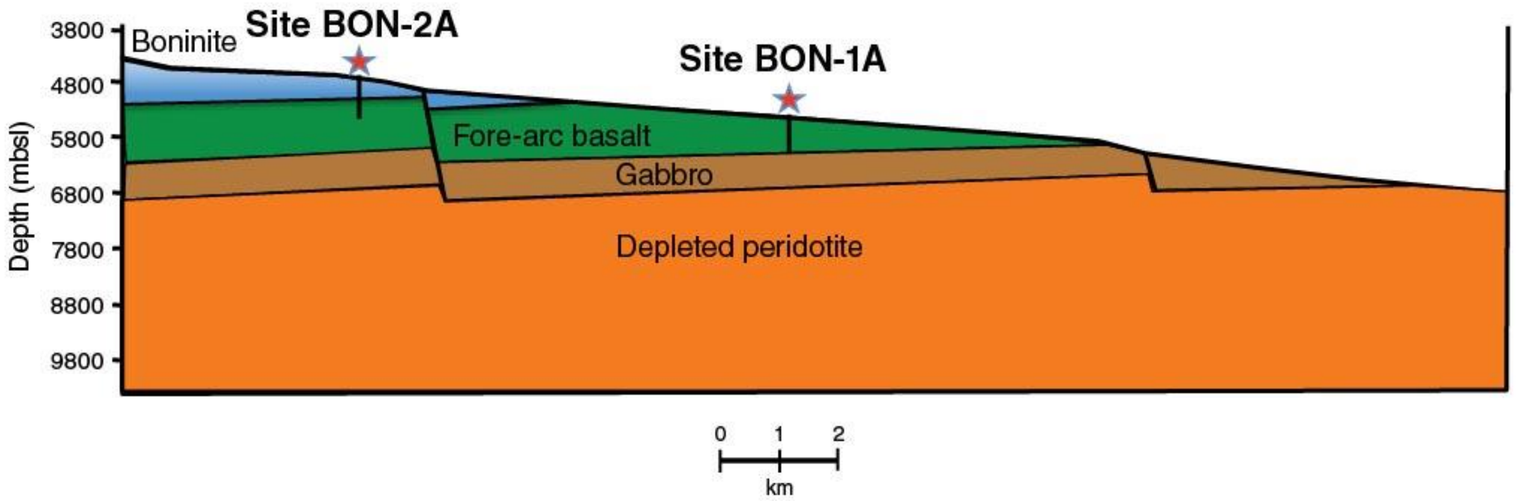


Igneous rocks of the IBM forearc recovered during IODP 352 formed during ~51 Ma subduction initiation event to form the Mariana convergent plate margin.

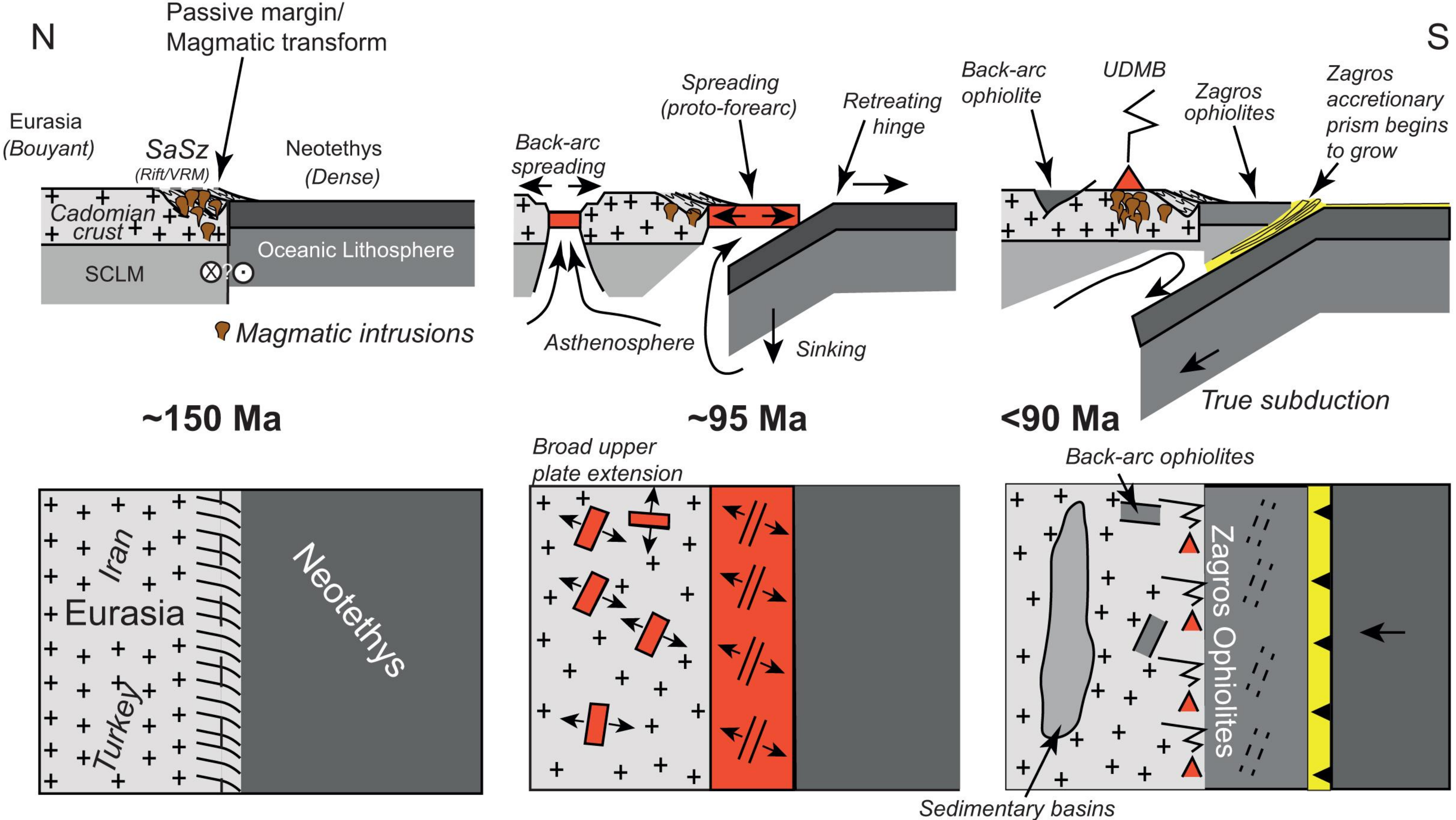
Similar sequences are observed on land in the Late Cretaceous ophiolites of Iran.

IODP 352 Drilled Sites sampled forearc crust like that of Late Cretaceous ophiolites of Iran

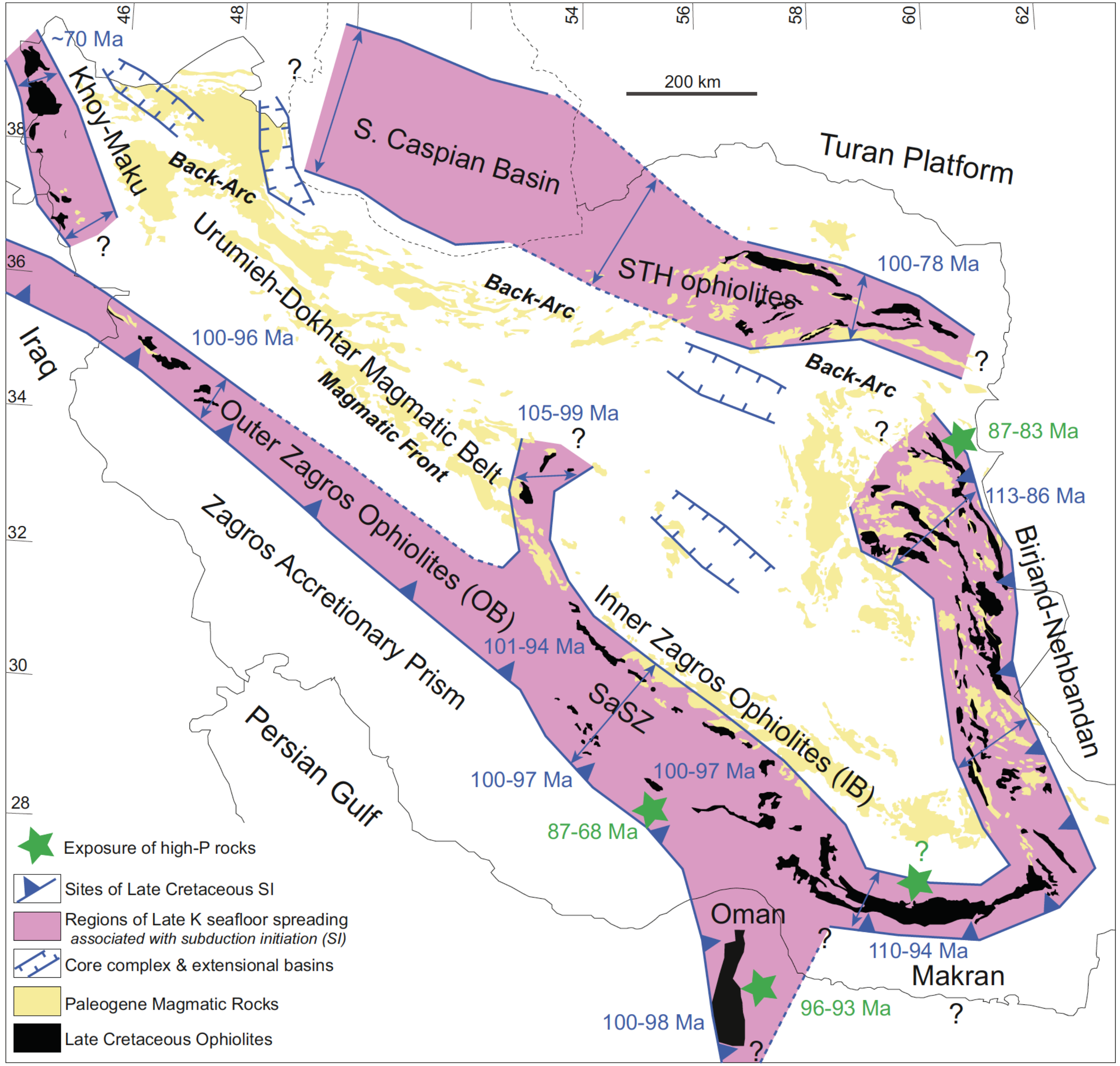




Late Cretaceous Subduction Initiation and Ophiolite Formation along the SW Eurasian margin



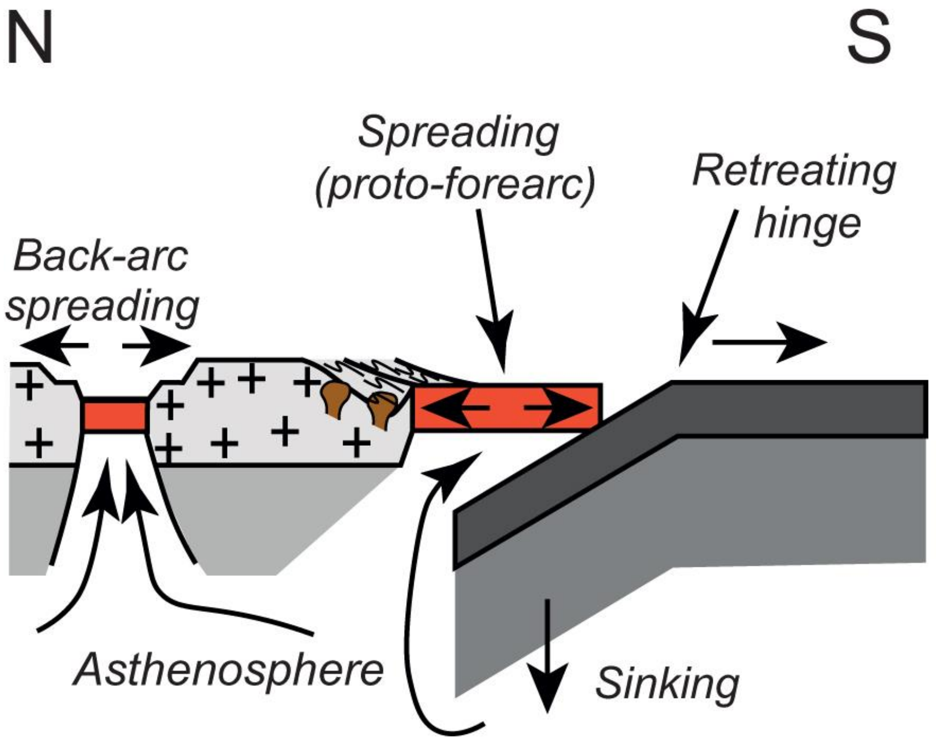
Subduction initiation causes broad upper plate extension: The Late Cretaceous Iran example



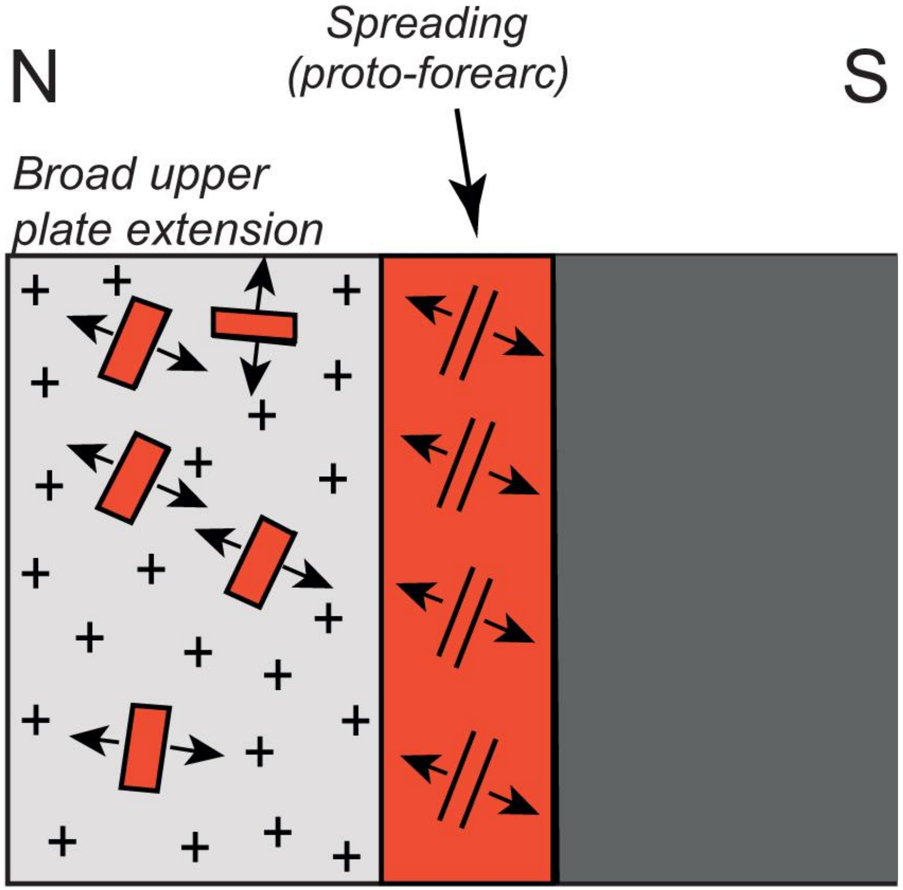
Simplified geological map of Iran emphasizing Late Cretaceous ophiolites and sedimentary basins as well as Cenozoic magmatic rocks. The tectono-magmatic traces of Late Cretaceous extensional regimes and basin opening are also represented. Ages in blue are zircon U-Pb ages, representing the crystallization age of ophiolite crust, whereas ages in green are for high-P metamorphism.

Moghadam and Stern, 2021 Lithos

~95 Ma (early Late Cretaceous)

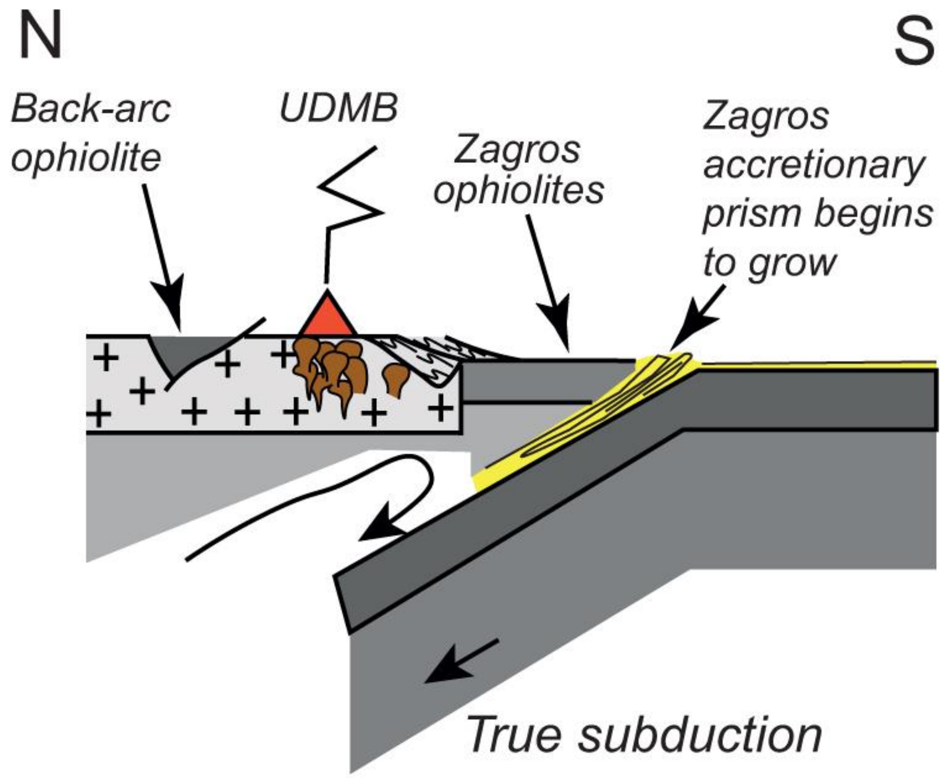


CrossSection

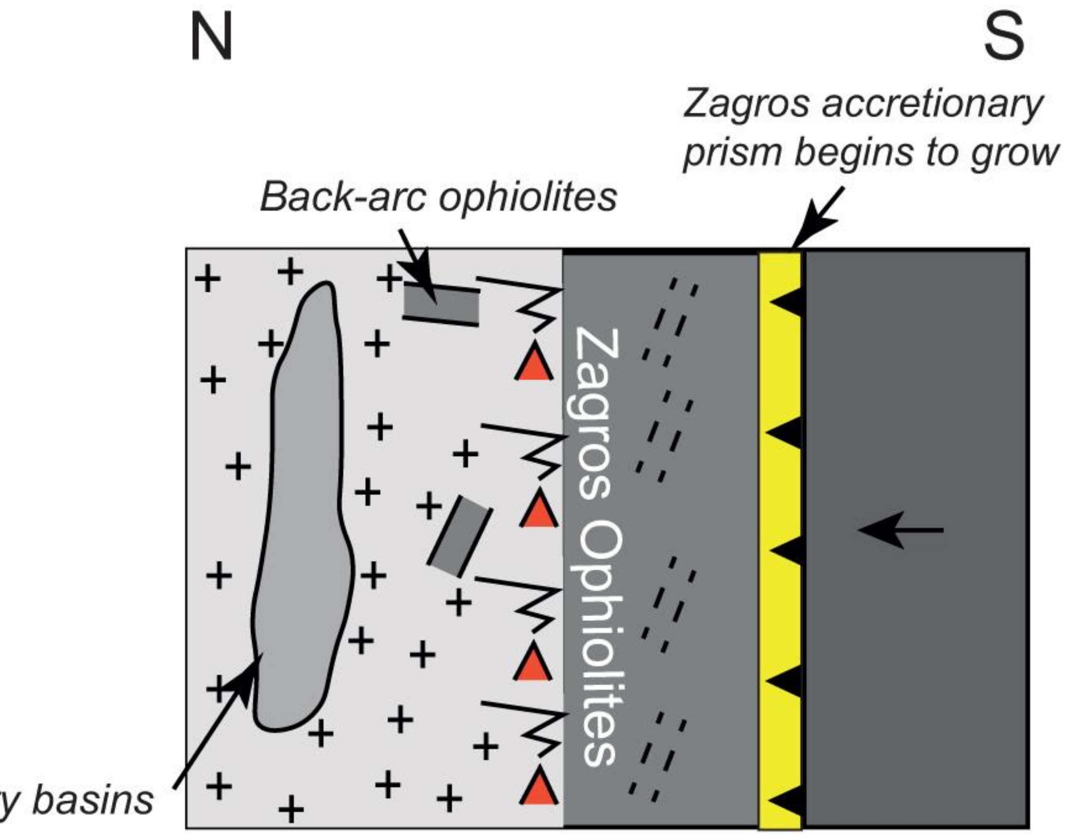


Map View

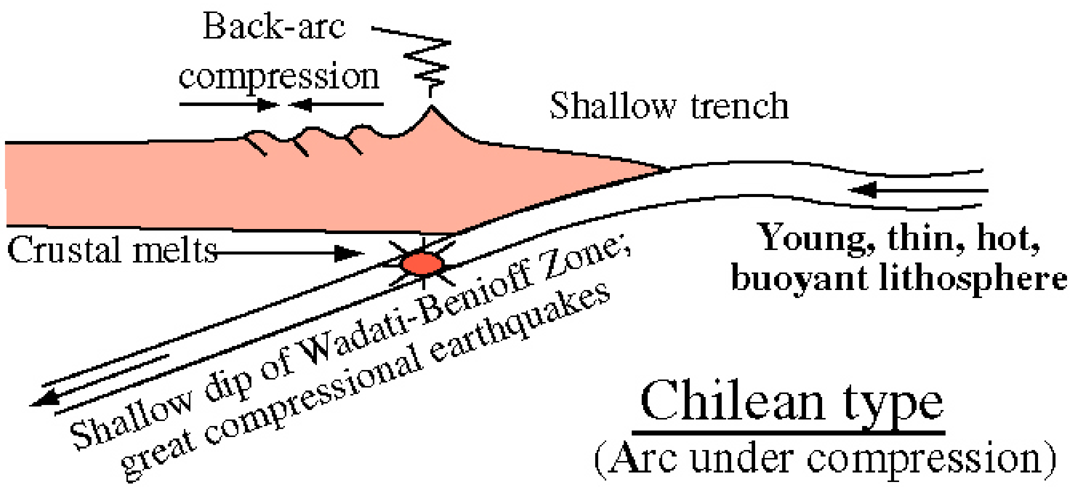
<90 Ma (Late Cretaceous)

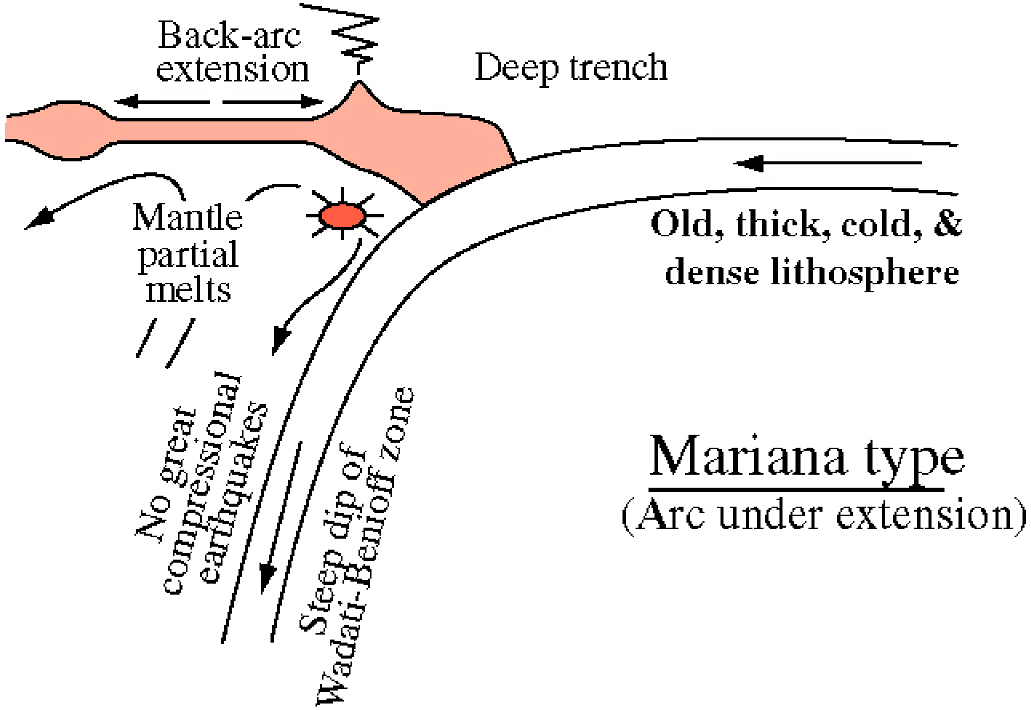


CrossSection



Map View



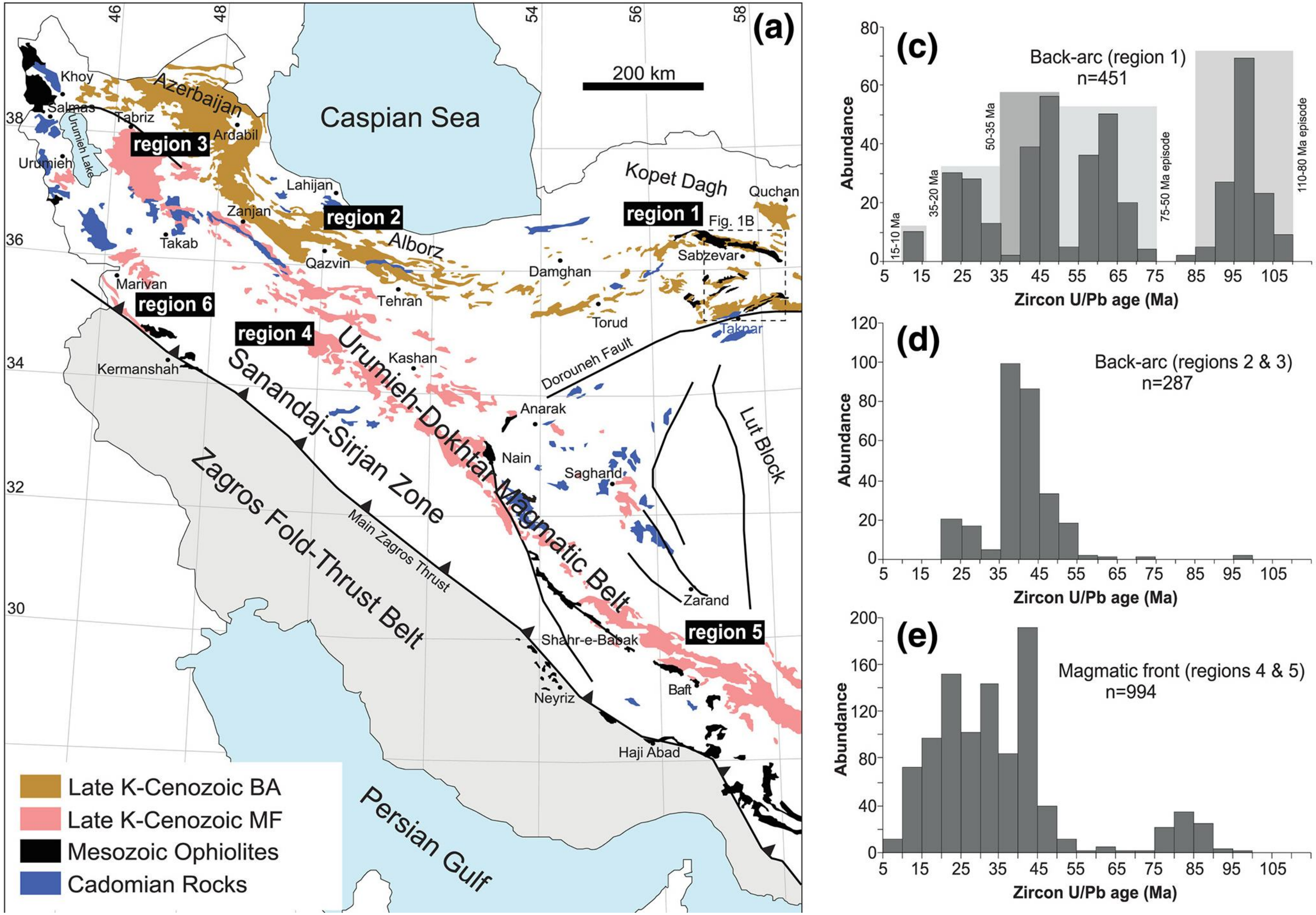


Convergent margins can be under compression or extension, depending on the buoyancy (age) of subducted lithosphere

Uyeda &
Kanamori, 1979

The Paleogene Iran arc was strongly extensional

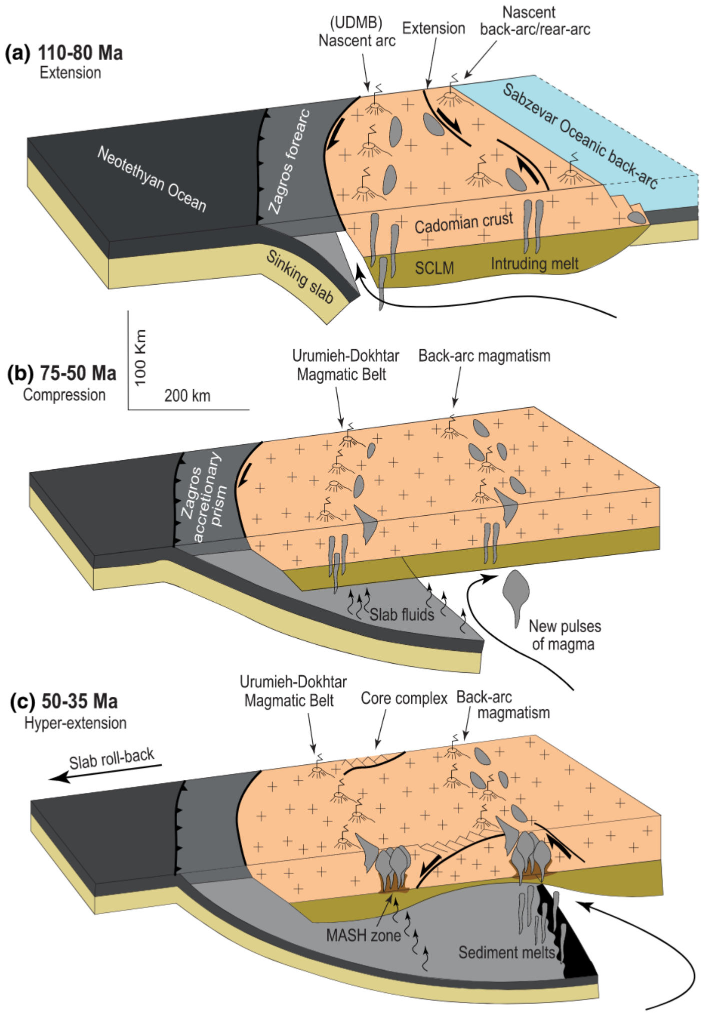
Paleogene Iran Magmatic Arc was unusually broad (up to 1000 km wide)



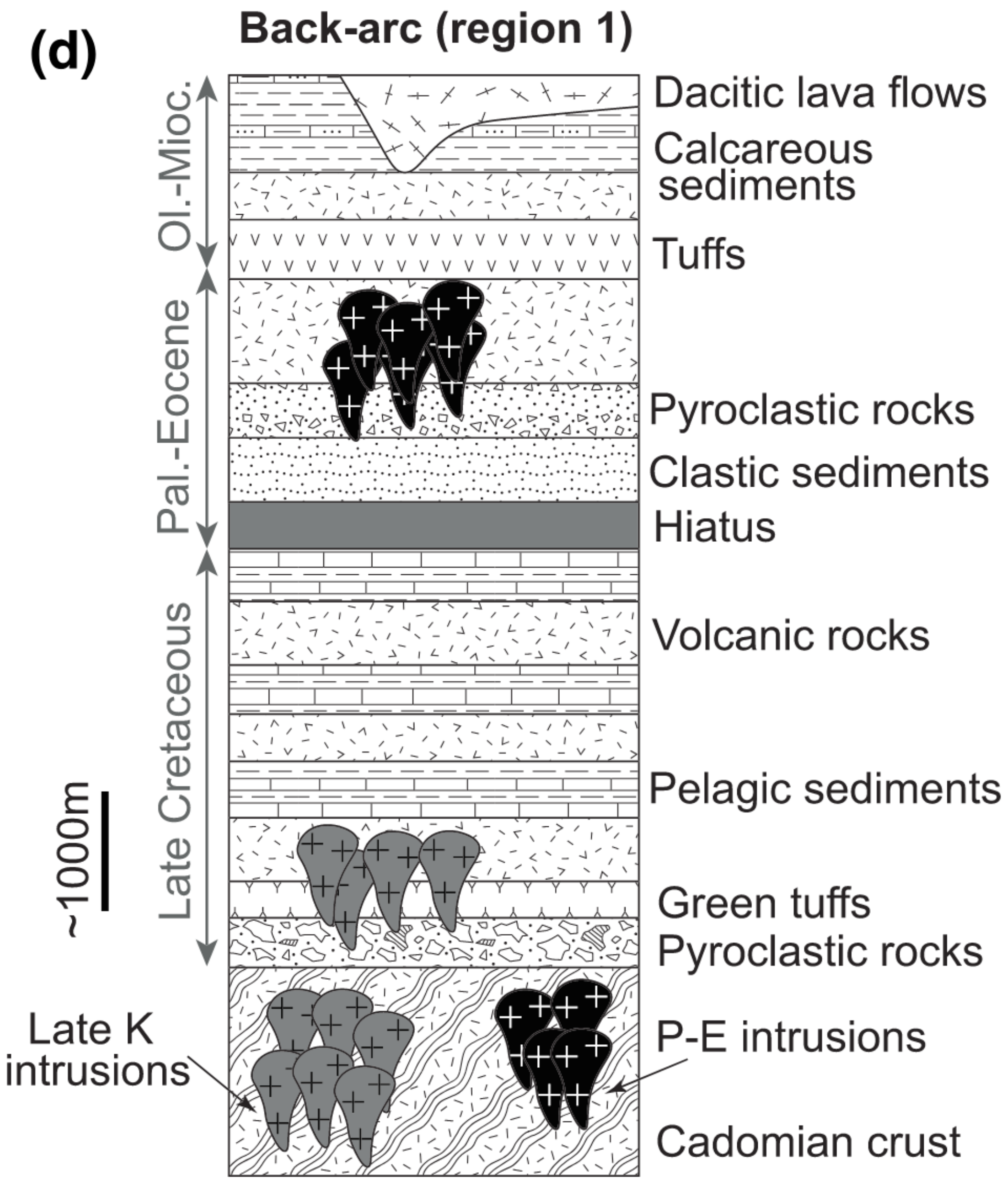
BA = Back Arc
MF = Magmatic Front

Moghadam et al., 2020 JGR

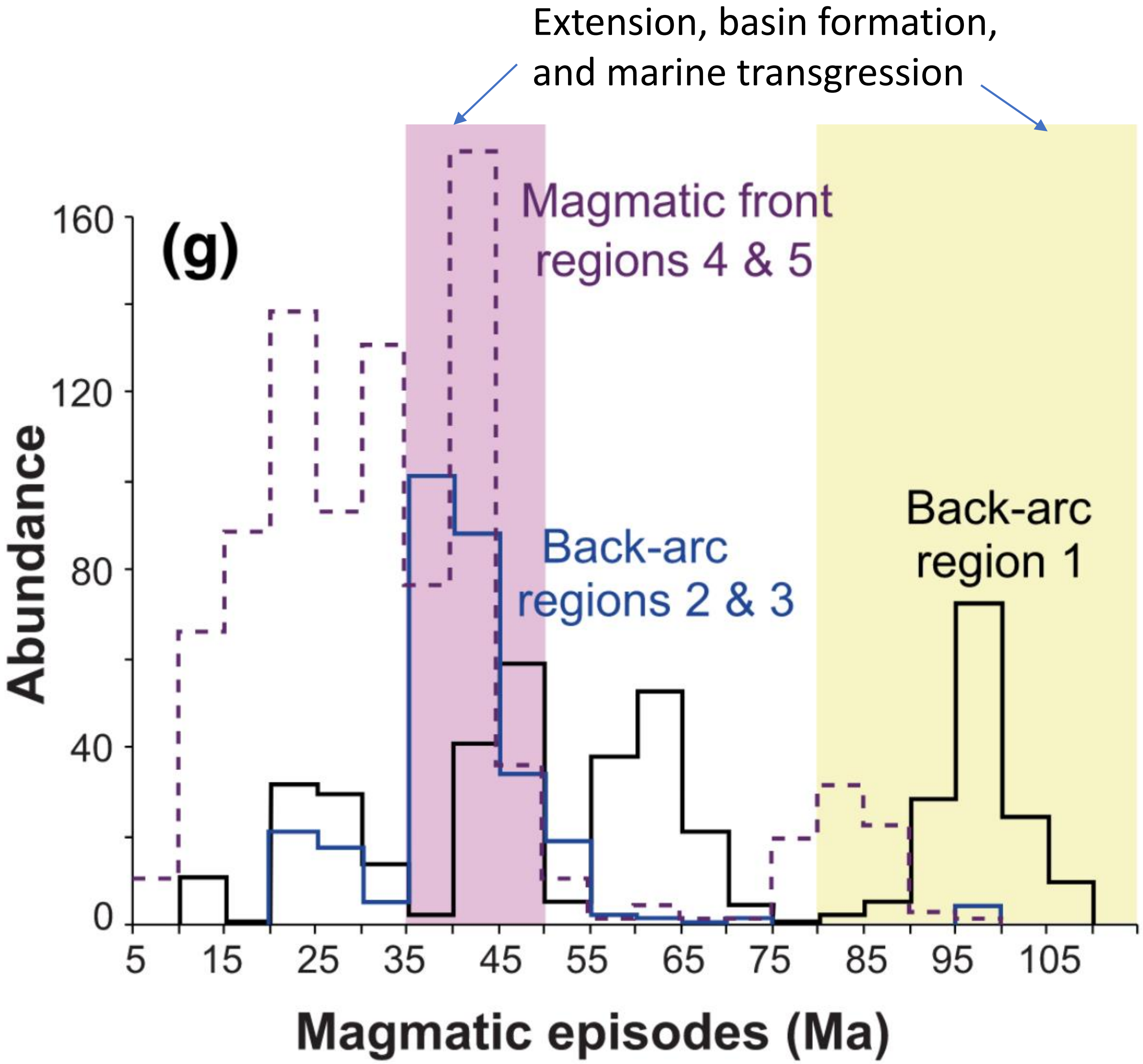
Paleogene Iran Convergent Margin was strongly extensional, as shown by interbedded marine sediments



Moghadam et al., 2020

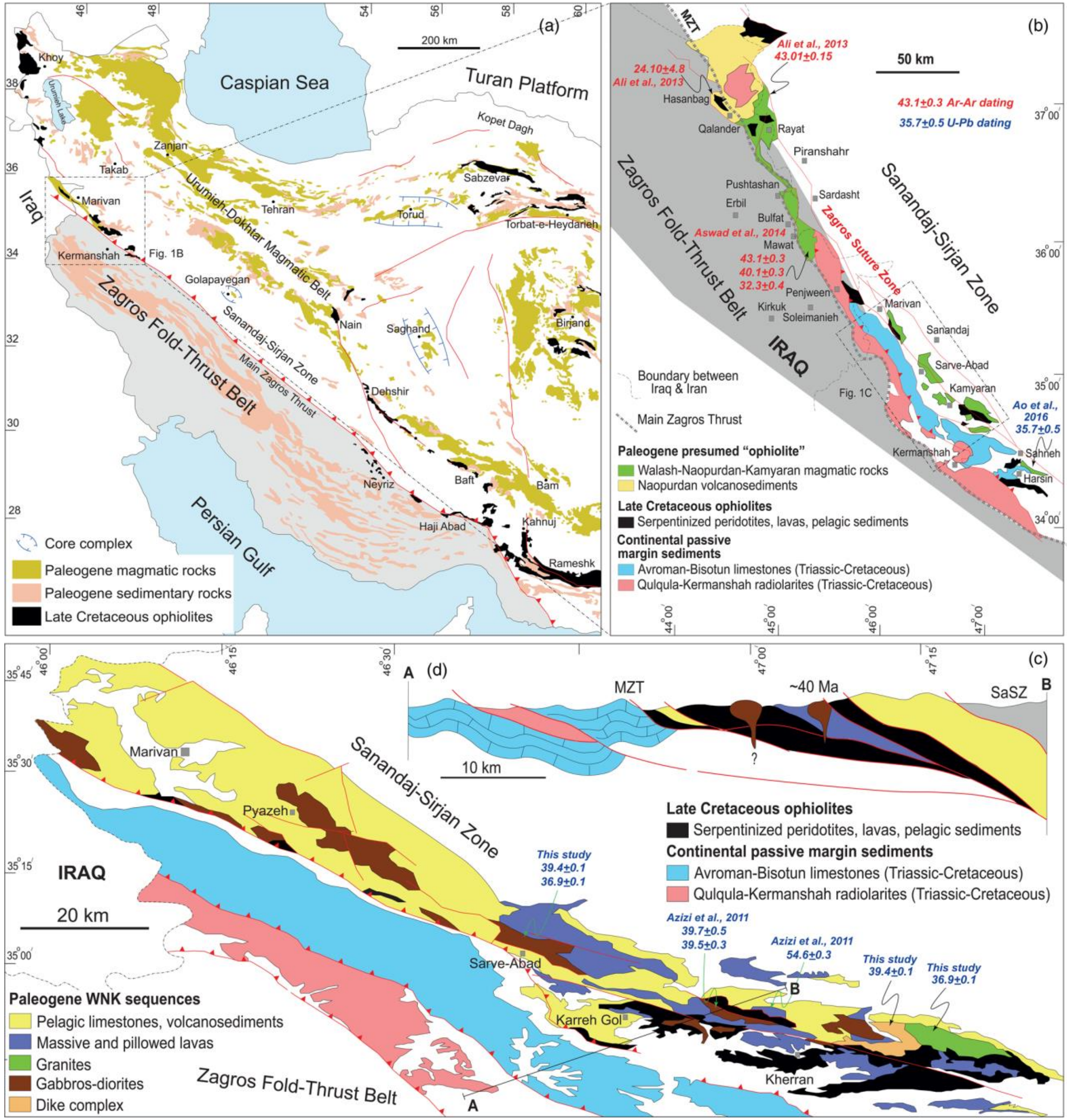


Iran magmatism, Mid-Cretaceous to present



Moghadam et al., 2020

Paleogene "Ophiolites" of Kurdistan testify to very strong extension ~37 Ma (Late Eocene)



Simplified map showing the distribution of Late Cretaceous forearc ophiolites and Paleogene oceanic rocks (Walash–Naopurdan–Kamyran series) along the Iran–Iraq border (modified after Ali et al. (2013)).

Schematic cross section showing the relations between the Paleogene intrusions and older lithological units (modified after Agard et al. (2005)).

Moghadam et al. 2020 JGSL

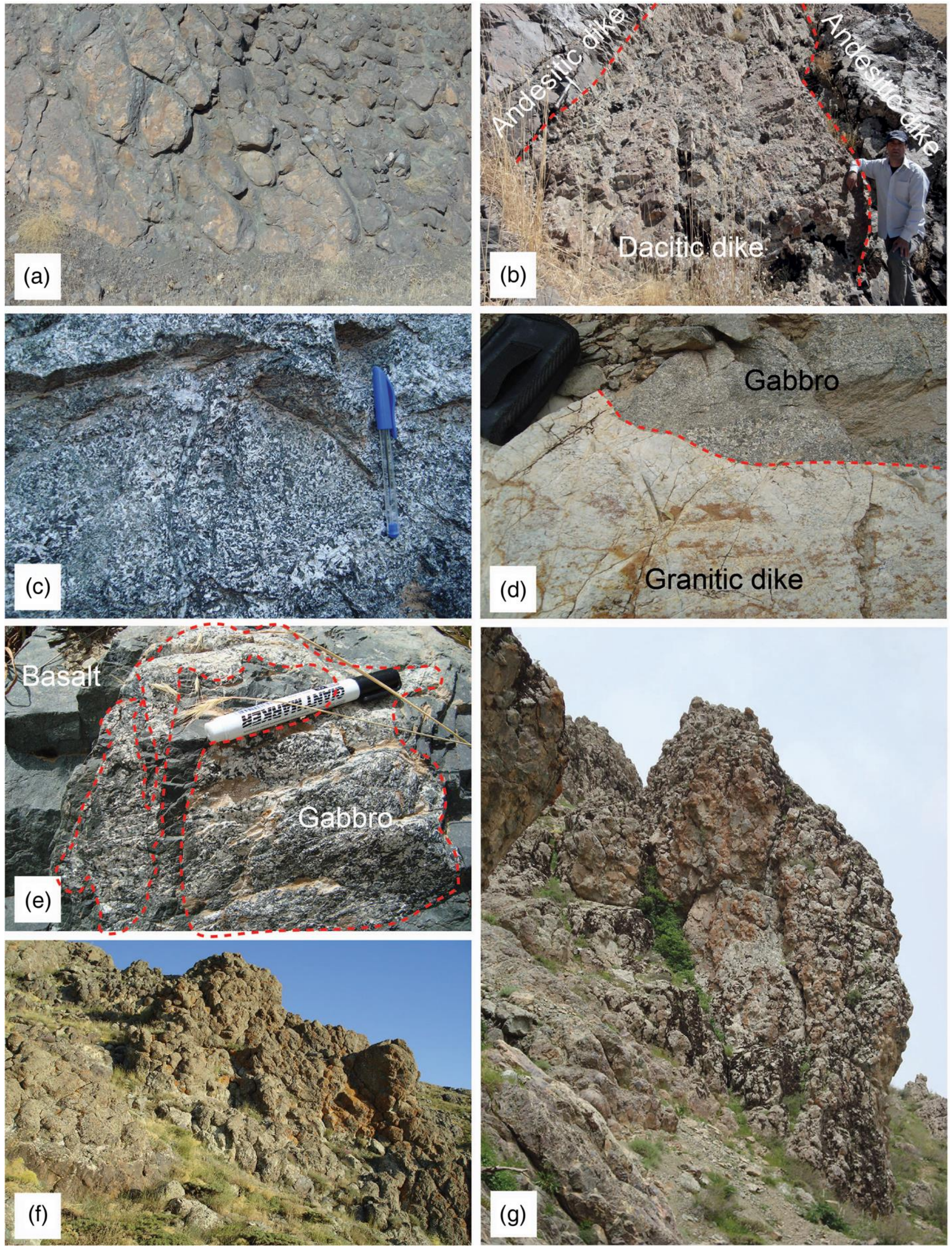
Paleogene “ophiolites” of Kurdistan

Outcrop of Paleogene pillow lavas from SE Kamyaran.

Granitic dikes injected into gabbros.

Gabbro inclusions within the overlying pillow lavas – at the contact between gabbros and pillow lavas.

F, G: Outcrops of NW Kamyaran pillow lavas.

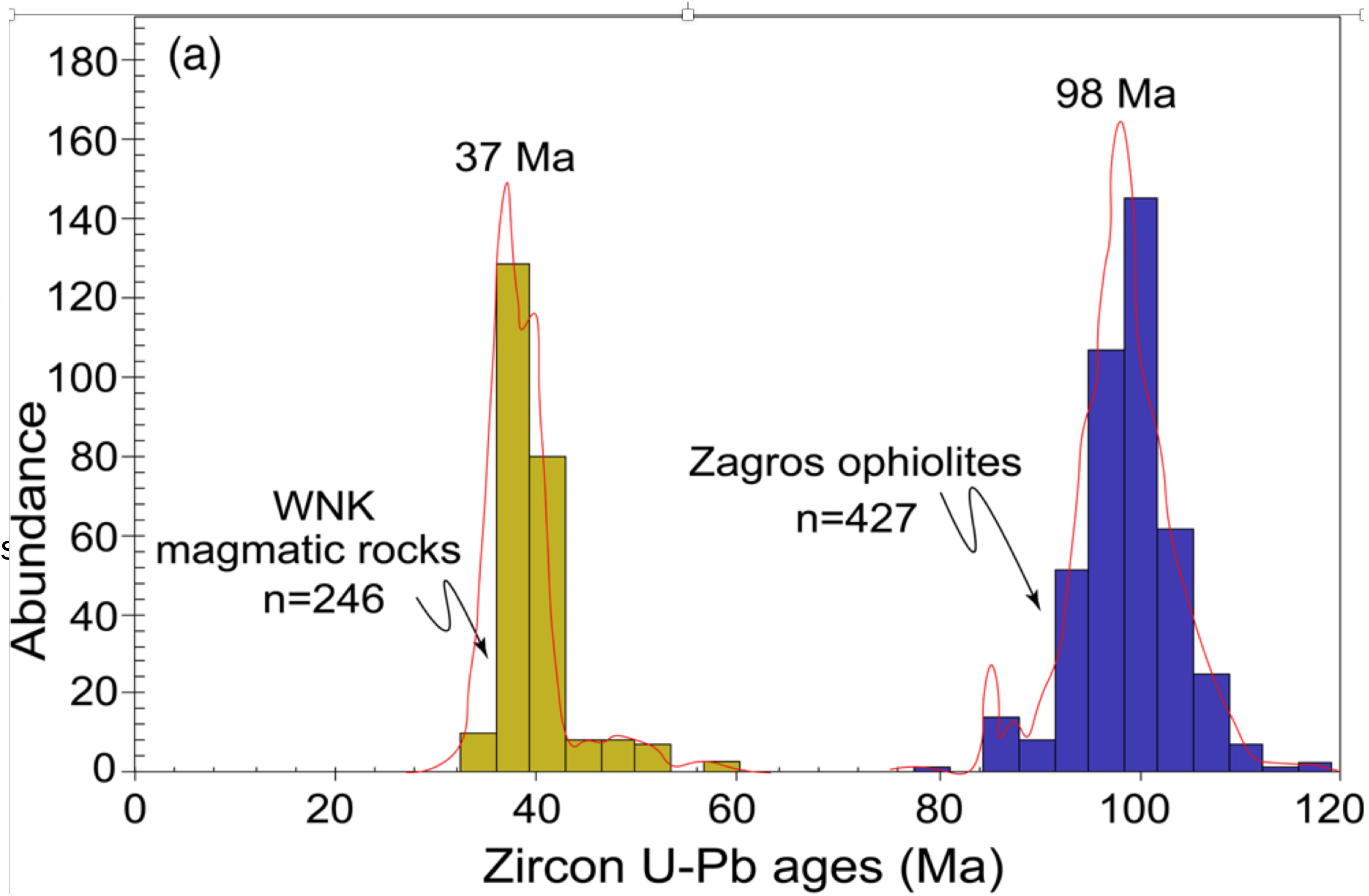


Contact between dacitic dikes and (basaltic-) andesitic dikes from SE Kamyaran.

Granitic dikes injected into gabbros.

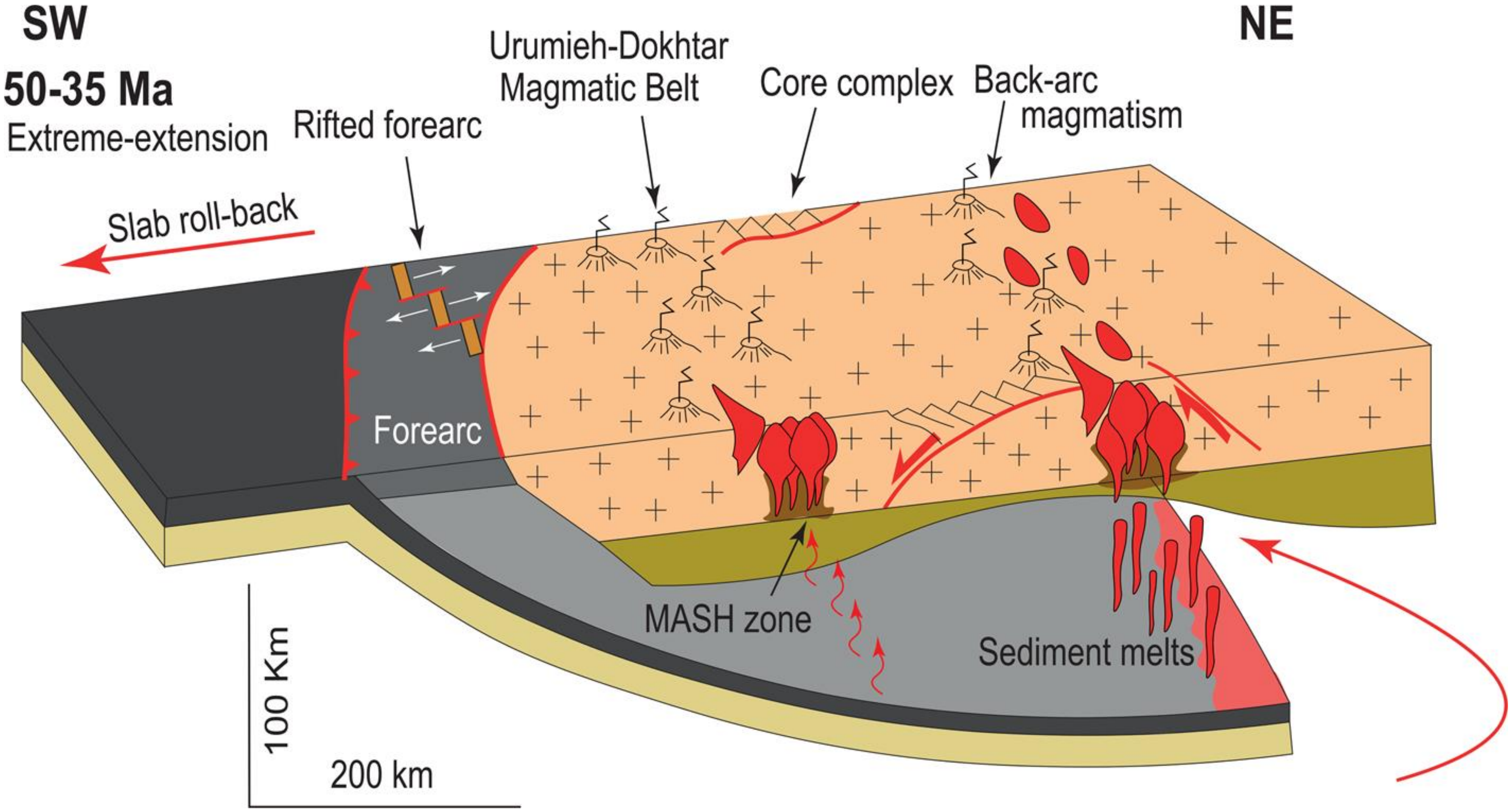
These demonstrate very strong extension!

Histograms showing the magmatic age distribution of (a) Walash–Naopurdan–Kamyran (WNK) series igneous rocks (including “ophiolites”) and Zagros Late Cretaceous ophiolites (-blue),



Moghadam et al. 2020 JGSL

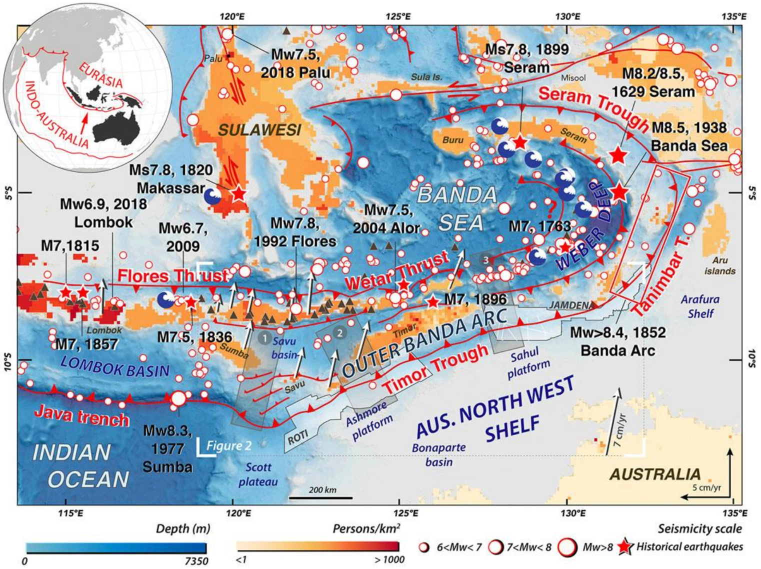
Simplified cross-section of the Paleogene convergent margin of Iran, emphasizing **extreme extension** in the Iranian plateau during Paleogene (50–35 Ma).



Moghadam et al. 2020 JGSL

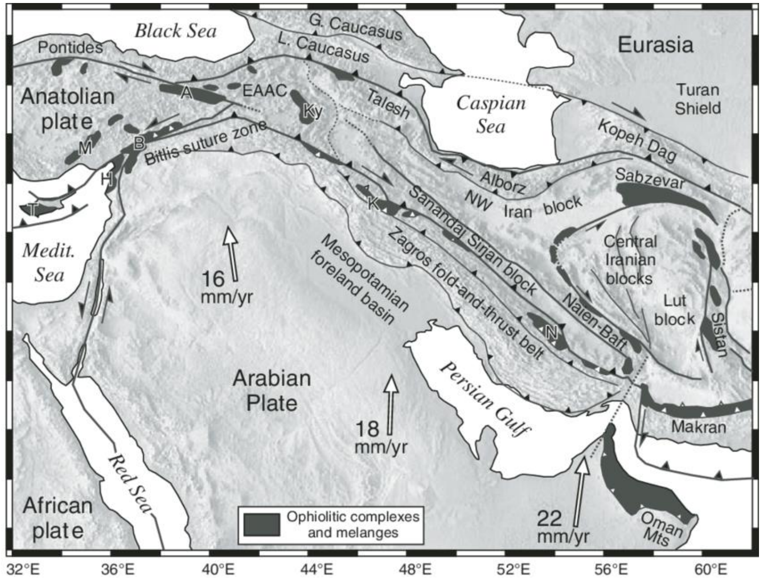
A Tale of Three Continental Collisions

Early Stage
(Australia-Indonesia)
Just beginning



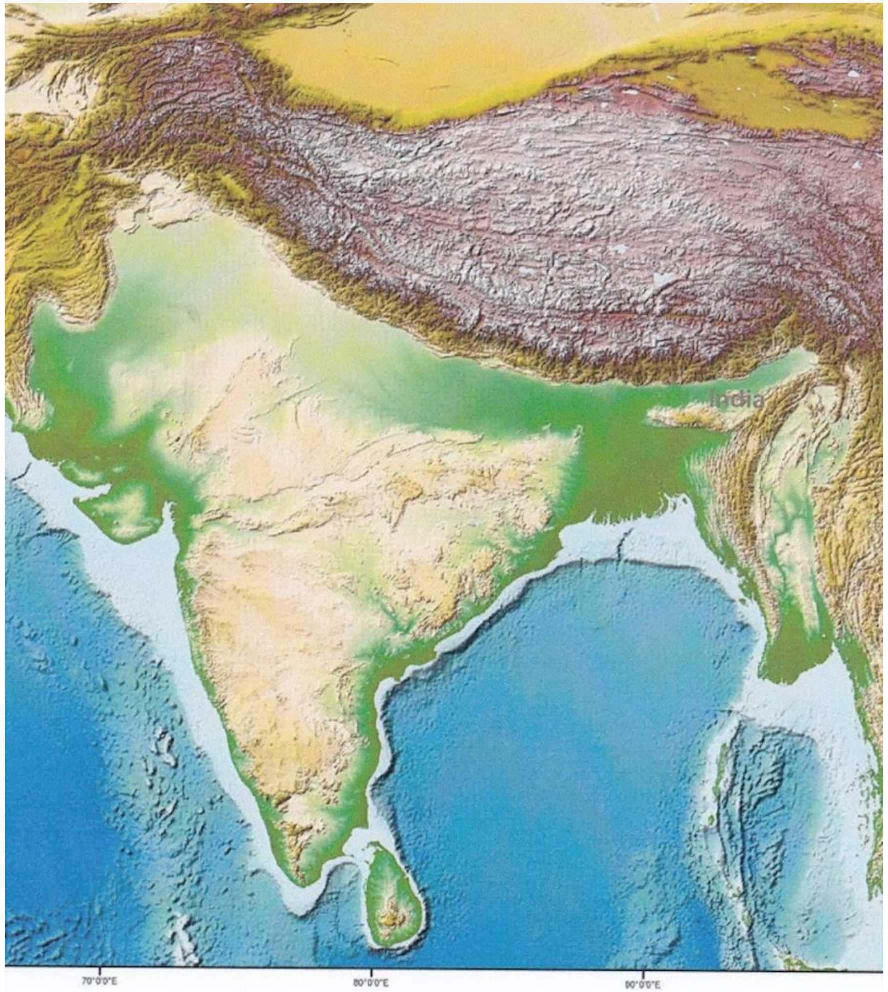
Coudurier-Curveur et al., 2021

Middle Stage
(Arabia-Iran)
Going on for 25 Ma



Homke et al. 2009

Late Stage
(India-Tibet)
Going on for 50 Ma



Iran is a Natural Geoscience Laboratory

- Study Cadomian rocks to understand how new continental crust forms
- Study Jurassic Sanandaj-Sirjan Zone rocks to understand the formation of continental rifts and volcanic passive margins
- Study Late Cretaceous ophiolites to understand how new subduction zones form
- Study Paleogene igneous rocks and associated sediments to understand extensional continental arcs
- Study Neogene igneous and sedimentary rocks and Zagros structure to understand early stages of continental collision